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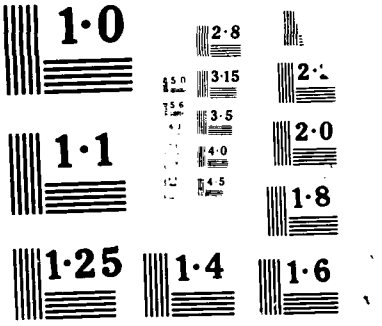
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Program

Third International Conference on Superlattices, Microstructures & Microdevices

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Electron Devices Society of the Institute of Electrical and Electronics Engineers, Inc.

Chicago Section of the Institute of Electrical and Electronics Engineers, Inc.

Chicago Section of The Metallurgical Society of the AIME, Inc.

Chicago August 17-20, 1987

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A Letter of Welcome

Welcome to the Third International Conference on Superlattices, Microstructures & Microdevices. Many people helped us get to this juncture, especially our financial sponsors—Amoco Corporation, the National Science Foundation, the Office of Naval Research, and the Air Force Office of Scientific Research. We are also grateful for the cooperation of the Electron Devices Society of the Institute of Electrical and Electronics Engineers, Inc., and the Chicago sections of the Institute of Electrical and Electronics Engineers, Inc. and of The Metallurgical Society of the AIME, Inc.

This conference follows two previous successes, in Urbana and Göteborg. With the help of active Program and International Advisory Committees, we have planned a conference that follows a tradition of excellent presentations and maximum interaction among conferees.

We hope you enjoy the conference and urge you to renew acquaintances, meet new colleagues, absorb new ideas, and explore the beautiful city of Chicago. The conference staff, as well as the hotel staff, will assist you in any way they can. Please read the "Conference Notes" for information about a few practicalities and procedures that will make your conference stay a more pleasant one.

Again, a warm welcome to Chicago and to the conference.

Sincerely,

Bruce Vojak
Conference Chairman

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The Third International Conference on Superlattices, Microstructures, and Microdevices was successfully held at the Westin Hotel, Chicago, on August 17-20, 1987. There were 286 attendees from around world who contributed 68 oral and 160 poster presentations on their research on ultra-small structures with application in optics and electronics. Unsolicited comments from attendees indicated that the quality of the technical presentations was very high. The conference was also a financial success based on costs relative to our 1985 estimates and value relative to price paid by attendees.

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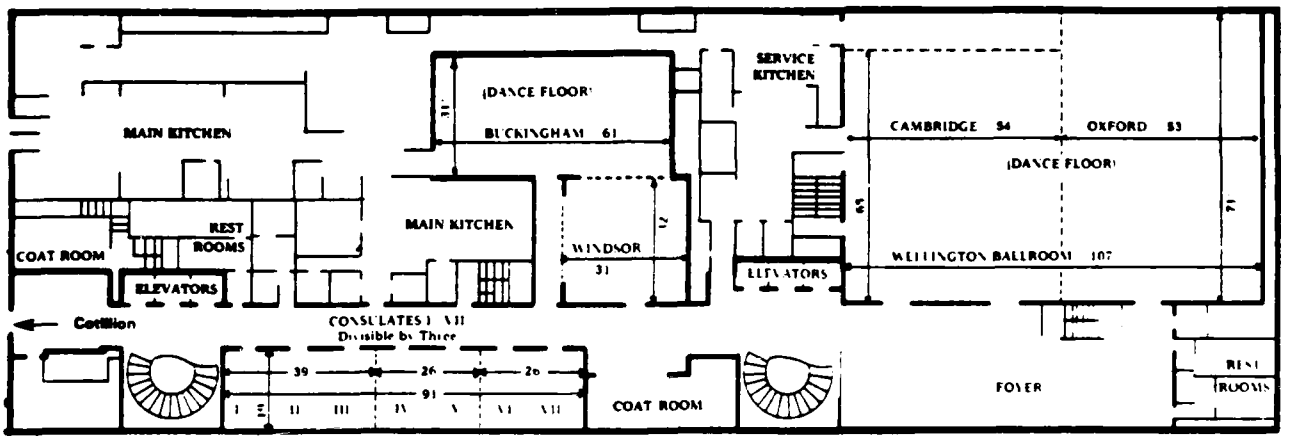
Schedule-at-a-Glance

All activities will be held at the Westin Hotel, Chicago.

Sunday					4:00-8:00	
August 16					Registration & reception (Cotillion)	
Monday	7:30-8:00	8:15-12:05	12:05-1:30	1:30-5:25		8:00-11:00
August 17	Breakfast (Cotillion)	Presentations Ma1-Ma9 (Wellington Ballroom)	Lunch (Cotillion)	Presentations Mp1-Mp10 (Wellington Ballroom)		Reception (Cotillion)
Tuesday	7:30-8:00	8:15-12:10	12:10-1:30	1:30-7:00	7:00-10:00	10:00-11:30
August 18	Breakfast (Cotillion)	Presentations Ta1-Ta9 (Wellington Ballroom)	Lunch (Cotillion)	Afternoon free	Presentations Tp1-Tp7 (Wellington Ballroom)	Nightcap & informal discussion (Cotillion)
Wednesday	7:30-8:00	8:15-12:00	12:00-1:30	1:30-5:00	6:30-7:30	7:30-10:00
August 19	Breakfast (Cotillion)	Presentations Wa1-Wa8 (Wellington Ballroom)	Lunch (Cotillion)	Presentations Wp1-Wp8 (Wellington Ballroom)	Reception (Cash bar) (Wellington Ballroom)	Banquet (Wellington Ballroom)
Thursday	7:30-8:00	8:15-12:10	12:10-1:30	1:30-5:00		
August 20	Breakfast (Cotillion)	Presentations Ra1-Ra9 (Wellington Ballroom)	Lunch (Cotillion)	Presentations Rp1-Rp8 (Wellington Ballroom)		

Poster sessions will run continuously in the Buckingham, Windsor, and Consulates.

- Session 1: Monday and Tuesday, 8:00 a.m. - 10:00 p.m.
- Session 2: Wednesday, 8:00 a.m. - 10:00 p.m., and Thursday, 8:00 a.m. - 5:00 p.m.



Conference Notes

Please read the following notes at your earliest convenience.

Posters

This notice pertains to **all** conferees who are either giving an oral presentation or presenting a poster.

Poster presenters for Session 1 and speakers scheduled for either Monday or Tuesday:

Set up: Sunday, 6:00-8:00 p.m.
Take down: Tuesday, 10:00-11:00 p.m.

Poster presenters for Session 2 and speakers scheduled for either Wednesday or Thursday:

Set up: Wednesday, by 8:00 a.m.
Take down: Thursday, by 5:00 p.m.

Please post your paper in the assigned spot, corresponding to your designation in the program schedule.

Push pins are provided in the poster area.

Special Programs and Tours

Spouses and friends can sign up at the registration/information area for several planned events:

- A brunch, Monday, at 10:00 a.m. **Babysitting is available during the Monday brunch** to give you a chance to meet and plan events for the week. You must sign up Sunday night at the registration desk to have the babysitting service available for you.
- A tour of Chicago, scheduled for Tuesday afternoon. This is an easy way to get a comprehensive view of Chicago.

Brochures about museums, walking tours, boat tours, and points of interest in Chicago are also available. (Sorry, the Cubs are not in town.)

Suggestion Box

To help planners of the fourth ICSMM, please write down your ideas, and drop your note in a suggestion box located at the registration desk.

Duplicating and Secretarial Services

Duplicating services are available at the Xerox Center on the third floor of the Westin. Charges are 20 cents per copy, or less for multiple copies.

Speakers and Session Presiders

To coordinate your presentations, please meet with your session presider at least 10 minutes before your session begins.

Manuscripts

Manuscripts intended for the editor of *Superlattices and Microstructures* can be left with Carole Dow at the registration area.

Medical Assistance

In case of a medical emergency, contact the Westin's front desk.

Currency Exchange

Several international currencies can be exchanged at the hotel desk. You can also exchange foreign currency at the Lake Shore Bank directly across the street on Michigan Avenue. Bank hours are M-F 8:00 a.m. to 6:00 p.m., and Sat. 8:00 a.m. to noon.

Messages

Messages can be left on the designated board in the registration/information area.

Conference Schedule

Every effort was made at the time of publication to make this program accurate. Changes and discrepancies will be announced at the conference.

Related presentations have been scheduled together under general topics that loosely describe the content of the manuscripts. Some presentations relate to multiple topics; their position in the program is, therefore, somewhat arbitrary and not intended to limit their scope.

Sunday Evening

4:00-8:00 *Registration & reception (Cotillion)*

Monday Morning

7:30-8:00 *Breakfast (Cotillion)*

8:15 *Welcome (Wellington for all presentations; the hallway for breaks)*

Transport and Tunneling I

Session presider: D. Ferry, Arizona State University

8:30 Ma1 (plenary) **Ballistic transport and its consequences in GaAs quantized regions**, M. Heiblum, IBM Thomas J. Watson Research Center

9:15 Ma2 (invited) **Perpendicular transport of carriers in superlattice minibands: Direct determination by subpicosecond luminescence spectroscopy**, J. Shah, B. Deveaud, T. C. Damen, AT&T Bell Laboratories (USA); A. Regreny, Centre National d'Etudes des Telecommunications (France)

9:35 Ma3 (invited) **Hot electron transistors grown by MOCVD**, H. Kawai, I. Hase, S. Imanaga, K. Kaneko, N. Watanabe, Sony Corporation (Japan)

9:55 *Break*

Spectroscopy I

Session presider: J. Faurie, University of Illinois—Chicago

10:15 Ma4 (invited) **II-VI heterostructures: Magnetooptics and band structure**, Y. Guldner, Groupe de Physique des Solides de l'Ecole Normale Superieure (France)

10:35 Ma5 (invited) **Raman, photoluminescence and modulation spectroscopy of semiconductor heterostructures**, A. K. Ramdas, Purdue University

10:55 Ma6 (invited) **Far-infrared studies of doped AlGaAs/GaAs multiple-quantum-well structures**, J-M Mercy, Y-H Chang, A. A. Reeder, G. Brozak, B. D. McCombe, State University of New York at Buffalo

11:15 Ma7 (invited) **Electro-optical studies of $Al_xGa_{1-x}As/GaAs$ coupled quantum wells**, H. Q. Le, J. J. Zayhowski, W. D. Goodhue, J. V. Hryniewicz, V. A. Mims, Lincoln Laboratory, Massachusetts Institute of Technology

11:35 Ma8 (invited) **Quantum wells and bulk AlGaAs under hydrostatic pressure**, M. Chandrasekhar, H. R. Chandrasekhar, University of Missouri at Columbia

11:50 Ma9 (contributed) **Auger recombination in GaSb/AlSb-multi quantum well heterostructures**, E. Zielinski, H. Schweizer, R. Stuber, Universitat Stuttgart (FRG); G. Griffiths, H. Kroemer, S. Subbanna, University of California at Santa Barbara (USA)

12:05 *Lunch*

Monday Afternoon

Novel Properties and Devices I

Session presider: B. Levine, AT&T Bell Laboratories

1:30 Mp1 (invited) **Piezoelectric effects in strained layer superlattices**, D. L. Smith, Los Alamos National Laboratory; C. Mailhiot, Xerox

1:50 Mp2 (contributed) **Ultrafast optical nonlinearity in quantum well structures with electric field**, M. Yamanishi, Hiroshima University (Japan)

2:05 Mp3 (contributed) **Strained layer and lattice matched transverse junction stripe quantum well lasers for continuous room temperature operation**, Y. J. Yang, K. Y. Hsieh, R. M. Kolbas, North Caroline State University

2:20 Mp4 (contributed) **Semiconductor microcrystallites in porous glass and their applications in optics**, J. C. Luong, Corning

2:35 Mp5 (contributed) **Control of carrier lifetime in PbTe nipi supperlattices by external photoinjection**, G. Bauer, J. Oswald, Montanuniversitat Leoben (Austria); W. Goltsos, A. V. Nurmikko, Brown University (USA)

2:50 *Break and Poster Session 1 (Monday & Tuesday)*

Microstructures and Microdevices I

Session presider: T. Andersson, Chalmers University of Technology

3:50 Mp6 (invited) **Spectroscopy of one-dimensional subbands on InSb**, U. Merkt, Ch. Sikorski, J. P. Kotthaus, Universitat Hamburg (FRG)

4:10 Mp7 (invited) **Aharonov-Bohm effects in disordered metals**, Y. Bruynseraede, C. Van Haesendonck, Katholieke Universiteit (Belgium)

4:30 Mp8 (invited) **Energy levels and magneto-electric effects in some quasi unidimensional semiconductor heterostructures**, J. A. Brum, G. Bastard, Groupe de Physique des Solides de l'Ecole Normale Superieure (France)

4:50 Mp9 (invited) **Quantum transport in an electron waveguide**, A. M. Chang, G. L. Timp, AT&T Bell Laboratories

5:10 Mp10 (contributed) **Transport in GaAs heterojunction ring structures**, C. J. B. Ford, T. J. Thornton, R. Newbury, M. Pepper, H. Ahmed, Cavendish Laboratory; G. J. Davies, D. Andrews, British Telecom Research Centre (UK)

Monday Evening

8:00-11:00 *Reception (Cotillion)*

Tuesday Morning

7:30-8:00 *Breakfast (Cotillion)*

Metallic Superlattices I
Session presider: C. Falco, University of Arizona

8:15 Ta1 (plenary) **Metallic superlattices,** I. K. Schuller, Argonne National Laboratory

9:00 Ta2 (invited) **Ferromagnetic/semiconductor hybrid structures,** G. A. Prinz, Naval Research Laboratory

9:20 Ta3 (invited) **Properties of synthetic magnetic superlattices,** J. Kwo, AT&T Bell Laboratories

9:40 Ta4 (contributed) **Observation of ferromagnetism in ultrathin f.c.c. films by spin polarised neutron reflection,** J. A. C. Bland, Oxford University; D. Pescia, R. F. Willis, Cambridge University (UK)

9:55 *Break and Poster Session 1*

Transport and Tunneling II
Session presider: M. Heiblum, IBM, T.J. Watson Research Center

10:40 Ta5 (invited) **Theoretical aspects of electron transport in modulated structures,** B. Vinter, T. Weil, Thomson-CSF (France)

11:00 Ta6 (invited) **Quantum transport theory of resonant-tunneling heterostructure devices,** W. R. Frensley, Texas Instruments

11:20 Ta7 (invited) **Resonant tunneling transistors and resonant tunneling hot electron spectroscopy,** F. Capasso, S. Sen, A. Y. Cho, A. C. Grossard, AT&T Bell Laboratories

11:40 Ta8 (contributed) **Superlattice doping interfaces,** S. W. Kirchoefer, H. S. Newman, J. M. Pond, Naval Research Laboratory; P. Uppal, Martin Marietta Laboratory

11:55 Ta9 (contributed) **Pressure-dependent measurements on n^+ GaAs (Si, Sn): The effect of deep donor (DX) states on the electrical properties and persistent photoconductivity effects,** J. C. Portal, L. Dmowski, INSA and SNCI-CNRS (France); D. K. Maude, T. Foster, L. Eaves, University of Nottingham (UK); M. Nathan, M. Heiblum, IBM, T. J. Watson Research Center (USA); G. G. Harris, R. B. Beall, Philips Research Laboratories (UK)

12:10-1:30 *Lunch (Cotillion)*

Tuesday Afternoon

Afternoon Free

Tuesday Evening

Microstructures and Microdevices II
Session presider: Y. Bruynseraede, Katholieke Universiteit

7:00 Tp1 (plenary) **Random quantum interference in microdevices,** W. J. Skocpol, AT&T Bell Laboratories

7:45 Tp2 (invited) **Quantum interference and transport in microstructures,** S. Wind, V. Chandrasekhar, M. J. Rooks, D. E. Prober, Yale University

8:05 Tp3 (contributed) **Excitonic properties of GaAs-AlGaAs nanostructures,** K. Kash, H. G. Craighead, A. Scherer, P. S. D. Lin, P. Grabbe, J. Harbison, L. Schiavone, Bell Communications Research

8:20 *Break*

Novel Properties and Devices II
Session presider: L. Cooper, Office of Naval Research

8:45 Tp4 (invited) **Infrared detectors based on the photon drag effect and intersubband absorption by a two-dimensional electron gas,** S. Luryi, AT&T Bell Laboratories

9:05 Tp5 (invited) **Properties of multilayers for soft x-ray optics,** C. M. Falco, F. E. Fernandez, University of Arizona

9:25 Tp6 (contributed) **10 μm photoexcited avalanche gain due to electron impact ionization from GaAs quantum well superlattices,** B. F. Levine, K. K. Choi, C. G. Bethea, J. Walker, R. J. Malik, AT&T Bell Laboratories

9:40 Tp7 (contributed) **Transport study on $Si/Si_{1-x}Ge_x$ superlattices selectively doped by secondary implantation of Sb,** H. Jorke, H.-J. Herzog, E. Kasper, AEG Research Center (FRG)

10:00-11:30 *Cash bar and informal discussion (Cotillion) (Session 1 posters should be removed after 10:00)*

Wednesday Morning

7:30-8:00 *Breakfast (Cotillion)*

Novel Properties and Devices III
Session presider: R. Burnham, Amoco Corporation

8:15 Wa1 (plenary) **Device potentials of interface asperities and corrugation in quantum heterostructures,** H. Sakaki, University of Tokyo (Japan)

9:00 Wa2 (invited) **Novel quantum well optical devices,** D. A. B. Miller, AT&T Bell Laboratories

9:20 Wa3 (invited) **Electrical properties of p-type and n-type ZnSe-ZnTe strained-layer superlattices,** M. Kobayashi, S. Dosho, A. Imai, R. Kimura, M. Konagai, K. Takahashi, Tokyo Institute of Technology (Japan)

9:40 *Break and Poster Session 2 (Wednesday & Thursday)*

Structural Studies I
Session presider: R. Kolbas, North Carolina State University

10:30 Wa4 (invited) **Direct imaging of the columnar structure of GaAs quantum wells,** D. Bimberg, J. Christen, Technischen Universitat, Berlin (FRG); T. Fukunaga, H. Nakashima, Optoelectronic Joint Research Laboratory (Japan); D. E. Mars, J. N. Miller, Hewlett-Packard Laboratories (USA)

10:50 Wa5 (invited) **EXAFS studies of the microstructure of semiconductor alloys, defects, and semiconductor-metal interfaces,** B. A. Bunker, University of Notre Dame

11:10 Wa6 (invited) **Lattice strain in heteroepitaxial films,** T. Yao, Electrotechnical Laboratory (Japan)

11:30 Wa7 (contributed) **MBE Growth of HgTe/CdTe superlattices on Si(100) substrates,** O. K. Wu, F. A. Shirland, J. P. Baukus, A. T. Hunter, I. J. D'Haenens, Hughes Research Laboratories

