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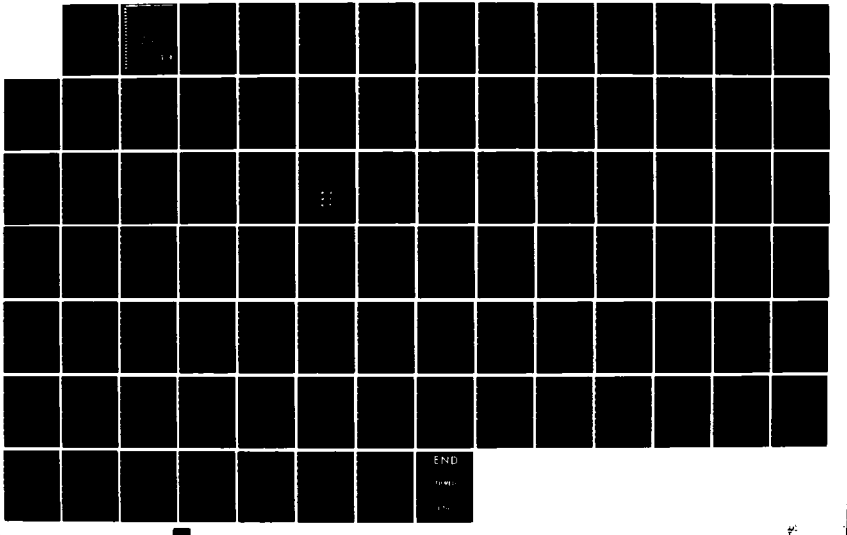

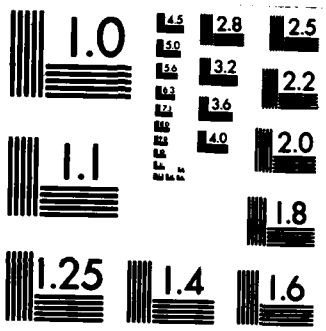

PROGRESS REPORT
FOR THE
JOINT SERVICES
ELECTRONICS PROGRAM

FOR THE PERIOD
JULY 1, 1984 THROUGH MARCH 31, 1985

FOR
CONTRACT N00014-84-C-0149

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

OFFICE OF NAVAL RESEARCH

PROGRESS REPORT

FOR

1 October 1984 through 30 March 1985

for

Contract N00014-84-C-0149

Title of Contract
Joint Services Electronics Program

Name of Principal Investigator
Timothy N. Trick
Coordianted Science Laboratory

Name of Organization
THE BOARD OF TRUSTEES OF THE UNIVERSITY OF ILLINOIS
Grants and Contracts Office

Address of Organization
506 S. Wright Street
Urbana, IL 61801

TABLE OF CONTENTS

WORK UNIT NUMBER 1

TITLE: Molecular Beam Epitaxy

SENIOR PRINCIPAL INVESTIGATORS:

H. Morkoç, Research Associate Professor

M.V. Klein, Research Professor

A.Y. Cho, Research Adjunct Professor

SCIENTIFIC PERSONNEL AND TITLES:

K.-T. Tsen, Research Associate
Dean Levi, Research Assistant
R. Fischer, Research Assistant
C.K. Peng, Research Assistant

SCIENTIFIC OBJECTIVE:

The objective of this work is to use mostly optical techniques to study quantum tunneling structures, quantum wells, semiconductor superlattices and alloys grown by MBE (and occasionally other techniques such as multitarget r.f. sputtering). Of primary interest are the effect of superlattice layering and alloy disorder on the phonon Raman and infrared spectra. Also of interest is the time-dependence of phonon and electronic Raman spectra of quantum wells following excitation with a picosecond laser pulse.

SUMMARY OF RESEARCH:

Our Raman study of phonons in GaAs/AsGaAs superlattices, where the phonons propagate normal to the interfaces, has shown that the longitudinal acoustic modes propagate through the interfaces with only small zone-folding effects. On the other hand, the optical modes show strong confinement (much stronger than that for electrons or holes). This work is currently being extended to a Raman study of phonons propagating parallel to the interfaces.

Raman spectra of metastable GaSb-Ge alloys grown by rf sputtering show anomalously broad and asymmetric peaks, whereas metastable GaAs-GaSb alloys show more normal behavior.

Two synchronously-pumped, mode-locked picosecond dye lasers were used to study carriers in undoped GaAs-AlGaAs quantum wells by pulse-probe Raman scattering. Preliminary results show that the higher subband levels empty in about 50ps, whereas the two lowest levels take several hundred picoseconds to empty.

Multiple and single quantum wells of varying well sizes were investigated in detail. Growth conditions, source type was optimized which led to the achievement of extremely sharp transitions. As a result identification of various transitions were made possible for the first time. The same samples were also studied under hydrostatic pressure, under high excitation pump and probe configuration, and in the presence of electric field both parallel and perpendicular to the interfaces. In addition both donor doped and acceptor doped samples were investigated. The quantum wells are currently being investigated under extremely low cw and pulsed excitation conditions. We as a result generated a wealth of

information regarding not only the origin of various transitions but also on the nature of crystal growth and island formation.

PUBLICATIONS:

Journal Articles:

1. L. P. Erickson, T. J. Mattord, G. L. Carpenter, OP. W. Palmberg, P. J. Pearah, M. V. Klein, and H. Morkoç "Effect of substrate temperature on molecular beam epitaxial GaAs growth using As2," *J. Appl. Phys. 56*, pp. 2231-2235, 1984. (JSEP)
2. C. Colvard, T. A. Gant, M. V. Klein, R. Merlin, R. Fischer, H. Morkoç and A. C. Gossard, "Folded acoustic and quantized optic phonons in (GaAl)As superlattices," *Phys. Rev. B 3l*, pp. 2080-2091, 1985. (JSEP)
3. Y. L. Sun, R. Fischer, M. V. Klein, and H. Morkoç "Photoluminescence of $Al_{0.4}Ga_{0.6}As$/GaAs quantum well structures prepared by molecular beam epitaxy," *Thin Solid Films*, vol. 112, pp. 213-215, 1984 (NSF/JSEP).
4. R. Fischer, J. Klem, T. J. Drummond, H. Morkoç E. Anderson, and M. Pion, "Improved AlGaAs/GaAs bulk lasers with superlattice interfaces," *Appl. Phys. Letts.*, vol. 44, pp. 1-3, 1984 (McDonnel Douglas/JSEP/AFOSR).
5. M. Teicher, R. Beserman, M. V. Klein, and H. Morkoç "Crystalline structure of mixed $GaP_{1-x}Al_xAs$ and $GaP_{1-x}As$ crystals," *Phys. Rev. B.*, vol. 29, pp. 4652-4658, 1984 (JSEP).
6. T. W. Hickmott, P. M. Solomon, H. Morkoç and R. Fischer, "Resonant Fowler-Nordheim tunneling in n-GaAs-undoped $Al_xGa_{1-x}As$—n^+GaAs capacitors," *Appl. Phys. Lett.*, vol. 44, pp. 90-93, 1984 (JSEP).
7. R. Fischer, Y. L. Sun, W. T. Masselink, J. Klem, M. V. Klein, and H. Morkoç "Improvements in MBE grown AlGaAs/GaAs single quantum well structures resulting from dimeric arsenic," *Jpn. J. Appl. Phys.*, vol. 23, pp. L126-L128, 1984 (JSEP/AFOSR/ONR).
8. W. T. Masselink, Y. L. Sun, R. Fischer, T. J. Drummond, Y. C. Chang, M. V. Klein , and H. Morkoç "Enhanced luminescence from AlGaAs/GaAs single quantum well structures through improved interfaces," *J. Vacuum Science and Technol.*, vol. B2, pp. 117-122, 1984 (JSEP/AFOSR/ONR/NSF).
9. Y. L. Sun, W. T. Masselink, R. Fischer, M. V. Klein, H. Morkoç and K. Bajaj, "Influence of arsenic species and growth temperature on the properties of AlGaAs/GaAs multiple quantum wells," *J. Appl. Phys.*, vol. 55, pp. 3554-3556, 1984 (JSEP/AFOSR/NSF).
10. R. Fischer, W. T. Masselink, Y. L. Sun, T. J. Drummond, Y. C. Chang, M. V. Klein, H. Morkoç and E. Anderson, "Improvement of the GaAs/AlGaAs heterointerface by the use of a graded superlattice," presented at the 5th Annual MBE Workshop, Atlanta, Oct. 6-7, 1983, *J. Vacuum Sci. and Technol.*, vol. B2, pp. 170-174, 1984 (AFOSR/JSEP/NSF).
11. T. W. Hickmott, P. M. Solomon, F. Fang, F. Stern, R. Fischer, and H. Morkoç "Sequential single phonon emission in $GaAs/Al_xGa_{1-x}As$ tunnel junctions," *Phys. Rev. Lett.*, vol. 52, pp. 2053-2056, 1984 (JSEP).
12. N. Chand, T. Henderson, J. Klem, W. T. Masselink, R. Fischer, Y. C. Chang, and H. Morkoç "Comprehensive analysis of Si doped $Al_xGa_{1-x}As$ (x=0 to 1): Theory and experiments," *Phys. Rev. B*, vol. 30, pp. 4481-4492, 1984 (AFOSR/JSEP).

Conference Papers:

1. C. Colvard, R. Fischer, T. A. Gant, M. V. Klein, R. Merlin, H. Morkoç and A. Gossard, Phonon freedom and confinement in GaAs—$Al_xGa_{1-x}As$ superlattices, *Superlattices and Microstructures*, vol. 1, p. 81, 1985. (JSEP)
2. R. Beserman, J. E. Greene, M. V. Klein, T. N. Krabach, T. C. McGlinn, L. T. Romano, and S. L. Shah, Raman scattering from metastable $(GaSb)_{1-x}Ge_{2x}$ alloys, *Proceedings of the 17th International Conference on the Physics of Semiconductors*, August 6-10, 1984, San Francisco, CA, to be published. (JSEP)
3. M. V. Klein, C. Colvard, R. Fischer, and H. Morkoç Raman probing of phonons and interfaces in semiconductor superlattices, *Proc. of Int. Conf. on the Dynamics of Interfaces*, September 12-14, 1983, Lille, France, *Journal de Physique*, vol. 45, no. 4, Colloque C5, pp. 131-137, 1984 (JSEP/AFOSR).
4. T. W. Hickmott, P. M. Solomon, F. F. Fang, R. Fischer, and H. Morkoç *Proc. International Conference of Physics of Semiconductors*, San Francisco, Aug. 6-10, 1984 (JSEP).

PUBLICATIONS (OTHER SUPPORT):

Journal Articles:

1. H. Morkoç and P. M. Solomon, "The HEMT: A superfast transistor," *IEEE Spectrum*, vol. 21, no. 2, pp. 28-35, February 1984 (AFOSR).
2. H. Morkoç and P. M. Solomon, "MODFET - Superschennelle transistoren," *Technische Rundschou TR 10*, 77 Jahrgang, pp. 74-79, 1985 (AFOSR).
3. K. Lee, M. S. Shur, T. J. Drummond, and H. Morkoç "Parasitic MESFET in (Al,Ga)As/GaAs modulatrion doped FETs and MODFET characterization," *IEEE Trans. on Electron Dev.*, vol. ED-31, pp. 29-35, 1984 (AFOSR).
4. T. J. Drummond, W. Kopp, R. Fischer, and H. Morkoç "The superlattice barrier capacitor: A structure for the investiation of heterojunction interfaces," *IEEE Electron Dev. Lett.*, vol. EDL-5, pp. 139-141, 1984 (AFOSR).
5. T. J. Drummond, R. Fischer, J. Arnold, H. Morkoç and M. S. Shur. "Current-voltage and capacitance-voltage characteristics of a metal/$Al_{0.5}Ga_{0.5}As$/GaAs capacitor," *Appl. Phys. Lett.*, vol. 44, pp. 214-216, 1984 (AFOSR).
6. T. J. Drummond, R. Fischer, W. Kopp, D. Arnold, J. Klem, H. Morkoç and M. S. Shur, "Temperature dependence of Al/undoped $Al_{0.5}Ga^{0.5}As$/GaAs capacitors," *IEEE Electron Dev.*, vol. ED-31, pp. 1164-1168, 1984 (AFOSR).
7. K. Lee, M. S. Shur, T. J. Drummond, and H. Morkoç "Charge control model of inverted GaAs-AlGaAs modulation doped FETs (IMODFETs)," *J. Vacuum Sci. and Technol.*, vol. B2, pp. 113-116, 1984 (AFOSR).
8. T. Henderson, W. Kopp, R. Fischer, J. Klem, H. Morkoç L. P. Erickson, and P. W. Palmbert, "Large capacity As_2 source for molecular beam epitaxy," *Rev. Sci. Instr.*, vol. 55, p. 1763, 1984 (AFOSR).
9. D. Arnold, W. Kopp, R. Fischer, T. Henderson, and H. Morkoç "Microwave performance of GaAs MESFETs with AlGaAs buffer layers: effect of heterointerfaces," *IEEE Electron Dev. Lett.*, vol. EDL-5, pp. 82-84, 1984 (AFOSR).
10. D. Arnold, W. Kopp, R. Fischer, J. Klem, and H. Morkoç "Bias dependence of capacitances in modulation doped FETs at 4 GHz," *IEEE Electron Dev. Lett.*, vol. EDL-5, pp. 123-125, 1984 (AFOSR).

11. L. P. Erickson, T. J. Mattord, G. L. Carpenter, Op. W. Palmberg, P. J. Pearah, M. V. Klein, and H. Morkoç, "Effect of substrate temperature on molecular beam epitaxial GaAs Growth Using As_2," *J. Appl. Phys., vol. 56, pp. 2231-2235, 1984 (AFOSR).*

12. D. Arnold, R. Fischer, W. Kopp, T. Henderson, and H. Morkoç, "Microwave characterization of (Al,Ga)As/GaAs modulation doped FETs: Bias dependence of small signal parameters," *IEEE Trans. on Electron. Dev.*, vol. ED-31, pp. 1399-1402, 1984 (AFOSR).

13. R. Fischer, T. J. Drummond, J. Klem, W. Kopp, T. Henderson, D. Perrachionne, and H. Morkoç, "On the collapse of drain I-V characteristics in modulation doped FETs at cryogenic temperatures," *IEEE Trans. on Electron Dev.*, vol. ED-31, pp. 1028-1032, 1984 (AFOSR).

14. A. A. Grinberg, M. S. Shur, R. Fischer, and H. Morkoç, "An investigation of the effect of graded layers and tunnelling in the performance of $Al_xGa_{1-x}As$/GaAs heterojunction bipolar transistors," *IEEE Trans. on Electron Dev*, vol. ED-31, pp. 1758-1765, 1984 (AFOSR/DARPA).

15. J. Klem, R. Fischer, W. T. Masselink, W. Kopp, and H. Morkoç, "GaAs/$GaAs_{1-y}Sb_y$ superlattice light emitting diodes," *J. Appl. Phys.*, vol. 55, pp. 3843-3845, 1984 (AFOSR).

16. D. C. Reynolds, K. K. Bajaj, C. W. Litton, P. W. Yu, W. T. Masselink, R. Fischer, and H. Morkoç, "Sharp line photoluminescence spectrum from GaAs-GaAlAs multi-quantum well structures," *Phys. Rev. B*, vol. 29, pp. 7038-7040, 1984.

17. K. Lee, M. S. Shur, J. Klem, T. J. Drummond, and H. Morkoç, "Parallel conduction correction to measured room temperature mobility in (Al,Ga)AsGaAs modulation doped layers," *Jpn. J. Appl. Phys. Lett.*, vol. 23, pp. L230-231, 1984 (AFOSR).

18. D. C. Reynolds, K. K. Bajaj, C. W. Litton, D. E. B. Smith, P. W. Yu, W. T. Masselink, R. Fischer, and H. Morkoç, "Discrete donor-acceptor pair spectrum in GaAs," *Solid State Comm.*, 52:7, pp. 685-688, 1984.

19. T. Henderson, P. Pearah, H. Morkoç and B. Nilsson, "Transient annealing of modulation doped GaAs/AlGaAs heterostructures," *Electron. Lett.*, vol. 20, pp. 371-372, 1984 (USAFWAL).

20. W. T. Masselink, Y. C. Chang, and H. Morkoç, "Binding energies of acceptors in GaAs/AlGaAs quantum wells," *J. Vacuum Sci. and Technol.*, vol. B2, pp. 376-382, 1984 (AFOSR/ONR).

21. D. Arnold, R. Fischer, J. Klem, F. Ponse, and H. Morkoç, "Reduction of backgating in GaAs/AlGaAs MESFETs by optimization of the active layer-buffer layer interface," *Electron. Lett.*, vol. 20, pp. 376-378, 1984 (AFOSR).

22. P. M. Solomon and H. Morkoç, "Modulation doped GaAs/AlGaAs heterojunction field effect transistors (MODFETs): Ultra high speed device for super computers," *IEEE Trans. on Electron Dev.*, vol. ED-31, pp. 1015-1028, 1984 (AFOSR).

23. P. Pearah, T. Henderson, J. Klem, H. Morkoç, B. Nilsson, O. WU, A. W. Swanson, and D. R. Ch'en, "Rapid thermal annealing of AlGaAs/GaAs modulation doped heterostructures for device applications," *J. Appl. Phys.*, vol. 56, pp. 1851-1855, 1984 (WPAFB/Honeywell).

24. J. Klem, M. I. NATHAN, T. J. Drummond, R. Fischer, R. Henderson, and H. Morkoç, "The structural dependence of light sensitivity in (Al,Ga)As/GaAs modulation foped heterostructures," *J. Electronic Materials*, vol. 13, pp. 741-748, 1984 (AFOSR).

25. X. N. Zang, A. Van Der Ziel, K. Duh, and H. Morkoç, "Burst and low frequency generation-recombination noise in double heterojunction bipolar transistors," *IEEE Electronic Dev. Lett.*, vol. EDL-5, pp. 277-279, 1984.

26. R. Fischer, W. T. Masselink, J. Klem, T. Henderson, and H. Morkoç, "The elimination of drain IV collapse in MODFETs through the use of thin n-GaAs/AlGaAs superlattice," *Electronics Letts.*, vol. 20, pp. 743-744, 1984 (AFOSR).

27. W. T. Masselink, R. Fischer, J. Klem, T. Henderson, P. Pearah, and H. Morkoç, "Polar semiconductor quantum wells on non-polar substrates: (Al,Ga)As/GaAs on (100) Ge," *Appl. Phys. Lett.*, vol. 45, pp. 457-459, 1984 (AFOSR).

28. A. Ketterson, F. Ponse, T. Henderson, J. Klem, and H. Morkoç "Extremely low contact resistance for AlGaAs/GaAs MODFET structures," *J. Appl. Phys.*, in print, March 15 (AFWAL/AFOSR).

29. P. Pearah, T. Henderson, J. Klem, W. T. Masselink, N. Chand, and H. Morkoç "Reduced light sensitivity and persistent photoconductivity in novel modulation doped heterostructures incorpating a GaAs/AlGaAs as the larger bandgap material," *J. Electron Mat.*, in print (AFOSR).

30. P. W. Yu, S. Chaudhuri, D. C. Reynolds, K. K. Bajaj, C. W. Litton, W. T. Masselink, R. Fischer, and H. Morkoç "Temperature dependence of sharp line photoluminescence in GaAs/$Al_{0.25}Ga_{0.75}As$ multiple quantum wells," *Solid St. Comm.*, in print.

31. T. J. Drummond, D. Arnold, R. Fischer and H. Morkoç "An investigation of an Al/AlGaAs/GaAs MIS structure for FET applictions," *Thin Solid Films*, in print (AFOSR).

32. W. T. Masselink, T. Henderson, J. Klem, R. Fischer, P. Pearah, H. Morkoç P. D. Wang, M. Hafish, and G. Y. Robinson, "Optical properties of GaAs on (100) Si using molecular beam epitaxy," *Appl. Phys. Lett.*, Dec. 1984 (AFOSR).

33. N. Chand, R. Fischer, T. Henderson, J. Klem, W. Kopp, and H. Morkoç "Temperature dependence of current gain in $Al_xGa_{1-x}As$/GaAs heterojunction bipolar transistors," *Appl. Phys. Lett.*, vol. 45, pp. 1086-1088, 1984 (AFOSR/IBM).

34. M. B. Das, W. Kopp, and H. Morkoç "Determination of carrier saturation velocity in short gate length modulation doped FETs," *IEEE Electron Dev. Lett.*, vol. EDL-5, pp. 446-449, 1984 (AFOSR).

WORK UNIT NUMBER 3

TITLE: Heterostructure Electronic Devices by Metalorganic Chemical Vapor Deposition

SENIOR PRINCIPAL INVESTIGATORS:

J.J. Coleman, Research Associate Professor

K. Hess, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

M. Emanuel, Research Assistant

T. Higman, Research Assistant

G. Costrini, Research Assistant

SCIENTIFIC OBJECTIVE:

Metalorganic chemical vapor deposition (MOCVD) is a sophisticated, automated epitaxial growth process for thin, high-quality epitaxial layers of GaAs and AlGaAs. The MOCVD process has a number of advantages important for the development of complex, thin-layer quantum limit electronic devices, such as high uniformity and accurate control over wide ranges of thickness (< 20 A to 10's of μm) and composition (x = 0 to 1) and interfaces that are abrupt on a monatomic scale. This growth process has allowed enormous advances in the development of heterostructure lasers and other optical devices. It is the objective of this research to utilize the advantages of the MOCVD process to fabricate high-quality epitaxial *electronic* devices such as heterostructure field effect transistors (high electron mobility transistors, HEMTs) and real-space transferred electron devices.

SUMMARY OF RESEARCH:

The research has, thus far, centered primarily on forming a two-dimensional electron gas at the interface of an undoped GaAs-doped AlGaAs heterostructure interface. Considering the parts of this structure individually, we have found that there is a large degree of variability in available starting source materials, such as arsine gas and trimethylgallium. These sources affect the background doping level and maximum electron mobility in layers of undoped GaAs. Careful choice of good starting materials and optimization of growth temperature and As-Ga ratio (which affect background impurity incorporation) has allowed growth of layers with background mobilities near 90,000 $cm^2/Vsec$ (77 K). AlGaAs doped n-type has been successfully grown over the entire composition range with controlled doping and reproducible thickness. Using parameters determined from a model previously developed by Hess and co-workers, we have grown single-interface selectively-doped heterostructures that show evidence of enhanced mobility in the conducting notch at the interface. The design of such structures is non-trivial since the doping and thickness relationship must be such that the wider-gap layer is not completely depleted, yet there must not be a significant parallel (parasitic) conduction path. This can be controlled to an extent by using gated test structures and optimizing interface conductance by varying gate voltage.

A number of single-interface structures have been fabricated into large area gated FETs. The large area (1000 μm source-to-drain, 970 μm gate width) is used to maintain sufficiently low source-to-drain electric fields for Shubnikov-de Haas measurements. Such measurements of magneto-resistance as a function of field strength have been performed in a super-conducting magnet. When the magnetic field is normal to the two-dimensional electron gas, oscillations in the current-field characteristics are observed, as expected. When the field is parallel to the high electron density interface, only bulk magnetoresistance is observed.

In summary, enhanced mobility heterostructure FETs have been made from MOCVD grown materials which have reasonably high background mobilities and exceptional uniformity. The presence of the two-dimensional electron gas has been confirmed by Shubnikov-de Haas measurements on large gated structures.

PUBLICATIONS:

Journal Articles:

1. T.C. Hsieh, K. Hess, J.J. Coleman, and P.D. Dapkus, "Carrier density distribution in modulation doped GaAs AlGaAs quantum well heterostructures," *Solid State Comm. 26*, 1173 (1983). (JSEP,ARO)
2. D. Widiger, K. Hess, and J.J. Coleman, "Two-dimensional numerical analysis of the high electron mobility transistor," *IEEE Electron Device Lett. EDL-5*, 266 (1984). (JSEP,ARO)
3. D. Widiger, I.C. Kizilyalli, K. Hess, and J.J. Coleman, "Two-dimensional transient simulation of the high electron mobility transistor," *IEEE Trans. Elect. Devices.* (JSEP,ARO)

Conference Papers:

1. D. Widiger, I.C. Kizilyalli, K. Hess, and J.J. Coleman, "Two-dimensional numerical analysis of the high electron mobility transistor," *Proc. First Int. Conf. on Superlattices, Microstructures and Microdevices* (Champaign, 1984), p. (JSEP,ARO)
2. D. Widiger, I.C. Kizilyalli, K. Hess, and J.J. Coleman, "Two-dimensional transient simulation of the high electron mobility transistor," *Proc. of the International Electron Devices Meeting* (San Francisco, 1984), p. 364. (JSEP,ARO)

ADDITIONAL INFORMATION:

Awards and Honors:

Karl Hess

IEEE Fellow, 1985
Beckman Associate, Center for Advanced Study, UIUC

WORK UNIT NUMBER 4

TITLE: Studies of Transport Phenomena in Semiconductors

SENIOR PRINCIPAL INVESTIGATORS:

K. Hess, Research Professor
J. P. Leburton, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

M. Artaki, Research Assistant
D. Arnold, Research Assistant
I. Kizilyalli, Research Assistant
S. Manion, Research Assistant
T. Wang, Research Assistant
K. Kahen, Research Assistant
P. Martin, Research Assistant
J. Higman, Research Assistant

SCIENTIFIC OBJECTIVE:

This research involves the study of basic properties of semiconductors, semiconductor-heterolayers, new device concepts and device modeling.

Both theoretical and experimental methods are employed in each of these categories. We are examining a variety of hot electron phenomena and their effects on present and future device performance, especially in connection with modulation doping. The experimental studies concern mainly electronic transport in heterolayers in high electric and high magnetic fields.

The theoretical studies include Monte Carlo simulations of electronic transport and modeling of III-V compound devices.

