UMENTATION PAGE

Form Approved
OMB No. 0704-0188

2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
August 31, 1992	Final Report - 12/15/86-6/30/92

4. TITLE AND SUBTITLE
Center for High-Frequency Microelectronics

5. FUNDING NUMBERS
DAAL03-87-K-0007

6. AUTHOR(S)
George Haddad, et al.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Center for High Frequency Microelectronics
University of Michigan
Department of Electrical Engineering & Computer Science
2228 EECS Bldg.
Ann Arbor, Michigan 48109-2122

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 24611.32S-EL-UIR

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

By any measure of productivity and impact this program has been highly productive and has had a major impact on III-V semiconductor technology as evidenced by the number of publications, graduate-student output, interactions with Army laboratories, and other D.O.D., industrial and academic laboratories. This program has provided tremendous leverage by enabling us to attract major programs from other federal agencies and industry. It has also enabled us to establish one of the leading facilities and programs in the nation for research in high-frequency microelectronics through major cost-sharing by the University, the State of Michigan and industrial and federal agencies. This program has had and will continue to have a tremendous impact on the field.

14. SUBJECT TERMS	15. NUMBER OF PAGES
	229
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

CENTER FOR HIGH-FREQUENCY MICROELECTRONICS

FINAL REPORT

George I. Haddad et al.

August 1992

U. S. Army Research Office

Contract/Grant Number: DAAL03-87-K-0007

University of Michigan
Department of Electrical Engineering and Computer Science
Ann Arbor, Michigan 48109-2122

24611-EL-UIR

FINAL REPORT
FIFTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 24611-EL-UIR
2. PERIOD COVERED BY REPORT: 15 DECEMBER 1986– 30 JUNE 1992
3. TITLE OF PROPOSAL: Center for Research on High- Frequency Microelectronics
4. CONTRACT OR GRANT NUMBER: DAAL03-87-K-0007
5. NAME OF INSTITUTE: University of Michigan
6. AUTHORS OF REPORT: George I. Haddad et al.
7. SUMMARY OF MAJOR ACCOMPLISHMENTS AND A LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES.

By any measure of productivity and impact this program has been highly productive and has had a major impact on III-V semiconductor technology as evidenced by the number of publications, graduate-student output, interactions with Army laboratories, and other D.O.D., industrial and academic laboratories. This program has provided tremendous leverage by enabling us to attract major programs from other federal agencies and industry. It has also enabled us to establish one of the leading facilities and programs in the nation for research in high-frequency microelectronics through major cost-sharing by the University, the State of Michigan and industrial and federal agencies. This program has had and will continue to have a tremendous impact on the field. The following presents a summary of major accomplishments under this program:

George I. Haddad
Department of Electrical Engineering
& Computer Science
University of Michigan
Ann Arbor, Michigan 48109-2122

7.1 PUBLICATIONS

The manuscripts published or submitted under the Army Research Office sponsorship includes:

1. A publication summary
2. A detailed list of publications including journal references.

PUBLICATION SUMMARY

			TOTAL
BOOK CHAPTERS			
	1987	0	
	1988	0	
	1989	2	
	1990	2	
	1991	3	
	1992	1	8
JOURNAL PUBLICATIONS			
	1987	10	
	1988	31	
	1989	44	
	1990	55	
	1991	60	
	1992	17	217
CONFERENCE PRESENTATIONS			
	1987	16	
	1988	22	
	1989	55	
	1990	44	
	1991	64	
	1992	26	227
	TOTAL		452

Accepted for Journal Publication (1992)		13
Accepted for Conference Presentation (1992)		10
Submitted to Journals		24
Submitted to Conferences		5
	(Total Pending	29)

GRAND TOTAL 504

PUBLICATION LIST

Books – Book Chapters

1. P. Mazumder, "Design of a Fault-Tolerant DRAM with New On- Chip ECC," Book Chapter, *Defects and Fault-Tolerance* (editor I. Koren) Plenum Publishers, 1989.

2. D. A. Weinberger, "Second harmonic generation in optical fibers," invited book chapter, published in *Nonlinear Optics in Solids*, Springer Ser. Wave Phen., O. Keller, ed. (Springer-Verlage, Berlin, Heidelberg, 1989).

3. P. Bhattacharya and J. Singh, "Molecular Beam Epitaxy and Its Application to Microwave and Optical Devices," *Handbook on Microwave and Optical Components* (ed. K. Chang), Wiley, Interscience, pp. 1–56, 1990.

4. K. Sahookar and P. Mazumder, " VLSI Cell Placement Techniques" book chapter to appear in *Computer Aided Design*, vol. II, (editor, T. N. Hajj), Jai Publishers, in press.

5. G. I. Haddad and I. Mehdi, "Device applications of resonant tunneling structures," chapter in *Optoelectronic Materials and Device concepts*, ed. M. Razeghi, SPIE press, November 1991.

6. R. Merlin, "Coupled Intersubband-Cyclotron Resonances in Quantum-Well Structures," in *Festscrift in honor of Rogerio Cerqueira Leite's 60th Birthday*, ed. by M. Balkanski, J. M. Worlock and C. E. T. Goncalves da Silva (World Scientific, Singapore, 1991) pp. 169–176.

7. J. Singh,"Strain Induced Band Structure Modifications in Semiconductor Heterostructures and Consequences for Electronic and Optical Devices," chapter in *Condensed Systems of Low Dimensionality*, eds. J. L. Beeby, et. al., Plenum Press, New York 1991.

8. D. G. Steel, H. Wang and S. T. Cundiff, "Four-wave mixing in quantum well systems," invited chapter in *Optics of Semiconductor Nanostructures*, Fritz Henneberger and Stefan Schmitt-Rink, eds. (VCH-GERMANY, 1992).

Journal Publications

1. M. Jaffe and J. Singh, "Inclusion of Spin-Orbit Coupling into Tight Binding Bandstructure Calculations for Bulk and Superlattice Semiconductors," *Solid State Communications*, **62**, 399, (1987).

2. K. Seo, P. K. Bhattacharya and K. R. Gleason, "D-C and Microwave Characteristics of an InGaAs/InAlAs Modulation-Doped Quasi-MISFET," *Electronic Letters*, **23**, 158, (1987).

3. M. Jaffe and J. Singh, "A Comparison of the Electronic Properties of (InAs)/(GaAS) and (InAs)(AlAs) Superlattices with Compositionally Similar Random Alloys," *IEEE Transactions of Electronic Devices*, ED-39, 2590, (1987).

4. M. Jaffe, Y. Sekiguchi and J. Singh, "A Theoretical Formalism to Understand the Role of Strain in Tailoring of the Masses in p-type In_xGa_{1-x}(on GaAs substrates) and $In_{0.53+x}Ga_{0.47-x}As$(on InP substrates) Modulation Doped Field Effect Transistors," *Applied Physics Letters*, **55**, 1943, (1987).

5. N. S. Dogan, J. R. East, M. E. Elta, and G. I. Haddad, "Millimeter- Wave Heterojunction MITATT Diodes," *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-35, No. 12, 1308– 1316, (1987).

6. U. Das, Y. Zebda, P. K. Bhattacharya and A. Chin, "Performance Characteristics of InGaAs/GaAs and GaAs/InGaAlAs Coherently Strained Superlattice Photodiodes," *Applied Physics Letters*, **51** 1164-1166, (1987).

7. Y. Zebda, P. K. Bhattacharya and M. Tobin, "Design and Performance of Very High Speed InGaAs/InAlAs PIN Photodiodes Grown by Molecular Beam Epitaxy," *IEEE Electron Device Letters*, EDL-8, 579-581, (1987).

8. M. Weiss and D. Pavlidis, "Power Optimization of GaAs Implanted FETs Based on Large Signal Modeling," *IEEE Transactions on MTT*, Vol. MTT-35, No. 2, pp. 175–188, February 1987.

9. Y. Archambault, D. Pavlidis and J. P. Guet, "GaAs Monolithic Integrated Optical Preamplifier," *IEEE Journal of Lightwave Technology* (Joint MTT Special Issue on Microwave Aspects and Applications of GHz/Gbit Technology), vol. LT-5, No. 3, pp. 366–369, March 1987.

10. P. Sandborn, J. East and G. I. Haddad, "Quasi-Two-Dimensional Modeling of GaAs MESFETs," *IEEE Transactions on Electron Devices*, May 1987.

11. W.-P. Hong and P. K. Bhattacharya, "D.C. and Microwave Characteristics of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ MODFETs with GaAs Gate Barriers," *Electronic Letters*, vol. 9, No. 7, pp. 352– 354, (1988).

12. W.-P. Hong, J. Oh, P. K. Bhattacharya and T. Tiwald, "Interface States in $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ Heterostructures," *IEEE Transactions on Electron Devices*, **35**, 1585 (1988).

13. W.-P. Hong and P. K. Bhattacharya, "Backgating Studies in InGaAs/InAlAs Modulation Doped Field-Effect Transistors," *IEEE Transactions on Electron Devices*, ED-35, 8-13, (1988).

14. W-Q Li, A. Chin, P. Bhattacharya and S. DiVita, "Molecular Beam Epitaxial GaAs Optical Detectors on Silica Fibers," *Applied Physics Letters*, vol. 52, No. 21, pp. 1768–1770, (1988).

15. M. Jaffe, Y. Sekiguchi, J. East and J. Singh, "Electronic Properties of Pseudomorphic InGaAs/AlGaAs (on GaAs) and InGaAs/InAlAs (on InP) MODFET Structures," *Superlattices and Microstructures*, vol. 4, No. 4, p. 395, (1988).

16. R. L. Tober, J. Pamulapati, J. E. Oh and P. K. Bhattacharya, "Piezoreflectance Characterization of Double-Barrier Resonant Tunneling Structures," *Applied Physics Letters*, **53**, 883 (1988).

17. U. Das, Y. Chen, P. K. Bhattacharya and P. R. Berger, "Orientation-Dependent Phase Modulation in InGaAs/GaAs Multiquantum Well Waveguides," *Applied Physics Letters*, **53**, 2129 (1988).

18. R. Boroff, R. Merlin, A. Chin, and P. K. Bhattacharya, "Raman Scattering by Optical Phonons in $In_{1-y-z}Al_yGa_zAs$ Lattice-Matched to InP," *Applied Physics Letters*, **53**, 1652 (1988).

19. C. Uher and J. L. Cohn, "Anomalous Thermal Conductivity of $La_{2-s}Sr_xCuO_4$ at Very Low Temperature," *J. Phys. C*, **21**, pp. L957–L963, (1988).

20. F. J. Lamelas, H. He and R. Clarke, "X-ray diffraction study of epitaxial Nb-Ta Overlayers on Sapphire," *Phys. Rev.*. **B38**, 6334, (1988).

21. H. G. Winful and S. S. Wang, "Stability of Phase Locking in Coupled Semiconductor Laser Arrays," *Appl Phys. Lett.* **53**. 1894, (1988).

22. K. Mullen, Y. Gefen, and E. Ben-Jacob, "The Dynamics of Mesoscopic Normal Tunnel Junctions," *Physica*, **B152**, 172 (1988).

23. K. Mullen, E. Ben-Jacob and S. T. Ruggiero, "Charging effects in coupled superconducting tunnel junctions and their implications for tunneling measurements of high T_c superconductors," *Physical Review B*, **38**, 5150 (1988).

24. J. B. Barner, K. Mullen, S. T. Ruggiero, E. Ben-Jacob and A. R. Pelton, "Single-electron Charging Effects and Implications for Tunneling Measurements of the High T_C Superconductors," *IEEE Trans. on Magn.*, 4810 (1988).

25. E. Ben-Jacob, Y. Gefen, K. Mullen and Z. Schuss, "Coherent vs. Non-Coherent Bloch Oscillations in the Presence of Direct and Alternating Fields," *Physical Review B.*, vol. 37, No. 13, (1988)

26. K. Mullen, E. Ben-Jacob, R. C. Jaklevic and Z. Schuss, "I-V Characteristics of Coupled Ultrasmall- Capacitance Normal Tunnel Junctions," *Physical Review B*, vol. 37, No. 1, pp. 98–105, January 1988.

27. M. Weiss and D. Pavlidis, "Influence of Device Physical Parameters on HEMT Large Signal Characteristics," *IEEE Transactions on MTT* Special Issue on Computer Aided Design, vol. 36, No. 2, pp. 239–249, February 1988.

28. G. I. Ng, D. Pavlidis, M. Quillec, Y. J. Chan, M. Jaffe, and J. Singh, " A Study of the Consequences of Excess Indium in the Active Channel of InGaAs/InAlAs HEMTs on Device Performance, *Applied Physics Letters*, **52**, 9, pp 728–730, February 29, 1988.

29. K. Mullen, E. Ben-Jacob and Z. Schuss, "The Combined Effect of Zener and Quasiparticle Transitions on the Dynamics of Mesoscopic Josephson Junctions," *Physical Review Letters*, vol. 60, No. 11, pp. 1097–1100, 14 March 1988.

30. D. Pavlidis, J. L. Cazaux and J. Graffeuil, "The Influence of Ion Implanted Profiles on Performance of GaAs MESFETs and MMIC Amplifiers," *IEEE Transactions on Microwave Theory and Techniques*, vol. 36, No. 4, pp. 642–652, April 1988.

31. G. Pataut and D. Pavlidis, "X-Band Varacter Tuned Monolithic GaAs FET Oscillators," *International Journal of Electronics*, Vol. 64, No. 5, pp. 731–751, May 1988.

32. I. Méhdi, G. Haddad and R. Mains, "Microwave and Millimeter-wave Power Generation in Silicon Carbide Avalanche Devices," *Journal of Applied Physics*, 64, August 1988.

33. P. Mazumder, "Parallel Testing of Parametric Faults in a Three-Dimensional Dynamic Random-Access Memory," *IEEE Journal of Solid-State Circuits*, vol. 23, No. 4, pp. 933– 942, August 1988.

34. W.-P. Hong, G. I. Ng, P. K. Bhattacharya, D. Pavlidis and S. Willing, "Low and High Field Transport Properties of Pseudomorphic $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ ($0.53 \leq x \leq 0.65$) Modulation-Doped Heterostructures," *Journal of Applied Physics*, vol. 64, No. 4, pp. 1945–1949, August 1988.

35. J. L. Cazaux, G. I. Ng and D. Pavlidis, "An Analytical Approach to the Capacitance Voltage Characteristics of Double Heterojunction HEMTs," *IEEE Transactions on Electron Devices*, vol. 35, No. 8, pp. 1223–1231, August 1988.

36. M. Weiss and D. Pavlidis, "An Investigation of Power Characteristics and Saturation Mechanisms in HEMT's and MESFETs," *IEEE Transactions on Electron Devices*, vol. 35, No. 8, pp. 1197–1206, August 1988.

37. J. L. Cohn, S. D. Peacor and C. Uher, "Thermal Conductivity of $YBa_2Cu_3O_{7-\delta}$ Below 1K: Existence for Normal-Carrier Transport Well Below T_c," *Phys. Rev. B, Rapid Communications*, vol. 38, No. 4, pp. 2892–2895, 1 August 1988.

38. J. M. Hinckley and J. Singh, "Theoretical Investigation of Hole Transport in Strained III-V Semiconductors: Application to GaAs," *Appl. Phys. Lett.*, vol. 53, No. 9, pp. 785-787, 29 August 1988.

39. G. I. Ng, W.-P. Hong, D. Pavlidis, M. Tutt and P. K. Bhattacharya, "Characteristics of strained $In_{0.65}Ga_{0.35}As/In_{0.52}Al_{0.48}As$ HEMT with Optimized Transport Parameters," *IEEE Electron Device Letters.* vol. 9, No. 9, pp. 439–441, September 1988.

40. R. K. Mains and G. I. Haddad, "Time-Dependent Modeling of Resonant-Tunneling Diodes from Direct Solution of the Schrödinger Equation," *Journal of Applied Physics*, vol. 64, No. 7, pp. 3564–3569, 1 October 1988.

41. R. K. Mains and G. I. Haddad, "Wigner Function Modeling of Resonant-Tunneling Diodes with High Peak-to-Valley Ratios," *Journal of Applied Physics*, vol. 64, No. 10, pp. 5041–5044, 15 November, 1988.

42. M. Jaffe and J. Singh, "Band Structure and Charge Contacts Studies of n- and p-type Pseudomorphic Modulations Doped Field Effect Transistors," *J. of Appl. Phys.*, **65**, 329, (1989).

43. J. Pamulapati, J. E. Oh, N. Debbar, and P. K. Bhattacharya, "A Critical Examination of the Molecular Beam Epitaxial Growth of $In_xGa_{1-x}As/GaAs$ Strained Quantum Well Structures," *Journal of Applied Physics*, vol. 65, p. 1361, (1989).

44. P. A. Sandborn, J. R. East and G. I. Haddad, "Diffusion Effects in Short Channel GaAs MESFET's," *Solid State Electronics*, vol. 32, No. 3, pp. 191–198, (1989).

45. X. Zhou, P. K. Bhattacharya, G. Hugo, S-C. Hong, and E. Gulari, "Intersubband Absorption in Strained $In_xGa_{1-x}As/Al_{0.4}Ga_{0.6}As$ ($0 \leq x \leq 0.15$) Multiquantum Wells," *Applied Physics Letters*, vol. 54, 855, (1989).

46. J. Pamulapati, P. Berger, K. Chang, J. Oh, Y. Chen, J. Singh, P. Bhattacharya and R. Gibala, "Growth Phenomena and Characteristics of Strained $In_xGa_{1-x}As$ on GaAs, *Journal of Crystal Growth*, **95**, 193–196, (1989).

47. J. Oh, I. Mehdi, J. Pamulapati, P. K. Bhattacharya and G. I. Haddad, "The effect of molecular-beam epitaxial growth conditions on the electrical characteristics of InAlAs/InGaAs resonant tunneling diodes," *Journal of Applied Physics*, **65**, 842, (1989).

48. J. T. Remillard, H. Wang, D. G. Steel, J. Oh, J. Pamulapati and P. K. Bhattacharya, "High Resolution Nonlinear Laser Spectroscopy of Heavy Hole Excitons in GaAs/AlGaAs Quantum Well Structures: A Direct Measure of the Exciton Lineshape," *Physical Review Letters*, **62**, pp. 2861–2864 (1989).

49. R. Wilkins, E. Ben-Jacob and R. C. Jaklevic, "STM Observations of Coulomb Blockade and Oxide Polarization in Small Metal Droplets," *Phys. Rev. Lett.*, 63, 801 (1989).

50. K. Mullen, E. Ben-Jacob and Z. Schuss, "The Combined Effect of Zener and Quasipartical Transitions on the Dynamics of Mesoscopic Josephson Junctions," *Physical Review Letters*, vol. 60, 2700, (1989).

51. J. Hu, K. Tomizawa and D. Pavlidis, "Transient Monte Carlo Analysis and Application to Heterojunction Bipolar Transistor Switching" *IEEE Transactions on Electron Devices*, special issue *Electron Device Letters*, vol. 10 pp. 415–416, (1989).

52. J. Singh, "A valley selective tunneling transistor based on valley discontinuitites in AlGaAs heterostructures," *Appl. Phys. Letters*, 55, 2652 (1989).

53. J. M. Hinckley, V. Sankaran and J. Singh, "Charged Carrier Transport in $Si_{1-x}Ge_x$ Pseudomorphic Alloys Matched to SI - – Strain Related Transport Improvements," *Appl. Phys. Lett.*, 55, 2008 (1989).

54. M. Jaffe, J. E. Oh, J. Pamulapati, J. Singh and P. K. Bhattacharya, "In-Plane Hole Effective Masses in $In_xGa_{1-x}As/Al_{0.15}Ga_{0.85}As$ Modulation Doped Heterostructures," *Applied Physics Letters*, 54, 2345 (1989).

55. G. I. Haddad, R. K. Mains, U. K. Reddy, and J. R. East, "A Proposed Narrow-Band-Gap Base Transistor Structure," *Journal of Superlattices and Microstructures*, vol. 5, No. 3, (1989).

56. I. Mehdi, G. I. Haddad and R. K. Mains, "Novel Use of Resonant- Tunneling Structures for Optical and IR Modulators," *Journal of Superlattices and Microstructures*, vol. 5, No. 3, (1989).

57. R. L. Tober, J. Pamulapati, P. K. Bhattacharya, and J. E. Oh, "Piezoreflectance Characterization of Resonant Tunneling and Modulation-Doped Heterostructures," *Journal of Electronic Materials*, 18, 379 (1989).

58. J. T. Remillard, H. Wang, M. D. Webb, D. G. Steel, J. Oh, J. Pamulapati and P. K. Bhattacharya, "High Resolution Nonlinear Laser Spectroscopy of Room Temperature GaAs Quantum Well Structures: Observation of Interference Effects," *Optics Letters*, 14 pp. 1131–1133 (1989).

59. M. Amman, K. Mullen and E. Ben-Jacob, "The Charge Effect Transistor," *Journ. of App. Phys*, 65, 339, (1989).

60. E. Ben-Jacob, K. Mullen and M. Amman, "Charge Effect Solitons," *Physics Letters*, 135, 390 (1989).

61. M. E. Sherwin and T. J. Drummond, "A Parametric Investigation of AlGaAs/GaAs Modulation Doped Quantum Wires," *J. Appl. Phys.*, 66, 5444 (1989).

62. S. D. Peacor and C. Uher, "Thermal Conductivity of Bi-Sr-Ca-Cu- O Superconductors: Correlation with the Low-Temperature Specific Heat Behavior," *Phys. Rev.*, B39, 11559 (1989).

63. C. Uher and W.-N. Huang, "Thermoelectric Power and Thermal Conductivity of Neutron-Irradiated $YBa_2Cu_3O_{7-\delta}$," *Phys. Rev. B Rapid Commun.* B40, 2694 (1989).

64. R. Wilkins, E. Ben-Jacob and R. C. Jaklevic, "Scanning Tunneling Microscope Observation of Coulomb Blockade and Oxide Polarization in Small Metal Droplets," *Physical Review Letters*, 63, 801 (1989).

65. J. T. Remillard, H. Wang, M. D. Webb and D. G. Steel, "Optical Phase Conjugation and Nonlinear Optical Band Pass Filter Characteristics in CdSSe Microcrystallite Doped Glass," *IEEE J. Quant. Elec.*, **QE-25** pp. 408-413 (1989).

66. M. Amman, E. Ben-Jacob and K. Mullen, "Charge Solitons in a 1-D Array of Mesoscopic Tunnel Junctions," *Physics Letters A*. 142, 431 (1989).

67. I. Mehdi, U. K. Reddy, J. Oh, J. R. East and G. I. Haddad, "Nonalloyed and alloyed low-resistance ohmic contacts with good morphology for GaAs using a graded InGaAs cap layer," *Journal of Applied Physics*, vol. 65, No. 121, pp. 867–869, 15 Jan. 1989.

68. J. Hu, K. Tomizawa and D. Pavlidis, "Monte Carlo Approach to Transient Analysis HBT's with Different Collector Designs," *IEEE Electron Device Letters*, vol. 10, pp. 55–57, February 1989.

69. T. Crandle, J. East and P. Blakey, "Monte Carlo Modeling of Electron Transport in Repeated Overshoot Structures," *IEEE Transactions on Electron Devices*, vol. 36, No. 2, pp. 300– 308, February 1989.

70. P. Mazumder and J. H. Patel, "Parallel Testing of Pattern- Sensitive Faults in Dynamic Random-Access Memory," *IEEE Transactions on Computers*, vol. 38. No. 3, pp. 394-404, March 1989.

71. R. H. Voelker and R. J. Lomax, "Three-Dimensional Simulation of Integrated Circuits Using a Variable Mesh TLM Method," *Microwave and Optical Technology Letters*, vol. 2, No. 4, pp. 125– 127, April, 1989.

72. G. I. Ng, D. Pavlidis, M. Tutt, J. Oh and P. K. Bhattacharya, "Improved Strained HEMT Characteristics Using Double- Heterojunction $In_{0.65}Ga_{0.35}As/In_{0.52}Al_{0.48}As$ Design," *IEEE Electron Device Letters*, vol. 10, pp. 114–116, March 1989.

73. P. Mazumder and J. H. Patel, "An Efficient Built-In Self-Testing of Random-Access Memories," *IEEE Transactions on Industrial Electronics* (special issue on testing), vol. 2, No. 5, pp. 172- -175, May 1989.

74. I. Mehdi, G. I. Haddad and R. K. Mains, "Performance criteria for resonant tunneling diodes as millimeter-wave power sources," *Optical and Microwave Technology Letters*, vol. 2, No. 5, pp. 172- -175, May 1989.

75. D. Pavlidis and M. Tutt, "A Novel Course on Microwave Monolithic Integrated Circuit (MMIC) Theory and Experiments," *IEEE Transactions on Education*, vol. 32, No. 2, pp. 73–84, May 1989.

76. L. D. Zhu, B. Z. Zheng, Z. Y. Xu and J. Z. Xu, and G.A.B. Feak, "Optical Gain in GaAs/GaAlAs Graded-Index Separate Confinement Single Quantum Well Heterostructures," *IEEE Journ. of Quantum Electron*, vol. 25, No. 6, pp. 1171–78, June 1989.

77. J. Dykstra and R. B. Brown, "A Comparison of Gold and Superconductors Used as Air-Bridge and Microstrip Interconnects for High-Speed VLSI," *IEEE Journal of Solid-State Circuits*, June 1989.

78. R. K. Mains, I. Mehdi and G. I. Haddad, "Resonant-Tunneling Devices for Millimeter-Wave Generation," *International Journal of Infrared and Millimeter Waves*, vol. 10, No. 6, pp. 595–620, July 1989.

79. R. K. Mains, J. P. Sun and G. I. Haddad, "Observation of Intrinsic Bistability in Resonant-Tunneling Diode Modeling," *Applied Physics Letters*, 55, 4, 24 July 1989.

80. L. D. Zhu, B. Z. Zheng, and G.A.B. Feak, "Temperature Dependence of Optical Gain, Quantum Efficiency and Threshold Current in GaAs/GaAlAs Graded-Index Separate-Confinement Heterostructure Single Quantum Well Lasers," *IEEE Journ. of Quantum Electronics*, vol. 25, No. 9, pp. 2007–2012, September, 1989.

81. G. I. Ng, D. Pavlidis, M. Jaffe, J. Singh and H. F. Chau, "Design and Experimental Characteristics of Strained InGaAs/InalAs ($x > 0.53$) HEMT's," *IEEE Transactions on Electron Devices*, vol. 36, No. 10, pp. 2249–2259, October 1989.

82. W. Q. Li and P. K.Bhattacharya, "Integration of a Modulated Barrier Photodiode with a Doped Channel Quasi-MISFET," on Heterostructure Transistors, vol. 36, No. 10, October 1989.

83. H. F. Chau, D. Pavlidis, J. L Cazaux and J. Graffeuil, "Studies of DC, Low Frequency and Microwave Characteristics of Uniform and Step-doped GaAs/AlGaAs HEMT's," *IEEE Transactions on Electron Devices*, special issue on Heterostructure Transistors, vol. 36, No. 10, pp. 2288–2298, October 1989.

84. U. Reddy, I. Mehdi, R. K. Mains and G. I. Haddad, "Design, Fabrication and Operation of a Hot Electron Resonant Tunneling Transistor," *Solid State Electronics*, vol. 32, No. 12, pp. 1377– 1381, December 1989.

85. R. K. Mains, I. Mehdi and G. I. Haddad, "Effect of Spatially Variable Effective Mass on Static and Dynamic Properties of Resonant Tunneling Devices," *Appl. Phys. Lett.*, vol. 55, No. 25, pp. 2631– 2633, 18 December 1989.

86. C. Kidner, I. Mehdi, J. East and G. Haddad, "Power and Stability Limitations of Resonant Tunneling Diodes," *IEEE Transactions on Microwave Tehory and Techniques*, vol. 38, No. 7, pp. 864–872, July 1990.

87. P. Bhattacharya, J. E. Oh, J. Singh, D. Biswas, R. Clarke, W. Dos Passos, R. Merlin, N. Mestres, K. H. Chang and R. Gibala, "Growth and Characterization of GaAs/AlGaAs Heterostructures," *Journal of Applied Physics*, **67**, 3700 (1990).

88. K. Chang, J. Pamulapati, P. Bhattacharya and R. Lai, "Lattice- Mismatched $In_{.5}Ga_{.5}As/In_{.5}Al_{.5}As$ Modulation Doped Field Effect Transistors on GaAs: Molecular Beam Epitaxial Growth and Device Performance," *Journal of Applied Physcis*, **67**, 3323 (1990).

89. J. E. Oh, P. K. Bhattacharya, J. Singh, W. Dos Passos, R. Clarke, N. Mestres, R. Merlin K. H. Chang and R. Gibala, "Epitaxial Growth and Characterization of GaAs/Al/GaAs Heterostructures," *Surface Science*, 288, pp. 16–19 (1990).

90. P. K. Bhattacharya (invited), "Superlattice Avalanche Photodiodes: Impact Ionization Phenomenon and Device Characteristics," *International Journal of Optoelectronics*, **5**, 1 (1990).

91. J. Pamulapati and P. K. Bhattacharya, "Single Mode Optical Waveguides and Phase Shifters Using InGaAlAs on InP Grown by MBE," *Applied Physics Letters*, **56**, 103 (1990).

92. T. J. Drummond and M. E. Sherwin, "Analytic MODFET Model Beyond the Triangular Well Approximation," *Solid State Electronics*, vol. 33, No. 7, pp. 885–891, (1990).

93. H. Wang, J. T. Remillard, M. D. Webb and D. G. Steel, "High Resolution Laser Spectroscopy of Relaxation and the Excitation Line Shape of Excitons in GaAs Quantum Well Structures," *Surface Science*, **228**, pp. 69–73, (1990).

94. R. Merlin, N. Mestres, A. McKiernan, J. Oh, and P. K. Bhattacharya, "Charge -Density Domains in Photoexcited Quantum- Well Structures," *Surface Science*, **228**, 88 (1990).

95. J. E. Oh, P. K. Bhattacharya, Y. C. Chen, O. Aina and M. Mattingly, "The Dependence of the Electrical and Optical Properties of Molecular Beam Epitaxial $In_{0.52}Al_{0.48}As$ on Growth Parameters: Interplay of Surface Kinetics and Thermodynamics," *Journal of Electronic Materials*, vol. 19, No. 5, 435–441, (1990).

96. A. Chin, D. Biswas, J. Pamulapati and P. Bhattacharya, " Traps in Molecular Beam Epitaxial $In_{0.53}(Ga_xAl1-x)_{0.47}As/InP$," *Journal of Applied Physics*, **67**, 2450 (1990).

97. I. Mehdi, G. I. Haddad, R. K. Mains and U. K. Reddy, "Properties and Device Applications of Deep Quantum Well Resonant Tunneling Structures," *Surface Science*, **228**, pp. 426–429, (1990).

98. J. H. Kim, P. K. Bhattacharya, J. Singh and E. Gulari, "Far Infrared Absorption Spectra Measured in $InAs/Al_{0.36}Ga_{0.64}Sb$ Quantum Wells," *Applied Physics Letters*, **56**, 1901 (1990).

99. R. Lai and P. K. Bhattacharya, "Performance Characteristics of $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ Modulation Doped Field Effect Transistors Realized by Two-Step Epitaxy: Effects of Molecular Beam Epitaxial Regrowth," *Journal of Applied Physics*, **67**, 4345 (1990).

100. J. M. Hinckley and J. Singh, "Hole Transport Theory in Pseudomorphic $Si_{1-x}Ge_x$ Alloys Grown on (001)Si Substrates," *Phys. Rev. B.*, **41**, 2912 (1990).

101. J. P. Loehr and J. Singh, "Effect of biaxial strain on acceptor level energies in $In_xGa_{1-x}As/Al_xGa_{1-x}As$ (on GaAs) quantum wells," *Phys. Rev. B*, **41** 3695 (1990).

102. J. Cohn, E. Ben-Jacob and C. Uher, "Low-temperature Electronic Transport and the Coulomb Blockade in Oxidized Films of Bismuth," *Physics Letters A*, 148, 110 (1990).

103. S. D. Peacor, R. A. Richardson, J. Burm, C. Uher and A. B. Kaiser, "Thermal conductivity of Ba-K-Bi-O: A Contrast to Copper Oxide Superconductors," *Physical Review B-Rapid Communication*, **42**, 2684 (1990).

104. R. Wilkins, M. Amman, E. Ben-Jacob and R. C. Jaklevic, "Single-Electron and Oxide-Impurity Effects in Junctions Formed by a Cryogenic Scanning Tunneling Microscope," *Physical Review B*, **42**, 8698 (1990).

105. J. Pamulapati, J. P. Loehr, J. Singh, P. K. Bhattacharya and M. J. Sudowise, "Electro-optic Effect in Stained and Lattice Matched Multiqunatum Well Structures – Role of Excitonic Resonances," *Superlattices and Microstructures*, vol. 8, No. 3, pp. 317–321, 1990.

106. G. I. Haddad, U. K. Reddy, J. P. Sun and R. K. Mains, "The bound state resonant tunneling transistor (BSRTT): Fabrication, D.C. I-V characteristics and high-frequency properties". *Superlattices and Microstructures*, vol. 7. No. 4. pp. 369–374, 1990.

107. M. Dagenais, R. F. Leheny, H. Temkyn and P. Bhattacharya (invited), "Applications and Challenges of OEIC Technology: A Report on the 1989 Hilton Head Workshop," *IEEE Journal of Lightwave Technology*, 8, pp. 846–862, (1990).

108. R. Lai, P. K. Bhattacharya, S. A. Alterovitz, A. N. Downey and C. Chorey, "Low temperature microwave characteristics of pseudomorphic $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ MODFETs," *IEEE Electron Device Letters*, **11**, pp. 564–566, (1990).

109. S. Gupta, P. K. Bhattacharya, J. Pamulapati and G. Mourou, "Sub-picosecond photoresponse of carriers in low-temperature MBE $In_{0.52}Al_{0.48}As/InP$," *Applied Physics Letters*, **57**, pp. 1543–1545, (1990).

110. J. P. Loehr, Y. C. Chen, D. Biswas, P. Bhattacharya and J. Singh, "Effect of Coherent Strain on hydrogenic acceptor levels in InGaAs/AlGaAs quantum well structures," *Applied Physics Letters*, **57**, pp. 180–182, (1990).

111. H. G. Winful and L. Rahman, "Synchronized Chaos and Spatio-Temporal Chaos in Arrays of Coupled Lasers," *Physical Review Letters*, **65**, 1575 (1990).

112. J. P. Loehr and J. Singh, "Role of stain on threshold current, modal purity and auger processes in strained quantum well lasers," *Superlattices and Microstructures*, vol. 8, No. 3, 1990.

113. S. Fishman, K. Mullen and E. Ben-Jacob, "Zener Tunneling in Systems Without Level Crossing," *Physical Review A*, 42, 5181 (1990).

114. R. K. Mains and G. I. Haddad, "Improved Boundary Conditions for the Time-Dependent Schrödinger Equation," accepted as a Communication to *Journal of Applied Physics*. vol. 67, No. 1, pp. 591–93, 1 January (1990).

115. A. Kamal, D. A. Weinberger and W. H. Weber, "Spatially resolved Raman study of self-organized $\chi^{(2)}$ gratings in optical fibers," *Opt. Lett.*, Jan. 1990.

116. M. Weiss, G. I. Ng and D. Pavlidis, "A New Generation MMIC Amplifier Using InGaAs/InAlAs HEMT's," *Electronic Letters*, vol. 26, No. 4, pp. 264–266, February 1990.

117. J. Singh and S. Hong, "Optoelectronic architecture for associative memory application to 2-D pattern comparison, *Applied Optics*, Feb. 1990.

118. I. Mehdi, C. Kidner, J. East and G. I. Haddad, "Millimeter-wave detection using the resonant tunnelling diodes," *Microwave and Optics Technology Letters*, vol. 3, No. 1, January 1990.

119. R. H. Voelker and R. J. Lomax, "A Finite-Difference Transmission Line Matrix Method Incorporating a Nonlinear Device Model," *IEEE Transactions on Microwave Theory and Techniques*, vol. 38, No. 3, March 1990.

120. I. Mehdi and G. I. Haddad, "Lattice matched and pseudomorphic $In_{0.53}Ga_{0.47}as/In_xAl_{1-x}As$ resonant tunneling diodes with high current peak-to-valley ratio for millimeter-wave power generation," *Journal of Applied Physics*, vol. 76, No. 5, pp. 2643–2646, March 1990.

121. M. Razeghi, F. Omnes, M. Defour, P. Maurel, P. Bove, Y. J. Chan and D. Pavlidis, "The First Fabrication of n- and p-type $Ga_{0.49}In_{0.51}P$/Ga(In) Lattice Matched and Strained HIGFET Structures Grown by MOCVD," *Semiconductor Science and Technology*, vol. 5, No. 3, pp. 274–277, March 1990.

122. M. Razeghi, F. Omnes, M. Defour, P. Maurel, J. Hu, E. Woelk and D. Pavlidis, "High Performance GaAs/GaInP Heterostructure Bipolar Transistors Grown by Low-Pressure Metal-Organic Chemical Vapour Deposition," *Semiconductor Science and Technology*, vol. 5, No. 3, pp. 278–280, March 1990.

123. K. Tomizawa and D. Pavlidis, "Transport Equation Approach for Heterojunction Bipolar Transistors," *IEEE Transactions on Electron Devices*, vol. 37, NO. 3, pp. 519–529, March 1990.

124. S. Tiwari, W. Wang and J. East, "An Analytic Theory of the Auger Transistor: A Hot Electron Bipolar Transistor," *IEEE Trans. on Electron Devices*, vol. 37, No. 4, pp. 1121–1131, April 1990.

125. R. Merlin and D. A. Kessler, "Photoexcited Quantum Wells: Nonlinear Screening, Bistability and Negative Differential Capacitance," *Phys. Rev. B*, vol. 41, No. 14, 15 May 1990.

126. K. Sahookar and P. Mazumder, "Genetic Algorithms for Standard-Cell Placement with Meta-Genetic Parameter Optimization," *IEEE Transactions on CAD-CAS*, May 1990.

127. R. Wilkins, M. Amman, R. E. Soltis, E. Ben-Jacob and R. C. Jaklevic, "Tunneling Spectroscopy Study of $YBa_2Cu_3O_7$ Thin Film Using a Cryogenic Scanning Tunneling Microscope," *Physical Review B*, vol. 41, No. 13, pp. 8904–8911, May 1990.

128. C. Kidner, I. Mehdi, J. East and G. Haddad, "Power and Stability Limitations of Resonant Tunneling Diodes," *IEEE Transactions on Microwave Theory and Techniques*, vol. 38, No. 7, pp. 864–872, July 1990.

129. S. D. Peacor, C. Uher, A. Francis and J. Shewchun, "Physical and Electromagnetic Properties of Y-Ba-Cu-O Superconductors Synthesized with Peroxides," *J. Appl. Phys.*, 67,(12), 15 June 1990.

130. J. Pamulapati, R. Lai, G. I. Ng, Y. C. Chen, P. R. Berger, P. Bhattacharya, J. Singh and D. Pavlidis, "The Relation of the Performance Characteristics of Pseudomorphic $In_{0.52+x}Ga_{0.47-x}/In_{0.52}Al_{0.48}As$ ($\leq x \leq 0.32$) Modulation Doped Field Effect Transistors to Molecular Beam Epitaxial Growth Modes," *Journal of Applied Physics*, vol. 68, No. 1, 1 July 1990.

131. Y. Zebda, P. K. Bhattacharya, D. Pavlidis and J. Harrang, "Performance characteristics of $In_{0.6}As_{0.40}Al$ modulation- doped field-effect transistor monlithically integrated with $In_{0.53}Ga_{0.47}As$ p-i-n photodiodes," *Journal of Applied Physics*, vol. 68, No. 4, pp. 1918–1920, 15 August 1990.

132. R. Kamoua, J. East and G. Haddad, "Ensemble Monte Carlo Characterization of Graded $Al_xGa_{1-x}As$ Heterojunction Barriers," *Journal of Applied Physics*, vol. 68, No. 3, pp. 1114–1122, 1 August 1990.

133. I. Mehdi, R. K. Mains and G. I. Haddad, "Effect of Spacer Layer Thickness on the Static Characteristics of Resonant Tunneling Diodes," *Applied Physics Letters*, vol. 57, No. 9, pp. 899–901, 27 August 1990.

134. J. M. Hinckley and J. Singh, "Influence of substrate composition and crystallographic orientation on the band structure of pseudomorphic Si-Ge alloy films," *Physical Review B*, vol. 42, No. 6, pp. 3546–3566, August 1990.

135. Y. Kwon, D. Pavlidis, M. Tutt, G. I. Ng, R. Lai and T. Brock, "W- Band Monolithic Oscillator Using InAlAs/InGaAs HEMT," *Electronics Letters*, vol. 26, No. 18, pp. 1425–1426, August 1990.

136. Y. J. Chan, D. Pavlidis, M. Razeghi and F. Omnes, "$Ga_{0.52}In_{0.48}P$/GaAs HEMT's Exhibiting Good Electrical Performance at Cryogenic Temperatures," *IEEE Transactions on Electron Devices*, vol. 37, No. 10, pp. 2141– 2147, October 1990.

137. J. Loehr and S. Singh, "Nonvariational numerical calculations of excitonic properties in quantum wells in the presence of strain, electric fields and free carriers," *Physical Review B*, vol. 31, No. 11, pp. 7154–7162, October 1990.

138. R. Venkateswaran and P. Mazumder, "A hexagonal array machine for multi-layer wire routing," *IEEE Transactions on CAD- CAS*, vol. 9, no. 10, pp. 1096–1112, October 1990.

139. C. Uher, "Thermal Conductivity of High-T_c Superconductors," a major review article for *Journal of Superconductivity*, December issue, 1990.

140. J.-S. Yih and P. Mazumder, "Neural network design for circuit partitioning," *IEEE Transactions on CAD-CAS*, vol. 9, No. 10, pp. 1265–1271, December 1990.

141. R. Wilkins, M. Amman, E. Ben-Jacob and R. C. Jaklevic, "Surface Oxide Effects of Tunneling Spectroscopy Measured with a Cryogenic Scanning Tunneling Microscope," *J. Vac. Sci. Tech. B*, 9, 996 (1991).

142. E. Woelk, M. E. Sherwin, G. O. Munns and G. I. Haddad, "Technical aspects of InGaAs MOMBE - shutter action, system drift and material quality," *J. Cryst. Growth*, 110, pp. 452–456, (1991).

143. G. O. Munns, M. E. Sherwin, T. Brock, G. I. Haddad, Y. Kwon, G. I. Ng and D. Pavlidis, "InAlAs/InGaAs/InP Submicron HEMT's Grown by CBE," *J. of Crystal Growth* December 1991.

144. E. Woelk, M. Sherwin and G. Munns, "Technical Aspects of InGaAs MOMBE - System Drift and Material Quality," *J. Cryst. Growth*, 107, pp. 10–14 (1991).

145. M. E. Sherwin, G. O. Munns, M. E. Elta, E. G. Woelk, S. B. Crary, F. L. Terry, Jr. and G. I. Haddad, "The optimization of $In_xGa_{1-x}As$ and InP growth conditions by CBE," *Journal of Crystal Growth*, **111**, pp. 594–598 (1991).

146. M. E. Sherwin, G. O Munns, E. G. Woelk, T. J. Drummond, M. E. Elta, F. L. Terry, Jr. and G. I. Haddad, "The design of an ECR plasma system and its application to InP grown by CBE," *Journal of Crystal Growth*, **111**, pp. 605–608 (1991).

147. M. D. Webb, S. T. Cundiff and D. G. Steel, "Observation of Time- Resolved Picosecond Simulated Photon Echoes and Free Polarization Decay in GaAs/AlGaAs Multiple Quantum Wells," *Physical Review Letters*, **66**, 934 (1991).

148. C. Uher, S. D. Peacor and J. Shewchun, "Thermal Conductivity of $T\ell_2Ba_2Ca_2Cu_3O_{10}$ Ceramics from 300K down to 0.1K," *Physical C*, **177**, 23 (1991).

149. J. Shewchun, Yi Chen, J. S. Holder and C. Uher, "Characteristics of Y-Ba-Cu-O Super Conductor Films on GaAs with $A\ell_2O_3$ Buffer Layer," *Applied Physics Letters*, **58**, 2704 (1991).

150. J. Loehr and J. Singh, "Theoretical Studies of the Effect of Strain on the Performance of Strained Quantum Well Lasers Based on GaAs and InP Technology," *IEEE Journal of Quantum Electronics*, **27**, 708 (1991).

151. J. M. Hinckley and J. Singh, "Dependence of Pseudomorphic Semiconductor Bandgap on Substrate Orientation," *Journal of Applied Physics*, **69**, 2694 (1991).

152. V. Sankaran and J. Singh, "Coherent Tunneling of Mixed State Hole Wavepackets in Coupled Quantum Structures," *Applied Physics Letters*, **58**, 1509 (1991).

153. M. Amman, R. Wilkins, E. Ben-Jacob, P. D. Maker, and R. C. Jaklevic, "Analytical Solution for the Current-Voltage Characteristics of Two Mesoscopic Tunnel Junctions Coupled in Series," *Phys. Rev. B*, **43**, 1146 (1991).

154. C. Uher, S. D. Peacor and A. B. Kaiser, "Thermoelectric Power of $Ba_{1-x}K_xBiO_3$," *Phys. Rev. B.*, **43**, 7955 (1991).

155. M. D. Webb, S. T. Cundiff and D. G. Steel, "Simulation picosecond photon echo studies of localized exciton relaxation and dephasing in GaAs/AlGaAs Multiple Quantum Wells," *Phys. Rev. B*, **43**, 12658 (1991).

156. D. T. Morelli, G. L. Doll, J. Heremans, S. D. Peacor, C. Uher, R. D. Gabbe, A. Cassanho, M. S. Dresselhaus and H. P. Jenssen, "Thermal Conductivity of Single Crystals Lanthanum Cuprates at Very Low Temperatures," *Solid State Commun.*, **77**, 773 (1991).

157. R. Clarke, W. Dos Passos, Y. J. Chan and D. Pavlidis, "Enhanced Annealing Kinetics in Ion-imganted $In_xAl_{1-x}As$ Studied by X-ray Diffractometry," *Applied Physics Letters*, **58**, 2267 (1991).

158. S. D. Peacor, J. L. Cohn and C. Uher, "Effect of Magnetic Field on Thermal Conductivity of $YBa_2Cu_3O_{7-\delta}$ Single Crystals," *Phys. Rev. B - Rapid Communication*, **43**, 8721 (1991).

159. A. Demos, H. S. Fogler, H. Etemad and M. Elta, "Enhanced Etching of Group III-V Semiconductors by Oscillating with Sputter Etching and Reactive Ion Etching," *The Journal of Electrochemical Society*, **138**, 1143 (1991).

160. F. L. Terry, Jr.,"A Modified Harmonic Oscillator Approximation Scheme for the Dielectric Constants of $Al_xGa_{1-x}As$," *Journal of Applied Physics*, **70**, pp. 409–417 (1991).

161. J. Herman and F. L. Terry, Jr., "A Two-Temperature Technique for PECVD SiO_2," *IEEE Elec. Dev. Lett.*, **12**, No. 5 pp. 236–237 (1991).

162. J. H. Kim, D. Yang, Y-C. Chen and P. Bhattacharya, "Growth and properties of $InAs_xSb_{1-x}$, Al_yGa_{1-y} Sb, and $InAs_xSb_{1-x}/Al_yGa_{1-y}Sb$ heterostructures," *Journal of Crystal Growth*, **111**, pp. 633-637 (1991).

163. S. Gupta, P. K. Bhattacharya, J. Pamulapati, and G. Mourou, "Optical Properties of High-Quality InGaAs/InAlAs Multiquantum Wells," *Journal of Applied Physics*, **69**, pp. 3219–3225 (1991).

164. J.-S. Yih and P. Mazumder, "Circuit behavior modeling and compact testing performance evaluation," *IEEE Journal of Solid State Circuits.* vol. 26, No. 1, pp. 62–6, January 1991.

165. R. Borroff, R. Merlin, J. Pamulapati, P. K. Bhattacharya and C. Tejedor, "Raman Scattering by Coupled Intersubband-Landau-Level Excitations in Quantum-Well Structures," *Phys. Rev. B.*, vol. 43, No. 5, pp. 2081–2087, 15 January 1991.

166. M. E. Sherwin, T. J. Drummond and D. J. Srolovitz, "The role or surface tension in the growth of strained quantum wire arrays," *J. Appl. Phys.*, 69, (2) pp. 717–721, 15 January 1991.

167. G. I. Haddad, J. R. East and C. Kidner, "Tunnel Transit- Time (TUNNETT) Devices for Terahertz Sources," *Microwave and Optical Technology Letters*, vol. 4, No. 1, pp. 23–30, January 1991.

168. T. N. Mudge, R. B. Brown, W. P. Birmingham, J. A. Dykstra, A. I. Kayssi, R. J. Lomax, O. A. Olukotun, K. A. Sakallah, and R. Milano, "The Design of a Micro-Supercomputer," *IEEE Computer Magazine*, pp. 57–64, January 1991.

169. R. Clarke, W. Dos Passos, W. Lowe, B. G. Rodricks and C. Brizard, "Real-time X-ray Studies of Strain Kinetics in $In_xGa_{1-x}As$ Quantum Well Structures," *Phys. Rev. Letters*, vol. 66, No. 3, pp. 317–320, January 1991.

170. C. Kidner, I. Mehdi, J. R. East and G. I. Haddad, "Bias Circuit Instabilities and their Effect on the d.c. Current-Voltage Characteristics of Double-Barrier Resonant Tunneling Diodes," *Solid-State Electronics*, vol. 34, No. 2 pp. 149–156, February 1991.

171. H-F. Chau, D. Pavlidis and K. Tomizawa, "Theoretical Analysis of HEMT Breakdown Dependence on Device Design Parameters," *IEEE Transactions on Electron Devices*, vol. 38, No. 2, pp. 213–221, February 1991.

172. R. Lai, P. K. Bhattacharya, D. Pavlidis and T. Brock, "Monolithically Integrated Planar Front-End Photoreceivers with 0.25 μm Gate Pseudomorphic $In_{0.6}Ga_{0.4}As/In_{0.52}Al_{0.48}As/InP$ Modulation Doped Field Effect Transistors," *Electronics Letters*, vol. 27, No. 4, pp. 364-365, February 1991.

173. M. Razeghi, F. Omnes, P. Maurel, Y-J. Chan and D. Pavlidis, "$Ga_{0.51}In_{0.49}P/Ga_xIn_{1-x}As$ Lattice-Matched (x = 1) and Strained (x = 0.85) Two Dimensional Electron Gas Field-Effect Transistors," *Semiconductor Science and Technology*, 6, No. 2, pp. 103–107, February 1991.

174. P. R. Berger, P. Bhattacharya and S. Gupta, "A Waveguide Directional Coupler with a Nonlinear Coupling Medium," *IEEE Journal of Quantum Electronics*, **27**, No. 3, pp. 788–795, March 1991.

175. J. Pamulapati, P. K. Bhattacharya, D. Biswas, P. J. McCleer and G. I. Haddad, "Noise Suppression Characteristics of InP-Based Monolithically Integrated Guided Wave Balanced Photodiodes," *IEEE Photonics Technology Letters*, **3**, No. 4, pp. 357–359, April 1991.

176. G. I. Ng and D. Pavlidis, "Frequency Dependent Characteristics and Trap Studies of Lattice-Matched ($x = 0.53$) and Strained ($x > 0.53$) $In_{0.52}Al_{0.48}As/In_xGa_{1-x}As$ HEMT's," *IEEE Transactions on Electron Devices*, vol. 38, No. 4, pp. 862–870, April 1991.

177. J. Pamulapati, J. P. Loehr, J. Singh and P. K. Bhattacharya, "Refractive Index and Electro-Optic Effect in Compressive and Tensile Strained Quantum Wells," *Journal of Applied Physics*, 69, (7), pp. 4071–74, April 1991.

178. O. A. Olukotun, R. B. Brown, R. J. Lomax, T. N. Mudge and K. A. Sakallah, "Multilevel Optimization in the Design of a High-Performance GaAs Microcomputer," *Journal of Solid State Circuits*, **26**, No. 5, pp. 763–767, May 1991.

179. S. Mohan, P. Mazumder, R. K. Mains, J. P. Sun and G. I. Haddad, "Ultra-fast pipelined adders using RRTs," *Electronic Letters*, **27**, No. 10, pp. 830–831, May 1991.