11:45 Wa8 (contributed) **Growth of high quality $CoSi_2$/Si - superstructures on Si(111),** H. von Kanel, J. Henz, M. Ospelt, P. Wachter, ETH Zurich (Switzerland)

12:00 *Lunch (Cotillion)*

Wednesday Afternoon

Phonons and Hot Electrons I
Session presider: A. Freeman, Northwestern University

1:30 Wp1 (invited) **Phonons in semiconductor superlattices,** E. Molinari, CNR, Instituto di Acustica "Corbino"; A. Fasolino, SISSA (Italy)

1:50 Wp2 (contributed) **Monte Carlo simulations of femtosecond relaxation of photoexcited electrons in AlGaAs/GaAs quantum wells,** C. J. Stanton, D. W. Bailey, K. Hess, Y. C. Chang, University of Illinois; F. W. Wise, C. L. Tang, Cornell University

2:05 Wp3 (contributed) **Electron-phonon interactions in $In_{0.53}Ga_{0.47}As$ and in $In_{0.53}Ga_{0.47}As$/InP quantum wells,** K. J. Nash, M. S. Skolnick, P. R. Tapster, S. J. Bass, Royal Signals and Radar Establishment; P. A. Claxton, J. S. Roberts, University of Sheffield (UK)

2:20 *Break and Poster Session 2*

Spectroscopy II
Session presider: A. Ramdas, Purdue University

3:20 Wp4 (invited) **Electronic structure of quantum-well states revealed under high pressures,** D. J. Wolford, T. F. Kuech, T. Steiner, J. A. Bradley, IBM Thomas J. Watson Research Center (USA); M. A. Gell, D. Ninno, M. Jaros, The University, Newcastle Upon Tyne (UK)

3:40 Wp5 (contributed) **Electron-hole correlation singularity in optical spectra of modulation doped GaAs-$Al_xGa_{1-x}As$ quantum wells,** D. Livescu, D. A. B. Miller, D. S. Chemla, AT&T Bell Laboratories

3:55 Wp6 (invited) **Magneto-optical studies of GaInAs-InP quantum wells,** D. J. Mowbray, N. A. Pulsford, J. Singleton, Oxford University; M. S. Skolnick, S. J. Bass, Royal Signals and Radar Establishment; R. J. Nicholas, W. Hayes, Oxford University (UK)

4:15 Wp7 (contributed) **a-Si:H/a-SiN_x:H superlattices: Confinement or contamination,** S. Kalem, University of Sheffield (UK)

4:30 Wp8 (contributed) **Extended and local plasmons in a lateral superlattice,** D. Heitmann and U. Mackens, Institut fur Angewandte Physik and Max Planck Institut fur Festkorperforschung (FRG)

Wednesday Evening

6:30 *Cash bar (Wellington)*

7:30 *Banquet (Wellington)*

Thursday Morning

7:30-8:00 *Breakfast (Cotillion)*

Phonons and Hot Electrons II
Session presider: J. Dow, University of Notre Dame

8:15 Ra1 (plenary) **(Title pending)**, L. Keldysh, Lebedev Institute (USSR)

9:00 Ra2 (invited) **Hot electrons in silicon dioxide: Ballistic to steady-state transport**, D. J. DiMaria, M. V. Fischetti, IBM Thomas J. Watson Research Center

9:20 Ra3 (invited) **The theory of electron-polar phonon scattering rates in semiconductor microstructures**, B. Mason, University of Illinois at Urbana-Champaign

9:40 Ra4 (contributed) **Direct measurement of ultrafast electron-hole plasma expansion at high density in an asymmetric GaAs quantum well**, K. Shum, M. Junnakar, H. Chao, R. Alfano, CUNY, H. Morkoc, University of Illinois

9:55 *Break and Poster Session 2*

Transport and Tunneling III
Session presider: D. Bimberg, Techischen Universitat, Berlin

10:40 Ra5 (invited) **Vertical electronic transport in novel semiconductor heterojunction structures**, M. A. Reed, Texas Instruments

11:00 Ra6 (invited) **Recent applications of Monte Carlo methods for semiconductor microdevice simulation**, U. Ravaioli, University of Illinois at Urbana-Champaign

11:20 Ra7 (contributed) **Resonant tunneling in InGaAs-InP double-barrier structures and superlattices**, T. H. H. Vuong, D. C. Tsui, Princeton University; W. T. Tsang, AT&T Bell Laboratories

11:35 Ra8 (invited) **Excellent negative differential resistance of InGaAs/InAlAs resonant tunneling barrier structures and applications to a new functional device, RHET**, S. Hiyamizu, Fujitsu (Japan)

11:55 Ra9 (contributed) **Non-effective-mass matching in superlattices**, P. Roblin, Ohio State University

12:10 *Lunch (Cotillion)*

Thursday Afternoon

Structural Studies II
Session presider: B. Wessels, Northwestern University

1:30 Rp1 (contributed) **Influence of interfaces on electronic and magnetic properties of MnSe/ZnSe superlattices near monolayer limit**, D. Lee, S.-K. Chang, H. Nakata, A. V. Nurmikko, Brown University; L. A. Kolodziejski, R. L. Gunshor, Purdue University

1:45 Rp2 (contributed) **Structural studies of (Ga,In)(As,P) alloys and $(InAs)_m(GaAs)_n$ strained-layer superlattices by fluorescence-detected EXAFS**, H. Oyanagi, Electrotechnical Laboratory; Y. Takeda, Kyoto University; T. Matsushita, National Laboratory for High Energy Physics; T. Yao, T. Ishiguro, Electrotechnical Laboratory; A. Sasaki, Kyoto University (Japan)

2:00 Rp3 (contributed) **Type III - Type I transition and strain effect in $Hg_{1-x}Cd_xTe$-CdTe and $Hg_{1-x}Zn_xTe$-CdTe superlattices**, S. Sivananthan, X. Chu, J. P. Faurie, University of Illinois at Chicago

2:15 Rp4 (contributed) **Atomistic simulation of stability, metastability, and growth of strained layer structures**, B. W. Dodson, P. A. Taylor, Sandia National Laboratories

2:30 Rp5 (contributed) **Ordering transitions of ternary alloys $A_{1-x}B_xC$**, K. E. Newman, J. Shen, University of Notre Dame

2:45 Rp6 (contributed) **Aperiodic superlattices: Structured randomness**, R. Clarke, T. D. Moustakas, Exxon Research and Engineering Company; R. Merlin, University of Michigan

3:00 *Break and Poster Session 2*

Metallic Superlattices II
Session presider: I. Schuller, Argonne National Laboratory

3:30 Rp7 (contributed) **Characterization of structural and magnetic order of Er/Y superlattices**, J. Borchers, M. B. Salamon, R. Du, C. P. Flynn, University of Illinois at Urbana-Champaign, R. W. Erwin, J. J. Rhyne, National Bureau of Standards

3:45 Rp8 (contributed) **Superconductivity of Cr/V superlattices**, B. M. Davis, P. R. Auvil, J. B. Ketterson, J. E. Hilliard, Northwestern University

4:00 *Concluding remarks and informal discussion*

Ballistic Transport and its Consequences in GaAs Quantized Regions

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The possibility of ballistic electron transport in semiconductors was speculated on for years, however, it was only recently that definite experimental verifications were provided for it in GaAs [1]. Moreover, the experiments enabled the determination of the fractions of the injected currents that had traversed thin GaAs layers ballistically. This was accomplished with the aid of the 'Tunnelling Hot Electrons Transfer Amplifier' (THETA) device, constructed from GaAs - AlGaAs heterostructures [2]. Using the THETA device as an electron spectrometer, we have measured ballistic-electrons energy-distributions on the order of 60 meV wide. Of the injected currents, ballistic fractions as high as 75% (15%), have been measured to traverse heavily doped GaAs layers 30 nm (80 nm) wide. As the transport regions increased in length, the ballistic electron distributions remained invariant, but the total number of ballistic electrons decreased [3].

Since the thin GaAs transport regions are confined between two potential barriers in the THETA device, quantum size effects are expected to occur. Their existence was verified via the observation of strong modulations in the ballistic currents injected into these confined regions [4]. We were able to see 'bound' and 'resonant' energy states (in the confined and continuum energy ranges, respectively), that were sensed by the ballistic, coherent, electrons. These quantum effects are expected to affect the scattering mechanisms that are dominant in thin, heavily doped, GaAs layers.

In addition, for sufficiently high injection energies, scattering of ballistic electrons into upper satellite valleys (the L - valleys) was observed [5]. Because these scattering events randomize the phase and the direction of some of the ballistic electrons, the above mentioned quantum interference effects, and the population of the ballistic ensembles propagating through the GaAs layers were observed to decrease above the onset of intervalley scattering.

Work was done with the collaboration of I. M. Anderson, E. Calleja, W. P. Dumke, M. V. Fischetti, C. M. Knoedler, M. I. Nathan, L. Osterling, D. C. Thomas, and G. C. Wilson.

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Abstract for invited talk at the Third International Conference on Superlattices, Microstructures and Microdevices

PERPENDICULAR TRANSPORT OF CARRIERS IN SUPERLATTICE MINIBANDS: DIRECT DETERMINATION BY SUBPICOSECOND LUMINESCENCE SPECTROSCOPY

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When the wavefunctions of carriers in the neighboring wells of a multilayered semiconductor heterostructures overlap significantly, the energy levels broaden into minibands with extended, Bloch-type states. These minibands are expected to lead to the transport of carriers perpendicular to the layers (Bloch Transport) and many interesting aspects of transport in such superlattices have been discussed in the literature.

We have directly measured the motion of carriers in superlattice minibands by using subpicosecond luminescence spectroscopy. These measurements determine the mobility of electron and hole transport in minibands for the first time and demonstrate clearly the existence of Bloch transport for sufficiently small barrier widths. In stepwise, graded gap superlattices, we find that the time to travel a distance of 1 micron increases dramatically from 50 ps to 1 ns as the barrier width is increased from 20 Å to 30 Å. This drastic change results from the fact that the transport proceeds via Bloch states in the former case but via localized states in the latter case. Similar

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Hot Electron Transistors Grown by MOCVD

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Monolayer-precision superstructure devices such as ulta-thin superlattices and quantum wells can be fabricated by metalorganic chemical vapor deposition (MOCVD) and their structural quality is favourably confirmed[1,2]. Energetic electron transport in III-V semiconductor is also investigated through the analysis of MOCVD grown single barrier diodes[3] and hot electron transistors (HET)[4] as well as MBE grown ones[5].

The characteristic behavior of injected hot electron in narrow base of AlGaAs/GaAs HETs was reported mainly by Heiblum. There are, however, still many issues which should deeply be discussed on the hot electron transport. For instance,

1. the significance of electron-electron interaction or plasmon scattering which is not yet clearly observed in the real HET,
2. direct observation of the transfer into the L and X valleys, which should be observed as a peak directly in a transfer ratio, $\alpha(=I_c/I_e)$, vs. V_{be} relation rather than in the derivative of α as was the case with the all published papers.

To better understand the mechanism of the hot electron transport, we have fabricated a series of HETs using the MOCVD in which we changed the values of several of the parameters, collector barrier height, base width, base doping concentration and base depth by incorporating In. The results of our experimentation are shown bellow.

1. A peak appeared in the α vs. V_{be} curve when $V_{be} \sim 350$ meV, and a shoulder appeared when $V_{be} \sim 480$meV, showing that transfer had occured from Γ into L and X valleys,respectively.
2. A double peak appeared around 300 meV in the derivative of α, showing elastic and inelastic transition into L valleys.
3. With base concentrations and a collector barrier height, which both had a wide range, α was equal to $\exp(-W_b/L)$, where W_b is the base width and L is a constant.
4. The emitter grouded current gain of a HET with W_b=50nm reached 5.6.
5. Critical comparison of the real HET with Monte Carlo particle simulation[6] showed that plasmon scattering has a significant effect on transport in HETs with highly doped bases.

This work was supported by the MITI's Project of Basic Technology for Furture Industries.

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II-VI HETEROSTRUCTURES : MAGNETOOPTICS AND BAND STRUCTURE .

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II-VI heterostructures are new and important materials which present a great fundamental and technical interest and exhibit different characteristics than the III-V heterostructures in particular because of the semi-metal band structure of some mercury compounds. We report recent magneto-optical results obtained on various II-VI systems grown by molecular beam epitaxy.

Magneto-absorption on HgTe-CdTe superlattices shows intraband and interband transitions which are interpreted by fitting the data with theoretical calculations done in the envelope function formalism. The superlattice band structure is deduced and the value of the valence band discontinuity is discussed.

Far infrared magneto-absorption experiments on $Hg_{1-x}Mn_xTe$-CdTe superlattices with a low Mn concentration ($x < 0.07$) are also reported. Hall measurements indicate large electron concentrations, $n \sim 3 \times 10^{12} cm^{-2}$, which are confined in the layers containing the dilute magnetic impurities. The observed transitions are interpreted in terms of electron cyclotron resonances and the experimental results are compared with calculations in the envelope function model taking into account the effects of magnetization.

We have also performed far infrared magneto-absorption experiments in $Hg_{0.8}Cd_{0.2}Te$-CdTe single heterojunctions which reveal the existence of a two dimensional electron gas at the interface, a charge tranfer occuring from deep-level traps in CdTe into $Hg_{0.8}Cd_{0.2}Te$ conduction band near the interface. The large band non-parabolicity allows the simultaneous observation of electron cyclotron resonance from the bulk and from the two dimensional electron gas. The results are compared with earlier experiments reported on MOS $Hg_{0.8}Cd_{0.2}Te$ structures.

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Raman, Photoluminescence and Modulation Spectroscopy of Semiconductor Heterostructures

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Collective and localized excitations in semiconductor heterostructures can be discovered and delineated with a number of spectroscopic techniques.

When subjected to an alternating strain, the piezomodulated optical properties – as in the bulk – display signatures characteristic of electronic transitions. Results for single-, double-, and multiple quantum wells in GaAs/$A\ell_xGa_{1-x}As$ quantum well structures reveal electronic transitions in the wells, the barriers and the buffer layer with exceptional clarity.

Raman scattering in a single quantum well of GaAs sandwiched between $A\ell_xGa_{1-x}As$ layers reveals longitudinal optical (LO) phonons confined to the well, resonance of the scattered radiation with the electronic transitions of the well being exploited. The frequencies of the confined LO phonons agree well with these deduced from the bulk dispersion of GaAs. Also observed in the Raman spectrum of superlattices of such structures are the "interface" optical phonons – they being more intense in less perfect interfaces.

Raman spectroscopy applied to heterostructures of diluted magnetic semiconductors (e.g. $Cd_{1-x}Mn_xTe/Cd_{1-y}Mn_yTe$) show (1) 'zone folded' acoustic phonons (2) 'propagating' and 'confined' optical phonons (3) 'interface' optical phonons. The large magnetic field shifts in the photoluminescence associated with the electronic transitions in the quantum wells demonstrate the existence of large exchange interaction between the band electrons and the magnetic ions, as in the bulk. This effect is exploited in the magnetically tuned resonance enhancement of the Raman spectrum of optical phonons. Magnetic excitations in diluted magnetic semiconductor heterostructures will be discussed.

FAR-INFRARED STUDIES OF DOPED AlGaAs/GaAs MULTIPLE-QUANTUM-WELL STRUCTURES

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Recent far infrared (FIR) experiments on doped AlGaAs/GaAs multiple-quantum-well (MQW) structures will be reviewed. Experiments were carried out between 4.2 and 70K in magnetic fields up to 9T with a FIR fourier transform spectrometer. The MQW structures were grown by MBE with well-widths between 80 and 450 Å and barrier widths between 125 and 150 Å. The structures were selectively doped with Si impurities in the center of the wells, or both in the center of the barrier and in the center of the wells. Magnetoabsorption measurements on the latter samples show three absorption lines in the vicinity of the hydrogenic donor 1s - 2p(m=+1) transition. The highest frequency line is due to neutral donor impurities in the well-centers. The strongest line, the lower frequency of the two "new" lines, is attributed to electrons in the wells bound to their positively charged parent donors in the center of the barriers. Experiments on the widest-well center-doped sample with the magnetic field in the plane of the sample and light propagation perpendicular to the magnetic field (Voigt geometry) have permitted the observation and identification of the 2p state for the hydrogenic donors that is associated with the first excited confinement subband. The energy of this state is in good agreement with calculations. Experiments have also been carried out under optical excitation with the pump photon energy greater than the gap of the AlGaAs. All MQW structures studied exhibit large excess free electron concentrations (as measured in-situ by cyclotron resonance) at low pump intensities, while the density of neutral donors remains unchanged or increases (as measured by the intensity of the hydrogenic 1s - 2p(m=+1) absorption line). The excess electrons under these conditions are attributed to the existence of substantial densities of compensating acceptors in the wells. This optical pumping effect has been used to study the effects of screening on the shallow donors in the wells. Within experimental error, no screening effect on the hydrogenic 1s - 2p transitions is observed for excess electron densities in the region where theoretical calculations predict substantial reduction in the binding energy. Possible explanations will be discussed.

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Samples were grown by J. Ralston and G.Wicks at Cornell U., and by J. Comas and W. Beard at NRL.

Electro-optical Studies of $Al_xGa_{1-x}As/GaAs$ Coupled Quantum Wells*.

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ABSTRACT

The interest in semiconductor quantum wells (QWs) is based, in part, on their promise for optoelectronic applications. For the majority of these applications, the key physical effects result from quantum confinement. The engineering of quantum confinement systems can benefit from more complex structures whose wavefunctions can be designed with more flexibility than in square QWs.

$Al_xGa_{1-x}As/GaAs$ coupled quantum well structures consisting of a pair of square QWs have been investigated experimentally. The influence of electric field on the optical properties differs significantly in this type of structure from that of square QWs, and in fact, effects appear that do not exist for square QWs. Analysis indicates that some of the observed properties are due to the shapes of the confinement wavefunctions. Novel effects also arise from the electrically tunable crossing of the quantized light hole and heavy hole levels in the valence band, and the shifting of Fermi levels in doped structures. These effects promise novel applications beyond those of square QWs.

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Quantum wells and bulk AlGaAs under hydrostatic pressure*†

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Excitonic and staggered transitions in quantum wells[1] and deep donor levels tied to indirect bands in $Al_xGa_{1-x}As$ are studied using spectroscopic techniques such as photoluminescence (PL) and photoreflectance[2] (PR) under high pressures (70 kbar) and low temperatures (8K and above).

In the quantum wells, valence band offsets have been determined using the staggered transition between the electron in the AlGaAs X well and the hole in GaAs VB well. The valence offset is found to be 30±3%. The pressure coefficients (α) of confined transitions have been studied as a function of well width L_z using PL and as a function of quantum number n using PR. These transitions are found to have α's upto 10% lower than that of the GaAs host as L_z decreases or n increases. While there are several competing factors, the major effect is due to the change in the electron effective mass[3] m_e^* as a function of pressure and the nonparabolicity of the Γ conduction band (CB).