SUMMARY OF RESEARCH:

*4.2.1. Electronic Transport at High Energies and Transient Phenomena**

We have completed a study of high field transport of holes in GaAs and InP. It is concluded that steady state and transient transport of holes in these materials can be understood in significant detail using the Monte Carlo simulation technique. We have been able to predict saturation velocities of holes which have been confirmed by recent experiments on avalanche photodiodes at Bell Laboratories.

Our research on the high electron mobility transistor (HEMT) has resulted in the first two-dimensional device model. We have developed both a Boltzmann moment equation code and a particle simulation. The model has proven conclusively the importance of the high mobility for the advantages due to a low source access resistance, the significance of velocity overshoot under the gate, and the importance of real space transfer.

* This work was supported by the Joint Services Electronics Program under contract N00014-79-C-0424, the Army Research Office under contract DAAG-29-80-K-0069 and the Office of Naval Research under contract N00014-76-C-806.

A third project, diffusion in very high electric fields, has also been completed. The results for the anisotropic diffusion coefficient are important for the assessment of the significance of diffusion in high field regions of devices (MOS transistors, IMPATT devices, etc.).

4.2.2. Electronic transport in semiconductor heterolayer structures.

In addition to work on the HEMT, reported in Section 4.2.1, we have performed research on two projects related to heterolayer structures. A model has been developed to calculate some electronic properties of superlattices. This is based on a general k.p method and goes beyond the naive effective-mass-Kronig-Penney approach. It has been applied to the following problems:

(i) We have studied the electronic structure of superlattices and multiple quantum wells under hydrostatic pressure .

(ii) We developed a realistic model to study the optical properties and the dielectric constant of superlattices. (For details see publication list.)

A second project has been an in-depth study of the so-called "Hickmott experiment" (J. W. Hickmott et al., Phys. Rev. Lett. 52, 2053, 1984), which shows that oscillations appear in the I-V characteristics of GaAs-AlGaAs tunnel junctions in the presence of high longitudinal magnetic fields. Although magnetic freeze-out of the substrate donors is necessary for the onset of the oscillations, the voltage period is rigorously independent of the magnetic field and correspond to the GaAs-L.O. phonon frequency. We have shown that any explanation of this effect by ballistic transport has to be incorrect under the given experimental conditions. The classic explanation on phonon-assisted tunneling appears also unsatisfactory and does not explain several experimental observations. We propose an explanation based on space charge effects induced by the generation of local perturbances of the distribution of optical phonons. This interpretation is in good agreement with the experimental results and provides a general basis for the understanding of similar effects encountered in the past 20 years in tunnel junction structures.

SIGNIFICANT RESEARCH ACCOMPLISHMENTS:

The most significant accomplishments of the research described in the previous sections are, in our opinion, the explanation of the Hickmott experiment and the development of the Monte Carlo code for the high electron mobility transistor. This code represents the first two-dimensional model of its kind and is currently perceived to give the most accurate predictions of overshoot effects.

INTERACTIONS AND/OR TECHNOLOGY TRANSFER:

Monte Carlo codes for impact ionization phenomena in GaAs and Si have been transferred to Rockedyne, Albuquerque, in connection with an Air Force project on second breakdown. Some of the simulation codes for transient transport have been developed in cooperation with the U.S. Army Electronics Technology and Devices Laboratory, Ft. Monmouth. Interactions on heterolayer transport have continued with several groups in the Electronics Technology Division of the Naval Research Laboratory.

PUBLICATIONS:

Journal Articles:

1. K. Brennan and K. Hess, "Theory of high-field transport of holes in GaAs and InP," *Phys. Rev.* B, Vol. 29, No. 10, 5581-5590 (1984). (JSEP/ONR)

2. T. Wang and K. Hess, "Calculation of high field diffusivity by a many- particle Monte Carlo simulation including a complete bandstructure for GaAs," *J. Appl. Phys.*, October (1984). (JSEP/ONR)

3. P. Gavrilovic, J. M. Brown, R. W. Kaliski, N. Holonyak, K. Hess, M. J. Ludowise, W. T. Dietz and C. R. Lewis, "Resonant tunneling in a GaAs$_{1-x}$P$_x$GaAs strained-layer quantum-well heterostructure," *Solid State Comm. 52*, 237-239 (3) (1984). (JSEP/ARO)

4. T. Wang and K. Hess, "Calculation of the electron velocity distribution in high electron mobility transistors using an ensemble Monte Carlo method," *J. Appl. Phys.* to be published. (JSEP/ONR/ARO)

5. J. P. Leburton, "Size effects on polar optical phonon scattering of 1-D and 2-D electron gas in synthetic semiconductors," *J. Appl. Phys. 56*, 2850 (1984). (JSEP, ARO)

6. J. P. Leburton, "Origin of the current oscillations in GaAs-AlGaAs tunnel junctions," *Phys. Rev. B 31* (1985). (JSEP)

PUBLICATIONS (OTHER SUPPORT):

1. D. Widiger, K. Hess and J. J. Coleman, "Two dimensional numerical analysis of the high electron mobility transistor," *IEEE Electron Device Lett.*, Vol. EDL-5, No. 7 (1984). (ARO/ONR)

2. D. Widiger, I. C. Kizilyalli, K. Hess and J. J. Coleman, "Two-dimensional transient simulation of the high electron mobility transistor," *Superlattices and Microstructures*, to be published. (ONR/ARO)

3. D. Widiger, I. C. Kizilyalli, K. Hess and J. J. Coleman, "Two-dimensional numerical analysis of the high electron mobility transistor," *IEEE Transactions on Electron Devices*, to be published. (ONR/ARO)

4. K. Kahen, J. P. Leburton and K. Hess, "General model of the transverse dielectric constant of GaAs-AlAs superlattices," *Superlattices and Microstructures, 1* (1985). (ARO/NASA)

5. K. Brennan, T. Wang and K. Hess, "Theoretical Calculation of Electron Impact Ionization in Superlattice Avalanche Photodiodes," *Applied Phys. Letters*, to be published. (ONR/NSF)

6. T. Wang, K. Hess and G. J. Iafrate, "Time-dependent ensemble Monte Carlo simulation for planar-doped GaAs structures," *J. Appl. Phys.* to be published. (ARO)

7. K. Yokoyama and K. Hess, "Intersubband phonon overlap integrals for AlGaAs/GaAs single-well heterostructures. *Phys. Rev. B*, to be published. (ARO)

8. J. P. Leburton and K. B. Kahen, "GaAs-AlGaAs superlattice band structure under hydrostatic pressure: an analysis based on the envelope function approximation," *Superlattices and Microstructures 1*, 49 (1985). (ARO/NASA)

ADDITIONAL INFORMATION:

Awards and Honors:

Karl Hess

Fellow, Institute of Electrical and Electronics Engineers, 1985
Beckman Associate, Center for Advanced Study, UIUC

WORK UNIT NUMBER 5A

TITLE: Crystal Growth of Semiconductor Alloys from the Vapor Phase and Controlled Doping: Ion-Surface Interactions

SENIOR PRINCIPAL INVESTIGATORS:

J.E. Greene, Research Professor
S.A. Barnett, Research Associate

SCIENTIFIC PERSONNEL AND TITLES:

S. Fang, Research Assistant
P. Fons, Research Assistant
S. Gorbatkin, Research Assistant
B. Kramer, Research Assistant
D. Lubben, Research Assistant
D. McIntyre, Research Assistant
D. Mei, Research Assistant
M.A. Ray, Research Assistant
A. Rockett, Research Assistant
L. Romano, Research Assistant
S.I. Shah, Research Assistant

SCIENTIFIC OBJECTIVES:

The primary objective of this research program is to investigate energetic particle-surface interactions which control the nucleation and growth kinetics, chemistry, and physical properties of alloy semiconductors during vapor phase crystal growth by UHV ion beam sputtering and accelerated-beam molecular beam epitaxy. In both of these growth techniques, low energy ion-surface interactions allow an efficient coupling of kinetic energy to the growth surface upon condensation thereby altering the surface reactivity as well as adsorption and adatom diffusion kinetics allowing single crystal film growth at lower temperatures, much more precise control over dopant incorporation probabilities and depth distributions, and the growth of unique metastable alloys. This work is being pursued from both an analytical and an experimental point of view in order to establish a detailed understanding of fundamental film growth mechanisms.

SUMMARY OF RESEARCH:

Elemental Incorporation Probabilities and Depth Distributions

We are developing a general model for predicting elemental incorporaton probabilities and depth distributions of both thermal and accelerated species incident upon the growing film surface during vapor phase deposition. The model framework contains both thermodynamic and kinetic components and accounts for dopant diffusion, surface segregation, and, in cases where the dopant flux is non-thermal (e.g., "accelerated-beam" MBE, sputter deposition, and plasma assisted CVD), low energy ion bombardment effects including implantation and enhanced diffusion. Initial calculations have been carried out for GaAs and Si MBE in which, especially for Si, common dopants are typically characterized by strong surface segregation and temperature-dependent incorporation probabilities σ.

The model predicts that a critical growth temperature exists which corresponds to the transition from "equilibrium" segregation to kinetically-limited dopant segregation. Moreover, this transition significantly affects both σ and the dopant profile broadening as a function of the film growth temperature T_s since the steady state segregation ratio r (surface to bulk dopant fraction) has the opposite dependence on T_s in the two regimes. In addition, we have predicted for the first time that because of the high segregation ratios of many dopants in MBE GaAs and Si (r can easily be $> 10^5$), surface structural phase transitions may occur during film growth due to the formation of ordered dopant overlayers. This is expected even when bulk dopant concentrations are $< 10^{17}$ cm^{-3}. We have recently obtained the first experimental evidence for this effect as noted below.

Calculated values of $\sigma(T_s)$ and calculated depth profiles have been found to agree very well with experimental data available in the literature for both group-III acceptors and group-V donors in Si. "Anomalies" in previously published data can now be explained, based on the model, as being due to variations in dopant desorption rates and/or surface segregation kinetics which occur in response to changes in film growth temperature and dopant surface coverage. We have also calculated profiles resulting from arbitrarily complex doping schedules and obtained excellent agreement with experimental results for Al, Ga, and Sb. In addition, the model predicts, in agreement with limited experimental data, that a growth parameter range exists in which abrupt doping profiles can be obtained, even for dopants which exhibit strong surface segregation. We have recently demonstrated this experimentally. Transition temperatures from equilibrium to kinetically-limited segregation have been determined for several important dopants in Si.

We have carried out extensive experiments, in collaboration with Prof. J.-E. Sundgren, on In in Si. In is a deep acceptor and from model calculations is expected to exhibit strong segregation in MBE Si. The In incorporation probability σ_{In} in (100) Si grown by molecular beam epitaxy was found, using secondary ion mass spectrometry (SIMS), to decrease from essentially unity at film growth temperatures T_s of $\sim$ 550°C to $< 10^{-4}$ at 840 °C. SIMS depth profiles of both uniformly-doped and modulation-doped samples showed evidence of strong surface segregation with the amount of profile broadening directly related to $\sigma_{In}(T_s)$. A combination of *in-situ* RHEED, LEED, and Auger electron spectroscopy were used to show that the surface segregation rate was sufficient over a wide range in T_s and In to Si flux ratios to cause the initial (2x1)-(100) Si surface reconstruction to transform to (3x4) due to the formation of an ordered In surface layer. The In surface coverage in the (3x4) state was $\sim$ 0.05-0.1 monolayer even though the bulk In concentration was $\leq 2 \times 10^{17}$ cm^{-3}. The (2x1) to (3x4) surface phase transition was reversible by either terminating film growth and re-evaporating the excess surface In or terminating the In flux while continuing Si film growth.

Initial experiments have also been carried out to determine the temperature dependence of dopant depth distributions in In-doped (100) Si films grown by MBE. The films were deposited at a rate of $\sim$ 1 μm h^{-1} with steady state In concentrations in bulk layers ranging from 1×10^{16} to 6×10^{17} cm^{-3}. The amount of segregation-induced profile broadening Δ_{In} in (2x1)-(100) films was found from SIMS analyses to reach a maximum of $\Delta_{In} \sim 600$ nm at a critical temperature, as predicted, and to decrease at both higher and lower T_s-values. Calculated In depth profiles were found to be in good agreement with experimental results. The shape of calculated profiles was determined primarily by a combination of the T_s-dependent In incorporation probability and the steady state ratio of the surface to bulk In fractions. Indium surface coverages θ_{In} large enough to be observed by AES were obtained in layers grown under conditions corresponding to strong segregation.

Experiments are presently underway to measure the desorption energy E_{In} of In on (100) Si as a function of In coverage θ_{In}, to investigate In overlayer growth mechanisms, and to determine the surface phase diagram for In on Si as a function of T_s and θ_{In}. This work is relevant to both the understanding of dopant segregation during MBE Si as well as the understanding of the early stages of the growth of metal films on Si. A variety of techniques are being employed including AES, LEED, RHEED, and modulated beam mass spectrometry with all measurements being carried out in UHV.

Ion/Surface Interactions

The choice of dopants in MBE GaAs and, particularly, in MBE Si is limited by the fact that most common dopants (e.g. Ga, In, As, P, and Sb in Si and Zn, Cd, S, Se, and Te in GaAs) have very low thermodynamic sticking probabilities. However, ionization and acceleration of these dopants to relatively low energies, 50 to a few hundred eV, results in enhancements in net incorporation probabilities σ of up to 8-10 orders of magnitude. We have made modifications in the unique single-grid, solid-source, UHV compatable, ion gun we reported last year (also see publication list) to allow us to form accelerated molecular beams of even low vapor pressure materials such as In. We are presently investigating the incorporation mechanism of accelerated Zn in MBE GaAs and accelerated In in MBE Si. In both cases we see orders of magnitude increases in σ at acceleration energies < 50 eV corresponding to extrapolated ion "ranges" of the order of or less than a monolayer. Similar experiments carried out using accelerated Sn, where σ is already ~ 1 for thermal beams, in epitaxial sputter-deposited GaAs shows evidence of a large decrease in the dopant segregation rate and hence a much more uniform doping profile.

We have also begun, in collaboration with Dr. G. Bajor of Harris Semiconductor, to extend our model for dopant/surface (see previous section and publications list) interactions to include ionized and accelerated beams. We have successfully calculated incorporation probabilities and depth profiles of accelerated ionized dopants in MBE GaAs and Si and used the model to explain doping behavior in sputter-deposited films. In the latter case, preferential sputtering and collisional mixing begin to play a role due to the large ion fluxes involved.

Growth and Characterization of Single Crystal Metastable Semiconductors

We are carrying out the first detailed study of the growth and physical properties of new single crystal metastable semiconductors. The key feature in stabilizing the growth of these materials is the controlled use of low energy ion bombardment during deposition to modify elemental sticking probabilities and adatom diffusivities and to promote dynamic collisional mixing during deposition. We have concentrated primarily on the study of $(GaAs)_{1-x}Ge_x$ because of the importance of the end-members, the interest in Ge/GaAs heterostructures, and the fact that it is representative of a new subclass of potentially important alloys, $(III-V)_{(1-x)}(IV_2)_x$.

Epitaxial metastable $(GaAs)_{1-x}Ge_x$ alloys with compositions ranging from $x = 0$ to $x = 1$ have been grown on (100) GaAs substrates by ion beam sputtering in an ultrahigh vacuum system. Electron channeling, double crystal X-ray diffractometry, and X-ray topography analyses indicate that the films are of very high crystalline perfection. The equlibirium GaAs-Ge pseudobinary phase diagram has been determined by differential thermal analysis and X-ray diffraction/annealing studies to be a simple eutectic with an invariant temperature and composition of 880°C and $\sim$ 8 mole % GaAs. We have also calculated the phase diagram, based upon a modified quasi-chemical approach, and found good agreement with the expeirmental results. The model is now being extended to other possible $(III-V)_{(1-x)}(IV_2)_x$ systems.

Either n-type or p-type conduction, with n and p varying over several orders of magnitude, can be obtained by varying the film composition, the growth temperature, and the As overpressure during deposition. The As incorporation probability σ_{As}, using an As_4 beam to provide the overpressure, was found to decrease rapidly with increasing Ge concentration in the films. Detailed measurements of σ_{As}, using both As_4 and As_2 sources, as a function of film growth temperature and Ge concentration are presently being carried out in order to understand and model surface interactions during film growth.

Recent high resolution triple-crystal X-ray diffractometry measurements of $(GaAs)_{(1-x)}(Ge_2)_x$ on (100) GaP show that the ratio of the (200) superlattice to (400) fundmanetal reflection intensities decrease precipitously to zero near $x \sim 0.3$. This is the first direct evidence of a long-range order/disorder phase transition in these materials. It is in agreement with our earlier prediction based upon a model developed, in collaboration with Professors Jack Dow and Kathie Newman, to explain the unusually large negative bowing in the direct Γ-point bandgap E_0 as a function of x. We are presently carrying out XPS measurements to map out the valence density of states which show a splitting in the s

and sp peaks due to the transition.

We have also grown epitaxial metastable alloys of $(GaAs)_{(1-x)}(Sn_2)_x$ and $Ge_{1-x}Sn_x$ representing two other classes of metastable semiconductors. $(GaAs)_{(1-x)}(Sn_2)_x$ exhibits essentially no solid solubility and requires not only non-isovalent substitution on both cation and anion sublattices as in $(GaAs)_{(1-x)}(Ge_2)_x$ but non-isostructural substitution as well. That is, Sn, at temperatures above 13.2°C is a tetragonal semi-metal and the growth of single phase $(GaAs)_{(1-x)}(Sn_2)_x$ alloys requires the stabilization of the low temperature diamond structure. We have successfully grown alloys which are not only single phase, but are single crystals, on (100) GaAs substrates, with Sn concentrations up to $\sim$ 15%. In addition, high temperature phase transition studies have shown that under the proper annealling conditions, $(GaAs)_{(1-x)}(Sn_2)_x$ can be decomposed to provide dispersed second-phase regions of α—Sn (diamond structure) which are completely coherent with the zinc-blende lattice at temperatures almost 200°C above the melting point of β—Sn! Initial Raman results show that the Sn-based $(III-V)_{(1-x)}(IV_2)_x$ alloys exhibit a "two-mode" behavior while high resolution X-ray diffraction analyses of superlattice and fundamental reflections indicates that $(GaAs)_{(1-x)}(Sn_2)_x$ with $x \leqslant 0.15$ is in the ordered zinc-blende phase.

Single crystal $(GaAs)_{1-x}Ge_x$ alloys with up to $\sim$ 15 % Sn have also grown on (100) GaAs even though the equilibirium Ge-Sn phase diagram exhibits essentially no mutual solid solubility with a eutectic point occurring at 0.1 at % Ge and a temperature $\sim$ 1°C less than the melting point of pure Sn, 232°C. This alloy represents a good test of our collisional mixing models since Sn has a very high diffusivity in Ge and hence the latitude in growth parameter space (growth temperature T_g, ion acceleration potential V_p, and deposition rate R) is extremely narrow. A complete growth phase map as a function of T_g, V_p, and x has been established. For a given value of x, there is a maximum growth temperature T_g^* at a particular value of V_p due to an interplay between dynamic collisional mixing of mobile surface adatoms and enhanced diffusion in the "bulk" lattice. The critical value of V_p^* at T_g^* corresponds to an ion range of the order of 1 monolayer. Both T_g^* and V_p^* decrease with increasing x.

Phase transition studies show that the crystalline-metastable to equilibrium transformation proceeds through a much different reaction path than for $(GaAs)_{(1-x)}(Ge_2)_x$. There are no intermediate metastable states in the $(GaAs)_{1-x}Ge_x$ due to structural constraints. The earliest observable reaction product is tetragonal Sn. Raman results indicate a one-mode behavior with the optical phonon frequency decreasing rapidly with increasing x.

Optical Information Storage Using Explosive Crystallization of $In_{1-x}Ga_xSb$ alloys

This work, carried out in collaboration with Dr. C.E. Wickersham, who received his Ph.D. in our group under JSEP support and is now the manager of the Thin Film Group at Varian, demonstrates a practical application of earlier research supported by JSEP on the crystal growth of III-V alloys by sputter deposition. We have utilized explosive crystallization, for which our group developed the first correct model in 1978, of amorphous $In_{1-x}Ga_xSb$ for optical information storage. Information encoding is accomplished using a low power, focused laser beam to crystallize local areas of the film by normal nucleation and grain growth. The remainder of the film is "developed" by spontaneously propagating an explosive crystallization (EC) front. The formation can be retrieved by rastering a low intensity laser beam across the storage media and detecting the difference in optical reflectivity between the roughened EC matrix and the smooth highly-reflecting laser-annealed regions. A 15:1 signal-to-noise ratio has been obtained in initial experiments with 5 μm diameter recorded spots. The spot temperature and laser power densities required for writing with this approach are much lower than in comparable techniques where melting or vaporization is required.

We have recently established experimentally that the periodic surface undulations in films transformed by self-sustained explosive crystallization are due to thermal instabilities at the advancing amorphous/crystalline boundary. Transmission and scanning electron microscopy studies were used to show that the amplitude of the undulation, which can be as large as micrometers, is directly related to the transformation temperature. The results can be explained using instability theory.

SIGNIFICANT RESEARCH ACCOMPLISHMENTS:

1. Our work on III-V crystal growth by sputter deposition has resulted in the development of an optical storage information device based upon explosive crystallization of amorphous $In_{1-x}Ga_xSb$. (See: C.E. Wickersham, G. Bajor, and J.E. Greene, Optical Information Storage Using Explosive Crystallization in Amorphous Films, *J. Vac. Sci. Technol. A1*, 1857 (1983) and C.E. Wickersham, G. Bajor, and J.E. Greene, Temperature Dependent Formation of Surface Undulations in Explosively Crystallized Films, *J. Vac. Sci. Technol.*, in press.)
2. Our work on accelerated beam doping during MBE has resulted in the design, development, and construction of a unique low-energy, ultra-high vacuum compatible, ion source which can be operated with gas, liquid, or solid source material. The ion gun utilizes single-grid optics and has been operated with Zn, As, and In for hundreds of hours at acceleration emergies as low as 20 eV (See: A. Rockett, S.A. Barnett, and J.E. Greene, A Low-Energy, Ultra-High Vacuum, Solid-Metal Ion Source for Accelerated-Ion Doping During Molecular Beam Epitaxy, *J. Vac. Sci. Technol. B2*, 306 (1984).)

PUBLICATIONS:

Books or Chapters in Books:

1. S.A. Barnett, B. Kramer, L.T. Romano, S.I. Shah, M.A. Ray, S. Fang, and J.E. Greene, "A review of recent results on single crystal metastable semiconductors: crystal growth, phase stability and physical properties," in *Layered Structures, Epitaxy, and Interfaces*, ed. by J.M. Gibson and L.R. Dawson, North Holland Publishing Co., in press. (JSEP/DOE)

Journal Articles:

1. J.E. Greene, "Epitaxial growth by sputter deposition: applications to semiconductors - Part 2," *CRC Critical Reviews of Solid State and Materials Science 11*, 189 (1984). (JSEP/DOE)
2. J.E. Greene, "A review of the epitaxial growth of compound and alloy semiconductors of sputter deposition," *J. Vac. Sci. Technol. A2*, 427 (1984). (JSEP/DOE)
3. S.A. Barnett, A. Rockett, G. Bajor, and J.E. Greene, "Model calculations for thermal and accelerated beam doping in semiconductor films grown by molecular beam epitaxy," *J. Vac. Sci. Technol. A2*, 406 (1984). (JSEP/SRC)
4. A. Rockett, S.A. Barnett, and J.E. Greene, "A low-energy, ultra-high vacuum, solid-metal ion source for accelerated-ior doping during molecular beam epitaxy," *J. Vac. Sci. Technol. B2*, 306 (1984). (JSEP/SRC)
5. J. Knall, J.-E. Sundgren, J.E. Greene, A. Rockett, and S.A. Barnett, "Indium incorporation during the growth of (100) Si by molecular beam epitaxy: surface segregation and reconstruction," *Appl. Phys. Letters 45*, 689 (1984). (JSEP/SRC)
6. J.E. Greene, S.A. Barnett, A. Rockett, and G. Bajor, "Modeling of dopant incorporation, segregation, and ion/surface interaction effects during semiconductor film growth by molecular beam epitaxy and plasma-based techniques," *Appl. Surf. Sci.*, in press. (JSEP/SRC)
7. A. Rockett, S.A. Barnett, J. Knall, and J.-E. Sundgren, "Dopant depth distributions as a function of growth temperature in In-doped (100) Si grown by molecular beam epitaxy," *J. Vac. Sci. Technol.*, in press. (JSEP/SRC)

8. C.E. Wickersham, G. Bajor, and J.E. Greene, "Temperature dependent formation of surface undulations in explosively crystallized films," *J. Vac. Sci. Technol.*, in press. (JSEP)

Conference Papers:

1. (Invited paper) S.A. Barnett and J.E. Greene, "Crystal growth, metallurgy, and physical properties of metastable $(III\text{-}V)_{1-x}(III_2)_x$ alloys," *American Physical Society Meeting*, Detroit, Michigan, March 1984. (JSEP/DOE)
2. (Invited paper) J.E. Greene, "Crystal growth of semiconductors by sputter deposition: ion/surface interactions," *Topical Symposium on Sputtering*, San Diego, California, April 1984. (JSEP)
3. (Invited paper) J.E. Greene, "Ion/surface interactions during crystal growth from the vapor phase," *International Conference on Metallurgical Coatings*, San Diego, California, April 1984. (JSEP/DOE)
4. (Invited paper) J.E. Greene, "Semiconductor crystal growth and doping from the vapor phase," *1st Annual Symposium, Ohio Valley Chapter, American Vacuum Society*, Cleveland, Ohio, May 1984. (JSEP)
5. (Invited paper) J.E. Greene, "Ion/surface interactions during film growth," *Gordon Conference on Thin Films and Solid Surfaces*, New London, New Hampshire, July 1984. (JSEP/DOE)
6. (Invited paper) J.E. Greene, "Ion/surface interactions during semiconductor crystal growth from the vapor phase," *6th International Conference on Thin Films*, Stockholm Sweden, August, 1984. (JSEP/DOE)
7. (Invited paper) J.E. Greene, S.A. Barnett, and D. Lubben, "A review of thermal and accelerated beam doping in semiconductor films grown by molecular beam epitaxy: incorporation probabilities and depth profiles," *3rd International Conference on Solid Films and Surfaces*, Sydney, Australia, August 1984. (JSEP/SRC)
8. (Invited paper) J.E. Greene, S.A. Barnett, "Crystal growth and physical properties of metastble semiconductors," *Materials Research Society*, Boston, Massachusetts, November 1984. (JSEP/DOE)
9. A. Rockett, S.A. Barnett, J.E. Greene, J. Knall, and J.-E. Sundgren, "In incorporation and segregation in (100) Si grown by MBE: theoretical and experimental results," *31st National Symposium of the American Vacuum Society*, Reno, Nevada, November 1984. (JSEP/SRC)
10. (Invited paper) J.E. Greene, "Ion/surface interactions during vapor phase crystal growth," *Workshop on Plasma-Based Surface Engineering*, Sponsored by the Department of the Army, University of Illinois, December 1984. (JSEP)
11. (Invited Paper) J.E. Greene, "Ion-surface interactions during vapor phase crystal Growth," *American Vacuum Society Meeting*, Scottsdale, Arizona, March (1985). (JSEP)

ADDITIONAL INFORMATION:

Awards and Honors:

J.E. Greene

Appointed Visiting Professor of Physics at Linkoping University, Linkoping, Sweden
Appointed Visiting Scientist, CSIRO Applied Physics Lab., Sydney, Australia
Editor, CRC Critical Review of Solid State and Materials Sciences
Associate Editor, Journal of Vacuum Science and Technology
Elected to Board of Directors, American Vacuum Society
Elected Chairman of the Thin Films Division, American Vacuum Society

Served on Advisory Committee, "International Symposium on Ion Sources and Ion Assisted Technology," Kyoto, Japan, Sept. 1983.
Served on Advisory Committee, "6th International Conference on Thin Films," Stockholm, Sweden, August, 1984.
Listed in Who's Who in Engineering
Listed in American Men and Women in Science
National Science Foundation Fellow
Member of Tau Beta Pi Honorary Society
Member of Pi Tau Sigma Honorary Society
Member of Eta Kappa Nu Honorary Society

WORK UNIT NUMBER 5B

TITLE: An Investigation of the Plasma and Chemistry Processes in Cylindrical Magnetron Reactive Ion Etching Discharges

SENIOR PRINCIPAL INVESTIGATOR:

John A. Thornton, Research Professor Telephone: 217-333-0417

SCIENTIFIC PERSONNEL AND TITLES:

Guen Y. Yeom, Research Assistant

SCIENTIFIC OBJECTIVE:

Investigate fundamental plasma and chemistry processes in a type of magnetically confined plasma discharge that has promise for reducing radiation damage during device processing by dry etching.