180. W-Q. Li, P. K. Bhattacharya and R. L. Tober, "Improved Performance of Strained InGaAs/GaAs Photodiodes Grown on Patterned GaAs Substrates by Molecular Beam Epitaxy, *Applied Physics Letters*, **58**, pp. 1931–1933, May 1991.

181. M. E. Sherwin and T. J. Drummond, "Predicted elastic constants and critical layer thicknesses for cubic phase AlN, GaN and InN on β-SiC," *Journal of Applied Physics*, **69**, No. 12, pp. 8423–8425, 15 June 1991.

182. R. Lai, P. K. Bhattacharya and T. Brock, "Optical Tuning of Monolithic $In_{0.53}Ga_{0.47}As$/ $In_{0.52}Al_{0.48}As$InP Modulation-doped Field Effect Transistor Oscillators at X- and R- Band," *Electronics Letters*, **27**, pp. pp. 1056–1058, June 1991.

183. P. K. Bhattacharya, Y. Zebda and J. Singh, "Electron and hole impact ionization coefficients in $GaAs/Al_{0.45}Ga_{0.55}As/Al_{0.3}Ga_{0.7}As$ coupled well systems," *Applied Physics Letters*, **58**, pp. 2791– 2793, June 1991.

184. Y. Zebda, R. Lai, P. K. Bhattacharya, D. Pavlidis, P. Berger and T. Brock, "Monolithically Integrated InP-Based Front-End Photoreceivers," *IEEE Transactions on Electron Devices*, **38**, No. 6, pp. 1324—1333, June 1991.

185. C. C. Chen, R. K. Mains and G. I. Haddad, "High-Power Generation in IMPATT Devices in the 100–200 GHz Range," *IEEE Transactions on Electron Devices*, **38**, No. 8, pp. 1701–1705, August 1991.

186. R. K. Mains and G. I. Haddad, "Switching speeds in double- barrier resonant tunneling diode structures," *Journal of Appl. Phys.*, **70**, No. 15, pp. 7638–7639, December 1991.

187. R. L. Lee and F. L. Terry, Jr., "Reactive Ion Etching of Tungsten Silicide Using NF_3 Gas Mixtures," *Journal of Vacuum Science Technology B*, **9**, No. 6, pp. 2747–2751, Nov/Dec. 1991.

188. R. Lai, J. Pamulapati, P. K. Bhattacharya and R. J. Baird, "Low Loss, Single Mode $In_{0.63}Ga_{0.47}As/In_{0.52}Al_{0.48}As$/InP Optical Wavguides Fabricated by Zn-Induced Impurity Induced Layer Disordering," *Journal of Applied Physics*, **70**, (9), 5136 (1991).

189. J. Singh, "Effect of structural disorder on electronic states in GaAs/ALGaAs quantum wires," *Appl. Phys. Lett.*, **59**, No. 24, pp. 3142–3144, December 1991.

190. V. Sankaran and J. Singh, "Tunneling and subband levels in GaAs quantum well with direct and indirect $Al_xGA_{1-x}As$ barriers," *Appl. Phys. Lett.*, **59**, No. 16, pp. 1963–1965, October 1991.

191. Y. Lam, J. P. Loehr and J. Singh, "Comparison of mode suppression and large signal modulation between lattice matched and strained InGaAs/AlGaAs quantum well lasers," *Appl. Phys. Lettt.* **59**, No. 19, pp. 2381–2383, November 1991.

192. V. Sankaran and J. Singh, "A Formalism for Tunneling of Mixed Symmetry Electronic States: Application to Electron and Hole Tunneling in Direct and Indirect $GaAs/Al_xGa_{1-x}$ Structures," *Physics Review B*, **44**, No. 7, pp. 3175–3186, August 1991.

193. Y.-J. Chan, D. Pavlidis and G. I. Ng, "The Influence of Gate-Feeder/Mesa-Edge Contacting on Sidegating Effects in $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ Heterostructure FET's," *IEEE Electron Devices Letters*, **12**, No. 7, pp. 360–362, July 1991.

194. W-Q. Li and P. K. Bhattacharya, "Molecular Beam Epitaxial $GaAs/Al_{0.2}Ga_{0.8}As$ p-channel Field-Effect Transistors on (311)A Facets of Patterned (100) GaAs Obtained by Silicon Doping," *IEEE Electron Device Letters*, **12**, No. 7, pp. 385–386, July 1991.

195. Y-J. Chan and D. Pavlidis, "$In_{.52}Al_{0.48}As/IN_xGa_{1-x}As(0.53 \leq x \leq 0.7)$ Lattice Matched and Strained Heterostructure Insulated Gate FET's," *IEEE Transactions on Electron Devices*, **38**, No. 9, pp. 1999- 2005, September 1991.

196. S. Mohan, P. Mazumder and G. I. Haddad, "Reduction of Soliton Interaction Forces by Bandwidth Limited Amplification," *Electronic Letters*, **27**, No. 21, pp.1929-1930, October 1991.

197. S. Mohan, P. Mazumder and G. I. Haddad, "A Subnanosecond 32-bit Multiplier Using Negative Differential Resistance Devices," *IEE Electronic Letters*, **27**, No. 21, pp. 1929–1931, October 1991.

198. J. P. Loehr, J. Singh, R. K. Mains and G. I. Haddad, "Theoretical Studies of the Applications of Resonant Tunneling Diodes as Intersubband Lasers and Interband Excitonic Modulators," *Appl. Phys. Lett.*, **59**, No. 17, pp. 2070–2072, 21 October 1991.

199. M. E. Sherwin, G. O. Munns, D. T. Nichols, P. K. Bhattacharya and F. L. Terry, Jr., "The Growth of High Quality InP/InGaAs/InGaAs/InGaAsP Interfaces by CBE for SCH Multi- Quantum Well Lasers, *Journal of Electronic Materials*, **20**, p. 979, December 1991.

200. Y. Kwon, D. Pavlidis and M. N. Tutt, "An Evaluation of HEMT Potential for Millimeter-Wave Signal Sources Using Interpolation and Harmonic Balance Techniques," *IEEE Microwave and Guided Wave Letters*, **1**, No. 12, pp. 365–367, December 1991.

201. D. Teeter, J. R. East and G.I. Haddad, "Use of self-bias to improve power saturation and intermodulation distortion in CW class b HBT operation," *Microwave and Guided Wave Letters*, vol. 2, No. 5, May 1992, pp. 174–176.

202. G. I. Ng, D. Pavlidis, M. Tutt, M. Weiss and P. Marsh, "Low- Frequency Noise Characteristics of Latttice-matched ($x = 0.53$) and Strained ($x > 0.53$) $In_{0.52}Al_{0.48}As/In_xGa_{1-x}As$ HEMT's," *IEEE Transactions on Electron Devices*, **39**, No. 3, pp. 523–532, March 1992.

203. Y-J. Chan and D. Pavlidis, "Single and Dual P-Doped Channel $In_{0.52}Al_{0.48}As/$ $In_xGa_{1-x}As$ ($x = 0.53, 0.65$) FET's and the Role of Doping," *IEEE Transactions on Electron Devices*, **39**, No. 3, pp. 466–472, March 1992.

204. J. Hu, D. Pavlidis and K. Tomizawa, "Monte Carlo Studies of the Effect of Emitter Junction Grading on the Electron Transport in InAlAs/InGaAs Heterojunction Bipolar Transistors," *IEEE Transactions on Electron Devices*, 39 No. 6, pp. 1272–1281, June 1992.

205. M. Y. Frankel and D. Pavlidis, "An Analysis of the Large-signal Characteristics of AlGaAs/GaAs Heterojunction Bipolar Transistors, *Microwave Theory and Techniques*, 40, No. 3, pp. 465– 474, March 1992.

206. J. Pamulapati, P. K. Bhattacharya, R. L. Tober, J. P. Loehr and J. Singh, "Characterization of High-Quality Pseudomorphic InGaAs/GaAs Quantum Wells by Luminescence and Reflectance Techniques, *Journal of Applied Physics*, **71**, 4487 (1992).

207. R. L. Tober, W-Q. Li and P. K. Bhattacharya "Differential Photocurrent Spectroscopy: A Novel Technique for Semiconductor Characterization," *Journal of Applied Physics*, **71**, 3506 (1992).

208. S. Gupta, L. Davis and P. K. Bhattacharya, "Optical Time-of- Flight Measurement of Carrier Transport in GaAs/AlGaAs and $In_{0.53}Ga_{0.47}As$/ $In_{0.52}Al_{0.48}As$ Multi-Quantum Wells," *Applied Physics Letters*, 60, 1456 (1992).

209. A. Claveri, K. M. Wu, W. Swider, Z. Liliental-Weber, P. K. Bhattacharya, J. Pamulapati, M. O'Keefe and R. Kilaas, "Structural Characterization of Low-Temperature MBE $In_{0.52}Al_{0.48}As$/InP Heterolayers," *Applied Physics Letters*, 60, 989 (1992).

210. W-Q. Li and P. K. Bhattacharya, "Molecular Beam Epitaxial GaAs/AlGaAs Heterojunction Bipolar Transistor on (311)A GaAs Substrates with All-Silicon Doping," *IEEE Electron Device Letters* **13**(1), 29 (1992).

211. D. Yang, Y. Chen, T. Brock and P. Bhattacharya, "D.C. and Microwave Performance of a 0.1 mm Gate InAs/$in_{0.52}Al_{0.48}As$ MODFET," *IEEE Electron Devices Letters*, **13** 250 (1992).

212. D. Nichols, M. Sherwin, G. Munns, J. Pamulpati, J. Loehr, J. Singh and P. Bhattacharya, "Theoretical and Experimental Studies of the Effects of Compressive and Tensile Strain on the Performance of InP/InGaAs Multi Quantum Well Lasers, *IEEE Journal of Quantum Electronics*, 28, 1239, (1992).

213. M. E. Sherwin and G. O. Munns. "CBE Growth of High Quality InAlAs Using TMMA," *Journal of Vacuum Science Technology, B*, **10**, 943, (1992).

214. S. W. Pang, "Processing of Materials," editor, *J. Electronic Materials*, January (1992).

215. M.E. Sherwin, F.L. Terry, Jr., G.O. Munns, J.S. Herman, E.G. Woelk, and G.I. Haddad, "Investigation and Optimization of InGaAs/InP Heterointerfaces Grown by Chemical Beam Epitaxy Using Spectroscopic Ellipsometry and Photoluminescence," *J. Elect. Mat.*, **21**, pp. 269–275, (1992).

216. J. L. Dupuie, E. Gulari, and F.L. Terry, Jr., "The Low Temperature Catalyzed Chemical Vapor Deposition and Characterization of Silicon Nitride Thin Films," *J. Electrochem. Soc.*, **139**, pp. 1151–1159, (1992).

217. J. S. Herman and F.L. Terry, Jr., "Hydrogen Sulfide Plasma Passivation of Gallium Arsenide," *Appl. Phys. Lett.*, **60**, pp. 716–717, (1992).

ACCEPTED

1. J. Singh, Y. Arakawa and P. Bhattacharya, "Consequences of Structural Disorder on Laser Properties in Quantum Wire Lasers," To appear in *Photonics Technology Letters.*

2. J. P. Sun, R. K. Mains, W. L. Chen, J. R. East, and G. I. Haddad, "C- V and I-V characteristics of quantum well varactors," accepted for publication in *J. Appl. Phys.*

3. K. Eisenbeiser, J. East, J. Singh, W. Li and G. Haddad, "Breakdown Voltage Improvements in Strained InGaAlAs/GaAs FET's," accepted for publication in *IEEE Electron Device Letters.*

4 H-F. Chau and D. Pavlidis, "A Physics-Based Fitting and Extrapolation Method for Measured Impact Ionization Coefficients in III-V Semiconductors," to appear in *Journal of Applied Physics.*

5. Y. Kwon, D. Pavlidis, P. Marsh and G. I. Ng, "Experimental Characteristics and Performance Analysis of Monolithic InP-Based HEMT Mixers at W-Band," to appear in *IEEE Transactions on Microwave Theory and Techniques.*

6. S. Kwok, R. Merlin, W-Q Li and P. Bhattacharya, "Raman Scattering from Heavily-Doped (311) GaAs: Si Grown by Molecular Beam Epitaxy," accepted for publication *Journal of Applied Physics.*

7. R. Lai, P. Bhattacharya, D. Yang, T. Brock, SI Alterovitz and A. Downey, "Characteristics of 0.8 mm and 0.2 mm Gate Length $In_xGa_{1-x}As$/ $In_{0.52}Al_{0.48}As$/InP ($0.53 \leq \times \leq 0.70$) Modulation-Doped field Effect Transistors at Cryogenic Temperatures," accepted for publication in *IEEE Transactions on Electron Devices.*

8. M. E. Sherwin, D. T. Nichols, G. O. Munns, E. G. Woelk, F. L. Terry, P. .K. Bhattacharya and G. I. Haddad, "The Growth of high Quality InP/InGaAs/InGaAsP Interfaces by CBE for SCH Quantum Well Lasers," accepted for publication in *Journal of Electronic Materials.*

9. G. O. Munns, M. E. Sherwin, T. Brock, G. I. Haddad, Y. K. Kwon, G. I. Ng and D. Pavlidis, "InAlAs/InGaAs/InP Sub-micron HEMT's Grown by CBE," accepted for publication in *Journal of Crystal Growth.*

10. S. W. Pang, K. T. Sung, and K. K. Ko, "Etching of Photoresist Using Oxygen Plasma Generated by a Multipolar Electron Cyclotron Resonance Source," accepted for publication *J. Vac. Sci. Technol. B.*

11. P. Mazumder and J.-S. Yih, "A Novel Built-In Self-Repair Approach to VLSI Memory Yield Enhancement by Using Neural Networks," accepted for publication in *IEEE Transactions on Computer-Aided Design of Circuits and Systems.*

12. P. Mazumder, "An On-Chip Double-Error-Correction Coding Circuit for Three-Dimensional DRAMS," accepted for publication in *IEEE Transactions on Computers.*

13. R. Venkateswaran and P. Mazumder, "An area-efficient algorithm for reconfiguring hexagonal processor arrays," accepted for publication in *IEEE Transactions on CAD-CAS 1992.*

SUBMITTED

1. T. Tanaka, M. Willatzen, Y. Arakawa, P. Bhattacharya, and J. Singh, "A Study of Valance Bandstructure and Polarization Dependence of Near Bandedge Optical Transistions in Quantum Dots and Quantum Wires," submitted to *Phys. Rev. B.*

2. R. K. Mains and G. I. Haddad, "An Accurate Re-Formulation of the Wigner Function Method for Quantum Transport Modeling," submitted to the *Journal of Computational Physics.*

3. W. L. Chen, J. P. Sun, G. I. Haddad, M. E. Sherwin, G. O. Munns, J. R. East and R. K. Mains, "InGaAs/InP Hot Electron Transistors Grown by Chemical Beam Epitaxy," submitted to *J. Appl. Phys.*

4. S. Mohan, P. Mazumder, R. K. Mains, J. P. Sun and G. I. Haddad, "Ultra-Fast pipelined arithmetic using quantum electronic devices," submitted to *IEEE J. of Solid State Circuits.*

5. S. Mohan, P. Mazumder, G. I. Haddad, R. K. Mains and J. P. Sun, "Logic design based on negative differential resistance characteristics of quantum electronic devices," submitted to *IEEE J. of Solid State Circuits.*

6. Y-J. Chan and D. Pavlidis, "Trap Studies in GaInP/GaAs and AlGaAs/GaAs HEMT's by Means of Low-Frequency Noise and Transconductance Disperson Characterizations," submitted to *IEEE Transactions on Electron Devices.*

7. Y-J. Chan and D. Pavlidis, "Orientation Effects in $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ Heterostructure Insulated-Gate FET's," submitted to *IEEE Transactions on Electron Devices.*

8. H. F. Chau, D. Pavlidis, J. Hu and K. Tomizawa, "Breakdown- Speed Considerations in InP/InGaAs Single and Double Heterostructure Bipolar Transistors, submitted to *IEEE Transactions on Electron Devices.*

9. M. Y. Frankel, D. Pavlidis and G. A. Mourou, "A Study and Optoelectronic Verification of AlGaAs/GaAs Heterojunction Bipolar Transistor Large-Signal Characteristics," submitted to *IEEE Journal of Quantum Electronics.*

10. M. N. Tutt, D. Pavlidis, A. Khatibzadeh and B. Bayraktaroglu, "Investigation of HBT Oscillator Noise Through 1/f Noise and Noise Upconversion Studies," submitted to *IEEE Transactions on Microwave Theory and Techniques Special Issues.*

11. D. R. Pehlke and D. Pavlidis, "Evaluation of the Factors Determining HBT High-Frequency Performance by Direct Analysis of S-Parameter Data," submitted to *IEEE Transactions on Microwave Theory and Techniques Special Issue.*

12. A. Samelis and D. Pavlidis, "Mechanisms Determining Third Order Intermodulation Distortion Mechanisms in AlGaAs/GaAs Heterojunction Bipolar Transistors," submitted to *IEEE Transactions on Microwave Theory and Techniques Special Issues.*

13. W-Q. Li, P. Bhattacharya, S. Swok and R. Merlin, "Molecular Beam Epitaxial Growth Characterization of Si-doped AlGaAs and GaAs on (311)A GaAs Substrates and Their Device Applications, submitted to *Journal of Applied Physics.*

14. M. E. Sherwin, G. O. Munns and F. L. Terry, Jr., "Uniformly Doped and Delta Doped InAlAs/InP HEMT Structures Grown by Chemical Beam Epitaxy," to be submitted to *Applied Physics Letters.*

15. S. W. Pang and K. K. Ko, "Comparison Between Etching in Cl_2 and BCl_3 for Compound Semiconductors Using Multipolar Electron Cyclotron Resonance Source," submitted for publication to *J. Vac. Sci. and Technol..*

16. K. T. Sung, W-Q. Li, S. W. Pang and P. K. Bhattacharya, "Application of High Quality SiO_2 Grown by Multipolar ECR source to SI/SiGe Modulation Doped FET," submitted for publication to *IEEE Electron Dev. Lett.*

17. A. Demos, H. S. Fogler, and M. Elta, "X-Ray Photoelectron (XPS) Study of InP RIE etched with BCl_3 and Argon," submitted for publication to *Journal of Vacuum Science and Technology B.*

18. A. Demos, H. S. Fogler, J. Fournier and M. Elta, "High Temperature Kinetic Study of InP RIE Etched with BCl_3, Argon and Oxygen," submitted for publication to *Journal of the Electrochemical Society.*

19. Y. Lam, E. Espinosa, D. Nichols, L. Davis and P. Bhattacharya, "Observation of Multiple Resonance Frequencies in Strip Geometry InGaAsP Quantum Well Lasers," submitted to *IEEE Quantum Electronic Letters.*

20. M. Amman, E. Ben-Jacob, and J. L. Cohn, "Thermoelectric and Thermo-Coulomb Effects in Tunnel Junctions," submitted to *Phys. Lett.* A.

21. D. Nichols and P. Bhattacharya, "Differential Gain in InP-Based Strained Layer MQW Lasers," submitted to *Applied Physics Letters.*

22. P. Mazumder and J.-S. Yih, "Neural Computing for Built-In Self- Repair of Embedded Memories in VLSI," submitted to *IEEE Transactions on Computers.*

23. K. Yang, J. East and G. Haddad, "Numerical Modeling of Abrupt Heterojunctions Using a Thermionic-Field Emission Boundary Condition," submitted to *Solid State Electronics.*

24. W. L. Chen, J. C. Cowles, G. Haddad, G. Munns, K. Eisenbeiser and J East, 'Ohmic Contact Study for Quantum Effect Transistors and Heterojunction Bipolar Transistors with InGaAs Contact Layers," submitted to *Journal of Vac. Sci. and Tech..*

Conference Presentations

1. Y. Chan, D. Pavlidis, G. I. Ng, M. Jaffe, J. Singh and M. Quillec, "Effect of Channel Strain on the Electrical Characteristics of InGaAs/InAlAs HEMTs," proceedings of IEDM, *IEDM87*, 427, 1987.

2. Y. Zebda, J. Hinckley, P. K. Bhattacharya, J. Singh and F-Y Juang, "High Speed MQW Avalanche Photodiodes," Presented at the International Symposium on the Technologies for Optoelectronics, Cannes, 1987.

3. J. Hinckley, W.-P. Hong, J. Singh and P. K. Bhattacharya, "Experimental and Theoretical Studies of Transport in Bulk $in_{0.52}Al_{0.48}As$ and InAlAs/InGaAs Modulation Doped Heterostructures," American Physical Society Meeting, New York, N.Y., March 1987.

4. J. East, "Noise Properties of Quasi-Ballistic Electrons," presented at Conference on Ballistic Electrons, Santa Barbara, CA, March 1987.

5. D. Pavlidis, G. Ng, H. F. Chau, M. Weiss, J. Hu and W.-P. Hong, "Electronic Properties of Power High Electron Mobility Transistors," Conference on Ballistic Electrons for Transistors, Santa Barbara, CA, March 1987.

6. M. Jaffe and J. Singh, "A Study of the Electronic Structure of GaAs/InAs Superlattices - Comparison with InGaAs Alloy," American Physical Society Meeting, New York, N.Y., March 1987.

7. F. Lamelas, H. Hui and R. Clarke, "Growth and Characterization of Nb/Ta Films," American Physical Society Meeting, New York, N.Y., March, 1987.

8. D. Pavlidis, M. Weiss and G. Ng, "HEMT Device Considerations for Large Signal Application," in the Proceedings 11th Workshop on Compound Semiconductor Devices and Integrated Circuits, Grainau, W. Germany, May 1987.

9. J. T. Remillard and D. G. Steel (invited), "Narrow Resonances in CdSSe Doped Glasses: An Application of Frequency Domain 4-Wave Mixing," in *Laser Spectroscopy VIII*, W. Persson and S. Svanberg, eds. Springer- Verlage, Berlin, pp. 264-266, 1987.

10. W-P. Hong, A. Chin, N. Debbar, J. Hinckley, P. Bhattacharya, J. Singh, and R. Clarke, "Summary Abstract:Material Properties and Clustering in Molecular Beam Epitaxial $In_{0.52}Al_{0.48}As$ and $In_{1-x-y}Ga_xAs$," presented at the 7th MBE Conference, Cambridge, 1986, *J. Vac. Sci. Tech. B*, 5, 800, May/June 1987.

11. M. Weiss and D. Pavlidis, "A Comparative Study of TEGFET and MESFET Large Signal Characteristics and Saturation Mechanisms," in the Proceedings 1987-IEEE MTT-S International Microwave Symposium Digest, Las Vegas, NV, pp. 553–556, June 1987.

12. N. Dogan, J. East, M. Elta and G. I. Haddad, "Millimeter Wave Heterojunction MITATT Diodes," presented at MTT Symposium, June 1987.

13. M. Jaffe, Y. Sekiguchi, J. Singh, Y. J. Chan, D. Pavlidis, and M. Quillec, "A Study of Charge Control in n- and p-type Lattice Matched and Strained Channel MODFETs with GaAs and InP Substrates," presented at the Cornell Conference, Ithaca, NY, August 1987.

14. J. T. Remillard and D. G. Steel, "Narrow Resonances in CdSSe Doped Glasses: An Application of Frequency Domain 4-Wave Mixing," 8th International Conference, Are, Sweden, June 1987, published in proceedings *Laser Spectroscopy VIII*, pp. 264–266.

15. P. K. Bhattacharya (Invited), "Properties of Multiple Quantum Wells and Their Use in High-Speed Detectors and Modulators," Proceedings of SPIE Conference on Optoelectronic Materials and Devices, San Diego, August 1987.

16. Y. Sekiguchi, Y. J. Chan, M. Jaffe, M. Weiss, G. I. Ng, J. Singh, M. Quillec and D. Pavlidis, "Theoretical and Experimental Studies on Lattice Matched and Strained MODFETs," International 14th GaAs and Related Compound Conference, Institute of Physics Conference Series, Crete, Greece, September 1987, Institute of Physics Conference Series No. 91, Bristol, UK, pp. 215–218.

17. D. G. Steel, J. T. Remillard, H.Wang and M. D. Webb, "Application of 4-Wave Mixing Spectroscopy to Semiconductor Material Studies"(invited) 1988 Conference on Lasers and Electro-Optics, *Technical Digest*, **7**, pp. 260–261, 1988.

18. J. T. Remillard, H. Wang, M. D. Webb and D. G. Steel, "Frequency domain four-wave mixing spectroscopy in semiconductor quantum wells and microcrystallites," XVI International Conference on Quantum Electronics, *Technical Digest* (Tokyo), pp. 278–279, 1988.

19. J. T. Remillard, H. Wang and D. Steel, "High resolution nonlinear laser spectroscopy of the heavy hole exciton at 5K: A direct measure of the exciton lineship," XIV International Conference on Quantum Electronics, *Postdeadline Digest*, (Tokyo), pp. 48- 49, 1988.

20. J. Hinckley, and J. Singh, " Theoretical Studies of Hole Transport in p-type Strained and Unstrained III-V Semiconductors," Presented at March 1988 Meeting of the American Physical Society, June 1988, New Orleans, LA.

21. M. Jaffe, J. Oh, J. Pamulapati, P. Bhattacharya and J. Singh, "Experimental and Theoretical Studies of Carrier Mass in Pseudomorphic n- and p- type MODFETs with Excess Indium in the Active Channel," GaAs and Related Compounds Conference Proceedings, (1988).

22. R. L. Tober, J. Pamulapati, P. Bhattacharya and J. Oh, "Piezoreflectance Characterization of Resonant Tunneling and Modulation-Doped Heterostructures," presented at Electronic Materials Conference, June 1988, Boulder, CO.

23. Y. Zebda, R. Lipa, M. Tutt, D. Pavlidis and P. K. Bhattacharya, "Theoretical and Experimental Studies of Monolithically Integrated Pseudomorphic InGaAs/AlGaAs MODFET-APD Photoreceivers," presented at Device Research Conference, June 1988, Boulder, CO.

24. G. I. Haddad, R. K. Mains, U. K. Reddy, and J. R. East, "A Proposed Narrow-Band-Gap Base Transistor Structure," Presented at Fourth International Conference on Superlattices, Microstructures and Microdevices in Trieste, Italy, August 1988.

25. I. Mehdi, G. I. Haddad and R. K. Mains, "Novel Use of Resonant- Tunneling Structures for Optical and IR Modulators," Presented at Fourth International Conference on Superlattices, Microstructures and Microdevices in Trieste, Italy, August 1988.

26. P. Mazumder, "A Test Methodology for Electronic Neural- Network Associative Memory," presented First Annual Conference of International Neural-Network Society, Boston, MA, September 1988.

27. G. I. Ng, M. Weiss, D. Pavlidis, M. Tutt, P. Bhattacharya and C. Y. Chen, "Microwave Properties of Strained $In_{0.53+x}Ga_{0.47-x}As/In_{0.52}Al_{0.48}As$ HEMT's," International 15th GaAs and Related Compounds Conference, Atlanta, GA, USA, September 1988. Published in *Institute of Physics Conference Series-1989*, **96**, Ch. 7, 465.

28. Y. Zebda and P. K. Bhattacharya, "Design and Performance of Very High Speed InGaAs and GaAs Photodiodes," SPIE Conference on High Speed Analog Communication, Boston, September 1988.

29. P. Mazumder, "An On-Chip Double-Bit Error-Correcting Code for Three-Dimensional Dynamic Random-Access Memory," presented at the International Test Conference, Washington, D.C., September 1988.

30. P. Mazumder, "Design of a Fault-Tolerant Dram with New On- Chip ECC," presented at the International Workshop on Fault-Tolerant Computing, Springfield, MA, October 1988.

31. J. Singh, "Kinetics and Energetics Issues in Semiconductor Heteroepitaxy using Molecular Beam Epitaxy,"(invited presentation), Annual Electrochemical Society Meeting, Chicago, October, 1988.

32. R. K. Mains, I. Mehdi and G. I. Haddad, "Resonant-Tunneling Devices for Millimeter-Wave Generation," Presented at 13th International Conference on Infrared and Millimeter Waves, Honolulu, Hawaii, December 1988.

33. R. K. Mains and G. I. Haddad, "Time-Dependent Modeling of Resonant-Tunneling Diodes," presented at the AFOSR Workshop on Quantum Devices, September 15–16, 1988, Atlanta, GA.

34. J. L. Cazaux, D. Pavlidis, G. I. Ng and M. Tutt, "The Use of Double Heterojunction Diodes in Monolithic Phase Shifters," Proceedings of the 18th European Microwave Conference, Stockholm, Sweden, September 1988, pp. 1005–1010.

35. J. L. Cazaux, D. Pavlidis, G. I. Ng and M. Tutt, "A HEMT Monolithic Double Channel Attenuator with Broadband Characteristics and Wide Dynamic Range," Proceedings of the 18th European Microwave Conference, Stockholm, Sweden, September 1988, p. 999-1004.

36. Y. J. Chan, D. Pavlidis, M. Razeghi, M. Jaffe and J. Singh, "Novel P-channel $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As/GaAs$ Strained (x = 0.1) and Lattice Matched (x = 0) HEMT's," International 15th GaAs and Related Compounds Conference, Institute of Physics Conference Series, Atlanta, GA, USA, September 1988.

37. M. Jaffe, J. Oh, J. Pamulapati, P. Bhattacharya and J. Singh, "Experimental and Theoretical Studies of Carrier Mass in Pseudomorphic n- and p-type MODFETs with excess In in the active channel," 15th International GaAs and Related Compounds Conference, Atlanta, GA, September 1988.

38. M. Tutt, D. Pavlidis, G. I. Ng, M. Weiss and J. L. Cazaux, "Monolithic Integrated Circuit Applications of InGaAs/InAlAs HEMT's," 1988 IEEE GaAs Integrated Circuit Symposium Digest, Nashville, TN, USA, November 1988, pp. 293–296.

39. J. Singh, R. Lai and P. Bhattacharya, "A New Vertical Transistor Based on $\Gamma - \Gamma$ and $X - X$ Discontinuities in the $Al_xGa_{1-x}As/Al_yGa_{1-y}As$ Heterostructures, Proceedings of the GaAs and Related Compounds Conference. Karuizawa, Japan, p. 719 (1989).

40. J. Singh. "Two dimensional pattern matching and associative memory using a simple optoelectronic architecture," Proceedings of the SPIE Intelligent Systems Conference, Philadelphia, November 1989.

41. J. Hinckley, V. Sankaran, J. Singh and S. Tiwari, "An Evaluation of Si and SiGe Bipolar Transistors for High Frequency and High Speed Application – Basic Transport and Design," Proceedings of the 1989 Cornell Advanced Concepts Conference.

42. Y. J. Chan, D. Pavlidis, M. Razeghi, F. Omnes and M. Defour, "Pseudomorphic $Ga_{0.51}In_{0.49}P/In_{0.15}Ga_{0.85}As/GaAs$ HIGFET's," *Inst. Phys. Conf. Ser.*, No. 106; Chapter 9, pp. 619–624. Paper presented at 16th International Symposium on GaAs and Related Compounds, Karuizawa, Japan, September 1989.

43. P. Mazumder, "An Efficient Design of Embedded Memories for Random Pattern Testability," presented at the International Conference on Wafer Scale Integration, San Diego, CA, January 1989.

44. D. Pavlidis, G. I. Ng, and M. Weiss, "Gain and Noise Characteristics of InAlAs/InGaAs Strained HEMT's," InP Based Microwave/Millimeter-Wave Technology Workshop, NOSC, San Diego, CA, January 25, 1989.

45. I. Mehdi and G. I. Haddad, "InP based resonant tunneling diodes for microwave and millimeter-wave application,"International Nanostructure Physics and Fabrication Conference, Texas, March 1989. Texas, March 1989, published in the proceedings *Nanostructure Physics and Fabrication*, ed. M. A. Reed and W. P. Kirk, Academic Press, 1989.

46. U. K. Reddy, G. I. Haddad, I. Mehdi and R. K. Mains, "Fabrication and room temperature operation of a resonant tunneling transistor with a pseudomorphic InGaAs base," International Nanostructure Physics and Fabrication Conference, College Station, Texas, March 1989, published in the proceedings *Nanostructure Physics and Fabrication*, ed. M. A. Reed and W. P. Kirk, Academic Press, 1989, pp. 189–193.

47. I. Mehdi and G. I. Haddad, "InGaAs based resonant tunneling diodes for microwave and millimeter-wave applications," American Physics Society, St. Louis, March 1989.

48. K. Mullen, "The Serially Resistive Junction Model and Charge Effect Solitions," American Physics Society, St. Louis, March 1989.

49. M. Amman, "The Charge Effect Transistor," American Physics Society Meeting, St. Louis, March 1989.

50. E. R. Borroff, R. Merlin, P. K. Bhattacharya and C. Tejedor, "Electronic Raman Scattering from Coupled Intersubband-Landau- Level Excitations in Quantum Wells," American Physics Society Meeting, St. Louis, March 1989.

51. R. Wilkins, "STM Observations of Coulomb Blockade and Oxide Polarization in Small Metal Droplets," American Physical Society Meeting, St. Louis, March 1989.

52. D. Li and H. G. Winful, "Nonlinear Propagation of Coherently Coupled Solitons Generated Through Parametric Processes," Conference on Nonlinear Guided Waves, Houston, TX, February 1989, 293–296.

53. D. G. Steel, J. T. Remillard, Hailin Wang, M. D. Webb, J. Oh, J. Pamulapati, and P. K. Bhattacharya, "High Resolution Nonlinear Laser Spectroscopy of GaAs/AlGaAs Multiple Quantum Wells," presented at the OSA Topical Meeting on Quantum Wells for Optics and Optoelectronics, *OAS Tech. Dig.*, **10**, pp. 62–65 (1989).

54. J. Hinckley and J. Singh, "Theoretical Studies of High Field Transport in the Si_xGe_{1-x} Alloy Grown on Si – Role of Strain on P-type Transport," presented at the 1989 American Physical Society Meeting, St. Louis, March 1989.

55. J. P. Loehr, M. Jaffe and J. Singh, "A Non Variational Approach to the Exciton Problem in Quantum Wells – Application to the FET Optical Modulator," presented at 1989 American Physical Society Meeting, St. Louis, March 1989.

56. B. Das, D. C. Miller, R. Reifenberger, S. Datta, W. Hong, P. Bhattacharya, J. Singh and M. Jaffe, "Spin Splitting in $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ Heterostructures as B $\rightarrow$ 0," the 1989 American Physical Society Meeting, St. Louis, March 1989.

57. D. Pavlidis, "Microwave and Millimeter-Wave Monolithic Integrated Circuits," (invited paper) Electro-89 Conference, New York NY, Professional Program Session Record, pp. 3/3.2–3/3.8, April 1989.

58. H. Wang, J. T. Remillard, M. D. Webb and D. G. Steel, "High Resolution Nonlinear Laser Spectroscopy and Efficient Optical Phase Conjunction in Semiconductor Microcrystallite Doped Glasses," Conference on Laser and Electro-Optics, 1989 (CLEO '89) *OSA Tech. Dig.*, **11**, pp. 156–157 (1989).

59. D. G. Steel, H. Wang, J. T. Remillard, M. D. Webb, P. K. Bhattacharya, J. Oh, and J. Pamulapati, "High Resolution Nonlinear Laser Spectroscopy of Excitons in GaAs/AlGaAs Multiple Quantum Well Structures," invited paper in *Laser Spectroscopy IX*, (Academic Press 1989).

60. D. G. Steel, P. K. Bhattacharya, J. T. Remillard, H. Wang, M. D. Webb, J. Pamulapati, and J. Oh, "High Resolution Nonlinear Laser Spectroscopy of Excitons in GaAs Quantum Well for Optic and Optoelectronics, *OSA Tech. Dig.*, **12**, pp. 4–7, (1989).

61. D. Pavlidis and G. I. Ng, "Improved Gain Designs of Strained InGaAs/InAlAs HEMT's" 13th Workshop on Compound Semiconductor Devices and Integrated Circuits held in Europe (WOCSDICE 89), Cabourg, France, May 1989.

62. D. Pavlidis, J. Hu, K. Tomizawa and D. Pehlke, "Fast Switching Design of Heterojunction Bipolar Transistors,"13th Workshop on Compound Semiconductor Devices and Integrated Circuits held in Europe (WOCSDICE 89), Cabourg, France, May 1989.

63. J.-S. Yih and P. Mazumder, "Neural Computing for Circuit Partitioning," presented at IEEE/ACM Design Automation Conference, June 1989.

64. R. Merlin, "Electronic Raman Scattering in Photoexcited Quantum Wells" Field Effects and Charge-Density Domains," (invited) NATO Advanced Research Workshop on Spectroscopy of Semiconductor Microstructures, Venice, May 1989 .

65. R. H. Voelker and R. J. Lomax, "Three-Dimensional Electromagnetic Field Simulation of Integrated Circuits Using the TLM Method," presented at the Progress in Electromagnetics Research Symposium, MIT, July 1989 and published in *Proc. Progress in Electromagnetics Research Symposium*, Boston, MA, July 1989, pp. 514–519.

66. U. K. Reddy, I. Mehdi, R. K. Mains and G. I. Haddad, "Design, fabrication and operation of a hot electron resonant tunneling transistor," presented at the 6th International Conference on Hot Carriers in Semiconductors, Tempe, Arizona, July 1989.

67. I. Mehdi, G. I. Haddad, R. K. Mains and U. K. Reddy, "Properties and device applications of deep quantum well resonant tunneling structures," presented at the 4th International Conference on Modulated Structures, Ann Arbor, Michigan July 1989.

68. H. Wang. J. T. Remillard, D. G. Steel, J. Oh, J. Pamulapati and P. K. Bhattacharya, "High Resolution Laser Spectroscopy of Relaxation and the Excitation Line Shape of Excitons at Low Temperature in GaAs Quantum Well Structures," presented at the 4th International Conference on Modulated Structures, Ann Arbor, Michigan July 1989.

69. G. I. Haddad, "Nanoelectronic Devices," Electro/89, New York, NY, April 1989.

70. G. I. Haddad, "Microwave/Millimeter-Wave Solid-State Devices," Electro/89, New York, NY, April 1989.

71. W.-Q. Li, Y. Zebda, P. Bhattacharya, D. Pavlidis, J. Oh and J. Pamulapati, "Monolithically Integrated GaAs- and InP-based Front-end Photoreceivers," presented at 1989 IEEE/Cornell Biennial Conference on Active Semiconductor Devices.

72. P. Mazumder, "An Efficient Design of Embedded Memories for Random Pattern Testability," presented at the International Conference on Wafer Scale Integration, San Diego, CA, January 1989.

73. J. P. Loehr, J. Singh, Y. C. Chen and P. K. Bhattacharya, "Biaxial Strain Induced Changes in Hole Bandstructures — Consequences for Hole Masses and Acceptor Levels in InGaAs (on GaAs) Wells," Proceedings of the Sixteenth International Symposium on Gallium Arsenide and Related Compounds, Karuizawa, Japan, p. 441 (1989).

74. N. Debbar, D. Biswas, P. K. Bhattacharya and J. Singh, "Recombination and Tunneling Dynamics in Square and coupled Quantum Wells," presented at the 16th International Symposium on GaAs and Related Compounds, Karuizawa, Japan, September 1989.

75. Y. J. Chan, D. Pavlidis, M. Razeghi and F. Omnes, "DC and Microwave Characteristics of GaInP/GaAs HEMT's Suitable for Cryogenic Operation," presented in the 16th International Symposium on GaAs and Related Compounds, Karuizawa, Japan, September 1989.

76. M. Tutt, D. Pavlidis and B. Bayraktaroglu, "An Assessment of Noise Sources and Characteristics of AlGaAs/GaAs Heterojunction Bipolar Transistors," presented at the 16th International Symposium on GaAs and Related Compounds, Karuizawa, Japan, September 1989.

77. G. Feak, D. Nichols, J. Singh, J. Loehr, J. Pamulapati and P. Bhattacharya, "The Influence of Strain on the Small Signal Gain and Lasing Threshold of GaInAs/GaAs and GaAs/GaInAlAs Strained Layer Quantum Well Lasers," IEEE Cornell University

Conference on Advanced Concepts in High Speed Semiconductor Devices and Circuits, Aug. 7–9, 1989, Ithaca, New York.

78. G. I. Ng, A. Reynoso, J. Oh, D. Pavlidis, J. Graffeuil, P. K. Bhattacharya, M. Weiss and K. Moore, "Low-Frequency Properties of Lattice-matched and Strained InGaAs/InAlAs HEMTs." presented at the IEEE/Cornell Conference on Advanced Concepts in High-Speed Semiconductor Devices and Circuits," Ithaca, August 1989.

79. P. K. Bhattacharya (invited), "Optoelectronic Integrated Circuits for Photoreceivers and Communication Systems," presented at the International Conference on VLSI and CAD, Seoul, Korea, October 1989.

80. H. G. Winful and L. Rahman, "Nonlinear Dynamics of Semiconductor Laser Arrays," invited paper, Lasers'89, New Orleans, December 1989.

81. H. G. Winful, "Self-Organization and Spatio-Temporal Chaos in Coupled Laser Arrays," Annual Meeting, Optical Society of America, Orlando, FL, October 1989.

82. D. A. Weinberger, A. Kamal and W. H. Weber, "Studies of efficient second harmonic generation in optical fibers," poster paper presented at the Gordon Conference on Nonlinear Optics and Lasers, Wolfeboro, NH, July 1989.

83. D. A. Weinberger, "Second harmonic generation in optical fibers," and "Nonlinear pulse propagation in optical fibers," invited lectures presented at the International Summer School on Nonlinear Optics in Solids, Aalborg, Denmark, August 1989.

84. A. Kamal, D. A. Weinberger and W. H. Weber, "Spatially resolved Raman study of self-organized $\chi^{(2)}$ gratings in optical fibers," Optical Society of America Annual Meeting, Orlando, Florida, October 1989.

85. S. F. Feldman, D. A. Weinberger and H. G. Winful, "Observation of polarization instabilities and modulational gain in a low-birefringence optical fiber," Optical Society of America Annual Meeting, Orlando, Florida, October 1989.

86. J. Singh, "An Optoelectronic Architecture for Image Recognition and Comparison," AUTOFACT '89, Detroit, MI, October 30-November 2, 1989, published as SME Technical Paper, AD89-661.

87. H. Wang, J. T. Remillard, J. Jiang, M. D. Webb and D. G. Steel (invited paper), "Frequency Domain Nonlinear Optical Studies of Multiple Quantum Well Structures," Proceedings of the Society of Photo Instrumentation Engineers, High Energy Laser and Optical Computing, Conference, 1216.

88. C. Uher, "Effect of Fast Neutron Irradiation on $YBa_cCu_3O_7$," presented at APS Meeting, St. Louis, March 1989, *Bull. Amer. Phys. Soc.*, 34, 741 (1989).

89. C. Uher, "Mechanisms of Heat Conduction in High-T_C Superconductors," invited paper at the 3rd Annual Conference on Superconductivity and Applications, NYSIS, Buffalo, September 19–21, 1989.

90. S. Tiwari, W. Wang and J. East, "The Auger Transistor," presented at IEEE/Cornell University Conference, Ithaca, NY, August 7–9 1989.

91. R. Venkateswaran and P. Mazumder, "A Hexagonal Array Machine for Multi-Layer Wire Routing," presented at the IEEE International Conference on CAD, Santa Clara, November 1989 (in proceedings).

92. V. Ramachandran and P. Mazumder, "Hardware Accelerator for Multi-Layer Routing," presented at the International Conference on CAD, 1989.

93. D. G. Steel, P. K. Bhattacharya, J. T. Remillard H. Wang, M. Webb, J. Pamulapati, and J. Oh, "High resolution nonlinear laser spectroscopy of excitons in GaAs quantum well structures," Quantum Electronics and Laser Science Conference, (Optical Society of America), Baltimore MD, April 1989, Technical Digest, vol 12.

94. R. Merlin, N. Mestres, A. McKiernan, J. Oh, and P. K. Bhattacharya, "Charge -Density Domains in Photoexcited Quantum- Well Structures," 4th International Conference on Modulated Semiconductors Structures, Ann Arbor, March 5–6. 1990.

95. G. I. Ng, Y. Kwon and D. Pavlidis, "Submicrometer Devices and Monolithic Functions Using InAlAs/InGaAs Heterostructures," 1st International Symposium on Space Terahertz Technology, Ann Arbor, March 5–6, 1990.

96. C. Kidner, I. Mehdi, J. East and G. I. Haddad, "Potential and capability of resonant tunneling diodes," 1st International Symposium on Space Terahertz Technology, Ann Arbor, March 5–6, 1990.

97. A. Kamal, D. A. Weinberger and W. H. Weber, "Properties of $\chi^{(2)}$ gratings in optical fibers using a spatially resolved Raman spectroscopic analysis," presented at Topical Meeting on Integrated Photonics Research, Hilton Head, SC, March, 1990.

98. A. Kamal and D. A. Weinberger, "Rate equation model for the evolution of $\chi^{(2)}$ gratings in optical fibers," presented at Topical Meeting on Integrated Photonics Research (Hilton Head, SC, March, 1990), and Conference on Lasers and Electro-Optics (Anaheim, CA, May, 1990).

99. D. G. Steel, H. Wang, J. T. Remillard, and M. Jiang (invited paper) "Application of Frequency Domain High Resolution Nonlinear Laser Spectroscopy to the Study of Excitons in GaAs/AlGaAs Quantum Well Structures," Fourth US-USSR Binational Symposium, Plenum Press, 1990.

100. G. Haddad, J. East, C. C. Chen and K. Hashim, "Tunnel Transit Time (TUNNETT) Devices for Terahertz Sources," 1st International Symposium on Space Terahertz Technology, Ann Arbor, March 5–6, 1990.

101. J. E. Oh, P. K. Bhattacharya, J. Singh, W. Dos Passos, R. Clarke N. Mestres, R. Merlin, K. H. Chang and R. Gibala, "Epitaxial Growth and Characterization of GaAs/AlGaAs Heterostructures," 4th International Conference on Modulated Semiconductor Structures, Ann Arbor, March 5–6, 1990.

102. C. Kidner, I. Mehdi, J. East and G. I. Haddad, "Resonant tunneling diode stability and its consequences for high frequency operation," presented at SPIE's 1990 Symposium on Advances in Semiconductors and Superconductors: Physics Towards Device Applications, San Diego, March 1990.

103. C. Uher, "Heat Conduction in High-T_c Superconductors," invited paper at the Intnernational Conference on Transport PRoperties of Superconductors, April 29–May 4, 1990, Rio de Janeiro, Brazil, proceedings published in *Progress in High Temperature Superconductivity*, ed. R. Nicolsky, World Scientific Publishing, Singapore, vol. 25, p. 404 (1990).

104. D. Teeter, J. R. East, R. K. Mains and G. I. Haddad, "A Numerical Large Signal Model for the Heterojunction Bipolar Transistor," presented at the Workshop on Computational Electronics, University of Illinois, May 1990 published in the proceedings, *Computational Electronicas*, edited by K. Hess, T. P. Leburton and U. Ravaioli, Kluever Academic Publishers, Boston.

105. D. Pavlidis, J. Hu and K. Tomizawa, "Design of InAlAs/InGaAs Heterojunction Bipolar Transistors for Optimum Speed Performance," 14th European Workshop on Computer Semiconductor Devices and Integrated Circuits (WOCSDICE), Cardiff, U. K., May 1990.

106. Y. Chan and D. Pavlidis, "P-Type Doped Channel FET's Using Strained and Lattice matched InAlAS/InGaAs Heterostructures," 2nd International Conference on Indium Phosphide and Related Materials, Denver, CO, April 1990.

107. G. I. Ng, R. Lai, D. Pavlidis, J. Pamulapati, P. K.Bhattacharya and K. Studer-Rabeler, "Submicron Double Heterojunction Strained InAlAs/InGaAs HEMT's: An Experimental Study of DC and Microwave Properties," 2nd International Conference on Indium Phosphide and Related Materials, Denver, CO, April 1990.

108. S. F. Feldman, D. A. Weinberger and H. G. Winful, "Observation of modulational gain and analysis of polarization instabilities in optical fiber with twist," presented at Topical Meeting on Integrated Photonics Research , Hilton Head, SC, March, 1990 and Conference on Lasers and Electro-Optics, Anaheim, CA, May 1990.

109. D. Pavlidis, Y. Kwon, G. I. Ng and M. Tutt, "94 GHz Heterostructure Mixer MMIC Using Submicrometer InAlAs/InGaAs HEMT's," 14th European Workshop on Compound Semiconductor Devices and Integrated Circuits(WOCSDICE), Cardiff, U. K., May 1990.

110. M. D. Webb, S. T. Cundiff, D. G. Steel, "Stimulated Photon Echoes: Spectral Diffusion of HH1 Excitons in GaAs/AlGaAs Multiple Quantum Wells," Ultrafast VII, 1990.

111. M. D. Webb, S. T. Cundiff, and D. G. Steel, "Stimulated Photon Echoes (SPE) and Free Polarization Decay (FPD) in Time Resolved Four-Wave Mixing Spectroscopy of HH1 Excitons in GaAs/AlGaAs Multiple Quantum Well Structures at 5K," presented, International Quantum Electonics Conference IQEC/CLEO '90.

112. G.A.B. Feak, L.D. Zhu, B.Z. Zheng, Z. Y. Xu and J. Z. Xu, "Optical Gain in GaAs/GaAlAs Graded-Index Separate Confinement Single Quantum Well Heterostructures," presented, International Conference on Opto-Electronic Science and Engineering (ICOESE '90), Aug. 22-25, 1990, Beijing, China.

113. H. Wang, J. T. Remillard, D. G. Steel, J. Oh, J. Pamulapati and P. K. Bhattacharya, "Frequency domain nonlinear optical studies of relaxation mechanisms and the homogeneous line shape of excitons in GaAs/AlGaAs quantum well structures," invited paper, SPIE Conference: Nonliear Optical Materials and Devices for Photonic Switching, (1990) published in proceedings, vol. 1216, pp. 206–214.

114. R. Wilkins, "Surface Oxide Effects on Tunneling Spectra Measured with a Cryogenic Scanning Tunneling Microscope," poster presented at STM'90 - Nano I Conference, Baltimore, MD, July 25, 1990.

115. R. B. Brown, "A GaAs Microcomputer," Fall DARPA Contractor's Meeting, Chapel Hill, NC, October 3–5, 1990.

116. J. Loehr, Y. C. Chen, D. Biswas, P. K. Bhattacharya and J. Singh, "Hydrogenic Acceptor Levels in Quantum Wells Under Biaxial Compressive and Tensile Strain," presented at the 20th International Conference on Physics of Semiconductors, Thessaloniki, Greece, August 1990.

117. G. I. Haddad, U. K. Reddy, J. P. Sun and R. K. Mains, "The bound state resonant tunneling transistor (BSRTT): Fabrication, D.C. I-V characteristics and high-frequency properties". Presented at the 5th International Conference on the Physics of Electro-optic Microstructures and Microdevices, July 1990 at Heraklion, Crete, Greece and published in *Superlattices and Microstructures*, vol. 7. No. 4, pp. 369–374, 1990.

118. G. I. Haddad, "Resonant tunneling devices for very high speed optoelectronics applications," Plenary Session Presentation, SPIE International Conference on Physical Concepts of Materials for Novel Optoelectronic Device Applications, October 28 – November 2, 1990, Aachen, Germany.

119. I. Mehdi, J. East and G. Haddad, "Resonant Tunneling Diode Video Detectors for 10–100 GHz Applications," presented at the Infrared and Millimeter-wave Conference, Orlando, FL, December 1990.

120. R. Clarke, W. Dos Passos, Y-J. Chan, D. Pavlidis, W. Lowe, B. Rodricks and C. Brizard, "Real Time X-ray Studies of Semiconductor Device Structures." Proceedings of the SPIE Conference, Aachen, October 1990, Proccedings *Physical Concepts of Materials for Novel Optoelectronic Device Applications*, vol. 1361.

121. M. Weiss, G. I. Ng and D. Pavlidis, "InP Based Monolithic Integrated HEMT Amplifiers and their Material Sensitivity," Proceedings of the 20th European Microwave Conference, Budapest, Hungary, pp. 959–964, September 1990.

122. M. Weiss, D. Pavlidis and G. I. Ng, "HEMT Control Circuits for Monolithic InP Applications," Proceedings of the 20th European Microwave Conference, Budapest, Hungary, pp. 429–434, September 1990.

123. Y. Kwon, D. Pavlidis, G. I. Ng, M. Tutt and T. Brock, "W- Band Monolithic Mixer Using InAlAs/InGaAs HEMT's," Technical Digest of the IEEE GaAs IC Symposium, New Orleans, pp. 181–184, October 1990.