Deep donor levels observed in AlGaAs are seen to be resonant states tied to initially to the L CB and at high pressures to the X CB. A detailed study for a series of temperatures and excitation intensity reveals luminescence from the DX center, and its behavior under pressure.

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** A.P. Sloan Foundation Fellow
† This work was done in collaboration with U. Venkateswaran, A. Kangarlu and the authors in Refs. 1 and 2.

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Auger Recombination in GaSb/AlSb-Multi Quantum Well Heterostructures

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We report the experimental determination of Auger recombination coefficients in GaSb/AlSb multi quantum well heterostructures. The samples investigated were grown by MBE and consist of a 1μm thick multi quantum well structure. The well widths range from 40 Å to 120 Å.

Auger recombination reduces the carrier lifetime and therefore strongly influences devices which are operated at high carrier densitiy levels like semiconductor lasers. Especially in GaSb, where the spin-orbit splitting and the band gap energy are comparable /1/ strongest Auger recombination rates are expected due to the negligible activation energy for the CHSH-process. This process, where a recombining electron-hole pair transfers energy and momentum to a heavy hole which is excited into the split-off band, gives rise to a weak emision (1 photon/sec.) at the energy of $E_g+\Delta_o$. This $E_g+\Delta_o$ luminescence is used to monitor the population processes of the split-off band via carrier scattering (CHSH-process) and inter valence band absorption.

We have investigated simultaneously the E_g and $E_g+\Delta_o$ luminescence under the same experimental conditions. The temperature and excitation power dependence (T= 2 - 340 K, P= 0.01 - 1 $MWcm^{-2}$) of both emissions was analyzed applying coupled carrier rate equations for the conduction and the valence subbands including the split-off band. Information on the actual carrier density was obtained by line shape analysis of the E_g emission. Density values up to $9 \cdot 10^{11}$ cm^{-2} are determined.

The most important results are

i) The dominant population process of the split-off band is the CHSH-Auger process as compared to the inter valence band absorption.

ii) The Auger coefficients exhibit a dependence on the well width: at wider wells ($L_z \geq 100Å$) the coefficients are comparable with bulk values /2/ whereas a decrease with decreasing well width is observed.

iii) No resonance of the Auger recombination is observed tuning the band gap energy over the spin-orbit splitting with temperature, as in bulk GaSb.

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PIEZOELECTRIC EFFECTS IN STRAINED LAYER SUPERLATTICES

by

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ABSTRACT

Because zincblende structure semiconductors are piezoelectric, polarization fields can be generated in the constituent materials of strained layer superlattices by lattice mismatch induced strain. The orientation of the polarization fields depends on the superlattice growth axis. For a [111] growth axis, the polarization fields are parallel to the growth axis; for a [110] growth axis, the polarization fields are perpendicular to the growth axis; and for a [100] growth axis, no polarization fields are generated. Because one of the constituent layers of the superlattice is in biaxial tension and the other is in biaxial compression, the sign of the polarization field is opposite in the two constituent layers making up the superlattice period. Thus, sheets of divergence of polarization occur at the interfaces of a [111] growth axis superlattice and sheets of curl of polarization occur at the interfaces of a [110] growth axis superlattice. The sheets of divergence of polarization generate internal electric fields and the sheets of curl of polarization generate electric displacement fields. The magnitude of these fields can be very large. For example, electric fields exceeding 10^5 V/cm can easily be reached. These fields significantly change the electronic structure of these superlattices. As a result, the optical response of these superlattices is strongly modified by the fields. The fields can be externally modulated by electrical bias, applied stress, and screening by photogenerated free carriers. Thus, the materials have large electro-optic, piezo-optic, and nonlinear optic coefficients. We illustrate these properties by a series of calculations on strained group III-V superlattices.

Ultrafast Optical Nonlinearity in Quantum Well Structures with Electric Field

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A new concept on field-induced optical nonlinearity due to virtual transitions in quantum well (QW) structures will be proposed, showing some examples of theoretical result on the nonlinearity. In a QW structure subjected to DC electric field E_0, negative and positive electric charges of which spatial profiles are given by wave functions at the subbands (1e, 2e,$\cdots$, and 1hh, 2hh,$\cdots$, 1ℓh, 2ℓh,$\cdots$) induced by the virtual transitions due to an intense pump light with a photon energy $\hbar\omega_p$ far below the band gap may produce a screening field E_s, cancelling out, to some extent, the external bias field E_0 (see Fig.1). As a result, one may expect a blue shift of the energy gap and changes in oscillator strengths for a weak signal light with a photon energy $\hbar\omega_s$. The switching times of the nonlinearity should be very short, $\sim$100 femtosec., both for the ON- and OFF-processes because the electric charges are induced by the virtual processes and the field cancellation results from the internal charges inside the QWs. In other words, the switching characteristic is free from life time limitation, in a contrast with those due to real excitation processes, and from C·R-time constant limitation.

As a consequence of numerical estimations, the following result is obtained for a $Ga_{1-x}Al_xAs$ graded gap ($x=0 \rightarrow 0.3$, $L_z=200$Å) QW structure. An increase in the 1e-1hh transition oscillator strength, 3.6%, and a blue shift of band gap, 0.17meV are expected for a pump power density of 10^8W/cm^2 with a photon energy, 100meV below the energy gap and for an electric field E_0 of 9×10^4V/cm. The variation in the oscillator strength is significantly larger than that (bleaching) due to conventional phase filling mechanism. The amount of blue shift is comparable to that due to dressed exciton mechanism.[1] The field-induced optical nonlinearity seems to be observable and quite useful for designing an ultrafast optical gate.

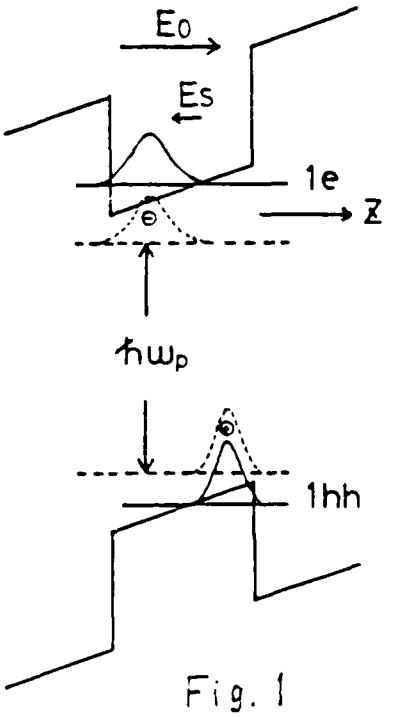

Fig. 1

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STRAINED LAYER AND LATTICE MATCHED TRANSVERSE JUNCTION STRIPE QUANTUM WELL LASERS FOR CONTINUOUS ROOM TEMPERATURE OPERATION

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Two new Transverse Junction Stripe (TJS) laser structures using lattice matched AlGaAs-GaAs and strained layer InGaAs-GaAs-AlGaAs quantum wells have been demonstrated. The lasers are grown by molecular beam epitaxy and the junction is produced by a two step zinc diffusion and anneal. The diffusion process produces a lateral heterojunction (in addition to the as grown heterojunctions) by diffusion enhanced compositional disordering of the quantum well active region. Both lasers exhibit low thresholds (20-30 mA, continuous wave, room temperature) and single mode operation. The excellent performance of both lasers indicates that high quality lateral p^+-p-n junctions and heterojunctions can be formed by zinc diffusion enhanced compositional disordering of both lattice matched GaAs-AlGaAs and strained layer InGaAs-GaAs-AlGaAs quantum well structures.

We will present data on the growth, processing and characterization of the lasers which confirms our claim of high quality lateral heterojunctions in a quantum well structure. The temperature dependence of the threshold current $T_o = 120K$ for $77K < T < 270K$; $T_o = 100K$ at 300K) are comparable to double heterostructure lasers. Preliminary lifetime data (200 hrs.) for the strained layer laser shows no observable degradation in the power-current characteristics. Also, the InGaAs-GaAs-AlGaAs laser result is the first demonstration of a continuous wave room temperature strained layer laser grown by molecular beam epitaxy.

Semiconductor Microcrystallites in Porous Glass and Their Applications in Optics

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Astract

Fabrication of semiconductor microcrystallites is of much current interest in the rapidly advancing field of artificial superlattices and quantum well structures. We wish to report on the utilization of the microporosity in Vycor brand porous glass to produce microcrystallites of semiconductors of groups II-VI, IV-VI and layered transition metal chalcogenides. Based on electronic spectral evidence, quantum confinement effects have been observed in some of the semiconductors when confined spatially within the pores of the porous glass. Nonlinear optical applications of the porous glass doped with semicoductors microcrystallites will be discussed.

CONTROL OF CARRIER LIFETIME IN PbTe nipi SUPERLATTICES BY EXTERNAL PHOTOINJECTION

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Versatile PbTe nipi superlattices have been recently demonstrated to reach near theoretical limits as infrared detectors (1). Apart from their epitaxial material quality, increased sensitivity arises from large enhancement of nonequilibrium carrier lifetimes due to electron and hole separation in real space by the built-in nipi potential. We have employed methods of time resolved photoconductivity to investigate the influence of photoinjected electron hole pairs on recombination rates over a wide range of experimental conditions. Large photoinduced lifetime changes from ~50 μsec to ~1 nsec have been observed. At very low excess carrier densities, two dominant recombination mechanisms can be identified. At low temperature, recombination rates are determined by the probability for tunneling into the nipi barrier while at higher temperatures thermally activation above the barrier leads to direct recombination by vertical transitions. For typical superlattice parameters the two mechanisms are comparable at about 130 K. At high excess carrier densities approaching the static space charge density of the ionized dopants, the nipi potential can in principle be neutralized with lifetime approaching the bulk PbTe limit. We have solved the nipi potential self-consistently to provide a good theoretical description to the experimental observations. The recombination dynamics following excitation by an intense ultrashort laser pulse are well described by properly including Auger recombination to account for the nonexponential carrier decay. Finally, we have also investigated the transition from the usual electric potential dominated regime to one controlled by an external magnetic field.

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Spectroscopy of One-Dimensional Subbands on InSb

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We prepare periodic metal stripes with grating constants a~250nm and small free widths w~100nm between stripes on InSb surfaces of metal-oxide-semiconductor structures (see Fig.)

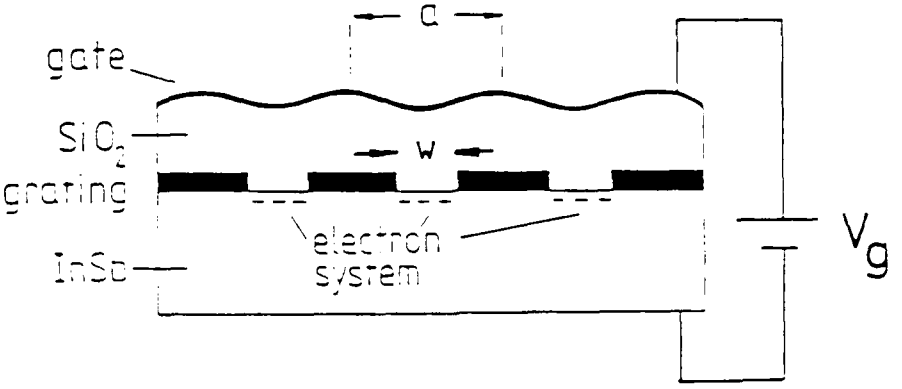

Fig.: Laterally microstructured MOS capacitor on InSb.

In such microstructures, electrons of fairly high mobility μ~20000 $cm^2V^{-1}s^{-1}$ are induced by a gate voltage into the channels between the metal stripes. Their optical excitations are studied by far-infrared laser and Fourier spectroscopy. Cyclotron resonance experiments in quantizing magnetic fields show the importance of a lateral confining potential and a transition from two-dimensional to one-dimensional (1D) behavior when the magnetic field strength is decreased. Resonance energies are measured in zero magnetic fields as a function of the applied gate voltage V_g and are discussed with the aid of simple theoretical pictures of the 1D quantization. The experimental results and their comparison with theoretically expected values demonstrate that we have in fact created quasi 1D subbands on InSb.

AHARONOV-BOHM EFFECTS IN DISORDERED METALS

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After the discovery of weak electron localization, it became clear that interference processes between diffusing electron waves in disordered metal films can not be neglected. Due to inelastic scattering and spin scattering by magnetic impurities, the interference only occurs over distances shorter than a characteristic phase breaking length L_φ (of the order of 1 μm at low temperatures).

In thin metal films with a size much larger than L_φ, ensemble averaging largely destroys the influence of the interference processes. For back-scattering along time-reversed paths, the destruction does not occur, since the phase difference between the two partial electron waves is always equal to zero. In a magnetic field perpendicular to the time-reversed paths, the back-scattering probability oscillates with flux-period h/2e. For cylindrical metal films (length much longer than L_φ), magnetoresistance oscillations with flux-period h/2e can be observed experimentally when $2\pi r \lesssim L_\varphi$ (r is the cylinder radius).

When the size of a metal film is smaller than L_φ, ensemble averaging is not complete. In this "mesoscopic" regime, interference between splitted electron waves traveling along different paths, can no longer be neglected. For a ring geometry, the direct interference gives rise to experimentally observable magnetoresistance oscillations with the fundamental Aharonov-Bohm period h/e. Due to the back-scattering processes, h/2e oscillations will also be present in the ring geometry. When N rings are measured in series, the amplitude of the h/e oscillations decreases inversely proportional to $N^{1/2}$, in agreement with stochastic ensemble averaging. As expected, the h/2e oscillation amplitude is independent of N, since the back-scattering probability is not influenced by the ensemble averaging.

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ENERGY LEVELS AND MAGNETO-ELECTRIC EFFECTS IN SOME QUASI UNI-DIMENSIONAL SEMICONDUCTOR HETEROSTRUCTURES

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We consider quantum wires in the quasi-decoupled situation: the side lengths L_x, L_z are characterized by $L_x >> L_z$. In this approximation the Schrödinger equation for the envelope functions becomes quasi-separable in x and z for states energetically close from the Γ_6 edges of the host materials. Accordingly, the eigenvalues are approximately classified in terms of closely spaced L_x levels derived from well separated L_z levels. To each of these eigenvalues is attached a one-dimensional subband due to the free motion along the y axis. For the Γ_8 valence states the subband structure is more complicated. In a rectangular quantum wire, the confinement in the x-direction introduces a mixing in the $J_z = \pm 3/2$ and $J_z = \pm 1/2$ levels. This mixing increases with increasing quantization along the x axis. Furthermore, it is enhanced at non zero wave-vector along the y-direction.

We consider also the case of rectangular quantum wires assumed to be n-type spike- and modulation-doped on one of the L_x sides. A self-consistent calculation is performed and the energy levels and the charge transfer are calculated.

Finally, we consider quantum wires subjected to crossed electric and magnetic fields perpendicular to the wire axis. At zero electric field the energy spectrum displays a cross over from a L_x-governed quantization to a B-governed quantization. At zero magnetic field the electric field leads to quadratic Stark shift of the energy levels followed by an interface accumulation regime. The two kinds of behaviours are mixed if both electric and magnetic fields are non vanishing.

Quantum Transport in an Electron Waveguide

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We have fabricated high mobility, one dimensional wires in GaAs/AlGaAs heterostructures in which the width of the conducting channel is comparable to the electronic wavelength, and measured the ohmic, four terminal, electrical resistance as a function of magnetic field and temperature. Because of the size of the devices and the high mobility, a few transverse channels carry the current at 35mK with minimal scattering. Fluctuations in the resistance are observed as a function of magnetic field for $0<\omega_c\tau<300$, where ω_c is the cyclotron frequency and τ is the scattering time, superimposed upon Shubnikov-deHaas oscillations. At low temperature the frequency and amplitude of fluctuation decrease as the magnetic field approaches the extreme quantum limit where only the lowest Landau level is occupied. We propose that the fluctuations in the resistance of the wire are due to the Aharonov-Bohm effect, and that the change in the frequency of oscillation is due to the change in the probability amplitude of the electronic wavefunction across the wire as the Landau level index changes with field. At sufficiently high fields in the regime of well developed quantized Hall effect, the fluctuations may arise from finite size percolation effects in the electron wavefunction. In contrast with recent results where the amplitude of fluctuation is approximately e^2/h for $\omega_c\tau<1$, we find that the rms amplitude of fluctuations in the conductance is larger than $80e^2/h$ at low fields, and for particular ranges of fields, negative dynamic resistance is observed for $\omega_c\tau>1$.

TRANSPORT IN GaAs HETEROJUNCTION RING STRUCTURES

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In earlier work we have shown that the split gate GaAs-AlGaAs heterojunction FET has been a very useful system for obtaining 1D transport.[1,2] We have now extended this work to the construction of ring structures. Here, a ring of resist (outside diameter 2.2μm, inside diameter 0.1μm) is formed on the AlGaAs surface using Electron Beam Lithography, and is covered with metal, thereby forming a Schottky gate inside and outside the ring. Application of a negative voltage to the gates depletes the high-mobility 2D electron gas at the interface, except in a narrow annulus between the gates. The width of this ring-shaped 2D electron gas can be varied by changing the gate voltage.

The magnetoresistance was measured down to ~50 mK and magnetic fields up to 10 Tesla. We present results on the Aharonov-Bohm effect and conductance fluctuations at low fields, and on magnetic quantisation at high fields.

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METALLIC SUPERLATTICES*

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I will describe the preparation, characterization and physical properties of metallic superlattices. The structure and growth of metallic superlattices is determined by a variety of epitaxial considerations, including the structure of the constituents as well as their equilibrium thermodynamic phase diagram. The structural properties determined using surface analytical and diffraction techniques will be related to numerical simulation studies, particularly molecular dynamics.

The physical properties including transport, elastic, magnetic, and superconducting properties will be related to structural properties. I will show that the physical properties depend strongly on the length scale of the physical phenomenon under study and that different structural characteristics should be emphasized accordingly. Some of the unusual physical properties such as anomalous elastic constants, electron localization, dimensional cross-over, magnetic coupling, etc. will be described to illustrate the richness of phenomena present in these microstructures.

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FERROMAGNETIC/SEMICONDUCTOR HYBRID STRUCTURES

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Recent work has shown that single crystal ferromagnetic films can be grown epitaxially on compound semiconductor surfaces using molecular beam epitaxy.[1,2,3,4] These heterostructures can provide the basis for new hybrid device structures which could exploit the properties of both the semiconductor as well as the ferromagnet. In particular it permits the growth of monolithic structures in which a magnetic field, provided by the ferromagnet element of the structure, may act upon the semiconductor component of the structure. This may affect either the electronic transport properties or radiation propagating through the semiconductor. A number of these heterostructures will be discussed, including Fe and Co grown on GaAs, ZnSe and $Zn_{1-x}Mn_xSe$. The growth conditions and interface properties will be described. Finally, several applications of these heterostructures will be illustrated, including high frequency and magneto-optical device applications.