SUMMARY OF RESEARCH:

This project is designed to consist of essentially three one-year phases. The first phase addresses the basic behavior of rf driven magnetron plasmas and the resultant plasma-surface interactions. It calls for the assembly of an apparatus configured to permit measurements of the plasma potential distribution and the ion bombardment energy at surfaces that could be used in reactive ion etching processes, and for the making of such measurements. The second phase would explore the plasma chemistry behavior in low pressure rf-driven magnetron discharges using CF_4H_2 and CF_4—0_2 as working gases. The third phase would examine silicon etching and the resultant radiation damage, computer modeling of the plasma chemistry process and the extension of our general findings to plasma-assisted deposition.

Work on the project began in September 1984 with the addition of graduate student Guen Yeom. The primary activities during this first six month period have been in preparing a laboratory area and in designing the experimental apparatus. We are also beginning some preliminary computer modeling of the chemistry reactions in CF_4H_2 and CF_4—0_2 plasmas in order to explore the systematic changes which can occur as one moves from the gas and electron density conditions that are typical of conventional reactive ion etching processes to those conditions of low gas density and high electron density that are accessible with magnetrons. A third activity involves plasma modeling studies done in collaboration with a former colleague of J. Thornton's. The objective of this work is to obtain a fundamental understanding of the plasma behavior that determines the current-voltage relationships in glow discharges and therefore that influences parameters such as the plasma potential which are important to this project.

The driving force in our work is the rapid growth over the past ten years or so in the extent to which rf driven glow discharges are used for both the development and manufacture of new materials and devices. Many of these applications, such as plasma-assisted etching and plasma assisted chemical vapor deposition, involve both plasma-volume and plasma-surface interactions. Despite the fact that glow discharges have been under investigation for over fifty years, even the general form for the current-voltage relationship for a dc planar electrode discharge cannot be derived from first principles. The situation is even more complex for the magnetron. Often the effectiveness of a particular plasma-surface interaction depends on the energy of positive ions incident on the surface in question. In the rf case this depends on the time variation of the potential of the surface in question relative to the plasma potential. These potential variations depend in turn on the relative areas of electrode surfaces that are

in contact with the rf driven plasma. Only very recently have these relationships been clarified for the relatively simple planar diode case.[1] The magnetron case is considerably more complex because the magnetic plasma confinement can cause the effective electrode areas to be much different from the physical areas.[2] Furthermore, and perhaps even more important, the relative electron and ion mobilities in a magnetically confined plasma can be very different for the various directions that connect the plasma to the electrodes.

Therefore our Phase One experiments are designed to explore the relative variations in plasma and electrode potential that develop when a cylindrical magnetron is driven at rf frequencies. The fundamental glow discharge modeling is being undertaken in an attempt to pull together nearly twenty years of collaborative efforts between J.A. Thornton and A.S. Penfold[3] in order to develop a fundamental formulation capable of explaining the current-voltage behavior of both conventional and magnetron discharges.

The experimental apparatus will consist of an 20 cm diameter by 30 cm high cylindrical vacuum chamber, with external magnetic field coils configured to provide a uniform axial magnetic field. The chamber is designed to mount on a pumping stand with an oil diffusion pump, and to accept axially mounted flange-type[3] cylindrical magnetron electrodes of various diameters. Ports are available for making electrostatic probe measurements in both the radial and axial directions across the magnetron discharge, and for making optical emission spectroscopy measurements. The initial configuration will mount a retarding potential electrostatic analyzer[4] on the grounded chamber wall. It is anticipated that as the Phase One experimental work proceeds, an electrostatic analyzer will also be installed within one of the larger cylindrical magnetron electrodes. Power supplies are available for driving the discharge at frequencies of 2 MHz and 13.56 MHz. Initial experiments will consist of a systematic investigation of the variation in plasma potential (relative to the electrode surfaces) as a function of the relative electrode areas, magnetic field strength, and rf frequency, while using inert gases such as He and Ar. Particular attention will be given to estimating the energy of the ions which bombard various surfaces that might be used to mount wafers for plasma etching.

Our preliminary plasma chemistry calculations treat the plasma volume as a thin slab with uniform electron density and temperature. (It is assumed that the electron energy distribution function permits the use of an effective temperature.) The densities of various active species are calculated by numerically solving a reduced set of rate equations, which are believed to account for the major reactions, under specified conditions of working gas density and electron density and temperature. The calculations are being made for various slab thicknesses and plasma conditions that span from those used in conventional planar diode reactive ion etching reactors to those that are accessible with the cylindrical magnetrons. Thus gas densities are being varied from $10^{13}cm^{-3}$ to $10^{15}cm^{-3}$, and electron densities from $10^{9}cm^{-3}$ to $10^{11}cm^{-3}$, with an effective electron temperature of 3 eV. The calculations are being made for both CF_4–H_2 and CF_4–O_2 plasmas. Our objective is to determine the effect of the high electron densities and/or low gas pressures, which are available in magnetrons, for promoting various reaction paths within the plasma chemistry. The specific goal is to provide guidance for planning the Phase Two experiments. The calculations will be refined later in the program to account for the ionization balance and the actual nature of the electron distribution function, as well as to more accurately model the geometry of the cylindircal magnetron plasma.

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1. K. Köhler, J.W. Coburn, D.E. Horne and E. Kay, "Plasma Potentials of 13.56 MHz rf Argon Glow Discharges in a Planar System," *J. Appl. Phys. 57*, 59 (1985).
2. J.A. Thornton, "High Rate Sputtering," *Thin Solid Films 80*, 1, (1981).
3. J.A. Thornton and A.S. Penfold, "Cylindrical Magnetrons," Chapter II-2 in *Thin Film Processes*, ed. by J. Vossen and W. Kern, Academic Press, New York (1978) p.75.
4. J.A. Simpson, "Design of Retarding Field Energy Analyzers," *Rev. Sci. Instr. 32*, 1283 (1961).

PUBLICATIONS:

Conference Papers:

1. J.A. Thornton, "Gas discharge processes for thin film deposition," invited paper, *Sixth International Conference on Thin Films*, Stockholm, Sweden, Aug. 13-17, 1984. (JSEP)

ADDITIONAL INFORMATION:

Awards and Honors:

John A. Thornton

Distinguished Lecturer - Spring 1985, Department of Electrical Engineering, University of Houston, Houston, Texas.

Appointed to Editorial board of *Surface Engineering*.

Appointed to Advisory board of *CRC Critical Reviews in Solid State and Materials Science*.

Served on Advisory Committee, Six International Conference on Thin Films, Stockholm, Sweden, August 1984.

WORK UNIT NUMBER 6

TITLE: Acoustic Charge Transport

SENIOR PRINCIPAL INVESTIGATORS:

Bill J. Hunsinger, Research Professor
M.J. Hoskins, Visiting Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

E. Bogus, Research Assistant
F. Fliegel, Research Assistant
R. Miller, Research Assistant
W. Hunt, Research Assistant
J. Peterson, Research Assistant
G. Pieters, Research Assistant
J. Pryst, Research Assistant
B. Schmukler, Research Assistant
C. Warren, Research Assistant

SCIENTIFIC OBJECTIVE:

6.0. *Introduction*

Electron transport is accomplished in a buried channel GaAs structure using the traveling wave electric field of a Surface Acoustic Wave (SAW) generated directly in the GaAs. The electronic transport over long distances in a low noise environment makes this technology highly dependent on GaAs layer parameters.

6.1. *Charge in Gallium Arsenide Layers Transported by Traveling Wave Electric Fields*

A new type of charge transfer based on a non-linear interaction between an electric field traveling waves and electrons in Gallium Arsenide has recently been reported.[1] In this structure, buried channel electron transport is accomplished by using a traveling wave electric field generated directly in Gallium Arsenide. A theoretical investigation of material on the basis of transport efficiencies is possible, primarily because the traveling wave excitation provides a nearly uniform drift field so that carrier transport occurs entirely under the influence of continuous electric fields.

Significant progress has been made towards the experimental demonstration of the theoretical transport efficiency. The charge transport efficiency is believed to be primarily material limited. A new simplified epitaxial layer structure is used to form the buried channel, and it is grown directly on a GaAs semi-insulating substrate. This simplified layer structure shows a lower defect density and a higher transport efficiency. In addition, the mesa structures previously used for lateral confinement of the charge transport have been replaced by a Schottky guard rail structure. These configuration improvements resulted in a transfer efficiency in excess of .996 when the traveling wave frequency was 358 MHz.

The transfer efficiency due to proportional loss was determined by leading edge measurements and measured as a function of signal level. These data compared closely to the theory predicted diffusion-limited efficiency for traveling wave electric field strengths of 8,000 volts/centimeter.

At large signal strengths, the ballooning effect observed due to the diffusion limited transport followed the predictions of the theoretical model. However, the exact cause of the transfer inefficiency at smaller charge loads is not precisely known. This inefficiency is believed to be due to static channel potential variations arising from structures at the surface and to trapping sites in the Gallium Arsenide layers.

The depth of buried channel transport is adjusted by applying bias to a Schottky plate located on top of the buried channel. It has been clearly demonstrated that the small charge load transport inefficiency is directly related to the position of the charge transport in the channel, possibly due to a variation in trapping site density in terms of depth.

The transport efficiency of electrons transported by traveling wave electric fields appears to be a very sensitive means for measuring trapping densities and lifetimes. Further work should be pursued to determine the value of these data in the characterization of Gallium Arsenide epitaxial layers.

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1. M.J. Hoskins, E.G. Bogus and B.J. Hunsinger, "Experimental Performance of the buried-channel Acoustic Charge Transport Device," *IEEE Electron Device Letters*, vol. EDL-4 no. 11, pp. 396-399, November 1983.

WORK UNIT NUMBER 7

TITLE: Vapor Phase Growth and Characterization of InGaAs and InGaAsP Heterostructures and Devices

SENIOR PRINCIPAL INVESTIGATOR:

G. E. Stillman, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

Sabya S. Bose, Research Assistant
Ruthanna DeJule, Research Assistant
Michael A. Haase, Research Assistant
Matt Kim, Research Assistant
Thomas R. Lepkowski, Research Assistant
Noren Pan, Research Assistant
Andrew Reed, Research Assistant
Virginia Robbins, Research Assistant
Douglas S. Ruby, Research Assistant
Brian J. Skromme, Research Assistant

SCIENTIFIC OBJECTIVE:

The goal of this research is a better understanding of the InGaAsP/InP quaternary alloy system for application to heterostructures and heterostructures devices, particularly avalanche photodiodes and microwave devices. In many of these applications it is important to have the capability of growing high purity material with abrupt compositional changes at heterojunction boundaries. Because of this, the purity attainable with the hydride growth technique will be studied and compared with the results obtained from other epitaxial growth techniques such as MOCVD and MBE. In this work, undoped epitaxial layers of InP, GaAs, and InGaAs are grown using the hydride technique, and the resulting samples as well as those obtained from other laboratories are characterized using as a wide variety of techniques. These techniques include Hall coefficient measurements and analyses, low temperature photoluminescence measurements, far infrared photothermal ionization measurements, double crystal x-ray diffraction I-V and microwave time-of-flight techniques. In addition, the detector structures fabricated in this work are characterized using relative spectral response measurements, I-V measurements, photomultiplication measurements and related techniques to help characterize the InGaAsP materials used in these structures. Correlation of the growth parameters with the results of these measurements will hopefully lead to optimization and better control of the epitaxial growth process and an understanding of the physics of transport processes in these materials which is important for development of higher performance devices.

SUMMARY OF RESEARCH:

High purity epitaxial layers are critical for many types of high performance III-V devices. Buffer layers in microwave FETs, multiplication regions in APDs, and the drift regions of IMPATT all require low net carrier concentrations for optimum device performance. With the inevitable small fluctuations in N_D and N_A the only way to reproducibly maintain a low net concentration, N_D-N_A, is to grow high purity material. When applied with proper caution, the 77 K Hall mobility, $\mu m_{77}K$, provides a good indication of sample purity, and is the usual figure of merit for high purity III-V material.

The Hall mobilities and carrier concentrations for eight of the best GaAs epitaxial layers grown in the hydride VPE system are presented in Table 2.1. quality and reproducibility obtained. These layers were grown all at a GaCl partial pressure, P_{GaCl}, of 10^{-2} atom with the noted III-V ratios. The parameter which we have found to have the greatest effect on the impurity incorporation is the III-V ratio for the range of growth conditions attempted. In these experiments the III-V ratio was varied by adjusting the arsine flow while maintaining P_{GaCl}, the growth and source zone temperatures and total flow in the reactor. The effect of this variation in P_{AsH_3} is illustrated in Fig. 2.2. There are two opposing effects to be noted in this set of photothermal ionization spectra. The middle peak due to sulfur is nearly constant for the range considered while Si concentration decreases and Ge concentration increases as AsH_3 increases. Both Si donors and acceptors (the acceptors are determined from PL) are suppressed by adding AsH_3. The Si is predominantly due to $SiCl_4$, which due to the chlorine atoms couples it to the growth reaction. Because both reactions liberate HCl the additional increase in AsH_3 suppresses Si. Germanium donors and acceptors increase with AsH_4 flow. Arsine flow was the only growth parameter found to influence Ge contamination. This along with the lack of Ge in InP grown in the same reactor indicates that the arsine tank itself is the Ge source in this system. III:V ratio studies in MOCVD reactors also show similar evidence for Ge in semiconductor grade arsine. If the Ge were a hydride (germane) it would not be suppressed by the growth reaction's liberation of HCl. Because it has the same molecular mass as AsH_4 it is difficult to detect by the means used to analyze gases in the part per billion range this mid 10^{14} cm^{-3} doping level would indicate.

Although the addition of oxygen in both hydride and chloride reactors had been shown to decrease the concentration of donors and acceptors, the evidence was from Hall effect measurements at room and liquid nitrogen temperatures. This led to some ambiguity about whether the phenomenon was a decrease in the activity of Si, a_{Si}, or a result of the oxygen being incorporated as a deep donor or trap. The photothermal ionization spectra for three samples grown with the indicated added oxygen and otherwise identical growth conditions in Fig. 1 illustrate that it is indeed the decrease in a_{Si} which is responsible for the decrease in N_D. This study has also provided some additional insight into the kinetics of the model used to explain the reduction of Si. In this model the H_2 and HCl reduce the hot silica glass walls of the reactor forming volatile chlorosilanes which are transported to the growth zone and incorporated into the growing crystal. From thermodynamic arguments alone it is possible to show the decrease in a_{Si} and 0_2 but these considerations do not account for the absence of the suppression of when the 0_2 is added downstream of the gallium source. If the component gas species came to equilibrium at each step as the usual thermodynamic arguments assume, there would be no difference. That the suppression only occurs when 0_2 is added to the source zone indicates the formation of a chlorosilane is the step in the process affected by the addition of 0_2. Once they are formed they are too stable to equilibrate with 0_2 introduced afterward in the short time they remain in the reactor.

PUBLICATIONS:

Journal Articles:

1. P. E. Brunemeier, T. J. Roth, N. Holonyak, Jr., and G. E. Stillman, "Inhomogeneity on liquid phase epitaxial InGaAsP lattice-matched on InP: Effects of transient growth," *J. Appl. Phy. 56*, Sept. 1984. (NSFECS, JSEP, NSFDMR)
2. B. J. Skromme, G. E. Stillman, A. R. Calawa, and G. M. Metze, "Photoluminescence characterization of molecular beam epitaxial GaAs grown using cracked AsH_3," *Appl. Phys. Lett. 44*, pp. 240-242, Jan. 1984. (AFOSR, JSEP)
3. B. J. Skromme, G. E. Stillman, J. D. Oberstar and S. S. Chan, "Identification of the residual acceptors in undoped high purity InP," *Appl. Phys. Lett. 44*, pp. 319-321, Feb. 1984. (AFOSR, JSEP)

4. B. J. Skromme and G. E. Stillman, "Excited-state-donor-to-acceptor transitions in the photoluminescence spectrum of GaAs and InP," *Phys. Rev. B, 29,* Feb. 1984. (AFOSR/DARPA/JSEP/NSF)

5. B. J. Skromme, B. E. Stillman, J. D. Oberstar, and S. S. Chan, "Photoluminescence identification of the C and Be acceptor levels in InP," *J. Electron, Mater, 13,* pp. 463-491, May 1984. (AFOSR/JSEP)

6. P. E. Brunemeier, T. J. Roth, N. Holonyak, Jr., and G. E. Stillman, "High-uniformity liquid phase epitaxial InGaAsP (λ = 1.3 μm)," *J. of Crystal Growth, 66,* pp. 484-486, 1984. (NSF-ECS/JSEP/NSF-DMR)

7. N. Tabatabaie, V. M. Robbins, N. Pan, and G. E. Stillman, "Impact ionization coefficients in (111) InP," *Appl. Phys. Lett.* (accepted for publication 8/84). (NSF-ECS/NSF-DMR/JSEP)

8. T. S. Low, M. H. Kim, B. Lee, B. J. Skromme, T. R. Lepkowski, and G. E. Stillman, "Neutron transmutation doping of high purity GaAs," *J. Electron Mater.* (accepted for publication, 8/84). (AFSOR/ONR/JSEP)

9. G. E. Stillman, T. S. Low, B. Lee, "Photothermal ionization Fourier transform spectroscopy of shallow donor states in III-V semiconductors," *Solid State Commun.* to be published No. 12, 1985. (AFSOR/DARPA/JSEP)

PUBLICATIONS (OTHER SUPPORT):

1. G. E. Stillman, V. M. Robbins, and N. Tabatabaie, "III-V compound semiconductor devices: Optical detectors," *IEEE Trans. Electron Devices, ED31,* pp. 1643-1655, 1984. (Invited Paper)

2. "III-V compound semiconductor optical detectors," International Symposium on GaAs and Related Compounds, Biarritz, 1984 *Inst. of Physics 1985, to be published.* (NSF-ECS)

3. M. A. Haase, V. M. Robbins, N. Tabatabaie, and G. E. Stillman, "Subthreshold electron velocity-field characteristics of GaAs and $In_{0.53}Ga_{0.47}As$", *J. Appl. Phys.* 57, pp. 2295-2295, 1984. (ONR)

4. N. Tabatabaie, V. M. Robbins, N.Pan. G. E.Stillman, "Impact ionization coefficients in (111) InP," *Appl. Phys. Lett. 46,* p. 182, 1985. (NSF-ECS, NSF-DMR, ONR, JSEP)

5. B. J. Skromme, S. S. Bose, B. Lee, T. S. Low, T. R. Lepkowski, R.Y. DeJule and G. E. Stillman, "Characterization of high purity Si-doped molecular beam epitaxial GaAs," *J Appl. Phys.* (AFOSR/DNNR)

6. R. Y. DeJule, M. A. Haase, D. S. Ruby, and G. E. Stillman, "Constant capacitance DLTS circuit for measuring high purity semiconductors," *Solid State Electronics.* (accepted for publication) (NSF-ECS)

7. R. Y. DeJule, M.A. Haase, S. C. Palmateer and G. E. Stillman, "CC-DLTS measurements of high-purity MBD grown GaAs," *J. Appl Phys.* (Accepted for publication). (NSF-ECS)

8. D. S. Ruby, K. Arai, G. E.Stillman, "Deep level electron traps in VPE GaAs grown with oxygen injection," *J. Appl. Phys.* (submitted).

ADDITIONAL INFORMATION:

Awards and Honors:

G.E. Stillman

Elected to the National Academy of Science, 1985
IEEE Fellow
President, IEEE Electron Devices, 1985

WORK UNIT NUMBER 8

TITLE: Direct Examination of the Metal-Semiconductor Interface

SENIOR PRINCIPAL INVESTIGATOR:

Gert Ehrlich, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

J. D. Wrigley, Research Associate

SCIENTIFIC OBJECTIVE:

Silicon interfaces have, for a long time, been of paramount importance in device technology. However, the atomic events significant for the formation of metal-silicon interfaces or for their stability are not well understood. The aim of this project is twofold: (1) to examine the interactions of silicon atoms with metal surfaces, using field ion microscopic techniques to attain a direct view, on the atomic level, of the processes important in layer formation; and (2) to characterize the atomic structure of the interface. Particular emphasis will be upon the variations in behavior dictated by the structure of the substrate, as well as upon the effect of foreign atoms upon the properties of the layers formed.

SUMMARY OF RESEARCH:

We have concentrated our efforts on characterizing interactions between a single silicon atom and a metal atom at a surface, so as to provide information about the energetics of silicon-metal overlayers. Recent work has emphasized tungsten and rhenium complexes with silicon on the (110) plane of tungsten. In order to establish the strength of interactions between silicon and metal, quantitative studies of the kinetics of dissociation of W-Si have been made at different temperatures, and are shown in Fig. 1. These led to a dissociation energy of 0.85eV, which is just the same as the barrier to motion of a single silicon on W(110). We conclude that the apparent binding energy between silicon and tungsten is small, and within the limit of error of the measurements. This is quite different from Pd-Si on W(110), where our previous studies indicated a binding energy of at most 0.26 eV and suggests very strong chemical effects.

In the last few months we have made an important discovery: it is possible to distinguish the location of the silicon from that of the metal atom in a cluster. With this entirely new capability we have been able to examine the mechanism of motion of metal-silicon complexes. For W-Si, movement appears to occur by the jump of a single atom to form an intermediate, shown in Fig. 2, in which both atoms are aligned along [001]. An alternative intermediate, oriented along [110], has a larger interatomic spacing, and therefore presumably a higher energy. No indication has been found that this contributes to the motion of W-Si below 280K. For Re-Si, however, both diffusion paths are possible, even though transitions through the [001] intermediate dominate. Quantitative studies of the different diffusion processes of Re-Si on W(110) have been carried out, allowing us to derive the rates of the different types of atomic jumps, as well as the barriers over which they occur. We are now in the process of deriving information about the silicon-metal potentials from these measurements.

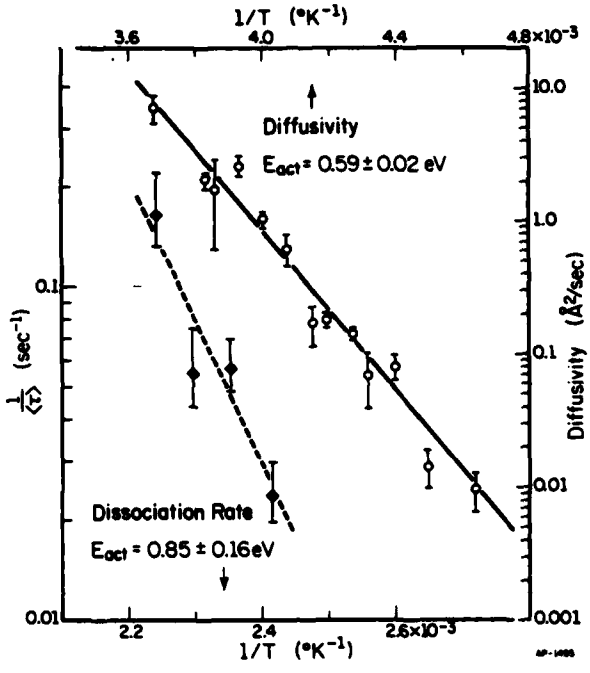

Fig. 1. Temperature dependence of dissociation rate (left) and diffusion (right) for individual W-Si molecules on W(110).