124. D. Pavlidis, "Millimeter-Wave and Optoelectronic Applications of Heterostructure Integrated Circuits," presented at the SPIE Conference, Aachen, October 1990.

125. J. Hu, D. Pavlidis and K. Tomizawa, "Transient and Steady-State Monte-Carlo Simulation of the Effects of Junction Gradings on Carrier Transport in InAlAs/InGaAs HBT's," *IEEE IEDM Technical Digest 1990*, San Francisco, pp. 439–442, December 1990.

126. R. Lai, P. R. Berger, P. Bhattacharya, Y. Zebda, W-Q. Li and D. Pavlidis, "Monolithically Integrated $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ Front-End Photoreceivers Realized by Molecular Beam Epitaxy and Regrowth Techniques," presented at the IEEE/LEOS Topical Meeting on Integrated Optoelectronics, Monterrey, CA, August 1990.

127. J. Pamulapati, J. P. Loehr, J. Singh, P. K. Bhattacharya and M. J. Ludowise, "Electro-Optic Effect in Strained and Lattice- Matched MQW Structures – Role of Excitonic Resonances," 5th International Conference on the Physics of Electro-Optic Microstructures and Microdevices, Heraklion, Crete, Greece, August 1990.

128. L. Davis, V. Sankaran, S. Gupta, J. Singh and P. Bhattacharya, "Role of Central Cell Symmetries in Tunneling of Electrons and Holes in $GaAs/Al_xGa_{1-x}As$ Quantum Well Structures," 17th International Symposium on Gallium Arsenide and Related Compounds, Jersey, United Kingdom, September 1990.

129. P. Bhattacharya and J. Singh, "Strained Semiconductors and Heterostructures: Synthesis and Applications," (invited) International Conference on Physical concepts of Materials for Novel Optoelectronic Device Applications," Aachen, Germany, October 1990.

130. M. E. Sherwin, G. O. Munns, E. G. Woelk, T. J. Drummond, M. E. Elta, F. L. Terry, Jr. and G. I. Haddad, "The Design of an ECR Plasma System and its Application to InP Grown by CBE," Presented at the 1990 MBE VI Conference.

131. M. E. Sherwin, G. O. Munns, M. E. Elta, E. G. Woelk, S. Crary, F. L. Terry, Jr. and G. I. Haddad, "The Optimization of InGaAs and InP Growth Conditions via MOMBE and CBE," Presented at the 1990 MBE VI Conference.

132. R. Clarke, W. Dos Passos, W. P. Lowe, B. Rodricks, and C. Brizard, "Time Resolved, X-Ray Scattering Studies using CCD Detectors," (invited) SPIE Symposium on Electro-optic and Optoelectronic Applications - Proceedings, vol. 1345.

133. A. Demos, H. S. Fogler, S. W. Pang and M. E. Elta, "Enhanced Etching of InP by Cycling with Sputter Etching and Reactive Ion Etching," SPIE's Conference on Microelectronic Processing Integration, Santa Clara, CA, October 1990.

134. A. Demos, H. S. Fogler, H. Etemad-Moghadam and M. E. Elta, "New Reactive Ion Etch Technique Based on Sputter Oscillation for GaAs," AIChE Annual Meeting, Electronic Materials Processing, Chicago, IL, November 1990.

135. M. D. Webb, S. T. Cundiff, D. G. Steel "Simulated Photon Echoes and Free Polarization Decay Signals in GaAs Quantum Wells: Evidence for Localized and Delocalized Excitons," published in the proceedings of the 7th International Conference, *Ultrafast Phenomena VII*, p. 233, C. B. Harris, E. P. Ippen, G. A. Mourou and A. H. Zewail, eds., Springer-Verlag, Berlin, 1990.

136. R. Wilkins, "Surface Oxide Effects on Tunneling Spectra Measured with a Cryogenic Scanning Tunneling Microscope," poster presented at STM'90 - Nano I Conference, Baltimore, MD, July 25, 1990.

137. P. Mazumder and J.-S. Yih, "A novel built-in self-repair approach to VLSI memory yield enhancement." Proceedings of the International Test Conference, pp. 833-841, September 1990.

138. D. G. Steel, (invited paper) "High Resolution Spectroscopy and Photon Echoes in GaAs Quantum Wells," APS March Meeting, *Bull. Am. Phys. Soc.*, **36**, p. 338 (1991).

139. D. G. Steel, H. Wang, S. T. Cundiff and M. Jiang, (invited paper) "Coherent Nonlinear Spectroscopy of Excitons in GaAs/AlGaAs Multiple Quantum Wells," Conference on Lasers and Electro Optics, CLEO '91, *Technical Digest Series*, **10**, pp. 308–309 (1991).

140. D. G. Steel, H. Wang, S. T. Cundiff and M. Jiang, (invited paper) "Nonlinear Optics and Spectroscopy in Systems with Reduced Dimensionality," Nonlinear Optics Gordon Conference, 1991.

141. M. Jiang, H. Wang and D. G., Steel, "Anomalous Nonlinear Optical Processes in GaAs/AlGaAs Quantum Wells," Quantum Electronics and Laser Science (QELS'91), *Technical Digest Series*, **11**, pp. 252–253 (1991).

142. S. T. Cundiff, M. D. Webb and D. G. Steel, "Measurement of picosecond excitation relaxation and dephasing of localized in GaAs/AlGaAs Multiple Quantum Wells," Quantum Electronics and Laser Science (QELS'91), *Technical Digest Series*, **11**, pp. 200-201 (1991).

143. D. G. Steel, S. T. Cundiff, M. Jiang, H. Wang and M. D. Webb, "Coherent Nonlinear Laser Spectroscopy Studies of Exciton Relaxation, Dephasing and Energy Transport in GaAs Quantum Wells," Quantum Optoelectronics, *OSA Technical Digest*, **7** (1991).

144. A. G. Engel, Jr. and L.P.B. Katehi, "Analysis of Microstrip Structures on and near Dielectric Ridges Using an Integral Equation- Mode Matching Technique," *1991 IEEE MTT-S International Microwave Symposium Digest*, No. D-4, pp. 135–138.

145. A. G. Engel, Jr. T. E. van Deventer and L.P.B. Katehi, "Low-Loss Guiding Structures for THz Frequency Applications," Proceedings of the Second International Symposium on Space Terahertz Technology, 1991, pp. 545–547.

146. S. Mohan and P. Mazumder, "Fault modeling and testing of GaAs static random access memories," International Test Conference 1991.

147. T. N. Mudge, R. B. Brown, W. P. Birmingham, J. A. Dykstra, A. I. Kayssi, R. J. Lomax, O. A. Olukotun, K. A. Sakallah and R. Milano, "The Design of a Micro-Supercomputer," Proceedings of 24th Annual Hawaii International Conference on System Sciences, January 8–11, 1991, vol. I, pp. 421–432.

148. T. Singh, G. Haddad and R. Lomax, "Quantum Devices for Arithmatic and Logic Operations," Presented at the 1991 IEEE International Solid-State Circuits Conference, Feb. 13–15, 1991, San Francisco CA.

149. Y. Kwon, D. Pavlidis, P. Mash, M. Tutt, G. I. Ng and T. Brock, " 90–180/GHz Heterostructure Monolithic Integrated Doubler," 2nd International Symposium on Space Terahertz Technology, Pasadena, CA, pp. 238–254, February 1991.

150. J. Steimel and J. East, "D-Band Network Analyzer Construction and Calibration," presented at the Second International Conference on Space Terahertz Technology, Pasadena, CA, February 1991.

151. R. Kamoua, Jack East and G. Haddad, "Fundamental Mode Operation of Gunn Devices above 100 GHz, " presented at the Second International Conference on Space Terahertz Technology, Pasadena, California, Feb. 1991.

152. A. I. Kayssi, K. A. Sakallah, R. B. Brown, R. J. Lomax, T. N. Mudge, and T. R. Huff, "Impact of MCM's on System Performance," *Proceedings of the 1991 Multichip Module Workshop*, Santa Cruz, CA, March 28–29, 1991, pp. 58–65.

153. R. J. Lomax, R. B. Brown, T. N. Mudge,and K. A. Sakallah "The Design of a GaAs Microsupercomputer," First Great Lakes VLSI Symposium, Kalamazoo, MI, March 1-2, 1991 (Late paper, not in proceedings.)

154. D. Pavlidis, "Possibilités des nouvelles filières de composants à hetérostructures pour ondes milimétriques," Resumes des Conferences 7èmes Journees Nationales Microondes, Grenoble, France, pp. 91-92, March 1991.

155. M. Amman, "Inelastic Tunneling in Current-Drive Mesoscopic Tunnel Junctions," presented at the American Physical Society Meeting, March 1991.

156. V. Sankaran and J. Singh, "Quantum Transport of Electrons Across $Al_xGa_{1-x}As/Al_yGa_{1-y}As$ Discontinuities," presented at the Picosecond Electronics Conference, Salt Lake City, UT, March 1991.

157. R. K. Mains, G. I. Haddad and J. P. Sun, "Self-Consistent Modeling of Resonant Tunneling Diodes and Transistors," Proceedings of the Seventh International Conference on the Numerical Analysis of Semiconductor Devices and Integrated Circuits (NASECODE VII), April 8–12, 1991, Copper Mountain, CO.

158. R. Lai, P. K. Bhattacharya and D. Pavlidis, "Monolithically Integrated $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$/InP Photoreceivers with Submicron Devices," Conference Digest of the 3rd International InP Conference, Cardiff, Wales, p. 115, April 1991.

159. D. Teeter, R. Mains and G. Haddad, "A comparison between heterojunction bipolar transistor power performances computer using signal Y parameters and a full time domain simulation," Presented at the NASCODE VII Conference, Copper Mountain, CO, April 4–12, 1991.

160. M. Tutt, G. I. Ng, D. Pavlidis and J. Mansfield, "Reliability Issues of InAlAs/InGaAs High-Electron-Mobility Transistors," Conference Digest of the 3rd International InP Conference, Cardiff, Wales, p. 101, April 1991.

161. Y-J. Chan and D. Pavlidis, "InAlAs/$In_xGa_{1-x}As$ HIGFET's ($x \geq 0.53$) for E/D FET Logic Applications," Conference Digest of the 3rd International InP Conference, Cardiff, Wales, p. 70, April 1991.

162. M. E. Sherwin, F. L. Terry, Jr., G. O. Munns, J. S. Herman, E. G. Woelk , and G. I. Haddad, "Investigation and Optimization of InGaAs/InP Heterointerfaces Grown by Chemical Beam Epitaxy Using Spectroscopic Ellipsometry and Photoluminescence," presented at the Fifth Biennial Workshop on OMVPE, Panama City Beach, FL, April 1991.

163. D. R. Pehlke and D. Pavlidis, "Critical Issues in Process Technology for High-Speed Self-aligned GaAs/AlGaAs Heterojunction Bipolar Transistors," Digest of the GaAs MANTECH Conference, Reno, NV, pp. 93–96, April 1991.

164. D. Nichols, J. Loehr, J. Pamulapati, J. Singh and P. Bhattacharya, "Experimental and Theoretical Studies of $In_xGa_{1-x}As/InP$ ($0.45 \leq x \leq 0.70$) Based Pseudomorphic QW Lasers," Presented at 3rd International Conference on InP and Related Compounds, Cardiff, Wales, April 1991.

165. J. Shewchun and P. F. Marsh, "Performance Characteristics of Y-Ba-Cu-O Microwave Superconducting Detectors," SPIE 1991 International Symposium on Optical Engineering and Photonics in Aerospace Sensing, Paper 1477-32, Superconducting Applications for Infrared and Microwave Devices II Conference, Orlando, FL, April 4, 1991.

166. M. E. Sherwin, G. O. Munns, E. G. Woelk, D. T. Nichols, F. L. Terry, Jr., P. K. Bhattacharya, and G. I. Haddad, "The growth of high quality InP/InGaAs/InGaAsP interfaces by CBE for SCH Quantum Well Lasers," accepted for presentation in the IEEE InP and Related Materials Conference, April 1991, Cardiff, UK.

167. D. Pavlidis, J. Hu and K. Tomizawa, "Fundamental Design and Technology Aspects Impacting the Performance of InP-Based HBTs," Digest of the 15th European Workshop on Compound Semiconductor Devices and Integrated Circuits (WOCSDICE), Ulm, Germany, Session D(5), May 1991.

168. D. Pavlidis, Y. Kwon and P. Marsh, "InGaAs/InAlAs HEMT Monolithic Integrated Circuit for Frequency Doubling to 180 GHz," Digest of the 15 European Workshop on Compound Semiconductor Devices and Integrated Circuits (WOCSDICE), Ulm, Germany, Session F(10), May 1991.

169. O. A. Olukotun, T. N. Mudge, and R. B. Brown, "Cache Architectures for a High-Performance GaAs Microprocessor," *Proceedings of the 18th International Symposium on Computer Architecture*, Toronto, May 27–30, 1991.

170. M. Upton, T. Hoy, T. Huff, R. Brown, R. Oettel and M. Rossman, "Module Generation for a GaAs Microprocessor," *Technical Digest of the Third Physical Design Workshop*, Laurel Highlands, PA, May 20–22, 1991, pp. 88-94.

171. Richard B. Brown, "The Silicon Compiler as a Tool for Teaching Microelectronic System Design," *Technical Digest of the Third Physical Design Workshop*, Laurel Highlands, PA, May 20–22, 1991, pp. 64-75.

172. M. Y. Frankel and D. Pavlidis, "Large Signal Modeling and Study of Power Saturation Mechanisms in Heterojunction Bipolar Transistors," IEEE MTT-S International Microwave Symposium Digest, Boston, p. 127–130, June 1991.

173. M. N. Tutt, D. Pavlidis and C. Tsironis, "Automated On-Wafer Noise and Load Pull Characterization Using Precision Computer Controlled Electromechanical Tuners," to appear in Proceedings of 37th Conference of the Automatic RF Techniques Group, Boston, MA, June 1991.

174. D. Teeter, J. East and G. Haddad "Large signal characterization and numerical modeling of the AlGaAs/GaAs HBT," presented at the 1991 MTT Symposium, June 1991 and published in the *1991 IEEE MTT-S Digest*, pp. 651–654.

175. D. Teeter, J. East and G. Haddad, "Error correction and power calibration of active load pull measurement systems," presented at the 37th ARFTG Conference, Boston, MA, June 1991.

176. W-Q. Li and P. Bhattacharya, "Molecular Beam Epitaxial GaAs/$Al_{0.2}Ga_{0.8}As$ Heterojunction Bipolar Transistor on (311)A GaAs Substrate with All-Sillicon Doping," presented at the Device Research Conference, Boulder, CO, June 1991.

177. R. Rodricks, C. Brizard, R. Clarke and W. Lowe, "An X-ray Detector for Time-resolved Studies," SPIE **1550** (1991).

178. M. A. Stroscio, G. I. Iafrate, K. W. Kim, S. M. Bedair, J. C. Hall, M. Dutta, T. Gant, R. Merlin, and P. Bhattacharya, "Frequencies of Confined Longitundinal-Optical Phonon Modes in Short Period Strained Semiconductor Superlattices," (invited) Workshop on Strained-layer Semiconductor Materials and Devices, Buffalo, NY, 23–24 August 1991.

179. Y. Kwon, M. Tutt, G. I. Ng, D. Pavlidis, T. Brock, J. Oh, J. Castagné and N. T. Linh, "Gate-Recess and Device Geometry Impact on the Microwave Performance and Noise Properties of 0.1 μm InAlAs/GaAs HEMTs," Digest of the 13th Biennial IEEE/Cornell Conference on Advanced Concepts in High Speed Semiconductor Devices and Circuits, Ithaca, NY, p. 33, August 1991.

180. D. Nichols, H. C. Sun, J. Pamulapati, J. Loehr, M. Sherwin, G. Munns, J. Singh and P. Bhattacharya, "High Speed Modulation of InP-Based Strained Quantum Well Lasers," Proceedings of the Cornell Conference, August 1991.

181. D. A. Teeter, J. R. East and G. I. Haddad, "High Frequency Large Signal Characterization of Heterojunction Bipolar Transistors," presented at the IEEE/Cornell Conference on Advanced Concepts in High Speed Semiconductor Devices and Circuits, August 5–7, 1991, pp. 315–324 in conference digest.

182. J. Hu, H-F. Chau, D. Pavlidis, K. Tomizawa and P. Marsh, "Control of InP/InGaAs Heterojunction Bipolar Transistor Performance Through the Use of Undoped Collectors," Digest of the 13th Biennial IEEE/Cornell Conference on Advanced Concepts in High Speed Semiconductor Devices and Circuits, Ithaca, NY, p. 27, August 1991.

183. W-Q. Li, Y. J. Chan and P. K. Bhattacharya, "Improved Performance of Highly Strained InGaAs/GaAs Heterostructures Devices Grown on Patterned (100)-GaAs Substrates," presented at the Annual MBE Workshop, Austin, TX, September 1991.

184. M. Tutt, D. Pavlidis, D. Pehlke, R. Plana and J. Graffeuil, "1/f Noise in AlGaAs/GaAs HBT's Using Ultrasensitive Characterization Techniques for Identifying Noise Mechanisms," the Proceedings of the 18th International Symposium on Gallium Arsenide and Related Compounds, Seattle, WA, September 1991.

185. P. Bhattacharya, "Molecular Beam Epitaxy of Strained Heterostructures and their Device Applications," presented at the 38th Sagamore Army Materials Research Conference, September 9- 12, 1991, Plymouth, MA.

186. Y. Keom, V. Sankaran and J. Singh, "Theoretical Studies of Impact Ionization in Pseudomorphic Structures – Applications to InGaAlAs and GaAs and InP Substrates," Proceedings of GaAs and Related Compounds Conference, 1991.

187. Y.J. Chan, D. Pavlidis and T. Brock, "InAlAs/InGaAs HIGFETs Using Novel 0.2 μm Self-Aligned T- gate Technology," to appear in the Proceedings of the 18th International Symposium on Gallium Arsenide and Related Compounds, Seattle, September 1991.

188. G. O. Munns, M. E. Sherwin, T. Brock, G. I. Haddad, Y. Kwon, G. I. Ng and D. Pavlidis, "InAlAs/InGaAs/InP Submicron HEMT's Grown by CBE," 3rd International Conference on Chemical Beam Epitaxy and Related Growth Techniques, Oxford, UK, September 1991. (appeared in J. of Crystal Growth-copy filed under journals).

189. Y. Kwon and D. Pavlidis, "Large Signal Analysis and Experimental Characteristics of Monolithic InP-Based W-Band HEMT Oscillators," Proceedings of the 21st European Microwave Conference, Stuttgart, Germany, pp. 161–166, September 1991.

190. Y. Kwon, D. Pavlidis, P. Marsh, M. Tutt, G. I. Ng and T. Brock, "180 GHz InAlAs/InGaAs HEMT Monolithic Integrated Frequency Doubler," Technical Digest of the 1991 IEEE GaAs IC Symposium, Monterey, CA, pp. 165–168, October 1991.

191. M. E. Sherwin, G. O. Munns, D. T. Nichols, F. L. Terry, Jr., P. K. Bhattacharya and G. I. Haddad, "Chemical Beam Epitaxy for the Growth of InP Based Electronic and Opto-Electronic Devices," presented at the Second Workshop on Electronic and Opto-electronic Materials for Tactical and Strategic Applications," Huntsville, AL, October 1991.

192. S. Mohan and P. Mazumder, "Fault modeling and testing of GaAs static random access memories," in the proceedings of the International Test Conference, pp. 665–674, October 1991.

193. Y. Kwon, G. I. Ng, D. Pavlidis, R. Lai, T. Brock, J. Castagné and N. T. Linh, "High Efficiency Monolithic Ka-Band Oscillators Using InAlAs/InGaAs HEMT's," Technical Digest of the 1991 IEEE GaAs IC Symposium, Monterey, CA, pp. 263–266, October 1991.

194. K. W. Eisenbeiser, J. R. East, J. Singh and G. Haddad, "Breakdown Voltage Improvement in Strained InGaAs/GaAs MESFET's," presented at the 1991 International Semiconductor Device Research Symposium, December 4–6, 1991, pp. 685–688 in conference digest.

195. Z. Liliental-Weber, W. Swider, P. K. Bhattacharya, S. Gupta and G. Mourou, "Xtem investigation of low temperature molecular beam epitaxial $In_{0.52}Al_{0.48}As/InP$," presented at the Materials Research Society Annual Meeting, Boston, MA, November 1991.

196. D. Nichols, P. Bhattacharya, J. Pamulapati and G. Munns, "Effect of Biaxial Compressive and Tensile Strain on the Performance of InP/InGaAs Multi Quantum Well Lasers Grown by Chemical Beam Epitaxy," presented at the IEEE Lasers and Electro-Optics Society 1991 Annual Meeting, San Jose, CA, November 1991.

197. W. L. Chen, J. P. Sun, G. I. Haddad, M. Sherwin, G. Munns, J. East and R. Mains, "CBE Grown InGaAs/InP Hot Electron Transistor (HET) with Pd/Ge Shallow Ohmic Base Contact," presented at the 1991 International Semiconductor Device Research Symposium, December 4-6, 1991, in conference digest pp. 297–300.

198. J. P. Sun, W. L. Chen, R. K. Mains, J. R. East and G. I. Haddad, "C-V Characteristics of Quantum Well Varactors," presented at and in the proceedings of the 1991 International Semiconductor Device Research Symposium, Charlottesville, VA, December 4–6, 1991.

199. Y-J. Chan and D. Pavlidis, "Low-Frequency Noise and Frequency Dispersion Characteristics of GaInP/GaAs and AlGaAs HEMT's," Proceedings of the 1991 International Semiconductor Device Research Symposium, Charlottesville, VA, pp. 677-680, December 1991

200. D. Pavlidis, "Advances in Heterostructure Field Effect Transistors and Their Integration for Millimeter-Wave Applications," Proceedings of the 1991 International Semiconductor Device Research Symposium, Charlottesville, VA, pp. 652–657, December 1991.

201. S. W. Pang, "A Comparison Between Dry Etching with an Electron Cyclotron Resonance Source and Reactive Ion Etching for GaAs and InP," Presented at Mat. Res. Soc. Symp. in Proceedings on "Advanced III-V Compound Semiconductor Growth, Processing, and Devices," Boston, Massachusetts, December (1991) (invited).

202. J. Singh, T. Takahasi and Y. Arakawa, "Consequences of Structural Disorder on Optoelectronic Properties of Quantum Wire Structures," presented at the American Physical Society Meeting, Indianapolis, 12-16, March 1992

203. D. Teeter, M. Karakucuck, J. East and G. I. Haddad, "Analysis of Intermodulation Distortion in AlGaAs/GaAs HBT's," presented at the International Microwave Symposium, June 1992 (pp. 263–267 in conference digest).

204. K. Moore, J. East, G. Haddad and T. Brock, "Optimized 0.1 micron GaAs MESFET's," presented at the 1992 International Microwave Symposium, June, 1992 (pages 643-646 in conference digest).

205. K. Eisenbeiser, J. East, G. Haddad and T. Brock, "High Breakdown Voltage Submicron Strained InGaAlAs/GaAs FET's," presented at the 1992 International Microwave Symposium, June, 1992 (pages 647-650 in conference digest).

206. Y-J. Chan and D. Pavlidis, "High Performance E/D-Mode InAlAs/InGaAs HIGFET Technology and Integrated Logic Functions," Proceedings of the 4th Annual InP and Related Materials Conference, Newport, RI, pp. 489–502, April 1992.

207. G. I. Ng, D. Pavlidis, Y. Kwon, T. Brock, J. I. Davies, G. Clarke and P. K. Rees, "0.1 μm MOVPE Grown InAlAs/InGaAs HEMT's with Above 150 GHz Operation Capability," Proceedings of the 4th Annual InP and Related Materials Conference, Newport, RI, pp. 18–21, April 1992.

208. Y. Kwon, T. Brock, G. I. Ng, D. Pavlidis, G. O. Munns, M. E. Sherwin and G. I. Haddad, "F_{max}-Enhancement in CBE-Grown InAlAs/InGaAs HEMT's Using Novel Self-Aligned Offset-Gate Technology," Proceedings of the 4th Annual InP and Related Materials Conference, Newport, RI, pp. 360–363, April 1992.

209. D. Pavlidis, "Materials Related Issues and Their Characterization in View of III-V Heterojunction Device Optimization," Programme and Abstracts of the 1st Workshop on Expert Evaluation and Control of Compound Semiconductor Materials and Technologies, (EXMATEC'92), Session 1(1), May 1992.

210. M. N. Tutt, D. Pavlidis and H-F. Chau, "1/f Noise Characteristics of InP/InGaAs Heterojunction Bipolar Transistors," Proceedings of the 4th Annual InP and Related Materials Conference, Newport, RI, pp. 364–367, April 1992.

211. H-F. Chau, D. Pavlidis, J. Hu and K. Tomizawa, "Analysis of InP/InGaAs Single and Double Heterostructure Bipolar Transistors for Simultaneous High Speed and High Breakdown Operations," Proceedings of the 4th Annual InP and Related Materials Conference, Newport, RI, pp. 410–413, April 1992.

212. D. Pavlidis, H-F. Chau, J. Hu and K. Tomizawa, "Evaluation of Speed-Breakdown Trade-offs in InP/InGaAs Heterojunction Bipolar Transistors," Digest of the 16th European Workshop on compound Semiconductor Devices and Integrated Circuits (WOCSDICE), Ulm, German, Session E(8), May 1992.

213. M. Tutt, D. Pavlidis, A. Khatibzadeh and B. Bayraktaroglu, "Investigation of HBT Oscillator Noise Through 1/f Noise and Noise Upconversion Studies," IEEE MTT-S International Microwave Symposium Digest, Albuquerque, NM, pp. 727–730, June 1992.

214. D. R. Pehlke and D. Pavl. . "Direct Calculation of the HBT Equivalent Circuit From Measured S-Parameters," IEEE MTT-S International Microwave Symposium Digest, Albuquerque, NM, pp. 735–738, June 1992.

215. A. Samelis and D. Pavlidis, "Analysis of Third Order Intermodulation Distortion Mechanisms in AlGaAs/GaAs Heterojunction Bipolar Transistors," IEEE MTT-S International Microwave Symposium Digest, Albuquerque, NM, pp. 1587–1590, June 1992.

216. Y. Kwon, D. Pavlidis, P. Marsh, G. I. Ng and T. Brock, "W-Band Monolithic Balanced Mixer Using InP-Based Heterostructure Diodes," Proceedings of the MMIC Space and Ground Applications Symposium pp. 83–991, April 1992.

217. R. Tober, T. Bahder, W-Q. Li and P. Bhattacharya, "Optically Induced Energy Shifts of Excitonic Resonances in Single [111]B and [100] InGaAs Quantum Wells," presented at the Electronics Materials Conference, Cambridge, MA, June 1992.

218. C. Raman, J. P. Sun, WI. L. Chen, G. O. Munns, J. East and G. I. Haddad, "Supperlatice Barrier Varactors," Third International Symposium on Space Terahertz Technology, Ann Arbor, MI, March 1992.

219. S. W. Pang and K. K. Ko, "Comparison Between Etching in Cl_2 and BCl_3 for Compound Semiconductors Using Multipolar Electron Cyclotron Resonance Source". Presented at the International Symposium on Electron Ion, and Photo Beams, Orlando, FL, May 1992.

220. D. Nichols and P. Bhattacharya, "InP-Based Strained Quantum Well Lasers," Presented at the Workshop on Compound Semiconductor Microwave materials and Devices, San Antonio, TX, February 1992.

221. D. Nichols, L. Davis, Y. Lam, E. Espinosa, J. Singh and P. Bhattacharya, "Modulation Characteristics of InP-Based MQW Lasers; The Impact of Biaxial Compressive and Tensile Strain, presented at the 50th Device Research Conference, Cambridge, MA, June 1992.

222. D. Nichols, L. Davis, Y. Lam, G. Munns, J. Loehr, J. Singh and P. Bhattacharya, "Carrier Dynamics and Modulation Characteristics of InP-Based Strained Quantum Well Lasers," presented at the International Quantum Electronics Conference, Vienna, Austria, June 1992.

223. Ayman I. Kayssi and Karem A. Sakallah, "Delay Macromodels for Point-to-Point MCM Interconnections," Proceedings of the 1992 MCM Conference, Santa Cruz, CA, Mar. 18–20,1992, pp. 79-82

224. R. Brown, A. Chandna, T. Hoy, T. Huff, R. Lomax, T. Mudge, D. Nagle, K. Sakallah, R. Uhlig, and M. Upton, "Synthesis and verification of a GaAs microprocessor from a Verilog hardware description," Proc. Open Verilog Int. User Group Meeting, Mar. 1992, pp. 85-92.

225. A. I. Kayssi, K. A. Sakallah, R. B. Brown, R. J. Lomax, T. N. Mudge, and T. R. Huff, "Impact of MCM's on system performance optimization," *Proc. of the 1992 IEEE Int. Symp. on Circuits and Systems*, vol. 2 of 6, San Diego, CA, May 1992, pp. 919-922.

226. O. A. Olukotun, T. N. Mudge, and R. B. Brown,"Performance optimization of pipelined primary caches," *Proc. of the 19th International Symposium on Computer Architecture*, May 19–21, 1992, pp. 181-190.

227. S. Mohan and P. Mazumder, "A distributed genetic algorithm for standard cell placement on a network of workstations," to appear in Proceedings of the European Design Automation Conference, 1992.

ACCEPTED

1. G. O. Munns, M. E. Sherwin, Y. Kwon, T. Brock, W. L. Chen, D. Pavlidis and G. I. Haddad, "Parametric Investigation of InGaAs/InAlAs HEMT's Grown by CBE," to be presented at the 7th International MBE Conference.

2. J. Kim, Y-J. Chan, S. Williamson, J. Nees, S-I. Wakama, J. Whitaker, D. Pavlidis, "A Novel High-Impedance Photoconductive Sampling Probe for Ultra-High Speed Circuit Characterization," to be presented at the GaAs IC Symposium, 1992.

3. Y. Kwon, D. Pavlidis, P. Mash, G. I. Ng, T. Brock, G. O. Munns and G. I. Haddad, "A Fully Integrated Monolithic D-band Oscillator- Doubler Chain Using InP-Based HEMTs," to be presented at the 1992 IEEE GaAs IC Symposium.

4. Y. Kwon, D. Pavlidis, P. Marsh, G. I. Ng and T. Brock, "A Planar Heterostructure Diode W-band Mixer Using Monolithic Balanced Integrated Approach on InP," to be presented at the 1992 GaAs IC Symposium.

5. Y. Kwon, T. Brock, G. I. Ng, D. Pavlidis, G. O. Munns, M. E. Sherwin and G. I. Haddad, "Novel Self-Aligned Offset G-Gate InAlAs/InGaAs HEMT's Grown by Chemical Beam Epitaxy," accepted for presentation at GaAs IC Symposium.

6. G. O. Munns, W. L. Chen, M. E. Sherwin and G. I. Haddad, "The Growth of InAlP Using Trimethl amine alane by Chemical Beam Epitaxy," to be presented at the Seventh International Conference on Molecular Beam Epitaxy, August 1992.

7. K. K. Ko, L. Davis, W-Q Li, S. W. Pang, J. Singh and P. K. Bhattacharya, "Effects of Processing Induced Fluctuations on the Optical Properties of InGaAs/AlGaAs Quantum Boxes Created by Dry Etching and Epitaxial Regrowth," accepted for presentation at the 19th International Symposium on Gallium Arsenide and Related Compounds, Nagano, Japan, September 1992.

8. J.S. Herman and F.L. Terry, Jr., "Hydrogen Sulfide Plasma Passivation of InP," submitted to the 1992 IEEE/TMS Electronic Materials Conference, accepted for presentation as paper C9.

9. R. Brown, A. Chandna, T. Huff, R. Lomax, T. Mudge, R. Oettel, and M. Upton, "Compound Semiconductor Device Requirements for VLSI," to be presented at the 19th Int. Symposium on Gallium Arsenide and Related Compounds, Karuizawa, Japan, Sep. 28 – Oct. 2, 1992, invited.

10. R. Brown, P. Barker, A. Chandna, T. Huff, R. Lomax, T. Mudge, K. Sakallah, P.J. Sherhart, R. Uhlig, and M. Upton, "GaAs RISC Processors," GaAs IC Symposium, Miami, FL, Oct. 4–7, 1992, invited.

SUBMITTED

1. W. L. Chen, G. O. Munns, J. C. Cowles, K. W. Eisenbeiser, J. R. East and G. I. Haddad, "Ohmic Contacts Study for Quantum Effect Transistors and Heterojunction Bipolar Transistors with InGaAs Contact Layers, submitted to 1992 EDMS, Tiawan..

2. J.S. Herman and F.L. Terry, Jr., "Plasma Passivation of Gallium Arsenide," submitted to the American Vacuum Society Conference, Chicago, Ill, under review.

3. L. Davis, Y. Lam, D. Nichols, E. Espinosa and P. Bhattacharya, "A Study of Modulation Characteristics, Auger Coefficients and Filamentation Related Noise Spectra in InP-based Strains Layer Quantum Well Lasers," submitted for presentation to the International Laser Conference, Takamatsu, Japan, September 1992.

4. J. Singh and P. Bhattacharya, "Role of Strained Layers in Improving the Structural Reliability of Quantum Well Lasers," submitted for presentation to International Laser Conference, Takamatsu, Japan, September 1992.

5. L. Davis, Y. Chen, D. Nichols, Y. Lam, J. Singh and P., Bhattacharya, "Auger Recombination and Impact Ionization Rates in Pseudomorphic InGaAlAs/GaAs and InGaAs/InP," submitted for presentation to International Laser Conference, Takamatsu, Japan, September 1992.

7.2 SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Total Number of Ph.D. Graduates	31
Total Number M.S. Graduates	41
Continuing students and Degree expected	24

A listing of the individual students follows:

7.2.1 Ph. D. Degrees Granted to Students in the Center for High Frequency Microelectronics

Name	Degree	Supervisor	Company
P. Berger	Ph.D.	P. Bhattacharya	University of Delaware
Y-J. Chan	Ph. D.	D. Pavlidis	University of Taiwan
H. F. Chau	Ph.D.	D. Pavlidis	Texas Instruments, Dallas, TX
Y. C. Chen	Ph.D.	P. Bhattacharya	University of Michigan
A. Chin	Ph.D.	P. Bhattacharya	General Electric, Syracuse, NY
U. Das	Ph.D.	P. Bhattacharya	University of Florida Gainesville, FL
N. Debbar	Ph.D.	P. Bhattacharya	Institute de Micro-et Opto-electronique, Lausanne, Switzerland
W. Dos Passos	Ph.D.	R. Clarke D. Pavlidis	University of Michigan
J. Dykstra	Ph.D.	R. Brown	Motorola Corp., R & D, Schaumburg, IL
S. Gupta	Ph.D.	P. Bhattacharya	University of Michigan
J. Hinckely	Ph.D.	J. Singh	Self employed in Kalamzoo and part-time at University of Michigan
W.-P. Hong	Ph.D.	P. Bhattacharya	Bellcore, Red Bank, NJ

Name	Degree	Supervisor	Company
J. Hu	Ph.D.	D. Pavlidis	Bell Northern, Ottawa, Canada
M. Jaffe	Ph.D.	J. Singh	IBM, Burlington, VT
R. Lai	Ph.D.	P. Bhattacharya	TRW, Redondo Beach, CA
W. Li	Ph.D.	P. Bhattacharya	University of Michigan
J. Loehr	Ph.D.	J. Singh	Air Force-Avionics Laboratory Wright-Patterson, OH
I. Mehdi	Ph.D.	G. Haddad	Jet Propulsion Laboratory
K. Mullen	Ph.D.	E. Ben-Jacob	University of Minnesota
G. Ng	Ph.D.	D. Pavlidis	University of Michigan
J. Pamulapati	Ph.D.	P. Bhattacharya	U.S. Army-ETDL, Fort Monmouth, NJ
S. D. Peacor	Ph.D.	C. Uher	University of Groningen, Holland
P. Sandborn	Ph.D.	G. Haddad	MCC, Austin, TX
K. S. Seo	Ph.D.	P. Bhattacharya	Seoul National University, Korea
M. Sherwin	Ph.D.	F. Terry	Sandia Laboratories, Albuquerque, NM
R. Voelker	Ph.D.	R. Lomax	University of Nebraska
H. Wang	Ph.D.	D. Steel	University of Michigan
M. Webb	Ph.D.	D. Steel	Center for Naval Analysis, Alexandria, VA
R. Wilkins	Ph.D.	E. Ben-Jacob	Texas A&M University
J-S. Yih	Ph.D.	P. Mazumder	IBM, T. J. Watson Research Center
Y. Zebda	Ph.D.	P. Bhattacharya	Jordan University of Science & Technology, Jordan

7.2.2 M.S. Degrees Granted to Students in the Center for High Frequency Microelectronics

M. Amman	D. Knightly
C. Beckner	Y. Kwon
R. Borroff	S. La
S. Brown	R-L. Lee
Y-J. Chan	D. Lemersal
H. F. Chau	R. Lipa
C. C. Chen	S. Mohan
R. Chen	K. Moore
W. L. Chen	D. Nichols
Y-C. Chen	R. Pappas
T. Cook	D. Pehlke
J. Cowles	C. Raman
B. Denheyer	V. Sankaran
A. Demos	M. Sherwin
K. Eisenbeiser	J. Steimel
A. Engel	J-P. Sun
K. Hashim	D. Teeter
J. Herman	M. Webb
G. Hugo	S. Willing
K. Kidner	K. Yang
J-H. Kim	

7.2.3 Current Students and Expected Degree Date

Faculty Supervisor	Graduate Students	Expected Ph.D. Degrees
J. Singh	V. Sankaran	December 1992
G. Haddad	K. Yang	August 1993
J. East	W. L. Chen	August 1993
R. Mains	K. Moore	August 1993
	J-P Sun	August 1993
	C. C. Chen	August 1993
	D. Teeter	August 1992
	J. Cowles	December 1993
	K. Eisenbeiser	December 1993
	M. Karaucuk	August 1994
	S. Peng	August 1993
	A. Afsali-Kushaa	August 1994

Faculty Supervisor	Graduate Students	Expected PH.D. Degrees
D. Pavlidis	D. Pehlke	December 1993
P. Bhattacharya	D. Nichols	December 1992
	A. Gutierrez-Aitken	August 1994
F. Terry	J. Herman	December 1992
M. Elta	A. Demos	December 1992
R. B. Brown	T. R. Huff	August 1994
P. Mazumder	S. Mohan	August 1993
S. Pang	K. Ko	August 1994

7.3 INTERACTIONS WITH ARMY LABORATORIES

Date	Individual/Group	Purpose/Interaction
1/19/87	Dr. M. Stroscio Visit to University of Michigan	Dr. Stroscio visited with Prof. Haddad and all the team leaders on the program and each team leader discussed his plans and progress in the various research areas. Dr. Stroscio gave a seminar to faculty and students on "Quantum Transport in Ultra-Submicron Electronic Devices".
4/13/87	Prof. G. I. Haddad, Director. Visit to ARO	Prof. Haddad visited Dr. Stroscio at ARO and met several other scientists at ARO
5/8/87	Profs. G. I. Haddad and P. Bhattacharya visited Harry Diamond Labs	Presentations were made by key individuals at HDL related to their programs and interests. Profs. Haddad and Bhattacharya gave presentations concerning the research programs at the Center and visited HDL laboratory facilities and discussed research interests with several groups. It was a very fruitful meeting.
5/13/87	Prof. Haddad along with Drs. Suttle, Iafrate and Stroscio visited Dr. Sculley, Assistant Secretary of the Army	Prof. Haddad gave Dr. Sculley a briefing relative to the Center, its activities, plans and importance.
6/16-6/17/87	ET&DL Personnel Visit to the University of Michigan – Drs. G. Iafrate, E. Poindexter, K. Jones, M. Dutta, D. Smith, R. Lux, E. Potenziani, W. Wilber, Mr. L. Poli and R. Ross	Dr. Iafrate gave an overview of the research programs and interests of ET&DL and presented a seminar entitled "Block Electron Transport in Electrical Fields" to faculty and graduate students. Professor Haddad gave an overview of the research program at the Center. A tour of the facilities was made and during the second day there were individual and group meetings between ET&DL and Center personnel on various topics. The meeting was very fruitful and it is anticipated that several of the Center faculty will visit ET&DL and significant interaction at the individual level will follow.

Date	Individual/Group	Purpose/Interaction
7/1/87	HDL Personnel visited the University of Michigan – Drs. T. Bhader, J. Bruno, R. Garver, R. Neifeld, G. Simonis, M. Tobin D. Wortman, Mr. H. Dropkin, Mr. C. Gavin, and Lt. Hay	During the morning a tour of the laboratory facilities was conducted and during the afternoon there were several individual and group discussions on various research topics. The visit was mutually beneficial and further interactions will follow.
8/13/87	Dr. R. K. Mains visit to HDL	Dr. Mains visited HDL, gave a seminar on Modeling of Resonant Tunneling Structures and held discussions with several scientists at HDL who are interested in these devices.
8/20/87	Dr. J. East Visit to ET&DL	Dr. J. East visited R. Ross of ET&DL to discuss fabrication procedures for Gunn devices and transfer technology for two-terminal device fabrication to E&DL.
9/3-9/4/87	Drs. M. Stroscio and G. Iafrate	Prof. Haddad attended a workshop at Stanford organized by Dr. Stroscio which included scientists from the U.S. and Japan on Resonant Tunneling Structures. Excellent discussions were held relative to the capabilities and potential applications of such devices.
10/22-10/23/87	Dr. J. Sculley, Assistant Secretary of the Army for Research Development and Acquisition, Lt. J. Benson, Office of the Assistant Secretary of the Army, Dr. G. Iafrate, ET&DL, Fort Monmouth, R. Lane, U.S. Army Missile Command, Redstone Arsenal, L. Madoo, HDL, M. Stroscio, ARO, M. Tobin, HDL, L. Heath and T. AuCoin, ET&DL, R. Graft, Fort Belvoir	Several individuals from the army attended a comprehensive research review carried out by scientist associated with the Center and many useful discussions were held among Army and Center Scientists. Dr. J. Sculley, Assistant Secretary for Army for Research Development and Acquisition gave a keynote address at the Research Review on the URI Program; its goals and importance to the Army

Date	Individual/Group	Purpose/Interaction
12/13-12/14/87	Drs. E. Poindexter and J. Kohn, ET&DL, Ft. Monmouth	Visited the Center and held discussions with several faculty members related to their interests in interface and surface structures.
1/27-29/88	Profs. Haddad Bhattacharya and Pavlidis	Attended workshop on HEMT Devices at ETDL; Profs.Bhattacharya and Pavlidis presented papers; Prof. Haddad spent an additional day visiting ETDL facilities and discussing research projects.
3/7/88	Dr. M. E. Elta	Gave a one-day tutorial course on clean room practices at ETDL. Approximately 50 people attended the course.
4/8/88	Prof. Bhattacharya	Visited HDL Laboratories and held technical discussions with Dr. M. Tobin and her group
5/11-5/12/88	Lt. Hays, HDL	Attended a two-day course at the University of Michigan on clean room usage and practices offered by Dr. Elta.
5/27/88	Dr. Tober, HDL	Visited the University of Michigan and held technical discussions with Prof. Bhattacharya and Dr. Oh.
6/6-6/10/88	Center faculty and Drs. Iafrate and Stroscio	Offered a course at the University of Michigan on High-Speed Heterojunction Electronic and Optoelectronic Devices; three people from ETDL attended the course.
6/29/88	Prof. Haddad, Dr. East (U. of M.) R. Ross and J. Ondria from ETDL	Had a meeting at U. of M. to develop joint project in mm-wave transferred electron devices
7/6/88	Profs. G. Haddad, P. Bhattacharya, J. Singh, D. Pavlidis, R. Lomax, R. Clarke, D. Steel and M. Elta	URI review. Presentations on various aspects of research were presented by faculty. In attendance were from ARO: J. Mink, B. Sander, M. Littlejohn, D. Hislot and Mike Stroscio; from ETDL: G. Iafrate; from HDL: M. Tobin; from Center for Night Vision: J. Pollard: from ONR: Y. Yoder, L. Cooper and from Office of Deputy Undersecretary of Defense for Research and Advanced Technology: M. Herbst

Date	Individual/Group	Purpose/Interaction
10/17/88	Prof. Haddad	Made a presentation to AGED group meeting on *Heterojunction Technology*
11/30/88	Prof. Haddad	Met with Dr. Stroscio, R. Lane and several individuals from MICOM to discuss and coordinate work on millimeter-wave devices and integrated circuits.
1/19/89	Dr. Stroscio	Presented a seminar on "Path Integral Approach to Quantum Transport in Electrical Structures".
5/16-5/17/89	Profs. Haddad, P. Bhattacharya, J. Singh, D. Pavlidis, R. Lomax, R. Clarke, M. Elta, D. Steel, R. Merlin, E. Ben-Jacob, P. Mazumder, J. East, T. Drummond, R. Mains, U. Reddy, F. Terry, P. Katehi, C. Uher, P. McCleer, H. Winful, G. Feak, D. Weinberger and T. Norris	URI Review, Presentations on various aspects of research were presented by faculty. Those in attendance were from ARO: M. Stroscio, M. Littlejohn; from ETDL: J. Shappirio and D. Smith; from HDL: M. Tobin: from MICOM R. Lane; from NASA: S. Alterovitz, K. Bhasin, E. Haugland; from Strategic Defense Command: W. Martin
6/15/89	M. E. Elta and T. J. Drummond	Visited Harry Diamond Laboratories to advise HDL on MOMBE system.
8/16-8/22/89	P. Bhattacharya and J. Singh	Held discussions with R. Tober from Harry Diamond laboratories relative to evaluation of MBE grown layered structures and to plan future research.
10/23/89	G. I. Haddad	Held research discussions with M. Stroscio relative to joint work on phonon interactions in quantum wells.

Date	Individual/Group	Purpose/Interaction
5/30/90 - 5/31/90	Profs. Haddad, P. Bhattacharya, J. Singh, D. Pavlidis, R. Lomax, R. Clarke, M. Elta, D. Steel, R. Merlin, P. Mazumder, J. East, R. Mains, U. Reddy, F. Terry, P. Katehi, C. Uher, P. McCleer, H. Winful, G. Feak, S. Pang, and E. Woelk	URI Review. Presentations on various aspects of research were presented by faculty. In attendance were from ARO: M. Stroscio and J. Prater, NASA: S. Alterovitz, U. S. Army Night Vision Laboratory: R. Graft and J. Pollard, U. S. Army Missile Command: R. Lane, U. S. Army strategic Defense Command: W. Martin, U. S. Army, Fort Monmouth: D. Smith, AFOSR-WRDC/ELR: R. E. Walline and AFOSR, Directorate Electronics and Materials Science: G. L. Witt
6/21/90	P. Bhattacharya	Dr. Richard Tober of HDL visited the Center for one day to discuss work on material characterization.
8/8/90	Profs. G. Haddad and D. Pavlidis	Visited MICOM. Drs. R. Lane and M. Stroscio, ARO were present. An overview of the research program at Michigan was presented. A detailed discussion was held on research on monolithic millimeter-wave integrated circuits. Discussions were held with Dr. J. L. Johnson on submillimeter-wave imaging.
9/20/90	Profs. G. Haddad, P. Bhattacharya and J. Singh	Visited the Night Vision Laboratory. An overview of work being done in the URI program was presented and mechanisms for further interactions were discussed with Dr. J. Pollard. Also discussed was the possibility of training individual(s) from Dr. Pollard's group on the MBE machine. This will be pursued further.
11/8/90	Prof. G. Haddad	Presented a seminar entitled "Resonant Tunneling Devices" at the Harry Diamond Laboratory. Research discussions were held with Mary Tobin.
11/30/90	Prof. G. Haddad	Held research discussions with Drs. M. Stroscio and G. Iafrate at the Army Research Office
1/24/91	Profs. G. Haddad and D. Pavlidis	R. Lane, R. Johnson and R. Halliday from MICOM visited the University of Michigan to discuss research on monolithic millimeter-wave integrated circuits and millimeter and submillimeter-wave devices for imaging.

Date	Individual/Group	Purpose/Interaction
1/8/91	Prof. J. Singh	Presented a seminar entitled "Pseudomorphic Structures for Electronic and Optoelectronic Devices," at the Harry Diamond Laboratories
2/12/91	Prof. P. Bhattacharya	Presented a seminar entitled "Growth of Strained Heterostructures by MBE and their Application to Optoelectronic Devices and Circuits," at the Harry Diamond Laboratories
3/14/91	Prof. P. Bhattacharya	Presented a seminar entitled "Molecular Beam Epitaxy of Strained Heterostructures and their Application to Optoelectronic Devices and Circuits" at the U.S. Army - Electronic Technology and Device Laboratory, Ft. Monmouth, NJ
5/8/91	G. Iafrate and M. Stroscio	Visited the University and held technical discussions on the research program
5/8/91	G. Iafrate	Presented a seminar entitled "The Physics of Nanoscale and Mesoscopic Dimensions; Nanoelectronics, Beyond and Revisited"
10/31 -11/1/91	G. I. Haddad, P. K. Bhattacharya and D. Pavlidis	Prof. Haddad and Bill Pittman organized a seminar on millimeter integrated circuits held a Redstone Arsenal. Prof. Bhattacharya and Pavlidis made presentations at this seminar. This seminar was attended by 40 and sets of notes were provided to these participants.
11/18/91	V. Sankaran	Presentation made in North Carolina on "Theory of Tunneling and Transport of Mixed Symmetry Electron States in Heterostructures." This presentation was made after Professor J. Singh held discussions with Drs. M. Stroscio and G. Iafrate on how scattering from heterostructures phonons should be included in tunneling processes.
12/81/91	Dr. W-Q. Li	Presented a seminar entitled "Molecular Beam Epitaxial Growth of Silicon Doped AlGaAs/GaAs Heterostructures on (311)A GaAs Surface and their Device Applications," at the Harry Diamond Laboratories.

Joint Publications with Army Scientists

1. Y. Zebda, P. K. Bhattacharya and M. Tobin, "Design and Performance of Very High Speed InGaAs/InAlAs PIN Photodiodes Grown by Molecular Beam Epitaxy," *IEEE Electron Device Letters*, EDL-8, pp. 579–581, 1987.

2. R. L. Tober, J. Pamulapati, P. Bhattacharya and J. Oh, "Piezoreflectance Characterization of Resonant Tunneling and Modulation-Doped Heterostructures," presented at Electronic Materials Conference, June 1988, Boulder, CO.

3. R. L. Tober, J. Pamulapati, J. E. Oh and P. K. Bhattacharya, "Piezoreflectance Characterization of Double-Barrier Resonant Tunneling Structures," *Applied Physics Letters*, 53, 883 (1988).

4. R. L. Tober, J. Pamulapati, P. K. Bhattacharya and J. E. Oh, "Piezoreflectance Characterization of Resonant Tunneling and Modulation-Doped Heterostructures," submitted to *Journal of Electronic Materials.*

5. W-Q. Li, P. K. Bhattacharya and R. L. Tober, "Improved Performance of Strained InGaAs/GaAs Photodiodes Grown on Patterned GaAs Substrates by Molecular Beam Epitaxy," *Applied Physics Letters*, 58, pp. 1931–1933 (1991). submitted for publication in the *Journal of Applied Physics.*

6. J. Pamulapati, P. K. Bhattacharya, R. L. Tober, J. P. Loehr and J. Singh, "Characterization of High-Quality Pseudomorphic InGaAs/GaAs Quantum Wells by Luminescence and Reflectance Techniques," *Journal of Applied Physics*, 71, 4487 (1992).

7. R. L. Tober, W. Q. Li and P. K. Bhattacharya, "Confinement Effects on Electroreflectance Spectra," accepted for presentation in SPIE's 1992 Symposium on Compound Semiconductor Physics and Devices, Somerset, NJ, March 1992.

8. R. L. Tober, W. Q. Li and P. K. Bhattacharya, "Differential Photocurrent Spectroscopy Using Novel Characterization Techniques," accepted for publication in *Journal of Applied Physics*, 71, 3506, (1992).

9. R. Tober, T. Bahder, W-Q. Li and P. Bhattacharya, "Optically Induced Energy Shifts of Excitonic Resonances in Single [111]B and [100] InGaAs Quantum Wells, presented at the Electronics Materials Conference, Cambridge, MA, June 1992.