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Properties of Synthetic Magnetic Superlattices

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Recent advances in the metal molecular beam epitaxy technique have produced high quality synthetic magnetic spin superlattices. The basic building blocks of the superlattices consist of magnetic rare earths e.g., Gd, Dy and Ho and their nonmagnetic analog e.g., Y. Systems studied to date include Gd-Y[1], D_y–Y[2], Ho - Y, Gd-D_y, periodic superlattices, as well as quasi-periodic Gd-Y superlattices in the Fibonacci sequence. The growth mode of rare earth metals follows the layer-by-layer type, and oscillations in the RHEED intensities were observed at low growth temperature ($\lesssim 200^{\circ}C$). The structural perfection of the superlattice crystals including the in-plane coherence length and the interfacial width of the chemical modulation are approaching those achieved in the semiconductor (III, VI) superlattices[3]. Magnetization measurements[4] and polarized neutron diffraction studies[5] have demonstrated that the overall magnetic order of the superlattice as a whole is modulated by the superlattice periodicities. This long range magnetic correlation is caused by the coherent propagation of the Ruderman-Kittel-Kasuya-Yosida (RKKY) coupling through the conduction electrons of the nonmagnetic intervening Y layer. These results will be presented along with an intriguing interplay between ferromagnetic and helimagnetic order recently observed in the Gd-Dy superlattices.

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OBSERVATION OF FERROMAGNETISM IN ULTRATHIN f.c.c. FILMS BY SPIN POLARISED NEUTRON REFLECTION.

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Abstract

We have used polarised neutron near critical reflection to probe for ferromagnetism in ultrathin f.c.c. Fe and Co films epitaxed to single crystal non-magnetic substrates. The films are overcoated with Cu(001) overlayers of thicknesses between 40 and 130Å in order to enhance the spin dependence of the neutron reflectivity via wave interference within the sandwich structures. We observe a strong ferromagnetic (FM) response for f.c.c. Co films of thicknesses 2,4,6 and 10 monolayers (ML) epitaxed to Cu(001) substrates with a magnetic moment per atom μ close to that of bulk (hcp) Co ($1.7\mu_B$). The temperature dependence of μ in the range 0 to 300K is very weak for all the Co films investigated, in agreement with recent spin resolved photoemission [1] experiments on uncoated Co films in the same thickness range.

The results for f.c.c. Fe films epitaxed to Rh(001) and Cu(001) substrates contrast sharply with those obtained for the f.c.c. Co films. The 300K spin dependent response is very weak if present [2] and not experimentally detectable ($\mu \leq 0.15\mu_B$). At 4K, a 9Å Fe/Rh(001) film displays a significant FM response which is however substantially smaller than that anticipated for a saturated film with the bulk phase value of μ ($2.2\mu_B$). The results are discussed in the context of recent theories which model the roles of lattice strain [3] and surface anisotropy [4] on moment formation in thin films.

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Abstract of paper to be presented at the Conference on Superlattices, Microstructures, and Microdevices, Chicago, August 17-20, 1987

THEORETICAL ASPECTS OF ELECTRON TRANSPORT IN MODULATED STRUCTURES

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In the theory of transport in modulated structures we have studied both transport perpendicular and parallel to the heterojunction interfaces.

In perpendicular transport we have investigated models for tunneling through double barriers and find that resonant tunneling and sequential tunneling lead to the same expression for the current as long as the width of the energy distribution of the injected electrons are larger than the width of the resonant level in the diode. We present results for phonon assisted tunneling between two wells in a model which remains valid even when the barrier shrinks and the tunneling probability becomes very high. Proposals for practical schemes for incorporating this model in programs for calculating the transport in generalized band-engineered structures are given.

In parallel transport we show that very saticfactory agreement with extensive measurements of the mobility in modulation doped structures in the whole temperature range from 4 K to 300 K can be obtained if one takes into account the complete quasi-two-dimensional subband structure and all the relevant scattering mechanisms. Having established this we apply this program to systems with more complicated double channel structures, and show how one can taylor the conductivity of a channel in which perpendicular resonant tunneling affects parallel transport.

Quantum Transport Theory of Resonant-Tunneling Heterostructure Devices

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The ability to fabricate very small semiconductor heterostructures has led to the development of devices which exploit quantum-mechanical effects in their operation. The quantum device which has received the most attention recently is the quantum-well resonant-tunneling diode. This device shows a negative-resistance characteristic which is manifestly quantum-mechanical in origin, and is potentially a very fast device. Existing techniques for analyzing and modeling devices are not able to adequately describe the transient behavior of such a device.

A form of quantum transport theory has been developed to model the resonant-tunneling diode and similar devices. The internal state of the device is represented by the Wigner distribution function. The boundary conditions applied to the Wigner function model the open-system nature of the device by coupling it to electron reservoirs. This coupling introduces irreversibility into the model, permitting meaningful calculations of the transient behavior of any physical observable.

The steady-state I-V curves derived from this model show the expected negative resistance. The calculations of the detailed transient response are the first reported for a tunneling device, and resolve the question of the response time of the tunneling current. For a structure with 2.8 nm AlGaAs barriers, the current switches from its peak to its valley value in about 0.2 ps.

Calculations of the frequency-domain linear and nonlinear response of the resonant-tunneling diode show that the maximum oscillation frequency is in the low Terahertz range, and that the rectification response extends to even higher frequencies.

Resonant Tunneling Transistors and Resonant Tunneling Hot Electron Spectroscopy

(Invited Paper)

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We present results on a variety of new resonant tunneling (RT) structures; both the under lying physical phenomena and the device applications will be emphasized. These include:

a. *RT Gate Field-Effect Transistors*

This new device[1] consists of a GaAs n-channel grown on a semi-insulating substrate with source and drain contacts and a double barrier (20 Å AlAs/70 Å GaAs/20 Å AlAs) gate followed by an ohmic metallization. Both negative transconductance and negative conductance in the drain current have been achieved by quenching RT through the double barrier via the gate voltage.

b. *RT Devices with Multiple Negative Differential Resistance (NDR) regions and 3-state memory circuits.*

These new devices exhibit two NDR regions with nearly equal peak currents and voltage-tunable peak separation. Three-state memory circuits, four bit parity generators and frequency multipliers (by 3 and by 5) with greatly reduced circuit complexity have been implemented.

c. *RT Bipolar Transistors*

RTBT's operating at room temperature with large peak-to-valley ratios in the collector current have been demonstrated.[2] These devices contain a double barrier in the base region; NDR is achieved by quenching RT via the base current or base-emitter voltage.

d. *RT Hot Electron Spectromters.*

We have demonstrated a new hot electron spectroscopy based on RT.[3] Information on the energy distribution is obtained directly from the current voltage characteristics without requiring derivative techniques. We have used this technique to show that ballistic motion of minority electrons in heavily doped p-type GaAs is not possible due to very strong electron-hole scattering.

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Superlattice Doping Interfaces

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The effect of background doping on current transport in quantum well structures is of great technological importance. Complicated doping - quantum well interactions are known to exist, yet remain poorly understood. The effects of doping on current vs. voltage characteristics in resonant tunneling devices (due to undoped spacer layer thickness)[1] and in quantum well electron barrier devices[2-4] serve as examples of these interactions. This study reports the use of n^+-n junctions superimposed on superlattices as a simplified system for such effects.

Four samples were grown and tested in this experiment. From substrate to surface, these samples consist of an n+ Si-doped substrate, a 0.5 μm 10^{17} Si-doped GaAs cladding layer, a 37 period 80 Å $Al_{0.3}Ga_{0.7}As$ - 50 Å GaAs superlattice uniformly doped with either 10^{16} or 10^{18} Si, a 30 period 80 Å $Al_{0.3}Ga_{0.7}As$ - 80 Å GaAs superlattice uniformly doped with either 10^{16} or 10^{18} Si, a 0.5 μm 10^{17} Si-doped GaAs cladding layer, and a 0.25 μm $2x10^{18}$ Si-doped GaAs cap layer. The difference between each of these four samples is the particular doping combination of the 50 Å-well and the 80 Å-well superlattices. The samples were grown as a sequential set by MBE so as to minimize uncontrolled variations.

Data are presented which show that the applied bias appears across only lightly doped and depleted regions. Slight asymmetry effects about the origin are observed which are consistent with expected electron barriers for these superlattice structures. Negative differential resistance effects and conductance oscillation effects are also observed, and are discussed in light of our present understanding of these devices.

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PRESSURE-DEPENDENT MEASUREMENTS ON n^+GaAs (Si, Sn): THE EFFECT OF DEEP DONOR (DX) STATES ON THE ELECTRICAL PROPERTIES AND PERSISTENT PHOTOCONDUCTIVITY EFFECTS

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ABSTRACT

Shubnikov-de Haas measurements up to magnetic fields of 20 T are used to study the effect of hydrostatic pressure ($P \leq 15$ kbar) on the free electron concentration (n) and mobility (μ) of MBE-grown n^+GaAs layers heavily doped with either Si or Sn. This type of layer forms the electrical contacts to a variety of (AlGa)As/GaAs tunnelling devices and superlattices that we and other workers have investigated under hydrostatic pressure. Increasing the pressure from zero causes an immediate and large decrease of n and increase of μ in n^+ samples doped at 1.8×10^{19} cm^{-3}. At 15 kbar n has fallen to 0.8×10^{19} cm^{-3}. At lower doping, n and μ start to fall only above a critical pressure whose value increases with decreasing n. Illumination with red light at low temperatures (40 K) leads to a persistent restoration of n to its zero pressure level. This is accompanied by a decrease in μ. It is concluded that the trap involved is a "deep" donor with DX character, present in the n^+GaAs layers, at concentrations comparable to the doping level. We find that the energy of the level relative to the L-minima decreases with increasing doping and that its pressure coefficient is close to that of the L-minima. At doping levels above 1.8×10^{19} cm^{-3}, the level is partially occupied even at atmospheric pressure. The properties of the "deep" donor level appear to be very similar for both Si- and Sn-doping.

We will give examples of how these DX centres affect the current-voltage characteristics of tunnelling devices as a function of hydrostatic pressure.

RANDOM QUANTUM INTERFERENCE IN MICRODEVICES

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Experiments on narrow silicon MOSFETs, metal wires and rings, and III-V devices of various sorts prove that the conductance of small electronic devices at low temperatures is affected by random quantum inteference of a suprisingly universal character. The quantum phase information of electron waves is not destroyed by elastic scattering. If the inelastic diffusion length L_ϕ is much greater than the mean free path, diffusing electrons will interfere in random patterns determined by the specific microscopic configuration of scatterers. As a result, the conductance of each quantum domain of size L_ϕ is changed by random amounts with an rms average deviation of just e^2/h, and is sensitive to changing even a single scatterer.

The range of possible interference patterns in a single device can be investigated by applying magnetic flux, or by changing the Fermi energy. In our own experiments, we have measured the conductance of submicron patterned silicon inversion layers (MOSFETs) with narrow channels and sidebranches used as potential probes. We have shown that the "universal conductance fluctuation" theory applies at low temperatures over a wide range of device sizes, shapes, and conductivities. Our attempts to probe "inside" a single quantum domain using closely spaced voltage probes show that each probe responds independently to quantum interference throughout the entire domain. Thus the fluctuation amplitude between two such probes is characteristic of scale L_ϕ, and can exceed the average voltage drop between them.

In typical semiconductor devices at room temperature, the mean free path is limited by inelastic scattering, so that these quantum diffusion effects are not significant. But in μm-scale semiconductor devices at liquid helium temperatures, the random phenomena can be large fractional effects. Would-be designers of small quantum-effect devices should be prepared either to "fix it" by obtaining unprecedented control over the microscopic details of the device structure, or "feature it" by figuring out ways to take advantage of these interference effects.

Quantum Interference and Transport in Microstructures

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Advances in microfabrication technology have made possible the production of structures with ever decreasing dimensions. As the size of these structures approaches certain characteristic lengths, quantum mechanical effects become evident. Electron interference phenomena may be observed in systems whose size is on the order of the electron phase coherence length, ℓ_ϕ. ℓ_ϕ can be 1 μm or more at 1 K. For a wire of width less than ℓ_ϕ, the interference of electron partial waves which are elastically scattered by impurities leads to one-dimensional localization. This effect manifests itself in the form of a small correction to the low temperature residual resistance, as first predicted by D. J. Thouless[1] in 1977. For ring structures of diameter ~ ℓ_ϕ, electron quantum interference leads to oscillations in the magnetoresistance of the ring with periods h/e and h/2e. These oscillations are the solid state analog of the Aharonov-Bohm effect. Experimental studies of these quantum interference effects in ultrasmall metal wires[2] and rings[3] fabricated by high resolution microlithographic techniques are reviewed. The mechanisms which determine electron energy and phase relaxation in these systems, as determined from these effects, are also discussed. These relaxation mechanisms may be relevant for new classes of semiconductor devices, such as the hot electron transistor.

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EXCITONIC PROPERTIES OF GaAs-AlGaAs NANOSTRUCTURES

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Recent advances in electron beam lithography and the etching of nanostructure features in semiconductor quantum wells have made possible the fabrication of structures in which excitons can be confined, in all three dimensions, to lengths of the order of a few times the exciton diameter (1). These achievements have led to structures with optical properties strikingly different from those of the original quantum wells (2).

We report here the first observation of exciton energy shifts due to lateral confinement in nanostructures etched from GaAs-AlGaAs quantum wells. We also report the first luminescence measurements from arrays of structures of varying lateral sizes etched from quantum wells. We observe surprisingly efficient photoluminescence of excitons, measured over five orders of magnitude in excitation intensity, from structures as small in lateral dimension as 40 nm. We also observe, at high intensities, the saturation and screening of excitonic recombination under both steady state and picosecond photoexcitation.

The structures are etched from a single GaAs-Al(0.3)Ga(0.7)As quantum well, approximately 5 nm thick, which was grown by molecular beam epitaxy. The samples were patterned using electron beam lithography and anisotropic reactive ion etching techniques (3). Wires, in which the carriers are confined in two dimensions, and dots, in which the carriers are confined in all three dimensions, were fabricated in sizes ranging from 40 to 200 nm.

We observe a blue shift of several meV in the ground state exciton for the smallest structures, which we attribute to lateral carrier confinement. This shift is of the same order of magnitude as the exciton binding energy in the original quantum well. The shift is independent of excitation intensity, which demonstrates that it is unrelated to band filling effects, to which a portion of the blue shift recently observed in InGaAs quantum well structures has been attributed (4).

We have measured the luminescence spectra of the structures at 10 K for excitation intensities ranging from approximately 0.1 Watt/cm2 through saturation of the exciton recombination. We find no evidence in the spectra of a "light hole bottleneck", in contrast to earlier reports (5). We find that even at the lowest excitation the luminescence efficiency of the smallest structures is comparable to that of the original quantum well. This result is consistent with our earlier measurements (2) at higher excitation intensities. The luminescence intensities of the nanostructures and of the original quantum well are approximately linear until saturation. This result is direct, and surprising, evidence that nonradiative recombination at the free, etched surfaces plays a minor role at low temperatures.

Measurements of the excitation and luminescence spectra under picosecond and steady state excitation show a dramatic size dependence of the exciton saturation. This is the first observation of exciton saturation in nanostructures.

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Infrared Detectors Based on the Photon Drag Effect and Intersubband Absorption by a Two-Dimensional Electron Gas

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ABSTRACT

Intersubband transitions stimulated by an infrared lightwave propagating in the plane of a two-dimensional electron gas (2DEG) are accompanied by a "photon-drag" current due to the momentum imparted by the absorbed photons. If the momentum relaxation times in the ground and the excited subbands are equal, $\tau_1 = \tau_2 \equiv \tau$, then the resultant current density J_0 corresponds to electrons moving in the direction of the incident photons, and $J_0/e \simeq (\hbar q/m)\alpha\tau\,\Phi$, where α is the absorption coefficient, Φ is the photon flux, and q the photon wave number in the medium. Each excited electron receives an extra momentum $\hbar q$, which, on the average, relaxes after the time τ. A simple way of understanding the above expression for J_0 is to note that $\alpha\,\hbar q\,\Phi$ represents the transferred momentum per unit volume per unit time, i.e., the drag-force density acting on electrons – whose mobility equals $e\tau/m$.

If, however, $\tau_1 \gg \tau_2$, as is usually the case in a high-mobility 2DEG, then the current response can be substantially enhanced – with the *polarity* of the photon-drag current depending on τ_1 and τ_2, as well as on the sign and magnitude of the frequency detuning $\Delta\omega$ off the intersubband resonance. The gist of the matter is that the photon-drag current considered above represents a small net difference between two oppositely directed larger currents: one due to excited electrons in the upper subband, the other to remaining holes in the lower subband. In the presence of radiation *both* subbands acquire an electron distribution disturbed from cylindrical symmetry, but carriers in the upper subband equilibrate much faster. During the time interval $\tau_2 < t < \tau_1$ the characteristic drift velocity in the 2DEG will be of the order of its Fermi velocity, $\hbar k_F / m$, rather than $\hbar q / m$. In a steady state, the resultant current J may be directed either along or against the "primary" current, depending on the sign of $\Delta\omega$, and its magnitude can be substantially higher than J_0. Calculations give the following estimate for the maximum current enhancement ratio $J/J_0 \simeq \hbar n \tau_1 / m$. For large 2DEG areal densities n this ratio can substantially exceed unity. The photon-drag effect permits a new type of spectroscopy containing information about the momentum-relaxation kinetics in 2D subbands.

It also allows the implementation of novel longwave infrared detectors. Estimates predict the possibility of achieving a detector sensitivity of order 1 A/W (or quantum efficiencies of order a few percent) at an incident photon wavelength of $\sim 10\,\mu$m. Performance of this detector at a given frequency is limited mainly by the thermal noise.

Properties of Multilayers for Soft X-Ray Optics+

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Appropriate physical description of multilayer structures to be used as soft x-ray optical elements is necessary to ensure agreement of predicted and actual performance. Deviations of the fabricated structures from an ideal design (interfacial roughness and diffusion, microvoids, impurities, thickness errors) degrade the reflectance properties. In addition, deviations of the physical properties of very thin films from those of the bulk materials can limit the validity of reflectance calculations. We describe these difficulties and how a particular fabrication-characterization procedure can help solve them. Characterization techniques used include a variety of x-ray diffraction techniques, Rutherford Backscattering Spectroscopy and Transmission Electron Microscopy. Examples of results obtained for samples prepared by triode magnetically confined dc sputtering will be given, as will a discussion of the implication of these results for other multilayer materials.