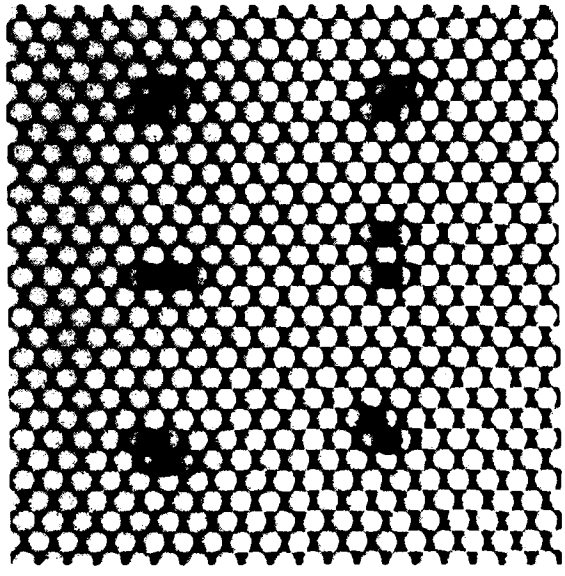

Fig. 2. Hard sphere models of hetero-dimer diffusion on W(110). At left, movement of grey adatom in the dimer occurs via a [001] oriented intermediate. Even after diffusion, grey atom is always at right of black atom. In sequence at right a jump of grey adatom leads to a [1$\bar{1}$0] intermediate, and finally to a dimer with adatoms inverted compared with final state at left.

PUBLICATIONS:

Journal Articles:

1. John D. Wrigley and Gert Ehrlich, "Diffusion and dissociation of silicon-metal complexes on W(110), *J. Vac. Sci. Technol.*, in press. (JSEP)

Conference Papers:

1. John D. Wrigley, Best Poster Award, *American Vacuum Society Meeting*, Reno, Nevada, Dec. 1984. (JSEP)

ADDITIONAL INFORMATION:

Awards and Honors

Gert Ehrlich

Guggenheim Fellow, 1984-85

WORK UNIT NUMBER 10

TITLE: Quantum Dynamics of Charge-Density Waves

SENIOR PRINCIPAL INVESTIGATOR:

J.R. Tucker, Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

W.G. Lyons, Research Assistant

SCIENTIFIC OBJECTIVE:

The goal of this research is to understand the basic mechanism of charge-density wave (CDW) transport in the "one-dimensional" metals $NbSe_3$, TaS_3, and related materials. This CDW conduction represents the second known example of current flow due to motion of a macroscopically occupied quantum state, superconductivity being the first. John Bardeen proposed that CDW acceleration in an electric field takes place via a collective tunneling process [1] and that the ac response of these systems can be characterized by applying the photon-assisted tunneling theory originally developed by the principal investigator for superconductor-insulator-superconductor (SIS) millimeter wave mixers. [2,3] This controversial hypothesis implies that quantum phenomena are observed in CDW systems in the MHz frequency region, where $h\omega \approx 10^{-6}$ kT at temperatures as high as T = 200 K. Such behavior is theoretically possible because very large numbers of electrons are acting together, so that the total energy involved is larger than thermal energies. If this interpretation is correct, CDW materials could become important systems for both long-wavelength detectors and for basic studies of macroscopic quantum tunneling and coherence. An extensive experimental program is now underway in our laboratory to characterize the dynamics of CDW response, and to test hypotheses based on the tunneling model.

SUMMARY OF RESEARCH:

During the past year, experimental work has focused on developing a phenomenological model which describes the complete response of $NbSe_3$, TaS_3, and related CDW conductors to arbitrary time-dependent applied potentials. Our previous studies [4,5] had demonstrated that the nonlinear conduction and mixing induced by small ac signals could be successfully interpreted using the tunneling theory when the applied dc voltage was above the threshold value. Recent measurements of the nonlinear response below threshold, together with experiments involving large as well as small ac signals, have led to a relatively simple model capable of characterizing the full range of experimental observations in the MHz frequency region. [6,7] The model is based on the tunneling theory, and we believe that this consistent and quantitative interpretation of the complex field and frequency dependent conduction in these systems is powerful evidence in favor of the quantum tunneling theory of CDW depinning.

SIGNIFICANT RESEARCH ACCOMPLISHMENTS:

During the past two years, work on the new ultra-low noise millimeter wave receivers which utilize photon-assisted tunneling in superconductor-insulator-superconductor (SIS) junctions has progressed rapidly. Many new programs have been established to engineer SIS receivers in the region between 36 GHz and 240 GHz in laboratories around the world. these nonlinear tunneling devices are theoretically capable of quantum limited receiver temperatures $T_R^{QL} \approx h\nu/k$, and a practical receiver system was recently constructed [8] with a single-sideband noise temperature T_R = 68°C K $\approx 10\ h\nu/k$ operating at 115 GHz. Much lower receiver temperatures should be realized during the next several years, and this revolutionary advance in detection capability is expected to have a major impact on radio astronomy research. Future intelligence and communication applications in space will also be possible. A complete review of the status of these receivers entitled "Quantum detection at millimeter wavelengths" has been written in collaboration with M.J. Feldman, and will be published in *Reviews of Modern Physics.*

REFERENCES:

1. John Bardeen, "Theory of non-ohmic conduction from charge-density waves in $NbSe_3$," *Phys. Rev. Lett. 42,* 1498 (1979).
2. John Bardeen, "Tunneling theory of charge-density wave depinning," *Phys. Rev. Lett. 45,* 1978 (1980).
3. J.R. Tucker, "Quantum limited detection in tunnel junction mixers," *IEEE J. Quantum Electron. QE-15,* 1234 (1979).
4. J.H. Miller, Jr., J. Richard, J.R. Tucker, and John Bardeen, "Evidence for tunneling of charge-density waves in TaS_3," *Phys. Rev. Lett. 51,* 1592 (1983).
5. R.E. Thorne, W.G. Lyons, J.H. Miller, Jr., J. Richard, and J.R. Tucker, "Frequency and bias dependent ac conductivity of charge-density waves in TaS_3," *Solid State Commun. 50,* 833 (1984).
6. J.H. Miller, Jr., R.E. Thorne, W.G. Lyons, J.R. Tucker, and John Bardeen, "Dynamics of charge-density waves in orthorhombic TaS_3," *Physical Review B* (to be published).
7. W.G. Lyons, R.E. Thorne, J.H. Miler, Jr., and J.R. Tucker, "Ac-dc coupling and polarization for charge-density waves in TaS_3," *Physical Review B* (to be published).
8. S.K. Pau, M.J. Feldman, A.R. Kerr, and P. Timbie, "Low-noise 115 GHz receiver using superconducting tunnel junctions," *Appl. Phys. Lett. 43,* 786 (1983).

PUBLICATIONS:

Books or Chapters in Books:

1. J.R. Tucker and M.J. Feldman, "Quantum defection at millimeter wavelengths," *Reviews of Modern Physics* (invited). (JSEP)

Journal Articles:

1. J.H. Miller, Jr., R.E. Thorne, W.G. Lyons, J.R. Tucker, and John Bardeen, "Dynamics of charge-density waves in orthorhombic TaS_3," *Physical Review B* (to be published). (JSEP/NSF)

2. W.G. Lyons, R.E. Thorne, J.H. Miler, Jr., and J.R. Tucker, "Ac-dc coupling and polarization for charge-density waves in TaS_3," *Physical Review B* (to be published). (JSEP/NSF)

3. J.H. Miller, Jr., J. Richard, R.E. Thorne, W.G. Lyons, J.R. Tucker, and John Bardeen, "Decoupling of ac dynamics from dc polarization below threshold for charge density waves in $NbSe_3$," *Phys. Rev. B29*, 2328 (1984). (JSEP/NSF)

4. R.E. Thorne, W.G. Lyons, J.H. Miller, Jr., J. Richard, and J.R. Tucker, "Frequency and bias dependent ac conductivity of charge-density waves in TaS_3," *Solid State Commun. 50*, 833 (1984). (JSEP/NSF)

5. J.H. Miller, Jr., R.E. Thorne, W.G. Lyons, and J.R. Tucker, "Possible direct evidence for quantum tunneling in the large signal ac response of charge-density waves in TaS_3," *Proceedings of the 17th Int. Conference on Low Temp. Physics*, North Holland, Vol. II, p. 1189 (1984). (JSEP/NSF)

6. J. Richard, R.E. Thorne, W.G. Lyons, J.H. Miller, Jr., and J.R. Tucker, "Mixing experiments in $NbSe_3$," *Solid State Commun. 52*, 183 (1984). (JSEP/NSF)

Conference Papers:

1. John Bardeen and J.R. Tucker, "Solitou model of charge-density wave depinning," *Charge Density Waves in Solids Proceedings* (Budapest, 1984), Springer-Verlag Lecture Notes in Physics *217*, 155 (1984). (JSEP)

WORK UNIT NUMBER 11

TITLE: Excited State Chemistry in Gases

SENIOR PRINCIPAL INVESTIGATOR:

Joseph T. Verdeyen, Research Professor

J. Gary Eden, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

C.C. Abele, Research Assistant
K.N. Badura, Research Assistant
K. Greenberg, Research Assistant

SCIENTIFIC OBJECTIVE:

The general objective of this research unit is to study the interaction of excited molecules, atoms or molecular fragments with solid surfaces with particular emphasis on the etching or growth of semiconducting materials. The excited species may be produced by a discharge, electron beam, ultraviolet or visible photons, or combinations of the three. Inasmuch as these excitation means produce an environment which is far from thermodynamic equilibrium, one can expect processes which deviate considerably from that found in conventional chemical processing. Our immediate experimental goals are to utilize many of the modern sophisticated diagnostic tools, such as laser induced fluorescence, optogalvanic spectroscopy, mass spectroscopy, and Raman spectroscopy to elucidate the physical processes occurring in the volume adjacent to the surface being etched or grown. One further goal is to grow (by laser or discharge techniques) electronic materials and structures which are difficult to fabricate by conventional means.

SUMMARY OF RESEARCH:

A. Laser Growth of Films

During this past year, emphasis has been placed on examining the effect of illuminating surfaces with visible or UV laser radiation during the CVD growth of films. While this work is still in an initial phase, it has been observed that even low fluences of laser radiation significantly alter the film growth rate and quality. For example, for Ge films grown by the pyrolysis (CVD) of GeH_4 at temperatures just beyond 300°C, the growth rate increases by roughly an order of magnitude when the substrate is illuminated with ArF laser (λ = 193 nm) radiation. Preliminary measurements indicate a dramatic change in the index of refraction of the deposited film as well. Similar observations have been made when an Ar^+ ion laser beam (λ = 514 nm) strikes the surface. In the next year, we expect to explore the laser wavelength and intensity dependence of this effect as it shows considerable promise for permitting the growth of high quality films at significantly reduced substrate temperatures.

We have also recently demonstrated the feasibility of detecting minute impurities in gases by laser-induced breakdown (LIB). A pulsed visible laser is focused into a cell containing a small sample of the gas in question and emission resulting from LIB in the gas is dispersed (spectrally) and detected. Already, argon has been detected in GeH_4 at the sub-ppm level *without the need for synchronous detection*. Therefore, this technique shows promise for detecting impurities which cannot be studied by

conventional means such as mass spectroscopy.

Finally, in the past year, the spectroscopic studies of a reactor in which germanium films are grown by photolytic, laser-induced CVD were completed and the results will be published in the May, 1985 issue of the *Journal of Applied Physics*. The results clearly point to the roles played by GeH_2 and GeH_3 in the deposition process.

B. Discharge Etching

In the last progress report, it was mentioned that considerable insight could be obtained on the kinetics involved in discharges used in plasma processing by pulsing the discharges and observing the time evolution of the plasma parameters such as: optical emission, dissociation, and the formation of new species. The kinetics of the NF_3 system has been examined in greatest detail and illustrates the wealth of information available from the pulsed discharge.

A discharge can be initiated on a time scale of a few microseconds or so, whereas the approach to equilibrium of any of those parameters requires hundreds of microseconds. For instance, consider the "well known" optical emission from fluorine at 704 nm from etching discharges. In our pulse discharge, the optical intensity would first grow linearly with time and then saturate at its equilibrium value.

All of our experiments are consistent with a two-step process; the first electron to dissociate the NF_3 and the second to excite it to the state from which the radiation is emitted.

$$e + NF_3 \rightarrow NF_{3-x} + xF + e \quad (1)$$

$$e + F \rightarrow F^* + 3 \quad (2)$$

$$F^* \rightarrow F + h\nu\,(704nm) \quad (3)$$

Note that this scenario is in contrast to that proposed by Donnelly, Flamn, *et al* [1] who suggested that dissociative attachment might be a major source of atomic fluorine. However, the square law dependence on electron density (or current) implied by Eqns. 1 and 2 was easily documented, and thus a dissociative attachment sequence Eq. 4-6 would require a simultaneous detaching and excitation collision

$$e + NF_3 \rightarrow NF_2 + F^- \quad (4)$$

$$e + F^- \rightarrow F^* + 2e \quad (5)$$

$$F^* \rightarrow F + h\nu\,(704nm) \quad (6)$$

Previously, [2] we had demonstrated that 100 mJ of excimer laser radiation at 308 nm was sufficient to completely deplete the negative ion population (F^-) and thus interrupt this kinetic sequence. No such interruption was observed and thus the channel indicated by Eqns. 4-6 was not considered important.

The channel leading to the excitation of the C-B band of N_2, a specie which is *formed* in the discharge, was also identified and is represented by the following sequence.

$$e + NF_3 \rightarrow NF + 2F + e \quad (7)$$

$$NF + NF \rightarrow N_2 + 2F \quad (8)$$

$$e + N_2 \rightarrow N_2 + e \quad (9)$$

$$N_2^* N_2^* \rightarrow +h\,(337nm) \quad (10)$$

It takes one electron to produce each NF molecule and thus the ground state population on N_2 would vary as the square of the electron density. The final electron would excite the molecule to the C state from which radiation was observed. This sequence was verified, and thus scenario indicated by 7 and 8 appears to be the logical path for the formation of N_2.

It appears that the approach to equilibrium of, say, the F^* emission is primarily due to the depletion of the NF_3 donor gas. Thus by utilizing the time history of the optical emission, one can determine the appropriate rate coefficients to predict the percentage *dissociation* in the discharge. Excellent agreement between the predictions and the experiments has been achieved. This work has been described in greater detail in Ref. 3.

In the course of this work, it was observed that the addition of N_2 to the NF_3 discharge increased the etch rate by as much as 50%. Although the effect was established, the mechanism(s) for this enhancement has not been identified. Some of the possibilities under consideration are: (a) a chemical reaction with some of the free radicals NF_{3-x} liberating excess fluorine: (b) An electronic energy transfer from the nitrogen metastable N_2 (A) to the donor gas; or (c) a change in the electron distribution function.

INTERACTIONS AND/OR TECHNOLOGY TRANSFER:

The research described above and in Ref. 3 has been transferred *en masse* to an Air Force contract involving the deposition of silicon from helium - SiH_4 mixtures.

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1. V.M. Donnelly, D.C. Flamn, W.C. Dantremont-Smith, D.J. Werder, *J. Appl. Phys. 53*, 242 (1983).
2. K.E. Greenberg, G.A. Hebner, and J.T. Verdeyen, *Appl. Phys. Lett. 44*, 299 (1984).
3. K.E. Greenberg, J.T. Verdeyen, *J. Appl. Phys. 57*, 1596 (1985).

PUBLICATIONS:

Journal Articles:

1. J.F. Osmundsen, C.C. Abele and J.G. Eden, "Activation energy and spectroscopy of the growth of germanium films by ultraviolet laser-assisted chemical vapor deposition," *J. Appl. Physics* (to appear, May 1985). (JSEP/AFOSR)
2. J.G. Eden, J.F. Osmundsen, C.C. Abele and D.B. Geohegan, "Laser photolysis and ionization of polyatomic molecules: Film growth and spectroscopic diagnostics," Proc. SPIE, vol. 459, *Laser Assisted Deposition, Etching and Doping*, pp. 22-24, 1984. (JSEP/AFOSR)
3. K.E. Greenberg, J.T. Verdeyen, "Kinetic processes of NF_3 etchant gas discharges" *J. Appl. Phys. 57*, 1596 (1985). (JSEP)

Conference Papers:

1. J.F. Osmundesen, C.C. Abele and J.G. Eden, "Gas phase spectroscopy of a Ge film LCVD reactor," *Mat. Res. Soc. Symp. Proc.*, vol. 29, pp. 259-267 1984. (JSEP/AFOSR)

2. K. Greenberg and J.T. Verdeyen, "Dissociation and product kinetics of NF_3 etchant gas discharges," Paper K-3, *37th Gaseous Electronics Conference*, Boulder, Colorado, Oct. 9-12, 1984. (JSEP)

Thesis:

1. K. Greenberg, "Plasma diagnostics of discharges in NF_3," Ph.D. Thesis in Electrical Engineering, May 1984. (JSEP)
2. J. Osmundsen, "Low temperature growth of semiconductor thin films by ultraviolet laser induced chemical vapor deposition," Ph.d. Thesis in Electrical Engineering, January 1985. (JSEP)

WORK UNIT NUMBER 12

TITLE: Electromagnetic Radiation and Scattering

SENIOR PRINCIPAL INVESTIGATOR:

R. Mittra, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

T. Kitazawa, Visiting Scholar
J. Nasalski, Visiting Scholar
Z. Pantic, Visiting Scholar
S. Bhooshan, Graduate Student
A. Ali, Graduate Student
A. Chang, Graduate Student
T. Blazeck, Graduate Student
E. Farr, Graduate Student
S. Castillo, Graduate Student
R. Jorgenson, Graduate Student
T. Cwik, Graduate Student
G. Salo, Graduate Student
K. Webb, Graduate Student

SCIENTIFIC OBJECTIVE:

There are four principal objectives of this effort. The first is to develop efficient iterative techniques for solving the problems of electromagnetic scattering from the coupling into complex structures. The second is to study techniques for reducing the radar cross-section of targets. The third is to analyze frequency selective surfaces (FSS) for radomes and other antenna applications. Finally, the fourth objective is to investigate the interconnection problem in Packaging and develop CAD tools for modeling the cross-talk, coupling, and pulse distortion in high speed digital circuits.

SUMMARY OF RESEARCH:

In this project we have been concentrating on four different aspects of electromagnetic scattering and coupling problems. The first of these is aimed toward developing analytical and numerical techniques for solving large body coupling and scattering problems. The second involves a study of techniques for reducing the Radar Cross-section of complex targets by loading them with either a resistive sheet, or with a lossy dielectric or magnetic material that may be arbitrarily inhomogeneous. The third area of investigation involves the study of radome antennas that employ frequency selective surfaces. Finally, the fourth aspect of our research is concerned with the investigation of the coupling, cross-talk and pulse distortion in high-speed digital circuits.

In the area of large body scattering and coupling problems, we feel that we have made significant progress during the last nine months. In the past, we have been involved in the development of the spectral domain approaches for solving electromagnetic scattering problems above the resonance region. During the course of this research it was determined that the original version of the spectral interatative technique (SIT), while it is very versatile and numerically efficient, did not possess the feature of guaranteed convergence for arbitrary structures. This was not totally unexpected, since SIT is an

asymptotic technique, similar in some ways to the geometrical theory of diffraction, or the GTD. It is well known that the asymptotic methods often yield a divergent series when the higher order terms are included. However, an alternate approach, viz., the conjugate gradient (CG) technique, has been recognized for its salutary feature that the convergence of the iteration algorithm employed in this procedure is guaranteed, albeit at the expense of slowing down the iteration.

During the last nine months we have solved a large class of representative problems by combining the moment method, as well as the spectral domain formulation, with the conjugate gradient technique. We found that while for many cases the speed of convergence the conjugate gradient technique was quite adequate, particularly when it was combined with the spectra domain or the discrete convolution techniques that allowed the use of the FFT, the efficiency had considerable room for further improvement for some large body coupling and scattering problems. In light of this fact, we proceeded to develop a new combinational technique that attempts to combine some of the desirable features of the SIT and the CG methods. We have been successful in doing so, and we are now able to guarantee the convergence of the spectral iterative technique while preserving its computational efficiency.

We are currently in the process of testing this algorithm by applying it to a variety of different problems involving low observable targets and microwave coupling into the interior of vehicles, e.g., missiles.

One of the important aspects of radome antenna design is to lower its RCS without an undue compromise of its performance as an antenna. For this reason we have studied the problem of FSS radomes that may be constructed with imperfectly conducting, e.g., resistive materials. We have developed a computer program for studying such FSS structures. Other studies of resistive materials have included the investigation of the scattering properties of bodies that are made up of resistive cards, arranged in periodic cells, which may be rectangular or hexagonal in shape. The attenuation of electromagnetic waves propagating through such lossy, anisotropic media is being computed together with the diffraction properties of this type of a medium as seen by an illuminating radar.

Finally, we have investigated the crosstalk and pulse distortion in multiconductor transmission lines, e.g., microstrip lines or striplines, when these lines are terminated by nonlinear loads, for instance, logic gates. We have developed a new time-domain technique for solving this problem which cannot be handled using the conventional frequency domain methods that employ the Fourier transform technique, since the nature of the circuits being investigated is nonlinear. We are currently studying more complex structures, such as connectors and discontinuities in the transmission lines, and are determining the effects of these discontinuities on the degradation of high speed digital pulses. We believe that the results of our investigation will be useful in the problem of developing CAD tools for Packaging of digital circuits.

SIGNIFICANT RESEARCH ACCOMPLISHMENTS:

We have developed a hybrid technique based upon the combination of the Spectral domain approach and the minimization of an error functional as in the Conjugate gradient technique. The new algorithm has the useful feature that the convergence of the spectral iteration procedure can now be guaranteed. We have also developed a technique for analyzing inhomogeneously coated conducting bodies and bodies that are constructed from resistive cards. A new time-stepping procedure for analyzing digital circuits with nonlinear loads has also been developed.

INTERACTIONS AND/OR TECHNOLOGY TRANSFER:

We have had interactions with MICOM at Huntsville who have been interested in our efforts to build a 220 GHz imaging radar. We have transferred the design of such a radar system to MICOM.

PUBLICATIONS:

Journal Articles:

1. C. H. Tsao and R. Mittra, "Spectral-domain analysis of frequency selective surfaces comprised of periodic arrays of cross dipoles and Jerusalem crosses," *IEEE Trans. of Antennas & Propagation*, vol. AP-32, no. 5, pp. 478-486, May 1984. (JSEP/ONR)
2. R. Mittra, R. Hall and C. H. Tsao, "Spectral-domain analysis of circular patch frequency selective surfaces," *IEEE Trans. on Antennas & Propagation*, vol. AP-32, no. 5, pp. 533-536, May 1984. (JSEP/ONR)
3. W. L. Ko and R. Mittra, "Computation of induced surface current of the main reflector of a shaped dual-reflector antenna, *AEU*, Band 38, Heft 5, pp. 297-302, Sept/Oct. 1984. (JSEP)
4. V. Galindo-Israel and R. Mittra, "Comments on 'Synthesis of offset dual shaped subreflector antennas for control of Cassegrain aperture distribution's," *IEEE Trans. on Antennas & Propagation*, vol. AP-32, no. 10, pp. 1144-1145, November 1984. (JSEP)

Conference Papers:

1. V. Galindo-Israel and R. Mittra, "Comments on 'synthesis of offset dual shaped subreflector antennas for control of Cassegrain aperture distributions,'" *IEEE Trans. on Antennas & Propagation*, vol. AP-32, no. 10, pp. 1144-1145, October 1984. (JSEP)
2. R. Mittra and T. M. Habashy, "Theory of wave-front-distortion correction by phase conjugation," *Journal of the Optical Society of America A*, vol. 1, no. 11, pp. 1103-1109, November 1984. (JSEP)
3. M.F. Sultan and R. Mittra, "An iterative moment method for analyzing the electromagnetic field distribution inside inhomogeneous lossy dielectric objects," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-33, no. 2, pp. 163-1689, February 1985. (JSEP/ONR)
4. S. Ray and R. Mittra, "Numerical analysis of open waveguide discontinuities," submitted to *Radio Science*, special issue. (JSEP/ONR)
5. J. Schutt-Aine and R. Mittra, "Analysis of pulse propogation in coupled transmission lines," submitted to *Trans. on Circuit and Systems*. (JSEP/ONR)
6. A.F. Peterson and R. Mittra, "The method of conjugate gradients for the numerical solution of large-body electromagnetic scattering problems," submitted to *Journal of the Optical Society of America*, special issue. (JSEP/ONR)
7. R.C. Hall and R. Mittra, "Scattering from a periodic array of resistive strips," submitted to *AP-S. (JSEP/ONR)*
8. R. Mittra and C.H. Chan, "Iterative solution of electromagnetic boundary value problems in the spectral domain," submitted to *Electromagnetics*, special issue. (JSEP/ONR)
9. E.G. Farr, C.H.Chan and R. Mittra, "Analysis of N-conductor transmission line systems terminated with non-linear digital devices," submitted to *MTT Special Issue*. (JSEP/ARO)
10. S.P. Castillo and R. Mittra, "Analysis of N-conductor transmission line system terminated with non-linear digital devices," submitted to *Electromagnetic Compatibility*. (JSEP/ONR)
11. S. Ray and R. Mittra, "Spectral-iterative analysis of electromagnetic radiation and scattering problems," N00014-81-K-0245 and N00014-84-C-0149, and Texas Instruments, EM Report No. 84-11, July 1984. (JSEP/ONR)

12. M. Hurst and R. Mittra, "Scattering center analysis for radar cross section modification," N00014-81-K-0245, N00014-84-C-0149, and Texas Instruments, EM Report No. 84-12, July 1984. (JSEP)

13. J. Schutt-Aine and R. Mittra, "Analysis of pulse propagation in coupled microstrip transmission lines," N00014-81-K-0245 and GTE Network Systems Inc., EMC Report No. 84-1, July 1984. (JSEP/ONR)

14. S. Castillo and R. Mittra, "A study of crosstalk and distortion of high speed pulses in digital circuits," AT&T Information Systems and GTE Communication Systems Corp., EMB Report No. 84-2, October 1984. (JSEP/ONR)

15. A. F. Peterson and R. Mittra, "The method of conjugate gradients for the numerical solution of large-body electromagnetic scattering problems," N00014-81-K-0245, EMC Report No. 85-1, January 1985. (JSEP/ONR)

Theses:

1. Roy Jorgenson, "Electromagnetic scattering from an artificial dielectric slab—a perturbation approach." M. S. Thesis (1985) (JSEP)

ADDITIONAL INFORMATION:

Awards and Honors:

Raj Mittra

Fellow, Institute of Electrical and Electronics Engineers
J.S. Guggenheim Foundation Fellowship
Past President, IEEE Antennas and Propagation Society
Editor, IEEE Transactions on Antennas and Propagation
Certificate of Recognition, National Aeronautics and Space Administration
Member, Editorial board, Space Communication and Broadcasting

WORK UNIT NUMBER 13

TITLE: Millimeter and Submillimeter Wave Integrated Circuits

SENIOR PRINCIPAL INVESTIGATOR:

R. Mittra, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

T. Kitazawa, Visiting Scholar
J. Nasalski, Visiting Scholar
Z. Pantic, Visiting Scholar
S. Bhooshan, Research Assistant
A. Ali, Research Assistant
A. Chang, Research Assistant
T. Blazeck, Research Assistant
E. Farr, Research Assistant
S. Castillo, Research Assistant
R. Jorgenson, Research Assistant
T. Cwik, Research Assistant
G. Salo, Research Assistant
K. Webb, Research Assistant

SCIENTIFIC OBJECTIVE:

Effective utilization of the millimeter-wave (mm-wave) spectrum, for communication, radar and electronic counter measure and for several other applications, depends rather critically on the development of reliable, low cost, planar integrated circuits. A major objective of our effort is the development of guiding structures and associated components for millimeter and submillimeter wave integrated circuits.