Other Interactions

- HDL has fabricated several masks for U. of M. programs.
- University of Michigan has supplied III-V semiconductor layers to HDL scientists.
- University of Michigan has supplied MBE grown metallic films on III-V Compounds to ETDL for Schottky-Barrier characterization.
- We worked with R. Ross of ETDL on the design and evaluation of Gunn devices.

- Discussions with Drs. M. Tobin and G. Simonis at HDL on picosecond measurements on high-speed detectors and integrated devices. Devices were provided to Dr. Simonis for optical Heterodyning measurements.
- Ring resonator samples/fabricated by DuPont Superconductive Systems (using our design) were supplied to Bill Wilbur at ETDL for evaluation at temperatures below 77K.
- Collaboration with Dr. Ken Jones of ETDL on the study of growth of epitaxial ohmic contacts on GaAs.
- Consulted with Dr. Tobin and her group at HDL on MOMBE systems.
- Consulted with Mr. R. Lane of MICOM on device technology for radar systems.
- One of the students working on this project (Doug Teeter) spent the summer working at the U.S. Army Electronics Command at Fort Monmouth on large signal device modeling and characterization. The contact person is Dr. Barry Perlman.
- Discussions with M. Stroscio about modular upgrades to defense systems. These discussions were prompted by inquiry from the Tactical Operations Office at the Pentagon.
- Discussions were held with R. Lane, Army Missile Command relevant to the GaAs processor.
- Supplied MBE layers to Dr. R. Tober of HDL and continued interactions relative to piezoelectric measurements on layered structures.

7.4 INTERACTIONS WITH OTHER D.O.D. FEDERAL AND INDUSTRIAL AGENCIES AND LABORATORIES

This program has had a major impact in establishing Michigan as one of the leading centers in III-V semiconductor technology and high-frequency/speed microelectronics and optoelectronics. This has lead to the establishment of very close interactions with and initiation of several major programs and centers from various federal and industrial organizations. These include:

- The NASA Center for Space Terahertz Technology. Through this Center we have established very close interactions with JPL and Goddard.
- The NSF-Science and Technology Center for Ultrafast Optics.
- The SRC Center for Automated Semiconductor Manufacturing.
- DARPA: Several major programs in GaAs microprocess design and fabrication (joint with several companies and monitored by Army Research Office), automated III-V semiconductor manufacturing (joint with Hughes Research Laboratories)and novel superlattice-based HBT devices for optically controlled phased-array radar applications (monitored by the Air Force-Rome Center).
- ONR: Programs in basic material growth studies, high-speed optoelectronic devices and wide bandgap semiconductors.
- AFOSR: Programs in Si/Ge materials technology and III-V optoelectronic devices for optical computing.
- Industry: Several programs and very close interactions with Hughes, Texas Instruments, Northern Telecom, IBM, National Semiconductor, Hewlett-Packard, MACOM, Rockwell, Alcatel, Raytheon, Allied-Signal and others.
- NSF: Several programs in material growth and characterization and optoelectronic devices and a recent program for curriculum-research developed in automated semiconductor manufacturing.

7.5 SUMMARY OF MAJOR TECHNICAL ACCOMPLISHMENTS

- ELECTRONIC, OPTICAL AND TRANSPORT PROPERTIES IN HETEROSTRUCTURE BASED DEVICES

  - A self-consistent formalism for design of n- and p-type pseudomorphic MODFETs: We developed a first formalism to understand p-type properties of pseudomorphic MODFETs by self- consistently solving the 4 band k·p equation and the poisson equation. The approach allowed us to design and predict carrier properties in p-type devices.
  - Theoretical and experimental studies on the effect of strain on electron and hole masses: Carrier masses were calculated using 8 band models. It was shown that for electrons the strain does not affect the carrier masses seriously. However, hole masses are dramatically affected. The results were verified experimentally using the Shubnikov de Haas approach.
  - Monte Carlo Studies of Hole Transport in p-Type Materials: The first studies of the effect of strain produced in pseudomorphic growth on hole transport were carried out. The studies were carried out for $In_xGa_{1-x}As$ and Si_xGe_{1-x} systems.
  - Performance limits of the Si/SiGe HBT: Material and device studies were carried out to study the performance of the Si/SiGe HBT. Predictions of 100 GHz f_{max} were made based on the improved carrier confinement and carrier transport.
  - Non Variational Techniques for Shallow Level Problems in Heterostructures: A general approach was developed to study excitonic and acceptor level problems in heterostructures. The approach allows us to study the excitonic phenomenon in presence of strain, excess carriers etc. and allows us to design superior excitonic devices.
  - Effect of Strain on Acceptor Levels: We carried out experimental and theoretical studies relating the effect of strain on acceptor levels. The measurement of acceptor levels was shown to provide a direct link to the effect of strain on hole masses.
  - Consequence of Strain on Quantum Well Laser Performance: A detailed formalism was developed to study the effect of strain on quantum well laser performance. The effect of strain on threshold, modal purity, polarization dependence and dynamical response was studied. Also the first calculations of the effect of strain on the Auger processes including the split off band effects were studied.
  - Coherent Tunneling Phenomenon in Heterostructures: The problem of tunneling of electrons in heterostructures has been addressed. In particular the tunneling in mixed symmetry states has been studied. The formalism is based on an 8-band tight binding model and is being used to study interband tunneling as well as Γ - X tunneling in GaAs/AlGaAs structures.
  - Physics of Quantum Dots and Quantum Wires: The physics of optical and electronic properties of sub 2-dimensional structures is being studied. In particular,

a formalism has been developed to understand the effect of structural disorder on the optoelectronic properties. The formalism allows us to predict the effect of disorder on optical and transport properties.

- Incorporation of phonon scattering into tunnel models using a time dependent formalism.
- Calculation of impact ionization thresholds in strained quantum wells.

• QUANTUM TRANSPORT MODELING OF RESONANT- TUNNELING STRUCTURES

- The time-dependent Schrödinger equation has been solved for the first time using open-system boundary conditions for the resonant-tunneling device. Transient switching characteristics as well as small-signal results have been obtained.
- The time-independent Schrödinger equation has been solved for an ensemble of states to calculate static I-V characteristics of resonant tunneling diodes and transistors.
- Variable effective mass has been incorporated in both the time-dependent and time-independent Schrödinger equations.
- The Wigner function method has been implemented using several different numerical schemes for DC and transient analysis of resonant tunneling devices. The effects of inelastic scattering and the self-consistent potential have been included in these programs.
- An accurate numerical re-formulation of the Wigner function method has been developed .
- Hybrid simulations using a Thomas-Fermi, near-equilibrium approximation in the contact regions self-consistently coupled with Schrödinger's equation in the quantum well or supperlattice region have been developed. These simulations are good practical tools for quantum device analysis and design. They have been used to study resonant tunneling structures and quantum well varactors.
- Quantum varactor structures with high capacitance ratios have been designed using our computer simulations and subsequently fabricated. Very good agreement between simulation results and experiment has been obtained.
- A new quantum device, the Bound-State Resonant Tunneling Transistor, has been proposed, analyzed, and fabricated in the course of this program.

• DEVICE APPLICATIONS OF RESONANT TUNNELING STRUCTURES

- Design and fabrication of very high peak-to- valley current ratio diodes in the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ material system. For the lattice matched system a peak-to-valley ratio of 7(300 K) and 21(77 K) with a corresponding peak current density of 10 kA/cm^2 was measured. For the InGaAs/AlAs devices a peak-to-valley ratio of 24(300 K) and 51(77 K) with a corresponding current density of 15 kA/cm^2 was measured.

- Design and fabrication of very high peak current density diodes in the InGaAs/AlAs material system. With the incorporation of very thin (17 Å) AlAs barriers a current density as high as 150 kA/cm^2 was measured.
- Proposed the use of resonant tunneling diodes as infrared and optical modulators and detectors. These concepts are based on the capability of fast charge transfer phenomena in the resonant tunneling diodes. These devices are predicted to operate at extremely high frequencies.
- Theoretical and experimental investigation concerning the stability of resonant tunneling diodes and its effect on the measured I-V. It has been shown that stable operation of the diode is difficult to obtain under normal experimental procedures and secondly each type of instability has a characteristic signature apparent in the measured current-voltage characteristic of the device.
- Theoretical analysis of the effect of stability requirements on the power generation capability of resonant tunneling diodes. It has been shown that for practical purposes it is highly desirable to obtain power from a device that is dc stable. However, requiring the resonant tunneling diode to be stable places severe restrictions on the power generation capability of the device.
- Characterization of a resonant tunneling diode as a video detector from 8 GHz to 100 GHz. The tangential signal sensitivity and the video impedance were both found to be a strong function of bias. The values obtained for the tangential signal sensitivity and the video impedance compare well with Schottky diode values at lower frequencies. Such properties as the open circuit voltage sensitivity, dynamic range and broad band frequency response have also been measured with encouraging results.
- Parametric analysis of the device performance as a function of device design parameters using a self- consistent quantum mechanical simulation has been carried out. One of the interesting results of this study was the observation that for high cathode doping levels the peak current decreases proportionally to the thickness of the spacer layer. It is suggested that this phenomena is due to the junction potential between the heavily doped and undoped regions.
- Process characterization and evaluation of shallow (less than 300 angstrom) n and p type ohmic contacts.
- Fabrication of InGaAs/InP based Hot Electron Transistors with excellent current and gain characteristics. (current gain of 100 at 77K).
- Fabrication of InGaAs/InP-based on resonant hot electron transistors (current gain of 5 and PVR of 4 at 77K.

• ENERGY-MOMENTUM TRANSPORT FOR SEMICONDUCTOR DEVICE SIMULATION

- A 2-valley, energy-momentum simulation program which allows spatial variation of material parameters and heterojunction potential discontinuities has been developed.

- A Monte-Carlo simulation program valid at high electric fields has been developed, which includes the full electronic band structure in the calculations. The simulation may be used to determine material parameters required for the energy-momentum (as well as drift-diffusion) simulations.
- Both energy-momentum and drift-diffusion simulations of millimeter-wave IMPATT's have been carried out to study the potential of these devices, as well as to compare the two simulation techniques.
- Better material parameters for GaAs have been determined by Monte Carlo simulation than were formerly available at high electric fields. These material parameters allow the use of the drift-diffusion simulation method at higher frequencies than previously believed.
- Calculations of high-power generation modes in Si IMPATT devices in the 100-200 GHz range have been carried out and published in the *IEEE Trans. on Electron Devices.*
- Work has been initiated on including tunneling in both energy- momentum and drift-diffusion transit-time device simulations.

• FET TRANSISTOR MODELING, DESIGN, FABRICATION AND CHARACTERIZATION

- Fabrication of conventional GaAs FET's with f_{max} above 150 GHz,
- Design and fabrication of power FET's with 50% improvement in gate to drain breakdown voltage and good RF performance using strained cap layers.
- Determine the effects of process design parameters on FET performance.
- Development of a device/circuit computer model to predict intermodulation performance and limitations of FET mixers.
- Fabricated and RF tested strained cap FET's with high breakdown voltages and good RF performance.

• STRAINED P AND N CHANNEL HEMT's

InP based lattice-matched and strained devices have been studied theoretically and experimentally. The effect of strain has been demonstrated using various FET designs such as HEMT's and HIGFET's. Both n and p-channel devices were explored. Major accomplishments in this area are listed below:

- Mobility improvement from 11500 cm^2/V-sec to 13900 cm^2/V-sec at room temperature using 12% excess Indium in InGaAs channels.
- Measurement of field-velocity characteristics in strained InGaAs/InAlAs heterostructures. Velocity improvement of 7.4% and 14.8% was demonstrated with 7% and 12% excess Indium respectively.

- Establishment of device design approach for strained InGaAs HEMT's. Optimum designs can be achieved using the results of this approach on the influence of strain, doping and channel thickness on sheet carrier density, strained channel carrier occupation, "parasitic- MESFET" conduction, etc.
- First demonstration of double-channel InGaAs/InAlAs HEMT's. Tremendous output conductance improvement using the double versus single designs. Record f_{max}'s of 66 GHz were achieved using 1μm long gates. f_{max} = 140 GHz was obtained with 0.25μm gates.
- Understanding of low frequency noise characteristics and impact of strain. The results demonstrated that a compromise had to be made between high-gain (large excess In%) and low-noise (low excess In%).
- A thorough study of the low-frequency dispersion characteristics of InGaAs/InAlAs HEMT's revealed smallest transconductance and output resistance dispersion for slight excess in (7%) in the channel. The dispersion is smaller than in MESFET's and is identified to originate from the channel region under the gate.
- First reliability studies of InGaAs/InAlAs HEMT's revealed DC and high frequency degradations. Changes in the channel buffer interface and layers manifested by additional trapping seem to be responsible for this.
- Demonstration of submicron bilayer technology and application to the fabrication of 0.1 μm InGaAs/InAlAs HEMT's. Record f_T's and f_{max}'s in the range of 200 GHz to 240 GHz were achieved.
- First realization of p-channel GaInP/InGaAs/GaAs HEMT's. Channel mobility and transconductance enhancement up to 47 mS/mm was demonstrated. N and p-channel HIGFET's were also realized for the first time using GaInP/InAs/GaAs.
- Demonstration of absence of threshold voltage shift and current collapse in cryogenic operation of GaInP/GaAs HEMT's. Superiority over AlGaAs/GaAs and InGaAs/InAlAs was shown.
- Investigations of i-layer and step-doped designs for HEMT's showed that better threshold voltage uniformity could be obtained in recessed devices together with improved linearity and reduced low- frequency noise in such designs.
- HEMT breakdown analysis using a two-dimensional approach. A screening effect of transverse from longitudinal electric field was identified. Double channel designs were analyzed to explain their breakdown advantages over single channel devices.
- Demonstration of E/D mode HIGFET technology with best recorded standard deviations of threshold voltage and state-of-the- art speed characteristics.
- Development of novel refractory metal WSi submicron gate technology. Unlike traditional technologies this approach employs lift-off rather than RIE for gate definition.
- Realization of state-of-the art InP-based HEMT characteristics using self-aligned gates for improved f_{max} characteristics and demonstration of f_{max} = 310 GHz using this technology with 0.1 μm long-gate.

- Analysis of subthreshold conduction in InAlAs/InGaAs HIGFET's and demonstration of more pronounced effects in strained devices related to higher carrier injection to the buffer and presence of a deeptrap ($E_{DT} = 0.34 \pm 0.01$, $N_{DT} = 2.4 \times 10^{16} cm^{-3}$).
- Demonstration of correlation between transconductance dispersion and low-frequency noise by generation-recombination in GaInP/GaAs and AlGaAs/GaAs HEMT's. Evaluation of trap presence at high temperature operated GaInP/GaAs devices but absence of such effects at low temperature.
- Demonstration of threshold voltage shift and orientation effects in InAlAs/InGaAs HIGFET's due to piezoelectric charges induced by the WSi refractory gate metallization.
- Report of the highest f_T obtained by MOVPE grown InAlAs/InGaAs HEMT's. A value of 180 GHz has been reached using 0.1μm long-gate.

• HETEROJUNCTION BIPOLAR TRANSISTORS

- Development of a self-aligned technology for AlGaAs/GaAs and InGaAs/InP HBT's. Special RIE approaches were established for controlled emitter definition and base contacting without severe damage of the dry etched surfaces. Methane-based gases were used for the InP-based devices and submicron "quantum-wire" type tests were conducted for the damage studies.
- Demonstration of InP/InGaAs HBT's with a gain of 100 and realization of the first GaInP/GaAs HBT's with a gain of 440 and a collector current density of 150 A/cm^2.
- Identification of low frequency noise sources in AlGaAs/GaAs and InP/InGaAs HBT's. Surface recombination at the base periphery and diffusion contributed to the collector 1/f noise, while G-R noise showed enhanced impact at low base currents.
- Demonstration of a novel self-aligned InP/InGaAs HBT technology using integrated air-bridge technology for reduced emitter pad parasitics. f_T values of $\sim$ 36 GHz were obtained using this approach. Significant performance improvement is expected by employing this approach in HBT layouts with reduced base-collector capacitance.
- Demonstration of speed-breakdown tradeoffs in InP-based HBT's and evaluation of such characteristics for devices with special collectors and double HBT designs.
- Verification of superior speed-breakdown tradeoff by p^-n^- collector InP HBT's as compared with conventional designs.
- Prediction of impact ionization coefficients for a variety of InP- based materials using physical models in view of evaluating their values over a wide range of electric fields as required for electronic device simulations.

- Experimental and theoretical demonstration of a collector transit-time reduction using AlGaAs/GaAs and InP/InGaAs HBT's with undoped-collector and inverted field designs. A Monte Carlo analysis was specially developed for this purpose.
- Development of a transient Monte-Carlo technique for studying the switching properties of HBT's. Inverted field designs showed best performance in switching.
- Study of the effect of graded Emitter-Base design in InAlAs/InGaAs HBT's. Intermediate (x=0.5) gradings showed cut-off frequencies as high as 270 GHz and 2.2 psec switching times.
- Development of a harmonic-balance based HBT-model for analyzing the power saturation mechanisms. Nonlinearities in transconductance, input and output capacitance were identified. These depend on class of operation and device terminating conditions.
- Establishment of speed-power criteria for GaAs and InP-based HBT's demonstrating the potential limitations of special collector structures for power applications.
- First study and analysis of noise upconversion mechanisms in HBT oscillators. This provides the means of correlating the oscillator noise with 1/f and other type of noise existing in the discrete HBT devices, as well as, with its nonlinearities.
- Evaluation of intermodulation characteristics of HBT's by Volterra-series analysis and demonstration of improved IMD3 performance through cancellation of various nonlinear current components at the base-emitter and base collector junctions.
- Demonstration of a hybrid optoelectronic technique for obtaining the small and large signal characteristics of HBT's.
- Development of a direct technique for extracting the equivalent circuit parameters of HBT's in view of providing more physical insight to the device characteristics.

• HETEROSTRUCTURE MICROWAVE MONOLITHIC INTEGRATED CIRCUITS

- Development of double-heterojunction AlGaAs/GaAs MMIC's improved performance over MESFET technology:
- Bridged-T/0.5-12.0 GHz attenuator with improved bandwidth, dynamic range and insertion loss.
- T-phase shifter with enhanced capacitance ratio and phase- shift.
- Development of InAlAs/InGaAs submicron heterostructure MMIC's with state-of-the-art characteristics:
- Improvement of intermodulation distortion point by 4 dB in InGaAs/InAlAs versus AlGaAs/GaAs HEMTs.
- Bridged-T, T and π monolithic amplitude control functions with excellent dynamic range, bandwidth and insertion loss.

- Analog monolithic T-phase shifter with excellent phase shift properties using the highest reported capacitance ratios (~10:1) for monolithic devices.
- First heterostructure monolithic integrated amplifier using three-stages of InAlAs/InGaAs HEMT's. Maximum gain was 22dB and return loss better than 10 dB from 6.0 to 9.5 GHz. Design goals were achieved using either lattice matched or strained heteroepitaxy.
- First demonstration of W-band monolithic HEMT oscillator with 1.2 mW output power at W-band.
- First demonstration of W-band monolithic HEMT mixer with 1 dB conversion gain.
- First demonstration of a monolithic integrated HEMT doubler for 90 GHz to 180 GHz signal upconversion. Conversion loss was 6 dB at only dBm input drive power.
- First demonstration of a fully integrated monolithic oscillator and doubler chain using submicron InAlAs/InGaAs technology for D- band (130.5 to 132.8 GHz) operation.

• GROWTH OF HIGH-QUALITY MBE LAYERS FOR CHARACTERIZATION AND HIGH-SPEED DEVICE APPLICATIONS

- Growth of GaAs- and InP-based single layers and quantum wells with narrowset photoluminescence linewidths (0.2 meV for 100 $\mathring{A}$ GaAs/AlGaAs SQW; 0.8 meV for 40 prd GaAs/AlGaAs MQW; 3.5 meV for 20 prd InGaAs/InAlAs MQW.
- First growth of high-quality InP-based pseudomorphic modulation doped heterostructures for high-speed and high- frequency FETs.
- Highest peak-to-valley ratios in InP-based pseudomorphic resonant tunneling diodes.
- Experimental demonstration of three-dimensional island growth modes in for misfits greater than 1.5%.
- Growth of Sb-bearing compounds and alloys with highest mobility (e.g. μ = 70,000 $cm^2/V.S$ and 110,000 $cm^2/V.S$. in InSb at 300 and 77 K, respectively.
- First measurement of recombination lifetimes and escape times in InGaAs/InAlAs MQW.
- First experimental determination of α(E) and β(E) in pseudomorphically strained single layer semiconductors.
- Demonstration of reproducible high p-type doping levels ($2 \times 10^{19} cm^{-3}$) by Si during MBE growth on (311) A GaAs.

- GROWTH, FABRICATION AND UNDERSTANDING OF 1-μm AND SUBMICRON InGaAs/InAlAs AND InGaAs/AlGaAs MODFET's AND BIPOLAR DEVICES

  - Pseudomorphic $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ modulation-doped heterostructures with $0.53 \leq x \leq 0.85$ have been grown with extremely high mobilities at 300K and lower temperatures. Sheet carrier concentrations as high as 5×10^{12} cm^{-12} have been measured in the 2-DEG. Analysis of the results give us an idea of the growth modes and roughness in the growth front. 1-μm and 0.25 μm gate MODFETs made with these heterostructures show state-of-art DC and microwave performance. Techniques such as migration enhanced expitaxy (MEE) will be used to further improve the quality of these heterostructures.

  - As- grown and regrown heterostructures have been developed for integrated opto-electronics. In particular, InP-based heterostructures have been developed for front-end photoreceivers consisting of a high-speed detector and a MODFET amplifier. The InP-based photoreceiver bandwidths are the highest measured to date.

  - Antimony- containing binary and ternary alloys and heterostructures are being developed for FETs, RT devices, bipolar transistors and optical devices. In particular, growth on lattice-mismatched GaAs and InP substrates is being studied in detail. The electron mobilities measured in InSb and InAsSb grown on GaAs and InP substrates are the highest measured in MBE-grown materials and comparable to the best reported data for LPE- grown crystals. More importantly, the mobility remains high ($\sim$ 110,000 cm^2/vs) at low temperatures and the crystals do not undergo type conversions. InAsSb will be used as the channel region of FET-type devices, as the base of HBTs, and as the low-bandgap material for superlattices and MQWs. It should be mentioned that these results have been obtained with a solid Sb_4 source. Further work will be done with a cracker source.

  - First experimental determination of α(E) and β(E) in thin strained InGaAs.

  - Optical time-of-flight measurements in InGaAs/InAlAs quantum wells.

  - First demonstration of enhanced low-field and high-field transport properties in InP-based pseudomorphic modulation doped structures and their application to high-speed and high-frequency devices.

  - Demonstration of the use of MEE growth technique to obtain superior MODFET device performance at 300 K and lower temperatures.

  - First demonstration of InAs channel 0.1μm gate MODFET (f_T = 128 GHz at 300K).

  - GaAs/AlGaAs HBTs on (311) B substrates with all-silicon doping. Devices have excellent dc and microwave characteristics.

- VERY-HIGH SPEED DETECTORS, MODULATORS AND MONOLITHICALLY INTEGRATED DEVICES

  - In the area of high-speed detectors, we have demonstrated as-grown and re-grown InP based p-i-n diodes which have measured temporal response times $\sim 15 - 20$ ps. and responsivities ≥ 0.4 A/W.
  - We have analyzed, designed and fabricated InP- based monolithically integrated front-end PIN-HEMT photoreceivers using one-step molecular beam epitaxy. These OEICs have measured bandwidths $\sim 2 - 2.5$ GHz, which are the best achieved till date with InP-based materials. Similarly, we have conceived and developed another integrated scheme for a front-end photoreceiver with a doped-channel FET and Camel diode, which have several advantages over the previous structure and should emerge as the simplest and fastest InP-based circuit.
  - For application in integration for communication and radar applications we have analyzed and measured the performance of regrown high speed MODFETs and p-i-n diodes. We have achieved performance nearly comparable to as-grown devices.
  - Development of low-loss waveguides and phase-shifters for the $1.3 - 1.6$ μm range, which leads the way for developing integrated optics with InP-based materials.
  - Monolithically integrated front-end photoreceivers with a bandwidth of 15.6 GHz have been fabricated.
  - First measurement of electro-optic coefficients in compressive and tensile strained InP-based quantum wells.
  - Understanding of the mechanism for enhancement of α/β in GaAs/AlGaAs quantum wells — the coupled quantum well experiment.
  - Realization and characterization of low-loss, single-mode Zn- diffused IILD waveguides.
  - Demonstration of a vertical all-optical coupler-switch using a non-linear MQW coupling region.

- CHEMICAL BEAM EPITAXY: HETEROSTRUCTURE GROWTH AND CHARACTERIZATION

  Excellent progress was achieved in the growth of III-V semiconductor using CBE. Some of the achievements include:

  - Bulk Material:

	μ @ 300°K	μ @ 77%	
InP	4,500 cm^2/Vs	70,000 cm^2/Vs	
InGaAs:	10,500 cm^2/Vs	62,500 cm^2/Vs	$\delta a/a < 2\times10\text{-}4$
InAlAs:	1,000 cm^2/Vs		$\delta a/a < 2 \times 10\text{-}4$
InAlP			$\delta a/a < 2 \times 10\text{-}3$

InGaP	$\delta a/a < 5 \times 10\text{-}3$
InGaAsP (1.1, 1.2, 1.4 mm)	$\delta a/a < 7 \times 10\text{-}4$

InAlAs was grown for the first time by CBE using trimethyl amine alane. This material is comparable to state of the art MBE grown InAlAs.

InAlP was grown for the first time by CBE using trimethyl amine alane.

- Doping
  Tin surface segregation was studied.
  Pulse doped heterostructures were characterized by Hall measurement.

- Selective Area Epitaxy:
  Both SiO_2 and Si_3N_4 were used as masks in the selective area growth of both InP and InGaAs. Both show no deposition on the dielectric and planar growth in the windows. InAlAs deposited using TMAA precursor is not selective on either surface however due to the reactive nature of the Al and its precursor.

- Heterointerfaces:
  X-ray analysis of multi quantum well structures showed excellent abruptness in InGaAs/InP and InGaAs/InAlAs systems.

  Spectroscopic ellipsometry showed monolayer abruptness in InGaAs on InP interfaces while InP on InGaAs showed 10–20 Angstroms transition regions.

- Devices

Lasers: InGaAs/InGaAsP/InP strained multi quantum well lasers showed threshold current densities and quantum efficiencies comparable to the best obtained by any growth technique.

HBT: InGaAs/InP npn heterojunction bipolar transistors with β of 200 have been grown and fabricated.

InGaAs/InAlAs npn HBT's with β of 300 have been grown and fabricated.

HEMT: Uniformly doped and planar doped lattice matched InGaAs/InAlAs high electron mobility transistors have been produced with 0.1 and 0.15 μm gate lengths which exhibit unity current gain cutoff frequencies (f_T) as high as 190 GHz and unity power gain cutoff frequencies (f_{max}) above 300 GHz for self aligned devices. These devices show excellent I-V and noise characteristics. Thermal stress and lifetime experiments indicate that these devices perform better than MBE grown material.

Uniformity doped and planar doped InP/InAlAs HEMT's have been grown and fabricated with mobilities higher (for a given carrier concentration) than recorded published reports of material grown by MOCVD. Devices fabricated from this material do show slightly improved I-V breakdown voltages than InGaAs channel samples and $f_T \sim 40$ GHz and $f_{max} \sim 51$ GHz for 0.15 μm long gates.

HET: InGaAs/InP hot electron transistors with differential current gain of 100 have been produced.

RHET: Pseudomorphic InGaAs/ALAS/InP resonant hot electron transistors were realized with reasonable current gains and peak to valley ratios.

RTD: Strained InGaAs/AlAs resonant tunneling diodes showed current densities of 1×10^5 A cm^{-2} with peak to valley ratios of 25.

Logic gates: Several logic function gates and memories were demonstrated using RHET's and RTD's, which included exclusive-NOR, multi-state memory and a frequency multiplier.

- DIGITAL ETCHING FOR DEVICE FABRICATION WITH HIGH SELECTIVITY AND LOW DAMAGE MAJOR ACHIEVEMENTS:
  - First study to characterize etch rate, etch profile, surface morphology, and selectivity of GaAs, InP, InGaAs, and AlGaAs using an ECR source in Cl_2/AR and BCl_3 gas mixtures.
  - Fabrication of nanometer quantum dots and wires for semiconductor waveguides with vertical profile and smooth surface morphology by etching with an ECR source.
  - Characterization of electron beam lithography for fabricating quantum wires and dots that are 30 nm in width or diameter.
  - Bilayer photoresist etching with fast etch rate (> 1 μm/min) and smooth morphology. First demonstration of uniformity better than 0.5% across 7.5-cm-diameter wafer in an ECR source.
  - GaAs etch profile and surface morphology improved at low pressure by RIE in CCl_2F_2/Ar.
  - InP etched with vertical profile and smooth morphology by RIE in Ch_4/H_2/AR.
- RIE FOR III-V DEVICE STRUCTURES
  - Developed III-V plasma etching techniques for general device fabrication use in the Solid-State Laboratory.
  - Gained an understanding of how sputter etching and chemical etching interact and how they can be isolated to enhance etch rates.
  - Studied stoichiometry of reaction layers that form on etched surfaces using surface analysis and determined how they inhibit or enhance etching.

- Developed new etch chemistry for etching InP ($BCl_3/Ar/O_2$).
- Developed a kinetic mechanism and surface model for the chlorine plasma etching of InP.

- ELLIPSOMETRY FOR NONDESTRUCTIVE CHARACTERIZATION OF III-V STRUCTURES
  - Development of a highly flexible software platform for SE data analysis.
  - Development of a new method (the modified harmonic oscillator model) to accurately estimate the dielectric response of $Al_xGa_{1-x}As$ as a continuous function of x.
  - Extension of the *modified harmonic oscillator model* to the lattice-matched InGaAsP and Si_xGe_{1-x} systems.
  - Use of SE to nondestructively determine the effectiveness of plasma surface treatments for removing native oxide films and the degree of damage to the underlying semiconductor.
  - Use of SE to assist in the development of CBE processes to yield highly abrupt structures with minimal cross-contamination of the group V element.
  - Use of SE to characterize the refractive indices and thicknesses of optical and electron beam resists to support deep submicron and conventional photolithography processes.

- INSULATED GATE DEVICES
  - Development of a state-of-the-art low temperature direct- plasma PECVD process for the deposition of SiO_2 which yields MOS results on Si wafers which are near the quality of thermally grown SiO_2 on Si.
  - Development of a highly repeatable, all dry process, state of the art process for passivation of GaAs surfaces with a widebandgap insulator (SiO_2);
  - Development of a deep submicron etch process for WSi_x self-aligned gate for FET structures.

- THEORY, DESIGN AND FABRICATION OF LASER DIODE SOURCES
  - Detailed theoretical and experimental study of InP-based strained quantum well lasers.
  - Characterization of small and large-signal modulation characteristics of InP-based quantum well lasers ($J_{th} \sim 600$ A/cm^2 for $In_{0.68}Ga_{0.32}As/InP$ laser. 3-dB bandwidths $\sim$ 6 GHz have been measured.
  - First experimental determination of Auger recombination coefficients of these lasers as a function of In composition in the well material.
  - Measurement of bandwidth from noise intensity spectrum and correlation with filamentation behavior.

- DYNAMICS OF PHASED-LOCKED SEMICONDUCTOR LASER ARRAYS
  - An analytical result for the Hopf bifurcation of N coupled lasers has been developed.
  - Obtained an analytical expression for the critical coupling strength at which an array of N lasers will become unstable. This is very important for laser array development.
  - Studied the effect of external light injection on laser array nodes.
- OPTOELECTRONIC MATERIAL AND DEVICE MEASUREMENTS
  - Development of a formalism for theoretical analysis of second harmonic generation in optical fibers, due to higher order nonlinearities involving electric quadrupole, magnetic dipole, and core-cladding interface effects. Calculation of expected conversion efficiencies, which indicated such effects were at least five orders of magnitude too small to explain experimental observations. Analysis of intermodal phase matching of SHG in fibers.
  - Analysis of transverse and longitudinal electric-field-induced SHG in fibers; prediction of relatively large conversion efficiencies ($\sim$1%) by utilizing proper electrode geometries.
  - First direct confirmation of the existence of a periodic structure in fibers conditioned for SHG, by observing a periodic variation of the low-frequency spontaneous Raman scattering spectrum emitted from a small segment of the core (length $\sim$ 5 μm) perpendicular to the fiber axis.
  - Development of a rate equation model which describes the evolution of the $\chi^{(2)}$ grating in fibers conditioned for SHG. Explanation of conversion efficiencies attainable in P-doped and GeO- doped fibers, in context of model predictions.
  - First direct observation of the asymmetry between the fast and slow axes of a weakly birefringent fiber due to polarization instabilities, in good agreement with theoretical predictions. Also the first demonstration of amplitude modulational (AM) gain due to polarization instabilities, where a 15% intensity modulation of an input pulse was transformed into 100% modulation of the output.
- NONLINEAR LASER SPECTROSCOPY OF SEMICONDUCTOR MATERIALS
  - A complete study based on new nonlinear laser spectroscopy methods was made of exciton relaxation in disordered quasi-two-dimensional systems. The work provided the first measurement of the quasi-equlibrium exciton distribution in GaAs quantum wells as well as the temperature dependence of the relaxation rate, verifying both the theory for exciton relaxation in disordered systems as well as our new theory for four-wave mixing.

- We provided the first measurment of the time resolved emission of the picosecond coherent excitation of excitons in quantum wells. The results were completely unexpected and showed the emission is comprised of two components: a delayed signal corresponding to a stimulated photon echo and a prompt signal corresponding to a free polarization (or induction) decay signal. The results conclusively showed that there are at least two separate classes of excitons in these systems. Further measurements using polarization techniques demonstrated that we could distinguish these two classes of excitons and that the echo arises from disorder induced localized excitons while the prompt signal arises due to delocalized excitons. The results are profound because they show that these two classes of states can coexist in these systems and most likely shows that the microscopic nature of the disorder is complex, perhaps bimodal in the scale length distribution as suggested by other measurements.
- We performed the first measurements of the cw nonlinear response of magneto-excitons in quantum well structures. Using the new high resolution nonlinear spectroscopy methods developed by our group, we frequency resolved the exciton Zeeman splitting within the inhomogeneous distribution, a result not previously possible by other methods and important since we have been able to show the g-factor is nonlinear as a function of the magnetic field for small fields. The work is of interest to people concerned about band structure in these systems and the effect of spin.

- HIGH T_C SUPERCONDUCTING THIN FILMS AND DEVICES

  - Construction of a Nd/YAG laser ablation system for superconducting film deposition on heated substrates.
  - Development of a spray technique for the deposition of grainy superconducting films.
  - Microwave detector measurements using distributed weak link mechanism in grainy superconducting films.
  - Growth of High-T_c superconducting films of GaAs substrates with Al_2O_3 buffer layer.

- GROWTH AND CHARACTERIZATION OF THIN FILM STRUCTURES

  - A technique for structural characterization of semiconductor heterostructures using high resolution X- ray techniques has been developed. This has been employed to determine quantitatively the degree of strain, thickness and crystalline coherence of various III-V epitaxial layers.
  - RTA is a discontinuous, collective phenomenon and not a gradual strain relief as previously thought. This implies that there are definite characteristic thresholds for annealing in terms of annealing temperature, and time during which the annealing takes place.

- A major achievement has been the development of *time-resolved* x-ray scattering techniques which can probe structural changes on very short time-scales (μsec) so that the RTA process could be investigated microscopically. The new techniques involve highly intense x-ray beams from synchrotron radiation sources.
- The presence of ion-implants in strained layers enhances the efficiency of the RTA process. A probable mechanism is the increased absorption in the infra-red region due to interband states from the ion-implants.

- EXPERIMENTAL AND THEORETICAL STUDY OF MESOSCOPIC TUNNEL JUNCTIONS

  - Designed and built a cryogenic scanning tunneling microscope (STM) capable of making topographic and spectroscopic meaurements at liquid helium temperatures.
  - Measured single electron charging effects in samples of confined geometries using a cryogenic STM.
  - Calculated new effects in the thermoelectric power and inelastic spectra of a tunnel junction due to single electron charging.

- ANALYSIS OF CROSSTALK AND SIGNAL COMMUNICATION IN VERY-HIGH FREQUENCY DIGITAL INTEGRATED CIRCUITS

  - Development of a finite-difference transmission line matrix (FDTLM) program for three-dimensional simulation of the electromagnetic properties of the interconnects and devices of ultra-high speed digital integrated circuits.
  - Design and fabrication of a test chip for the integer part of the CPU of a GaAs Microprocessor which uses the MIPS architecture.

- RESEARCH AND DEVELOPMENT ON A HIGH PERFORMANCE GaAs MICROCOMPUTER SYSTEM

  - Computer-Aided Design Environment
    * Schematic capture was added to microwave simulation and optimization.

      Our interface between Super-Compact and the Mentor Graphics schematic capture package allowed microwave IC designers to take advantage of the graphical input tools developed in the silicon VLSI area. A design could be entered as a schematic using 67 elements available from a menu; after the design was optimized by SUPER- COMPACT^{TM}, the schematic was updated (back-annotated) with the results. This interface was made available to the URI community, and was distributed commercially by Compact Software, Inc.
    * A circuit compiler was developed for direct-coupled FET logic (DCFL).

      This tool, developed with Cascade Design Automation, includes

- design entry in VHDL, Verilog or EDIF (Synopsis and schematic interface),
- design-rule-driven generation of GaAs cell layout, and SPICE- based simulation models,
- simulation output and back annotation of both gate delays and interconnect RC delays,
- automatic power rail sizing,
- synthesis and optimization of circuits from functional descriptions, and
- automatic buffer sizing, block placement and routing driven by timing analysis to minimize critical paths.

There is an opportunity with these performance-driven CAD tools to actually improve the speed of VLSI designs over that of hand crafted methodologies, while significantly reducing the design time. The design-rule-based approach has the important advantage of allowing designers to capitalize quickly on advances in technology. Our work has led to a commercial version of the GaAs compiler, to be announced by Cascade at the 1992 GaAs IC Symposium. Cascade will donate the GaAs compiler to all of the Universities doing DCFL design with DOD funding. Such tools should have a significant enabling effect on the digital GaAs area.

* Efficient delay macromodels have been developed for DCFL gates and interconnects.

  This modeling approach, based on SPICE simulations, represents performance of low-level digital circuits as functions of loading, output device size, and input rise or fall time, in a two-dimensional table. By interpolating between points in the table, a gate-level simulator can efficiently assign accurate delays (within a few percent of SPICE) to each instance of a gate type. The approach enables accurate timing analysis and simulation of VLSI circuits in a practical amount of time. When interconnect exceeds some user-specified length, interconnect delays are calculated separately from gate delays.

– Technologies

  * Our analysis of III/V technologies and logic styles for VLSI circuits has influenced major U.S. GaAs foundries.

    Collaborative relationships with these foundries have made their models and design rules available to us, and our insights regarding VLSI issues available to them. The ability in our CAD tools to implement VLSI circuits quickly with various rule sets and constraints, enables us to evaluate the impact of various process features on circuit size and performance. These results will be summarized in an invited paper at the 19th Int. Symposium on Gallium Arsenide and Related Compounds, titled "Compound Semiconductor Device Requirements for VLSI."

* Our study of on-chip interconnects, one of the major sources of delay in high-performance systems, was the first to realistically compare superconducting and optical approaches to conventional metal interconnect.

  Optical connections are not advantageous for on-chip interconnect. And contrary to the common wisdom at the time, we found that little would be gained by using superconductors. In realistic FET circuits, the delay is dominated by the output impedance of gates and the capacitance of interconnect. Superconductors would be advantageous if they can be placed on a finer grid than metal lines, but superconducting interconnects are undamped, so they would require impedance-matched receivers to avoid ringing, a high price to pay for slightly faster on-chip signal propagation. A significant improvement in propagation speed is seen for metal lines or superconductors implemented as air bridges, but air bridges are not practical for VLSI. Our approach has been to use conventional metal lines, but minimize interconnect length on critical paths with advanced CAD tools.

* We have analyzed the effects of various material and process parameters on multichip module (MCM) performance, and the effect of MCM packaging on system performance.

  We have shown that in a representative GaAs microprocessor design, system-performance can be improved by 50% by using multichip module packaging. Delay macromodels have also been developed for MCMs.

– VLSI Digital GaAs Demonstrations

  * Through the design of 12 integrated circuits, we have identified many important issues in VLSI GaAs.

    The issues in high-performance GaAs design are the same as in any other technology. The higher the switching speed, though, the more critical these issues become; delays from chip-crossings, on-chip interconnect, and loading effects can easily overwhelm the switching speed of gates. Furthermore, DCFL logic gate structures are very restrictive compared to CMOS gates; ratioing, limited fan-in and fan-out, no dynamic circuits, no complex gates, and only limited use of pass gates and stacked transistors make circuits less efficient. Buffering must be done properly in DCFL or gates will be either very slow, or overdriven, causing logic faults. The GaAs compiler hides from the designer many of the limitations and potential problems in DCFL design.

    All of the circuits fabricated in this project have been designed as part of the effort toward a GaAs microprocessor, but a number of them are interesting in their own right. For example, a 32-bit binary-tree look-ahead adder was fabricated which has a worst-case delay of 2.3 ns. A unique buffer design, which we call the 'squeeze buffer,' drives large loads with short propagation delays, and dissipates no more power than needed. Many primitive cells have been optimized both for performance and for layout efficiency; these

are available for the use of others in the GaAs compiler.

* Our first GaAs CPU chip, named Aurora, operates at 137 MHz.

  The CPU chip is a reduced-function version of the MIPS architecture, implemented in the Vitesse HGaAs II process (0.8 μm effective gate length). The circuit consists of 60,500 transistors. It measures 12.175 $\times$ 7.941 mm, dissipates 11 watts, and executes 28 instructions. The primary purpose in designing this chip was to exercise our CAD tools. It served as a qualification vehicle for both the circuit design and the design methodology. The chip was designed by five students in five months, including writing the cell generators for the GaAs circuit compiler. The chips were then tested using our new HP82000, which was funded in part by a separate ARO equipment grant. It has only one design error, which was found shortly after the design was submitted for fabrication: some source-follower buffers are driven by lines that also drive DCFL gates. Since the chip has a scan chain throughout, we were still able to test everything.

* A 1K-word x 32-bit static RAM chip has been designed in DCFL to serve as instruction and data cache for our GaAs processor.

  Two versions of this circuit are currently in fabrication at Vitesse. The second of these should have an access time (latch-to-latch) of 2.5 ns. The design includes a novel electrically programmable redundancy scheme.

* The crowning accomplishment of this work is the design of a 250-MHz RISC-architecture CPU chip having 110,000 transistors; this chip is in fabrication at Vitesse.

  The efficient design of this circuit was made possible by the GaAs circuit compiler.

- DIGITAL CIRCUITS

  - We have been the first to recognize the tremendous potential of neural networks for built-in self-repair of embedded memories. We clearly demonstrated how the chip yield can improve from 20% to 99% by using the combinatorial optimization capabilities of the electronic neural network.
  - We have also developed a very powerful reconfiguration algorithm that applies to hexagonally interconnected systolic processor arrays. It achieves improved fault-tolerance at minimal switching cost.
  - We also designed HAM (Hexagonal Array Machine), which we believe is the first to implement concurrent multiple-layer wire routing.
  - A new fault model was developed to capture the leakage current sensitivity to processing parameters. New parametric test procedures were designed based on this model.

- New Design-For-Testability approaches to accelerate test procedures by a factor of 1000 have been developed.
- Test methodology for embedded RAMs has been developed.
- New error correcting circuits have been designed to decrease the soft error rate by a factor of 10^6.
- Neural type circuits have been used for the first time to automatically repair and reconfigure large memory and processor arrays.
- A powerful algorithm based on graph and switching theory techniques was developed for reconfiguring hexagonal processor arrays.
- A 1 kbit HEMT RAM cell was designed and the effect of processing variations and defects on the performance of the cell were studied to identify the possible fault effects at the circuit/system level. Efficient test procedures were suggested for these faults.
- A small circuit simulator to perform transient and DC analyses of RTT/RTD circuits has been designed based on a simulation model derived from device simulations and measurements.
- Several basic digital logic elements such as AND/OR/XOR gates were designed and/or fabricated using RTTs, RTDs and RHETs.
- Properties of bistable logic (self-latching logic) circuits using NDR devices were studied.
- Arithmetic functions such as addition and multiplication were studied to understand the impact of NDR logic; the projected speeds are in the sub-nanosecond range for 32-bit a ithmetic.
- Multi-valued logic elements using NDR devices were studied.
- Design of ultra-dense storage elements using NDR devices was investigated.

RESEARCH

CONTINUING RESEARCH TASKS

I. ELECTRONIC, OPTICAL AND TRANSPORT PROPERTIES IN HETEROSTRUCTURE BASED DEVICES

FACULTY SUPERVISOR: J. Singh

GRADUATE STUDENT PARTICIPANT:

V. Sankaran

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

To develop theoretical formalisms necessary to study and conceptualize novel high speed electronic and optoelectronic devices based on heterostructures.

WORK PERFORMED:

- Polarization dependence of optical transitions in quantum dots and wires: A 3D Schrödinger equation has been solved for the description of electron and hole states in quantum dots and wires. The effect of structure symmetry on polarization dependence has been studied.
- Disorder and Localization in Quantum Wires: The effect of structural disorder on the localization of electron and hole states in quantum wires is studied. It is shown that the disorder can seriously limit the performance of quantum wire based devices.
- Interband tunneling related breakdown in narrow gap semiconductors has been studied by using an eight band formalism developed by us.

PUBLICATIONS:

1. T. Tanaka, M. Willatzen, Y. Arakawa, P. Bhattacharya and J. Singh, "A Study of Valence Bandstructure and Polarization Dependence of Near Bandedge Optical Transitions in Quantum Dots and Quantum Wires," submitted to *Phys. Rev. B.*
2. J. Singh, Y. Arakawa and P. Bhattacharya, "Consequences of Structural Disorder on Laser Properties in Quantum Wire Lasers," to appear in *Photonics Technology Letters.*
3. J. Singh, T. Takahasi and Y. Arakawa, "Consequences of Structural Disorder on Optoelectronic Properties of Quantum Wire Structures," presented at the American Physical Society Meeting, Indianapolis, 12-16, March 1992.

INTERACTIONS WITH D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

Discussions with Drs. M. Stroscio and G. Iafrate on how scattering from heterostrucure phonons should be included in tunneling processes.

II. QUANTUM TRANSPORT MODELING OF RESONANT TUNNELING STRUCTURES

FACULTY SUPERVISOR: G. I. Haddad
RESEARCH SCIENTIST: R. K. Mains

GRADUATE STUDENT PARTICIPANT:

J. P. Sun

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

The objective is to develop simulation programs to predict the behavior of quantum devices. The simulations will be capable of modeling transient behavior, i.e. the time dependence of the Schrödinger equation will be included. The goal is to simulate the switching characteristics and high-frequency behavior of quantum devices.

WORK PERFORMED:

The accurate re-formulation of the Wigner function method for quantum transport modeling has been submitted to the *Journal of Computational Physics* for publication. Additional calculations using the method have also been carried out. Although the method is promising, further problems remain in its implementation, particularly due to finite computer resources. These problems and proposed solutions are discussed in the *Journal of Computational Physics* article.

Work was begun on a formulation to study Γ-X mixing in tunneling through quantum barriers. The method used has been proposed by Liu[1] and involves calculation of both Γ and X valley wave functions which are coupled at the hetero-interfaces. The method will be used to study the effects of this mixing on I-V characteristics of quantum devices.

The work on quantum well varactor design and analysis has been accepted for publication in the *Journal of Applied Physics.*

PUBLICATIONS:

1. J. P. Sun, R. K. Mains, W. L. Chen, J. R. East and G. I. Haddad, "C-V and I-V characteristics of quantum well varactors," accepted for publication in *J. Appl. Phys.*

2. R. K. Mains and G. I. Haddad, "An Accurate Re-Formulation of the Wigner Function Method for Quantum Transport Modeling," submitted to the *Journal of Computational Physics.*

---

[1]H. C. Liu, *Appl. Phys. Lett.* **51**, 1019 (1987).

3. W. L. Chen, J. P. Sun, G. I. Haddad, M. E. Sherwin, G. O. Munns, J. R. East and R. K. Mains, "InGaAs/InP Hot Electron Transistors Grown by Chemical Beam Epitaxy," submitted to *J. Appl. Phys.*

4. S. Mohan, P. Mazumder, R. K. Mains, J. P. Sun and G. I. Haddad, "Ultra-Fast pipelined arithmetic using quantum electronic devices," submitted to *IEEE J. of Solid State Circuits.*

5. S. Mohan, P. Mazumder, G. I. Haddad, R. K. Mains and J. P. Sun. "Logic design based on negative differential resistance characteristics of quantum electronic devices," submitted to *IEEE J. of Solid State Circuits.*

III. INVESTIGATION OF NOVEL HIGH-FREQUENCY DEVICES BASED ON QUANTUM TRANSPORT IN III-V SEMICONDUCTORS

FACULTY SUPERVISOR: G. Haddad
RESEARCH SCIENTIST: J. East
RESEARCH ENGINEER: G. Munns

GRADUATE STUDENT PARTICIPANT:

W. L. Chen

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

The main objective of this task is to model,design, fabricate and RF test transistors based on phenomena such as resonant tunneling and hot electron transport and to examine their potential for high speed/ high frequency applications. The main emphasis is on unique resonant tunneling transistor (RTT) structures. These include REsonant Hot Electron Transistors (RHET) and a unique structure that uses a bound state in the quantum well base to improve the base resistance and a stepped barrier in the collector to improve the leakage and yield a larger base-collector voltages. This is referred to as the Bound State Resonant Tunneling Transistor (BSRTT). The shorter term goal is to improve the range of individual process steps required to build these devices.

WORK PERFORMED:

The main effort under this task has been process development to improve the base contact characteristics of RHET's, HET's and HBT's and fabrication of transistors using the improved contacts. Two types of contacts are needed for transistors; deep ohmic contacts for the emitter and collector and a shallow contact for the thin base region. The base is n type material for the transistors under consideration in this section and p type material for the HBT's discussed in section IV. The same contact was optimized for n and p shallow contacts. For comparison purposes the properties of the Au/Ge/Ni/Ti/Au contact that we use for deep n type contacts was also studied. For a wide range of anneal temperatures, the depth of the ohmic contact was found to be controlled mainly by the ohmic metal thickness. The ohmic metals react with the semiconductor material to form an alloy on the surface. The thickness of the alloy region depends on the amount of metal that can react. Diffusion of the ohmic metals deeper into the semiconductor only occurs after relatively long (several minutes) anneal times. A Pd/Ge/Ti/Al shallow ohmic contact can be used for both n and p type contacts. Based on SIMS measurements of test structures the ohmic contact depth is less than 300 Angstroms on InGaAs. The specific contact resistance was 5×10^{-7} ohm cm^2 on n type material and 3×10^{-6} ohm cm^2 on p type material. The n type contacts work for a range of semiconductor

dopings. The p contacts form a rectifying contact for p doping levels below 3e18/cm^3. These new contacts were used to fabricate the HBT's discussed in section IV and several InP/InGaAs unipolar transistors. The optimized fabrication process has been used to build several HBT and RHET devices. A hot electron transistor using the InGaAs/InP has been fabricated and DC characterized. The device had a DC current gain of 100 at 77 K. A second structure with a resonant tunneling barrier in the emitter has also been fabricated. This device has a current gain of 5 and a peak to valley ratio of 4 at 77 K. A variety of logic functions and a frequency multiplier have been demonstrated using this device in simple circuits.

PUBLICATIONS:

1. W. L. Chen, J. C. Cowles, G. I. Haddad, G. O. Munns, K. Eisenbeiser and J. R. East, "Ohmic Contact Study for Quantum Effect Transistors and Heterojunction Bipolar Transistors with InGaAs Contact Layers," submitted to *Journal of Vac. Sci. and Tech.*

IV. HETEROJUNCTION BIPOLAR TRANSISTOR MODELING, DESIGN, FABRICATION AND EVALUATION

FACULTY SUPERVISOR: G. Haddad
RESEARCH SCIENTIST: J. East
RESEARCH ENGINEER: G. Munns

GRADUATE STUDENT PARTICIPANTS:

J. Cowles
M. Karakucuk
D. Teeter
K. Yang

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

The major objectives of this task are to model, design, fabricate and RF test heterojunction bipolar transistors that take advantage of the wide range of material systems possible with MBE and CBE growth systems. These devices will be used to improve the high frequency performance and produce higher power.