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10 μm Photoexcited Avalanche Gain due to Electron Impact Ionization from GaAs Quantum Well Superlattices

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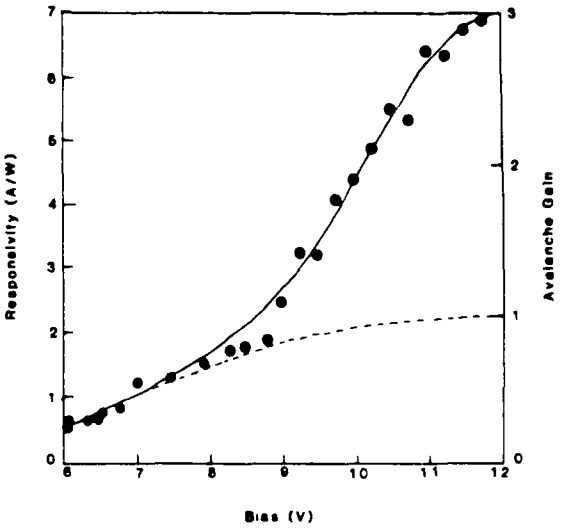
We report here the first demonstration of far infrared photoinduced impact ionization of electrons out of GaAs/$Al_xGa_{1-x}As$ quantum well superlattices. The avalanche gain for detection of λ = 10 μm radiation is measured to be G = 3. The MBE grown structure consists of a 50 period superlattice of 72 Å GaAs quantum wells (doped n = 1.5 x 10^{18}cm-3) separated by 133 Å undoped $Al_{0.38}Ga_{0.62}As$ tunneling barriers. The incident 10 μm radiation is strongly absorbed by the quantum well intersubband resonance[1,2] raising the electron from the ground to the first excited state which is designed to be 124 meV higher in energy.

The photoexcited electron efficiently tunnels out in 150 fsec and travels a hot electron mean free path through the superlattice (measured to be 4500 Å) and produces a large photocurrent before being recaptured by the quantum wells. The measured absolute responsivity R, increases with bias voltage and is in excellent agreement with theory[2] (which neglects avalanche gain) over three orders of magnitude from 0 to 9 V. The high field portion of the data is shown in the figure where the dashed line is the non-avalanche theory. Note that the theory saturates above 9 V since the photoexcited tunneling escape probability approaches unity at these high fields. A more complete theory (solid curve in the figure) which includes infrared photoelectron initiated impact ionization of carriers out of the doped quantum wells[3,4] is in excellent agreement with the data and quantitatively explains the responsivity increase of 300% from 9-12 V, and the large measured value of R = 7 A/W at 12 V bias. The responsivity of these GaAs/$Al_xGa_{1-x}As$ superlattice detectors at λ = 10 μm is comparable to that of HgCdTe alloys and has the advantages of a more advanced technology, a narrow bandwidth $\Delta\lambda/\lambda$ = 10% and importantly the wavelength of operation can be readily tuned from less than 5 μm to over 100 μm by simply changing the superlattice parameters (i.e., the well widths and barrier heights).



Responsivity vs bias from 6 to 12 V (measured at T = 20° K); the circles are the measured values, while the dashed (solid) curves are theory ignoring (including) far infrared initiated impact ionization of carriers out of the wells.

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Transport study on $Si/Si_{1-x}Ge_x$ superlattices selectively doped by secondary implantation of Sb

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Strained layer superlattices made of lattice mismatched semiconductor materials offer possibilities of tailoring bandgaps and band offsets by strain adjustment. This has been demonstrated impressively for $Si/Si_{1-x}Ge_x$ superlattices and heterostructures, grown by molecular beam epitaxy. The built-in strain leads to a split-off of the sixfold degeneracy of the conduction band minima and influences dominantly band ordering.

However, the full electronic potential of these structures becomes accessible only by methods which allow selective doping in a range comparable to the superlattice period length. Particularly doping by secondary implantation has been found to enable sharp and precisely localized structures. In the present study MBE grown $Si/Si_{1-x}Ge_x$ heterostructures have been selectively doped by secondary implantation of Sb. Transport properties and dopant concentrations are determined by Hall measurements and secondary ion mass spectrometry, respectively. The results demonstrate that

(i) full dopant activation is achieved.

(ii) room temperature electron mobility of selectively doped $Si/Si_{1-x}Ge_x$ superlattices is considerably enhanced compared to equally doped Si bulk material. As confirmed by Shubnikov de-Haas measurements this is due to the formation of a twodimensional electron gas.

(iii) electron transport properties are dominantly influenced by the strain adjustment within the layers.

These unique properties of selectively doped $Si/Si_{1-x}Ge_x$ strained layer heterostructures open new facilities for novel electronic devices.

Abstract pending

Novel Quantum Well Optical Devices

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This talk will review some of our recent work on novel quantum well (QW) optical devices based on quantum-confined Stark effect (QCSE) electroabsorption. The QCSE is seen for electric fields perpendicular to the QW layers, and it is physically now well understood,[1] with good quantitative agreement with experiment for both GaAs/AlGaAs and recently also InGaAs/InP QWs [2] that are compatible with long-wavelength optical communications. The flexibility of the layered growth technique has also made possible a variety of novel and sophisticated QCSE device structures. Recently we have demonstrated a high-contrast waveguide modulator based on pairs of coupled wells,[3] demonstrating the potential of electroabsorption in non-rectangular QW structures. We have also used the epitaxial growth to construct an integral multilayer dielectric mirror, giving a reflecting modulator.[4]

In the so-called self-electro-optic effect devices (SEEDs), the QCSE modulation is combined with photodetection to make devices that can operate with both optical inputs and outputs. Such devices become particularly attractive if they can be integrated so that they have no electrical parasitics, allowing scaling to small, efficient devices. Using a $\sim$2500 layer structure $\sim 6\mu$m thick, we demonstrated such an integrated SEED.[5] It can operate as an optically-bistable device, and very uniform, fully-functional 2×2 and recently 6×6 arrays can be made with good yields. This device can also be used as a spatial light modulator, and as a self-refreshing optical dynamic memory.[6] Another recent development has been the symmetric SEED that can operate as a set-reset latch, and can also show time-sequential optical signal gain.[7]

These developments show the potential of QW structures for practical optical devices with characteristics that can be tailored to the application, and represent only the begining of a family of novel opto-electronic devices.

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Electrical properties of p-type and n-type ZnSe-ZnTe strained-layer superlattices

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ZnSe and ZnTe are semiconducting materials ideally suited for the fabrication of short wavelength light emitting devices. The realization of this potential hinges on obtaining low-resistivity material of controlled conduction type, carrier density, and carrier mobility. Superlattice structures using these materials, and introduction of modulation doping technique may prove to be a good technique to fabricate p-n junctions from wide-gap II-VI compounds semiconductor materials.

ZnSe-ZnTe strained-layer superlattices (SLSs) were grown on InP substrates by MBE. Two kinds of modulation doped SLS samples were prepared in this study. One of them consisted of Ga-doped ZnSe layers and non-doped ZnTe layers. The other consisted of non-doped ZnSe layers and Sb-doped ZnTe layers. The van der Pauw measurements of the SLS samples at room temperature showed that their electrical properties could be controlled by using modulation doping technique. A sample without modulation doping exhibited n-type conduction, an electron mobility of $760cm^2/Vs$ and an electron concentration of $3.6x10^{13}/cm^3$. When Ga was modulation doped in the SLSs, n-type conduction was observed. The electron mobility then varied from $230cm^2/Vs$ to $750cm^2/Vs$, and electron concentration from $2.7x10^{13}/cm^3$ to $7.3x10^{13}/cm^3$, respectively, as the Ga cell temperature varied from 170°C to 320°C. On the other hand, modulation doping with Sb resulted in p-type conduction. In this case, the hole mobility varied from $130cm^2/Vs$ to $220cm^2/Vs$, and the hole concentration from $5.1x10^{13}/cm^3$ to $9.2x10^{13}/cm^3$, respectively, as the Sb cell temperature varied from 400°C to 450°C. Then, temperature dependence of the electrical properties was measured for a modulation doped sample with Sb. The hole concentration increased with temperature, however, the hole mobility did not change drastically.

These results serve as a major step toward the realization of p-n junctions from wide bandgap II-VI semiconductor materials using strained-layer superlattice structures.

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DIRECT IMAGING OF THE COLUMNAR STRUCTURE OF GaAs QUANTUM WELLS

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Direct images of growth islands differing by 2.8 Å (one monolayer) height at GaAs/AlGaAs heterointerfaces and of the columnar structure of quantum wells are reported for the first time. The structures are grown by MBE with interruptions of the growth of ≈2 min at the interfaces. The novel method used to obtain these images is scanning cathodoluminescence. The dependence of the lateral extension of these islands on growth conditions is investigated. For fixed growth rate $r_s \approx 0.5$ monolayer/s the mean island size decreases from 6 -7 µm upon an increase of growth temperature from T_g = 600° C to 660° C. Apparently the growth process changes from a planar to a three-dimensional one. For low growth temperature and rate the lateral extension of such islands can be larger than the carrier diffusion length. Under these conditions inter-island thermalization of carriers is largely suppressed. Time resolved cathodoluminescence images directly visualize the extent of thermalization.

EXAFS Studies of the Microstructure of Semiconductor Alloys, Defects, and Semiconductor-Metal Interfaces.*

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The Extended X-ray Absorption Fine Structure (EXAFS) technique is an extremely useful probe of local atomic-scale structure, revealing bond lengths, types and number of neighbors, and vibronic motion of atoms. Further, this information is available for the various constituent atomic species separately. The technique is applicable to micro-crystalline materials, amorphous or glassy materials, or disordered alloys.

Here, we show the applications of EXAFS to the study of disordered semiconductor alloys and to semiconductor surfaces and interfaces. We will present EXAFS results on four quite different systems:

First, we show bond lengths are essentially constant as a function of composition x in the dilute magnetic semiconductor $Zn_{1-x}Mn_xSe$, where the lattice constant changes by over 0.1Å and the alloy undergoes a zincblende-to-wurtzite transition as a function of composition. This result implies a large local distortion in the alloy structure.

In the second example, we show that the local alloy disorder in the IV-VI alloy $Pb_{1-x}Ge_xTe$ is enough to induce a ferroelectric phase transition. The EXAFS results strongly imply that the transition is precipitated by an order-disorder transition of off-center Ge^{+2} ions in the lattice.

The third example concerns Fe-implanted in Si. Using EXAFS, we show that the lattice expands in a breathing-mode distortion about the Fe, while the second-shell actually contracts.

Finally, we show that by using total external reflection of x-rays and EXAFS, we may study buried interfaces such as the Al-GaAs interface.

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Lattice strain in heteroepitaxial films

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Lattice strain in heteroepitaxial films will be discussed in this paper. There are two dominant causes for the lattice strain in heteroepitaxial films. One is the lattice misfit between the epilayer and the substrate. The lattice strain due to the lattice misfit is caused as a result of the matching in the in-plane lattice constant at the heterointerface. However, dislocations will be induced in the epitaxial films when the film thickness exceeds a critical thickness and the misfit strain will be relaxed as the film thickness exceeds the critical thickness. The other is the difference in thermal expansion coefficients of the epilayer and the substrate. The thermal stress has been investigated in terms of the bimetallic strip model and becomes dominant after the misfit stress is relaxed by the introduction of dislocations. There are four cases of the relations between the lattice parameter and the thermal expansion coefficient of the epilayer and the substrate. These include: (1) $a_e > a_s$, and $\alpha_e > \alpha_s$, (2) $a_e > a_s$, and $\alpha_e < \alpha_s$, (3) $a_e < a_s$, and $\alpha_e > \alpha_s$, (4) $a_e < a_s$, and $\alpha_e < \alpha_s$. A model calculation has been done for each of these four cases and the residual lattice strain is calculated as a function of the film thickness. The residual lattice strain in heteroepitaxial systems of InGaAs/GaAs, ZnSe/GaAs, and GaAs/Si is measured by the X-ray diffraction technique for various thicknesses. We discuss the lattice strain in terms of the model described above and obtain at least qualitative agreement between the measured lattice strain and the calculation. Furtheremore, we discuss the influence of the lattice strain on the energy band structure in the heteroepitaxial systems.

MBE Growth of HgTe/CdTe Superlattices on Si(100) Substrates

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ABSTRACT

MBE growth of $Hg_{1-x}Cd_xTe$ alloys and HgTe/CdTe superlattices are of great interest because of their potential applications in infrared imaging systems and fiber optical communication devices. Recently, there has been a great deal of interest in growing $Hg_{1-x}Cd_xTe$ alloys and HgTe/CdTe superlattices on foreign substrates such as GaAs, InSb and sapphire. An epitaxial layer of $Hg_{1-x}Cd_xTe$ alloys or HgTe/CdTe superlattices on silicon could provide the basis for a monolithic focal plane array with the signal processing devices fabricated on the silicon. In this paper, we report MBE growth of HgTe/CdTe superlattices on Si(100) substrates. About 3 μm of GaAs as the first buffer layer was deposited on silicon (100) substrate in the III-V MBE system. Then the sample was moved to the II-VI MBE system for a 0.5 μm of CdTe deposition as the second buffer layer prior to the HgTe/CdTe superlattice growth. One hundred and fifty periods of HgTe(33 Å)/CdTe(78 Å) superlattices were grown at 175°C. RHEED pattern was observed during the superlattice growth. Infrared photoluminescence measurements showed luminescence signals occurred at 2000 cm^{-1}. A comparison of HgTe/CdTe superlattices grown on CdTe(111) and (100) substrates will be made. In addition, structural and electrical properties will be discussed.

Growth of high quality $CoSi_2$/Si - superstructures on Si(111)

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The growth of epitaxial films of $CoSi_2$ on Si (111) with excellent crystallinity has been demonstrated by a number of workers in the past few years [1]. Films with a thickness of the order of 100 Å or less (usually grown by solid phase epitaxy) seemed, however, to be always characterized by an extraordinary large density of pinholes (typically $10^6/cm^2$). We have now for the first time been able to grow $CoSi_2$ - layers as thin as 30 Å with a detectable pinhole density of essentially zero. This has been achieved by a modified solid phase epitaxy (SPE) technique, in which Co and Si are coevaporated near room temperature, followed by an anneal up to typically 450°C. We have found the complete elimination of pinholes to be rigorously required for the subsequent overgrowth of untwinned Si. Whereas the silicide is well known to grow with type B orientation (rotated by 180 degrees about the surface normal) on Si(111), the overgrown silicon can unambiguously be shown to have the same orientation as the underlying $CoSi_2$ (type A orientation). Hence, Si on top of $CoSi_2$ is rotated with respect to the Si substrate. This explains the mixed type A and B grains obtained by other authors [2] on a silicide containing pinholes.

Using a combination of SPE and MBE $CoSi_2$/Si superlattices with periods as small as 70 Å have successfully been grown.

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PHONONS IN SEMICONDUCTOR SUPERLATTICES

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The phonon spectra of semiconductor superlattices along the growth direction are calculated using a new approach which provides realistic dispersions and displacement patterns for both acoustical and optical modes at the same time. The method is based on an exact mapping to one dimension of the full three-dimensional problem. The difference in lattice dynamics of the two components is shown to be accurately described by keeping the same interactions and by assigning masses and effective charges appropriate to each material ("mass and charge approximation"). The interfaces are then simply treated as changes localized on the atomic planes and not affecting the interactions between planes. We are then in a position to use a realistic description of the bonding - based on an ab-initio determination of the bulk interplanar force constants - without loosing the conceptual and computational simplicity of a linear chain formalism.

We show results for GaAs/AlAs, InAs/GaSb and Si/Ge (001) superlattices, with particular emphasis on the following features: i) longitudinal (L) and transverse (T) optical (O) modes: in InAs/GaSb and Si/Ge a confined behaviour of LO modes in each material - similar to what appens in GaAs/AlAs - is predicted also at frequencies which are allowed for both bulk components, where the displacements extend to the whole superlattice; for GaAs/AlAs we discuss how the confinement depends on the layer thicknesses and on the polarization of the modes; ii) interface modes of microscopic origin: in InAs/GaSb they are predicted both in the L and T polarizations, with energy (and Raman strength) crucially dependent on the nature of the interface (In-Sb or Ga-As); in Si/Ge they are expected to arise in the T case, at frequencies between the bulk TO branches of Si and Ge; iii) acoustic (A) modes: confinement of TA modes is predicted in the region between the edges of the TA bulk branches of the two components for GaAs/AlAs and Si/Ge; moreover in the LA and TA region of Si/Ge the very different sound velocities of the two components for some layer thickness cause some of the zone-center or zone-edge acoustical floded doublets to come together showing unusually small splittings.

Finally the one-dimensional character of the method allows us to treat superlattices with a great total number of atomic planes: preliminary results will be presented for superlattices with surfaces and for superlattices with non-periodic distributions of layer thicknesses (disordered and quasi-periodic).

MONTE CARLO SIMULATIONS OF FEMTOSECOND RELAXATION OF PHOTOEXCITED ELECTRONS IN AlGaAs/GaAs QUANTUM WELLS

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The development of femtosecond lasers has enabled the study of ultrafast energy relaxation processes in semiconductors. In this paper we compare the results of ensemble Monte Carlo simulations of the femtosecond energy relaxation of electrons photoexcited with a 2 eV laser in AlGaAs/GaAs quantum well structures at room temperature with that of bulk GaAs. The simulations include self-consistent two-dimensional numerical eigenfunctions for up to five electron subbands, take into account Pauli exclusion, and electron-electron, electron-phonon and electron-ionized impurity scattering.

We find a short ($\sim$ 45 fs) relaxation component in both bulk and quantum wells due to electron-electron and Γ-L intervalley scattering as previously suggested [1]. The simulations indicate that Γ-L scattering is the dominant process.

We also find an intermediate ($\sim$ 160 fs) relaxation component associated with polar optical phonon scattering in bulk GaAs, but not in the quantum well structures. The lack of this component in the quantum well is basically due to the spread in the initial photoexcited electron energy distribution. Because of valence subband mixing away from the band edge, the $\Delta n = 0$ selection rule is no longer valid. This leads to transitions from several of the hole subbands to each electron subband creating an initial electron distribution which is very broad in energy relative to the distribution in bulk. This broad distribution effectively suppresses the intermediate time component because most of the electrons which scatter with an optic phonon still remain within the optically coupled region (OCR), and also because electrons that scatter back into the Γ valley from the L valley are still within the OCR. These results are in agreement with the experimental data of Rosker *et al* [1]

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Electron–Phonon Interactions in $In_{0.53}Ga_{0.47}As$ and in $In_{0.53}Ga_{0.47}As$/InP Quantum Wells

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We present studies of the longitudinal optic (LO) phonon sideband 'X_{LO}' of the low–temperature exciton photoluminescence (PL) line 'X' in (In,Ga)As/InP quantum wells (QWs). We have extended the theory of LO phonon satellites[1] to this multi–mode low–dimensional system.