Successful development of these waveguides and associated components requires the use of sophisticated analytical tools capable of handling complex structures comprising dielectric rods and substrates of various cross-section, with and without metallic shields. The discontinuities in these waveguides, that are inevitably present when a circuit such as a filter, a transition or an oscillator is integrated in a monolithic system, pose an even more challenging problem to the designer of the system. The availability of computer-aided design tools offers great help to the designer and a major objective of our effort is to develop such tools.

Since few reliable and efficient analytical techniques are currently available for investigating planar inhomogeneous waveguides and discontinuities that can often support higher order modes, it is essential that the analytical methods we develop be thoroughly tested experimentally. For this reason, we also plan to pursue an experimental program that would support and complement the theoretical studies.

SUMMARY OF RESEARCH:

During the past nine months we have investigated a number of different wave-guiding configurations that are suitable for monolithic millimeter wave circuits. These include microstrip lines, finlines as well as striplines with periodic stubs. The design of monolithic integrated circuits requires as reliable knowledge of the equivalent circuits of discontinuities that are inevitably present in these circuits. With this in mind, we have been investigating a number of different techniques for analyzing and characterizing these discontinuities in planar waveguides. We have also been pursuing a complementary experimental program to verify the theoretical results. We have applied the finite element technique to calculate the equivalent circuit of discontinuities in planar transmission lines, e.g., a microstrip line. We have also developed the mode-matching solution of the discontinuity problem in microstrips and finlines. The mode matching method has been extensively applied in the past to solve the discontinuity problem in conventional, hollow metallic, rectangular or circular waveguides. However, in the past, a lack of knowledge of the higher order modes in planar waveguides prevented the use of this technique for the solution of the discontinuity problem in a microstrip line or in a finline. For this reason, we have developed a technique for accurate computation of the higher order modes in such waveguides. The availability of these higher order modes will now enable us to solve complex discontinuity problems using the mode matching procedure.

In addition to the above two methods, we have also been pursuing the development of the spectral domain approaches for solving the discontinuity problems. Iterative techniques are currently being developed for attacking a wide class of discontinuity problems that are either of more general nature than could be handled with the mode matching technique, or are too time-consuming or unwieldy to be treatable with the finite element method.

Experimental efforts in the monolithic integrated circuit area have included the modeling of the discontinuities and the verification of the theoretical results. Discontinuities typically present in monolithic designs, e.g., transitions or tapers from the source to an active module, or from the source to the antenna, are being investigated. Other types of discontinuities being studied include the transition between two different dielectric substrates, for instance duroid (ϵ_r=2.2) in a microstrip line and the GaAs (ϵ_r=12.3) substrate in the active module.

In addition to these dielectric antennas compatible with the planar waveguides have been experimentally developed for operation in the 90 GHz and the 220 GHz frequency ranges. These antenna systems have been used to measure the scattering characteristics of a number of canonical geometries.

In the area of quasi-optical circuits and systems, we have developed a technique for analyzing fiber optical guides with anisotropic and inhomogeneous cores that have special single-mode propagation characteristics. We have also investigated mesh filters that find application in infrared signature work. These filters are often printed on substrates whose loss characteristics can be controlled electrically, with a corresponding alteration of their reflection, transmission and absorption characteristics.

PUBLICATIONS:

Journal Articles:

1. T. Kitazawa and R. Mittra, "An investigation of striplines and fin lines with periodic stubs," *IEEE Trans. on Microwave Theory & Techniques*, vol. MTT-32, no. 7, pp. 684-688, July 1984. (JSEP/ARO)

2. T. Kitazawa and R. Mittra, "Analysis of fin line and finite metallization thickness, *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-32, no. 11, pp. 1484-1487, November 1984. (JSEP/ARO)

Conference Papers:

1. T. Kitazawa and R. Mittra, "Analysis of fin line and finite metallization thickness," *IEEE Trans. on Antennas & Propagation*, vol. AP-32, no. 10, pp.1144-1145, October 1984. (JSEP)
2. E. Farr, K. Webb and R. Mittra, "Studies in fin line antenna design for phased array application," submitted to *AEU*. (JSEP/ONR)
3. T. Kitazawa and R. Mittra, "Asymmetrical coplanar transmission lines," submitted to *AP-S. (JSEP/ARO)*
4. T. Kitazawa and R. Mittra, "Analysis of asymmetric coupled striplines," submitted to *MTT. (JSEP/ARO)*
5. T. Kitazawa and R. Mittra, "Quasistatic characteristics of coupled coplanar-type transmission lines," submitted to *MTT*. (JSEP/ARO)
6. K.J. Webb, E.G. Farr and R. Mittra, "A note on the numerical solution for fin line and microstrip modes," submitted to *MTT Special Issue*. (JSEP/ARO)
7. K.J. Webb and R. Mittra, "Solution of the fin line discontinuity problem using the generalized variational technique," submitted to *MTT*. (JSEP/ARO)
8. K. J. Webb and R. Mittra, "Investigation of planar waveguides and components for millimeter-wave integrated circuits," DAAG29-82-K-0084 and N00014-84-C-0149, EMC Report No. 84-3, October, 1984. (JSEP/ARO)

Theses:

1. Albert Chang, "Analysis of microstrip discontinuities using the finite element method," M. S. Thesis (1985). (JSEP)
2. Sean Doran, "An experimental study of dielectric rod antennas for millimeter-wave imaging application," M. S. Thesis (1985). (JSEP)
3. Sunil Bhooshan, "A novel technique for the analysis of dielectric waveguides," M. S. Thesis (1985). (JSEP)

ADDITIONAL INFORMATION:

Awards and Honors:

Raj Mittra

Fellow, Institute of Electrical and Electronics Engineers
J.S. Guggenheim Foundation Fellowship
Past President, IEEE Antennas and Propagation Society
Editor, IEEE Transactions on Antennas and Propagation
Certificate of Recognition, National Aeronautics and Space Administration
Member, Editorial board, Space Communication and Broadcasting

WORK UNIT NUMBER 14

TITLE: Control and Decision Strategies for Systems Under Imperfect Information

SENIOR PRINCIPAL INVESTIGATORS:

J.B. Cruz, Jr., Research Professor

W.R. Perkins, Research Professor

P.V. Kokotovic, Research Professor

N. Wax, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

R. Amir, Research Assistant

R. Milito, Research Assistant

H. Tharp, Research Assistant

SCIENTIFIC OBJECTIVE:

Problems of control systems under imperfect information arise in a variety of applications. Computer control of aircraft, electronic guidance and navigation of missiles and submarines, and fire control systems are typical areas of application. Uncertainties arise because of unknown system parameters, unknown signal environments, and hardware tolerances. Related complexities arise in situations involving multiple system performance criteria and multiple decision agents having access to different information sets. In addition, such systems may consist of interconnections of systems, i.e., be modeled as a large scale system.

The principal objective of this research unit is to gain basic understanding of the behavior and control of complex systems containing uncertainty. Conceptual, analytical, and computational tools fundamental to the synthesis of controllers and control strategies for such systems will be developed. Stochastic adaptive systems, robust reduced order adaptive systems, sensitivity, and nonlinear systems will receive specific attention.

SUMMARY OF RESEARCH:

During the past year, we have continued our research activities on the fundamental study of the role of modeling and information uncertainties in complex systems, specifically in the context of stochastic adaptive control, stochastic adaptive Nash strategies, robust reduced order adaptive control, sensitivity and robustness of multivariable linear systems, and nonlinear systems.

In adaptive control, one area of focus has been the development of a new stability criterion for systems subjected to parameter drifts. Although several researchers have observed parameter drift instabilities in adaptive schemes for identification and control, an analytical explanation of this phenomenon was lacking. We have recently developed a theory of slow adaptation which not only explains this type of instability, but also suggests the means to counteract it. Our stability criterion shows an explicit dependence on input signals and requires that most of signal energy be in the frequency range where the real part of the transfer function is positive. The criterion has attracted the

attention of many researchers not only in this country, but also in Australia and Sweden, and is being extended to many other schemes for parameter estimation and control. In another study in the adaptive field, we have developed an optimization oriented approach to the adaptive control of systems described by Markov Chains, and have investigated convergence properties of the resulting algorithms. Furthermore, we have extended the notion of adapation to multiple decision makers' problems under various modes of decision making, including Nash and hierarchical solution concepts. Also, the Generalized Hessenberg Representation (GHR) as an aggregation oriented model of large systems has continued to receive development. A summary of recent results may be found in the references below. Especially noteworthy has been an interpretation via the GHR of multivariable zeros and their role in controller design.

During this period, we have also continued work on the theory of oscillators and on ways of using the decomposition of large scale systems (both controlled and uncontrolled) to deduce various properties, such as controllability or stability. A list of papers describing these new developments, and published either in the second half of 1984 or in 1985 (or to be published) is provided below.

PUBLICATIONS:

Books or Chapters in Books:

1. D.K. Lindner and W.R. Perkins, "The generalized Hessenberg representation and model reduction," in *Advances in Large Scale systems*, vol. 1, J.B. Cruz, Jr., ed., JAI Press, Greenwich, CT, 1984. (JSEP)

Journal Articles:

1. P.A. Ioannou and P.V. Kokotovic, "Instability analysis and improvement of robustness of adaptive control," *Automatica*, vol. 20, no. 5, pp. 583-594, 1984. (JSEP/NSF)
2. P.A. Ioannou and P.V. Kokotovic, "Robust redesign of adaptive control," *IEEE Trans. on Automatic Control*, vol. AC-29, no. 3, pp. 202-211, March 1984. (AF/JSEP)
3. B. Riedle, B. Cyr, and P. Kokotovic, "Disturbance instabilities in an adaptive system," *IEEE Trans. on Automatic Control*, vol. AC-29, no. 9, pp. 822-824, September 1984. (JSEP)
4. B. Riedle, B. Cyr, and P.V. Kokotovic, "Disturbance instabilities in an adaptive system," *IEEE Trans. on Automatic Control*, vol. AC-29, no. 9, September 1984. (JSEP/AF)
5. V.R. Saksena and J.B. Cruz, Jr., "Robust nash strategies for a class of nonlinear singularly perturbed problems," *International J. Control*, vol. 39, no. 2, pp. 293-310, 1984. (JSEP)
6. B.D. Riedle and P.V. Kokotovic, "Stability analysis of an adaptive system with unmodeled dynamics," *Int. J. Control*, 1985. (to appear) (NSF/JSEP)
7. B.D. Riedle and P.V. Kokotovic, "A stability-instability boundary for disturbance-free slow adaptation with unmodeled dynamics," *IEEE Trans. on Automatic Control*, July 1985. (to appear) (NSF/JSEP)
8. B.D. Riedle and P.V. Kokotovic, "Stability analysis of an adaptive system with unmodeled dynamics," *Int. J. Control*, 1985. (to appear) (JSEP)
9. P.V. Kokotovic, B.D. Riedle, and L. Praly, "On a stability criterion for slow adaptation," submitted to *Systems and Control Letters*. (JSEP)
10. R.A. Milito and J.B. Cruz, Jr., "An optimization oriented approach to the adaptive control of Markov chains," *IEEE Trans. on Automatic Control*, vol. AC-30, 1985. (to appear) (JSEP)

11. P.J. Ponzo and N. Wax, "Periodic solutions of generalized Lienard equations," *J. Mathematical Analysis and Applications*, vol. 104, no. 1, pp. 117-127, Nov. 1984. (JSEP)

12. N. Wax, "Systems structure: Stability and controllability," *J. Mathematical Analysis and Applications*, 1985/1986. (to appear) (JSEP)

Conference Papers:

1. J.S. Freudenberg and D.P. Looze, "Limitations on feedback properties imposed by unstable open loop poles," *Proc. 1984 American Control Conf.*, San Diego, CA, June 6-8. (JSEP/NSF)

2. J.S. Freudenberg and D.P. Looze, "Phase in multivariable feedback systems," *Proc. 23rd IEEE Conf. on Decision and Control*, Las Vegas, NV, December 12-14, 1984. (JSEP/NSF)

3. J.S. Freudenberg and D.P. Looze, "The relation between open loop and closed loop properties of multivariable feedback systems: A practical example," *Proc. 23rd IEEE Conf. on Decision and Control*, Las Vegas, NV, December 12-14, 1984. (JSEP/NSF)

4. P.V. Kokotovic and B. Riedle, "Instabilities of an adaptive system," *Proc. 1984 American Control Conf.*, San Diego, CA, June 6-8. (JSEP/NSF)

5. D.K. Lindner and W.R. Perkins, "The GHR and compensator design," *2nd Istanbul Workshop on Large Scale Systems*, Istanbul, Turkey, June 25-27, 1984. (JSEP)

6. D.K. Lindner and W.R. Perkins, "The generalized Hessenberg representation and pole-zero structure," *Proc. 9th world Congress of IFAC*, Budapest, Hungary, July 2-6, 1984. (JSEP/NSF)

7. D.K. Lindner and W.R. Perkins, "Information structure and decomposition of large scale systems," *Proc. IEEE 23rd Conf. on Decision and Control*, Las Vegas, NV, December 1984. (JSEP)

8. B. Riedle and P.V. Kokotovic, "Bifurcating equilibria of adaptive control systems," *Proc. 1984 American Control Conf.*, San Diego, CA, June 6-8. (JSEP/NSF)

9. B. Riedle and P.V. Kokotovic, "A stability-instability boundary for disturbance-free slow adaptation and unmodeled dynamics," *Proc. 23rd IEEE Conf. on Decision and Control*, Las Vegas, NV, December 12-14, 1984. (NSF/JSEP)

10. T.L. Ting, J.B. Cruz, Jr., and R.A. Milito, "Adaptive incentive controls for Stackelberg games with unknown cost functionals," *Proc. 1984 American Control Conf.*, San Diego, CA, pp. 1457-1463, June 6-8, 1984. (JSEP)

11. B.D. Riedle and P.V. Kokotovic, "Integral manifold approach to slow adaptation," submitted to *24th IEEE Conf. on Decision and Control*, Dec. 1985. (JSEP/NSF)

12. L. Praly and D. Rhode, "A local analysis of a one step ahead adaptive controller," submitted to *24th IEEE Conf. on Decision and Control*, Dec. 1985. (JSEP/NSF)

ADDITIONAL INFORMATION:

Awards and Honors:

Jose B. Cruz, Jr.

Member, National Academy of Engineering
Fellow, Institute of Electrical and Electronics Engineers
Past President, IEEE Control Systems Society
Member, Board of Directors, Institute of Electrical and Electronics Engineers, 1980-85

Vice President for Publication Activities, Institute of Electrical and Electronics Engineers, 1984-85
Halliburton Award for Engineering Education Leadership, College of Engineering, UIUC, 1981
Outstanding Scientist and Engineer, Philippine Engineers and Scientists Organization, 1982.
IEEE Centennial Medal Recipient, 1984

William R. Perkins

Fellow, Institute of Electrical and Electronics Engineers
IEEE Centennial Medal, 1985
President, IEEE Control Systems Society, 1985.

Petar V. Kokotovic

IEEE Fellow
Keating-Crawford Visiting Professor, University of Notre Dame

T. Başar

IEEE Fellow
Sedate Simavi Foundation Award in Mathematical Sciences

WORK UNIT NUMBER 15

TITLE: Implementation Constrained Decomposition and Hierarchical Control

SENIOR PRINCIPAL INVESTIGATORS:

J.B. Cruz, Jr., Research Professor

W.R. Perkins, Research Professor

P.V. Kokotovic, Research Professor

T. Başar, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

J.V. Medanic, Research Professor
M. Zeytinoglu, Visiting Assistant Professor
D. Connors, Research Assistant
R.A. Gerth, Research Assistant
B. Pavlovic, Research Assistant
M. Shor, Research Assistant
P. West, Research Assistant
Y.-W. Wu, Research Assistant

SCIENTIFIC OBJECTIVE:

In large scale systems, control tasks may be decomposed and hierarchical levels may be imposed on the basis of analytically derived strategies. This project is devoted to a study of such hierarchical strategies, and to associated constraints arising from computer implementation of the resulting controllers. Questions such as information flow, time scales, decentralization and loss of feedback loops will be examined in coordinating the multiple controllers in a network.

SUMMARY OF RESEARCH:

During the past year, we have concentrated our efforts primarily on (i) time-scale properties of networks, (ii) integral manifold design of nonlinear two-time scale systems, (iii) decentralized control of large scale systems using aggregation techniques, projective controls or, dominance, (iv) computer-aided-design of control systems, (v) minimax design philosophy and its applications to stochastic control systems with unknown parameters, and to communication and jamming problems with partially unknown statistics, and (vi) developing decentralized algorithms for multiple decision maker problems.

For graphs representing massive nodes connected with 0-1 branches, we have developed a methodology, showing how to represent them in a simpler aggregate form. This methodology exploits a newly established fact about the relationship between the connection density and graph eigenvalues. Using the eigenvalues as time-scale indicators, the aggregate graph interpretation is that it represents slow system-wide phenomena, while the faster phenomena are localized in the areas of denser connections. Several tests on graphs of large scale systems confirm this modeling procedure.

In the field of nonlinear systems, by approaching the design of two-time scale systems in two stages, first, to reach the manifold, and, second, to satisfy a performance requirement in the manifold,

we have been able to solve several nonlinear problems of practical interest. Among them are the feedback linearization problem for a flexible robotic manipulator, and a design method for systems with imperfect actuators. For a manipulator with flexible joints, our design achieves a performance close to that of a perfectly rigid manipulator. These designs have validated the general approach suggested by one of us (PVK) during a plenary talk at the 1984 IFAC World Congress, that the concept of an integral manifold can be used to unify most nonlinear studies.

On the topic of minimax design philosophy, we have developed a number of theoretical results verifying existence of saddle points for stochastic optimization problems with nonclassical decentralized information, with one source of motivation being jamming problems arising in communications. We have also applied this philosophy to the design of controllers for stochastic systems with a hybrid type of uncertainty, and have conducted a numerical study on the comparison between performance measures under the minimax and the traditional stochastic design techniques.

Furthermore, development of the computer-aided design package L-A-S continues. L-A-S provides both design support for simulation experiments with large scale systems, and a forum for algorithm-oriented control law synthesis as well.

A list of papers describing these or earlier research results, and published either in 1984 or in 1985 (or to be published) is provided below.

PUBLICATIONS:

Books or Chapters in Books:

1. Tamer Başar and A. Haurie, "Feedback equilibria in differential games with structural and modal uncertainties," in *Advances in Large Scale Systems*, vol. 1, J.B. Cruz, Jr., ed., JAI Press, Inc., Greenwich, CT, pp. 163-201, 1984. (ONR/JSEP)
2. V.R. Saksena and Tamer Başar, "Multimodeling, singular perturbations and stochastic decision problems," in *Advances in Control and Dynamic systems*, vol. XXII, C.T. Leondes, ed., Academic Press, 1985. (JSEP)

Journal Articles:

1. Tamer Başar, "Affine incentive schemes for stochastic systems with dynamic information," *SIAM J. Control and Optimization*, vol. 22, no. 2, pp. 199-210, March 1984. (JSEP)
2. Tamer Başar and Tangul U. Başar, "A bandwidth expanding scheme for communication channels with noiseless feedback and in the presence of unknown jamming noise," *J. Franklin Institute*, vol. 317, no. 2, pp. 73-88, February 1984. (JSEP)
3. A. Bensoussan, F. Delebecque, C. Gomez, M. Goursat, P.V. Kokotovic, J.P. Quadrat, A. Sulem, and M. Viot, "Commande optimale de systemes stochastiques," *RAIRO Automatique/Systems Analysis and Control*, vol. 18, no. 2, pp. 225-250 1984. (JSEP)
4. J.C. Darragh and D.P. Looze, "Noncausal minimax linear state estimation for systems with uncertain second-order statistics," *IEEE Trans. on Automatic Control*, vol. AC-28, pp. 555-557 June 1984. (JSEP)
5. F. Delebecque, J.P. Quadrat, and P.V. Kokotovic, "A unified view of aggregation and coherency in networks and Markov chains," *Int. J. Control*, vol. 40, no. 5, pp. 939-952, 1984. (JSEP)
6. P.V. Kokotovic, "Applications of singular perturbation techniques to control problems," *SIAM Review*, vol. 26, no. 4, pp. 501-550, October 1984. (NSF/JSEP)

7. B.H. Krogh and P.V. Kokotovic, "Feedback control of overloaded networks," *IEEE Trans. on Automatic Control*, vol. 29, no. 8, pp. 704-711, August 1984. (JSEP)

8. V.R. Saksena, J.O'Reily, and P.V. Kokotovic, "Singular perturbations and time-scale methods in control theory: Survey 1976-1983," *Automatica*, vol. 20, no. 3, pp. 273-293, 1984. (JSEP/NSF)

9. Y.P. Zheng, Tamer Başar, and J.B. Cruz, Jr., "Stackelberg strategies and incentives in multiperson deterministic decision problems," *IEEE Trans. on Systems, Man, and Cybernetics*, vol. SMC-14, no. 1, p. 10-24, January/February 1984. (JSEP/ONR)

10. P.V. Kokotovic, "Recent trends in feedback design: An overview," *Automatica*, May 1985. (JSEP/NSF)

11. Tamer Başar, "An equilibrium theory for multi-person decision making with multiple probabilitistic models," *IEEE Trans. on Automatic Control*, vol. AC-30, no. 2, pp. 118-132, February 1985. (ONR/JSEP)

12. V.R. Saksena and J.B. Cruz, Jr., "A unified approach to reduce order modeling and control of large scale systems with multiple decision makers," *Optimal Control Applications and Methods*, August 1985. (JSEP)

13. Hans P. Geering and Tamer Başar, "Existence of dominant solutions in linear output feedback," *IEEE Trans. on Automatic Control*, June 1985. (to appear) (JSEP)

14. V.R. Saksena and J.B. Cruz, Jr., "Optimal and near-optimal incentive strategies in the hierarchical control of Markov chains," *Automatica*, 1985. (to appear) (JSEP)

15. V.R. Saksena and J.B. Cruz, Jr., "An approach to decentralized control of large scale systems using aggregation methods," *IEEE Trans. on Automatic Control*, vol. AC-30, no. 8, August 1985. (to appear) (JSEP)

16. J.H. Chow and P.V. Kokotovic, "Time scale modeling of sparse dynamic networks," 1985. (to appear) (JSEP)

17. M.W. Spong, K. Khorasani, and P.V. Kokotovic, "A slow manifold approach to feedback control of nonlinear flexible systems," *American Control Conf.*, June 1985. (JSEP)

18. D.H. Cansever and Tamer Başar, "A minimum sensitivity approach to incentive design problems," *Large Scale Systems*, September 1984. (ONR,JSEP)

19. P.V. Kokotovic, "Applications of singular perturbation techniques to control problems," *SIAM Review*, 1984. (to appear) (NSF/JSEP)

20. Tamer Başar and Y.W. Wu, "A complete characterization of minimax and maximin encoder-decoder policies for communication channels with incomplete statistical information," *IEEE Trans. on Information Theory*, July 1985. (to appear) (JSEP)

21. J. Medanic, D. Petranovic, and N. Gluhajic, "The design of output regulators for discrete-time linear systems by projective controls," *Int. J. Control*, 1985. (to appear) (JSEP)

22. J.A.C. Meo, J. Medanic, and W.R. Perkins, "Design of PI + dynamic controls using projective controls," *Int. J. Control*, 1985. (to appear) (JSEP)

23. Tamer Başar and Y.W. Wu, "Solutions to a class of minimax decision problems arising in communication systems," *J. Optimization Theory and Applications*, 1986. (to appear) (JSEP)

Conference Papers:

1. Tamer Başar, "Theory of dynamic games and applications in large scale systems design and optimization," *Proc. 9th World Congress of IFAC*, vol. X, Budapest, Hungary, pp. 177-181, July 1984. (JSEP)

2. Tamer Başar and Y.W. Wu, "A complete class of minimax and maximin encoder-decoder policies for communication channels with incomplete statistical information," *Proc. 1984 Princeton Conf.*

on Information Sciences and Systems, Princeton, NJ, pp. 373-377, March 1984. (JSEP)