WORK PERFORMED:

There were three main areas of work on this task: (1) large signal microwave and millimeter wave measurements, (2) process optimization for InGaAs HBT's; and (3) numerical analysis of abrupt heterojunctions. Earlier progress reports have described the large signal measurement systems used to characterize the power performance of HBT's. These systems have been extended to measure the intermodulation performance of HBT's between 8 and 40 GHz. The measured data has been used with an analytic device model in the Libra software. The results of this work are described in more detail in publications 1 and 2 below. The process development work on self-aligned InGaAs/InP HBT's has continued. A major improvement has been the development of the good shallow base contacts discussed in section III. A combination of improved CBE growth understanding and the use of RIE and wet chemical etching has produced a good etch stop for the base contact. With these two improvements, the first InGaAs/InP HBT's with reasonable DC performance has been fabricated. These devices have a Beta of (170) at room temperature. We have finished a numerical analysis of current transport across abrupt heterojunction interfaces. Both n-n and n-p heterostructures over a range of dopings and temperatures were considered. The main new result is the relatively large effect of tunneling current present in these structures.

PROGRAM FOR THE NEXT PERIOD:

The CW portion of the HBT measurements and characterization has been completed and the student involved is writing his thesis. The next step is to being large signal measurements of devices under pulsed conditions. The HBT fabrication process needs to be improved to better reduce the parasitic effects in the devices in order to extend the high frequency performance. Finally, the numerical model is being extended to include band mixing at abrupt heterojunction interfaces.

PUBLICATIONS:

1. D. Teeter, J. R. East and G.I. Haddad, "Use of self-bias to improve power saturation and intermodulation distortion in CW class b HBT operation," *Microwave and Guided Wave Letters*, vol. 2, No . 5, May 1992, pp. 174–176.

2. D. Teeter, M. Karakucuck, J. East and G. I. Haddad, "Analysis of Intermodulation Distortion in AlGaAs/GaAs HBT's," presented at the International Microwave Symposium, June 1992 (pp. 263–267 in conference digest).

3. K Yang, J. R. East and G. I. Haddad, "Numerical Modeling of Abrupt Heterojunctions Using a Thermionic-Field Emission Boundary Condition," submitted to *Solid State Electronics*.

INTERACTIONS WITH D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

The main experimental portion of this project is large signal characterization of devices. We have obtained devices from Texas Instruments with the help of Dr. Ali Khatibzadeh and from Raytheon Research Division with the help of Dr. Michael Adlerstein. Both groups are funded by Marko Afendykiw from the Naval Weapons Center at China Lake. We are also working with Drs. Larry Larson and Paul Greiling at Hughes Research Laboratory and Dr. Tim Drummond at Sandia Laboratory.

V. FET TRANSISTOR MODELING, DESIGN, FABRICATION AND CHARACTERIZATION

FACULTY SUPERVISOR: G. Haddad
RESEARCH SCIENTISTS: J. East
P. McCleer
RESEARCH ENGINEER: T. Brock

GRADUATE STUDENT PARTICIPANTS:

A. Afzali
K. Eisenbeiser
K. Moore
S. Peng

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

The main objectives of this task are to model, design, fabricate and RF test FET devices operating above 100 GHz,to better understand the limitations on power generation in FET's at lower frequencies and to understand FET mixer performance.

WORK PERFORMED:

There were four main areas of work on this task in the last six months: (1) evaluation of high frequency submicron transistors, (2) fabrication and evaluation of high breakdown voltage power FET's using strained cap layers, (3) development of tools to understand intermodulation in FET mixers, and (4) modeling of FET performance at high frequencies. The 0.1 micron FET's described in the last report have been extensively RF characterized. A quarter of a two inch GaAs wafer was fabricated using our submicron transistor fabrication process. Almost all the transistors on the wafer were good at the DC test stage and approximately 50 transistors were RF characterized from 500 MHz to 26.5 GHz. The best devices had extrapolated f_{max} values over 150 GHz. The devices were fabricated with channel openings of two and three microns, either "gamma" or "T" gates, two types of channel recess chemistry and a range of gate positions in the channel between the center and the source side of the channel. The idea behind the experiment was to have a common process and GaAs substrate and then to study the effects of design on the transistor performance. The performance data for each group of similar transistors on the wafer was measured and average values and standard deviations calculated. The results showed the design tradeoffs for different transistor parameters. For example, the optimal device structure for f_{max} and f_T were different. The results show the critical importance of parasitics in device performance at high frequencies. The details of the results are given in publication 1 below. The use of strained layers to improve the breakdown

voltage of FET's has been tested using several different layer structures. The idea is to modify the band structure and resulting ionization rates in the cap layer under the gate of an FET. A series of layer structure pairs have been fabricated. The idea is to grow two MBE layers with the same channel and contact dimensions and doping, and with the only difference being a strained layer near the gate. The layers are processed at the same time. The performance of transistors from the two wafers can be compared, with differences being due to the presence of the strained layer. Early results showed an improvement in the breakdown voltage with the same DC and RF performance. The strained devices appeared to have traps in the channel that resulted in a kink in the drain current at high drain bias. Additional experience in growth has improved the quality of the material and reduced the kink effect. The best strained devices with a 0.2 micron gate had an f_{max} of 80 GHz, and breakdown voltages larger than 10 volts. Additional details are given in publication 2 below. Two Fortran programs have been developed for diode and FET mixer intermodulation analysis. Both programs have the ability to calculate the conversion loss/gain and any second order frequency components as well as the third-order intermodulation (IM3) power level at the output. The method is based on a large signal/small signal analysis, in which the large signal portion is based on the reflection technique and the small signal signal analysis is based on the method of nonlinear currents to the third order. A systematic study of the correlation between the circuit environment and the IM output was first made for a diode mixer. The contribution to the IM product from the components at the image frequency at a component at twice the IF frequency was studied by adjusting their impedances. The results show a weak change with impedance. The effect of higher harmonics of the LO were also studied. Finally, the performance of active gate, resistive gate and drain mixers were studied. The results showed that conversion gain can be achieved in the active gate and drain mixers, with the drain mixer having a poorer IM3 performance. Although the resistive gate mixer does not have conversion gain, it has the best IM3 performance.

A first group of Y parameter data from a two dimensional Monte Carlo FET model has been calculated. This initial data shows that the Y parameters typically measured at low frequencies must be modified to describe transistor performance above 100 GHz.

PUBLICATIONS:

1. K. Moore, J. East, G. Haddad and T. Brock, "Optimized 0.1 micron GaAs MESFET's," presented at the 1992 International Microwave Symposium, June, 1992 (pages 643-646 in conference digest).

2. K. Eisenbeiser, J. East, G. Haddad and T. Brock, "High Breakdown Voltage Submicron Strained InGaAlAs/GaAs FET's," presented at the 1992 International Microwave Symposium, June, 1992 (pages 647-650 in conference digest).

3. K. Eisenbeiser, J. East, J. Singh, W. Li and G. Haddad, "Breakdown Voltage Improvements in Strained InGaAlAs/GaAs FET's," accepted for publication in *IEEE Electron Device Letters.*

INTERACTIONS WITH D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

We are continuing our interactions with Dr. Paul Greiling and his group at Hughes Research Laboratories and Dr. Sandip Tiwari at IBM Watson Laboratories about transistor design and fabrication.

VI. ENERGY-MOMENTUM TRANSPORT MODELS FOR SEMICONDUCTOR DEVICE SIMULATION

FACULTY SUPERVISOR: G. I. Haddad
RESEARCH SCIENTIST: R. K. Mains

GRADUATE STUDENT PARTICIPANT:

C. C. Chen

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

The objective is to develop methods for implementing the energy-momentum transport model for a more general class of semiconductor devices than is currently available. The model will be interfaced with various types of injectors, including quantum mechanical tunneling injectors, to study relaxation effects in transit-time devices. Also, the model will allow spatial dependence of material parameters, so that relaxation effects across heterojunction interfaces can be studied.

WORK PERFORMED:

The high-field Monte Carlo simulation program has been further developed during this period. Also, work has been initiated to include the tunneling mechanisms in both the energy-momentum and drift diffusion simulations (the drift-diffusion simulation including tunneling will be required to generate an initial guess, either for the energy-momentum model or Monte Carlo device simulations). The availability of final states will be included in the tunneling model, so that information about the band structure is also being incorporated in the simulations.

VII. STRAINED P AND N CHANNEL HEMT's

FACULTY SUPERVISOR: D. Pavlidis
RESEARCH SCIENTIST: G. I. Ng

GRADUATE STUDENT PARTICIPANT:

Y. J. Chan

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

This project addresses the effects of strain on P and N channel HEMT and HIGFET characteristics including their DC and microwave performance. P channel devices benefit enormously from the reduction of hole masses, while N-channel transistors take advantage of the better confinement and reduced carrier scattering. Submicron device studies are conducted in order to evaluate the high-frequency potential of the HEMT's.

WORK PERFORMED:

Near subthreshold conduction on InAlAs/$In_xGa_{1-x}As$ HIGFET's has been studied for the case of lattice matched (x=0.53) and strained (x=0.65) channels. With excess In content in the InGaAs channel, carrier injection from the buffer becomes more significant, resulting in a higher output conductance and soft pinchoff under high V_{ds} operating conditions. Implant straggle in the tested HIGFET's was estimated at 900Åand the space-charge depth of 65% In devices was found to be about 20% higher than for the 53% In case. An SCLC current related to deep trap ($E_{DT} = 0.34 \pm 0.01$, eV, $N_{DT} = 2.4 \times 10^{16}cm^{-3}$) in the InAlAs buffer was finally introduced to describe the complete conduction mechanism in InAlAs/InGaAs HIGFET's operated under subthreshold conditions.

The increase of drain-source current (kink effect) observed in the high V_{ds} bias region of p-type doped channel InAlAs/InGaAs FET's was systematically studied. An impact ionization process initialized by holes in the InGaAs channels was suggested as a possible mechanism for the kink effect. Temperature dependent measurements confirm this possibility as evidenced by the reduction of the excess current under high temperature operation. A parasitic bipolar effect caused by ionized minority carriers, originating by impact ionization from the p-channel, has also been described and supports the generation of excess channel current by impact ionization.

Trap effects in GaInP/GaAs and AlGaAs/GaAs have been studied by means of low-frequency noise and transconductance frequency dispersion characterization. LF noise and g_m dispersion show some correlation, as manifested by the fact that the trap-related spectra obtained by LF noise measurements occur at temperatures where g_m dispersion is maximum. Unlike AlGaAs/GaAs HEMT's, GaInP/GaAs devices show no trap effect at low temperatures. They present, however, some trapping at high temperature which seem to

be related to transconductance dispersion enhancement. Two traps (E_{a1} = 0.58 eV, E_{a2} = 0.27 eV) were found in AlGaAs/GaAs HEMT's. The E_{a2} manifests the DX-center and causes current collapse at low temperature. GaInP/GaAs heterostructures show on the other hand a single trap (E'_{a1} = 0.52 eV) which impacts the high temperature operation of the devices.

Orientation effects ($In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HIGFET's with WSi_x gates have been investigated experimentally. The threshold voltage shift with gate-length in the [001] direction does not depend on film thickness and is mainly due to short channel effects. Compared to the [001] direction, the threshold voltage shifts to positive or negative values depending on whether the gates are orientated in the [011] or [01$\bar{1}$] directions. The degree of V_{th} change in the latter two directions was found to be proportional to the WSi_x film thickness. The results suggest that piezoelectric charges induced by tensile stress between the WSi_x and the semiconductor are responsible for the V_{th} shift. Finally the effect of stress enhanced lateral diffusion from the source/drain to gate was found negligible in the tested HIGFET's.

State-of-the-art device performance has been demonstrated using lattice-matched InAlAs/InGaAs HEMT's grown by MOVPE. A record f_T value of 180 GHz was obtained using 0.1μm mushroom- gate technology.

This is to-date the highest ever reported f_T value of MOVPE grown HEMT's and compares favorably with MBE results. an f_{max} of 200 GHz has also been recorded for the devices. Care has been taken in selecting the buffer layer for good carrier confinement and low leakage. A thin InAlAs layer was used for this purpose. It is believed that MOVPE offers an excellent alternative to other growth techniques for realizing InAlAs/InGaAs HEMT's for ultra-high frequency applications.

The self-aligned technology has been advanced by demonstrating offset gates with 0.1μm gate-length. Chemical-Beam-Epitaxy grown layers were used for this purpose. A record performance of f_{max} 310 GHz has been recorded extending the gain capability of our InAlAs/InGaAs devices to much higher frequencies than earlier work.

PUBLICATIONS:

1. G. I. Ng, D. Pavlidis, M. Tutt, M. Weiss and P. Marsh, "Low-Frequency Noise Characteristics of Latttice-matched (x = 0.53) and Strained (x > 0.53) $In_{0.52}Al_{0.48}As/In_xGa_{1-x}As$ HEMT's," *IEEE Transactions on Electron Devices*, **39**, No. 3, pp. 523–532, March 1992.

2. Y-J. Chan and D. Pavlidis, "Single and Dual P-Doped Channel $In_{0.52}Al_{0.48}As/In_xGa_{1-x}As$ (x = 0.53, 0.65) FET's and the Role of Doping," *IEEE Transactions on Electron Devices*, **39**, No. 3, pp. 466–472, March 1992.

3. Y-J. Chan and D. Pavlidis, "High Performance E/D-Mode InAlAs/InGaAs HIGFET Technology and Integrated Logic Functions," Proceedings of the 4th Annual InP and Related Materials Conference, Newport, RI, pp. 489–502, April 1992.

4. G. I. Ng, D. Pavlidis, Y. Kwon, T. Brock, J. I. Davies, G. Clarke and P. K. Rees, "0.1 μm MOVPE Grown InAlAs/InGaAs HEMT's with Above 150 GHz Operation Capability,"

Proceedings of the 4th Annual InP and Related Materials Conference, Newport, RI, pp. 18–21, April 1992.

5. Y. Kwon, T. Brock, G. I. Ng, D. Pavlidis, G. O. Munns, M. E. Sherwin and G. I. Haddad, "F_{max}-Enhancement in CBE-Grown InAlAs/InGaAs HEMT's Using Novel Self-Aligned Offset-Gate Technology," Proceedings of the 4th Annual InP and Related Materials Conference, Newport, RI, pp. 360–363, April 1992.

6. D. Pavlidis, "Materials Related Issues and Their Characterization in View of III-V Heterojunction Device Optimization," Programme and Abstracts of the 1st Workshop on Expert Evaluation and Control of Compound Semiconductor Materials and Technologies, (EXMATEC'92), Session 1(1), May 1992.

7. G. O. Munns, M. E. Sherwin, Y. Kwon, T. Brock, W. L. Chen, D. Pavlidis and G. I. Haddad, "Parametric Investigation of InGaAs/InAlAs HEMT's Grown by CBE," to be presented at the 7th International MBE Conference.

8. Y-J. Chan and D. Pavlidis, "Trap Studies in GaInP/GaAs and AlGaAs/GaAs HEMT's by Means of Low-Frequency Noise and Transconductance Disperson Characterizations," submitted to *IEEE Transactions on Electron Devices.*

9. Y-J. Chan and D. Pavlidis, "Orientation Effects in $In_{0.52}Al_{0.48}As/In_{0.53}$ $Ga_{0.47}As$ Heterostructure Insulated-Gate FET's," submitted to *IEEE Transactions on Electron Devices.*

10. J. Kim, Y-J. Chan, S. Williamson, J. Nees, S-I. Wakama, J. Whitaker, D. Pavlidis, "A Novel High-Impedance Photoconductive Sampling Probe for Ultra-High Speed Circuit Characterization," To be presented at the GaAs IC Symposium, 1992.

Ph.D. STUDENTS WHO GRADUATED DURING THIS PERIOD:

Dr. Yi Jen Chan - Associate Professof, National Central University, Department of Electrical Engineering, Chungli, Taiwan. Thesis: *Studies of InAlAs/InGaAs and GaInP/GaAs Heterostructure HBT's for High Speed Application.*

INTERACTIONS WITH D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

COMSAT
Alcatel-Espace
PICOGIGA
EPI
JPL
Thomson-CSF

VIII. MICROWAVE PERFORMANCE AND NOISE CHARACTERISTICS OF InP BASED HBT's

FACULTY SUPERVISOR: D. Pavlidis

GRADUATE STUDENT PARTICIPANTS:

H. F. Chau
M. Tutt

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

The objectives are to study experimentally various HBT designs based on InP. Conventional, undoped collector and inverted field InP/InAlAs HBT's are investigated. A self-aligned technology using Reactive-Ion-Etching approaches is developed.

WORK PERFORMED:

The breakdown and speed characteristics of InP/InGaAs HBT's with different collector designs and doping profiles have been studied. Drift-diffusion and Monte Carlo modeling was used for the breakdown and speed analysis respectively. Temperature- dependent- two- and three-terminal measurements suggest that avalanche impact ionization is the dominant breakdown mechanism in InGaAs collector HBT's. Criteria for the speed-breakdown tradeoffs were established with the help of a figure of merit. The maximum breakdown voltages achieved for designs with 3000Åthick collector are: 3.2 V (n^- InGaAs), 2.2 V (p^- InGaAs), 3.9 V (i InGaAs), 3.3 V (p^--n^- InGaAs) 7.4 V (n^- abrupt InP) and 4.6 V (n^- graded InP). The p^- collector SHBT has the highest speed but the lowest breakdown voltage among all designs. Fast SHBT's do not therefore necessarily translate to high breakdown voltage. The p^--n^- collector SHBT shows the best breakdown-speed tradeoff among the SHBT's. DHBT's outperform all SHBT's in terms of breakdown-speed performance as long as they are graded or the collector-emitter is biased at sufficiently high V_{CE} voltage. A cutoff frequency up to 200 GHz was found to be feasible with graded DBHT's. The non-graded DHBT's can finally be optimized to perform better in terms of breakdown-speed tradeoffs than the graded devices by increasing the doping of the collector.

The physical model and theoretical expressions derived by Okuto and Crowell have been used to fit impact ionization experimental data at 300 K for GaAs, $Al_xGa_{1-x}As$ (x = 0.1 to 0.4), InP, $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Ga_{0.48}As$. This study has been of prime importance forthe evaluation of the breakdown characteristics of InP-based HBT's but also GaAs. It was found that the expressions derived by the proposed approach are consistent not only over the range of measured data but are also plausible at very large or small electric fields not covered by the measurments. This approach yielded values with physical significance for parameters such as the ionization threshold energy E_i, average energy loss per phonon scattered E_r, and mean

free path for optical phonons λ. The optimized ionization coefficient parameters, coupled with the temperature dependence capability of Okuto and Crowell's model, can be used to predict impact ionization coefficients over a wide range of electric fields and temperatures. They are consequently very useful in simulating device performance, such as the avalanche breakdown characteristics of electronic devices operating at various temperatures.

The self-aligned technology reported earlier for InP and GaAs-based HBT's has been employed for the fabrication of HBT's with conventional and p^--n^- collectors. f_T values of 34.9 GHz have been demonstrated experimentally using the p^-n^- collector design. This is the first demonstration of experimental characteristics using a special collector of this type which permits a good speed-breakdown tradeoff in InP HBT's. A comparision of experimental performance showed that the p^--n^- collector HBT's outperform indeed conventional designs in terms of speed-breakdown as predicted by the theoretical analysis.

PUBLICATIONS:

1. M. N. Tutt, D. Pavlidis and H-F. Chau, "1/f Noise Characteristics of InP/InGaAs Heterojunction Bipolar Transistors," Proceedings of the 4th Annual InP and Related Materials Conference, Newport, RI, pp. 364–367, April 1992.

2. H-F. Chau, D. Pavlidis, J. Hu and K. Tomizawa, "Analysis of InP/InGaAs Single and Double Heterostructure Bipolar Transistors for Simultaneous High Speed and High Breakdown Operations," Proceedings of the 4th Annual InP and Related Materials Conference, Newport, RI, pp. 410–413, April 1992.

3. D. Pavlidis, H-F. Chau, J. Hu and K. Tomizawa, "Evaluation of Speed-Breakdown Trade-offs in InP/InGaAs Heterojunction Bipolar Transistors," Digest of the 16th European Workshop on compound Semiconductor Devices and Integrated Circuits (WOCSDICE), Ulm, German, Session E(8), May 1992.

4. J. Hu, D. Pavlidis and K. Tomizawa, "Monte Carlo Studies of the Effect of Emitter Junction Grading on the Electron Transport in InAlAs/InGaAs Heterojunction Bipolar Transistors," *IEEE Transactions on Electron Devices,* **39** No. 6, pp. 1272–1281, June 1992.

5. H-F. Chau and D. Pavlidis, "A Physics-Based Fitting and Extrapolation Method for Measured Impact Ionization Coefficients in III-V Semiconductors," to appear in *Journal of Applied Physics.*

6. H. F. Chau, D. Pavlidis, J. Hu and K. Tomizawa, "Breakdown-Speed Considerations in InP/InGaAs Single and Double Heterostructure Bipolar Transistors, submitted to *IEEE Transactions on Electron Devices.*

Ph.D. STUDENTS WHO GRADUATED DURING THIS PERIOD:

Hin Fai Chau - Thesis: *Technological Issues for High-Speed AlGaAs/GaAs HEMT's and InP/InGaAs HBT's,* — accepted a position with Texas Instruments, Dallas TX.

INTERACTIONS WITH D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

Texas Instruments
Alcatel-Espace
University of Toulouse
EPI
Thomson-CSF

IX. HETEROJUNCTION BIPOLAR TRANSISTORS (HBT's)

FACULTY SUPERVISOR: D. Pavlidis

GRADUATE STUDENT PARTICIPANTS:

D. Pehlke
M. Tutt

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

The objectives are to investigate HBT transistor designs suitable for high frequency operation. The theoretical understanding of the devices is supported by a transient and/or steady-state Monte-Carlo approach.

WORK PERFORMED:

Monte Carlo techniques and a 1-D drift-diffusion model were used to investigate the speed and breakdown characteristics of graded- heterojunction AlGaAs/GaAs HBT's with various collector designs. Breakdown-speed consideration were made in view of their sensitivity to bias conditions, doping levels and layer thicknesses. An insight to the physical mechanisms responsible for these effects was also given with the help of base current reversal effects and peak electric field position changes. All devices (inverted collector field), undoped collector and launcher designs), show better speed performance than the conventional HBT. The results however demonstrate that the use of special collectors does not always guarantee a good speed-breakdown compromise. Although the speed and breakdown characteristics of collector launcher HBT's was found to be sensitive to doping and thickness parameters, these devices can be optimized to give the best breakdown-speed compromise among all designs.

A potentially high-bandwidth hybrid optoelectronic technique has been implemented for obtaining small and large-signal characteristics of microwave circuits. This time-domain technique relies on synchronous sampling. It utilizes a terahertz-bandwidth electro-optic transducer gated by ultrashort laser pulses for microwave stimulus signal measurement, and a synthesizer phase- locked to the laser for microwave signal generation. The measurements have been successfully applied to the verification of the large-signal AlGaAs/GaAs HBT characteristics at 1 GHz. The latter were determined by a harmonic balance analysis method and equivalent circuit element extraction using physical model constraints. This method provides HBT power characteristics and time-domain waveforms for various input powers. The power and time-domain results of the model agree very well with the measurements in both the linear and saturated power regions. Thus, the validity of the large-signal analysis is established in terms of amplitude as well as phase characteristics.

Work is in progress to extend the bandwidth of the reported measurement system to exploit the hybrid optoelectronic technique's full potential, and to apply it to more

complicated circuits. Possible sensitivity improvements of the electro-optic transducer are being investigated to extend the measurement noise floor to lower limits.

A formalism has been developed for direct calculation of the HBT equivalent circuit from measured S-parameters without test structure characterization and a minimum of numerical fitting. This approach can serve as a useful tool toward optimization of process technologies and HBT high-speed performance, revealing the factors that limit device performance and allowing direct insight into the HBT device physics. It was applied very successfully to AlGaAs/GaAs HBT's providing exact information on the various equivalent circuit parameters of the transistors. Various bias and frequency dependent trends of the devices were confirmed and a separation between transit time and RC-time constant effects allowed a better insight to the factor limiting the HBT performance.

The IMD3 performance of AlGaAs/GaAs HBT's was studied using a generalized Volterra Series approach, which allows device analysis under variable second harmonic load conditions. The mechanisms dominating IMD3 are determined by the nonlinear current entering the base junction. C_{je} is the strongest non-linearity of the device. C_{bc} is the most important element contributing in IMD3. Its interaction with the rest of the elements either improves IMD3 (in the presence for example of C_{bc} - g_m third order currents) or degrades it (i.e. in the presence of C_{je} + g_{je} + C_{bc} currents). IMD3 can be optimized by selecting the load at the second harmonic at the point where the total base and collector nonlinear current are close to their minimum, i.e. close to open load conditions ($G_{l,DC,ph}$ = 3.14 Rad).

The $\mathcal{L}$(f) of a AlGaAs/GaAs HBT DRO has been measured as a function of bias and low frequency base termination. Best $\mathcal{L}$(f) obtained was -124dBc/Hz at a 100kHz offset at V_{CE} = 5V, I_C = 50mA, and a short circuit base termination. The phase noise decreased by as much as 7dB (at a 10kHz offset frequency) by increasing I_C, from 20mA to 50mA, due to a reduction k'_{FM}, $\mathcal{L}$(f) also decreased by as much as 7dB (at a 10kHz offset) with the use of a short circuit base termination due to shunting the input noise of the transistor. The low frequency collector noise spectra. S_{IC}(f), was measured as a function of I_C and base termination. S_{IC}(f) increased with I_C over most of the measurement band, which is opposite to that observed for $\mathcal{L}$(f). In addition, S_{IC}(f) increased with $R_{b,t}$ which is consistent with what is observed $\mathcal{L}$(f). S_{IC}(f) of the HBT did not follow an ideal 1/f dependence under any condition due to traps. The measured K'_{FM} of the oscillator is constant with offset frequency and decreases with I_C. This decrease in K'_{FM} with bias is consistent with what is observed $\mathcal{L}$(f). It is possible to approximate $\mathcal{L}$(f) using K'_{FM} and the transistor noise. Agreement to within 3dB between measured and calculated $\mathcal{L}$(f) has been obtained in most test cases. However, under some conditions other mechanisms (possibly PM-PM conversion) play a significant role, d$\mathcal{L}$(f)/df is found to increase with increasing offset frequency, in a manner corresponding to the frequency dependence of the low frequency noise of the HBT.

PUBLICATIONS:

1. M. Y. Frankel and D. Pavlidis, "An Analysis of the Large-signal Characteristics of AlGaAs/GaAs Heterojunction Bipolar Transistors, *Microwave Theory and Techniques*, 40, No. 3, pp. 465–474, March 1992.

2. M. Tutt, D. Pavlidis, A. Khatibzadeh and B. Bayraktaroglu, "Investigation of HBT Oscillator Noise Through 1/f Noise and Noise Upconversion Studies," IEEE MTT-S International Microwave Symposium Digest, Albuquerque, NM, pp. 727–730, June 1992.

3. D. R. Pehlke and D. Pavlidis, "Direct Calculation of the HBT Equivalent Circuit From Measured S-Parameters," IEEE MTT-S International Microwave Symposium Digest, Albuquerque, NM, pp. 735–738, June 1992.

4. A. Samelis and D. Pavlidis, "Analysis of Third Order Intermodulation Distortion Mechanisms in AlGaAs/GaAs Heterojunction Bipolar Transistors," IEEE MTT-S International Microwave Symposium Digest, Albuquerque, NM, pp. 1587–1590, June 1992.

5. M. Y. Frankel, D. Pavlidis and G. A. Mourou, "A Study and Optoelectronic Verification of AlGaAs/GaAs Heterojunction Bipolar Transistor Large-Signal Characteristics," submitted to *IEEE Journal of Quantum Electronics.*

6. M. N. Tutt, D. Pavlidis, A. Khatibzadeh and B. Bayraktaroglu, "Investigation of HBT Oscillator Noise Through 1/f Noise and Noise Upconversion Studies," submitted to *IEEE Transactions on Microwave Theory and Techniques Special Issues.*

7. D. R. Pehlke and D. Pavlidis, "Evaluation of the Factors Determining HBT High-Frequency Performance by Direct Analysis of S-Parameter Data," submitted to *IEEE Transactions on Microwave Theory and Techniques Special Issue.*

8. A. Samelis and D. Pavlidis, "Mechanisms Determining Third Order Intermodulation Distortion Mechanisms in AlGaAs/GaAs Heterojunction Bipolar Transistors," submitted to *IEEE Transactions on Microwave Theory and Techniques Special Issues.*

INTERACTIONS WITH OTHER D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

Bell Northern Research
Texas Instruments
University of Toulouse
General Electric
Thomson-CSF

X. HETEROSTRUCTURE MICROWAVE MONOLITHIC INTEGRATED CIRCUITS

FACULTY SUPERVISOR: D. Pavlidis
RESEARCH SCIENTIST: G. I. Ng

GRADUATE STUDENT PARTICIPANTS:

K. Kwon
M. Tutt

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

The objectives are to study the performance of Microwave Monolithic Integrated Circuits (MMIC's) fabricated on heterostructures. The InGaAs/InAlAs system is used primarily for these investigations. Circuit types include phase shifters, attenuators, oscillators, mixers and amplifiers.

WORK PERFORMED:

A fully integrated monolithic oscillator and doubler chain has been successfully implemented using submicron InAlAs/InGaAs technology. The monolithic module has on-chip bias and integrated probes for signal radiation and operates between 130.5 and 132.8 GHz. This is the highest frequency signal generation reported out of monolithic chips using three-terminal devices.

Large-signal HEMT modeling was used for the oscillator and doubler design. The oscillator uses a common source HEMT configuration with a series feedback from source to ground. The necessary condition for oscillation was provided by the microstrip interconnect lines and stubs. The termination impedance at the drain port of the oscillator is defined by the input impedance of the doubler stage transistor and selected for optimum power output. Proper gate width scaling was performed in the doubler transistor for this purpose and no interstage matching was therefore necessary. Edge- coupled lines were used for interstage DC blocking and output matching was achieved by microstrip stubs. The D-band output signal was coupled to a waveguide using a monolithically integrated on-chip E-field probe and no bonding was thus need on the RF side of the chip. The complete biasing circuitry together with stabilizing resistors and capacitors was also integrated on the chip.

The circuits were fabricated using the in-house developed InP MMIC technology which is based on a mix-and-match approach including air-bridges and sputtered SiO_2 overlay capacitors. Thin film resistors for biasing and stablization were realized using 600 $\mathring{A}$- thick Titanium layer. E-Beam lithography was employed to define 0.1μm mushroom gate lines. The total chip size is 1.82 mm $\times$ 1 mm. For testing, the circuit was mounted in a fixture with a WR-5 waveguide and aligned for proper positioning of the E- field probe inside the waveguide. The

conversion loss of the doubler was minimized by proper selection of the HEMT-bias and was estimated to be of the order of 10 dB. The oscillation signal was detected over a frequency range of 130.5 GHz to 132.8 GHz depending on the gate bias. The output power at the chip level was dependent on the drain bias of both oscillator doubler and was of the order -10 dBm to -13 dBm. This was in the range of the expected power level for the small 45μm gate width devices used in the module.

PUBLICATIONS:

1. Y. Kwon, D. Pavlidis, P. Marsh, G. I. Ng and T. Brock, "W-Band Monolithic Balanced Mixer Using InP-Based Heterostructure Diodes," Proceedings of the MMIC Space and Ground Applications Symposium pp. 83–991, April 1992.

2. Y. Kwon, D. Pavlidis, P. Marsh and G. I. Ng, "Experimental Characteristics and Performance Analysis of Monolithic InP-Based HEMT Mixers at W-Band," to appear in *IEEE Transactions on Microwave Theory and Techniques.*

3. Y. Kwon, D. Pavlidis, P. Mash, G. I. Ng, T. Brock, G. O. Munns and G. I. Haddad, "A Fully Integrated Monolithic D-band Oscillator-Doubler Chain Using InP-Based HEMTs," to be presented at the 1992 IEEE GaAs IC Symposium.

4. Y. Kwon, D. Pavlidis, P. Marsh, G. I. Ng and T. Brock, "A Planar Heterostructure Diode W-band Mixer Using Monolithic Balanced Integrated Approach on InP," to be presented at the 1992 GaAs IC Symposium.

Publications pertinent to the work by the the Center:

Y. Kwon and D. Pavlidis, "A Study of Subterahertz HEMT Monolithic Oscillators," To appear in the Proceedings of the 3rd International Symposium on Space Terahertz Technology, March 1992.

INTERACTIONS WITH D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

COMSAT
Alcatel-Espace
PICOGIGA

XI. GROWTH OF HIGH-QUALITY MBE LAYERS FOR CHARACTERIZATION AND HIGH-SPEED DEVICE APPLICATIONS

FACULTY SUPERVISOR: P. Bhattacharya
RESEARCH SCIENTIST: W-Q. Li

GRADUATE STUDENT PARTICIPANT:

S. Gupta

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

To grow high-quality heterostructures and quantum wells with precise control on thickness and doping for devices such as HEMT's, resonant tunneling structures, photodetectors and integrated devices of QW structures for optical spectroscopy. Investigation of electronic transport properties, recombination lifetimes and electro-optic properties of quantum wells. Investigation of electron and hole avalanche processes in coherently strained $In_xGa_{1-x}As$ ($0.2 \leq x \leq 0.8$) thin layers. Growth and characterization of high reflectivity AlAs/GaAs distributed Bragg reflectors (DBR) for surface emitting lasers. Understanding of growth of semiconductors at low substrate temperatures.

WORK PERFORMED:

GaAs and InP-based lattice matched single layers and quantum wells with one of the narrowest photoluminescence linewidths have been grown. Some typical linewidth values for 100$\mathring{A}$ uncoupled wells are: 0.2 meV for GaAs/AlGaAs SQW and 1.0 meV for 100 period GaAs/AlGaAs MQW 3.5 meV for $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ SQW and 5.7 meV for 20 period $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ MQW; and 1-2 meV in $In_{0.15}Ga_{0.85}As$/GaAs pseudomorphic SQW and MQW. In single layer $In_{0.53}Ga_{0.47}As$ on InP, 10K PL linewidths as low as 1.4 meV have been measured. These linewidths confirm the perfection of the materials and heterointerfaces.

Resonant tunneling diodes and transistor structures have been realized with GaAs and InP-based lattice-matched and pseudomorphic heterostructures. Some of the highest peak-to-valley ratios (PVR) have been measured in the resonant tunneling diodes made with these heterostructures. PVRs measured in lattice- matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$/InP RT diodes are 6.1 and 21.6 at 300K and 77K, respectively. In pseudomorphic $In_{0.53}Ga_{0.47}As$/AlAs RT diodes, PVRs as high as 24 and 52 at 300K and 77K have been measured. Resonant tunneling transistors are currently being fabricated with these heterostructures.

Combination of in-situ RHEED measurements and ex-situ reflectance and STM measurements conclusively show that the normal growth mode for the epitaxy of InGaAs on GaAs with misfits $\geq 1.5\%$ is three dimensional. The results agree with theoretical predictions.

This growth mode has been exploited to realize in-situ lower dimension quantum confined structures such as quantum boxes.

Growth of Sb-bearing alloys with very high room-temperature mobilities on InP has been done. These materials also show high mobilities at cryogenic temperatures – a first with MBE. For example $\mu \sim$ 70,000 cm^2/V.sec at 300K and 110,000 cm^2/V.sec at 77K in InSb. Similar results are obtained in InAsSb on InP substrates. InAs/InAlSb MQW for a novel far-infrared detector has also been realized.

AlGaAs/GaAs and InAlAs/InP have been grown at temperatures as low as 150°C. These materials have photoconduction response times $\sim$ 400 fs and will be extremely important for high-speed switches and detectors and as a buffer layer for several electronic and optical devices.

Pseudomorphic $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ modulaton-doped heterostructures with $0.53 \leq x \leq 0.85$ have been grown with extremely high mobilities at 300K and lower temperatures. Sheet carrier concentrations as high as $5 \times 10^{12} cm^{-12}$ have been measured in the 2-DEG. Analysis of the results give us an idea of the growth modes and roughness in the growth front. 1-μm and 0.25 μm gate MODFETs made with these heterostructures show state-of-art DC and microwave performance. Techniques such as migration enhanced epitaxy (MEE) will be used to further improve the quality of these heterostructures.

As- grown and regrown heterostructures have been developed for integrated opto-electronics. In particular, InP-based heterostructures have been developed for front-end photoreceivers consisting of a high-speed detector and a MODFET amplifier.

We have investigated the characteristics and reproducibility of Si- doped p-type (311)A GaAs layers for application to heterojunction bipolar transistors grown by molecular beam epitaxy. We have obtained $p = 2.2 \times 10^{19} cm^{-3}$ in a layer grown at 670°C. Raman scattering spectroscopy shows that Si atoms predominantly incorporate into As-sublattice sites under the specified growth conditions. We have used all-Si doping to grown n- p-n transistors. These devices exhibit excellent d.c. characteristics with $\beta = 240$ in a device with base doping of $p = 4 \times 10^{18} cm^{-3}$.

We have designed lateral structures with thin coherently strained InGaAs regions for carrier multiplication to characterize electron and hole impact ionization processes. The devices consist of 150 Å$In_xGa_{1-x}As$ ($0.2 \leq x \leq 0.8$) QW's grown on S.I. InP substrates. Lateral pn junctions were obtained by either selective ion implantation or diffusion of Zn (p) and GeAu (n). It is seen that both α(E) and β(E) are very sensitive to the amount of strain. The measured value of α/β varies from 0.2-0.5, in contrast to $\alpha/\beta \sim 1$ in most bulk III-V semiconductors. The results agree very well with theoretical calculation which includes effects of two-dimensional confinement and scattering. This is the first direct measurements of α(E) and β(E) in coherently strained InGaAs system.

To realize vertical cavity surface emitting lasers (VCSEL), it is necessary to grow high quality DBR with reflectivity over 99% in lasing wavelength. We have successfully grown 18.5 period $\lambda/4$ AlAs/GaAs DBR with measured reflectivity $\sim$ 100% at designed spectrum region. This lays the foundation for growing high performance VCSEL with monolithic DBR.

We have initiated work to study the optical nonlinearity in strained symmetric and asymmetric InGaAs/AlGaAs QW's grown on (111)B GaAs. The built-in piezoelectric fields remove the inversion symmetry in QW's and lead to large $\chi^{(2)}$ (SHG). This will have many

applications in optical modulators and lasers. This work is being continued.

An all-optical time-of-flight technique is used for measuring perpendicular carrier transport in multiquantum wells (MQWs). This technique is based on measuring a change in surface reflectance due to the absorption non-linearities induced by the carriers, and has a temporal resolution of $\sim$ 1 ps. Typical results on GaAs/$Al_xGa_{1-x}As$ MQW and an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ MQW are compared. The observed fast transport times can only be explained by a field-dependent carrier emission out of the quantum well, after which transport through the continuum states can occur. Due to larger barriers in the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ system, this intrinsic limit to transport is much larger, and hence these devices are observed to be slower than their GaAs/$Al_xGa_{1-x}As$ counterparts.

A systematic study of structural quality and arsenic content of as- grown $In_{0.52}Ga_{0.48}As$/InP layers deposited InP by molecular beam epitaxy at temperatures between 150°C and 450°C was performed using transmission electron microscopy and particle-induced X-ray emission. We found that the amount of As incorporated in the layers generally increases with decreasing growth temperature, with the crystalline quality of the layers being good at growth temperatures higher than 200oC. At 150°C, a large density of pyramidal defects is formed, the defects are related to the very large amount of excess As incorporated into the layer. At 200°C, however, the amount of excess As is lower than expected, and wavy streaks of diffuse scattering are seen in electron diffraction. It is shown that small ordered domains of the CuPt type on the group III atoms are responsible for these features.

PUBLICATIONS:

1. J. Pamulapati, P. K. Bhattacharya, R. L. Tober, J. P. Loehr and J. Singh, "Characterization of High-Quality Pseudomorphic InGaAs/GaAs Quantum Wells by Luminescence and Reflectance Techniques, *Journal of Applied Physics,* **71**, 4487 (1992).

2. R. L. Tober, W-Q. Li and P. K. Bhattacharya "Differential Photocurrent Spectroscopy: A Novel Technique for Semiconductor Characterization," *Journal of Applied Physics,* **71**, 3506 (1992).

3. S. Gupta, L. Davis and P. K. Bhattacharya, "Optical Time-of-Flight Measurement of Carrier Transport in GaAs/AlGaAs and $In_{0.53}Ga_{0.47}As/ In_{0.52}Al_{0.48}As$ Multi-Quantum Wells," *Applied Physics Letters,* **60**, 1456 (1992).

4. A. Claveri, K. M. Wu, W. Swider, Z. Liliental-Weber, P. K. Bhattacharya, J. Pamulapati, M. O'Keefe and R. Kilaas, "Structural Characterization of Low-Temperature MBE $In_{0.52}Al_{0.48}As$/InP Heterolayers," *Applied Physics Letters,* **60**, 989 (1992).

5. S. Kwok, R. Merlin, W-Q Li and P. Bhattacharya, "Raman Scattering from Heavily-Doped (311) GaAs: Si Grown by Molecular Beam Epitaxy," accepted for publication *Journal of Applied Physics.*

6. W-Q. Li, P. Bhattacharya, S. Swok and R. Merlin, "Molecular Beam Epitaxial Growth Characterization of Si-doped AlGaAs and GaAs on (311)A GaAs Substrates and Their Device Applications, submitted to *Journal of Applied Physics.*

7. R. Tober, T. Bahder, W-Q. Li and P. Bhattacharya, "Optically Induced Energy Shifts of Excitonic Resonances in Single [111]B and [100] InGaAs Quantum Wells," presented at the Electronics Materials Conference, Cambridge, MA, June 1992.

Ph.D. STUDENTS WHO GRADUATED DURING THIS PERIOD:

Dr. S. Gupta - Ultrafast Science Laboratory, University of Michigan

INTERACTIONS WITH ARMY LABORATORIES

Harry Diamond Laboratories
ETDL, Fort Monmouth
M. Stroscio, Army Research Office

INTERACTIONS WITH OTHER D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

IBM Yorktown Heights	Bellcore
Boeing Electronics	Hewlett-Packard Laboratories

XII. GROWTH, FABRICATION AND UNDERSTANDING OF 1-μm AND SUBMICRON InGaAs/InAlAs AND InGaAs/AlGaAs MODFET's AND BIPOLAR DEVICES

FACULTY SUPERVISOR: P. Bhattacharya
RESEARCH SCIENTISTS: W-Q. Li
T. Brock

GRADUATE STUDENT PARTICIPANT:

D. Yang

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

MBE and migration enhanced epitaxy (MEE) growth and development of high-speed and high-frequency MODFET amplifiers and oscillators for microwave and millimeter wave application. Development of FETs bipolar transistors and resonant tunneling modulators using low- bandgap strained semiconductors. Development of high-quality transistors on patterned substrates and higher index planes.

WORK PERFORMED:

We have investigated analytically and experimentally the performance characteristics of InP-based $In_xGa_{1-x}As/In_{0.52}Al_{0.48}$ ($0.53 \leq x \leq 0.70$) pseudomorphic modulation doped field-effect transistor (MODFETs) as a function of strain in the channel, gate-length and the temperature. The strain in the channel was varied by varying the In composition x. The temperature was varied in the range of 40-300 K and the device have gate lengths, L_g, of 0.8μm and 0.2μm and 0.1μm. Analysis of the devices was done using a one-dimensional self-consistent solution of the Poisson and Schrödinger equations in the channel, a two-dimensional Poisson solver to obtain the channel electrical field and Monte Carlo simulation to estimate the carrier transit times in the channel. An increase in the value of the cutoff frequency is predicted for an increase in In composition, a decrease in temperature and a decrease in gate- length. The improvement seen with decreasing temperature is smaller as the In composition is increased in the channel. Also, the improvement seen with decreasing temperature is smaller with decreasing gate length. It is also seen that under far certain values of misfit, use of the MEE growth technique improves device performance.

We have measured and analyzed the performance characteristics of 0.1μm gate $InAs/In_{0.52}Al_{0.48}As$/InP MODFETs grown by molecular beam epitaxy. The transistors are characterized by measured g_m(max) = 840 mS/mm, f_T = 128 GHz and a very high current carrying capability, e.g. I_{dss} = 934 mA/mm at V_{gs} = 0.4 V. This is the first report on the microwave characteristics of an InAs channel MODFET and establishes the superiority of this heterostructure system.

We have also investigated MBE growth characteristics on higher-index plane substrate orientations and on higher-index facets created by etching. By using non-uniform atom migration on these planes, we have demonstrated higher breakdown voltages in FETs delineated on the facets. Using the incorporation behavior of Si on these higher index planes, we have successfully demonstrated n-p-n HBT's with all-silicon doping.

PUBLICATIONS:

1. W-Q. Li and P. K. Bhattacharya, "Molecular Beam Epitaxial GaAs/AlGaAs Heterojunction Bipolar Transistor on (311)A GaAs Substrates with All-Silicon Doping," *IEEE Electron Device Letters* **13**(1), 29 (1992).

2. D. Yang, Y. Chen, T. Brock and P. Bhattacharya, "D.C. and Microwave Performance of a 0.1 mm Gate InAs/$in_{0.52}Al_{0.48}As$ MODFET," *IEEE Electron Devices Letters*, **13** 250 (1992).

3. R. Lai, P. Bhattacharya, D. Yang, T. Brock, S. Alterovitz and A. Downey, "Characteristics of 0.8 mm and 0.2 mm Gate Length $In_xGa_{1-x}As$/ $In_{0.52}Al_{0.48}As$/InP ($0.53 \leq \times \leq 0.70$) Modulation-Doped field Effect Transistors at Cryogenic Temperatures," accepted for publication in *IEEE Transactions on Electron Devices.*

INTERACTIONS WITH ARMY LABORATORIES:

Harry Diamond Laboratories
ETDL, Fort Monmouth

INTERACTIONS WITH OTHER D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

Hughes Research Labatories	IBM Yorktown Heights
Bellcore	TRW

XIII. VERY-HIGH SPEED DETECTORS, MODULATORS AND MONOLITHICALLY INTEGRATED DEVICES

FACULTY SUPERVISOR: P. Bhattacharya
RESEARCH SCIENTIST: W-Q. Li

GRADUATE STUDENT PARTICIPANT:

A. Gutierrez-Aitken

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

To develop new materials, physical understanding and device structures for very high speed detectors, modulators, monolithically integrated photoreceivers and externally modulated quantum well lasers.

WORK PERFORMED:

By analyzing the intrinsic and extrinsic limitations on the bandwidth of p-i-n detectors and modulators, we have grown and characterized high-speed detectors, phase shifters and QCSE modulators. This has included the study of monolithically integrated balanced detectors for low-noise applications. Development of monolithically integrated photoreceivers using PIN diodes, MODFET amplifiers and passive circuit elements has been undertaken in several stages. Very high circuit bandwidths have been realized ($\sim$16 GHz) using 0.25μm gate MODFETs and epitaxial regrowth. Development of a three-stage transimpedance PINFET amplifier is in progress. Superlattice avalanche photodiodes have been studied for low-noise applications. Electro-optic coefficients in InP-based strained quantum wells have been measured for the first time. A large enhancement in the quadratic electro-optic effect has been observed. Electro-optic phase shifters, passive waveguides and QCSE modulators made with these devices have been characterized. Such modulations have been monolithically integrated with quantum well lasers. Oscillator circuits have been made with 0.25μm gate InP-based pseudomorphic MODFETs and their properties under optical excitation have been investigated. The ultimate aim is to use these integrated circuits as elements of phased away radars.

INTERACTIONS WITH ARMY LABORATORIES:

M. Tobin, Harry Diamond Laboratories.
R. Tober, Harry Diamond Laboratories
Huntsville, Alabama
M. Stroscio, Army Research Office

INTERACTIONS WITH OTHER D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

Boeing Electronics
Hewlett-Packard Labatories
Bellcore
University of Florida
University of South Florida

XIV. CHEMICAL BEAM EPITAXY: HETEROSTRUCTURE GROWTH AND CHARACTERIZATION

FACULTY SUPERVISORS: G. I. Haddad
P. K. Bhattacharya
RESEARCH ENGINEER: G. Munns

GRADUATE STUDENT PARTICIPANTS:

D. Nichols
W. L. Chen
G. Munns

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

The objective of this program was to provide a wide variety of epitaxial structures using a variety of material systems for device fabrication and testing. Samples were also to be provided for basic materials research. Because chemical beam epitaxy offers unique capabilities in handling phosphorus containing compounds while potentially offering excellent interface control, structures which exploited these advantages of CBE were to be of primary interest. The following procedure was used to accomplish this goal.

1. Bulk material characteristics were optimized and the growth process was empirically modeled. both phosphorus containing alloys (such as InP, InAlP, InGaAsP, and InGaP) and lattice matched arsenic containing alloys (such as GaAs, InAlAs, and InGaAs) were evaluated for surface morphology, uniformity, Hall mobility and background carrier concentration and species, photoluminescence efficiency and half width, lattice match, and crystallinity. advanced design of experiment techniques and statistical process control modeling were used to minimize the number of experiments necessary while maximizing the amount of empirical growth process information obtained.

2. Optimized bulk material was subsequently doped both n and p type in order to evaluate the suitability of solid sources, determine attainable ranges, and study such effects as diffusion and adatom surface segregation. Secondary ion mass spectroscopy was used to determine diffusion of delta doped Si planes.

3. Heterointerface abruptness, a weakness in growth techniques such as MOCVD, was investigated using a variety of techniques including spectroscopic ellipsometry, photoluminescence spectroscopy, double crystal x-ray diffraction analysis, secondary ion mass spectroscopy, and Hall techniques.

4. Both optical and electrical device results were correlated with the basic material characterization outlined above. such devices as strained InGaAs(P) lasers, InGaAs/InAlAs and InP/InAlAs high electron mobility transistors, InGaAs/InP and InGaAs/InGaAs/InAlAs heterojunction bipolar transistors, and resonant tunneling transistors which critically depend on smooth, abrupt interfaces were studied. Gunn diodes TUNNETT's, and IMPATT's which are very sensitive to low doping levels were also investigated.

WORK PERFORMED:

The work performed during this period is outlined above. For perspective a short chronological description is offered. The system was first brought on line in May of 1989 as a metal organic MBE system (i.e. metalorganic group III sources with solid As). Hydride installation was completed one year later. Since its commission as a true CBE system it has grown approximately 700 layers of which nearly 600 were grown consecutively without vacuum interruption. This is one of the longest continuous vacuum system uptime reports in print. Of the layers grown approximately half of them were used as calibration/parameter characterization samples with the balance being delivered for specific experiments.

While device results and basic material characteristics are outlined above, much of the material was used for wet chemical and dry etching studies, to establish etch rates and determine selectivities. It is/was the primary source of heterostructures for these purposes. In its three years of service it has been the direct source for approximately 20 refereed papers with the bulk of these being published in the last two years. Many other technical presentations and papers also benefited from the foundation provided by the CBE system.

PUBLICATIONS:

1. M. E. Sherwin, D. T. Nichols, G. O. Munns, E. G. Woelk, F. L. Terry, P. .K. Bhattacharya and G. I. Haddad, "The Growth of high Quality InP/InGaAs/InGaAsP Interfaces by CBE for SCH Quantum Well Lasers," accepted for publication in *Journal of Electronic Materials.*

2. D. Nichols, M. Sherwin, G. Munns, J. Pamulpati, J. Loehr, J. Singh and P. Bhattacharya, "Theoretical and Experimental Studies of the Effects of Compressive and Tensile Strain on the Performance of InP/InGaAs Multi Quantum Well Lasers, *IEEE Journal of Quantum Electronics,* **28**, 1239, (1992).

3. M. E. Sherwin and G. O. Munns. "CBE Growth of High Quality InAlAs Using TMMA," *Journal of Vacuum Science Technology, B,* **10**, 943, (1992).

4. M. E. Sherwin, G. O. Munns, D. T. Nichols, P. K. Bhattacharya ad F. L. Terry, Jr., "The Growth of InGaAsP by CBE for SCH Quantum Well Lasers Operating at 1.55 and 1.4 μm," accepted for publication in *Journal of Crystal Growth.*

5. G. O. Munns, M. E. Sherwin, T. Brock, G. I. Haddad, Y. K. Kwon, G. I. Ng and D. Pavlidis, "InAlAs/InGaAs/InP Sub-micron HEMT's Grown by CBE," accepted for publication in *Journal of Crystal Growth.*

6. Y. Kwon, T. Brock, G. I. Ng, D. Pavlidis, G. O. Munns, M. E. Sherwin and G. I. Haddad, "Novel Self-Aligned Offset G-Gate InAlAs/InGaAs HEMT's Grown by Chemical Beam Epitaxy," accepted for presentation at GaAs IC Symposium.