Electron–phonon interactions in the bulk alloy $In_{0.53}Ga_{0.47}As$ are considered. We discuss the Fröhlich interaction and the Lyddane–Sachs–Teller splittings of the optic modes of 'mixed crystals'. We describe the existing theory of these properties, and the experimental results for $In_{0.53}Ga_{0.47}As$, including our own studies of phonon satellites of recombination in QWs. The Fröhlich interaction is much weaker for the lower–energy LO modes (labelled 'InAs–like') than for the higher–energy LO modes ('GaAs–like'), due to electrostatic coupling of the LO distortions, which causes the lower–energy modes to have a much smaller macroscopic electric field than the higher–energy modes.

The phonon sideband X_{LO} of recombination in (In,Ga)As/InP QWs consists of separate lines arising from LO modes of the InP and 'GaAs–like' and 'InAs–like' LO modes of the (In,Ga)As. We calculate the intensity of each phonon satellite, taking account of the contribution of interface modes. Experimental results have been obtained for (In,Ga)As/InP QWs grown by molecular beam epitaxy (MBE) with well widths from 10Å to 110Å. The satellite spectrum is dominated for the wider wells by the 'GaAs–like' modes of the (In,Ga)As, and for the narrower wells by the InP modes. The weakness of the 'InAs–like' phonon satellite compared to the 'GaAs–like' satellite is accounted for by the theory mentioned above for the Fröhlich interaction in a mixed crystal. The strength of coupling to well and barrier phonons is interpreted in terms of the charge density, as a function of well width, of a bound exciton formed from the lowest electron and heavy–hole subbands in each QW.

In QWs grown by atmospheric–pressure metal–organic chemical vapour deposition (MOCVD), the LO phonon satellites are much stronger than in MBE QWs, with up to 5% of the intensity of the zero–phonon luminescence. This result, together with the large electron diamagnetic shift, shows that the hole is bound within a radius 10Å to 30Å. It is proposed that the hole is bound by alloy fluctuations in the $In_{0.53}Ga_{0.47}As$.

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Electronic Structure of Quantum-Well States Revealed Under High Pressures

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High pressure has become a powerful tool in electronic structure of semiconductors. In the bulk, band states formed from the periodic atomic potential and bound states formed from isolated potentials have been shown to depend, often sensitively, on pressure-induced changes in interatomic distance. And since in multi-valley semiconductors, both free and localized states may contain momentum values from across the reduced zone, pressure has become particularly useful in revealing secondary electronic structure and inducing "mixing" between states of differing k-value.

We have extended such studies, focussing on electronic and optical properties under pressure, from the bulk to two dimensions, using isolated quantum wells and superlattices. Sample systems consisting of undoped GaAs and $Al_xGa_{1-x}As$ have been studied at low temperatures, versus x (0 - 1), layer thickness (15 - 200 Å), and hydrostatic pressure (1 - 100 kbar) using photoluminescence (PL), PL-excitation, and fast time-resolved PL (> 200 psec), together with full-scale pseudopotential simulation of the electronic structure. Complete and accurate description has been obtained of the electronic and optical properties of these structures in all interesting ranges of energy, taking into account the complete multi-valley band structure and heterojunction band offsets of the hosts.

Spatially quantized electron states formed from both the principal direct-gap Γ band and the subsidiary indirect-gap X bands have been observed experimentally and modelled theoretically. Arising from valence-band offset-induced staggered band alignment, the X-related electron bound states are located within the $Al_xGa_{1-x}As$ and optical transitions occur across both k-space and the semiconductor interface with holes localized within the GaAs. Critical pressures for observation of these new X-electron bound states decrease with increasing x and decreasing well width. We thus obtain, with meV resolution, direct optical measure of the $GaAs/Al_xGa_{1-x}As$ band offsets, giving $\Delta E_V \sim (0.32 \pm 0.02)\Delta E_g$ across the alloy system.

Using pressure we have also examined the intervalley "mixing" (i.e., short wavelength scattering processes) connecting the quantized electron states of differing k-value, but identical symmetry, as crossings between them are induced. Energy levels, transition energies and intensities, radiative lifetimes, level perturbations (anticrossings), matrix elements, and oscillator strengths have been obtained with good agreement between experiment and theory. We show that coupling between the familiar zone-center quantum-well states and the new zone-edge states revealed under pressure is significant and observable, and must be taken into account for full description of quantum-well states. Further, we show that these intervalley mixings become increasingly pronounced as well widths become narrow. We thus find that with increasing spatial localization caused by quantum confinement, wavefunctions spread reciprocally in k-space to involve subsidiary band structure.

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Electron-hole correlation singularity in optical spectra of modulation doped GaAs-$Al_xGa_{1-x}As$ quantum wells

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Modulation doped quantum wells are characterized by the presence of a highly mobile, quasi two-dimensional electron or hole gas, which makes them most interesting both for devices and fundamental physics. We report here temperature dependent absorption and luminescence spectra of n-modulation doped multiple quantum wells of GaAs-$Al_xGa_{1-x}As$. The underlining structure of the absorption spectra at low temperatures is qualitatively similar to those of the undoped quantum wells, allowing us to identify transitions corresponding to n=2 and 3. However, the low energy peak behaves very differently. It is blue shifted with respect to the luminescence and exhibits a strong temperature dependence. As temperature is increased from 10K to 80K, this peak becomes lower and broader, in marked contrast to the behavior of the n=1 exciton in undoped quantum wells[1]. The blue shift decreases as the temperature is increased and at room temperature the luminescence practically coincides with the onset of the absorption.

Since at these high carrier densities ($\sim 3.5 \times 10^{11} cm^{-2}$) conventional excitons cease to exist, many body effects must be invoked to explain the spectra. Recently[2], it has been predicted theoretically, including the effects of exchange and screened Coulomb potential, that an electron-hole correlation singularity peak should exist at energies close to the chemical potential, $\mu(T)$, because of the correlation of the photoexcited hole with the sea of electrons. It also has been predicted that the peak should broaden and decrease with temperature. Our spectra confirm this behavior in the temperature range studied. The blue shift we are measuring nicely follows the temperature dependence $\mu(T)$. We are able to calculate the temperature dependence of the lineshape of the first peak, which qualitatively agrees with our experimental findings. Comparing the temperature dependence of the various transitions energies, we conclude that the band gap renormalization is changing with temperature, and that it is different for different subbands.

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MAGNETO-OPTICAL STUDIES OF GaInAs-InP QUANTUM WELLS

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We have performed a study of the optical properties of a series of $Ga_{0.47}In_{0.53}As$-InP quantum wells grown by Atmospheric Pressure Metal Organic Chemical Vapour Deposition (AP-MOCVD) in magnetic fields from 0 to 16 T. Both single (SQW) and multiple quantum well (MQW) samples have been studied with well widths from 50 Å to 200 Å and sheet electron concentrations of zero to $N_s = 10^{12}$ cm^{-2}.

A comparison of low temperature Photoluminescence (P.L) and Photoconductivity (P.C) spectra in magnetic fields up to 9.5T shows the existence of a Stokes' shift between features in PL and PC, indicating that the hole states associated with the PL recombination are localised, probably at fluctuations in the alloy composition of the well material. The observation of the Stokes' shift in a highly doped sample having $N_s = 10^{12}$ cm^{-2} shows that this hole localisation is not screened out by the high electron density. In addition, a measurement of the diamagnetic shift for the ground state of the HH1-E1 exciton in a 100 Å MQW shows a larger value in PC than PL, providing further evidence for a localised hole state observed in the PL.

In transmission measurements performed on a series of undoped MQWs in magnetic fields from 0 to 16 T, we observe Landau level transitions with Landau indices up to $l = 16$, originating from the first heavy hole to electron (HH1-E1) transition and indicating the very high quality of the samples. Theoretical fits to the experimental data allow us to deduce values for the exciton binding energies, in-plane electron and heavy hole masses and electron non-parabolicity factor.

a-Si:H/a-SiN$_x$:H SUPERLATTICES : CONFINEMENT OR CONTAMINATION

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Changes in the optical and electronic properties of the a-Si:H/a-SiN$_x$:H superlattices are commonly observed when the a-Si:H sublayer thickness(d_{Si}) is reduced below $\sim$40 Å. However, there is not yet a clear evidence for quantum confinement effects in these structures(1-4). In this work, photothermal deflection spectroscopy(PDS) and infrared photoluminescence excitation($h\nu$ < 1.5 eV) are used to study in detail the size effects in the plasma deposited a-Si:H/a-SiN$_x$:H superlattices(x=1.1) with d_{Si} as small as 11 Å. Thickness induced changes in the band gap(determined by transmittance technique), Urbach energy and defect density are observed for d_{Si}<30 Å and the results are analysed in order to clarify the origin of the effects. It is found that despite of the explanation of the blue shift in the band gap by a Kronig-Penney model, the results suggest that the variations in the optical parameters may instead be due to the nitrogen contamination of the quantum well layer. The properties of these amorphous superlattices are compared with those of hydrogen rich a-Si:H deposited at low temperatures and a-SiN$_x$:H alloys(0 < x < 1.1) contaminated deliberatly by nitrogen. Also, new ir-excitation results in the same structures will be reported and discussed in terms of the size effects.

In addition the first double beam photoluminescence measurements on these modulated structures are presented.

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Extended and local plasmons in a lateral superlattice

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Si-metal-oxide-semiconductor (MOS) structures have been prepared with a periodically varying oxide thickness. Via a continuous gate the originally two-dimensional (2D) charge density N_s is spatially modulated $N_s = N_s(x)$. It is $N_{s1} = \epsilon\frac{(V_g - V_t)}{ed_1}$ in the region t_1 with oxide thickness d_1 and $N_{s2} = \epsilon\frac{(V_g - V_t)}{ed_2}$ for the rest of the period $t_2 = a - t_1$ (periodicity $a \approx 500nm$,V_g =gate voltage, V_t=threshold voltage). For the investigations discussed here we have prepared samples where the region t_2 of high density N_{s2} is about 3 to 4 times larger than the lower density region t_1. Using far infrared spectroscopy we have studied the excitation of " 2D " plasmons propagating perpendicular to the grating grooves of the microstructure. For small plasmon wavevectors $q = 2\pi/a$, where the plasmon oscillation extends over several superlattice periods, we observe, similarily as in Ref. [1], mini gaps in the plasmon dispersion due to the superlattice effect of the periodical charge density modulation. For this q the plasmon frequency is governed by the avaraged charge density $\overline{N_s} = N_{s1}t_1/a + N_{s2}t_2/a$. For higher wave vectors ($q \geq 4(2\pi/a)$) the plasmon frequency increases significantly stronger with q than expected from the classical $\sqrt{q}$ dependence for the plasmon frequency of a 2D-electronic system. We will discuss that this indicates that the plasmons become the local modes of parts of the superlattice period, i.e., of the regime t_2 of the high electron density N_{s2}.

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Abstract pending

Hot Electrons in Silicon Dioxide :

Ballistic to Steady-State Transport.

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Hot electron transport in silicon dioxide is examined with emphasis on current experimental and theoretical results. For oxide layers thicker than 100 Å, steady-state transport has been shown to control the carrier flow at all fields studied. The steady-state transition from a nearly thermal electron distribution at electric fields less than approximately 1.5 MV/cm to significantly hot distributions with average energies between 2 and 6 eV at higher fields of up to 16 MV/cm is discussed. The significance of non-polar phonon scattering in controlling the dispersive transport at higher electric fields, thereby preventing run-away and avalanche breakdown, is reviewed. With very thin oxides, total ballistic transport of the electrons is observed for voltages of $\lesssim 1$ V dropped across the remaining oxide portion after tunneling. For voltage drops of > 1 V, a transition from the ballistic to the steady-state regime is seen. Monte-Carlo simulations are used to predict the observed experimental behavior including quantum mechanical interference effects and phonon-induced side bands in the electron distribution. This latter effect is the first direct observation in any material of the interaction of ballistic electrons with single phonons of the lattice.

The Theory of Electron-Polar Phonon Scattering Rates in Semiconductor Micro-structures

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The scattering of electrons by the optical phonon modes in polar semiconductors is the most important energy loss mechanism for an electron gas at temperatures above 100K. This polar interaction is effectively stronger when the electrons are confined in narrow wells than it is in the bulk, making the study of the electron-phonon interaction of even greater importance in quasi-two-dimensional electron systems. The effects of confinement, screening, and electronic degeneracy can cause significant qualitative and quantitative changes in the electronic scattering rates. In this talk, a many-body method of calculating the scattering rate is presented which can include the effects of degeneracy, screening, temperature and well size and shape. Both phonon absorption and emission rates are obtained explicitly by this method. It is found that the inclusion of the quantum well size and shape and electronic population and degeneracy are vital for accurate calculations. Results are presented to show the effects of various parameters (temperature, electron density, etc.) on the scattering rates. These results will be discussed with consideration of their implications for experimental systems.

ABSTRACT SUBMITTED
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Direct measurement of ultrafast electron-hole plasma expansion at high density in an asymmetric GaAs quantum well--Kai Shum, M. R. Junnarkar, H. S. Chao, and R. R. Alfano, **Institute for Ultrafast Spectroscopy and Lasers, Physics and Electrical Engineering Departments, The City College of New York,** and H. Morkoc, **University of Illinois**--The ultrafast spatial expansion of photoexcited electron-hole plasma created by a femtosecond laser pulse excitation in an asymmetric GaAs single quantum well at 4.3K was directly measured using a 3ps time resolution streak camera system. The experimental results show that the diffusion D is four orders of magnitude larger than the conventional ambipolar diffusivity (about 10^6cm/sec) and the ballistic velocity of the plasma is about four times larger than its Fermi-velocity. The mechanism which causes the photoexcited carriers to be so diffusive will be discussed.

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VERTICAL ELECTRONIC TRANSPORT IN NOVEL SEMICONDUCTOR HETEROJUNCTION STRUCTURES*

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The investigation of vertical transport in semiconductor heterojunction systems has recently undergone a renaissance due to improved epitaxial techniques in a number of material systems. These systems are suitable for electronic spectroscopy (using techniques such as resonant tunneling through single quantum well / double barrier structures) to determine the band structure, effective masses, and space charge layers of the heterojunction system. In this paper, we present investigations in a number of novel bandgap engineered structures, devices, and material systems. For example, one of the intriguing systems investigated is a multi-component resonant tunneling structure consisting of a GaAs contact - AlGaAs barrier - InGaAs quantum well structure. In this structure, the high electron affinity of the quantum well creates a "deep" quantum well, in which we demonstrate that quantum well states can be hidden from transport. The high field magnetotransport measurements of these structures yields an anomolously small effective mass of electrons tunneling through the quantum well, which is resolved by a correct modeling of the structure involving the space charge layers of the structure. We also present results of vertical transport in a semiconductor - semimetal system, HgCdTe/HgTe, where the physics of this heterojunction system is distinctly different from that of the now familiar GaAs/AlGaAs system. Analysis of transport through various multilayer structures verifies the existence of the proposed intrinsic interface state model and allows for an accurate determination of the bandstructure, specifically the valence band offset, which is found to be approximately 0 meV.

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RECENT APPLICATIONS OF MONTE CARLO METHODS FOR SEMICONDUCTOR MICRODEVICE SIMULATION

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Ensemble Monte Carlo (EMC) calculations offer probably the most accurate tool for the investigation of the behavior of submicron devices, since nonlinear hot electrons effects are naturally included and, due to the stochastic nature of the method, no assumptions are needed for the particle distribution function. EMC techniques are however extremely time consuming and the available computational resources are mainly limiting their applications. The introduction of supercomputers allows an enormous speed-up in the calculations, however, this option is still very expensive and standard EMC codes need to be redesigned since they do not exploit efficiently the vector or parallel computing capability of supercomputers. At the same time there is still considerable need of fast converging device simulation codes with much simpler schemes than Monte Carlo, to be used in optimization procedures. This talk will present some new techniques which address the vectorization of EMC programs, and the extension of EMC calculations to include overshoot effects in more conventional drift-diffusion simulations.

The main problem in the vectorization of a standard EMC code lies in the fact that the particles in the ensemble must be followed in parallel during their free-flights between two consecutive scattering events. Due to the random nature of the free-flight times, the particles will always be in an after-scattering state at widely different times for realistic device simulations. This is not desirable for the averaging procedures and for the solution of Poisson's equation, and extra bookkeeping is therefore needed in the codes. A new technique proposed makes the flight times identical, randomizing the self-scattering rate for each scattering event and without altering the correct statistics of the flight durations. While for optimization of conventional EMC codes the reduction or elimination of self-scattering is desired, since it requires unnecessary computation, for this vectorizing technique the self-scattering becomes a useful adjusting tool and the additional computational work required becomes a little disadvantage when a vector-efficient algorithm can be achieved.

It is also possible to use EMC methods to calculate field dependent coefficients in extended drift-diffusion equations with extra terms including overshoot effects, at least at first order. Such equations could allow the extension of traditional drift-diffusion schemes to submicron structures with little modifications, provided that an accurate calibration of the additional terms is done with precise EMC calculations. The problems generated by stochastic fluctuations in such EMC calculations will be presented, along with preliminary results.

Resonant Tunneling in InGaAs-InP double-barrier structures and superlattices.

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In the last few years, there have been a great deal of renewed interest in the vertical, tunneling transport in double-barrier tunneling structures (DBTS), which have been shown to be possible microwave oscillators. To date, most of the work on DBTS have been carried out using GaAs-AlGaAs structures because of the excellent control in both the growth and the device processing of this system. We present the first study of DBTS of the $In_{0.53}Ga_{0.47}As$-InP system, which is an important one in optoelectronics. Our samples were grown by Chemical Beam Epitaxy (CBE). The first devices fabricated using the usual mesa-etching procedure showed a large non-tunneling current which we ascribe to surface leakage current at the sides of the mesas, since this has often been a problem with similar devices of this system. By additional mesa-etching which selectively etch the InGaAs layer faster than the InP layer, the surface leakage current was greatly reduced, and the characteristic current peaks associated with resonant tunneling became well developed. The maximum peak-to-valley ratio observed for selectively-etched devices was 3.1 at 4.2K, while for the devices not selectively-etched it is only 1.1 . The voltage values at the resonances are in fair agreement with theoretical predictions. The transport properties of the InGaAs-InP DBTS show interesting differences with those of the GaAs -AlGaAs system, of which the most remarkable is the symmetry about zero bias voltage in the former devices. In the latter system, the asymmetry has been ascribed to the problem of the inverted interface and to the different doping of the two electrodes. These results will be discussed with preliminary results related to the vertical transport in superlattices of the InGaAs-InP system.