3. Tamer Başar and Y.W. Wu, "Solutions to a class of minimax decision problems arising in communication systems," *Proc. of 23rd IEEE Conf. on Decision and Control*, Las Vegas, NV, December 12-14, 1984. (JSEP)
4. Hans P. Geering and Tamer Başar, "Existence of dominant solutions in linear output feedback," *Proc. 23rd IEEE Conf. on Decision and Control*, Las Vegas, NV, pp. 1496-1500, December 12-14. (JSEP)
5. P.V. Kokotovic, "Control theory in the 80's: trends in feedback design," Invited Plenary Session Talk, *9th world Congress of IFAC*, Budapest, Hungary, July 2-6, 1984. (JSEP/NSF)
6. P.V. Kokotovic and K. Khorasani, "Feedback control design of nonlinear singularly perturbed systems: A geometric approach," *Proc. JUREMA Symp. on Trends in Control Theory*, Cavtat, Yugoslavia, July 1984. (NSF/JSEP)
7. S.P. Bingulac, P.J. West and W.R. Perkins, "Recent advances in the L-A-S software used in computer-aided design of control systems," *3rd IFAC/IFIP Symp. on Computer-Aided Design in Control and Engineering Systems*, Copenhagen, Denmark, Jul. 31-Aug. 2, 1985. (JSEP)
8. P.J. West, S.P. Bingulac, and W.R. Perkins, "Recent advances in the L-A-S language used for CACSD," *2nd IEEE Symp. on CACSD*, Santa Barbara, CA, 1985. (JSEP)
9. K. Khorasani and P.V. Kokotovic, "A corrective feedback design for nonlinear systems with fast actuators," submitted to *24th IEEE Conf. on Decision and Control*, Dec. 1985. (JSEP)
10. Tamer Başar and S. Li, "Recursive algorithms for optimal solutions of stochastic teams with decentralized information," *Proc. 1985 American Control Conference*, Boston, Mass., June 19-21, 1985. (to appear) (JSEP)
11. Z. Uskokovic and J. Medanic, "Design of decentralized controllers incorporating integral action for large-scale linear systems," *Proc. 9th world Congress of IFAC*, Budapest, Hungary, July 1984. (JSEP)
12. Tamer Başar and Tangül Ü. Başar, "Minimax transmission policies for continuous-time channels with correlated partial jamming," *IEEE International Symp. on Information Theory*," Brignton, England, June 1985 (JSEP)

PUBLICATIONS (OTHER SUPPORT):

1. Tamer Başar, "Stackelberg strategies in multilevel systems," in *Encyclopedia of Systems and Control*, Pergamon Press, 1984-85, to appear. (AF)
2. Tamer Başar, "Stochastic Multimodeling for teams in game-theoretic framework," in *Economic Applications in Control Theory*, G. Feichtinger, ed., North Holland, 1984-85, to appear. (ONR,AF)
3. Tamer Başar, "Dynamic games and incentives," *Lecture Notes in Control and Information Sciences*, A. Bagchi, ed., Springer-Verlag, 1984-85. (ONR, AF)
4. Tamer Başar and D. H. Cansever, "Robust incentive policies for stochastic problems in the presence of parametric uncertainty," *Proc. 9th World Congress of IFAC, Vol. V*, Budapest, Hungry, July, 1984. (AF)
5. Tamer Başar and J. B. Cruz, Jr., "Deterministic incentives," *Encyclopedia of Systems and Control*, Pergamon Press, 1984-85. (AF)
6. D. H. Cansever and Tamer Başar, "Near-optimum incentive policies in stochastic team problems and discrepancies in goal perceptions," *Proc. 4th IFAC Conf. on Dynamic Modeling and Control of National Economies*," Pergamon Press, pp. 263-270, 1984. (ONR)

7. J. B. Cruz, Jr., "An incentive approach to the coordination of multi-controlled systems," *Proc. Conf. on Optimization Problems in Engineering*, Cassino, Italy, December, 1984. (AF)

8. B. H. Krogh and P. V. Kokotovic, "Feedback control of overloaded networks," *IEEE Trans. on Automatic Control*, Vol. 29, No. 8, pp. 704-711, August 1984. (NSF)

9. Rodolfo A. Milito and J. B. Cruz, Jr., "Robust control of systems modeled as Markov chains," *Proc. 9th World Congress of IFAC*, Budapest, Hungry, July 2-6, 1984. (NSF-INT)

10. Rodolfo A. Milito and J. B. Cruz, Jr., "An optimization-oriented approach to the adaptive control of Markov chains," *Proc. 23rd IEEE Conf. on Decision and Control*, Las Vegas, NV, December 1984. (NSF-INT/NSF)

11. W. R. Perkins, "Chained aggregation," *Encyclopedia of Systems and Control*, Pergamon Press, 1984. (NSF-INT/NSF)

12. L. Praly, "Stochastic controllers with and without a positivity condition," *Proc. 23rd IEEE Conf. on Decision and Control*, Las Vegas, NV, December 12-14, 1984. (NSF/pk)

13. L. Praly, "Robust model reference adaptive controllers, Part I: stability analysis," *Proc. 23rd IEEE Conf. on Decision and Control*, Las Vegas, NV, December 12-14, 1984. (NSF/pk)

14. Vikram R. Saksena and J. B. Cruz, Jr., "Optimal and near-optimal incentive strategies in the hierarchical control of Markov chains," *Automatica*, to appear. (Af,NSF,NSF-INT)

15. V.R. Saksena and J. B. Cruz, Jr., "An approach to decentralized control of large scale systems using aggregation methods," *International J. Control*, Vol. 39, No. 2, pp. 293-310, 1984. (AF)

16. T. L. Ting, J. B. Cruz, Jr., and R. A. Milito, "Adaptive incentive controls for Stackelberg games with unknown cost functionals," *Proc. 1984 American Control Conf.*, San Diego, CA pp. 1457-1463, June 6-8 (AF, NSF)

17. Tamer Başar, "Informational uniqueness of closed-loop equilibria for a class of nonstandard dynamic games," *J. Optimization Theory and Applications*, August, 1985. (AF, ONR)

18. Derya H. Cansever and Tamer Başar, "Optimum or near-optimum incentive policies for stochastic decision problems in the presence of parametric uncertainty," *Automatica*, to appear. (AF)

19. R.A. Milito and J.B. Cruz, Jr., "An optimization oriented approach to the adaptive control of Markov chains," *IEEE Trans. on Automatic Control*, Vol. AC-30, 1985, to appear. (NSF-INT,NSF)

20. B.R. Barmish and Tamar Başar, "A new class of market share games and their equilibria," *5th International Conf. on Math. Modeling*, Berkeley, CA, July 1985. (NSF)

ADDITIONAL INFORMATION:

Awards and Honors:

Jose B. Cruz

Member, National Academy of Engineering
Fellow, Institute of Electrical and Electronics Engineers
Past President, IEEE Control Systems Society
Member, Board of Directors, Institute of Electrical and Electronics Engineers, 1980-85
Founding Member, Phil-American Academy of Science and Engineering
Vice President for Technical Activities, Institute of Electrical and Electronic Engineering, 1982-83.

Founding Member, Phil-American Academy of Science and Engineering
Vice President for Technical Activities, Institute of Electrical and Electronic Engineering, 1982-83.
Vice President for Publication Activities, Institute of Electrical and Electronics Engineers, 1984-85
Halliburton Award for Engineering Education Leadership, College of Engineering, UIUC, 1981
Outstanding Scientist and Engineer, Philippine Engineers and Scientists Organization, 1982.
IEEE Centennial Medal Recipient, 1984

William R. Perkins

Fellow, Institute of Electrical and Electronics Engineers
IEEE Centennial Medal, 1985
President, IEEE Control Systems Society, 1985.

Petar V. Kokotovic

IEEE Fellow
Keating-Crawford Visiting Professor, University of Notre Dame

WORK UNIT NUMBER 16

TITLE: Multiple-Terminal Digital Communication Systems

SENIOR PRINCIPAL INVESTIGATOR:

B. Hajek, Research Associate Professor

M.B. Pursley, Research Professor

D.V. Sarwate, Research Professor

SCIENTIFIC OBJECTIVE:

The objectives of the proposed research are to develop new analytical methods for performance evaluation of multiple-terminal digital communication systems; devise new techniques for modulation, coding, and diversity which will provide increased jamming protection and multiple-access capability in spread-spectrum systems; evaluate alternative receiver structures and diversity combining methods for spread-spectrum communication in a fading environment; and investigate new approaches to transmission scheduling and routing in mobile radio networks.

SUMMARY OF RESEARCH:

1. Diversity Combining for Frequency-Hop Communications

Diversity transmission is often employed in frequency-hop systems to provide reliable communication in the presence of fading or partial-band interference. Some of the methods for combining the diversity receptions require side information regarding the presence or absence of interference on the diversity receptions. Because of implementation considerations, diversity combining techniques that do not require side information from external sources are particularly attractive. One diversity combining scheme that does not require side information is called *clipped linear combining* [1]. In this system, the output of the envelope detector of each diversity reception is clipped before it is added with the other diversity receptions. It is shown in [1] that clipped linear combining is effective against partial-band interference. There is a practical disadvantage to this diversity combining scheme, however, since the clipping level depends on the average received signal voltage in the absence of the interference. This signal voltage may be difficult to measure in practice.

It is desirable to employ diversity combining techniques that do not depend on the received signal power. One such diversity combining technique is *Viterbi's ratio threshold technique* [2]-[4]. Each diversity reception is determined to be accepted or rejected based on the relative values of the envelope detector outputs. More specifically, for each diversity reception, the ratio of the largest envelope detector output to the second largest envelope detector output is compared to a threshold which is a fixed number greater than one. If the ratio is less than the threshold, the diversity reception is rejected, and if it is greater than the threshold, it is accepted. If at least one reception is accepted, then only the accepted diversity receptions are combined. If all diversity receptions are rejected, then all of them are combined and a hard decision is made (the resulting symbol may be flagged for erasure if the decoder has a provision for correcting erasures [5]).

We have computed the average probability of error for Viterbi's ratio threshold technique used in conjunction with diversity for frequency-hop communications in the presence of partial-band Gaussian interference. The system with binary orthogonal signaling and noncoherent demodulation is analyzed. A comparison is made between the system employing Viterbi's ratio threshold technique with linear

diversity combining and the system that utilizes clipped linear combining [1] as the diversity scheme. We allow a nonzero background or quiescent noise level to account for thermal noise in the receiver and other wideband noise sources.

2. Fast Frequency Hopping for Mobile Radio Applications

We have continued out investigation of the performance of a class of fast frequency hopped spread-spectrum multiple-access communication schemes proposed for mobile radio communications. We have studied the performance of the sub-optimum receiver (derived in earlier work) when it uses hard decisions instead of soft decisions on each hop. Both the additive white Gaussian noise channel and the nonselective Rayleigh fading channel have been considered. We have also analyzed the performance of this receiver when interfering signals from other users are present. Analytical results have been obtained for both the nonfaded and the nonselective Rayleigh faded channel. These results indicate that the performance of this receiver is somewhat different than the performance of previously considered receivers for this system [6].

3. Spread-Spectrum Multiple-Access Communication for the Low Frequency Band

We have continued our investigation of DS/SSMA communication over the low frequency (LF) band. In previous work, we had derived a locally optimum receiver for such a system operating in a mixture of Gaussian and impulsive noise. The receiver consists of a bandpass correlator followed by a sampler, a zero-memory nonlinearity, and M discrete-time matched filters. More recently, we have studied the performance of such a receiver when the optimum nonlinearity is replaced by more easily realizable nonlinearities such as limiting amplifiers, hard limiters, and hole-punchers. Our results indicate that performance (as measured by the signal-to-noise ratio) is degraded only slightly when such nonlinearities are used, and that the performance is not very critically dependent on the parameters defining these nonlinearities. Error probability as a performance measure is also being considered.

4. Transmission Scheduling and Retransmission Control in Spread-Spectrum Radio Networks

We have made more progress on the problem of scheduling transmissions in a spread-spectrum mobile packet radio network to avoid primary collisions. We have recently discovered a polynomial time algorithm for computing a schedule of minimal length. This minimal length is also the multichromatic index of a graph. The algorithm is based on work of Grotschel, Lovasz, and Schrijver and work of Edmonds. The algorithm proves false the previously held belief that the scheduling problem is NP-complete.

In another line of JSEP funded research, we have shown how the theory of stochastic approximation can be used to fruitfully study adaptive control of retransmission probabilities. A quite general family of retransmission control strategies was introduced such that, on the basis of very limited feedback, the transmission probabilities of various stations can be controlled.

Issues of fairness and priorities are addressed through the introduction of a cost function which the stations endeavor to minimize in a distributed fashion. The estimators appear to be quite effective in simulations. The use of stochastic approximation provides a fairly systematic approach which can be applied as well to the control of transmission power, code rates, etc. These possibilities deserve further study.

5. Clustering Algorithms for Packet Radio Networks

We have begun a study of algorithms for organizing a packet radio network into overlapping clusters. Two strategies were proposed and compared. The strategies incorporate heuristics for generating priorities which determine which nodes will become cluster heads. Simulations were used to generate trade-off curves for the strategies. A small mean distance to the nearest cluster head can be traded off to obtain a low density of cluster heads. As we found, some clustering strategies tend to have more favorable trade-off curves.

DoD INTERACTIONS

Our research program has benefitted from interactions with several DoD personnel including the following: Dr. Lloyd Griffiths (ONR), Dr. Barry Leiner (DARPA), Dr. P. Papantoni-Kazakos (ONR), Dr. William Sander (ARO), Dr. Paul Sass (USACECOM), and Dr. Jeff Wieselthier (NRL). In addition, our work on coding and diversity has been influenced by considerations arising from the USAF jam-resistant digital voice communications program at RADC (J. Patti, Project Engineer).

REFERENCES:

1. C. M. Keller and M. B. Pursley, "Diversity combining for frequency-hop spread-spectrum communications with partial-band interference," *IEEE Military Communications Conference*, pp. 32.1.1-5, October 1984.
2. A. J. Viterbi, "A robust ratio-threshold technique to mitigate tone and partial band jamming in coded MFSK systems," *IEEE Military Communications Conference*, pp. 22.4.1-5, October 1982.
3. L. F. Chang and R. J. McEliece, "A study of Viterbi's ratio-threshold AJ technique," *IEEE Military Communications Conference*, pp. 11.2.1-5, October 1984.
4. L. F. Chang, "An information-theoretic study of ratio-threshold antijam techniques," PhD Thesis, University of Illinois at Urbana-Champaign, January 1985.
5. M. B. Pursley and W. E. Stark, "Performance of Reed-Solomon coded frequency-hop spread-spectrum communications in partial-band interference," accepted for publication in *IEEE Transactions on Communications*, 1985.
6. A. W. Lam and D. V. Sarwate, "Multiple-user interference in FHMA-DPSK spread-spectrum communications," submitted for publication to *IEEE Transactions on Communications*, 1984.

PUBLICATIONS:

Books or Chapters in Books:

1. E. Wong and B. Hajek, *Stochastic Processes in Engineering Systems*, Springer-Verlag, New York, (1985). (ARO/JSEP/NSF/ONR)

Journal Articles:

1. B. Hajek, "Stochastic approximation methods for decentralized control of multiaccess communications," (Invited Paper) to appear in *IEEE Transactions on Information Theory, (Special Issue on Multi-Access Communications)*, vol. IT-31, March 1985. (JSEP)
2. M.B. Pursley and W.E. Stark, "Performance of Reed-Solomon coded frequency-hop spread-spectrum communications in partial-band interference," accepted for publication in *IEEE Transactions on Communications*, 1985. (JSEP)

Conference Papers:

1. C.M. Keller and M.B. Pursley, "Diversity combining for frequency-hop spread-spectrum communications with partial-band interference," *Conference Record, 1984 IEEE Military Communications Conference*, Los Angeles, California, October 1984, vol. 3, pp. 464-468. (JSEP)
2. C.M. Keller and M.B. Pursley, "Diversity combining and Viterbi's ratio threshold technique for frequency-hop communications in the present of partial-band interference," to appear in *Proceedings of the 1985 Conference on Information Science and Systems*, The Johns Hopkins University, Baltimore, Maryland, March 27-29, 1985. (JSEP)

Technical Reports:

1. A. W.-H. Lam, "Multiple-user interference in a frequency-hoped spread-spectrum communication system using differential phase shift keying," Report R-1016, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois, September 1984. (JSEP)
2. J. Rossi, "Clustering algorithms for hierarchical routing in networks," Report R-1025, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois, December 1984. (JSEP)
3. W.F. Brady, "Correlation in coupled queues and simulation of a stochastic approximation procedure for multi-access communications," Report R-1103, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois, March 1985. (JSEP)

PUBLICATIONS (OTHER SUPPORT):

Journal Articles

1. D.V. Sarwate, "An upper bound on the aperiodic autocorrelation function for a maximal-length sequence," *IEEE Transactions on Information Theory*, vol. IT-30, pp. 685-687, July 1984. (ARO)
2. B. Hajek, "*Review of Semimartingales: A Course on Stochastic Processes* by M. Metivier,", *Bulletin of the American Mathematical Society*, vol. 11, pp. 198-203, July 1984.
3. B. Hajek and R. Ogier, "Optimal dynamic routing in communication networks with continuous traffic," *Networks*, vol. 14, pp. 457-487, 1984. (ONR/NRL)
4. B. Hajek, "Mean stochastic comparison of diffusions," *Z. Wahrscheinlichkeitstheorie verw. Geb.*, vol. 68, pp. 315-329, 1985. (ONR/ARO)
5. D.V. Sarwate, "Review of Error Control Coding: Fundamentals and Applications by S. Lin and D.J. Costello, Jr.," to appear in *IEEE Transactions on Information Theory*, 1985.
6. B. Hajek, "Extremal splittings of point processes," to appear in *Mathematics of Operations Research*, 1985. (ONR)
7. E.Q. Geraniotis and M.B. Pursley, "Performance of coherent direct-sequence spread-spectrum communications over specular multipath fading channels," to appear in *IEEE Transactions on Communications*, 1985. (DARPA)

Conference papers

1. B. Hajek, "Extremal splittings of point processes - applications to service allocation problems," *ORSA-TIMS Bulletin*, vol. 18, pp. 152-153, 1984. (ONR)
2. B. Hajek, "Mean stochastic comparison of diffusions," *Proceedings of the IEEE Control and Decision Conference*, Las Vegas, Nevada, pp. 1490-1491, December 12-14, 1984.
3. A.W. Lam and D.V. Sarwate, "Throughput of time-hopping and frequency-hopping communications in slotted ALOHA," to appear in *Proceedings of the 1985 Conference on Information Science and systems*, The Johns Hopkins University, Baltimore, Maryland, March 27-29, 1985. (ARO)
4. R.L. Cruz and B. Hajek, "Global load balancing by local adjustments," to appear in *Proceedings of the 1985 Conference on Information Sciences and Systems*, The Johns Hopkins University, Baltimore, Maryland, March 27-29, 1985. (ONR/NSF)
5. R.G. Ogier, "Optimal flows in generalized networks with submodular capacities," to appear in *Proceedings of the 1985 Conference on Information Sciences and systems*, The Johns Hopkins University, Baltimore, Maryland, March 27-29, 1985. (ONR)
6. G.H. Sasaki and B. Hajek, "Optimal dynamic routing by iterative methods," to appear in *Proceedings of the 1985 Conference on Information Sciences and Systems*, The Johns Hopkins University, Baltimore, Maryland, Marcy 27-29, 1985. (ONR)
7. D.J. Taipale and M.B. Pursley, "An upper bound on the packet error probability for convolutional codes with Viterbi decoding," accepted for presentation at the *1985 IEEE International Symposium on Information Theory*, Brighton, England, June 23-28, 1985. (DARPA)
8. D.V. Sarwate, "Bounds on the aperiodic correlation of shift register sequences," accepted for presentation at the *1985 IEEE International Symposium on Information Theory*, Brighton, England, June 23-28, 1985. (ARO)

Technical Reports

1. M.B. Pursley, "Frequency-hop transmission for satellite packet switching and terrestrial packet radio networks," Report T-144, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois, July 1984. (ARO/DARPA)
2. G.H. Sasaki, "Optimal dynamic routing by iterative methods," Report T-143, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois, July 1984. (ONR)
3. D.J. Taipale, "Direct-sequence spread-spectrum packet radio performance," Report T-155, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois, September 1984. (DARPA)
4. J.S. Lehnert, "Direct-sequence spread-spectrum signaling with applications to packet radio systems," Report T-153, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois, November 1984. (ARO/DARPA)

ADDITIONAL INFORMATION:

Awards and Honors:

Bruce Hajek

National Science Foundation Presidential Young Investigator Award, 1984
Beckman Associate, Center for Advanced Study, UIUC, 1984-85
Eckman Award, American Automatic Control Council
Xerox Award for Faculty Research, College of Engineering, UIUC

Michael B. Pursley

Associate, Center for Advanced Study, UIUC
Fellow, Institute of Electrical and Electronics Engineers
President, IEEE Information Theory Group

WORK UNIT NUMBER 17

TITLE: Digital Detection and Estimation

SENIOR PRINCIPAL INVESTIGATOR:

H. Vincent Poor, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

B. Aazhang, Research Assistant

SCIENTIFIC OBJECTIVES:

The primary goal of this research is the development of practical and efficient implementations for signal detection and estimation systems with potential applications to communication receivers, sonar and radar tracking and detection, and other statistical signal processing functions. The main emphasis is on the development of techniques for the design and analysis of digital systems for use in such applications. particular attention will be paid to situations in which signal and noise models do not obey standard assumptions or in which accurate modeling is not possible. Such situations invite the utilization of nonlinear, robust, adaptive, and/or nonparametric systems which, while exhibiting superior performance, often require complex structures for exact implementation. Advances in integrated circuitry have made practical the approximation of such structures with digital systems, and thus this study is motivated in part by the desire to utilize fully the flexibility and power of the new technology.

SUMMARY OF RESEARCH:

Our JSEP sponsored research during this reporting period has been focused primarily on two problems: (1) performance evaluation of direct-sequence spread-spectrum multiple-access (DS/SSMA) communications in non-Gaussian noise environments; and (2) analysis of data quantization schemes in signal detection and estimation. Also, during this period we have prepared an extensive survey for the *Proceedings of the IEEE* describing our work on the problem of robust filtering that has been conducted under JSEP and other sponsorship over the past six years.

Non-Gaussian, impulsive noise is a key noise source in many multiple-access communication systems (such as military radio networks). Thus, when studying such systems, the evaluation of their performance in non-Gaussian noise is of interest. We have considered two techniques for evaluating the average error probabilities of conventional linear DS/SSMA receivers in impulsive noise, one of which uses a characteristic function method and is useful for small spreading sequence lengths and the other of which uses a Taylor-series expansion method for longer spreading sequences. We carry these results further by considering nonlinear correlation receivers to improve the receiver performance against impulsive noise. These results indicate that substantial performance gain can be obtained by using nonlinear reception, particularly for long spreading sequences and heavily impulsive noise.

We also have considered several problems relating to the quantization of data for various purposes. In this work we have concentrated on the problem of fine quantization and on the development of performance expressions and design methods for this case. Specific problems that we have treated are the analysis and design of quantizers for signal-detection data, the analysis of the effects of data quantization on MMSE filtering, and the design of quantizers that have good distortion performance for data with uncertain statistics.

A further study has treated the analysis of the efficiencies of a class of multistage signal-detection algorithms. These algorithms are seen in our analysis to have efficiencies near that of the optimum sequential-probability-ratio detector while retaining the design and implementational simplicity of conventional fixed-sample-size detection algorithms. These new algorithms are seen to be particularly efficient for applications, such as search radar, in which the presence of a signal occurs rarely relative to the absence of one.

PUBLICATIONS:

Journal Articles:

1. B. Aazhang and H.V. Poor, "On optimum and nearly optimum data quantization for signal detection," *IEEE Trans. Commun.*, vol. COM-32, pp. 745-751, July 1984. (JSEP)
2. S.A. Kassam and H.V. Poor, "Robust techniques for signal processing: A survey," (invited) *Proc. IEEE*, vol. 73, pp. 433-481, March 1985. (ARO/AFOSR/JSEP/NSF/ONR)
3. H.V. Poor, "Robust quantization of ϵ-contaminated data," *IEEE Trans. Commun.*, vol. COM-33, pp. 218-222, March 1985. (JSEP)
4. S. Tantaratana and H.V. Poor, "Asymptotic relative efficiencies of multistage tests," *IEEE Trans. Inform. Theory*, vol. IT-31, 1985. (to appear) (JSEP)

Conference Papers:

1. B. Aazhang and H.V. Poor, "Non-Gaussian effects in DS/SSMA communications," *Proc. 1984 IEEE Mil. Comm. Conf.*, Los Angeles, CA, November 14-16, 1984. (ARO/JSEP)
2. H.V. Poor, "Quantization effects in filtering of stationary Gaussian processes," (invited) *Proc. 23rd IEEE Conf. on Decision and Control*, Las Vegas, NV, pp. 1430-1435, December 12-14, 1984. (JSEP)
3. B. Aazhang and H.V. Poor, "Asymptotic and approximate results on the performance of DS/SSMA receivers in non-Gaussian noise," *Proc. 1985 Conf. on Information Science and Systems*, The John Hopkins University, Baltimore, MD, March 22-29, 1985. (JSEP)
4. B. Aazhang and H.V. Poor, "Performance of the hard-limiting DS/SSMA receiver in non-Gaussian noise," *1985 IEEE International Communication Conf. Rec.*, Chicago, IL, June 23-26, 1985. (JSEP)
5. B. Aazhang and H.V. Poor, "Performance analysis of DS/SSMA receivers in non-Gaussian noise," *Proc. 1985 North American Radio Science Meeting*, Univ. of British Columbia, Vancouver, Canada, June 17-21, 1985. (to appear) (JSEP)

PUBLICATIONS (OTHER SUPPORT):

1. J. Franke and H.V. Poor, "Minimax robust filtering and finite-length robust predictions," in *Robust and Nonlinear Time Series Analysis* (J. Franke, W. Härdle, and R.D. Martin, Eds.) Springer-Verlag: Heidelberg, 1984. (ONR)
2. S. Verdu and H.V. Poor, "Backward, forward, and backward-forward dynamic programming models under commutativity conditions," *Proc. 23rd IEEE Conf. on Decision and Control*, Las Vegas, NV, pp. 1081-1086, December 12-14, 1984. (NSF/ONR)

3. S. Verdu, "On the selection of memoryless adaptive laws for blind equalization in binary communications," in *Lecture Notes in Control and Information Sciences*, vol. 63, (A. Bensoussan and J.L. Lions, Eds.), pp. 239-249, Springer-Verlag: Berlin, 1984. (ARO/ONR)

4. E.A. Geraniotis and H.V. Poor, "Minimax discrimination for observed Poisson processes with uncertain rate functions," *IEEE Trans. Inform. Theory*, vol. IT-31, 1985. (to appear) (ONR)

ADDITIONAL INFORMATION:

H. Vincent Poor has recently published (in March 1985) an invited survey paper in the *Proceedings of the IEEE* that surveys the field of robust signal processing, much of which was developed under JSEP and other support at the Coordinated Science Laboratory.