7. C. Raman, J. P. Sun, WI. L. Chen, G. O. Munns, J. East and G. I. Haddad, "Supperlatice Barrier Varactors," Third International Symposium on Space Terahertz Technology, Ann Arbor, MI, March 1992.

8. M. E. Sherwin, F. L. Terry, Jr., G. O. Munns, J. S. Herman, E. G. Woelk, and G. I. Haddad, "Investigation and Optimization of InGaAs/InP Heterointerfaces Grown by Chemical Beam Epitaxy Using Spectroscopic Ellipsometry and Photoluminescence," *Journal of Electrical Materials,* **21**, 269, (1992).

9. G. O. Munns, W. L. Chen, M. E. Sherwin and G. I. Haddad, "The Growth of InAlP Using Trimethl amine alane by Chemical Beam Epitaxy," to be presented at the Seventh International Conference on Molecular Beam Epitaxy, August 1992.

10. .G. O. Munns, M. E. Sherwin, Y. Kwon, T. Brock, W. L. Chen, D. Pavlidis and G. I. Haddad, "Parametric Investigation of InGaAs/InAlAs HEMT's Brown by CBE," accepted for a poster presentation at the Seventh International Conference on Molecular Beam Epitaxy, August 1992.

11. W. L. Chen, G. O. Munns, J. C. Cowles, K. W. Eisenbeiser, J. R. East and G. I. Haddad, "Ohmic Contacts Study for Quantum Effect Transistors and Heterojunction Bipolar Transistors with InGaAs Contact Layers, submitted to 1992 EDMS, Tiawan.

12. Y. Kwon, D. Pavlidis, P. Marsh, G. I. Ng, T. Brock, G. Munns and G. I. Haddad, "A Fully Integrated Monolithic D-band Oscillator-Doubles Chain Using InP-Based HEMT's," submitted to GaAs IC Symposium, October 1992.

13. Y. Kwon, T. Brock, G. I. Ng, D. Pavlidis, G. O. Munns, M. E. Sherwin, and G. I. Haddad, "F_{max}-Enhancement in CBE-Grown InAlAs/InGaAs HEMT's Using Novel Self-Aligned Offset-Gate Technology," presented at the InP and Related Materials Conference, Rhode Island, 1992.

14. M. E. Sherwin, G. O. Munns and F. L. Terry, Jr., "Uniformly Doped and Delta Doped InAlAs/InP HEMT Structures Grown by Chemical Beam Epitaxy," to be submitted to *Applied Physics Letters.*

INTERACTIONS WITH D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

Formal and informal discussion have been held with:

AT&T, Murray Hill	Dr. C. Abernathy
	Dr. R. Fischer
Hewlett-Packard	Dr. D. Hong
Sandia Laboratories	Dr. T. Drummond
	Dr. J. Klem
Varian/Intevac	J. Cerny
	Dr. P. McCleod
Univ. of California (San Diego)	Dr. C. Tu and graduate students
University of Illinois	S. Jackson
McDonnell Douglas	Dr. C. Balestra
	Dr. S. Whiteley
	G. Conger
Ecole Polytechnique, Lausannne Switz.	Dr. A. Rudra
	Dr. R. Houdre
Air Products (metalorganic division)	S. Stork
NTT	Dr. T. Yamada
Texas Instruments	Dr. T. Henderson
Ball Aerospace	Dr. D. Begley

A significant portion of the laser work was also supported by cooperation with Boeing (Dr. Figueroa), Hewlett Packard (Dr. M. Ludowise), and Allied Signal (Dr. Fhattimulla).

XV. DIGITAL ETCHING FOR DEVICE FABRICATION WITH HIGH SELECTIVITY AND LOW DAMAGE

FACULTY SUPERVISOR: S. W. Pang

GRADUATE STUDENT PARTICIPANT:

K. K. Ko

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

The objective of our work is to develop a hgihly controllable layer by layer dry etching technique (digital etching) for the fabrication of high frequency devices with nanometer dimensions. Digital etching is expected to provide atomic controllability, high selectivity, and minimum surface damage, which are important for heterostructure devices. High resolution lithography and dry etching techniques will be applied to the fabrication of semiconductor waveguides with quantum wire and dot structures.

WORK PERFORMED:

The etch characteristics of GaAs, InP, InGaAs, and AlGaAs in a plasma reactor with an electron cyclotron resonance (ECR) source have been studied as a function of microwave power, rf power, gas composition, pressure, temperature, and distance to the ECR source. Using Cl_2/Ar ;mixture with low microwave power, low pressure and low CL_2 concentration, quantum dots and wires that are 0.1 μm wide and 1 μm deep have ben successfully fabricated with vertical profile and smooth morphology. Etch rate is found to increase with microwave power when etching is limited by the reactive radicals concentrations and decreases with microwave power when the ion and surface morphology are improved by the addition of rf power. In contrast to RIE, a slight increase in $|V_{dc}|$ with pressure is observed due to the presence of high densities charged particles. At high temperature, InP can be etched as a comparable rate as GaAs because of the increased volatility of $InCl_3$, although the etch profile and surface morphology tend to deteriorate. Semiconductor waveguides with 30 nm wide quantum dots and wires have also been demonstrated using a combination of electron beam lithography and dry etching with the ECR source.

PUBLICATIONS:

1. S. W. Pang, "Processing of Materials," editor, *J. Electronic Materials*, January (1992).
2. S. W. Pang, K. T. Sung, and K. K. Ko, "Etching of Photoresist Using Oxygen Plasma Generated by a Multipolar Electron Cyclotron Resonance Source," accepted for publication *J. Vac. Sci. Technol. B.*

3. S. W. Pang and K. K. Ko, "Comparison Between Etching in Cl_2 and BCl_3 for Compound Semiconductors Using Multipolar Electron Cyclotron Resonance Source". Presented at the International Symposium on Electron Ion, and Photo Beams, Orlando, FL, May 1992. (submitted for publication to *J. Vac. Sci. and Technol.*).

4. K. T. Sung, W-Q. Li, S. W. Pang and P. K. Bhattacharya, "Application of High Quality SiO_2 Grown by Multipolar ECR source to SI/SiGe Modulation Doped FET," submitted for publication to *IEEE Electron Dev. Lett.*

5. K. K. Ko, L. Davis, W-Q Li, S. W. Pang, J. Singh and P. K. Bhattacharya, "Effects of Processing Induced Fluctuations on the Optical Properties of InGaAs/AlGaAs Quantum Boxes Created by Dry Etching and Epitaxial Regrowth," accepted for presentation at the 19th International Symposium on Gallium Arsenide and Related Compounds, Nagano, Japan, September 1992.

RELATED PUBLICATIONS:

- K. T. Sung and S. W. Pang, "Low Temperature Silicon Oxidation with Electron Cyclotron Resonance Oxygen Plasma," Material Research Society Symposium, Proceedings on "Photon and Low Energy Particles in Surface Processing," Boston, MA, **236**, 319–324, (1991).

- M. L. Passow, J. T. Pender, M. L. Brake, K. T. Sung, Y. Liu, S. W. Pan, and M. E. Elta, "Relative Fluorine Concentration in rf and Electron Cyclotron Resonance Microwave/rf Hybrid Glow Discharges," *Appl. Phys. Lett.*, **60**, 818–820, (1992).

- K. T. Sung and S. W. Pang, "Low Temperature Silicon Oxidation with Oxygen Plasma Generated by an Electron Cyclotron Resonance Source," submitted to *J. Vac. Sci. Technol.*.

- K. T. Sung and S. W. Pang, "Selective Etching of Bilayer Photoresist using Multipolar Electron Cyclotron Resonance Source". Presented at the Electrochemical Society 9th Symposium on Plasma Processing, St. Louis, MO, May 1992. (submitted for publication to *J. Electrochem. Soc.*)

- K. T. Sung, J. P. Fournier and S. W. Pang, "Low Temperature Etching of Si with Cl_2 using an Electron Cyclotron Resonance Source," submitted to 39th National Symposium of the American Vacuum Society, Chicago, IL, November 1992.

- K. T. Sung and S. W. Pang, "High Quality SiO_2 Grown at Room Temperature using Oxygen Plasma Generated by a Multipolar Electron Cyclotron Resonance Source," submitted to the 1992 International Electron Device and Materials Symposium..

INTERACTIONS WITH D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

- Collaborative work with Mark Horn at Lincoln Laboratory, Massachusetts Institute of Technology for high resolution dry etching of resist and semiconductors.

- Visit with Professor Jes Asmussem and seminar presentation at Michigan State University.
- Joint development work with Plasma Therm Inc. on new dry etch system with ECR source.
- Visit Professor Otto Leistiko and seminar presentation at Technical University of Denmark.

XVI. RIE FOR III-V DEVICE STRUCTURES

FACULTY SUPERVISOR: M. Elta
RESEARCH SCIENTISTS: H. S. Folger
J. Fournier

GRADUATE STUDENT PARTICIPANT:

A. Demos

PERIOD: January 1, 1986 –June 30, 1992

TASK OBJECTIVES:

To develop new etch techniques for III-V compounds and gain insight into the etching mechanisms of these compounds.

WORK PERFORMED:

During this period, a kinetic mechanism and model for the RIE of InP in a chlorine plasma was developed. This mechanism contains the formation of indium and phosphorous chlorides with the removal of indium chloride as the rate limiting step. The surface model developed is based on the elementary reaction steps (absorption, surface reaction and thermal and sputter desorption). Both physical and chemical mechanisms were combined in mass balances in the model which predicts chlorine surface coverage, etched film stoichiometry and the fraction of the reaction layer sputtered. A paper of this kinetic mechanism and model is being written.

PUBLICATIONS:

1. A. Demos, H. S. Fogler, and M. Elta, "X-Ray Photoelectron (XPS) Study of InP RIE etched with BCl_3 and Argon," submitted for publication to *Journal of Vacuum Science and Technology B.*

2. A. Demos, H. S. Fogler, J. Fournier and M. Elta, "High Temperature Kinetic Study of InP RIE Etched with BCl_3, Argon and Oxygen," submitted for publication to *Journal of the Electrochemical Society.*

XVII. ELLIPSOMETRY FOR NONDESTRUCTIVE CHARACTERIZATION OF III-V STRUCTURES

FACULTY SUPERVISOR: F. Terry

GRADUATE STUDENT PARTICIPANT:

L. Kamlet

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

The major objectives of this work are: (1) routine characterization of the thicknesses and index of refraction of epitaxial heterojunction layers and related thin films; and (2) research in the use of ellipsometry for characterization of bulk film and interface quality.

WORK PERFORMED:

The major early work under this project was the development of a highly flexible software system for the analysis of spectroscopic ellipsometry data. This program has also been used in modified forms for the analysis of other reflection problems. Use of highly modular programming techniques, linked-list data data structures, and pointer-based data transfers have allowed this code to operate efficiently and has also allowed rapid addition of new models for material dielectric behavior to be added as they are developed with very minimal amounts of reprogramming time. Simplified versions of this software for single wavelength ellipsometry have been incorporated into our laboratory classes and have been supplied to industrial users (Allied Signal).

The most serious problems in the application of spectroscopic ellipsometry to practical measurement problems in the III-V compound semiconductor area (and, in fact, in most applications areas) are: (1) obtaining reference data sets for the materials used in the structures to be analyzed; and (2) accurately interpolating between the dielectric spectra of known compound compositions to estimate the response of intermediate compositions. While the dielectric response of many compounds have been well characterized and published, very many commonly used materials have not been studied adequately. A particular problem in this work has been the lack of accurate dielectric response data for InAlAs lattice matched to InP. This material is problematic due to the difficulties in obtaining a smooth, native oxide free surface. We have obtained a reasonably good data set using variable angle of incidence spectroscopic ellipsometry and are using this data set in the analysis of InP-based SISFET and MODFET structures. However, this data is currently not accurate enough and we are working to improve our measurements using new CBE-grown structures.

Also in the area of reference data problems, we have begun work on the theoretical and experimental characterization of the dielectric response of strained layer materials. Accurate

measurement of the dielectric response of very thin films is fundamentally a serious problem. For strained layer films, this problem is critical since it is impossible to grow thick reference layers with the same band structure as the coherently strained films. Our current approach is to model the dielectric response using lineshape fits to critical points from experimental measurements, and to model the dielectric response by using band structure theory to predict the changes in the critical point behavior with strain/composition changes. This work is currently in its early changes. We are presently concentrating on data analysis techniques for accurately determining the critical point lineshape parameters for very thin films from SE data.

In the related area of interpolation of dielectric response data, we have made considerable progress during the course of this program. Our major contribution has been the development of an empirical technique which we call the Modified Harmonic Oscillator Approximation (MHOA). This method uses a relatively small number of damped harmonic oscillators with phase delays to reconstruct the dielectric response of known materials to $\ll 1\%$ residual error levels. A significant advantage of this method over earlier techniques is that it can be used to obtain accurate fits over the entire near IR to near UV photon energy range, including regions below the fundamental bandgap of the material under study. By interpolating the oscillator coefficients, the dielectric response of unknown intermediate compositions can be accurately estimated. This technique has been quantitatively demonstrated for the AlGaAs/GaAs system, and we are routinely using in other materials systems. This technique is useful for both the SE application for which it was developed, as well as many other reflection and transmission problems using these materials.

We have made the first reported investigations of the interface transition regions of CBE grown InGaAs/InP and InP/InGaAs films using spectroscopic ellipsometry. Our results indicate that the CBE InGaAs/InP is virtually abrupt (within a resolution limit of about 15 Å) and that any nonidealities in the InGaAs are due to very slight lattice mismatch. The InP/InGaAs transition is similar to that observed by others for MOCVD material. The InP contains significant quantities of As at least 75 Åinto the film. Very thick film of InP show no As, but we have not yet been able to conduct experiments to determine the extent of the As contamination. The thin film results have been confirmed by ESCA surface analysis. This transition region of InAsP has been found to cause etching problems in our InP-based HBT work. The SE data has been used to aid in developing a wet etch problem to remove the transition region. Modifications are currently being made to the CBE system in an attempt to reduce this problem and SE analysis will be used as part of the evaluation of this effort.

PUBLICATIONS:

1. M.E. Sherwin, F.L. Terry, Jr., G.O. Munns, J.S. Herman, E.G. Woelk, and G.I. Haddad, "Investigation and Optimization of InGaAs/InP Heterointerfaces Grown by Chemical Beam Epitaxy Using Spectroscopic Ellipsometry and Photoluminescence," *J. Elect. Mat.*, **21**, pp. 269–275, (1992).

2. J. L. Dupuie, E. Gulari, and F.L. Terry, Jr., "The Low Temperature Catalyzed Chemical Vapor Deposition and Characterization of Silicon Nitride Thin Films," *J. Electrochem. Soc.*, **139**, pp. 1151–1159, (1992).

INTERACTIONS WITH D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

A number of computer readable copies of the modified harmonic oscillator coefficients for estimation of the dielectric response of $Al_xGa_{1-x}As$ have been supplied to government, industry, and university research labs including:

- Sandia National Laboratory for use in GaAs/AlGaAs solar cell design
- NIST
- Rudolph Research Corporation, for incorporation in their commercial software system for their spectroscopic ellipsometer system.

XVIII. INSULATED GATE DEVICES

FACULTY SUPERVISOR: F. Terry

GRADUATE STUDENT PARTICIPANTS:

R.-L. Lee
J. Herman

PERIOD: January 1, 1992 – June 30, 1992

TASK OBJECTIVES:

The major objectives of this work are: (1) to develop narrow gap semiconductor gate - wide gap, undoped semiconductor quasi- insulator - narrow gap semiconductor SISFET technology; (2) to develop improved capacitance - voltage analysis methods for studying interface states and other charged defects in these systems; (3) to develop improved wide bandgap deposited insulator technology for true insulated gate devices on III-V compound devices.

WORK PERFORMED:

- We have developed a moderate pressure direct plasma PECVD deposition process for low temperature deposition of SiO_2 which yields results on control Si wafers which are very close to the quality of thermally grown SiO_2 on Si. Interface state densities in the low $10^{10}/eV/cm^2$ range are easily achievable with low levels of slow trapping (hysteresis in CV curves). This process makes use of moderate pressures (~400mT) in a heavily He diluted environment to minimize ion damage to the substrate. Very high N_2O to SiH_4 rations are used to reduce the level of oxygen vacancy defects in the SiO_2.

- We have used this process in conjunction with various plasma surface treatments on GaAs, InP, and InGaAs on InP to develop surface passivation techniques for III-V devices. We have found two successful schemes for GaAs surfaces. The first makes use of a H_2 plasma surface clean to remove native oxides followed by a surface passivation layer formation in an NH_3 plasma. The MOS structure is completed with the SiO_2 deposition. This process results in apparently unpinned GaAs surfaces with interface state densities in the low $10^{11}/eV/cm^4$ range at midgap. However, slow trapping effects (presumably in the interface layer) remain a problem. Also, we have found, using spectroscopic ellipsometry and electrical tests, that the H_2 plasma etch has a critical threshold time for success which is very difficult to control. Short times may be ineffective while over etches by as little as 1 minute can lead to very poor electrical results. Attempts to apply this type of process to the InP system were unsuccessful to the extreme difficulty of H_2 plasma etching of the InP native oxide without significant P removal from the InP surface. These problems, and the reports in the literature of encouraging results on aqueous sulfide treatments of GaAs, led us to investigate H_2S plasma treatments. Initial investigations centered on elevated temperature plasma treatments (100-300°C).

We found that following these treatments, no SiO_2 deposition would occur on the substrates. We attribute this problem to SiH_4 reactions with the sulfur deposited in the reaction chamber. We found, however, that treating the GaAs or InP surfaces at room temperature with a low power H_2S plasma and then heating the substrate in H_2 without plasma excitation and then depositing an SiO_2 film yields very good MOS characteristics. Again, interface state densities in the low $10^{11}/eV/cm^2$ range could be achieved on GaAs and InP. We are still working to achieve similar results on InGaAs. The major disadvantage of this method which we have found is that at high temperatures (>800°C for GaAs) the sulfur diffuses from the surface into the semiconductor, forming a relatively heavily doped n-type surface layer. No n-type doping is observed at low temperatures (<500°C). We are currently working on non- self aligned MOS transistors to further study surface properties, and on the use of this method to reduce surface recombination velocity problems in GaAs/AlGaAs HBTs.

- We have demonstrated operational InGaAs/InAlAs/InGaAs/InP SISFET devices using MBE grown material. We have developed a stress-balanced WSi_x cosputtering process for the gates of these devices. We have also developed a robust, deep submicron etch process capable of producing high aspect ratio gates (<0.2μm wide and 1μm tall). We are currently working to integrate the developed technologies to produce deep submicron self-aligned SISFET and MODFET devices.

- Also, we have used combined high/low frequency capacitance voltage (CV) analysis to examine interface state densities in CBE grown InAlAs/InGaAs structures. This technique was used to identify growth conditions which yield minimum interface state densities.

PUBLICATIONS:

1. J. S. Herman and F.L. Terry, Jr., "Hydrogen Sulfide Plasma Passivation of Gallium Arsenide," *Appl. Phys. Lett.*, **60**, pp. 716- 717, (1992).

2. J.S. Herman and F.L. Terry, Jr., "Hydrogen Sulfide Plasma Passivation of InP," submitted to the 1992 IEEE/TMS Electronic Materials Conference, accepted for presentation as paper C9.

3. J.S. Herman and F.L. Terry, Jr., "Plasma Passivation of Gallium Arsenide," submitted to the American Vacuum Society Conference, Chicago, Ill, under review.

INTERACTIONS WITH D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

Discussions on SiO_2 deposition techniques and MOS capacitor measurement methods have been conducted on several occasions with Paul Young of the NASA Lewis Research Center. We have also provided reference measurements and capacitors for his efforts.

We have also performed SiO_2 depositions for a NASA Lewis- Ohio State Si solar cell program.

XIX. THEORY, DESIGN AND FABRICATION OF LASER DIODE SOURCES

FACULTY SUPERVISOR: P. K. Bhattacharya
RESEARCH SCIENTISTS: G. Munns
W-Q. Li

GRADUATE STUDENT PARTICIPANT:

D. Nichols

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

The overall objective of this project is to grow high quality laser structures by chemical beam epitaxy (CBE). In particular, interest is focussed on the properties of 1.3 and 1.55 μm InP-based lasers with strained pseudomorphic quantum well lasers. Radiative and non-radiative recombination phenomena and temporal behavior of these devices are to be studied in detail.

WORK PERFORMED:

We have studied, both theoretically and experimentally, the effects of biaxial strain upon the performance characteristics of broad area InP/InGaAsP/$In_xGa_{1-x}As$ ($0.33 \leq x \leq 0.73$) separate confinement heterostructure multi-quantum well lasers grown by CBE. The theoretical calculations include the effects of strain on the bandstructure and the Auger recombination rates. We observed a pronounced dependence of the threshold current density J_{th} upon x. The lowest measured J_{th} is 600 A/cm^2 in an 800 μm laser with $x = 0.68$. Also, internal quantum efficiencies as high as unity and loss coefficients as low as 5.6 cm^{-1} have been measured for $x = 0.58$. We have also measured the near- and far-field patterns of these lasers, filamentation, noise intensity spectra, and differential gain characteristics.

We have successfully fabricated ridge waveguide lasers on semi- insulating InP in an effort to measure their small-signal modulation characteristics. These measurements yielded band-widths of 3 GHz for lattice-matched devices and 5 GHz for devices with 10% excess In in the wells. The large-signal modulation characteristics have also been measured and from these data the Auger recombination coefficients as a function of strain (misfit) have been estimated. The experimental results are in good agreement with theoretical predictions.

PUBLICATIONS:

1. M. Sherwin, G. Munns, D. Nichols, P. Bhattacharya and F. Terry, "The Growth of InGaAsP by CBE for SCH Quantum Well Lasers Operating at 1.44 and 1.4 mm," *Journal of Crystal Growth*, (1992).

2. D. Nichols and P. Bhattacharya, "Differential Gain in InP-Based Strained Layer MQW Lasers," submitted to *Applied Physics Letters.*

3. Y. Lam, E. Espinosa, D. Nichols, L. Davis and P. Bhattacharya, "Observation of Multiple Resonance Frequencies in Strip Geometry InGaAsP Quantum Well Lasers," submitted to *IEEE Quantum Electronic Letters.*

4. D. Nichols and P. Bhattacharya, "InP-Based Strained Quantum Well Lasers," Presented at the Workshop on Compound Semiconductor Microwave materials and Devices, San Antonio, TX, February 1992.

5. D. Nichols, L. Davis, Y. Lam, E. Espinosa, J. Singh and P. Bhattacharya, "Modulation Characteristics of InP-Based MQW Lasers; The Impact of Biaxial Compressive and Tensile Strain, presented at the 50th Device Research Conference, Cambridge, MA, June 1992.

6. D. Nichols, L. Davis, Y. Lam, G. Munns, J. Loehr, J. Singh and P. Bhattacharya, "Carrier Dynamics and Modulation Characteristics of InP-Based Strained Quantum Well Lasers," presented at the International Quantum Electronics Conference, Vienna, Austria, June 1992.

7. L. Davis, Y. Lam, D. Nichols, E. Espinosa and P. Bhattacharya, "A Study of Modulation Characteristics, Auger Coefficients and Filamentation Related Noise Spectra in InP-based Strains Layer Quantum Well Lasers," submitted for presentation to the International Laser Conference, Takamatsu, Japan, September 1992.

8. J. Singh and P. Bhattacharya, "Role of Strained Layers in Improving the Structural Reliability of Quantum Well Lasers," submitted for presentation to International Laser Conference, Takamatsu, Japan, September 1992.

9. L. Davis, Y. Chen, D. Nichols, Y. Lam, J. Singh and P., Bhattacharya, "Auger Recombination and Impact Ionization Rates in Pseudomorphic InGaAlAs/GaAs and InGaAs/InP," submitted for presentation to International Laser Conference, Takamatsu, Japan, September 1992.

INTERACTIONS WITH ARMY LABORATORIES:

T. Aucoin, ETDL, Fort Monmouth
M. Tobin, Harry Diamond Laboratories.

INTERACTIONS WITH D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

Boeing Electronics
Hewlett-Packard Labs.

XX. COMPUTER-AIDED DESIGN OF HIGH-FREQUENCY MONOLITHIC MICROELECTRONICS

FACULTY SUPERVISOR: Richard B. Brown

GRADUATE STUDENT PARTICIPANT:

Thomas R. Huff

A number of unsupported students have contributed to this work as part of directed study projects: Ker-Ching Liu, Robert Hou, Shailendra Save, Greg Francisco, Ed Maddox, Lilly Pao, Gladys Lim, Kelwin Ko, and Freddy Sugihwo.

The digital GaAs activity grew into a GaAs computer project funded by DARPA. This leveraged the investment of ARO by adding the efforts of three other faculty members and the following graduate students: Ajay Chandna, Phil Barker, Tom Hoy, Dave Johnson, Ayman Kayssi, Robert McVay, Kunle Olukotun, Dave Nagle, Patrick Sherhart, Tim Stanley, Rich Uhlig, and Mike Upton.

PERIOD: January 1, 1992 –June 30, 1992

TASK OBJECTIVES:

1. To develop a computer-aided design environment for high-speed integrated circuits,
2. To evaluate device and interconnect technologies for use in integrated circuits, and
3. To demonstrate the feasibility of digital VLSI GaAs circuits.

WORK PERFORMED:

In the past six months, we have made significant continuing developments in modeling, in the GaAs circuit compiler, and in the architecture of our system. All of this was focused on the design of the SRAM and new CPU, Aurora II. Compared to the first CPU, this chip includes more functionality. It executes more instructions, and has shifting, exception handling (traps to the operating system on unimplemented instructions), stalls (so the processor can run at full speed in testing, even if the memory cannot keep up), and cache control (tag generation, matching, etc.). In addition to the normal 'cache' mode of operation, this CPU will operate in three other modes that will be useful for testing: 1) on-chip instruction cache mode (only 32 words will be provided on chip); 2) a buffer mode, using the 1K word external instruction and data caches for memory, but ignoring cache tags; and 3) an autonomous mode, where instructions are taken from an MMU bus (similar to the HP PA-RISC MMU bus).

The critical paths in this chip have been optimized for speed — we are confident that it will operate at 250 MHz. We have written a C compiler for this machine using the

GCC compiler from the Free Software Foundation. The ability to trap on unimplemented instructions will allow us to execute programs compiled on other MIPS compilers. Aurora II is being implemented first in HGaAs III, the 0.6-μm process from Vitesse. Though this chip has 110,000 transistors (compared to 60,500 in the previous CPU), it is implemented in the same pad frame, an indication of the improvement in the process and even more importantly, the improvement in the compiler.

PUBLICATIONS:

1. Ayman I. Kayssi and Karem A. Sakallah, "Delay Macromodels for Point-to-Point MCM Interconnections," Proceedings of the 1992 MCM Conference, Santa Cruz, CA, Mar. 18–20,1992, pp. 79-82

2. R. Brown, A. Chandna, T. Hoy, T. Huff, R. Lomax, T. Mudge, D. Nagle, K. Sakallah, R. Uhlig, and M. Upton, "Synthesis and verification of a GaAs microprocessor from a Verilog hardware description," Proc. Open Verilog Int. User Group Meeting, Mar. 1992, pp. 85-92.

3. A. I. Kayssi, K. A. Sakallah, R. B. Brown, R. J. Lomax, T. N. Mudge, and T. R. Huff, "Impact of MCM's on system performance optimization," *Proc. of the 1992 IEEE Int. Symp. on Circuits and Systems*, vol. 2 of 6, San Diego, CA, May 1992, pp. 919-922.

4. O. A. Olukotun, T. N. Mudge, and R. B. Brown,"Performance optimization of pipelined primary caches," *Proc. of the 19th International Symposium on Computer Architecture*, May 19–21, 1992, pp. 181-190.

5. R. Brown, A. Chandna, T. Huff, R. Lomax, T. Mudge, R. Oettel, and M. Upton, "Compound Semiconductor Device Requirements for VLSI," to be presented at the 19th Int. Symposium on Gallium Arsenide and Related Compounds, Karuizawa, Japan, Sep. 28 – Oct. 2, 1992, invited.

6. R. Brown, P. Barker, A. Chandna, T. Huff, R. Lomax, T. Mudge, K. Sakallah, P.J. Sherhart, R. Uhlig, and M. Upton, "GaAs RISC Processors," GaAs IC Symposium, Miami, FL, Oct. 4–7, 1992, invited.

INTERACTIONS WITH ARMY LABORATORIES:

Richard Brown, being on sabbatical during this period, has had less interaction with Army laboratories than normal. Bob Trew from ARO visited the students involved in April.

INTERACTIONS WITH OTHER D.O.D. LABORATORIES, INDUSTRIES AND UNIVERSITIES:

We have had regular interaction with John Toole from DARPA.

Dr. Brown's sabbatical at Cascade Design Automation has both facilitated a closer collaboration with the company whose software is the foundation of our design methodology, and has presented many opportunities to interact with other industrial companies that are interested in our work. These include: Vitesse, Silicon Graphics, DEC, CDC, HP, Cray, Amdahl, Texas Instruments, and Rockwell.

ABSTRACTS

(Included in this report are abstracts from current reporting period. Abstracts of earlier publications were included in prior reports)

A Study of the Valence Bandstructure and Polarization Dependence of Near Bandedge Optical Transitions in Quantum Dots and Quantum Wires

T. Tanaka, M. Willatzen, Y. Arakawa, *P. Bhattacharya and J. Singh

Research Center for Advanced Science and Technology,
The University of Tokyo
4-6-1 Komaba, Meguro-ku
Tokyo 153 Japan

**Solid State Electronics Laboratory,*
Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor MI 48109 USA

Abstract

A general technique is developed to solve a $\vec{k} \cdot \vec{p}$ multiband Schrödinger equation in arbitrarily shaped 3-dimensional structures. The approach is used to study the valence bandstructure, using the Kohn Luttinger formalism for a quantum dot which is allowed to grow in one dimension to become a quantum wire. As the quantum dot tends towards a quantum wire, we study its optical properties focusing on near bandedge polarization dependence of the optical transitions. The effects of the altering symmetry as we go from a symmetric dot to a wire are reflected in this study.

Consequences of Structural Disorder on Laser Properties in Quantum Wire Lasers

Jasprit Singh, Yasuhiko Arakawa, and Pallab Bhattacharya

Abstract—The effect of interface-roughness-related disorder on the electronic and optoelectronic properties of a quantum wire structure are studied. It is seen that the disorder causes strong localization in the quasi-one-dimensional system. While the electronic states are seriously perturbed, the density of states is not affected drastically. Optoelectronic properties as reflected in the interband transitions related phenomenon are not found to suffer significant deterioration by the disorder. However, our results suggest that intraband relaxation processes may be seriously affected because of electron (hole) states being localized in different regions of the wire.

Consequences of Structural Disorder on Optoelectronic Properties of Quantum Wire Structures

J. Singh, T. Takahasi and Y. Arakawa

NO ABSTRACT AVAILABLE

C-V and I-V Characteristics of Quantum Well Varactors †

J.P.Sun, R.K.Mains, W.L.Chen, J.R.East, and G.I.Haddad

Center for High-Frequency Microelectronics

Solid State Electronics Lab

Department of Electrical Engineering and Computer Science

The University of Michigan, Ann Arbor, MI 48109

Abstract

A theoretical model for quantum well varactors is presented. The model is used to calculate the device C-V and I-V characteristics and very good agreement has been found between the calculated and measured results. Based on the model, a Triple Barrier Double Well (TBDW) varactor has been designed and fabricated. Very high capacitance ratio within a very small bias range is achieved, as designed. Details of the design calculations and experimental results are presented.

† A part of the results has been presented at 1991 International Semiconductor Device Research Symposium, Charlottesville, Virginia, December 4-6, 1991. Proceedings 1991 ISDRS, pp. 61-64.

An Accurate Re-Formulation of the Wigner Function Method for Quantum Transport Modeling

R. K. Mains and G. I. Haddad

Department of Electrical Engineering and

Computer Science

The University of Michigan

Ann Arbor, Michigan 48109

Abstract

The Wigner function is a promising method for including such effects as time dependence, self consistency and inelastic scattering in quantum transport calculations. However, issues regarding the accuracy and consistency of the method need to be resolved. This paper presents a numerical method for determining the Wigner function which is derived from an accurate discretization of the Schrödinger equation. Results of self-consistent calculations under low bias conditions are presented. Further work must be done on the proper formulation of scattering rates, and on determining the device dimensions and k-space discretizations required for realistic quantum device calculations.

InGaAs/InP hot electron transistors grown by chemical beam epitaxy

W. L. Chen, J. P. Sun, G. I. Haddad, M. E. Sherwin, G. O. Munns, J. R. East, and R. K. Mains

Center for High Frequency Microelectronics, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109-2122

(Received 3 February 1992; accepted for publication 23 April 1992)

In this letter, we report on the dc performance of chemical beam epitaxy grown InGaAs/InP hot electron transistors (HETs). The highest observed differential β (dI_C/dI_B) is over 100. The HETs have Pd/Ge/Ti/Al shallow ohmic base contacts with diffusion lengths less than 300 Å. Furthermore, we also demonstrated ballistic transport of electrons in an InGaAs/InP HET by obtaining an energy distribution of electrons with ~60 meV full width at half maximum. The measured conduction band discontinuity of InGaAs/InP is 250.3 meV, which is 39.8% of the band gap difference.

Ultra-Fast Pipelined Arithmetic Using Quantum *Electronic Devices*

S. Mohan, P. Mazumder, R. K. Mains, J. P. Sun
and G. I. Haddad

NO ABSTRACT AVAILABLE

LOGIC DESIGN BASED ON NEGATIVE DIFFERENTIAL RESISTANCE CHARACTERISTICS OF QUANTUM ELECTRONIC DEVICES

S. Mohan, P. Mazumder, G. I. Haddad, R. K. Mains and J. P. Sun

Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, MI 48109
Phone: (313) 763 2107
email: mazum@dip.eecs.umich.edu

Abstract

New quantum electronic devices such as resonant tunneling diodes and transistors, have negative differential resistance characteristics that can be exploited to design novel high-speed circuits. The high intrinsic switching speed of these devices, combined with the novel circuit structures used to implement standard logic functions, leads to ultra-fast computing circuits. The new circuit structures presented here provide extremely compact implementations of functions such as carry generation and addition. The most significant impact of these circuits on the field of logic design is the introduction of a totally new set of relative costs of various basic gates; re-evaluation of the logic in the light of these new cost functions leads to ultra-fast and compact designs as illustrated by the example of a 32-bit adder, in the companion paper.

Use of Self Bias to Improve Power Saturation and Intermodulation Distortion in CW Class B HBT Operation

Douglas A. Teeter, Student Member, IEEE, Jack R. East, Member, IEEE,
George I. Haddad, Fellow, IEEE

Department of Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, MI 48109-2122, U.S.A.

Abstract: **In this letter, it is shown that the DC base bias circuit can be used to control the RF performance of an HBT operating under CW conditions near class B mode. By a careful choice of base bias resistance, gain can be linearized, output power at 1 dB gain compression increased, and intermodulation distortion reduced. Measurements on HBT's biased near class B operation showed a 10 dB improvement in 1 dB gain compression point and 10 dB reduction in intermodulation distortion for moderate power levels. Results for various values of DC base resistance for a typical HBT are presented.** [1]

I. Introduction

Over the past ten years, significant progress has been made toward the development of microwave heterojunction bipolar transistors (HBTs). Output powers as high as 5 Watts have been obtained for a 6 cell monolithic HBT amplifier [1] and intermodulation intercept points as high as 35 dBm have been reported [2]. Through the use of self aligned base technology, values of f_{max} exceeding 100 GHz have become possible [3]. These excellent figures of merit have prompted the use of HBT's in a number of power applications.

In situations where efficiency is an issue, it is often desirable to bias the transistor in class B mode. The bias scheme in this case can strongly influence the RF performance. It has been shown that by biasing a common emitter HBT with a constant base voltage, the collector current increases

[1]This work is being supported by the Army Research Office under the URI program, Contract No. DAAL03-87-K-0007.

Analysis of Intermodulation Distortion in GaAs/AlGaAs HBT's [1]

Douglas A. Teeter, Mete Karakucuk, Jack R. East, George I. Haddad

Center for High Frequency Microelectronics
Solid State Electronics Laboratory
The University of Michigan, Ann Arbor, MI 48109-2122
Tel: (313) 763-6132 or (313) 763-0212

Abstract

The purpose of this work is to help explain the third order intermodulation distortion properties of the heterojunction bipolar transistor at millimeter wave frequencies. By using both measured data and an accurate computer model that includes transit time effects, we have investigated the frequency and bias dependence of the IMD3 intercept point from 8 to 35 GHz. A discussion of our measurement techniques along with a comparison between theoretical and experimental results will be made.

[1]This work is being supported by the Army Research Office under the URI program, Contract No. DAAL03-86-K-0007

Optimized 0.1 μm GaAs MESFET's

Karen E. Moore, Jack R. East, George I. Haddad, Tim Brock

Center for High Frequency Microelectronics
Solid State Electronics Laboratory
The University of Michigan, Ann Arbor, MI 48109-2122
Tel: (313) 763-6132 or (313) 747-1781 (FAX)

Abstract

We have optimized the design of conventional GaAs MESFET's for high frequency operation. FET's were fabricated using electron beam lithography to define 0.1 μm "mushroom" gates. The best results obtained include $g_m = 600$mS/mm, $f_t = 93$ GHz, and $f_{max} \geq 150$ GHz.

This work is being supported by the Army Research Office under the URI program, Contract No. DAAL03-86-K-0007

High Breakdown Voltage, Sub-micron, Strained InGaAlAs/GaAs FET's

K.W. Eisenbeiser, J.R. East, G. I. Haddad and T. Brock
Center for High Frequency Microelectronics
The University of Michigan
Ann Arbor, MI 48109-2122

Abstract:

Sub-micron GaAs FET's with a pseudomorphic surface layer of InGaAlAs to increase breakdown voltage have been fabricated. A 0.2 μm gate length device with I_{dss} of 360 mA/mm has a BV_{d-s} of 9.3 v and a BV_{g-d} of 11.5 v. The effect upon device performance of gate length, source-to-drain spacing and Al mole fraction was also investigated.

Breakdown Voltage Improvement in Strained InGaAlAs/GaAs FET's

K. W. Eisenbeiser, J. R. East, J. Singh, W. Li and G. I. Haddad
Center for High Frequency Microelectronics
The University of Michigan
Ann Arbor MI, 48109-2122

Abstract- GaAs MESFET's with a surface layer of pseudomorphic InGaAlAs have been fabricated. The compressive strain and wide bandgap in the InGaAlAs layer reduce the impact ionization rate in this layer and improve the breakdown voltage of the device. A 1 μm x 75 μm gate device with the pseudomorphic surface layer showed an improvement in gate to drain breakdown of over 60% and an improvement in channel breakdown of 50% as compared to a similar device without the pseudomorphic layer. Both devices had a peak transconductance of about 190 mS/mm and a saturation current of about 265 mA/mm.

Low-Frequency Noise Characteristics of Lattice-Matched ($x = 0.53$) and Strained ($x > 0.53$) $In_{0.52}Al_{0.48}As/In_xGa_{1-x}As$ HEMT's

Geok Ing Ng, *Member, IEEE*, Dimitris Pavlidis, *Senior Member, IEEE*, Marcel Tutt, Rainer Matthias Weiss, and Phil Marsh

Abstract—**Extensive bias-dependent and temperature-dependent low-frequency (LF) noise measurements were performed on lattice-matched and strained $In_{0.52}Al_{0.48}As/In_xGa_{1-x}As$ ($0.53 < x < 0.70$) HEMT's. The input-noise voltage spectral density is insensitive to V_{DS} bias and shows a minimum at V_{GS} corresponding to the peak g_m condition. The corresponding output-noise voltage spectral density, which depends strongly on the gain of the devices, increases with V_{DS}. The input noise was found to be rather insensitive to indium (In) content. Temperature-dependent low-frequency noise measurements on these devices reveal shallow traps with energies of 0.11, 0.15, and 0.18 eV for the 60%, 65%, and 70% In HEMT's. Noise transition frequencies for these devices were found to be in the order of 200–300 MHz and remain almost the same for different channel In content and V_{DS} bias.**

Single and Dual P-Doped Channel $In_{0.52}Al_{0.48}As/In_xGa_{1-x}As$ (x=0.53, 0.65) FET's and the Role of Doping

Yi-Jen Chan and Dimitris Pavlidis

Center for High Frequency Microelectronics

Solid State Electronics Laboratory

Department of Electrical Engineering and Computer Science

University of Michigan, Ann Arbor, MI 48109-2122

ABSTRACT

The properties of lattice matched(x=0.53) and strained(x=0.65) $In_{0.52}Al_{0.48}As/In_xGa_{1-x}As$ p-doped channel FET's are reported. The role of doping density is studied with the help of two designs (dual-channel with low doping and single-channel with high doping). The strained dual-channel devices demonstrate an improvement of mobility from 108 cm^2/V-sec(53% In) to 265 cm^2/V-sec(65% In) at 300K. The corresponding intrinsic transconductance enhancement is from 23mS/mm(53% In) to 46.5mS/mm(65% In) using 1.0μm long gates. The cut-off frequency(f_T) also improves from 1.0GHz to 1.4GHz. The impact of strain in the highly doped single-channel device is small. The bandstructure under lattice matched and strained conditions and the position of Fermi-level according to doping seem to be the main factors determining the reported features.

High Performance E/D-Mode InAlAs/InGaAs HIGFET Technology and Integrated Logic Functions

Yi-Jen Chan and Dimitris Pavlidis
Center for High Frequency Microelectronics
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, MI 48109-2122

Introduction

InAlAs/InGaAs Heterostructure Insulated-Gate FET's (HIGFET's) have demonstrated excellent potential for use in high speed and high frequency integrated circuits[1]-[7]. Compared to AlGaAs/GaAs, this material system provides higher two-dimensional electron gas mobility, carrier drift velocity, and a larger conduction band discontinuity. This results in good carrier confinement and transport properties in N-channel FET's. Lattice-matched (x= 0.53) and strained (x> 0.53) InAlAs/$In_xGa_{1-x}As$ HIGFET's have been reported by the authors, to show enhancement of electrical performance up to x= 0.65[1]. Submicron HIGFET's made with these heterostructures have also shown an f_T value of 63 GHz for 0.3 μm long gates[2]. Moreover, Enhancement/ Resistor (E/R)[4], Enhancement/ Depletion (E/D)[5], and complementary (P/N)[6] logic functions with this heterostructure have also shown very promising features as required for high-speed, low-power digital circuits; small propagation delay of 26 ps/gate has for example been achieved using E/R-mode logic[4].

In this study, we integrated both E- and D-HIGFET's on the same wafer by using a selective ion implantation approach. The details of the fabrication steps together with the characteristics of the devices and the DCFL logic gates built with them are presented and discussed below.

0.1μm MOVPE Grown InAlAs/InGaAs HEMT's with Above 150GHz Operation Capability

G. I. Ng, D. Pavlidis, Y. Kwon, T. Brock

Solid-State Electronics Laboratory
Department of EECS
The University of Michigan
Ann Arbor, MI 48109-2122, U.S.A

J. I. Davies, G. Clarke, P. K. Rees

Epitaxial Products International Ltd
Cypress Drive, St. Mellons
Cardif, CF3 OEG, United Kingdom

INTRODUCTION

InAlAs/InGaAs HEMT's have primarily used MBE grown heterostructures. MOVPE offers, however, an attractive alternative due to its better compatibility with optoelectonic requirements. Phosphorus containing compounds can for example be grown by MOVPE, high growth rates can be achieved and the technique lends itself better for production. This paper reports for the first time on the above 150GHz operation capability of MOVPE grown InAlAs/InGaAs HEMT's using 0.1μm T-gate technology.

F_{max}-Enhancement in CBE-Grown InAlAs/InGaAs HEMT's Using Novel Self-Aligned Offset-Gate Technology *

Y. Kwon, T. Brock, G. I. Ng, D. Pavlidis
and
G. O. Munns, M. E. Sherwin, G. I. Haddad

Solid-State Electronics Laboratory, Department of EECS,
The University of Michigan, Ann Arbor, MI 48109-2122, U.S.A

INTRODUCTION

High f_{max} values are an essential requirement for microwave applications. f_{max} enhancement to 350 GHz [1] has been reported in AlGaAs/InGaAs HEMT's by offsetting the gate to source. High f_{max} values of 455 GHz [2] have also been obtained from MBE grown InAlAs/InGaAs HEMT's. Ultimate f_{max} performance is, however, expected by combining the offset-gate advantages with small gate-source spacing. The latter is possible by a self-aligned gate technology and is the subject of this work, which presents a novel approach with offset self-aligned gates. Furthermore, we applied this technique to InAlAs/InGaAs HEMT's grown by Chemical Beam Epitaxy (CBE) rather than MBE. A first demonstration of the feasibility of CBE growth for HEMT's has recently been reported by the authors [3].

Material Related Issues and Their Characterization With a View to III-V Heterojunction Device Optimization

Dimitris Pavlidis
Solid State Electronics Laboratory
Department of Electrical Engineering
and Computer Science
The University of Michigan
Ann Arbor
Michigan 48109-2122, U.S.A.

Abstract

The impact of various material choices, i.e. InAlAs/InGaAs, AlGaAs/GaAs, GaInP/GaAs on device characteristics is analyzed. Traps located at various regions of the device impact its performance and can be identified by device characterization such as g_m,R_{ds} dispersion and low-frequency noise. Reliability characteristics can be related to material modifications under stress, i.e. traps and dopant diffusion and degradation can be minimized by growth optimization. Process induced damage by dry-etching can be minimized by proper selection of etching conditions. A strong interaction between material and device research is necessary for best results in optimizing III-V technology.

Work supported in part by NASA (Contr. No. NAGW-1334), URI-ARO (Contr. No. DAAL 03-87-K-0007) and Texas Instruments (Contr. No. 109106476).

Parametric Investigation of InGaAs/InAlAs HEMT's Grown by CBE

G. O. Munns, M. E. Sherwin, Y. Kwon, T. Brock, W. L. Chen, D. Pavlidis, and G. I. Haddad
Center for High Frequency Microelectronics
The University of Michigan
1135 EECS Building
Ann Arbor, MI 48109-2122

The InAlAs/InGaAs high electron mobility transistor offers excellent high frequency, low noise operation for ~~MMIC's and low noise~~ amplifiers. While this material system has been grown primarily by conventional MBE other growth techniques have been examined for improved throughput. Chemical beam epitaxy offers semi-infinite souces, good source stability, the flexibility to utilize phosphorus, and extended uptime (up to 560 growth runs over 1.5 years). However, CBE has only been recently been shown to produce excellent quality InAlAs suitable for the growth of InAlAs/InGaAs HEMT's.[1]

This is the first parametric investigation of the properties of InAlAs/InGaAs HEMT's grown by CBE. A series of lattice matched, pulse doped HEMT's have been grown in which the dopant dose, spacer layer, and channel thickness were systematically varied. Low field 300K Hall mobilities as high as 8,700 cm2/Vs for a sheet carrier concentration of $3x10^{12}$ cm^{-2} have been measured. This mobility is somewhat lower than uniformly doped HEMT's which have shown mobilities over 10,000 cm2/Vs at room temperature. A figure of merit (the product of the measured Hall mobility and carrier concentration) has been correlated among the device structure, gateless saturation currents, and DC and microwave device performance. Its applicability as a rough predictor of device performance will be discussed.

Contrary to other reports of MBE grown material the low field Hall mobility does not increase as the dopant pulse is increased, and in fact the dopant pulse to InAlAs/InGaAs interface distance has been increased to improve Hall results and device performance. Secondary ion mass spectroscopy has shown no increase in carbon or oxygen levels at the dopant pulse. This has led to speculation that interface scattering at the top InAlAs/InGaAs interface may be important. Initial SIMS results do not conclusively show intermixing of the Group III elements at this interface however. It is possible that a reduction in the substrate temperature during growth may improve the electrical properties which depend on the interface. Results of this modification in growth conditions shall be reported.

Self aligned 0.1 micron HEMT's fabricated from these layers have shown external DC transconductances over 1,000 mS/mm, (unity current gain cutoff frequencies as high as 190 GHz and unity power gain frequencies up to 300 GHz. These results and those of more conventional 0.1 micron gate length HEMT's demonstrate the potential of InAlAs/InGaAs HEMT's grown by CBE.

[1] G. O. Munns, M. E. Sherwin, T. Brock, G. I. Haddad, Y. Kwon, G. I. Ng, D. Pavlidis, presented at ICCBE-3, September 1991.

Trap Studies in GaInP/GaAs and AlGaAs/GaAs HEMT's by Means of Low-Frequency Noise and Transconductance Dispersion Characterizations

Yi-Jen Chan and Dimitris Pavlidis

Center for High Frequency Microelectronics

Department of Electrical Engineering and Computer Science

The University of Michigan, Ann Arbor, MI 48109-2122

Abstract: The presence of traps in GaInP/GaAs and AlGaAs/GaAs HEMT's was investigated by means of low frequency noise and frequency dispersion measurements. Low frequency noise measurements showed two deep traps (E_{a1}= 0.58 eV, E_{a2}= 0.27 eV) in AlGaAs/GaAs HEMT's. One of them (E_{a2}) is responsible for the channel current collapse at low temperature and is associated with the DX-center. A deep trap (E'_{a1}= 0.52 eV) was observed in GaInP/GaAs HEMT's only at a much higher temperature (~ 350K). These devices showed a transconductance dispersion of ~ 16% at 300K which reduced to only ~ 2% at 200K. The dispersion characteristics of AlGaAs/GaAs HEMT's were very similar at 300K (~ 12%) but degraded at 200K (~ 20%). The low frequency noise and the transconductance dispersion are enhanced at certain temperatures corresponding to trap level crossing by the Fermi-level. The transition frequency of 1/f noise is estimated at ~ 180 MHz for GaInP/GaAs HEMT's and resembles that of AlGaAs/GaAs devices.

This work is supported by U.S. Army Research Office (Contract no. DAAL-03-87-K-0007).

Orientation Effects in $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ Heterostructure Insulated-Gate FET's

Yi-Jen Chan and Dimitris Pavlidis

Center for High Frequency Microelectronics

Department of Electrical Engineering and Computer Science

The University of Michigan, Ann Arbor, MI 48109-2122

Abstract

Orientation effect studies in $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HIGFET's are reported. Piezoelectric charges induced by tensile stress at the interface of the WSi_x gate and the semiconductor were found to be responsible for these effects. Positive and negative V_{th} shifts are observed in [011] (+94 mV) and [01$\bar{1}$] (-121 mV) direction respectively for 5500Å thick WSi_x gates. The shifts become smaller when the WSi_x thickness is reduced down to 2500Å (+28 mV for [011], -27 mV for [01$\bar{1}$]). The V_{th} characteristics in [001] direction are not influenced by the stress and are primarily determined by short-channel effects. Studies as a function of the WSi_x film thickness confirm that the stress originates from the WSi_x/semiconductor interface.

This work is supported by the U.S. Army Office under Contract DAAL-03-87-K-0007

Novel High-Impedance Photoconductive Sampling Probe for Ultra-High Speed Circuit Characterization

Jounghio Kim, Yi-Jen Chan*, Steven Williamson, John Nees,
Shin-ichi Wakana, John Whitaker, Dimitris Pavlidis*

Center for Ultrafast Optical Science, *Center for High Frequency Microelectronics
The University of Michigan, EECS
2200 Bonisteel, 1006 IST
Ann Arbor, MI48109-2099

Abstract

We report on a novel probe technology applied to the measurement of high-speed guided electrical signals. The probe, based on the optoelectronic technique of photoconductive sampling, consists of a high-impedance gate fabricated using an interdigitated electrode structure on semi-insulating low-temperature-MBE-grown GaAs or on Silicon-on-Sapphire. Its resistance is 100 MΩ and its capacitance is less than 0.1 fF, making this probe very attractive for the non-invasive, external circuit testing of ultrahigh-speed devices and circuits with a 120-GHz measurement bandwidth. A 30 ps switching time was measured for an E/D-Mode InAlAs/InGaAs HIGFET inverter using the probe.