Excellent Negative Differential Resistance of InGaAs/InAlAs Resonant Tunneling Barrier Structures and Applications to a New Functional Device, RHET

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Since the first proposal of negative differential resistance (NDR) for GaAs-AlGaAs resonant tunneling barrier (RTB) structures by Tsu and Esaki in 1973, extensive study of NDR has followed, mainly based on for GaAs-AlGaAs RTB structures. NDR characteristics of a GaAs-AlGaAs RTB structure, however, is still unsatisfactory for practical device applications. Recently, we have achieved excellent NDR characteristics using an InGaAs/InAlAs RTB structure, lattice-matched to an InP substrate, grown by MBE, which opened the door to the development of a new functional device, RHET (resonant tunneling hot electron transistor), with practical high-speed performance capability.

InGaAs/InAlAs RTB structures, which have an InGaAs well layer (44-61.5 Å thick) sandwiched between two InAlAs barrier layers (41 Å), are grown on (100)-oriented n^+-InP substrates at 470 °C by MBE. We obtained the best NDR characteristics ever reported for any RTB structure (a peak-to-valley current ratio of 11.4 with a peak current density of 6.3×10^4 A/cm^2 at 77K) using the InGaAs/InAlAs RTB with a 44 Å well layer.

The RHET is a new, vertical-transport device, first developed by our group in 1985. It has a GaAs-AlGaAs RTB structure as an emitter barrier and exhibits several new functional characteristics, such as frequency-multiplier, Exclusive-NOR logic and memory, due to the NDR characteristics of the RTB emitter barrier. A GaAs-AlGaAs RHET, however, has serious limitations for improving device characteristics because of the intrinsic properties of the material. Very recently, we developed an InGaAs/In(GaAl)As RHET, lattice-matched to InP. A heterostructure for the InGaAs/In(GaAl)As RHET, which has an InGaAs/InAlAs RTB as an emitter barrier, a 250 Å-thick InGaAs base layer and a quaternary In(GaAl)As collector barrier (2000 Å), has been grown by the pulsed molecular beam method. A current gain as high as 28 has been obtained at a collector voltage of 1.6 V and a base current of 0.2 mA in the common-emitter configuration at 77K. This is not only about five times as large as the current gain of a corresponding GaAs/AlGaAs RHET, but is also the best data ever reported for any RHET.

This work (development of RHETs) was supported by MITI's Project of Basic Technology for Future Industries.

Non-Effective-Mass Matching in Superlattices

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An analytic theory for the matching of the bandstructure of different crystals at the interface of a heterojunction is presented. The Generalized Wannier functions serve as a basis. For a simple uniform band, the Hamiltonian matrix elements then reduce to the k-space Fourier coefficients of the bandstructure along the superlattice direction [1]. The technique therefore accounts for non-effective mass effects, and the lower and upper valleys, and enables us to invoke both the quasi-k-space periodicity together with the spatial variations of the bandstructure [2]. The superlattice Hamiltonian is a system of difference equations taking the form of a band matrix. A new definition of current not effective-mass based is introduced for this higher-order Schroedinger equation. The enforcement of current continuity leads to analytic connection rules for the overlap Hamiltonian matrix elements. The latter can be expressed in terms of a single ideality coefficient measuring the transparency of the heterojunction. A maximum transparency for all energies is achieved only for geometrically related bandstructures.

Non-effective-mass effects are demonstrated for the two-dimensional electron-gas and resonant-tunneling systems. Both systems involve self-consistent solutions of the band Hamiltonian and the Poisson equation.

The technique presented offers new theoretical insights together with efficient numerical tools for the study of non-effective-mass superlattices.

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INFLUENCE OF INTERFACES ON ELECTRONIC AND MAGNETIC PROPERTIES OF MnSe/ZnSe SUPERLATTICES NEAR MONOLAYER LIMIT

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The preparation of semiconductor superlattices in which layer thicknesses approach molecular monolayer limits presents a situation where effects of heterointerfaces can become a key factor in determining the physical properties of these artificial microstructures. A so far unexploited possibility is to use magnetic phenomena as a complement to conventional electronic probes for interface specific information. A potentially interesting material class in this connection are II-VI compounds with a transition metal element, notably Mn, as the isoelectronic cation. At low and moderate concentrations of Mn (say, less than 50% of the total cation concentration) the bulk growth of the alloys in single phase is possible and the magnetic properties of such so-called diluted magnetic semiconductors (DMS) have been the subject of much study. The development of advanced epitaxial preparation methods are now paving the way for microstructures at high concentration of the magnetic constituent. In particular, versatile superlattice structures based on the MnSe/ZnSe heteropair have been recently synthesized (1). An unusual aspect of this particular superlattice, grown on zincblende ZnSe epitaxial layers, is the opportunity to study electronic and magnetic properties of **zincblende** MnSe for the first time. Bulk grown MnSe, an **anti**ferromagnetic semiconductor, crystallizes in the NaCl structure. We report on direct magnetization and optical measurements on these 'metastable' superlattices with well defined electronic bandgaps which display strikingly large, nearly paramagnetic contributions to the susceptibility in structures containing ultrathin, highly strained MnSe layers near the 2D magnetic limit. The experimental results show dramatically the importance of real interfaces to magnetic properties which probe atomic arrangements on the scale of chemical bondlengths. Effective frustration of magnetic ordering is attributed to interfacial microstucture, very likely to to intrinsic reconstruction effects on a monolayer scale.

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Structural Studies of (Ga,In)(As,P) Alloys and $(InAs)_m(GaAs)_n$ Strained-Layer Superlattices by Fluorescence-Detected EXAFS

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Local structures of (Ga,In)(As,P) alloys and $(InAs)_m(GaAs)_n$ strained-layer superlattices have been studied *as grown* by fluorescence-detected extended X-ray absorption fine structure (EXAFS) using synchrotron radiation from the 2.5 GeV storage ring. Ga K- and As K-edge EXAFS data were Fourier-analyzed to obtain bondlengths. In (Ga,In)(As,P) quaternary allloys lattice-matched to InP, the deviation of bondlengths between cation (Ga,In) and anion (As,P) species from VCA (virtual crystal approximation) are more than three times larger than those from binary compounds and are nearly constant for a wide range in composition, indicating that the lattice relaxation is primarily due to *bond-bending*. The composition-weighted average bondlength determined from EXAFS results agreed well with the average inter-atomic distance based on X-ray diffraction data and VCA . On the other hand, a large amount of bond-stretching relaxation was found for the Ga-As distance (as much as 2.4 % increase) in $(InAs)_m(GaAs)_n$ strained-layer superlattices with m=6.45 and n=0.51 while the In-As distance showed no appreciable change on going from a binary compound to the strained-layer superlattices. These results suggest the existence of *bond-stretching* relaxation localized at the interface region between the two alternating layers. The difference in the local structure between random alloys and strained-layer superlattices will be discussed in this conference.

Type III – Type I Transition and Strain Effect in $Hg_{1-x}Cd_xTe$-CdTe and $Hg_{1-x}Zn_xTe$-CdTe Superlattices

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Since 1979, when the HgTe-CdTe superlattice (SL) was first proposed as a new infrared material significant theoretical and experimental attention has been given to the study of this new superlattice system. The interest in this SL system is due to the fact that the light particles of host materials have effective masses of opposite signs but the same band edge symmetry.

Most of the superlattices grown exhibit a n to p-type transition. We have carried out Hall measurements on several p-type superlattices. They exhibit high hole mobilities which cannot be explained in the framework of the current superlattice valence band structure. The change in sign of the effective mass at the interface implies that an interface state is formed which is localized at this interface. The hybridization of this interface state with the heavyhole subband leads to an unexpected subband structure which could contribute significantly to optical and transport properties in these microstructures. This peculiar band structure configuration leads to the conclusion that HgTe-CdTe SLs represent a new type of superlattice i.e., a Type III SL system. In order to investigate this high hole mobility problem, we have grown $Hg_{1-x}Cd_xTe$-CdTe and $Hg_{1-x}Zn_xTe$-CdTe superlattices in which the valence band structure is expected to change with x.

They have been characterized by electron and X-ray diffraction, infrared transmission and Hall measurements. The presence of satellite peaks in the X-ray spectra show the superlattices to be of high quality. Infrared transmission spectra show that $Hg_{1-x}Zn_xTe$-CdTe and $Hg_{1-x}Cd_xTe$-CdTe superlattices have narrower bandgaps than the equivalent alloys. These superlattices are p-type.

The investigation of $Hg_{1-x}Zn_xTe$-CdTe SLs for which the lattice parameter of $Hg_{1-x}Zn_xTe$ varies considerably with x, opens up a possibility for investigating effect of strain in this system. $Hg_{1-x}Zn_xTe$-CdTe SLs have been grown recently with x ranging from 0.06 to 0.15. In $Hg_{1-x}Zn_xTe$ the semimetal-semiconductor transition is not yet very well defined but it is expected to occur at 77 K for a zinc concentration between 0.10 and 0.12. A $Hg_{0.89}Zn_{0.11}Te$-CdTe SL shows a hole mobility of 20,000 $cm^2V^{-1}s^{-1}$ at 25 K, while that of $Hg_{0.98}Zn_{0.02}Te$-CdTe is only 5,000 $cm^2V^{-1}s^{-1}$. The observed increase in mobility with x might be related to strain. We are continuing to investigate this matter.

Hall measurements have shown that the hole mobility drops drastically between Type III and Type I. Thus, Hall characterization, along with magnetotransport experiments, seem to indicate that high hole mobilities observed in p-type HgTe-CdTe superlattices are due to some kind of relationship between the 2D heavy hole gas and the interface state existing in Type III superlattices.

Atomistic simulation of stability, metastability, and growth of strained layer structures†

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The potential importance of strained-layer heterostructures is, at this point, well established for both semiconductor and metal systems. It is clear from experiment that structures which are formally metastable, but which persist for long periods can be grown. The increase in strained-layer thickness and/or mismatch made possible by metastability is often of practical importance. It is therefore desirable to understand the material and growth factors which control the production of equilibrium and metastable strained-layer structures. A comprehensive program to study the structural energetics of semiconductor and metal strained-layer heterostructures has been in progress at Sandia for almost two years.

The thermodynamic stability of coherently strained overlayers in metal and semiconductor systems has been studied using Monte Carlo based microscopic techniques and accurate many-body empirical potentials. We find that earlier continuum models represent the asymptotic limit of our atomistic calculations for large film thickness, but that thin layers are generally less stable than predicted by the continuum models. This represents a transition from bulk-dominated to interface-dominated stability behavior. Metastability against nucleation of misfit dislocations in an initially perfect strained layer has also been investigated for semiconductors. The resulting metastability limits are much greater than the corresponding equilibrium stability limits, which agrees with experimental results in systems such as SiGe/Si and GaAs/InAs.

The growth of strained-layer heterostructures has been simulated for atoms interacting through a Lennard-Jones potential to study the influence of lattice mismatch and substrate temperature on vapor phase growth of mismatched systems. A molecular-dynamics technique is used to simulate the growth process. We find that, at substrate temperatures less than 50% of melting, epitaxial growth occurs for mismatch less than 4%, whereas above 4% mismatch, the overlayer is defective. This result agrees reasonably well with the stability calculations. At higher temperatures, interdiffusion occurs, and is accompanied by rapidly moving misfit dislocations, resulting in a pseudo-molten surface layer.

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Ordering Transitions of Ternary Alloys $A_{1-x}B_xC$

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Alloys of the form $A_{1-x}B_xC$ may form ordered structures for special values of the composition x. We investigate this possibility by considering alloys that have in their disordered high-temperature form the zincblende crystal structure. That is, we consider compounds that have a tetrahedral bonding of the type sp^3, e.g., alloys of III-V compounds, II-VI compounds (including the diluted magnetic semiconductors), and alloys that are mixtures of the natural chalcopyrites (e.g., II-IV-V_2 compounds such as $ZnGeAs_2$) with natural zincblende-structure materials.

Possible ordered forms of the alloys $A_{1-x}B_xC$ include, for x = 0.5, a superlattice structure of alternating layers ACBC oriented along the (001) axis, such as has been seen in the III-V compound $GaAlAs_2$. Alternatively, for x = 0.5, alloys $A_{1-x}B_xC$ may order in a low-temperature phase as a ABC_2 chalcopyrite structure, e.g., $ZnGeAs_2$. We address the question of the relative stabilities of the possible ordered and disordered phases of $A_{1-x}B_xC$ compounds by using the Kikuchi approximation. Our calculations include chemical energies as well as strain effects. We will show calculated phase diagrams that exhibit the ordered phases of this type of alloy.

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APERIODIC SUPERLATTICES: STRUCTURED RANDOMNESS*

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The successful realization of quasiperiodic superlattices was recently demonstrated by Merlin et al. [1] using MBE techniques. These experiments open the way to studies on a wide variety of model systems in which the multilayers are not periodic but are deposited according to some predetermined mathematical sequence. Such aperiodic systems are of interest because they offer the potential to fabricate new materials whose physical properties [2,3] are quite unlike those of either crystalline or amorphous solids. In this paper we present the results of extensive X-ray and Raman scattering experiments which probe the unusual structural and vibrational properties of aperiodic superlattices. Specifically, we compare the behavior of quasiperiodic (Fibonacci) GaAs-AlAs superlattices [1,4] with similar MBE-grown samples in which some disorder has been introduced deliberately during growth. It appears that different kinds of disorder have markedly different effects on the structural properties. The question of what constitutes randomness in a finite size system (thin film) is important in this context. With this in mind, we have explored various strategies for introducing randomness into the superlattices. The experiments take advantage of the high degree of control that is possible with a computerized MBE system. Moreover, atomically abrupt interfaces with perfect periodicity in the plane of the film ensure that the randomness is one-dimensional.

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CHARACTERIZATION OF STRUCTURAL AND MAGNETIC ORDER OF Er/Y SUPERLATTICES

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As an extension of previous studies of magnetic Dy/Y superlattices[1], crystalline superlattices of erbium and yttrium have been prepared epitaxially with layer thicknesses on the scale of the magnetic periodicity of Er. X-ray characterization of these samples reveals that, although the lattice mismatch between Er and Y is 2.5% and the crystal structures are highly strained, they are still coherent and exhibit sharp interfaces. Neutron diffraction and magnetometer measurements show that the magnetic properties of these systems differ significantly from pure Er. In zero field, the spins are c-axis modulated (CAM) in a sinusoidal manner below the Neel temperature ($\approx$ 78K). Below $T_{C\|} \approx$ 28K the spins also order in a basal plane spiral and the CAM "squares-up." Unlike pure Er, however, the superlattice does not develop a conical spin structure at low temperatures. Overall, the transition temperatures are lower than those for pure Er, and the first order transition to the conical phase is suppressed, possibly due to the lattice "clamping" effects such as observed in Dy/Y superlattices. Neutron diffraction data for one sample with 23 Er layers per bilayer shows little variation of the modulation wavevector with temperature. This behavior suggests a "lock-in" of the modulated spins to one of the commensurate spin-slip structures observed by Gibbs, et.al.[2] in pure Er.

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SUPERCONDUCTIVITY OF Cr/V SUPERLATTICES

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Cr_mV_n superlattices, where m and n denote the number of atomic planes of Cr or V, have been grown in an ultra-high vacuum unit[1](base pressure less than $5x10^{-9}$ Torr) containing two e-guns and a rotating substrate table. Up to 20 samples could be made in each run. Samples were grown on "c" cut sapphire substrates at 520K at deposition rates of approximately 2Å/s. Samples consisted of between 7 and 10 wavelengths and were characterized using x-ray diffraction and stylus profilometry. All specimens were found to have a strong (110) texture. The zero field transition temperature and upper critical field (in both parallel and perpendicular fields) have been measured.

The zero field transition temperature of the samples will be discussed in terms of various proximity effect theories. These include the procedures of Werthamer[2] and Menon-Arnold[3]. In addition a detailed numerical solution has been performed based on de Gennes method of expanding the kernel of the linearized self-consistency condition in terms of the eigenfunctions of the diffusion equation[4]. Results of this modeling will be presented including findings on the pair breaking strength of thin Cr layers.

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Poster Session 1

Structural Studies

1-1 **The effect of layer thickness fluctuations on superlattice diffraction**, J. G. Gay, B. M. Clemens, General Motors Research Laboratories

1-2 **Study of impurity induced disordering in GaAs/AlGaAs multi-quantum well structures by photothermal deflection spectroscopy and photoluminescence**, C. Shieh, J. Mantz, C. Colvard, K. Alavi, R. Engelmann, Siemens Research and Technology Laboratory; Z. Smith, S. Wagner, Princeton University

1-3 **Epitaxial growth of PbTe on (111) BaF_2 and (100) GaAs**, H. Clemens, B. Tranta, H. Krenn, G. Bauer, Montanuniversitat Leoben (Austria)

1-4 **Electron beam processing of structural and magnetic properties of amorphous Mn-Ga films**, J. Strzeszewski, Kansas State University

1-5 **Molecular beam synthesis and properties of $In_xAl_{1-x}As$ strained layers**, P. Chu, C. H. Lin, A. L. Kellner, W. S. C. Chang, H. H. Wieder, University of California at San Diego

1-6 **Observations of structural deviations in MBE grown II-VI superlattices with single periods**, R. D. Knox, J.-L. Staudenmann, Iowa State University; G. Monfroy, J.-P. Faurie, University of Illinois at Chicago

1-7 **X-ray studies of interfacial roughness in ZnSe/GaAs heterostructures**, A. Krol, C. J. Sher, S. C. Woronick, Y. H. Kao, State University of New York at Stony Brook; R. J. Dalby, D. A. Cammack, R. N. Bhargava, Philips Laboratories

1-8 **Abstract withdrawn.**

1-9 **Simulations of microscopic processes at semiconductor surfaces**, M. Menon, R. E. Allen, Texas A & M University

1-10 **Structure of heteroepitaxial GaAs on Si: A glancing angle synchrotron x-ray study**, H. Zabel, University of Illinois at Urbana-Champaign (USA); R. Feidenhans'l, J. ALs-Nielsen, Riso National Laboratory (Denmark); H. Morkoc, University of Illinois at Urbana-Champaign (USA)

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1-12 **Shubnikov-De Haas oscillations and universal conductance fluctuations in quasi-one dimensional GaAs-AlGaAs heterostructures**, H. van Houten, Philips Research Laboratories; B. J. van Wees, J. E. Mooij, Delft University for Technology (The Netherlands)

1-13 **Polarization dependent absorption spectra in quantum wire structures**, I. Suemune, L. A. Coldren, S. W. Corzine, University of California, Santa Barbara

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1-16 **Optical transition and recombination lifetimes in quasi-zero dimensional electron system in CdS_xSe_{1-x}**, K. Shum, G. C. Tang, M. R. Junnarkar, R. R. Alfano, City College of New York

1-17 **InGaAs/InP quantum boxes and wires through use of atmospheric OMVPE and holographic photolithography**, B. I. Miller, U. Koren, and P. J. Corvini, AT&T Bell Laboratories

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1-19 **Dual-gate silicon permeable base transistor with high transconductance**, A. Gruhle, L. Vescan, H. Beneking, Aachen Technical University (FRG)