Awards and Honors:

H. Vincent Poor

Xerox Award for Research by an Associate Professor, University of Illinois, College of Engineering

WORK UNIT NUMBER 18

TITLE: Hierarchical Simulation and Design Verification of VLSI Circuits and Systems

SENIOR PRINCIPAL INVESTIGATORS:

I.N. Hajj, Research Associate Professor

V.B. Rao, Research Assistant Professor

T.N. Trick, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

K. Cioffi, Research Assistant

P. Gee, Research Assistant

D. Yeh, Research Assistant

K.-M. Ivy Lui, Research Assistant

SCIENTIFIC OBJECTIVE:

Since the introduction of the integrated circuit chip, chip complexity has doubled every two years. However, concurrent with this growth in complexity, the design cycle has lengthened and the design expense has been increasing by a factor of three or more about every five years. We are now at the point where the design of a custom VLSI circuit will require over one hundred man-years with present design methodologies. Thus, the initiation of a new VLSI circuit is a very major investment risk. This trend in design complexity is a major concern of leaders in the electronics industry. New design methodologies as well as better computer-aids for the synthesis, layout, simulation, verification, and testing of VLSI systems are needed. Unfortunately, the computational complexity of the problems in this area are typically NP-complete. From the point of view of the development of design automation tools, the apparent intractability of NP-complete problems leads one to the use of suboptimal heuristic algorithms. Because of this complexity a hierarchical approach will have to be taken in the solution of the problems in this field.

The objective of our research in this area is to study hierarchical approaches to the simulation and verification of VLSI circuit designs. In particular, models and design verification aids for the various hierarchical levels will be investigated. The trend in VLSI design is to use a top-down structured design approach in which systems are implemented by means of a number of identical cells which communicate to each other in a predefined way. It is important in the bottom-up design verification phase to be able to model and accurately simulate the timing of these communication links, particularly in high speed signal processing systems.

SUMMARY OF RESEARCH:

This past year a new DC circuit model for modulation doped GaAs FET's was developed [1,10]. Other models are unnecessarily complex and have discontinuous derivatives at the boundaries between the different regions of operation. Thus, in circuit simulation the models are very costly. Furthermore, past experience with MOSFET models has shown that models with discontinuities in their derivatives have serious convergences problems. Unfortunately, only recently have researchers discovered that these discontinuities were the source of this very serious problem which has plagued simulation experts for a decade. Our new model overcomes these difficulties, and it is simple and accurate. The model can be used for both MODFET's (HEMT's) or MOSFET's, and even though the model parameters have different interpretations for each of these transistor types, physical arguments can be made as to why the model can be used for both devices [1].

The model has been implemented in a parameter characterization system which consists of a HP 4145 Semiconductor Parameter Analyzer and a HP 9836 computer. An optimization routine is used to fit the model parameters to the measured device characteristics. Excellent agreement has been obtained between the measured characteristics and the model on several MODFET samples provided by Professor Morkoç.

Work is continuing on the hierarchical simulation of VLSI circuits for timing analysis. Several years ago under JSEP sponsorship we used node tearing methods to partition large circuits hierarchically. This allowed us to (a) use block LU factorization techniques in the solution of the circuit equations, (b) declare circuits latent at higher levels in the hierarchy, and (c) reduce memory requirements. The block LU factorization of each subcircuit equations can proceed in parallel on a multiprocessor system. Recently a study was completed on the use of special purpose computer architectures for the LU factorization of this partitioned system of equations [11]. The performance of both systolic and wavefront array processors was investigated. However, the LU factorization of the interconnect equations remains a bottleneck in the effort to obtain significant speed improvement. Thus, our attention turned to decoupling methods. Unfortunately these methods add another iteration loop to the solution process, and one must be concerned about convergence within this loop. We studied the convergence properties of two decoupling methods, an incremental Gauss Seidel relaxation algorithm and the waveform relaxation algorithm. In the algorithms used in standard circuit simulators the convergence depends on the local truncation error and thus the timestep can be controlled by the rate of change of the waveform. However, when relaxation techniques are employed, we found that the convergence is now a function of the coupling among the partitioned circuits. If the coupling is sufficiently weak the time step can still be controlled by the local truncation error. However, it is not always easy to determine the degree of coupling and so the time step must not only be controlled by the local truncation error but also by the number of iterations in order to achieve good convergence [2,8,9]. In cases where strong coupling exists the method can be extremely costly. Thus, the performance of these relaxation algorithms is critically dependent on the partitioning of the circuit.

Earlier it was pointed out that in the solution of nonlinear circuit equations, the convergence of the algorithm depends on the functional description of the model. We have found that piecewise linear solution techniques result in very robust algorithms [4,5]. These techniques require that the nonlinear device characteristics be described by a series of piecewise linear segments. This model is more flexible and more readily adaptable to changing technology, however, the description is not in terms of physical parameters. It may be necessary to use a physical model description externally, but internally a piecewise linear description could be generated in order to achieve reliable convergence to the solution.

Finally, several publications have appeared on work in the design verification area. This work was initially funded by JSEP. The goal was to develop algorithms to automatically partition a transistor netlist description of a VLSI circuit into functional blocks, to then generate functional expressions to describe the logic behavior of each block [3], and to generate timing models [12]. These algorithms have been implemented into two programs EXPRESS and MOSTIM under industrial support.

In order to generate accurate timing information it is essential to have good circuit models for the interconnect. Thus, under JSEP support work was initiated on the generation of RC models for the

interconnect. Recently under industrial support some of these models were compared to measured results from several test wafers [7]. Taking into account tolerance effects, the measured results for both self-capacitance and coupling capacitance of the interconnect compared favorably with the numbers predicted by the model.

INTERACTIONS AND/OR TECHNOLOGY TRANSFER:

We have 5 to 10 request a year from industry and universities for the circuit simulation program SLATE. SLATE has the same input format as SPICE but is a hierarchical simulator which typically runs 2 to 3 times faster than SPICE and requires half the memory. It also has much better convergence than SPICE2 because of an improved MOSFET model.

As a result of our research on interconnect models, Intel Corporation is finding our results useful to estimate interconnect capacitance in VLSI circuits.

PUBLICATIONS:

Journal Articles:

1. K.R. Cioffi and T.N. Trick, "A DC circuit model for modulation doped FET's," submitted to *IEEE Electron Device Letters.* (JSEP)

Conference Papers:

2. W.K. Chia, T.N. Trick, and I.N. Hajj, "Implementation of a relaxation technique in a general purpose circuit simulator," *Proc. of Int. Conference on Circuits and Systems*, June 10-12, 1985, to appear. (JSEP)
3. I.N. Hajj and D. Saab, "On the function logic representation of digital transistor circuits," *IEEE Int. Symp. on Circuits and System*, Kyoto, Japan, June 1985. (SRC/JSEP)
4. L.G. Mao and I.N. Hajj, "A piecewise-linear approach to dc analysis of large-scale integrated circuits," *The Fifth Int. Symp. on Network Theory*, Sarajevo, Yugoslavia, pp. 472-476, September 1984. (JSEP)
5. L.G. Mao and I.N. Hajj, "A Gauss-Seidel piecewise-linear method for the analysis of large-scale integrated circuits," *International Conf. on Circuits and Systems*, Beijing, China, June 1985. (JSEP)
6. D.C. Yeh and T.N. Trick, "Suboptimal and optimal algorithms for PLA folding," *Proc. IEEE Symp. on Circuits and systems*, Kyoto, Japan, June 5-7, 1985, to appear. (JSEP)
7. C.P. Yuan and T.N. Trick, "Calculation of capacitance in VLSI circuits," *Proc. IEEE Int. Conf. on Computer-Aided Design*, pp. 263-265, Nov. 12-15, 1984. (JSEP/IBM)
8. T.N. Trick, (Invited talk) "Experiences using a relaxation based simulator for timing analysis," *Spring ACM Design Automation Workshop*, January 21-22, 1985. (JSEP/SRC)

Theses:

9. W.K. Chia, "A study of relaxation techniques for the transient analysis of digital circuits," Ph.D. Thesis, August 1984. (JSEP/SRC)

10. K.R. Cioffi, "Modeling modulation doped field effect transistors for use with the TECAP systems," M.S. Thesis, May 1984. (JSEP)
11. V.B. Rao, "Switch-level timing simulation of MOS VLSI circuits," Ph.D. Thesis, January 1985. (JSEP/IBM)
12. K.-M. Ivy Lui, "Special purpose computer architecture for LU factorization of partitioned systems," M.S. Thesis, August 1984. (JSEP)

PUBLICATIONS (OTHER SUPPORT):

Journal Articles

1. D.E. Hocevar, M.R. Lightner and T.N. Trick, "An extrapolated yield approximation technique for yield maximization," *IEEE Trans. on Computer-Aided of Integrated Circuits and Systems*, CAD-3, pp. 279-287, Oct. 1984. (NSF)
2. D.E. Hocevar, P. Yang, T.N. Trick, and B.P. Epler, "Transient sensitivity computation for MOSFET circuits," *IEEE Trans. on Computer-Aided Design of Integrated Circuits and Systems*, CAD-4, October 1985, to appear.

Conference papers

1. I.N. Hajj, D. Saab and B. Rosario, "Logic and timing simulation of bipolar ECL circuits," *1984 Int. Conf. on Computer-Aided Design*, Santa Clara, CA, pp. 194-196, November 1984. (SRC, TRW, TEKTRONIX)
2. V.B. Rao and T.N. Trick, "A new approach to processing strongly connected circuit blocks in a waveform relaxation switch-level timing simulator," *Proc. IEEE Int. Conf. on Computer Design: VLSI in Computer*, pp. 502-506, Oct. 8-11, 1984. (IBM)
3. V.B. Rao and T.N. Trick, "Switch-level simulation of MOS VLSI circuits," *Proc. IEEE Symp. on Circuits and Systems*, June 5-7, 1985, to appear. (IBM).
4. D. Saab and I.N. Hajj, "Parallel and concurrent fault simulation of MOS circuits," *IEEE Int. Conference on Computer Design (ICDD'84)*, Port Chester, NY, pp. 752-756, October 1984. (SRC)

ADDITIONAL INFORMATION:

Awards and Honors:

I.N. Hajj

Associate - Editor IEEE Trans. on Circuits and Systems

T.N. Trick

Fellow, IEEE
Member IEEE Publication Board
Awarded IEEE Centennial Medal, 1984

WORK UNIT NUMBER 20

TITLE: Computer Architecture

SENIOR PRINCIPAL INVESTIGATORS:

Edward S. Davidson, Research Professor

Janak H. Patel, Research Associate Professor

Prithviraj Banerjee, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

Hoichi Cheong, Research Assistant
Daniel J. Colglazier, Research Assistant
Richard J. Eickemeyer, Research Assistant
Peter Y.-T. Hsu, Research Assistant
Subhasis Laha, Research Assistant
Mohammad Malkawi, Research Assistant
Geoffrey D. McNiven, Research Assistant
Gurindar S. Sohi, Research Assistant
Shu-Hui Sung, Research Assistant

SCIENTIFIC OBJECTIVES:

This unit seeks to develop, model, and analyze efficient, high-performance computer architectures. We have identified several aspects of computer architecture for particular attention due both to their emerging importance from a technology-driven point of view and to the lack of known structures or analysis techniques for meeting our objective.

1.1 *Parallel-pipeline architectures*

This section is devoted to exploring the limits of highly concurrent VLSI processors and multiprocessors. VLSI technology affords large on-chip complexity but has relatively limited capability for interchip communication. Accordingly, there is a heavy emphasis on using on-chip storage effectively to reduce off-chip communication. Furthermore, the long access times, albeit with high bandwidth, associated with off-chip requests creates the need for issuing such requests earlier to achieve effective forwarding of information to a processor so as to minimize the wait time of a highly pipelined processor. Finally, dependencies and linkages between tasks allocated to different processors must be studied to achieve minimal dependency-related performance degradation.

1.2 *Memory organizations*

In recent years, the memory has become one of the most expensive parts of a typical computing system. In addition, the overall performance of a system is also primarily governed by its memory organization. Therefore, the investigation of memory organizations is essential to the development of high-performance computing systems. In particular, multiprocessor systems are becoming increasingly important due to the cost-effectiveness considerations of VLSI technology. To exploit this potential,

memory system architectures must be appropriately organized for such systems. The objective of this research is to develop, model, and analyze high-performance memory organizations for multiprocessing and multiprogramming systems, including cache and virtual memories, for symbolic and numeric processing.

SUMMARY OF RESEARCH:

1.1 *Parallel-pipeline architectures*

We have developed a program-referencing analysis facility that determines the best use of an expanded capability for on-chip storage for the purpose of minimizing off-chip memory references. Optimal tradeoffs between storing instructions, memory accessing parameters, program control parameters, and operands can be found and the effectiveness of various amounts of on-chip storage can be determined.

We have developed a formal model that characterizes the information-accessing needs of program modules at various levels of granularity. State-saving requirements for rapid exception and error recovery, as well as insights for scheduling and allocation of modules to processors and effective information-forwarding techniques will be derived from the use of this model.

A new architecture for LISP machines is being developed that employs small associative tables for storing S-expressions. This representation is compact and breaks through the traditional serial-execution barrier for LISP posed by the traditional representation using indirect pointer chains. Parallel garbage collection and information forwarding capabilities will allow highly concurrent pipelined LISP machines to be developed.

1.2 *Memory organizations*

We have studied several numerical programs in the context of our research on virtual memory management. Our study revealed that program localities can be quantitatively reconized through some analysis of source code. Localities so identified can then be made into memory management directives to be used at execution time. This is the basic idea behind the *compiler-directed* (CD) memory management policy. Our initial experiments in a uniprocessor, uniprogramming environment show that the CD policy out-performs the well-known *least-recently used* (LRU) replacement policy and the *working set* policy in terms of number of page faults and dynamic memory usage.

For list processing, we have developed a parallel garbage collection scheme and the underlying architecture which avoids the synchronization overhead found in most other parallel schemes. Moreover, in our method, the page faults caused by the garbage collector do not adversely affect the list processor performance, unlike in other schemes.

PUBLICATIONS:

Journal Articles:

1. T.C.-K. Chou and J.A. Abraham, "Distributed control of computer systems," *IEEE Trans. Comput. (to appear). (JSEP/VHSIC)*

Conference Papers:

1. P.Y.-T. Hsu, J.T. Rahmeh, E.S. Davidson, and J.A. Abraham, "TIDBITS: Speedup via time-delay bit-slicing in ALU design for VLSI technology, *Proc. 12th Int. Symp. Comput. Arch.*, June 17-19, 1985 (to appear). (SRC/JSEP)

2. A. Ram and J.H. Patel, "Parallel garbage collection without synchronization overhead," *Proc. 12th Int. Symp. Comput. Arc.*, June 17-19, 1985 (to appear). (JSEP)

3. G.S. Sohi, E.S. Davidson, and J.H. Patel, "An efficient LISP-execution architecture with a new representation for list structures," *Proc. 12th Int. symp. Comput. Arch.*, June 17-19, 1985 (to appear). (JSEP)

4. W.A. Sufah, R. Lee and M. Malkawi, "Identifying two program categories for memory management purposes," *Proc. 8th Int. Conf. Comput. Software and Applications*, Nov. 7-9, 1984. (NSF/DOE/JSEP)

Technical Reports and Documents:

1. D. Colglazier, "A performance analysis of multiprocessors using two-level caches," CSL Rept. CSG-36, Univ. of Ill., 1984. (JSEP)

2. A. Ram and J.H. Patel, "Parallel garbage collection without synchronization overhead," CSL Rept. CSG-35, Univ. of Ill., 1984. (JSEP)

Theses:

1. D. Colglazier, "A performance analysis of multiprocessors using two-level caches," M.S. thesis, Elec. and Comp. Eng., Univ. of Ill., Urbana, IL, 1984. (JSEP)

ADDITIONAL INFORMATION:

Awards and Honors:

E.S. Davidson

Fellow, IEEE
Chairman, ACM SIGARCH

J.A. Abraham

Fellow, IEEE

WORK UNIT NUMBER 21

TITLE: Fault-Tolerant Computer Systems

SENIOR PRINCIPAL INVESTIGATORS:

Jacob A. Abraham

Ravi K. Iyer

W. Kent Fuchs

SCIENTIFIC PERSONNEL AND TITLES:

Santosh Abraham, Research Assistants
Ram Chillarege, Research Assistants
Gary Koob, Research Assistants
Rene Llames, Research Assistants
Doug Sanders, Research Assistants
V. Sridhar, Research Assistants

SCIENTIFIC OBJECTIVES:

This unit will focus on the fundamental issues in the design and analysis of fault-tolerant computers. As computational power and the physical complexity of computer systems increase, so does the need for increased reliability and fault tolerance. In addition, there is a pressing need for systems which will continue to function under a variety of workload environments and failure conditions. We have identified several issues which require particular attention due to both technology and systems viewpoints. These approaches are necessary for realizing effective fault tolerance without extreme cost and performance penalties.

1.1 *Hierarchical testing and algorithm-based fault tolerance*

Many computer systems are being designed with multiple units (processors and memories) which cooperate to perform various tasks. Each of the units is usually quite complex and is designed in a hierarchical fashion. We propose to exploit these characteristics of computer systems in deriving techniques to analyze and design fault-tolerant systems.

We propose to derive techniques which will enable the results obtained at any level in a system to be applied to higher levels in the hierarchy. Currently, no useful techniques exist which are hierarchically decomposable. Thus, for example, many techniques exist to derive test patterns for modules. However, given a collection of modules (with associated test patterns) and their interconnection, it is not easy to derive tests for the collection. The same problem exists in applying fault-tolerance techniques such as error detection or recovery to higher levels.

Another objective of this research is to study fault-tolerant algorithms for systems consisting of multiple intelligent units. Existing techniques for fault tolerance are largely brute force, involving massive amounts of redundancy in schemes such as triplication and voting. Utilizing the knowledge of

the algorithms which execute on the system as well as the knowledge of the intelligent units in the system and their interconnection can result in fault tolerance techniques which require only negligible overhead in hardware or performance. This novel approach to fault tolerance will be studied in detail in this unit.

We will also develop a formal, theoretical foundation for the analysis and design of fault-tolerant systems. This theory will allow the designer to decide just how much and what form of redundancy is appropriate for a given functional module in a given environment. The analysis tools will enable the study of trade-offs between performance and reliability, and the relation of these to system complexity.

1.2 *Measurement- and symptom-based analysis of fault-tolerant systems*

Modeling hardware and software fault tolerance is a complex analytical problem. Results based on real measurements and experiments are essential if a scientific basis is to be developed for accurate analytical modeling. This research is concerned with the development of effective reliability models to describe both the performance and reliability aspects of computer systems. This work is primarily motivated by the fact that previous research shows that system reliability is a dynamic function of the level and nature of system activity as described by the system workload. These results have major significance because they indicate that (in contrast with conventional wisdom) it is not useful to push a system close to its performance limits, since the gain in performance is more than offset by degradation in reliability. The proposed research is in two related directions.

First, we propose to develop hardware and software reliability models to explicitly take the nature and level of system activity into account. These models will be based on real error and workload data being collected on several systems on campus. IBM, DEC and Cyber systems are being monitored to provide appropriate data for both model development and validation.

Second, it is proposed to study possible cause-and-effect relationships to model the observed workload/failure dependency. Two important investigations, in this context, are: (a) the effect of workload variations on error/fault latency characteristics and (b) the reliability impact of electrical and thermal stresses induced by varying levels of system activity.

We also propose to develop theoretical foundations and practical models for inference-based adaptive recognition of related errors in large computer systems. The objective is to investigate the feasibility of recognizing the symptoms of severe errors based on relating simpler but similar observed error symptoms. The validation of captured error symptoms will primarily be through recurrence. It is envisaged that the methodology developed will allow capturing of symptoms (patterns) of severe faults in large systems. The patterns found are expected to form the basis of an inference-based error prediction methodology. It is proposed that the technique developed be based on the observed error rate and the type of activity in progress at the time of the error and validated pattern recurrence. The technique is expected to be general so as to encompass different machine architectures and configurations.

1.3 *Reliable algorithms and architectures for database systems*

This research is concerned with the analysis and development of fault tolerant special purpose architectures and algorithms for database systems. The recent interest in knowledge-based fifth generation computing systems has resulted in new challenges concerning special purpose database system architectures. Though there has been a considerable amount of research concerning large scale database systems there has been little fundamental work on architectures and algorithms for special purpose fault-tolerant multiprocessor systems appropriate for VLSI implementation. We propose to derive an integrated approach to fault tolerance in both tightly-coupled and loosely distributed database systems that includes novel fault tolerant distributed algorithms and reconfigurable architectures with high performance reliable operation in harsh environments. Previous approaches to fault tolerance in such

systems have relied on system crashes or vague notions of assertion checking to detect errors during system operation. Our approach is to use algorithm-specific architectural enhancements to detect module-level failures and allow real-time system level reconfiguration and recovery.

SUMMARY OF RESEARCH:

2.1 *Algorithm-based fault tolerance*

The concept of algorithm-based fault tolerance deals with system-level methods for obtaining reliable results from computations, especially when performed on array processor systems. In this scheme, algorithms have their outputs encoded in a system-level error-detecting or -correcting code and provide appropriate error-checking procedures. We have performed a probabilistic analysis of the scheme. Expressions for the reliability of the results of the computation and the time for completion of the computation, using a particular algorithm, have been derived in terms of various parameters: the number of processors involved, the time for execution, and the fault-detecting, -locating, and -tolerating capabilities of the algorithm. Using a semi-Markov process, we have modeled the system with concurrent error detection, with recovery and reconfiguration. The model can handle any failure distribution of the processors and any reconfiguration and retry time distribution. The only restriction is that it is assumed that the time for executing a single instance of a problem is fixed. This simplification can be justified if the algorithms have the property that the execution time depends on the problem size and not the values of the data elements. Hence, given a certain problem size, the algorithm always takes a fixed amount of time. For most array processor algorithms which are characterized by a relatively simple control flow, this assumption is valid. This measure can aid in comparing various alternate algorithms to solve a given problem if the selection is made on the basis of the reliability of the produced results. Another measure of effectiveness of a fault-tolerance scheme that has been proposed is related to the number of problems that can be solved on a system with a bound on the number of processors that can be used and a bound on the reliability of the result. This measure is restricted, however, to problems that can be partitioned into smaller subproblems.

2.2 *Measurement- and symptom-based analysis of fault-tolerant systems*

Our preliminary investigations have resulted in the development of a general methodology to determine the effect of workload variations on error latency. This technique was applied to determine the effect of latent memory errors on a VAX 11/780 system. Preliminary results on thermal stresses due to system activity show a strong contribution due to supervisor state activity.

We have implemented a methodology to detect and relate automatically the pattern for frequent errors on two Cyber systems. This technique captures symptoms of severe faults, including those which propagate across coupled machines.

2.3 *Reliable algorithms and architectures for database systems*

Our initial investigations have resulted in two novel methods of incorporating redundancy in linked data structures which allow concurrent checking of structural integrity during normal access path traversal. Our first proposal is referred to as *distributed and appended checks* and is based on code-theoretic concepts. The second proposal incorporates compressed structural checks in the form of signatures and is called *signatured access path* checking. In contrast to the few suggestions made by previous researchers, our results provide a unified approach to real-time error detection in large database systems.

PUBLICATIONS

Journal Articles:

1. R. K. Iyer and P. Velardi, "Hardware-Related Software Errors: Measurement and Analysis," *IEEE Trans. on Software Eng.*, vol. SE-11, no. 2, pp. 223-231, February 1985. (ARO, CNR, JSEP)
2. R. K. Iyer and D. J. Rossetti, "Effect of System Workload on Operating System Failures: A Study on IBM 3081," *IEEE Trans. on Software Eng.* (to appear in Special Issue on Software Reliability). (DOE, ARO, JSEP)
3. R. K. Iyer and D. J. Rossetti, "Permanent CPU Errors and System Activity: Measurement and Modeling," *ACM Trans. on Comp. Sys.* (to appear). (DOE, JSEP)

Technical Reports and Documents:

1. R. Chillarege and R. K. Iyer, "The effect of system workload on error latency," CSL Rept. CSG-40, Univ. of Ill., 1985. (JSEP/Graduate Research Board)

Theses:

1. P. Banerjee, "A Theory for Algorithm-Based Fault Tolerance in Array Processor Systems," Ph.D. Dissertation, Univ. of Ill., 1985. (VHSIC, JSEP, SRC)

ADDITIONAL INFORMATION:

Awards and Honors:

E.S. Davidson

Fellow, IEEE
Chairman, ACM SIGARCH

J.A. Abraham

Fellow, IEEE

WORK UNIT NUMBER 22

TITLE: Efficient Computation Techniques

SENIOR PRINCIPAL INVESTIGATORS:

D. J. Brown, Research Associate Professor

M. C. Loui, Research Assistant Professor

D. E. Muller, Research Assistant Professor

F. P. Preparata, Research Professor

V. Ramachandran, Research Assistant Professor

D. B. West, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

H. H. Abu Amara, Research Assistant
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P. Czerwinski, Research Assistant
P. R. Everhardt, Research Assistant
S. Hornick, Research Assistant
S. Maddila, Research Assistant
M. Sarrafzadeh, Research Assistant
A. M. Schwartz, Research Assistant
P. Tiwari, Research Assistant
I. Tollis, Research Assistant

SCIENTIFIC OBJECTIVE:

Current technologies require the development of efficient computational techniques and the analysis of the capabilities of various models of computation. We are concerned with the resources - such as time, equipment, memory, interconnection - that are used or needed in the algorithmic solution of given problems. This dynamic discipline, known as concrete computational complexity, not only contributes to a fundamental understanding of computing, but is also extremely relevant to both hardware and software applications. It is only natural that the great technological innovations represented by Very-Large-Scale-Integration (VLSI) and the advent of computer networks have had a substantial impact on this field, opening new horizons and posing challenging problems. Much of our current research (organized below in six subsections) has been motivated by these innovations.