1/f Noise Characteristics of InP/InGaAs Heterojunction Bipolar Transistor's

Marcel N. Tutt, Dimitris Pavlidis, and Hin-Fai Chau

Solid-State Electronics Laboratory, Department of EECS,
The University of Michigan, Ann Arbor, MI 48109-2122, U.S.A

INTRODUCTION

InP/InGaAs HBT's have demonstrated very good high-frequency/speed performance [1] and have received a great deal of study for optical front-ends and both analog as well as digital applications. The sensitivity of optical receivers, the noise content of amplifying modules and the noise of signal sources can be severely limited by low frequency noise including 1/f, and trap related noise. Minimization of such noise can only be accomplished by understanding the noise mechanisms present in the device. Numerous studies have been done on AlGaAs/GaAs HBT's [2], [3], however little work has been done on InGaAs/InP HBT's. This paper addresses the low frequency noise characteristics of InGaAs/InP HBT's. To this end, results of systematic frequency, bias, and geometry studies of the base and collector noise spectra are presented.

FOURTH INTERNATIONAL CONFERENCE ON INDIUM
PHOSPHIDE AND RELATED MATERIALS
April 20-24, 1992
Newport, Rhode Island, USA

Analysis of InP/InGaAs Single and Double Heterostructure Bipolar Transistors for Simultaneous High Speed and High Breakdown Operation

Hin-Fai Chau, Dimitris Pavlidis, Juntao Hu * and Kazutaka Tomizawa †

Solid-State Electronics Laboratory, Department of EECS,
The University of Michigan, Ann Arbor, MI 48109-2122, U.S.A

† Department of Computer Science, Meiji Univerisity, Kawasaki 214, Japan

INTRODUCTION

InP/InGaAs Heterostructure Bipolar Transistors (HBT's) have demonstrated excellent microwave characteristics [1] and enhanced performance using a p^- [2] and an i-δp^+ collector [3]. In contrast to AlGaAs/GaAs HBT's, however, InP/InGaAs devices show in general low breakdown voltages due to the small bandgap energy of the InGaAs collector. This paper presents InP/InGaAs HBT characteristics with different collector materials and doping profiles in view of high breakdown operation and possibly high speed characteristics.

Evaluation of Speed-Breakdown Trade-offs in InP/InGaAs Heterojunction Bipolar Transistors

Dimitris Pavlidis, Hin-Fai Chau, Juntao Hu[1] and Kazutaka Tomizawa[2]
Solid-State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, Michigan 48109-2122, USA

Abstract

InP/InGaAs Heterojunction Bipolar Transistors (HBT's) offer a promising alternative to the more traditional AlGaAs/GaAs designs. Their injection efficiency can be higher due to their larger ΔE_V and overshoot can be better sustained even without special collector structures due to their larger Γ-L valley separation. The small bandgap energy of the InGaAs is, however, believed to be responsible for their generally low-breakdown characteristics compared to GaAs-based devices. Thus, although very promising for very high frequency operation, InP/InGaAs HBT's do not appear to be suitable for power applications unless special designs are sought. This paper addresses the speed-breakdown trade-offs in various designs of InP-based HBT's.

An experimental study was performed first on single InP/InGaAs HBT's grown by MOCVD. A self-aligned process involving RIE of the emitter in $CH_4/H_2/Ar$ plasma was used for the fabrication. WSi_x air-bridges connected the emitter pads to the emitter fingers. They were fabricated by a trench technology involving selective etching of the semiconductor under part of the fingers (Fig. 1). Devices with a single 3×11 μm^2 finger showed a dc gain β of 44 and a cutoff frequency f_T of 20.4 GHz. Two terminal characterization of the devices between the base (B) and collector (C) revealed a positive temperature coefficient of the breakdown voltage, indicating that avalanche impact ionization in the B-C junction is responsible for the breakdown. Three terminal measurements supported this finding.

A 1-D drift-diffusion model was developed evaluating the breakdown characteristics. It accounted for breakdown by carrier generation due to impact ionization; this was solved self-consistently in the model. Monte Carlo simulations were also performed to evaluate the speed characteristidcs. Base current reversal was used for identifying the breakdown and was confirmed experimentally and theoretically.

The results show that among single HBT's, the highest breakdown voltage can be achieved by i-collector designs (Fig. 2), but in terms of speed-breakdown tradeoff p^--n^- collectors show the best compromise. Double HBT's outperform all other designs in speed-power trade-off (Fig. 3) provided that the B-C junction is graded.

---

[1] Presently with Bell Northern Research, Ottawa K1Y 4H7, Canada

[2] University of Meiji, Tama-Ku Kawasaki 214, Japan

Work supported by ARO (Contract No. DAAL03-87-K-0007) and Bell Northern Research.

Monte Carlo Studies of the Effect of Emitter Junction Grading on the Electron Transport in InAlAs/InGaAs Heterojunction Bipolar Transistors

Juntao Hu, *Member, IEEE*, Dimitris Pavlidis, *Senior Member, IEEE*, and Kazutaka Tomizawa, *Member, IEEE*

***Abstract*—InAlAs/InGaAs HBT's with various emitter junction gradings are simulated using a self-consistent Monte Carlo simulator. The effects of the emitter junction grading and the shift of the emitter–base p-n junction into the emitter depletion region due to diffusion of the base dopant are investigated. A minimum transit time (τ_{ec}) of 1.18 ps is predicted for an $In(Ga_{1-x}Al_x)As$ grading with $x = 0.6$ at the E-B interface and $J_C = 0.7 \times 10^5$ A/cm^2. Graded-base designs do not offer any transit time performance improvement compared with the graded E-B approach. For transient performance, the device switching time is found to remain constant at about 2.2 ps up to $x_0 \sim 0.7$ but increases for larger values. A cutoff frequency (f_T) of as high as 270 GHz was observed for $x_0 = 0.7$, indicating that best transport can be achieved from intermediately graded rather than abrupt E-B junction designs.**

A Physics-Based Fitting and Extrapolation Method for Measured Impact Ionization Coefficients in III-V Semiconductors

Hin-Fai Chau and Dimitris Pavlidis

Center for High-Frequency Microelectronics

Solid-State Electronics Laboratory

Department of Electrical Engineering and Computer Science

The University of Michigan

Ann Arbor, MI 48104-2122

ABSTRACT

This paper describes a general approach based on a physical model of impact ionization to fit and extrapolate measured ionization coefficients of electrons (α) and holes (β) in III-V semiconductors. Materials being considered include GaAs, $Al_xGa_{1-x}As$ ($x = 0.1$ to 0.4), InP, $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$. Expressions giving the correct dependencies are obtained at very large or small electric fields outside the range of most measurements while at the same time a reasonable fit is achieved for experimental data. The results of the proposed approach yielded a set of physical parameters, which can be coupled with the temperature dependence relationships in the model to predict impact ionization coefficients over a wide range of electric fields at different temperatures, and can be useful in calculations of temperature dependent avalanche breakdown voltages of electronic and optical devices.

Breakdown-Speed Considerations in InP/InGaAs Single and Double Heterostructure Bipolar Transistors

Hin-Fai Chau, Dimitris Pavlidis, Juntao Hu[†],
Solid-State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, Michigan 48109-2122, USA

and Kazutaka Tomizawa
Department of Computer Science
Meiji University
1-1-1 Higashimita
Tama-Ku Kawasaki 214, Japan.

Abstract

The breakdown and speed characteristics of InP/InGaAs single and double HBT's are presented. Temperature-dependent two-terminal and three-terminal measurements suggest that avalanche impact ionization is the dominant breakdown mechanism in InGaAs collector HBT's. Monte Carlo techniques and 1-D drift-diffusion modeling are used for speed and breakdown simulation respectively. Special doping profiles are evaluated for improving the breakdown-speed characteristics of single HBT's (SHBT's) with conventional uniformly doped InGaAs collectors. Double HBT's (DHBT's) outperform all SHBT's in terms of speed-breakdown tradeoffs as long as they use graded base-collector junctions or they operate under sufficiently high collector-emitter voltage conditions. A cutoff frequency of 200 GHz was found to be feasible with graded DHBT's and breakdown voltages up to 4.6 V were evaluated with 3000 Å thick collector. Non-graded DHBT's can be optimized to perform better in terms of speed-breakdown tradeoffs provided that a high collector doping is used.

[†] J. Hu was with the Solid-State Electronics Lab., Dept. of Elect. Eng. & Comp. Sci., Univ. of Michigan, Ann Arbor, MI-48109-2122, USA. He is now with Bell Northern Research, Ottawa, Canada K1Y 4H7.

This work was supported by the U.S. Army Research Office under Contract DAAL03-87-K-0007 and Bell Northern Research.

An Analysis of the Large-Signal Characteristics of AlGaAs/GaAs Heterojunction Bipolar Transistors

Michael Y. Frankel, *Student Member, IEEE*, and Dimitris Pavlidis, *Senior Member, IEEE*

***Abstract*—The large-signal characteristics of AlGaAs/GaAs heterojunction bipolar transistors are reported. A harmonic balance analysis technique is used for their analysis. This is based on equivalent circuit extractions using approximate physical equations for constraining the fitted solutions and for describing certain circuit element value bias trends. Class A and Class AB large signal behavior was measured and modeled satisfactorily. Power saturation is shown to occur due to the input signal entering the cutoff or the saturation region of the HBT operation. This is illustrated by time-dependent current/voltage waveforms and the power dependence of large-signal equivalent circuit elements. Depending on device bias and matching conditions the main sources of nonlinearities in device output may be caused by the nonlinearities in transconductance, input conductance, and base-collector capacitance.**

Investigation of HBT Oscillator Noise Through 1/f Noise and Noise Upconversion Studies†

Marcel N. Tutt, Dimitris Pavlidis, Ali Khatibzadeh[1], and Burhan Bayraktaroglu[1]

Solid-State Electronics Laboratory
Department of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, MI 48109-2122

Central Research Laboratories[1]
Texas Instruments
13588 North Central Expressway
Dallas, TX

ABSTRACT

It is shown that the $\mathcal{L}$(f) characteristics of a HBT DRO can be approximated using the HBT's low frequency noise spectra and the oscillator's upconversion factor, K'_{FM}. Experimental studies have been used for this purpose and the measured $\mathcal{L}$(f) ranged -89dBc/Hz to -101dBc/Hz at a 10kHz offset frequency (-124dBc/Hz best performance at 100kHz). It was shown that the upconversion of the low frequency noise is the primary cause of $\mathcal{L}$(f) in the oscillator and its frequency dependence is directly impacted by the low frequency noise spectrum rather than K'_{FM} itself. $d\mathcal{L}$(f)/df deviates from the -30dB/decade rate, expected for upconversion of ideal 1/f noise, due to traps in the device.

Direct Calculation of the HBT Equivalent Circuit From Measured S-Parameters

David R. Pehlke and Dimitris Pavlidis

Center for High Frequency Microelectronics
Solid State Electronics Laboratory
The University of Michigan, Ann Arbor, MI 48109-2122

Abstract

A new approach for directly calculating the HBT equivalent circuit from measured S-parameters is presented. Analytically derived rather then fitted solutions are obtained in this way. Extrinsic as well as intrinsic element values are computed without the use of special test structures or additional measurement steps. Bias dependent results for base resistance, collector resistance, base-collector capacitance, base transport factor, and base and collector transit times are discussed in detail.

Analysis and Optimization of Third Order Intermodulation Distortion Mechanisms in AlGaAs/GaAs Heterojunction Bipolar Transistors [1]

Apostolos Samelis and Dimitris Pavlidis

Solid State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, MI 48109-2122

Abstract: In this paper the third order intermodulation distortion (IMD3) mechanisms of HBT's are analyzed using Volterra Series theory. The third order nonlinear currents generated by the device nonlinearities are evaluated for this purpose. Second harmonic loading is addressed in view of IMD3 optimization while, at the same time, maintaining high gain through conjugate matching at the fundamental frequency. It is shown that IMD3 depends on a complex process involving interactions between various nonlinear elements and is highly sensitive to C_{bc} generated nonlinear current. The interaction of the latter with the other HBT elements significantly impacts the IMD3. Optimum IMD3 occurs at high second harmonic reflection coefficients corresponding to open load conditions. Up to $27\,dBm$ IMD3 improvement can be obtained by proper loading.

A Study and Optoelectronic Verification of AlGaAs/GaAs Heterojunction Bipolar Transistor Large-signal Characteristics

Michael Y. Frankel, *member IEEE*, Dimitris Pavlidis, *senior member, IEEE*, and Gerard A. Mourou, *member IEEE*

Solid State Electronics Laboratory and Ultrafast Science Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, MI 48109-2099

Abstract

A hybrid optoelectronic measurement system is constructed and used to obtain the large-signal characteristics of AlGaAs/GaAs heterojunction bipolar transistors. The measurement system utilizes a terahertz bandwidth electro-optic transducer gated by 100 fs laser pulses to interrogate the time-domain waveforms at the device input and output nodes. A microwave signal phase-locked to the laser pulse-train is used to synchronously excite the device in both small-signal and large-signal regimes. The measurement system is capable of 50 GHz bandwidth and provides time-domain voltage waveforms that can be used directly to verify the time-domain results of the large-signal analysis.

Michael Y. Frankel is now with the Naval Research Laboratory, CODE 6570, Washington, DC 20375-5000

This work was supported by Air Force Office of Scientific Research, University Research Initiative (Contr. No. F49620-87-C-0016), Alcatel-Espace (Contr. No. 393 500 143), and Army Research Office (Contr. No. DAAL-03-87-K-0007).

Investigation of HBT Oscillator Noise Through 1/f Noise and Noise Upconversion Studies [1]

Marcel N. Tutt, Dimitris Pavlidis, Ali Khatibzadeh†, and Burhan Bayraktaroglu††

Solid-State Electronics Laboratory
Department of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, MI 48109-2122

†Central Research Laboratories
Texas Instruments
13588 North Central Expressway
Dallas, TX 75265

†† North Carolina State University
Department of Electrical and Computer Engineering
Raleigh, NC 27695

ABSTRACT

The $\mathcal{L}$(f) of an HBT DRO has been investigated in terms of the HBT's low frequency noise and the oscillator's upconversion coefficient. Experimental studies have been used for this purpose and the measured $\mathcal{L}$(f) ranged -89dBc/Hz to -101dBc/Hz at a 10kHz offset frequency (-124dBc/Hz best performance at 100kHz). It was shown that, in most test cases, the upconversion of the low frequency noise is the primary cause of $\mathcal{L}$(f) in the oscillator. The frequency dependence, of $\mathcal{L}$(f), is directly impacted by the low frequency noise spectrum rather than K'_{FM} itself. $d\mathcal{L}(f)/df$ deviates from about -30dB/decade rate, expected for upconversion of ideal 1/f noise, due to traps in the device. Reduced oscillator phase noise at high collector current is attributed to improved linearity of the HBT and weaker noise upconversion.

[1]This work is supported by: Contract MDA904-90-C-4096, ARO (Contract No. DAAL03-87-U-0007), and NASA (Contract No. NAGW-1334).

Evaluation of the Factors Determining HBT High-Frequency Performance by Direct Analysis of S-Parameter Data

David R. Pehlke and Dimitris Pavlidis
Solid-State Electronics Laboratory
Department of Electrical Engineering and Computer Science
University of Michigan
1301 Beal Avenue
Ann Arbor, Michigan 48109-2122

ABSTRACT

A novel parameter extraction formalism for the evaluation of Heterojunction Bipolar Transistor (HBT) device physics is presented. The technique employs analytically derived expressions for direct calculation of the HBT T-Model equivalent circuit element values in terms of the measured S-parameters. All elements are directly calculated with the exception of the emitter leg of the T-model. This approach avoids errors due to uncertainty in fitting to large, overdetermined equivalent circuits and does not require the use of test structures and extra measurement steps to evaluate parasitics. Detailed bias dependent results for the directly calculated circuit elements are presented. An analysis is also reported of the short circuit current gain that separates the transit times and RC products and allows evaluation of their individual contribution to the measured f_T and significance in limiting the HBTs high frequency performance.

Mechanisms Determining Third Order Intermodulation Distortion in AlGaAs/GaAs Heterojunction Bipolar Transistors [1]

Apostolos Samelis and Dimitris Pavlidis

Center for High Frequency Microelectronics

Solid State Electronics Laboratory

Department of Electrical Engineering and Computer Science

The University of Michigan

Ann Arbor, MI 48109-2122

Abstract: **The third order intermodulation distortion (IMD3) mechanisms of HBT's are analyzed using Volterra Series theory. A T-equivalent circuit is used for the large-signal model of the HBT. The third order nonlinear currents generated by the device nonlinearities are evaluated for this purpose and current cancellation is discussed. It is found that, even though the C_{je} and g_{je} related currents do not show pronounced cancellation, the total base-emitter current and the total base-collector current cancel partially. Second harmonic loading is addressed in view of IMD3 optimization while, at the same time, maintaining high gain through conjugate matching at the fundamental frequency. IMD3 is very sensitive to the nonlinear currents generated by g_{je} and α. Optimum IMD3 occurs at high second harmonic reflection coefficients corresponding to open load conditions. Finally, minimum and maximum IMD3 occurs for second harmonic load reflection coefficient phases close to analogous extremes of the dominant nonlinear current of the device.**

[1]This work has been supported by Alcatel-Espace (Contract No. 393/550.760), Bell Northern Research and ARO (Contract No. DAAL 03-87-K-0007)

W-Band Monolithic Balanced Mixer using InP-Based Heterostructure Diodes*

Y. Kwon, D. Pavlidis, P. Marsh, G.I. Ng and T. Brock
Center for Space Terahertz Technology &
Center for High Frequency Microelectronics
Solid State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, MI 48109-2122, USA

Abstract

A monolithic InP-based balanced mixer has been realized using InAlAs/InGaAs heterostructure diodes. A minimum conversion loss of 12.8 dB with a 91 GHz LO drive of 11 dBm has been measured with an IF of 2 GHz. This first InP-based monolithic diode mixer opens new ways for fully monolithic integration with HEMT functions at W-band.

Experimental Characteristics and Performance Analysis of Monolithic InP-Based HEMT Mixers at W-Band*

Youngwoo Kwon, Dimitris Pavlidis, Phil Marsh,
Geok-Ing Ng and Tim Brock

Center for Space Terahertz Technology
Solid State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, MI 48109-2122, USA

Abstract

Experimental characteristics of monolithic InAlAs/InGaAs HEMT mixers are presented together with a theoretical analysis. Experiments at W-band show a maximum conversion gain of 0.9 dB with 2 dBm of LO power level. This is the first demonstration of a monolithic HEMT mixer with conversion gain at W-band. The conversion gain dependence on LO power, RF frequency and gate bias is measured and compared with the theoretical predictions. Good agreement between the theory and experiment could be found.

A Fully Integrated Monolithic D-band Oscillator-Doubler Chain Using InP-Based HEMT's

Y. Kwon, D. Pavlidis, P. Marsh, G.I. Ng, T. Brock, G. Munns and G. I. Haddad
Center for Space Terahertz Technology
Solid State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, MI 48109-2122, USA
Tel : 313 747-1778, Fax : 313-747-1781

Space-based remote sensing and radiometry require signal generation above 100 GHz. This is traditionally achieved by hybrid approaches using Gunn sources and diodes for signal upconversion. The excellent high frequency performance demonstrated by InAlAs/InGaAs High Electron Mobility Transistors (HEMT's) on InP-substrates, with f_{max} values of several hundred GHz opens new possibilities for signal generation. Fundamental monolithic oscillators have, for example, been realized by the authors up to W-band showing more than 1 mW power with only 36 μm gate periphery InAlAs/InGaAs HEMT's [1]. A monolithic InP-HEMT doubler to 180 GHz has also been demonstrated [2]. This paper is the first report on a fully monolithic oscillator-doubler chain and signal generation at D-band using InP-HEMT's.

Large-signal HEMT modeling was used for the oscillator and doubler design. The oscillator uses a common source HEMT configuration with a series feedback from source to ground. The necessary condition for oscillation was provided by the microstrip interconnect lines and stubs. The termination impedance at the drain port of the oscillator is defined by the input impedance of the doubler stage transistor and selected for optimum power output. Proper gate width scaling was performed in the doubler transistor for this purpose and no interstage matching was therefore necessary. Edge-coupled lines were used for interstage DC blocking and output matching was achieved by microstrip stubs. The D-band output signal was coupled to a waveguide using a monolithically integrated on-chip E-field probe and no bonding was thus needed on the RF side of the chip.. The complete biasing circuitry together with stabilizing resistors and capacitors was also integrated on the chip.

The circuits were fabricated using the in-house developed InP MIMIC technology which is based on a mix-and-match approach including air-bridges and sputtered SiO_2 overlay capacitors. Thin film resistors for biasing and stabilization were realized using 600 $\AA$-thick Titanium layer. E-Beam lithography was employed to define 0.1μm mushroom gate lines. The total chip size is 1.82 mm x 1 mm. For testing, the circuit was mounted in a fixture with a WR-5 waveguide and aligned for proper positioning of the E-field probe inside the waveguide. The conversion loss of the doubler was minimized by proper selection of the HEMT-bias and was estimated to be of the order of 10 dB. The oscillation signal was detected over a frequency range of 130.5 GHz to 132.8 GHz depending on the gate bias. The output power at the chip level was dependent on the drain bias of both oscillator and doubler and was of the order of -10 dBm to -13 dBm. This was in the range of the expected power level for the small 45 μm gate width devices used in the module.

In summary, a fully integrated monolithic oscillator and doubler chain has been successfully implemented using submicron InAlAs/InGaAs technology. The monolithic module has on-chip bias and integrated probes for signal radiation and operates between 130.5 and 132.8 GHz. This is the highest frequency signal generation reported out of monolithic chips using three-terminal devices.

[1] Y. Kwon and D. Pavlidis, European Microwave Conf., pp. 161–166, September 1991.

[2] Y. Kwon, D. Pavlidis, P. Marsh, G. I. Ng and T. Brock, 1991 GaAs IC Symp., pp. 165–168, October, 1992.

[0]Work supported by NASA under contract NAGW-1334 and URI under contract DAAL 03-87-K-0007

A Planar Heterostructure Diode W-Band Mixer Using Monolithic Balanced Integrated Approach on InP

Y. Kwon, D. Pavlidis, P. Marsh, G.I. Ng and T. Brock
Center for Space Terahertz Technology
Solid State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, MI 48109-2122, USA
Tel : 313 747-1778, Fax : 313-747-1781

Recent advances in monolithic technology have allowed the realization of high frequency MMIC's using GaAs and InP based semiconductor devices. Heterostructure MMIC's based on InP seem to be of prime interest for very high frequency/low noise applications due to the unique features of InAlAs/InGaAs heterostructures. Frequency mixing at millimeter wave frequencies has traditionally been achieved using GaAs nonplanar Schottky diodes. "HEMT-type" diode mixers are another alternative. The diodes are in this case realized on the same layers as the HEMT and present therefore a unique advantage, namely, planarity and compatibility with other receiver functions utilizing HEMT's; a fully monolithic integration of all receiver functions on a single substrate can in this way be achieved. The work reported in this paper combines the advantages of InP-based heterostructures and "HEMT-type" diode designs. It reports on the design and experimental characteristics of the diodes and a monolithic W-band integrated mixer built with them.

"HEMT-type" diode mixers have been implemented up to W-band [1] only on GaAs substrate. The monolithic balanced mixer employed in this work operates at W-band, but uses instead a pair of InP-based HEMT diodes. The circuit employs the balanced configuration using a pair of antiparallel diodes. The balanced design is easily achievable with diodes and has the property of canceling the AM noise of the LO source. This is a very attractive approach especially at high frequencies where the noise figure of the mixer is often determined by a noisy LO source. The HEMT diode mixer presented in this work is the first demonstration of this type using InAlAs/InGaAs heterostructures.

The circuit design was based on the large-signal modeling of the "HEMT"-diode using harmonic balance analysis. Input and output matching circuits are realized in microstrip stub form and a 0°-180° rat race coupler has been used. An antiparallel diode pair has been connected to the Σ and Δ port of the rat race coupler for balanced operation. The circuit performance was evaluated with the help of a nonlinear analysis. The simulated conversion loss was 9 dB with LO drive power greater than 10 dBm.

The "HEMT"-diode is formed by the Schottky junction of the gate with the source-drain ohmic terminals of the HEMT connected together. It has three 4 μm fingers with a submicron (0.1 μm) footprint and is fully planar. The effective anode area was 1.2 μm^2. The diode shows a leakage current of -2.9 mA/mm at -7 V and the breakdown voltage is around -9 V. The turn-on voltage is 0.35 V and the ideality factor is 1.6. The rather small turn on voltage is due to the small Schottky barrier height of Ti on InAlAs, which is also associated with the relatively large ideality factor. The diodes were characterized using on-wafer probing and a high cut-off frequency of 760 GHz was determined. This is much higher than typical "MESFET"-diodes and required no sophisticated technologies as selectively doped ohmic regions.

The circuits were fabricated using the in-house developed InP MIMIC technology which is based on a mix-and-match approach including air-bridges and sputtered SiO_2 overlay capacitors. E-Beam lithography was employed to define 0.1μm mushroom gate lines. The circuits were tested in a fixture which uses a finline-to-microstrip transition at the 94 GHz input. IF matching was not included on-chip due to the area considerations. This resulted in slight conversion loss degradation of the order of 3 dB. First results of measured performance of the monolithic balanced mixer indicate a conversion loss of 12.8 dB with an LO drive of 11 dBm. The conversion loss was measured as a function of RF signal frequency and a fairly flat frequency response (within $\pm$ 2 dB) was observed from 86.5 GHz to 95.5 GHz (10 % bandwidth) with the LO fixed at 91 GHz.

In summary, a monolithic balanced mixer has been successfully implemented at W-band. It employs planar InAlAs/InGaAs heterostructure diodes instead of GaAs devices used up to now, and shows acceptable conversion loss with flat frequency response. The results demonstrate the possibility of full monolithic integration of diode mixer circuits in the millimeter wave range with other InP-based receiver functions of identical heterostructure design.

[1] K. W. Chang, H. Wang, K. L. Tan, S. B. Bui, T. H. Chen, G. S. Dow, J. Berenz, T. N. Ton, D. C. Garske, T. S. Lin and L. C. T. Liu, IEEE Trans. MTT, pp. 1972-1979, December 1991

[0]Work supported by NASA under contract NAGW-1334 and URI under contract DAAL 03-87-K-0007

Characterization of high-quality pseudomorphic InGaAs/GaAs quantum wells by luminescence and reflectance techniques

J. Pamulapati and P. Bhattacharya
Center for High-Frequency Microelectronics, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109-2122

R. L. Tober
U.S. Army Laboratory Command, Harry Diamond Laboratories, 2800 Powder Mill Road, Adelphi, Maryland 20783-1197

J. P. Loehr and J. Singh
Center for High-Frequency Microelectronics, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109-2122

ABSTRACT

Reflectance and photoluminescence spectroscopy have been used to study the optical properties of high quality $In_xGa_{1-x}As/GaAs$ $(0.13<x<0.30)$ single quantum wells. The results show strong agreement with the theoretical model used taking into account the strain potential. The agreement of the theoretical model, though, deviates from the experimental results for large values of excess strain in the well. For the case of the large strain $(x = 0.30)$ the reflectance indicates the strain in the well is hydrostatic rather than biaxial. The relevance of this fact is discussed in relation to device performance.

Differential photocurrent spectroscopy: A novel technique for semiconductor characterization

Richard L. Tober
Harry Diamond Laboratories, U.S. Army Adelphi Laboratory Center, 2800 Powder Mill Road, Adelphi, Maryland 20783-1197

W. Q. Li and P. K. Bhattacharya
Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109-2122

Differential photocurrent spectra of various $In_xGa_{1-x}As$ diodes demonstrate that modulated photocurrent techniques can easily be used to characterize *p-i-n* and Schottky diode structures. The spectra were obtained in such a way as to produce a first derivative with respect to either the photon energy or an electric field. A simple model yields an expression for the differential photocurrent spectra in terms of the derivative functional form normally used to fit modulated spectra. Therefore, the sharp spectral features produced with these techniques can be used to determine not only band-gap energies and spectral linewidths but built-in electric fields as well.

Optical time-of-flight measurement of carrier transport in $GaAs/Al_xGa_{1-x}As$ and $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ multiquantum wells

S. Gupta, L. Davis, and P. K. Bhattacharya
Solid State Electronics Laboratory and Ultrafast Science Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109-2122

(Received 19 September 1991; accepted for publication 6 January 1992)

An all-optical time-of-flight technique is used for measuring perpendicular carrier transport in semiconductor heterostructures and multiquantum wells (MQWs). This technique is based on measuring a change in surface reflectance due to the absorption nonlinearities induced by the carriers, and has a temporal resolution of ~1 ps. Typical results on a $GaAs/Al_xGa_{1-x}As$ MQW and an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ MQW are compared. The observed fast transport times can only be explained by a field-dependent carrier emission out of the quantum well, after which transport through the continuum states can occur. Due to larger barriers in the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ system, this intrinsic limit to transport is much larger, and hence these devices are observed to be slower than their $GaAs/Al_xGa_{1-x}As$ counterparts.

Structural characterization of low-temperature molecular beam epitaxial $In_{0.52}Al_{0.48}As/InP$ heterolayers

A. Claverie,[a] K. M. Yu, W. Swider, and Z. Liliental-Weber
Materials Science Division, Lawrence Berkeley Laboratory, Berkeley California 94720

M. O'Keefe and R. Kilaas
National Center for Electron Microscopy, Lawrence Berkeley Laboratory, Berkeley, California 94720

J. Pamulapati and P. K. Bhattacharya
Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109-2122

A systematic study of the structural quality and arsenic content of as-grown $In_{0.52}Al_{0.48}As/InP$ layers deposited on InP by molecular beam epitaxy at temperatures between 150 and 450 °C was performed using transmission electron microscopy and particle-induced x-ray emission. We found that the amount of As incorporated in the layers generally increases with decreasing growth temperature, with the crystalline quality of the layers being good at growth temperatures higher than 200 °C. At 150 °C, a large density of pyramidal defects is formed, the defects are related to the very large amount of excess As incorporated into the layer. The mechanisms leading to the formation of these defects are discussed. At 200 °C, however, the amount of excess As is lower than expected, and wavy streaks of diffuse scattering are seen in electron diffraction. It is shown that small ordered domains of the CuPt type on the [illegible]II atoms are responsible for these features.

Raman scattering from heavily doped (311) GaAs:Si grown by molecular beam epitaxy

S. H. Kwok and R. Merlin
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan 48109-1120

W. Q. Li and P. K. Bhattacharya
Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109-2122

Raman scattering by localized vibrational modes and plasmons has been used to characterize heavily *p*- and *n*-type silicon-doped (311)*A* GaAs layers grown by molecular beam epitaxy. Consistent with the doping character, *p*-type samples show two modes associated with Si(As) and the complex defect Si-X. Acceptor-related lines were not observed in *n*-type samples, an indication that compensation levels in the layers are very low. The results are discussed in relation to growth conditions on (311)*A* surfaces.

Molecular Beam Epitaxial Growth and Characterization of Silicon Doped AlGaAs and GaAs on (311)A GaAs Substrates and their Device Applications

W.Q .Li and P.K. Bhattacharya
Solid State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, MI 48109-2122

S.H. Kwok and R. Merlin
The Harrison M. Randall Laboratory of Physics
The University of Michigan, Ann Arbor, MI 48109-1120

ABSTRACT

We have investigated the possibility of reliable and reproducible p-type doping of (311)A GaAs by Si during molecular beam epitaxial growth and the application of such doping in the realization of high performance electronic devices. It is seen that p-type doping upto a free hole concentration of 4×10^{19} cm^{-3} can be obtained under conditions of low As_4 flux and high ($\geq 660°C$) growth temperatures. N-type doping upto a level of 1×10^{19} cm^{-3} is obtained at low ($\leq 500°C$) growth temperature and high As_4 flux. The p-type doping is extremely reproducible and the incorporation of Si atoms into electrically active As sites is at least 95%. The doping behavior has been studied and confirmed by Raman spectroscopy. N-p-n heterojunction bipolar transistors grown by all Si doping exhibit excellent current voltage characteristics and a common emitter current gain $\beta = 240$. Doped channel p-type heterojunction field effect transistors have transconductance $g_m = 25$ mS/mm.

Optically Induced Energy Shifts of Excitonic Resonances in Single[111]B and [100] InGaAs Quantum Wells

R. Tober, T. Bahder, W. Q. Li and P. Bhattacharya

NO ABSTRACT AVAILABLE

Molecular Beam Epitaxial GaAs/AlGaAs Heterojunction Bipolar Transistors on (311)A GaAs Substrates with All-Silicon Doping

W. Q. Li and Pallab K. Bhattacharya, *Fellow, IEEE*

Abstract—**We have investigated the characteristics and reproducibility of Si-doped p-type (311)A GaAs layers for application to heterojunction bipolar transistors (HBT's) grown by molecular beam epitaxy (MBE). We have obtained $p = 2.2 \times 10^{19}$ cm^{-3} in a layer grown at 670°C. We have used all-Si doping to grow n-p-n transistors. These devices exhibit excellent dc characteristics with $\beta = 230$ in a device with base doping of $p = 4 \times 10^{18}$ cm^{-3}.**

DC and Microwave Performance of a 0.1-μm Gate $InAs/In_{0.52}Al_{0.48}As$ MODFET

D. Yang, Y. C. Chen, T. Brock, and Pallab K. Bhattacharya, *Fellow, IEEE*

Abstract—**We have measured and analyzed the performance characteristics of 0.1-μm gate $InAs/In_{0.52}Al_{0.48}As$ MODFET's grown by molecular beam epitaxy. The transistors are characterized by measured g_m (max) = 840 mS/mm, f_T = 128 GHz, and a very high current carrying capability, e.g., I_{dss} = 934 mA/mm at V_{gs} = 0.4 V and V_{ds} = 2.7 V. The value of f_T is estimated from extrapolation of the current gain (H_{21}) at a −6-dB/octave rolloff. This is the first report on the microwave characteristics of an InAs-channel MODFET and establishes the superiority of this heterostructure system.**

Characteristics of 0.8 μm and 0.2 μm Gate Length $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As/InP$ $(0.53 \leq x \leq 0.70)$ Modulation Doped Field Effect Transistors at Cryogenic Temperatures

R. Lai, P. K. Bhattacharya, D. Yang and T. Brock
Center for High-Frequency Microelectronics and Solid State Electronics Laboratory
The University of Michigan, Ann Arbor, MI 48109-2212

S. A. Alterovitz and A. N. Downey
Space Electronics Division, NASA Lewis Research Center
Cleveland, OH 44135

ABSTRACT

We have investigated analytically and experimentally the performance characteristics of InP-based $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ $(0.53 \leq x \leq 0.70)$ pseudomorphic modulation-doped field-effect transistors (MODFETs) as a function of strain in the channel, gate-length and temperature. The strain in the channel was varied by varying the In composition x. The temperature was varied in the range of 40-300K and the devices have gate lengths, L_g, of 0.8 μm and 0.2 μm. Analysis of the device was done using a one-dimensional self-consistent solution of the Poisson and Schrodinger equations in the channel, a two-dimensional Poisson solver to obtain the channel electric field and a Monte Carlo simulation to estimate the carrier transit times in the channel. An increase in the value of the cutoff frequency is predicted for an increase in In composition, a decreased in temperature and a decrease in gate-length. The improvement seen with decreasing temperature, decreasing gate length and increasing In composition were smaller than those predicted by analysis. The experimental results on pseudomorphic InGaAs/InAlAs MODFETs have shown that there is a 15-30% improvement in cutoff frequency in both the 0.8 and 0.2 μm gate length devices when the temperature is lowered from 300K to 40K.

The Growth of High Quality InP/InGaAs/InGaAsP Interfaces by CBE for SCH Multi-Quantum Well Lasers

M. E. SHERWIN, D. T. NICHOLS, G. O. MUNNS, P. K. BHATTACHARYA and G. I. HADDAD

Center for High Frequency Microelectronics
Electrical Engineering and Computer Science Dept.
The University of Michigan, 2435 EECS Building, Ann Arbor, MI 48109-2122

Bulk InGaAsP and heterointerfaces of InP/InGaAs and InGaAsP/InGaAs have been grown by chemical beam epitaxy for use in multi-quantum well separate confinement heterostructure lasers. InGaAsP has been successfully grown for λ = 1.1, 1.2 and 1.4 μm. The TMI and TEG incorporation coefficients have strong dependencies on substrate temperature and also charge as the InGaAsP composition tends towards InP. InP/InGaAs and InGaAsP/InGaAs quantum wells have been grown to determine the optimum gas switching sequence to minimize the measured photoluminescence FWHM. InGaAs quantum wells as narrow as 0.6 nm have been grown with 7K FWHM of 12.3 meV. Lattice matched MQW-SCH lasers were grown using different interface switching sequences with the best laser having a threshold current density of 792 A/cm^2 for an 800 $\times$ 90 μm broad area device.

Key words: CBE, InGaAsP, MQW-SCH lasers

Theoretical and Experimental Studies of the Effects of Compressive and Tensile Strain on the Performance of InP–InGaAs Multiquantum-Well Lasers

D. Nichols, M. Sherwin, G. Munns, J. Pamulapati, J. Loehr, J. Singh, P. Bhattacharya, and M. Ludowise

Abstract—**We have studied, both theoretically and experimentally, the effects of biaxial strain upon the performance characteristics of broad-area InP–InGaAsP–$In_xGa_{1-x}As$ ($0.33 \leq x \leq 0.73$) separate confinement heterostructure multiquantum-well lasers. The theoretical calculations include the effects of strain on the bandstructure and the Auger recombination rates. We observe a pronounced dependence of the threshold current density J_{th} upon x. The lowest measured J_{th} is 589 A/cm^2 in an 800 μm laser with $x = 0.68$. Also, internal quantum efficiencies as high as unity and loss coefficients as low as 5.6 cm^{-1} have been measured for $x = 0.58$.**

CBE Growth of High Quality InAlAs Using TMAA

M. E. Sherwin and G. O. Munns

Solid State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, MI 48109-2122

Despite its application in a wide variety of devices including HEMTs, HBTs, and lasers, there have been no reports of InAlAs grown by CBE. This is the first report of InAlAs grown by CBE using the novel precusor trimethyl amine alane (TMAA). Trimethyl amine alane ($AlH_3N(CH_3)_3$) which has no aluminum carbon bonds (as does tri ethyl aluminum) has several advantages over TEAl including a higher vapor pressure and less transport of oxygen to the growth surface.[1]

Bulk InAlAs has been grown with 300 K background carrier concentrations ~8E14 cm-3 and mobility of 1000 cm2/Vs. The layers are lattice matched to InP with $|\Delta a/a| < 5e\text{-}4$, with a best 17K bulk photoluminescence FWHM of 18.5 meV. A large number of Pendellosung fringes (7) has been observed during X-ray diffraction, indicating the high crystalline quality of the films. Exploration of growth parameter space has shown that the relative incorporation of Al and In is quite sensitive to the V/III ratio. With increasing arsine flow the layers become indium rich. At 530°C we have also observed a saturation of the growth rate as the total group III flow rate is increased. In contrast to the observed sensitivity to V/III ratio, the substrate temperature window is quite large, ~75°C, with good crystal quality down to 505°C. Below this tempeature the x-ray diffraction peak becomes very broad, indicating that the crystal quality is greatly reduced, even though the growth rate remains constant. The interplay between surface chemical kinetics and surface mobility will be discussed.

Uncoupled quantum wells of various thicknesses have been reproducably grown as thin as two monolayers, 6 Å, with a corresponding 17 K energy shift of 570 meV and a FWHM of 18 meV.

Pseudomorphic HEMTs have been grown with room temperature (77K) carrier concentrations of ~2e12 cm-2 with a corresponding mobility of 10,250 cm2/Vs (43,000 cm2/Vs). DC and microwave device results will be presented.

•This work was supported by the U.S. Army Research Office under contract No. DAAL03-87-K-0007.

[1] C.R. Abernathy, A.S. Jordan, S.J. Pearton, W.S. Hobson, D.A. Bohling and G.T. Muhr, Appl. Phys. Lett. 56(26), 2654 (1990).

The growth of InGaAsP by CBE for SCH quantum well lasers operating at 1.55 and 1.4 μm

M.E. Sherwin, G.O. Munns, D.T. Nichols, P.K. Bhattacharya and F.L. Terry, Jr.

Center for High Frequency Microelectronics, Electrical Engineering and Computer Science Department, 2435 EECS Building, The University of Michigan, Ann Arbor, Michigan 48109-2122, USA

InGaAsP has been grown by CBE at compositions of 1.1, 1.2 and 1.4 μm for the development of MQW-SCH lasers. The observed incorporation coefficients for TMI and TEG show strong temperature sensitivity while the phosphorus and arsenic incorporation behavior is constant over the substrate temperature range explored, 530 to 580°C setpoint. For higher substrate temperatures the growth rate increases with the largest growth rates occurring for the 1.4 μm quaternary. Low temperature photoluminescence indicates the possibility of compositional grading or clustering for the 1.1 μm material and also for the 1.2 μm material grown at the lowest substrate temperature. The final laser structure was grown with the InP cladding regions grown at 580°C with the inner cladding and active regions grown at 555°C. Using this approach we have successfully grown MQW-SCH lasers with the composition of the active $In_xGa_{1-x}As$ ranging from $x = 0.33$ to $x = 0.73$. Threshold current densities as low as 689 A/cm^2 have been measured for an 800 μm × 90 μm broad area device with $x = 0.68$.

Journal of Crystal Growth 120 (1992) 184–188
North-Holland

JOURNAL OF CRYSTAL GROWTH

InAlAs/InGaAs/InP sub-micron HEMTs grown by CBE

G.O. Munns, M.E. Sherwin, T. Brock, G.I. Haddad, Y. Kwon, G.I. Ng and D. Pavlidis

Center for High Frequency Microelectronics, 1135 EECS Building, The University of Michigan, Ann Arbor, Michigan 48109-2122

The InAlAs/InGaAs/InP high electron mobility transistor (HEMT) lattice matched to InP offers excellent high frequency, noise operation for MMICs and low-noise amplifiers. The InP channel in the InP/InAlAs HEMT offers the advantage improved high field velocity and higher breakdown voltages (the potential for higher power applications) over InGaAs char HEMTs. InAlAs has been grown for the first time by CBE using TMAA producing InGaAs/InAlAs and InP/InAlAs HEM Sub-micron InGaAs/InAlAs HEMTs with planar Si doping have been fabricated with f_t values of 150 GHz and f_{max} values of GHz. This device showed excellent pinch-off characteristics, with a maximum transconductance of 890 mS/mm. The planar dor InGaAs channel HEMT had a higher f_t than a similar uniformly doped device. However, the non-optimized structure of the pla doped device resulted in a large output conductance of 120 mS/mm, limiting f_{max} for that device. A sub-micron InP chan device was grown with a quantum well channel and double-sided planar Si doping. A sheet charge density of 4.4×10^{12} cm^{-2} a associated room temperature mobility of 2800 cm^2/V·s were achieved; however, the saturation current was low. The most lik causes for this are diffusion of the planar doping beneath the channel and the poor quality of the InP on InAlAs interface at t bottom of the quantum well channel.

Novel Self-Aligned Offset Γ-Gate InAlAs/InGaAs HEMT's Grown by Chemical Beam Epitaxy*

Y. Kwon, T. Brock, G. I. Ng, D. Pavlidis
and
G. O. Munns, M. E. Sherwin, G. I. Haddad
Solid State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, MI 48109-2122, USA

InAlAs/InGaAs HEMT's using self-aligned T-gates have achieved f_T's as high as 250 GHz [1]. High f_{max} values can be obtained by offsetting the gates towards the source and f_{max} = 350 GHz has been reported using this approach in AlGaAs/InGaAs HEMT's [2]; a lower parasitic source resistance and a higher g_m/g_{ds} and c_{gs}/c_{gd} ratio are responsible for the f_{max} enhancement. In this work, a novel self-aligned offset Γ-gate (shown in Fig. 1) is employed which unlike previous techniques [1], maintains the self-aligned features while profiting from the advantages of offsetting the gate. Furthermore, the 0.25 μm offset self-aligned gate HEMT's were fabricated for the first time on layers grown by chemical beam epitaxy (CBE) and showed performance comparable to that obtained by MBE.

InAlAs/InGaAs was grown by CBE on semi-insulating InP substrates using triethyl-gallium, trimethyl-indium, trimethyl-amine-alane (TMAA) and arsine. CBE offers an attractive method for growing InP-based HEMT's due to the semi-infinite sources and the ability to utilize phosphorous, as in MOVPE, along with the molecular beam nature and monolayer interface abruptness of MBE. An undoped InGaAs cap layer was used to improve the power gain of the device [3] and planar doping was employed in the InAlAs donor layer.

The offset self-aligned Γ-gate technology has been developed using a tri-layer E-beam resists and double exposure technique. A tri-layer structure consisting of a bottom 950 K PMMA, a middle 496 K PMMA and a top copolymer P(MMA-MAA) has been used to obtain a Γ-gate with a tall pedestal and high aspect ratio. The middle 496 K PMMA was adopted to have the necessary profile for better gate yield; the gate yield over the wafer was greater than 80 %. The offset gate was formed by lift-off of Pt/Ti/Pt/Au. After gate metalization, the ohmic metals were deposited, followed by two-step rapid thermal annealing at 250°C-7sec and 325°C-7sec. In order to study the effect of offsetting the gate, the gate-to-drain separation (L_{gd}) was varied from 0.2 μm to 0.4 μm, while the gate-to-source (L_{gs}) was fixed at 0.2 μm. The position and width of the top opening was precisely controlled with the help of selective exposure using a lower-dose rectangular scan.

The DC characteristics of the offset self-aligned gate HEMT with L_{gd} = 0.4 μm are shown in Fig. 2. The device shows the DC transconductance of 750 mS/mm and output conductance of 83 mS/mm. The Schottky diode characteristics are also shown in Fig. 3. A high turn-on voltrage (0.5-0.6V) and very low reverse leakage current (0.68 mA/mm at -5 V) can be observed. The microwave properties of the HEMT's were measured by on-wafer probing. From the measured S-parameters, the small-signal equivalent circuit was extracted using a direct extraction technique based on "cold" and "hot" measurements. This allows one to obtain results with better physical significance. Fig. 4 shows the measured and modeled microwave results for L_{gd} = 0.4 μm. The summary of microwave data is presented in Table 1. f_T varies from 127 GHz to 119 GHz while the g_m/g_{ds} and c_{gs}/c_{gd} ratios increase from 9.3 and 7.8 to 23.4 and 12.0 with L_{gd} changing from 0.2 to 0.4 μm. As a result, f_{max} values increase from 202 to 251 GHz. The f_{max}/f_T ratios are 1.6 for the centered gate and 2.1 for the offset self-aligned gate demonstrating the f_{max} enhancement that can be achieved by gate offsetting. With a different doping density in the barrier, f_{max}/f_T ratio as high as 2.7 has been achieved.

In summary, a high f_{max}/f_T ratio and good microwave characteristics have been achieved using 0.25 μm offset self-aligned InAlAs/InGaAs HEMT's grown by CBE.

*Work supported by NASA (Contract No. NAGW-1334) and ARO (Contract No. DAAL 03-87-U-0007)

[1] L. D. Nguyen et al, IEDM. Tech. Dig., pp. 499-502, 1990.
[2] L. F. Lester et al, IEDM. Tech. Dig., pp. 172-175, 1988.
[3] Y. C. Pao et al, IEEE Trans. on ED, pp. 312-314, 1990.

Superlattice Barrier Varactors*

C. Raman, J. P. Sun, W. L. Chen, G. Munns,
J. East and G. Haddad
Solid State Electronics Laboratory
University of Michigan, Ann Arbor, Michigan

Abstract

SBV (Single Barrier Varactor) diodes have been proposed as alternatives to Schottky barrier diodes for harmonic multiplier applications. However these show a higher current than expected. The excess current is due to X valley transport in the barrier. We will present experimental results showing that the use of a superlattice barrier and doping spikes in the GaAs depletion regions on either side of the barrier can reduce the excess current and improve the control of the capacitance vs. voltage characteristic.

The experimental results consist of data taken from two types of device structures. The first test structure was used to study the performance of AlAs/GaAs superlattice barriers. The wafer was fabricated into 90 micron diameter mesa diodes and the resulting current vs. voltage characteristics were measured. A 10 period superlattice structure with a total thickness of approximately 400 Å worked well as an electron barrier. The structure had a current density of about one A/cm^2 at one volt at room temperature. The capacitance variation of these structures was small because of the design of the GaAs cladding layers. The second test structure was used to study cladding layer designs. These wafers were InGaAs and InAlAs layers lattice matched to an InP substrate. The layers have n^+ doping spikes near the barrier to increase the zero bias capacitance and control the shape of the capacitance vs. voltage characteristic. These structures have a capacitance ratio of 5:1 and an abrupt change from maximum to minimum capacitance. The measurements were made at 80 K. Based on the information obtained from these two structures, we have designed a structure that combines the low current density barrier with the improved cladding layers. The capacitance and current-voltage characteristics from this structure are presented.

*This work was supported by the Center for Space Terahertz Technology under NASA Contract No. NAGW-1334 and by the URI-ARO Program Contract No. DAAL03-87-K-0007.

Investigation and Optimization of InGaAs/InP Heterointerfaces Grown by Chemical Beam Epitaxy U Spectroscopic Ellipsometry and Photoluminescence

M. E. SHERWIN, F. L. TERRY, Jr., G. O. MUNNS, J. S. HERMAN, E. G. WOELF and G. I. HADDAD

Center for High Frequency Microelectronics
Electrical Engineering and Computer Science Dept.
The University of Michigan, 2435 EECS Building, Ann Arbor, MI 48109-2122

Spectroscopic ellipsometry (SE) has been used to investigate transition layers for GaAs/InP heterointerfaces. For the case of InGaAs on InP, we have found that samples can be best modeled by a strained $In_xGa_{1-x}As$ film with the possible prese of a thin interface region (<15Å). We are unable to conclusively determine the existe of such a thin transition region. For InP on InGaAs, we find clear indications of contamination in the bulk film, and that the addition of a thin interface region $In_{0.75}Ga_{0.25}As_{0.5}P_{0.5}$ improves both the numerical fit and shape of the dielectric respor curves, especially around E_1 and $E_1 + \Delta_1$, where the effects of a transition region a most pronounced. However, difficulties in modeling the dielectric response of the co taminated InP film make identification of an interface transition region only specu tive at this point. Multiple single quantum well structures have also been grown a analyzed with 7K photoluminescence. The quality of the quantum wells shows stro dependence on the gas switching sequence used at the heterointerfaces. The best switc ing sequence produced a 0.5 nm well with a 7K FWHM of only 12.3 meV. Multi quantum wells have also been grown to investigate the uniformity and repeatability our system. Twenty period MQWs with a well width of 1.6 nm display a 14K FWH of 7.9 meV.

Key words. Spectroscopic ellipsometry, chemical beam epitaxy, InGaAs, InP, Inte faces

The Growth of InAlP Using Trimethyl amine alane by Chemical Beam Epitaxy

G. O. Munns, W. L. Chen, M. E. Sherwin, and G. I. Haddad

Center for High Frequency Microelectronics, 1135 EECS Building,The University of Michigan, Ann Arbor, Michigan 48109-2122, USA

The growth of InAlP and related compounds such as InGaP lattice matched to GaAs has attracted a great deal of interest for optoelectronic devices emitting in the range from 638 to 700 nm and for electronic devices such as the heterojunction bipolar transistor. Although some gas source MBE work has been performed in this material system, very little CBE work has been done, largely attributable to the lack of a suitable aluminum source. This is the first report of trimethyl amine alane (TMAA) being used to grow InAlP. TMAA offers advantages of less carbon incorporation and less oxygen sensitivity compared to triethyl aluminum, tri isobutyl aluminum, or trimethyl aluminum.

Trimethyl amine alane has been used to grow AlGaAs HBT's and more recently to grow InAlAs/InGaAs HEMT's by CBE. One of the principal strengths of CBE is its ability to handle phosphorus based compounds efficiently, offering excellent interface control. InAlP films with carbon concentrations below $7x10^{17}$ cm^{-3} lattice matched $|\delta a/a| < 2x10^{-3}$ with good surface morphology have been grown. Double crystal x-ray diffraction exhibits a single epi peak with a full width at half max of 46 arcseconds with multiple Pendellosung fringes. The epitaxial films are semi-insulating, completely depleted for thicknesses up to 1.6 microns. Oxygen levels measured by secondary ion mass spectroscopy are somewhat higher than levels measured in InAlAs films (~$2.5x10^{18}$ cm^{-3}) lattice matched to InP. The likely source of this oxygen is the hydride precursor as has been shown for the growth of InAlAs.