SUMMARY OF RESEARCH:

1. Computational aspects of VLSI

Our research in this area can be broadly subdivided into two main categories: VLSI Algorithms and Layout Theory.

1.2 VLSI Algorithms

A dictionary is a data structure that supports insertion, deletion, and retrieval operations. To maintain a database, a dictionary machine accepts an arbitrary sequence of instructions at a constant rate. We designed new VLSI dictionary machines on a shuffle-exchange network (SEN) and on a cube-connected cycles network (CCC). The SEN design has a novel pipelined architecture. Each stage of the pipeline operates on batches of instructions, not on individual instructions. The SEN runs forward to execute instructions, backward to deliver the responses to the instructions. To implement a dictionary machine on a CCC we gave the first explicit proof that every CCC has a Hamiltonian path.

With the intent to take a further step toward the development of a coherent theory of VLSI complexity, we have concentrated on the information exchange that takes place in a chip during the execution of an algorithm. In particular, we have investigated subdivisions of the chip that are more demanding on the information flow than the traditional balanced-bisection technique. The novel technique, called "square tessellation", partitions the chip into a collection of square cells, subsumes bisection, and in many cases leads to stronger lower bounds on the AT^2 measure; moreover, it reveals, in chips with a high input density (measured in bit/area), a new phenomenon – called "saturation" –, where storage limitations pose stronger requirements on the information flow. We have obtained new, more powerful general lower-bound techniques, which we have successfully applied to problems such as sorting and shifting. In addition we have explored the complementary upper-bound problem and produced a full spectrum of optimal or near-optimal parallel architectures for the above problems.

1.3 Layout Theory

Under the Thompson model, it is well-known that bounded-degree n-node graphs with $O(\sqrt{n})$ separator can be laid out in linear area with maximum edgelength $O(\sqrt{n}/\log n)$, and n-node bounded-degree graphs with $F=\Omega(\sqrt{n})$ bifurcator can be laid out in $O(F^2\log^2(n/F))$ area with maximum edgelength $O(F\log(n/F)/\log\log(n/F))$. These results are also existentially optimal (to within a constant factor) in the sense that, for each class, there exists a graph in the class that requires the specified amount of area, and has the specified maximum edgelength.

We generalize and unify these results by considering embeddings in variable aspect-ratio bounding rectangles. We show that if we consider minimum-area embeddings of classes of graphs with separator $F=o(\sqrt{n})$ or bifurcator $F=\Omega(\sqrt{n})$, then, if the longer side of the bounding rectangle is a and the shorter side is b, there exists a graph in the class for which the maximum edgelength in the embedding is $\Omega(a/\log(b/F))$. For the special case when $a=\theta(b)=\theta$ (squareroot of the area), this gives the previously known results. Further, our proof is simpler than the earlier proof for the lower bound on the maximum edgelength for bifurcator-based embeddings, and the results are existentially optimal, since we have exhibited layout strategies that achieve this bound on the maximum edgelength.

Frequently in the context of layout theory one must face a variety of geometric retrieval problems. We have developed an efficient, general search technique (called "groping" search) that applies to problems for which only inefficient solutions were known, such as circular and half-space retrieval.

2. Distributed Computation

We have continued to study fundamental problems in distributed computation.

First, we devised an election algorithm on a complete network of n processors that has a sense of direction with $O(n)$ messages. In contrast, it is known that on a complete network without a sense of direction the message complexity of election is $O(n \log n)$.

Second, we characterized completely the shared memory requirements for achieving agreement in an asynchronous system of n fail-stop processes that die undetectably. There is no agreement protocol that uses only read and write operations. This result implies the impossibility of Byzantine agreement in asynchronous message-passing systems, which had been established by M.J. Fischer, N.A. Lynch, and M. Paterson under slightly different conditions. Furthermore, there is an agreement protocol with test-and-set operations if and only if either memory cells have at least three values or $n = 2$.

INTERACTION WITH OTHER RESEARCHERS:

At Illinois we expect to work closely with B. E. Hajek in CSL, D. B. West in the Department of Mathematics, and C. L. Liu in Computer Science. Professor Hajek's activity in computer communication networks provides a source of relevant problems for distributed computation. Professors West and Liu provide expertise on the combinatorial aspects of our work. Our research in all of the above areas is related and complements analogous activity in major research institutions; indeed, we communicate regularly with researchers at M.I.T., Yale University, Berkeley, Cornell University, Carleton University, University of Rochester, and IBM Research / San Jose.

PUBLICATIONS:

Journal Articles:

1. G. Bilardi and F. P. Preparata, "An architecture for bitonic sorting with optimal VLSI performance," *IEEE Trans. on Computers*, vol. C-33:7, pp. 646-651, July 1984 (JSEP).

2. G. Bilardi and F. P. Preparata, "A minimum area VLSI architecture for O(logN) time sorting," *IEEE Transactions on Computers*, to appear (JSEP/IBM/NSF).

3. D. T. Lee and F. P. Preparata, "Euclidean shortest paths in the presence of rectilinear barriers," *Networks*, vol. 14, pp. 393-410, Dec. 1984 (JSEP).

4. V. Ramachandran, "Upper bounds for the area increase caused by local expansions in a VLSI layout," in *Advances in Computing Research (Vol. 2): VLSI Theory*, F. P. Preparata, Ed., Greenwich, Conn.: Jai Press Inc., Dec. 1984 (JSEP).

Conference Papers:

1. M.C. Loui, T. A. Matsushita, and D. B. West, "Election in a complete network with a sense of direction," *Proc. 1985 Conf. on Information Sciences and Systems*, Baltimore, MD, March 27-29, 1985, to appear (JSEP/NSF/Kodak).

2. G. Bilardi and F. P. Preparata, "Tessellation techniques for area-time lower bounds with application to sorting," *Proc. 1985 Conf. on Information Sciences and Systems*, Baltimore, MD, March 27-29, 1985, to appear (JSEP/IBM).

PUBLICATIONS (OTHER SUPPORT):

Journal Articles

1. G. Bilardi and X. L. Jim, "Permutation-exchange graphs that emulate the binary cube," *Mathematical System Theory*, vol. 17, pp. 193-198, 1984 (IBM/NSF).

2. M. Brady and D. J. Brown, "VLSI routing: Four layers suffice," to appear in *Advances in Computing Research (Vol. 2): VLSI Theory*, F. P. Preparata, ed., Jai Press Inc., Conn., Dec. 1984 (NSF/SRC).

3. D. T. Lee and F. P. Preparata, "Computational geometry: A survey," invited paper, *IEEE Trans. on Computers*, vol. C-33:12, pp. 1072-1101, Dec. 1984 (NSF).

4. E. L. Lloyd and M. C. Loui, "On the worst case performance of buddy systems," to appear in *Acta Informatica*, (NSF).

5. M. Sarrafzadeh and F. P. Preparata, "Compact channel routing of multiterminal nets," *Annals of Discrete Mathematics*, to appear (SRC/NSF).

6. D. B. West and D. B. Shmoys, "Recognizing graphs with fixed interval number is NP-complete," *Discrete Appl. Math.*, vol. 8:3, pp. 295-305, 1984.

7. D. B. West, W. T. Trotter, G. W. Peck, and P. Shor, "Regressions and monotone chains: a Ramsey-type extremal problem in partial orders," *Combinatorica.*, vol. 4:1, pp. 117-119, 1984.

8. D. T. Lee and F. P. Preparata, "Euclidean shortest paths in the presence of rectilinear barriers," *Networks*, vol. 14, pp. 393-410, 1984 (NSF).

Conference Papers

1. F. P. Preparata, "VLSI algorithms and architectures," invited paper, *Proc. 11th Symp. on Mathematical Foundations of Computer Science*, Sep. 1984, Prague, Czechoslovakia, pp. 149-161, Springer-Verlag, 1984 (NSF).

2. P. Tiwari, "Lower bounds on communication complexity in distributed computer networks," *Proc. 25th Annual Symp. on Foundations of Computer Sci.*, Oct. 24-26, 1984, Palm Beach Shores, Fla., pp. 109-117, 1984 (NSF/Kodak).

3. D. B. West and D. B. Shmoys, "Recognizing graphs with fixed interval number is NP-complete," *Discrete Appl. Math.*, vol. 8:3, pp. 295-305, 1984.

ADDITIONAL INFORMATION:

Awards and Honors:

Donna J. Broan

Outstanding Young Woman of America, 1984
Member-at-Large, ACM, SIGACT, 1983-85

Michael C. Loui

Everitt Award for Teaching Excellence, College of Engineering, UIUC, 1984

Franco P. Preparata

Fellow, Institute of Electrical and Electronics Engineers
Associate, Center for Advanced Studies, UIUC, 1984-85

Vijaya Ramachandran

IBM Faculty Development Award, 1983 and 1984

WORK UNIT NUMBER 23

TITLE: Multi-Sensor Digital Array Processing

SENIOR PRINCIPAL INVESTIGATORS:

T.S. Huang, Research Professor

W.K. Jenkins, Research Profressor

D.C. Munson, Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

S. Blostein, Research Assistant
A.C. Bovik, Research Assistant
G.R. Case, Research Assistant
H.H. Chen, Research Assistant
M. Desai, Research Assistant
E.J. Diethorn, Research Assistant
H. Fan, Research Assistant
G. Kakazu, Research Assistant
B.C. Mather, Research Assistant
J.J. Staehling, Research Assistant
B.L. Yen, Research Assistant

SCIENTIFIC OBJECTIVE:

The term multi-sensor array system refers to a large class of remote sensing systems in which data are collected and recorded by many independent sensors, or by one sensor that is moved to different spatial positions. The recorded data are processed by a digital array algorithm to produce a high resolution object function. Some of the more important multi-sensor array systems now in use are synthetic aperture radar (SAR), computer-aided tomography (CAT) and beamforming sonar. The objective of the research in this unit is to develop both the theory and computer verification of new signal processing methods with the goal of overcoming current limits on resolution and data throughput rates for these systems.

SUMMARY OF RESEARCH:

During the past year our JSEP research has concentrated on band-limited signal extrapolation and phase retrieval, multidimensional windowing, and on the development of the convolution back-projection image reconstruction algorithm for spotlight mode SAR.

SIGNIFICANT RESEARCH ACCOMPLISHMENTS:

Both band-limited signal extrapolation and phase retrieval are techniques for reconstructing sensor array images from incomplete observations. Our studies of these techniques have produced a number of major results, including:

(1) Alternative formulation of the extrapolation problem in the presence of noise, which may lead to robust algorithms.

(2) Linking results on extrapolation in the signal processing literature to those in mathematics (integral equations, Hilbert space).

(3) Two generalized discrete band-limited extrapolation algorithms which are much more flexible than existing algorithms.

(4) Characterization of algorithms for band-limited extrapolation using a linear time-varying model that clearly shows why certain algorithms work well for some examples and fail for others.

(5) Proving that the phase retrieval problem is both stable and ill-conditioned.

In many multi-sensor problems only a finite region of the spatial or frequency domain can be sampled. In previous work we developed a computer optimization technique for generating "optimal" windows that can be used to improve image quality when finite areas of irregular shape are processed [1]. Windows designed by this technique are optimal in the sense that as much energy as possible is concentrated within a narrow mainlobe in the spectral domain, while maintaining the finite and irregularly shaped support in the spatial domain. While this procedure produces useful windows that have been shown to improve image quality, the design procedure is numerical, and is not easily characterized by a closed form analytic expression.

Our work on this problem during the past year consisted of a study that attempted to determine the best way to construct good 2-D windows from a good 1-D window when the support is irregularly shaped. The approach was to consider a small set of 2-D geometric shapes (rectangles, squares, diamonds, circles, L's, cones, dual-cones, etc.) to window these regions by placing the 1D window along certain selected contours, and to calculate the spectrum of the result by means of a 2-D FFT. The resulting patterns were characterized by the mainlobe widths and peak sidelobe responses along each frequency axis, and along the 45° contours in the frequency plane. After analyzing a large number of experimental windows and tabulating the results, a general rule suggesting the best way to apply the 1-D window to the 2-D area began to emerge. The rule is that, to the extent possible, the 1-D window should be placed along contours which meet the edges of the support at right angles. For rectangles, the 1-D window should be applied along perpendicular lines that run parallel to the axes. For circles the 1-D window should be applied along each diameter, creating a circularly symmetric window. On an annular sector, the 1-D window should lie along circular contours and radial contours, etc. Although it is difficult to form an analytical basis for the 90 ° guideline, this rule does appear to be useful for constructing 2-D windows of reasonable quality when the region of support has an irregular shape.

In some of our past work we were able to show that there is a similarity between computer-aided tomography (CAT) and synthetic aperture radar (SAR), and that the reconstruction of a SAR image can be interpreted as a tomographic reconstruction based on a coherent limited-angle recording of spatial domain "projections" or Fourier domain "slices" [2]. This discovery led to the suggestion that convolution back-projection (CBP) reconstruction, which is a state-of-the-art algorithm in medical imaging, could also be used for SAR. The advantages of using CBP for SAR are that the algorithm operates directly on polar data, thereby eliminating the need for error-prone polar-to-cartesian interpolation [3]. Also, CBP is known in CAT for being relatively insensitive to noise in the recording. The disadvantage is that CBP reconstruction is a point-by-point reconstruction algorithm that has an order of complexity of $O(N^3)$, where N x N is the size of the final image. In contrast, the order of complexity for FFT-based Fourier domain algorithms is $O(kN^2)$, where k is a function of the order of the polar-to-cartesian interpolators. Since $k << N$ in typical problems, the CBP algorithm requires more computation than the FFT algorithms.

However, several results have been obtained which suggest that CBP may be a viable SAR algorithm having a parallel structure which is more suitable for VLSI implementation than the batch FFT algorithms. First, it has been shown by computer experiments for point target responses that the CBP algorithm produces high quality reconstructions, and in some cases eliminates the production of spurious responses that originate in the polar-to-cartesian interpolators. Also, it has been discovered that the

CBP algorithm can be more easily implemented in real-time and in step with the data gathering process. This is because it can make use of the interpulse transmission intervals for the filtering of the projections (convolution), and can carry out the back-projection in real-time as the recording evolves. Also, because the CBP algorithm is a point-by-point algorithm (rather than a batch algorithm) it can be implemented by many small processors working in parallel to produce a sub-area of the final image. This suggests a type of systolic array architecture which is attractive for VLSI implementation. Also, a multiprocessor architecture has been proposed that offers a degree of fault tolerance that can be achieved with the inclusion of error detection and the proper management of the total resources.

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1. J. D. O'Brien, "A consideration of signal processing for spotlight synthetic aperture radar", *Ph.D Dissertation*, Department of Electrical and Computer Engineering, University of Illinois, October 1983.
2. D. C. Munson, Jr., J. D. O'Brien, and W. K. Jenkins, "A tomographic formulation for synthetic aperture radar," *IEEE Proceedings, vol. 71, No. 8*, pp. 917-925, August 1983.
3. M. D. Desai and W. K. Jenkins, "Convolution back-projection image reconstruction for synthetic aperture radar," *Proceeding of the 1984 Int. Symposium on Circuits and Systems*, Montreal, Canada, pp. 261-263, May 1983.

PUBLICATIONS:

Books or Chapters in Books:

1. D. A. Hayner and W. K. Jenkins, "Missing core problem in computer tomography," *Advances in Computer Vision and Image Reconstruction From Incomplete Data: Theory and Applications*, T.S. Huang, Ed., Springer-Verlog, Chapter 2, pp. 83-144, 1984, (JSEP).
2. W. J. Jenkins, "Signal processing, analog," *The Encyclopedia of Physical Science and Technology*, R.A. Meyers, Ed.-in-Chief, Academic Press, Inc., to appear. (JSEP/NSF)
3. J. L. C. Sanz and T. S. Huang, "Support-limited signal and image extrapolation," *Advances in Computer Vision and Image Processing, vol.1*, ed. by T. S. Huang, JAI Press, 1984. (JSEP)

Journal Articles:

1. H. Fan, E. I. El-Masry, and W. K. Jenkins, "Resolution enhancement of digital beamformers," *IEEE Trans. on Acoustics, Speech, and Signal Processing, vol. ASSP-32, No. 5*, pp. 1041-1052, October 1984. (JSEP)
2. D.C. Munson, Jr., "Minimum sampling rates for linear shift-variant discrete-time systems," *IEEE Trans. Acoust. Speech, Signal Processing*, to appear. (JSEP)
3. J. L. C. Sanz and T. S. Huang, "Continuation techniques for a certain class of analytic functions, *SIAM J. App. Math., 44* :4, pp. 819-838 (Aug. 1984) (JSEP)
4. J. L. C. Sanz and T. S. Huang, "A note on iterative Fourier transform phase reconstruction turn magnitude," *IEEE Trans. ASSP, vol. 32*, pp. 1251-1254, Dec. 1984. (JSEP)

5. J. L. C. Sanz and T. S. Huang, "Phase reconstruction from magnitude of bandlimited multidimensional signals," *J. Math. Analy. and its Appl.*, (to appear). (JSEP)

Conference Papers:

1. A. C. Bovik and D. C. Munson, Jr., "Boundary detection in speckle images," *Proc. IEEE International Conf. Acout, Speech, Signal Processing*, Tampa, FL, March 26-29, 1985, to appear. (JSEP)
2. M. Desai and W. K. Jenkins, "Performance evaluation and architectural implications of convolution back-projection image reconstruction for synthetic aperture radar," *Proceedings of the International Symposium on Circuits and Systems*, Kyoto, Japan, June 5-7, 1985, to appear. (JSEP)
3. E. J. Diethorn and D. C. Munson, Jr., "Linear time-varying filtering of short data records," *Proc. International Symp. Circuits and Syst.* Kyoto, Japan, June 5-7, 1985, to appear. (JSEP)
4. W. K. Jenkins, "The discrete-frequency Fourier transform: a missing tool in digital signal processing," *Proceedings of the International Symposium on Circuits and Systems*, Kyoto, Japan, June 1985, to appear. (JSEP)
5. W. K. Jenkins, "Adaptive noise canceling filters based on orthogonal decomposition," *Proceedings of the 1985 Int. Conf. on Circuits and Systems*, Beijng, China, June 10-12, 1985, to appear. (JSEP)
6. H. Lee and T. S. Huang, "On discrete band-limited signal extrapolation," *Proc. ICASSP*, March 26-29, 1985, Tampa, FL. (JSEP)
7. D. C. Munson, Jr. and G. C. Case, "Error spectrum shaping relations for quantization of FIR digital filter coefficients," *Proc. China 1985 International Conf. Circuits Syst.*, Beijung, China, June 10-12, 1985, to appear. (JSEP)
8. J. L. C. Sanz and T. S. Huang, "On the stability and sensitivity of multidimensional signal reconstruction from Fourier transform magnitude," *Proc. ICASSP*, March 26-29, 1985, Tampa, FL. (JSEP)

Theses and Technical Reports:

1. J.J. Staeling, "Two-dimensional windowing methods in digital signal processing," M.S. Thesis, Department of Electrical and Computer Engineering, University of Illinois, 1984. (JSEP)

PUBLICATIONS (OTHER SUPPORT):

Books or Chapters in Books:

1. M. R. Soderstrand, W. K. Jenkins, C. A. Jullien, and F. S. Taylor (eds), *Modern Applications of Residue Number System Arithmetic to Digital Signal Processing, IEEE Press*, New York, NY, 1985, to appear (NSF).

Journal Articles:

1. H. H. Chen, N. Ahuja and T. S. Huang, "Septree representations of moving objects using hexagonal cylindrical decomposition," *Optical Eng., 23* :5, pp. 531-535 (Sep./Oct. 1984). (NSF)
2. J. Q. Fang and T.S. Huang, "Some experiments on estimating the 3-D motion parameters of a rigid body from two consecutive image frames," *IEEE Trans. Pattern Analysis and Machine Intelligence, 6* :5, pp. 545-554, Sep. 1984. (NSF)
3. W. K. Jenkins, "Industry or academia: what's a young Ph.D to do," *Circuits and Devices Magazine*, to appear, (Invited (NSF)

Conference Papers:

1. S.D. Blostein and T. S. Huang, "Estimating 3-D motion from range data," *Proc. 1st. Conf. AI Applications*, (Dec. 5-7, 1984, Denver, CO.). (NSF)
2. J.-P. Gambotto and T. S. Huang, "Motion analysis of isolated targets in infrared image sequences," *Proc. 7th Int. Conf. Pattern Recognition* (Jul. 30-Aug. 2, 1984, Montreal, Canada). (NSF)
3. W. K. Gu, J. Y. Yang, T. S. Huang, "Matching perspective views of a 3-D object using circuits," *Proc. 7th Int. Conf. Pattern Recognition*, (July 30 - Aug. 2, 1984, Montreal, Canada). (NSF)
4. W. K. Gu and T. S. Huang, "Connected line drawing extraction from a perspective view of a polyhedron," *Proc. 1st Conf. AI Applications* (Dec. 5-7, 1984, Denver, CO). (NSF)
5. W. K. Gu and T. S. Huang, "Matching perspective views of a polyhedron," *Proc. SPIE Conf. Intelligent Robots*, (Nov. 4-8, 1984, Cambridge, Mass.). (NSF)
6. T. S. Huang and H. H. Chen, "Generating cylindrical representation of solid objects from surface representation," *Proc. SPIE Conf. Intelligent Robots*, (Nov. 4-8, 1984, Cambridge, Mass.). (NSF)
7. W. K. Jenkins, "Hardware architectures for complex digital signal processors based on quadratic number codes," *Proceedings of the International Symposium on Circuits and Systems*, Kyoto, Japan, June 1985, to appear. (NSF)
8. W. K. Jenkins, B. C. Mather, and D. C. Munson, Jr., "Nearest neighbor and generalized inverse distance interpolation for Fourier domain image reconstruction," *Proc. of the Int. Conf. on Acoustics, Speech, and Signal Processing*, Tampa, FL, March 1985, to appear. (Lockheed)
9. W. K. Jenkins, D. F. Paul, and E. S. Davidson, "A custom-designed integrated circuit for the realization of residue number digital filters," *Proc. of the Inter. Conf. on Acoustics, Speech, and Signal Processing*, Tampa, FL, March 1985, to appear. (NSF)
10. D. C. Munson, Jr., J. L. C. Sanz, W. K. Jenkins, G. Kakazu, and B. C. Mather, "A comparison of algorithms for polar-to-cartesian interpolation in spotlight mode SAR," *Proc. of the International Conf. on Acoustics, Speech, and Signal Proc.*, Tampa, FL, March 1985, to appear. (Lockheed)
11. D. F. Paul, W. K. Jenkins, and E. S. Davidson, "Residue arithmetic for real-time applications: high throughput and reliability using customized modules," *Proc. of the 1984 Int. Conf. on Circuits and Computers*, Rye, NY, pp. 689-694, October 1984. (NSF)
12. B. L. Yen and T. S. Huang, "Determining 3-D motion structure of a rigid body over 2 frames using correspondences of straight lines lying on parallel planes," *Proc. 7th Int. Conf. Pattern Recognition*, July 30 - Aug. 2, 1984, Montreal, Canada. (NSF)

Theses and Technical Reports:

1. W.K. Jenkins, "Computer modeling for the study of adaptive algorithms for echo cancellation," Technical Report (Dept. 45224), AT&T Bell Laboratories, North Andover, MA, 1984. (AT&T Bell Labs)
2. W.K. Jenkins, "Results from computer based studies of time domain and frequency domain algorithms for continuously-adaptive echo cancellation," Technical Report (Dept. 45224) AT&T Bell Laboratories, North Andover, MA, 1984. (AT&T Bell Labs)

ADDITIONAL INFORMATION:

Awards and Honors:

T.S. Huang

IEEE Fellow
J.S. Guggenheim Foundation Fellow
Alexander V. Humboldt Foundation Senior Scientist Award

W.K. Jenkins

President, CAS Society of IEEE
Fellow IEEE
Myril B. Reed Award for Best Paper at the Midwest Symposium on Circuits and Systems

WORK UNIT NUMBER 26

TITLE: Basic Research in Electronics

SENIOR PRINCIPAL INVESTIGATOR:

T.N. Trick

SCIENTIFIC OBJECTIVE:

The objective of the research is to tackle fundamental problems of electronic materials, devices and systems in a timely manner, and to provide early funding on start-up of projects which present immediate opportunities of high scientific merit.

SUMMARY OF RESEARCH:

The funds in this unit were used to initiate a new project on the laser growth of films under the direction of Professor J.G. Eden. Graduate student C.C. Abele has been studying the effect of illuminating surfaces with visible or UV laser radiation during the CVD growth of films. A more detailed summary of this research appears in Unit 11 under the subtitle "Laser Growth of Films."

In addition, these funds are supporting one-half the salary of a research associate, Scott Barnett. Scott Barnett recently received his Ph.D. degree under the direction of Professor J.E. Greene. Dr. Barnett agreed to accept a post-doctorate position until next fall in order to maintain continuity in their research program and to complete several unfinished projects. More details of their work appears in Unit 5.

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