As the substrate temperature is raised the films become increasingly indium-rich. Breaking the growth rate down into its constituent binaries indicates an enhanced TMI incorporation rate. The quality of the films as measured by x-ray full width at half max and the surface morphology is extremely sensitive to substrate temperature. A very narrow window exists for the growth of good quality material in the range from 535 to 545° C.

Ohmic Contact Study for Quantum Effect Transistors and Heterojunction Bipolar Transistors with InGaAs Contact Layers

W. L. Chen, J. C. Cowles, G. I. Haddad, G. O. Munns,
K. W. Eisenbeiser and J. R. East

Center for High Frequency Microelectronics
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, MI 48109-2122

Abstract

Two ohmic contact systems for quantum effect devices and heterojunction bipolar transistors (HBT's) were investigated and compared. Ni/Ge/Au/Ti/Au and Pd/Ge/Ti/Al were characterized for diffusion length after annealing and specific contact resistivity on chemical beam epitaxy grown $In_{0.53}Ga_{0.47}As$. It was found, in general, that the diffusion length could be controlled by varying the total metal thickness and that the specific contact resistivity maintained reasonably low values as long as the compositional ratio of each system remained constant. The diffusion length for Ni/Ge/Au/Ti/Au ranged from 1000 Å to 2000 Å and that of Pd/Ge/Ti/Al was approximately 300 Å. In both cases the specific contact resistivity on n-type InGaAs was $5\times10^{-7}\Omega cm^2$. Furthermore, the Pd/Ge/Ti/Al was applied to p-type InGaAs and showed a specific contact resistivity of $3\times10^{-6}\Omega cm^2$. Finally, both systems were used to fabricate an InGaAs/InP hot electron transistor and an InAlAs/InGaAs HBT with excellent dc results.

Uniformly Doped and Delta Doped InAlAs/InP HEMT Structures Grown by Chemical Beam Epitaxy

M. E. Sherwin, G. O. Munns and F. L. Terry, Jr.

NO ABSTRACT AVAILABLE

Processing of Materials

S. W. Pang

NO ABSTRACT AVAILABLE

Etching of Photoresist Using Oxygen Plasma Generated by a Multipolar Electron Cyclotron Resonance Source

S. W. Pang, K. T. Sung, and K. K. Ko

Solid State Electronics Laboratory

Department of Electrical Engineering and Computer Science

The University of Michigan

Ann Arbor, MI 48109-2122

Abstract

Etching of photoresist in an O_2 plasma generated by an electron cyclotron resonance source (ECR) was investigated. The ECR source was a microwave multipolar reactor at 2.45 GHz and the stage was connected to a rf power supply at 13.56 MHz. Effects of microwave power, rf power, ECR source to sample distance, and pressure on photoresist etch rate were characterized. It has been found that the photoresist etch rate increases with microwave and rf power, but decreases with source to sample distance. With microwave power at 1000 W and rf power at 300 W, smooth morphology and fast etch rate at 1.61 μm/min were obtained. Self-induced dc bias voltage increases with rf power and source to sample distance but decreases with microwave power. Etch rate uniformity better than 0.5% was obtained across 7.5 cm diameter wafer even with a very close source to sample distance of 3 cm. Etch profile can be varied depending on the etch conditions. Vertical profile in polyimide has been obtained using a trilayer resist scheme.

Comparison Between Etching in Cl_2 and BCl_3 for Compound Semiconductors Using A Multipolar Electron Cyclotron Resonance Source

S. W. Pang and K. K. Ko
Solid State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, MI 48109-2122

Abstract

Controllable dry etching of GaAs and InP using a multipolar electron cyclotron resonance (ECR) source and a rf-powered electrode was investigated. The etch characteristics were studied as a function of microwave power, rf power, distance from the ECR source, pressure, and temperature. Etch rate is found to increase with microwave power initially, then decrease at higher microwave power due to reduction in ion energy. Surface morphology becomes rougher and etch profile is more undercut at higher microwave power, but can be improved using higher rf power or by Ar addition. As the ECR source distance increases, the concentration of ions and neutral species decrease, but the ion energy increases. Therefore, when etching is limited by the arrival rate of reactive radicals, etch rate decreases with source distance. When the process is limited by the ion-enhanced reaction or removal rates, etch rate increases with source distance. Etch rate and self-induced dc bias voltage ($|V_{dc}|$) typically increase with pressure. The increase in $|V_{dc}|$ is believed to be caused by the lower ion flux at higher pressure. However, when the reactive species concentrations and the ion energy are low, etch rate decreases with pressure. Low pressure was observed to favor smooth surface morphology and vertical etch profile. Etch rates for both GaAs and InP increase with temperature, with InP etch rate exceeding GaAs at 380°C. Using a Cl_2/Ar mixture with 10% Cl_2, 70 W rf power and 25 W microwave power at 0.5 mTorr, 0.1-μm-wide features that are 1-μm-deep have been fabricated in GaAs with vertical profile and smooth surface morphology.

APPLICATION OF HIGH-QUALITY SiO_2 GROWN BY MULTIPOLAR ECR SOURCE TO Si/SiGe MODULATION DOPED FET

K. T. Sung, W. Q. Li, S. H. Li, S. W. Pang, and P. K. Bhattacharya

Solid State Electronics Laboratory

Department of Electrical Engineering and Computer Science

University of Michigan, Ann Arbor, MI 48109-2122

ABSTRACT

A 5-nm-thick gate SiO_2 was grown at 26°C with oxygen plasma generated by a multipolar electron cyclotron resonance source. The ultrathin oxide has breakdown field >12 MV/cm and fixed charge density ~$3x10^{10}$ cm^{-2}. A $Si(p^+)/Si_{0.8}Ge_{0.2}$ modulation-doped heterostructure was grown by gas source molecular beam epitaxy and the thin oxide layer was used as a Schottky gate barrier layer. The device with 1.5 μm x 50 μm gate shows maximum drain current of 20 mA/mm and peak transconductance of 3.5 mS/mm. No gate leakage was found even at high gate-source bias voltage, indicating that this oxide growth technique is very promising for high-performance devices.

Effects of Processing Induced Fluctuations on the Optical Properties of InGaAs/AlGaAs Quantum Boxes Created by Dry Etching and Epitaxial Regrowth

K.K. Ko, L. Davis, W-Q. Li, T. Brock, S.W. Pang, J. Singh, and P.K. Bhattacharya
Solid State Electronics Laboratory,
Department of Electrical Engineering and Computer Science,
The University of Michigan, Ann Arbor, Michigan 48109-2122, USA
Tel. (313) 763-6132, FAX (313) 747-1781

ABSTRACT

Remarkable new phenomenon with implications in both physics and devices are promised by quasi 1-D and quasi 0-D structures. Quasi-1D systems, for example, have a tremendous potential for high speed electronic devices and extremely low threshold current lasers. The excitonic properties of such structures also promise to be quite remarkable. The effect of processing induced disorder on the properties of these lower-dimension quantum confined structures is not well-known or understood at the present time. The fabrication steps can induce surface and interface roughness due to imperfect growth and defects and disorder due to non-optimal processing. The effects of such perturbations from the perfect 'textbook' scenario is to alter the electronic and optical properties of the structures. The extent of this perturbation is not exactly known and may even wipe out the expected advantages.

The purpose of the present study is to examine, theoretically and experimentally, the cause and extent of processing induced disorder, the effect of such disorder on the optical properties of quantum boxes, and to eventually minimize process induced fluctuations. In the theoretical formalism the valence band is described by a 4×4 $\mathbf{k} \cdot \mathbf{p}$ formalism and the full three-dimensional confinement problem is solved.

The buried quantum boxes are being realized by a combination of MBE growth of pseudomorphic $In_{0.1}Ga_{0.9}As/Al_{0.15}Ga_{0.85}As$ quantum wells, followed by electron beam lithography and dry etching by an ECR source to define the boxes, and finally epitaxial regrowth. The finished samples are schematically shown in Fig. 1. The quality of the structures are extremely sensitive to epitaxial regrowth, which produces a disordered region at the regrown interface. Therefore the etching and regrowth procedures play an important role. We find that a good calibration parameter is the optical quality of the regrown AlGaAs.

The buried quantum boxes of approximately 350 Å diameter and 600Å height (4 periods of QW) were characterized by low-temperature photoluminescence measurements. The results are shown in Fig. 2. The distinct luminescence from the quantum boxes is red-shifted from the QW luminescence. We believe this could be due to bandtail states created by disordered interfaces or the interface depletion field which can cause the quantum confined Stark effect. We are analyzing these effects in details. Work on the changes in the optical properties due to variation in processing and their effects on the electro-optic properties of the 0-D structures is in progress and will be presented.

Work supported by the Office of Naval Research and the Army Research Office

Key words: Quantum box, epitaxial regrowth, reactive ion etching, photoluminescence, structural disorder.

X-Ray Photoelectron Spectroscopy Surface Study of InP RIE Etched with BCl_3 and Argon

Alexandros T. Demos, and H. Scott Fogler
Department of Chemical Engineering

Michael E. Elta
Department of Electrical Engineering and Computer Science

The University of Michigan
Center for High-Frequency Microelectronics
Ann Arbor, MI 48109-2122
Phone No. (313) 747-1782

Abstract

X-Ray Photoelectron Spectroscopy (XPS) was used in a surface study of RIE etched InP. The gas etchants used were BCl_3 and argon. The etching conditions used produced an indium chloride layer on the InP substrate. Both angle-resolved and sputter depth profiling with XPS were performed to characterize this indium chloride reaction layer. The analysis was aided by showing the Cl/In and P/In ratios of atomic concentrations. At the wafer surface we see a Cl/In ratio near three and P/In ratio near zero. Deeper into the layer, the Cl/In ratio goes to zero and the the P/In ratio approaches one. By cycling with sputter etching and RIE etching we obtained etch rate enhancements over our RIE etch rate. From XPS spectra, it was found that the indium chloride layer is removed by the sputter cycle. Also studied in this paper were how long a steady state layer takes to form for InP. The data indicates that InP becomes chlorinated in minutes. The XPS analysis also showed that different etching conditions produced thicker films with different etch rates. The trend of thicker indium chloride layer with small etch rate was observed.

High temperature kinetic study for the reactive ion etching of InP in $BCl_3/Ar/O_2$

Alex T. Demos, H. Scott Fogler
Department of Chemical Engineering

Jeffrey Fournier, Michael E. Elta
Department of Electrical Engineering and Computer Science

University of Michigan
Ann Arbor, Michigan 48109

Abstract

The reactive ion etching (RIE) kinetics of InP was studied using BCl_3/Ar and $BCl_3/Ar/O_2$ as etchants. High temperature etching produced negligible etch rate increases using BCl_3/Ar. With the addition of 30 % oxygen in the gas feed, etch rates of 1.5 microns/minute were obtained at wafer temperatures of 250 °C. The effect of oxygen addition to different BCl_3 flows was studied. At high BCl_3 flows, high oxygen flows were required to produce high etch rates. Using XPS surface analysis, it was found that oxygen removes the boron species that adsorb on the InP surface. Apparently, the oxygen addition helps scavenge the boron by forming volatile boron oxides. At high oxygen flows greater than 50 %, solid boron oxide formed on the InP surface. To study the gas-phase chemistry, optical emission spectroscopy was used on the different gas mixtures to monitor atomic chlorine intensity. The chlorine intensity showed a Guassian dependence with oxygen addition which was similar to the etch rate dependence. Arrhenius plots were developed for two power densities of 0.13 and 0.21 W/cm^2. Two regimes of etching were found from the Arrhenius plots. Below 180 °C, activation energies near 3 kcal/mol were calculated were etching is $InCl_3$ desorption limited. At temperatures above 180 °C, activation energies of approximately 9 kcal/mol were calculated where etching appears to be chlorine flux limited. In terms of surface morphology, roughness increased as temperature increased. This was due to increased chemical etching. At high power densities (0.21 W/cm^2) and intermediate temperatures (150 °C), high aspect ratios were obtained.

Investigation and Optimization of InGaAs/InP Heterointerfaces Grown by Chemical Beam Epitaxy Using Spectroscopic Ellipsometry and Photoluminescence

M. E. SHERWIN, F. L. TERRY, Jr., G. O. MUNNS, J. S. HERMAN, E. G. WOELK and G. I. HADDAD

Center for High Frequency Microelectronics
Electrical Engineering and Computer Science Dept.
The University of Michigan, 2435 EECS Building, Ann Arbor, MI 48109-2122

Spectroscopic ellipsometry (SE) has been used to investigate transition layers for InGaAs/InP heterointerfaces. For the case of InGaAs on InP, we have found that the samples can be best modeled by a strained $In_xGa_{1-x}As$ film with the possible presence of a thin interface region (<15Å). We are unable to conclusively determine the existence of such a thin transition region. For InP on InGaAs, we find clear indications of As contamination in the bulk film, and that the addition of a thin interface region of $In_{0.75}Ga_{0.25}As_{0.5}P_{0.5}$ improves both the numerical fit and shape of the dielectric response curves, especially around E_1 and $E_1 + \Delta_1$, where the effects of a transition region are most pronounced. However, difficulties in modeling the dielectric response of the contaminated InP film make identification of an interface transition region only speculative at this point. Multiple single quantum well structures have also been grown and analyzed with 7K photoluminescence. The quality of the quantum wells shows strong dependence on the gas switching sequence used at the heterointerfaces. The best switching sequence produced a 0.5 nm well with a 7K FWHM of only 12.3 meV. Multiple quantum wells have also been grown to investigate the uniformity and repeatability of our system. Twenty period MQWs with a well width of 1.6 nm display a 14K FWHM of 7.9 meV.

Key words. Spectroscopic ellipsometry, chemical beam epitaxy, InGaAs, InP, Interfaces

The Low Temperature Catalyzed Chemical Vapor Depo and Characterization of Silicon Nitride Thin Films

Jeffrey L. Dupuie, Erdogan Gulari, and Fred Terry

The University of Michigan, Ann Arbor, Michigan 48109

ABSTRACT

Silicon nitride thin films have been grown via low pressure chemical vapor deposition at substrate temper- ing from 662 to 904 K by the catalytic action of a heated tungsten filament. A tungsten filament heated to 2020 to decompose ammonia, which reacted with silane introduced downstream of the filament to form silicon nitr- deposition rates between 50 and 250 nm/min. The resultant films were characterized by Fourier-transform inf- troscopy, x-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM), and spectroscopic el (SE). Infrared spectroscopy indicated that, under appropriate deposition conditions, the amount of bonded h- the films could be reduced to less than 3%. XPS sputter depth profiles showed that the level of oxygen in th. creased as the silane flow rate was increased. Oxygen free silicon nitride films were obtained at high silane flow - and SE were used to profile the films and to establish the thickness and composition of the bulk, surface, and layers. SEM confirmed the specular nature of the deposited silicon nitride films.

Hydrogen Sulfide Plasma Passivation of Gallium Arsenide

J. S. Herman, F. L. Terry, Jr.
Center for High Frequency Microelectronics
Electrical Engineering and Computer Science Dept.
University of Michigan
Ann Arbor, MI, 48109-2122

Abstract

Improvement in the electrical properties of the GaAs surface has been accomplished using a room temperature hydrogen sulfide plasma. The surface has then been protected by a 300° C plasma enhanced chemical vapor deposition (PECVD) SiO_2 film. This treatment is highly reproducible due to computer control of process parameters and long-lasting due to the SiO_2 cap. Improved C-V characteristics were observed, showing interface trap densities in the high 10^{11} $cm^{-2}eV^{-1}$ range. Photoluminescence (PL) measurements on the sulfided samples showed increased intensity over the untreated samples.

Hydrogen Sulfide Plasma Passivation of Indium Phosphide

J. S. Herman, F. L. Terry, Jr.
Center for High Frequency Microelectronics
Electrical Engineering and Computer Science Dept.
University of Michigan
Ann Arbor, MI, 48109-2122

Abstract

The electrical properties of the SiO_2-InP interface are improved using *in-situ* H_2S plasma pretreatments as a reliable method of sulfidizing the InP surface prior to film deposition. High frequency (1 MHz) and quasi-static C-V measurements on metal-insulator-semiconductor structures show reduced interface trap densities. X-ray photoemission spectroscopy analysis indicates that prior to film deposition, sulfur is bonded to phosphorus at the surface, but after film deposition very little sulfur remains. Spectroscopic ellipsometry measurements confirm that the interface does remain modified even after film deposition, and photoluminescence data shows increased signal intensity for thin SiO_2 film on InP with H_2S pretreatments as compared to untreated samples.

PLASMA PASSIVATION OF GALLIUM ARSENIDE

J. S. Herman, F. L. Terry Jr.

University of Michigan, Ann Arbor, MI, 48109-2122

A comparison is presented of various *in-situ* hydrogen based plasma surface treatments in conjunction with a PECVD SiO_2 film to examine the improvements that can be obtained in the SiO_2-GaAs interface. Hydrogen was used alone in a H_2 plasma, combined with nitrogen in either an NH_3 or sequential H_2/N_2 plasmas, or combined with sulfur in a H_2S plasma. Hydrogen removes the native oxides, then nitrogen or sulfur form passivating surface layers on the exposed GaAs surface. The H_2S plasma was operated at room temperature, while the other treatments were all performed at the SiO_2 deposition temperature (300° C).

Samples were characterized using metal-insulator-semiconductor C-V analysis, spectroscopic ellipsometry, and X-ray photoemission spectroscopy (XPS) for both surface scans and depth profiling. The H_2/N_2 and H_2S treated samples display improved C-V characteristics, exhibiting interface trap densities in the mid 10^{11} $cm^{-2}eV^{-1}$ range. However, tight control is required for the H_2 plasma in the H_2/N_2 sequence, since over-etching roughens the surface. XPS indicates the presence of nitrogen (from H_2/N_2) or sulfur (from H_2S) on the surfaces of the uncapped samples, although depth profiles show little evidence of these elements at the interface after SiO_2 deposition. H_2S plasmas offer the most robust passivation method, providing a self-terminating process that prevents GaAs surface roughening by hydrogen plasma etching.

After high temperature processing, i.e., RTA at 1000° C, GaAs samples treated with H_2S plasmas were found to be significantly doped n-type, presumably from sulfur diffusion. This was verified with electrochemical profiling. Excess sulfur doping has thus far prevented the development of a self-aligned MISFET technology using this technique. No such doping problems were observed after lower temperature processing, such as the 400° C ohmic contact anneal.

Differential Gain in InP-Based Strained Layer Multiple Quantum Well Lasers

D. Nichols and P. Bhattacharya

Solid State Electronics Laboratory,

Department of Electrical Engineering and Computer Science,

University of Michigan, Ann Arbor, MI 48109-2122

Abstract

Compressive biaxial strain has been predicted to enhance the small-signal modulation bandwidth of quantum well lasers, owing to increased differential gain in these devices. However, the effect of tensile strain on these devices is less clear. We have investigated the effects of both compressive and tensile strain on the differential gain for multiple quantum well lasers with $In_xGa_{1-x}As$ quantum wells for $0.33 \leq x \leq 0.73$. We observe markedly increased differential gain for both compressive and tensile strain, indicating that large modulation bandwidths can be obtained in both cases.

Observation of Multiple Resonance Frequencies in Stripe Geometry InGaAsP Quantum Well Lasers

Yeeloy Lam, Enrico Espinosa, Doyle Nichols, Larry Davis and Pallab Bhattacharya

Solid State Electronics Laboratory,

Department of Electrical Engineering and Computer Science,

The University of Michigan, Ann Arbor, Michigan 48109-2122

ABSTRACT

Intensity fluctuation noise in strained InGaAsP multi-quantum well lasers are analyzed in both ridge guided and broad-area gain-guided structures. A single resonance peak is observed in the noise spectrum for the ridge guided laser, as expected. However, the noise spectrum for the broad-area lasers shows multiple (~2–5) resonance peaks, *distinctly* spaced, from ~2 to ~5 GHz. Combining with near-field measurements, the experiments show that these peaks originate from lasing filaments having significantly *nonuniform* optical power. We also determined the resonance frequency of the single-mode laser from both small signal modulation and turn-on relaxation oscillation measurements, and found the results to be consistent with the measured peak noise frequency.

InP-Based Strained Quantum Well Lasers

D. Nichols and P. Bhattacharya

NO ABSTRACT AVAILABLE

Modulation Characteristics of InP-Based MQW Lasers: The Impact of Biaxial Compressive and Tensile Strain

D. Nichols, L. Davis, Y. Lam, E. Espinosa, J. Singh and P. Bhattacharya
Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, MI 48109-2122
Tel. (313) 763-6132, FAX (313) 747-1781

The application of biaxial strain to direct bandgap semiconductors has a profound impact on the bandstructure and, consequently, on the optoelectronic properties of these materials. These bandstructure changes result in significant changes in the operating characteristics of multiple quantum well lasers. These changes essentially result from bandstructure changes in the valence band due to the application of biaxial strain. The effective masses of the holes change appreciably as do the positions of the light and heavy hole bands in energy. By examining the output polarization, for instance, it is seen that lasing occurs in the heavy hole band for lattice-matched and compressively strained devices and in the light hole band for tensilely strained devices. In this paper, we relate observed modulation characteristics of strained $In_xGa_{1-x}As/InP$ ($0.33 \leq x \leq 0.73$) MQW-SCH lasers to properties of the bandstructures of biaxially strained $In_xGa_{1-x}As$ quantum wells. This work represents a systematic report of these characteristics *purely* as a function of strain.

The differential gain is an important factor in determining the intrinsic small signal modulation bandwidth of a semiconductor laser. Strain has an important effect on the differential gain and, thus, the modulation bandwidths of these devices. By examining output spectra of the lasers at various levels of drive current below threshold, the gain spectra were calculated and information on the differential gain extracted. The differential gain was found to increase significantly for both compressive and tensile strain with respect to its lattice-matched value. A value of $4.1 \cdot 10^{-16} cm^2$ was measured for lattice-matched devices while values of $7.7 \cdot 10^{-16} cm^2$ and $9.1 \cdot 10^{-16} cm^2$ for In concentrations of 0.33 and 0.73, respectively. This indicates that strained devices will have larger 3-dB bandwidths than their lattice-matched counterparts. We have made measurements of the microwave responses of both strained and lattice-matched devices and found that the bandwidths of of the lattice-matched devices are 3 GHz and 5 GHz for devices with 63 % In in the quantum wells. The intrinsic bandwidths of InP-based devices are somewhat lower than GaAs-based devices, due to differences in intrinsic material properties.

The spontaneous emission lifetime and relaxation oscillation frequency are important for understanding the upper limits in large signal and large signal modulation speed as well as the impact of Auger recombination rates on the carrier dynamics of these devices. It is possible to make an evaluation of the Auger coefficient by considering the alteration of the carrier lifetime with strain and cavity length. By measuring the turn-on delay time at various levels of drive current we have measured a spontaneous lifetime of 0.78 ns for compressively strained ridge waveguide devices. We have calculated Auger coefficients of 4.4 $\cdot 10^{-28} cm^{-6}/s$ for lattice-matched devices and 26 $\cdot 10^{-28} cm^{-6}/s$ for devices with 73 % In in the wells. We will compare these values with those arrived at experimentally. Devices with other In compositions have been fabricated and their turn-on delays are in the process of being measured. These results will be discussed..

Carrier Dynamics and Modulation Characteristics of InP-Based Strained Quantum Well Lasers

D. Nichols, L. Davis, Y. Lam, G. Munns, J. Loehr, J. Singh and P. Bhattacharya
Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, MI 48109-2122
Tel. (313) 763-6132, FAX (313) 747-1781

The application of biaxial strain to direct bandgap semiconductors has a profound impact on the bandstructure and, consequently, on the optoelectronic properties of these materials. Compressively strained quantum well lasers generally have improved performance characteristics over unstrained lasers. The improvements essentially result from the bandstructure changes in the valence band due to compressive strain. The InP-based system is uniquely well suited to a study of the effects of biaxial tensile as well as compressive strain upon device performance. In multiple quantum well separate confinement heterostructure (MQW-SCH) lasers, strain allows the output wavelength to be independent of the well width. In this paper, the results of our theoretical and experimental studies of the carrier dynamics and modulation properties of strained $In_xGa_{1-x}As/InP$ ($0.33 \leq x \leq 0.73$) MQW-SCH lasers grown by CBE are reported. It is important to mention that only the In concentration in the wells is varied in the various structures in order to isolate the effect of strain.

In order to calculate the device parameters of the strained quantum well laser accurately, we have developed a model that utilizes the 4×4 $\mathbf{k \cdot p}$ Hamiltonian, in which we include the effects of strain via the deformation potential theory, in order to calculate the laser gain spectra and the operating characteristics directly from the bandstructure. Using the calculated gain spectra and the multimode rate equations, a small-signal analysis was performed and the relaxation oscillation frequency, f_r, the threshold gain, the differential gain and 3-dB bandwidth were calculated as a function of strain. Having theoretically calculated the radia-

tive carrier lifetime, one can extract the lifetime due to Auger recombination by examining the turn-on delay time, which is related to the total carrier lifetime. For our experiments, MQW-SCH laser structures utilizing four 50Å $In_xGa_{1-x}As$ quantum wells sandwiched between 100Å InGaAsP barriers on semi-insulating InP have been grown by chemical beam epitaxy (CBE). These structures have been fabricated into ridge lasers. Measurements were made on these structures to determine the relaxation oscillation frequency, f_r, and the 3-dB bandwidth.

The measured threshold currents of the ridge lasers were 40 mA for the lattice matched devices and 20 mA for the devices with 63 % In in the wells. The calculated Auger rates are shown in Fig. 1. It is estimated that the turn-on will decrease by a factor of two using the Auger rates. From the measured relaxation oscillations (Fig. 2), f_r for x = 0.53 and 0.63 in the wells are 1.5 and 1.7 GHz respectively, which compares favorably with theoretical values of 2.8 GHz and 3.16 GHz. The corresponding 3-dB bandwidths were measured to be 2.8 GHz for lattice-matched devices and 4.8 GHz for devices with 63% In in the wells (Fig. 3). These also compare well with our theoretically calculated values of 5.0 and 5.5 GHz, respectively, and we will compare experimental data across a wider range of device parameters with the theory. An electrical bandwidth of 12 GHz is obtained from a microwave measurement on the laser diodes, suggesting that the bandwidths are intrinsic to the devices. Higher bandwidths can be obtained with higher power and more efficient heat dissipation. These issues will be discussed.

Work supported by the Army Research Office and the Office of Naval Research

A Study of Modulation Characteristics, Auger Coefficients and Filamentation related Noise Spectra in InP-based Strained Layer Quantum Well Lasers

Larry Davis, Yeeloy Lam, Doyle Nichols, Enrico Espinosa,
Jasprit Singh and Pallab Bhattacharya
Solid State Electronics Laboratory,
Department of Electrical Engineering and Computer Science,
The University of Michigan, Ann Arbor, Michigan 48109-2122
Tel. (313) 763-6132, FAX (313) 747-1781

ABSTRACT

The InP-based system is uniquely suited for investigating the properties of quantum well lasers with pseudomorphic active layers, allowing *both* tensile and compressive biaxial strain. In quantum well lasers, the resulting modification of the bandstructure has a dramatic impact on the most important operating characteristics, including the threshold current, the differential gain and the bandwidth. We have conducted a systematic investigation and have obtained the following novel results: 1) the Auger coefficients in *strained quantum wells* have been obtained from large signal measurements, 2) the small signal 3-dB bandwidths have been measured and correspond well to measured relaxation oscillation frequencies, and 3) the filamentary nature of broad area lasers has been correlated between the intensity noise spectra and the near-field emission patterns.

Large signal modulation experiments were carried out and a minimum turn-on time of 140 pS for a 250μm device at $3.8I_{th}$ was measured. We fit the experimental turn-on times to our theory in order to extract the Auger coefficient,C_a, for various cavity lengths. Furthermore, we use the fact that the Auger coefficient is independent of cavity length to verify our fit. For $In_{0.63}Ga_{.37}As$, we arrive at a value of C_a=7.0x10^{-30} cm^{6}s^{-1}. The relaxation oscillation frequency of the large signal transients was determined to be 4.5 GHz.

The modulation bandwidth of single mode devices is a very important property, and we have done a systematic study of the effect of strain on the modulation characteristics. Enhanced differential gain has been measured for *both* compressive and tensile strain, and this should lead to improved frequency performance. We have seen this demonstrated in measured 3-dB bandwidths of 2.8 GHz for lattice-matched devices and 4.8 GHz for devices with 10% excess Indium in the wells.

While the microwave modulation measurement itself does provide the 3-dB bandwidth of the laser *device*, this does not easily serve as an effective tool in probing the intrinsic characteristics and limits of the laser *structure*, due to extrinsic parasitics and heating effects. Although we observed that the relaxation oscillation frequency from large signal transients does provide equivalent bandwidth information, but the extrinsic parasitics similarly prevents the accurate extraction of the intrinsic temporal response. The parasitic effects can be circumvented through intensity noise measurement. We measured a resonance frequency of 3.9 GHz from the noise spectra for a single mode laser. In broad area lasers, we have observed multiple (~2-5) resonance peaks, *distinctly* spaced, from ~2 to ~5 GHz, in the noise spectrum. Combined with near field measurements, the experiments show that these

Role of Strained Layers in Improving the Structural Reliability of Quantum Well Lasers

Jasprit Singh and Pallab Bhattacharya
Solid-State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, MI 48109-2122, USA

Abstract

Recently, strained layer quantum well lasers have attracted attention for their low threshold performance. The effect of strain on the laser lifetime also appears to be very beneficial as found by a few experimental groups. In this paper we study the role of strain in defect generation and propagation in heterostructures. The theory is based on calculations of total energy of a strained system and the effects of defect propagation on this energy. We find that the presence of strain forces any defect trying to propagate into the active device region to follow a path along the unstrained cladding region. This is due to high energy cost of introducing defects into the strained region from the outside. The barrier to this defect introduction increases strongly with strain as long as the system is below critical thickness.

On the other hand the barrier for spontaneous dislocation generation is seen to be much lower in the strained system compared to the lattice matched system. Thus if the laser failure system is due to defects propagating into the active (quantum well) region, the strain is expected to greatly improve the laser lifetime. However, if the failure mechanism involves generation of dislocation loops in the active region, the strain would reduce the lifetime. The effects of strain values and strained layer thicknesses on these issues will be discussed.

Auger Recombination and Impact Ionization Rates in Pseudomorphic InGaAlAs/GaAs and InGaAs/InP

L. Davis, Y.C. Chen, D. Nichols, Y. Lam, J. Singh, and P.K. Bhattacharya
Solid State Electronics Laboratory,
Department of Electrical Engineering and Computer Science,
The University of Michigan, Ann Arbor, Michigan 48109-2122, USA
Tel. (313) 763-6132, FAX (313) 747-1781

ABSTRACT

Auger recombination and its inverse process, impact ionization, are important physical processes in semiconductors. The former strongly affect the performance of long wavelength quantum well lasers while the latter determines the performance of devices such as avalanche photodiodes (APDs), impact ionization avalanche transit time diodes(IMPATTs) and the voltage breakdown of field-effect transistors (FETs). Auger rates and impact ionization coefficients have been measured for bulk materials. No such measurement has been made for pseudomorphically strained semiconductors. Biaxial strain is known to change the bandgap, carrier effective masses and valence bandstructures. Consequently, we expect significant changes in the impact ionization and Auger rates in strained material. We have conducted an in-depth theoretical and experimental study of impact ionization in GaAs-based heterostructures and Auger and impact ionization rates in InP-based heterostructures for both tensile and compressive strain.

We have used a large signal analysis of strained InGaAs/InP multiquantum well separate confinement heterostructure (MQW-SCH) lasers in order to extract the Auger rates. The measurement was carried out over a number of cavity lengths, with the minimum measured turn-on time being 140 ps for a 250μm device at $3.8I_{th}$. We fit the measured delay times to our theory in order to extract the Auger coefficient,C_a, in the *strained quantum wells* for various cavity lengths. We use the fact that the Auger coefficient is independent of cavity length to verify our fit. For example, in $In_{0.63}Ga_{.37}As$, we arrive at a value of C_a=7.0x10^{-30} cm^{6}s^{-1}. We will present the data over the full range of compressively and tensilely strained ($0.33 \leq x \leq 0.73$) $In_xGa_{1-x}As$ wells.

A 4×4 $\mathbf{k}\cdot\mathbf{p}$ is used to study the effect of strain on the valence bandstructure for impact ionization. It is seen that the significant decrease in the hole masses causes an increase in the threshold energy for the electron impact ionization. This effect is especially important for systems where the strain is introduced *without* decreasing the bandgap of the material. In this case the threshold energies are found to increase by up to 20% as compared to the unstrained material with the same bandgap. We have measured impact ionization coefficients, α and β, in 150 Åpseudomorphically strained materials for the first time. The measurements were made on specially designed lateral p-i-n diodes. α and β in $In_{0.15}Ga_{0.63}Al_{0.22}As$/GaAs are found to be lower than those in $In_{0.2}Ga_{0.8}As$/GaAs and higher than those in GaAs. β is larger than α in all the samples. The results are discussed in terms of the changes in the bandstructure due to biaxial strain. The trend of these results is in excellent agreement with the theory. We have also conducted an investigation of the impact ionization rates in InP-based strained heterostructures.

The results for the Auger recombination and the impact ionization rates will be presented together with any correllation between the strain and the two processes.

Work supported by the Office of Naval Research and the Army Research Office

Key words: Auger recombination, impact ionization, pseudomorphic, heterostructures, quantum wells.

THERMOELECTRIC AND THERMO-COULOMB EFFECTS IN TUNNEL JUNCTIONS

M. Amman[1] *E. Ben – Jacob*[2] *J. L. Cohn*[3]

January 20, 1992

Abstract

We present a study of the thermoelectric effects in tunnel junctions. In particular we calculate the thermoelectric power coefficient S and the Peltier coefficient Π. For macroscopic junctions we demonstrate the sensitivity of S and Π to the structure of the density of states. For mesoscopic junctions we show that Coulomb effects modify the ordinary Onsager picture and the relation $\Pi = TS$. The coefficients S and Π are found to be very sensitive to the coupling of the junctions to the external world. We comment on the relevance of these effects to scanning tunneling microscope measurements.

[1]Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA

[2]School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel-Aviv University, 69978 Tel-Aviv, Israel

[3]Naval Research Laboratories, Washington, DC 20375, USA

Delay Macromodels for Point-to-Point MCM Interconnections *

Ayman I. Kayssi and Karem A. Sakallah

Advanced Computer Architecture Lab
Department of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, MI 48109-2122

1 Introduction

Timing analysis is an essential step in the design of high-performance, MCM-based computer systems. Accurate delay models are needed for MCM interconnect to alleviate the need to do circuit or transmission line simulations. In this paper we use *dimensional analysis* to develop a macromodel for point-to-point MCM interconnect delay, which applies to lossless and lossy lines, and show the macromodel to be accurate to within 5% of HSPICE, at five orders of magnitude speedup in computation time.

Synthesis and Verification of a GaAs Microprocessor from a Verilog Hardware Description

R. Brown, A. Chandna, T. Hoy, T. Huff,
R. Lomax, T. Mudge, D. Nagle,
K. Sakallah, R. Uhlig, and M. Upton

Advanced Computer Architecture Laboratory
Solid State Electronics Laboratory
The University of Michigan
Ann Arbor, Michigan

K. Olukotun

CIS, Stanford University
Stanford, California

D. Johnson

Cascade Design Automation Corporation
Bellevue, Washington

Abstract

The University of Michigan Gallium Arsenide MIPS Project is using Verilog in the design of a 250 MHz MIPS architecture microprocessor. The design system is based on a single Verilog model which is used for simulation, synthesis, and hardware verification. The model is composed of a mixture of Register Transfer Level (RTL) and behavioral descriptions. Datapaths are represented by RTL structural components, while the control logic has behavioral descriptions.

To simplify verification and test development, a number of operating system functions have been implemented using the Verilog PLI (Programming Language Interface). These functions allow the model to load and execute programs compiled for the DECstation 5000. To ensure the model's functional correctness, a verification tool compares simulation results against the execution of an physical MIPS processor. Any inconsistencies are flagged as errors. Once the model is deemed functionally correct, it is synthesized into a logic level implementation. Datapath logic, described at the register transfer level, is directly mapped into a netlist for automatic placement and routing. The control logic is translated to the Finesse logic synthesis language. The Finesse compiler then synthesizes each control block into a netlist which is passed to the physical design tools from Cascade Design Automation (CDA) for final layout.

The combination of front-end verification and back-end synthesis results in a very short design time. Our first chip, Aurora I, was completed by a team of 5 graduate students in about 5 months, including tool development and library cell layout.

IMPACT OF MCMs ON SYSTEM PERFORMANCE OPTIMIZATION*

A. I. Kayssi, K. A. Sakallah, R. B. Brown, R. J. Lomax, T. N. Mudge, and T. R. Huff
Department of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, MI 48109-2122

Abstract *We present a performance model for the University of Michigan MCM-based GaAs microcomputer. The model takes into account architectural as well as MCM packaging considerations such as the chip-to-substrate bonding method, the dielectric constant of the insulator, and the resistivity of the metal conductor. We illustrate the use of the model by finding the I-cache size which maximizes the MIPS rating for given MCM technology parameters.*

Performance Optimization of Pipelined Primary Caches *

Kunle Olukotun
Computer Systems Laboratory
Stanford University, CA 94305
email: kunle@mojave.stanford.edu
tel: 415-725-3713

Trevor Mudge
Dept. Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, MI 48109
email: tnm@eecs.umich.edu
tel: 313-764-0203

Richard Brown
Dept. Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, MI 48109

Abstract

In new high-end processors, the critical path is through cache rather than through the ALU. This paper explores pipelining of primary cache to optimize performance of a GaAs implementation of the MIPS architecture. Long traces of multiprogrammed applications are used to evaluate instruction and data caches having various pipeline depths, cache sizes, block sizes, and refill penalties. Several representative strategies are considered for hiding the branch and load delays which result from pipelining cache access. We show that software-based methods for mitigating the penalty of branch delays can be as successful as the hardware-based *branch target buffer* approach, despite the code-expansion inherent in the software methods. The situation is similar for load delays; while hardware-based dynamic methods hide more delay slots than do static approaches, they may give up the advantage by extending the basic machine cycle. Because these methods are quite successful at hiding branch and load delays, and because pipelined caches allow faster CPU clock times and larger caches, a significant performance advantage is seen in pipelining cache access.

*This work was supported by Defense Advanced Research Projects Agency under DARPA/ARO Contract No. DAAL03-90-C-0028

Compound Semiconductor Device Requirements for VLSI

R. B. Brown, A. Chandna, T. R. Huff, R. J. Lomax, T. N. Mudge, R. Oettel *, and M. Upton

Department of Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, Michigan 48109-2122

Cascade Design Automation *
Bellevue, Washington 98006

Since the introduction of GaAs circuits, high-performance digital systems have been considered a major application area for compound semiconductor technology. Early overoptimistic predictions of the digital GaAs performance advantage over silicon, followed by the fabrication challenges of this immature technology, caused a negative reaction among system designers which hindered acceptance of GaAs. Only recently has the promise for high-speed VLSI in GaAs begun to be fulfilled.

For example, we have prototyped a simplified version of a MIPS RISC (reduced instruction set computer) microprocessor, which is implemented with 60,500 transistors in the Vitesse 0.8-μm HGaAs II process [1]. (See Fig. 1.) This chip, called Aurora, was packaged in a 344-pin package which required a frame size of 12.175 x 7.941 mm. Aurora includes a control section, a 3-port register file and a 5-stage pipeline with these functions: instruction fetch, operand read, ALU execution, memory load/store, and write back to the register file. It can execute 10 3-operand ALU operations, 8 immediate instructions, and 8 branch and jump instructions. Though this first prototype was not optimized for speed, it still operates at 137 MHz. While this speed is far from what is possible in the technology, it does compare favorably with the CMOS R3000 and ECL R6000 versions of the MIPS architecture, which operate at 40 and 62.5 MHz, respectively. A second version of the CPU has been implemented in the 0.6-μm HGaAs III process. It includes more functionality and is optimized for speed.

The digital market for GaAs was initially smaller and slower to develop than the microwave and analog areas, but it is now as large, and growing faster, at a compound annual rate of over 45% per year [2]. Digital GaAs circuits are being delivered in supercomputers, signal processors, and telecommunications systems. Future digital growth will come in high-end engineering workstations and in the replacement of high-speed analog circuits. Because of the potential size of the digital market, it is important for compound semiconductor device researchers to understand the process requirements of VLSI circuits.

The attention given to transistor switching time can obscure other equally important characteristics of a process. Unless certain minimum requirements are met in these other parameters, a process is still not viable for digital systems. The first issue to be considered is integration level. The 'package delay' associated with getting signals through an output buffer, off-chip interconnect, and an input buffer can account for a large percentage of the clock cycle time in high-performance systems, even when the most advanced multichip-module packaging is used. This means that a slower technology which has high enough integration levels to keep the critical path on one chip can outperform a faster technology which includes chip-crossings in the critical path. Pipelining and judicious partitioning can partially ameliorate the problem, but still, many applications will require 100,000 to 1,000,000 devices on a chip.

Integration level is, in turn, dependent on yield, power dissipation, active device area, logic style efficiency, and interconnect density. Yield is a function of material defect density, process complexity, and other factors inherent in each technology, which influence the level of transistor parameter control that can be maintained. Most potential applications for digital GaAs require air cooling. Power dissipation, therefore, becomes the integration limiting parameter for many high-speed processes. On-chip interconnect presents a number of the most important issues for VLSI. In large circuits, the layout density is usually controlled by metallization parameters. Some technologies are more sensitive to the parasitic loading of interconnect than others. Furthermore, wire-delays remain about constant whether the propagation delays of the gates driving them are fast or slow; in high-speed technologies, circuit delays are often dominated by interconnect.

Other system-level issues, such as noise margins and sensitivity to variations in power supply and temperature, must also be considered. And finally, in VLSI design, the practicality of a given technology is also dependent on the design tools available for it. In addition to proper management of the complexity of large designs, such tools should efficiently place and route modules, minimizing interconnect length on critical paths, they should optimally size buffers for their loads, and they should support accurate simulation of the circuits and interconnect. Use of such design automation tools can improve performance of a circuit in a given technology by a significant margin.

In summary, device development for digital applications should be guided by all of these considerations in addition to switching speed. It is the performance of compound semiconductors in systems, not ring-oscillator speeds, that will dictate their future in digital applications.

---

[1] R. B. Brown, et al., "GaAs RISC Processors," to be presented at 1992 IEEE GaAs IC Symposium, Miami Beach, FL, USA.

GaAs RISC Processors

R. B. Brown, P. Barker, A. Chandna, T. R. Huff, A. I. Kaysi, R. J. Lomax,
T. N. Mudge, D. Nagle, K. A. Sakallah, P. J. Shernan, R. Uhlig, and M. Upton

Department of Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, Michigan 48109-2122
Phone: 313-763-4207 FAX: 313-747-1781

Intense competition in the engineering workstation computer market has resulted in a performance/price increase of 3 orders of magnitude in the past decade. The performance of these systems is largely dependent on the speed and interconnections of a few integrated circuits, which, in the most successful implementations, include reduced instruction-set computer (RISC) processors. The merits of various technologies for implementing these chip sets will continue to be debated. One GaAs logic family which has achieved the integration levels needed to make it a practical choice for RISC chip-sets is DCFL (direct-coupled FET logic) [1]. The workstation application demands not only ever-increasing system throughput, but also air cooling. At high clock frequencies, DCFL is more power efficient than CMOS. However, DCFL logic gate structures are very restrictive compared to CMOS; ratioing, limited fan-in and fan-out, lack of dynamic circuits and complex gates, and only limited use of pass gates and stacked transistors make the circuits less efficient.

To explore the potential of very large scale integration in GaAs, our group has designed and tested a prototype MIPS-architecture microprocessor, named Aurora. This is the first of three CPU chip designs which we will implement. The third of these prototypes will be packaged on an MCM with cache, a floating point accelerator (FPA), and a memory management unit (MMU), and will run a conventional UNIX environment. In this project, we are addressing three topics which are required to achieve the optimum performance in a GaAs RISC processor:

- The architecture must be adjusted to fit the technology,
- Appropriate packaging must be used, and
- The design methodology must minimize parasitic loading.

We have made many changes to the MIPS architecture to better fit the implementation technology [2]. Our work includes MCM design and modeling [3]. And our chips are being designed with a GaAs circuit compiler which generates layout comparable to full-custom [4].

The first of our CPU prototypes was designed to exercise the CAD tools during their development. It executes 28 of the instructions from the MIPS instruction set. The chip is restricted to full-word load and store instructions. It has a fully functional ALU, a 3-port register file and set-on-less-than logic, allowing execution of 10 3-operand ALU operations, 8 immediate instructions, and 8 of the branch and jump instructions. Compared to a MIPS R3000, the functions not implemented in this first CPU include shifting, traps, stalls, system calls, integer multiply/divide and cache control.

Aurora was designed by five graduate students in just five months (including much work on the CAD tools). It was not optimized for speed; no buffer sizing or minimization of critical path length was done. The chip, which is implemented in the Vitesse 0.8-μm HGaAs II process, includes 60,500 transistors and dissipates 11 watts. (See Fig. 1.) It was packaged in a 344-pin package which required a frame size of 12.175 x 7.941 mm. Aurora has one human design error which disables some output pins; fortunately, the scan chain allows complete testing despite the error. The chip is otherwise fully functional. The fastest chip tested operates at 137 MHz. While this speed is far from what is possible with DCFL, it does compare favorably with the CMOS R3000 and ECL R6000 versions of the MIPS architecture, which operate at 33 and 62.5 MHz, respectively.

The RISC processor chip set being developed in this project is helping to identify the challenges and opportunities of VLSI GaAs. DCFL has achieved the integration levels and yields needed to implement this type of design. When the microarchitecture is adjusted to fit the technology, appropriate packaging is used, and an efficient design methodology is employed, DCFL is a serious contender for large, high-performance digital designs.

---

[1] *Foundry Design Manual – Version 5.0*, Vitesse Semiconductor Corporation, Camarillo, CA, 1991.

[2] T. N. Mudge, R. B. Brown, W. P. Birmingham, J. A. Dykstra, A. I. Kaysi, R. J. Lomax, O. A. Olukotun, K. A. Sakallah, and R. Milano, "The Design of a Micro-Supercomputer," IEEE Computer Magazine, Vol. 24, No. 1, January 1991, pp. 57–64.

[3] Ayman I. Kaysi and Karem A. Sakallah, "Delay Macromodels for Point-to-Point MCM Interconnections," Proceedings of the 1992 MCM Conference, March 1992, pp. 79-82.

[4] M. Upton, T. Hoy, T. Huff, R. Brown, R. Oettel and M. Rossman, "Module Generation for a GaAs Microprocessor," *Technical Digest* ... PA, May 20–22, 1991, pp. 88-94.

AN ON-CHIP ECC CIRCUIT FOR CORRECTING SOFT ERRORS IN DRAM'S WITH TRENCH CAPACITORS

P. Mazumder
Dept. of Electrical Engineering and Computer Science
University of Michigan Ann Arbor, MI 48109

ABSTRACT

This paper proposes a modified error-correcting code which can correct up to two soft errors on each row (word-line) in a dynamic random-access memory (DRAM) chip. Double-bit soft errors frequently occur in DRAM cells with trench capacitors, when charged alpha particles impinge on the intervening space between two vertical capacitors causing plasma shorts between them. The conventional on-chip error-correcting codes (ECCs) cannot correct such double-bit/word-line soft errors, which significantly increase the uncorrectable error rate (UER). The paper presents an ECC circuit that employs an augmented rectangular product code to detect and correct double-bit soft errors. The proposed circuit automatically corrects the addressed bit if it is faulty, and then quickly locates the other faulty bit. A comprehensive study is made to estimate improvements in soft error rate (SER) and mean time to failures (MTTF). The ability of the circuit to correct soft errors in the presence of multiple-bit errors has also been analyzed by combinatorial enumeration.

WOLVERINES: STANDARD CELL PLACEMENT ON A NETWORK OF WORKSTATIONS

S. Mohan and P. Mazumder
Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, MI 48109

Abstract

The typical computer-aided design environment today consists of a number of workstations connected together by a high-speed local area network. While many CAD systems make use of the network to share files or design databases, few, if any, CAD programs make use of this distributed computing resource to parallelize and speed up their work. This paper presents a placement program that makes use of this distributed computing environment to achieve linear speedup without sacrificing the quality of the results obtained by the serial version of the program. The placement program is based on the genetic algorithm which is a heuristic search method inspired by biological evolution models. The parallel implementation has other desirable features such as the ability to operate in a heterogeneous network environment and dynamic and static load balancing. This paper describes the implementation of the placement program and detailed experimental studies of the behavior of the algorithm.

NEURAL COMPUTING FOR BUILT-IN SELF-REPAIR OF EMBEDDED MEMORY ARRAYS

P. Mazumder and J. S. Yih

Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, MI 48109

Abstract

As VLSI chip size is increasing, more and more circuit components are becoming inaccessible for external testing, diagnosis and repair: Memory devices are abundantly used in VLSI chips, and repairing partially faulty arrays by the available spare rows and columns is a very difficult problem. Conventional memory repair algorithms cannot be readily implemented within the VLSI chip to diagnose and repair these faulty memory arrays. Intelligent hardware based on a neural-network model provides an effective solution for such built-in self-repair applications. This paper clearly demonstrates how to represent the objective function of the memory repair problem as a neural network energy function, and how to utilize the neural net's convergence property to find optimal solutions. Two algorithms have been developed using a neural network, and their performance is compared with the Repair Most algorithm that is commercially used. For randomly generated defect patterns, the proposed algorithm with a hill climbing capability has been found to be successful in repairing memory arrays in 98% cases, as opposed to Repair Most's 20% cases. The paper also demonstrates how to implement this algorithm within the chip for built-in self-repair.

Keywords: Reconfiguration, Self-Repair, Embedded Memory, Yield Improvement, Neural Networks.

Restructuring WSI Hexagonal Processor Arrays

R. Venkateswaran, Student Member IEEE, Pinaki Mazumder,
Member IEEE,
Kang G. Shin, Fellow IEEE

Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, Michigan 48109–2122 [1]
Phone Number: 313-763-2107

Abstract

Fault-tolerant approaches have been widely employed to improve the yield of ULSI and WSI processor arrays. In this paper, we propose a host-driven reconfiguration scheme, called *HEX-REPAIR*, for hexagonal processor arrays characterized by a large number of relatively simple cells. Such arrays have been shown to be the most efficient for many digital signal processing applications such as matrix multiplication and for some classes of filtering operations. Reconfiguration for these arrays is made difficult by the asymmetric nature of the interconnection network and the need for keeping the switching overheads at a minimum. The algorithm presented in this paper meets these requirements. In addition, it has excellent fault-coverage characteristics even in the presence of multiple faults and can accommodate multiple rows/columns of spare cells. The restructured array is transparent to the users and no modification is required in any application program using the array.

Keywords: Cover Table, H (V) Lines, Hexagonal Processor Arrays, Horizontal Cover Graph, Reconfiguration by Table Lookup, Vertical Cover Graph.

[1]This research was partly supported by the Army Research Office under the URI program grant number DAAL 03-87-K-0007.

NUMERICAL MODELING OF ABRUPT HETEROJUNCTIONS USING A THERMIONIC-FIELD EMISSION BOUNDARY CONDITION

Kyounghoon Yang, Jack R. East and George I. Haddad
Solid State Electronics Laboratory
Department of Electrical Engineering and Computer Science,
The University of Michigan, Ann Arbor, Michigan 48109-2122

Abstract

We present a numerical model in which the thermionic and tunneling mechanisms across an abrupt heterojunction interface are taken into account on the basis of the one dimensional drift-diffusion formulation. We use an expression of thermionic-field emission current formulated based on the WKB approximation as a boundary condition at the abrupt heterointerface which eventually limits the current transport over the barrier while maintaining the current continuity. The I-V characteristics of three types of GaAs/AlGaAs heterojunctions are analyzed by varying device dimension, doping density, and temperature and compared with those obtained by the thermionic emission model to illustrate the significance of both tunneling and thermionic emission mechanisms. We demonstrate that the role of tunneling in the overall current transport is very important in these abrupt heterojunctions especially at high doping densities and low temperatures. In the case of an MBE-grown AlGaAs triangular heterojunction barrier, the temperature-dependent I-V characteristics are measured and compared with the theoretical results. Good agreement is obtained when the tunneling process is taken into account by employing the thermionic-field emission boundary condition presented here.