1-20 **Analytical formulation of nonstationary electron dynamics in the AlGaAs/GaAs high electron mobility transistor**, T. A. Fjeldly, L. Johansen, University of Trondheim (Norway)

1-21 **Band-Edge Electroabsorption in GaSb/AlGaSb multiple quantum wells (MQWs) and its application to optical modulators**, T. H. Wood, E. C. Carr, C. A. Burrus, Jr., R. S. Tucker, T.-H. Chiu, W.-T. Tsang, AT&T Bell Laboratories

1-22 **Field spectrum anisotropy in multiple quantum well semiconductor lasers subjected to high magnetic fields**, K. Vahala, California Institute of Technology; Y. Arakawa, University of Tokyo (Japan)

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1-24 **Prospects of three dimensional isotopic superlattices**, A.A. Berezin, McMaster University (Canada)

1-25 **Nonlocal effects in helicon wave propagation in a superlattice**, B. N. Narahari Achar, Memphis State University

1-26 **Optical transition and recombination lifetimes in quasi-zero dimensional electron system in CdS_xSe_{1-x}**, K. Shum, G. C. Tang, M. R. Junnarkar, R. R. Alfano, City College of New York

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1-31 **Excitations of superlattice with a complex unit cell and effect of background dynamics in an external magnetic field**, Y. Zhu, S. Zhou, Fudan University (PRC)

1-32 **Band structure of non-ideal semiconductor superlattices**, H. X. Jiang, Michigan State University; J. Y. Lin, Syracuse University

1-33 **Mean-field calculations of electronic states in optically excited CdMnTe-CdTe quantum wells**, F. Crowne, Martin Marietta Laboratories

1-34 **An improved tight binding band structure calculation of III-V semiconductor superlattices**, S. Nara, Mitsubishi Electric Corporation (Japan)

1-35 **Exchange correlation energy in the subbands of a doping superlattice**, K. H. Teo, G. H. McKinnon, J. N. McMullin, H. G. Schmidt-Weinmar, University of Alberta (Canada)

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1-39 **Optical study of the electronic structure of $In_xGa_{1-x}As$-GaAs strained-layer quantum wells**, J. Menendez, A. Pinczuk, D. J. Werder, R. C. Miller, A. Y. Cho, D. L. Sivco, AT&T Bell Laboratories

1-40 **Photoluminescence from GaAs under the picosecond-laser-driven shock compression**, X. Z. Lu, R. Garuthara, S. Lee, R. R. Alfano, The City College of New York

1-41 **Optical absorption in a silicon doping superlattice**, J. N. McMullin, G. H. McKinnon, H. G. Schmidt-Weinmar, K. H. Teo, University of Alberta (Canada)

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1-46 **Measurement of superlattice optical properties from 1.45-3.5 eV by variable angle of incidence spectroscopic ellipsometry**, P. G. Snyder, J. A. Woollam, University of Nebraska at Lincoln, D. W. Langer, C. E. Stutz, R. Jones, Avionics Lab. WPAFB; A. K. Rai, K. Evans, Universal Energy Systems

1-47 **Photoreflectance of GaAs doping superlattices**, Y.-S. Tang, B.-S. Wang, D.-S. Jiang, W.-H. Zhuang, Semiconductors Institute, C. A. S. (PRC)

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1-49 **Dielectric function due to carrier confinement in semiconducting quantum well systems**, H. N. Spector, Illinois Institute of Technology (USA); H. H. Hassan, Military Technical College (Egypt)

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1-51 **Effects of uniaxial stress on hole subband in quantum wells**, J. Lee, M. O. Vassell, GTE Laboratories

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1-54 **The mobility of electrons in strained silicon structures**, C. Smith, M. E. Jones, British Telecom Research Laboratories (UK)

1-55 **Resonant tunneling through GaAs/AlGaAs heterostructures**, L. A. Cury, Universidade de Sao Paulo; N. Studart, Universidade Federal de Pernambuco (Brazil)

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1-59 **Warm electron coefficient of two dimensional electron gas in a GaAs-AlGaAs heterojunction at low temperatures**, P. K. Basu, K. Bhattacharyya, CAS in Radio Physics and Electronics (India)

1-60 **The transient and steady-state response of the two-dimensional electron gas in heterojunctions subject to an external electric field**, Π. S. Tang, University of Texas at Austin

1-61 **Complex band structure calculations of the electric field dependence of the reflection and transmission of valence band states from a (100) GaAs/AlGaAs quantum well (barrier)**, S. Monaghan, S. Brand, University of Durham (UK)

1-62 **Numerical evaluation of Feynman integrals over paths in real and imaginary time**, L. F. Register, North Carolina State University; M. A. Stroscio, M. A. Littlejohn, U.S. Army Research Office

1-63 **Shubnikov-De Haas measurements of the 2-D electron gas in pseudomorphic $In_xGa_{1-x}As$ ($x \geq 0.20$) grown on GaAs**, P. P. Szydlik, State University of New York at Plattsburgh; S. A. Alterovitz, E. J. Haugland, NASA-Lewis Research Center; B. Segall, Case Western Reserve University; C. Soehn, J. Klem, H. Morkoc, University of Illinois at Urbana-Champaign

1-64 **Resonant tunneling transistors**, S. Y. Chou, E. Wolak, J. S. Harris, Jr., R. F. W. Pease, Stanford University

1-65 **Resonant tunneling of electrons of 2 or 1-degrees of freedom**, S. Y. Chou, E. Wolak, J. S. Harris Jr., R. F. W. Pease, Stanford University

1-66 **Simulation of charge transport in a GaAs MESFET using the time dependent Schrodinger equation**, M. C. Yalabik, J. D. Gunton, G. Neofotistos, K. Diff, Temple University

1-67 **Wigner function simulation of quantum tunneling**, N. Kluksdahl, D. K. Ferry, Arizona State University

1-68 **Resonant tunneling transistors**, T. K. Woodward, T. C. McGill, California Institute of Technology; R. D. Burnham, H. F. Chung, Xerox Corporation

Phonons and Hot Electrons

1-69 **Screening of the exciton-LO phonon interaction in $In_{0.53}Ga_{0.47}As/InP$ quantum wells**, K. J. Nash, M. S. Skolnick, P. R. Tapster, D. J. Mowbray, S. J. Bass, A. D. Pitt, Royal Signals and Radar Establishment (UK)

1-70 **Abstract withdrawn.**

1-71 **Excitons and optical phonons as studied by resonant Raman spectroscopy in CdTe/(Cd,Mn)Te quantum wells**, S.-K. Chang, H. Nakata, A. V. Nurmikko, Brown University, L. A. Kolodziejski, R. L. Gunshor, Purdue University

1-72 **Far-infrared reflectance and anisotropy of phonon modes in GaAs-AlAs superlattices**, R. Sudharsanan, S. Perkowitz, B. Lou, Emory University

1-73 **Direct measurement of ultrafast electron-hole plasma expansion at high density in an asymmetric GaAs quantum well**, K. Shum, M. R. Junnarkar, H. S. Chao, R. R. Alfano, City College of New York; H. Morkoc, University of Illinois

1-74 **Nonequilibrium carrier phonon effect on the time-dependent relaxation of hot carriers in GaAs quantum wells**, K. Shum, M. R. Junnarkar, H. S. Chao, R. R. Alfano, City College of New York; H. Morkoc, University of Illinois

1-75 **Phonon dispersion curves of GaAs/AlAs superlattices**, S. F. Ren, H. Y. Chu, Y. C. Chang, University of Illinois at Urbana-Champaign

1-76 **Raman scattering from periodic and nonperiodic GaSb/AlSb strained-layer lattices**, G. P. Schwartz, G. J. Gualtieri, W. A. Sunder, AT&T Bell Laboratories; L. A. Farrow, Bell Communications Research

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1-77 **The effect of inelastic scattering on resonant and sequential tunneling through double barrier heterostructures**, Anna Grincwajg and M. Jonson, Chalmers University of Technology (Sweden)

1-78 **LPE grown AIII BV heterostructures spontaneous radiations and laser parameters**, Zh. I. Alferov, D. A. Garbuzov, A. F. Ioffe Physico-Technical Institute (USSR)

The Effect of Layer Thickness Fluctuations on Superlattice Diffraction

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ABSTRACT

The diffraction pattern of a perfect superlattice with a precise composition-modulation wavelength may have superlattice peaks in the growth direction at any scattering vector Q that is a multiple of 2π over the wavelength. Whenever a real superlattice possesses strong composition modulation and a well defined average composition-modulation wavelength, its x-ray diffraction pattern exhibits these superlattice peaks at small scattering vector Q. However, at large scattering vector two qualitatively different behaviors may occur. In one case, which is usually observed when there is structural size mismatch of 10% or less, the superlattice peaks reappear in the vicinity of the Q corresponding to a plane spacing in the growth direction. In the other case, which tends to occur with more severe structural size mismatch, no superlattice peaks appear at large Q.

We have developed a Patterson function approach that yields analytic diffraction patterns which can display either of the two behaviors depending on the nature of the fluctuations in layer spacing. In agreement with earlier work, we find, when the fluctuations are continuously distributed about the average, that fluctuations with a rms value of as little as 0.1 nm can completely remove the high Q peaks. However, when the fluctuations are not continuous but rather are discrete multiples of a lattice spacing, high Q superlattice peaks occur in the vicinity of Q values that are a multiple of 2π over the lattice spacing. These superlattice peaks persist even when the rms fluctuation value is 0.2 nm or larger.

We have carried out computer simulations which confirm the correctness and accuracy of our theoretical results. The simulations are also used to study more complex situations: when fluctuations occur at more than one discrete spacing, and when fluctuations are accompanied by systematic variations in superlattice wavelength.

Study of Impurity Induced Disordering in GaAs/AlGaAs Multi-Quantum Well Structures by Photothermal Deflection Spectroscopy and Photoluminescence

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Selective disordering of III-V multi-quantum well (MQW) structures and superlattices is of considerable interest for its application in the fabrication of planar laterally confined heterojunction devices [1]. Excellent results have been obtained with buried MQW heterostructure lasers and with non-absorbing laser mirrors fabricated by impurity induced disordering (IID) techniques[2]. A full understanding of the disordering process is still lacking and, hence, further analysis of the phenomenon is called for. Additionally, a detailed description of the optical properties of disordered and non-disordered material is necessary for device design purposes.

In this paper IID material from the AlGaAs/GaAs system is characterized by absorption measurements using photothermal deflection spectroscopy (PDS) and by photoluminescence (PL). Close attention is paid also to changes in the MQW structure not subject to the influence of impurities, since it has been reported that partial disordering can take place even in the absence of impurities due to the involvement of vacancies or other native defects (DID) [3]. The MQW structures investigated were grown by MBE. A typical sample consists of 65 periods of 7.5 nm GaAs and 8.0 nm $Al_{0.3}Ga_{0.7}As$ on top of a 3 µm $Al_{0.3}Ga_{0.7}As$ layer. All layers, nominally undoped, are grown on a s.i. GaAs substrate.IID was performed by diffusion of Zn (at 630°C), S and Si (both at 850°C). Additionally, complete DID was found in material capped with plasma CVD Si_3N_4 and subjected to 16 h anneal at 850°C contrary to extrapolated results from other authors [4]. This is believed to be an indication that in our process the conditions for native defect involvement are enhanced. However, for a shorter 4 h heat treatment at the same temperature no appreciable disordering is observed which makes the process compatible with selective disordering by S diffusion.

For the calorimetric PDS measurements the s.i. GaAs substrate was removed by selective wet chemical etching. The observed free carrier absorption is consistent with carrier densities determined from Hall and/or C(V) profile data. The shift of the absorption edge in disordered material is in good agreement with PL emission results. Partial disordering can be easily identified. Detailed results on the absorption and PL emission characteristics for the various disordering methods will be presented and discussed.

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Epitaxial Growth of PbTe on (111) BaF_2 and (100) GaAs

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Epitaxial layers of PbTe were deposited on (111) cleavage planes of BaF_2 substrates and polished (100) GaAs substrates using molecular beam epitaxy. The growth process was studied by an in-situ characterization using reflection high energy electron diffraction. Using an appropriate heat treatment the cleaved BaF_2 surface is a suitable substrate for epitaxial growth as evidenced by the RHEED patterns. On cleaved BaF_2 the growth process starts three dimensional in form of islands which merge together for layer thicknesses of about 1000 Å. Then the growth process becomes quasi-two dimensional as evidenced from the RHEED pattern taken along the $\langle\bar{1}10\rangle$ and $\langle\bar{2}11\rangle$ azimuths. The influence of the Te flux on the PbTe surface reconstruction was studied.
In addition PbTe was deposited on (100) GaAs substrates after the usual cleaning procedure for this material. Despite the large lattice misfit and the fact that PbTe crystallizes in the NaCl and not in the zincblende structure single crystalline growth is observed. Also for the nucleation of PbTe on GaAs the influence of Te on the orientation and reconstruction was studied by RHEED. These results are similar to those obtained by Yoshino et al. for the MBE growth of PbTe on CdTe[1].

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ELECTRON BEAM PROCESSING OF STRUCTURAL AND MAGNETIC PROPERTIES OF AMORPHOUS Mn-Ga FILMS. Jan Streesewski*, Kansas State University, Department of Physics, Manhattan, KS 66506

Magnetic properties of manganese compounds and alloys are much more sensitive to structural order or disorder than those of other transition metals. The amorphous films of Mn_xGa_{1-x} for x between 0.10 and 0.30 are nonmagnetic as opposed to intermetallic compounds of $MnGa_6$, $MnGa_4$, and Mn_2Ga_5 which are ferromagnetic. The crystallisation process of these films proceeds by nucleation and growth of separate crystals at the expense of amorphous matrix. In partially crystallised $Mn_{28}Ga_{72}$ films, we observed Mn_2Ga_5 crystals with a clear domain structure which were surrounded by an amorphous matrix with no domains. The crystallisation process can be stimulated by local heating with the help of an electron beam. In this way, a preselected pattern of crystalline and magnetic Mn_2Ga_5 tracks or spots can be drawn into a nonmagnetic amorphous matrix. In amorphous $Mn_{20}Ga_{80}$ films we observed simultaneous growth of different crystalline phases. Depending on the rate of heating it was possible to transform locally the amorphous area into Mn_2Ga_5 single crystal, or $MnGa_4$ single crystal or polycrystalline multiphase area. Because magnetic properties such as magnetisation or magnetic anisotropy of all these phases are quite different, we could modify the structure, magnetic domain in and magnetic properties in micron scale. The smallest pattern dimensions obtained were 2-3 μm.

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Molecular Beam Synthesis and Properties of $In_xAl_{1-x}As$ Strained Layers

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Abstract

We have investigated the molecular beam epitaxial synthesis and properties of pseudomorphic $In_xAl_{1-x}As$ layers strained in compression and in tension relative to their (100)-oriented InP and GaAs substrates using double crystal x-ray diffraction to determine the lattice constants, photoluminescence to determine the fundamental bandgaps and capacitance vs voltage and internal photoemission measurements to measure the metal-semiconductor barrier heights as a function of Al concentration. The measured changes in the fundamental bandgaps as a function of composition attributed to a tetragonal lattice deformation of the layers are in fair agreement with values calculated from the elastic stiffness coefficients C_{11} and C_{12}, hydrostatic isothermal pressure dependence coefficients of the fundamental bandgaps, $(\partial E_g/\partial P)_T$, and shear deformation potentials interpolated linearly between those of the corresponding parameters of AlAs and InAs. Within the direct gap range the Schottky barrier height increases monotonically with increasing Al fraction reaching a value of 1.2eV and its composition dependence is similar to that of $Ga_xAl_{1-x}As$.

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OBSERVATIONS OF STRUCTURAL DEVIATIONS IN MBE GROWN II-VI SUPERLATTICES WITH SINGLE PERIODS

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An X-ray diffraction analysis of HgTe-CdTe, HgZnTe-CdTe, and CdTe-ZnTe superlattices (SL's) has revealed a few exceptional samples possessing complex satellite structures that can not be attributed to a single modulation period of one specific average composition. All of the examined SL's were made in an MBE Riber 2300 unit and were intentionally grown to have only one well-defined period. These unique SL's are reviewed and the observed deviations with respect to a single period SL model are illustrated.

The SL samples were characterized by several diffraction techniques. A precession camera was used to evaluate the crystalline quality of each sample. Then extended X-ray ω-2θ scans were performed with the scattering vector along the SL growth direction. In many cases, these scans were complemented by ω scans to obtain structural information that is slightly off the growth axis. The growth of the most recently produced CdTe-ZnTe SL's were monitored using in-situ RHEED (Reflective High Energy Electron Diffraction) apparatus. The RHEED and X-ray results are compared in an attempt to correlate the complex X-ray structure with the SL growth history.

The X-ray analyses suggest that several SL regions coexist within one macroscopic SL sample. Applying this interpretation, two predominant effects are observed. First, some X-rays scans reveal one central peak centered about a superposition of satellite peaks. This represents the presence of several regions having different modulation lengths, but sharing a common average chemical composition. Second, there is evidence of multiple SL structures, each represented by a central peak and corresponding satellites, and having calculated periods that are nearly identical. This indicates the coexistence of several modulated regions having different average chemical compositions, but sharing a common modulated length.

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X-ray Studies of Interfacial Roughness in ZnSe/GaAs Heterostructures.* A. KROL, C.J SHER, S.C. WOROWICK, Y.H. KAO, Department of Physics, State University of New York at Stony Brook, Stony Brook, NY 11794, USA, R.J. DALBY, D.A. CANNACK, R.N. BHARGAVA, Philips Laboratories,North American Philips Corporation, Briarcliff Manor, NY 10510, USA

A recently developed x-ray reflectivity technique for measuring interfacial roughness was employed in the study of ZnSe/GaAs heterostructures. This technique was supplemented by simultaneous x-ray fluorescence investigation near the zinc edge. A combination of these two methods yields information about the nature of surface and interfacial roughness. The examined samples, grown by MBE, had varying ZnSe epilayer thicknesses from 100 to 5000Å. Experimental curves displaying angular dependence of x-ray reflectivity and fluorescence in the range from 3 to 15 mrad were taken at fixed energies ranging from 9.5 to 9.7 keV. Their features can be explained by a modified scalar-scattering model assuming a normal distribution of roughness. The results are consistent with a relatively small surface (<10Å) and moderate interfacial (>15Å) rms roughnesses.

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Abstract withdrawn

Simulations of Microscopic Processes at Semiconductor Surfaces

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The kinetics of interfacial growth can be of dominant importance in determining the electronic properties of semiconductor interfaces. A microscopic understanding of interfacial growth would also be valuable in controlling the properties of superlattices and other artificial semiconductor structures. Because of the covalent nature of semiconductors, central potentials such as Lennard-Jones are utterly inadequate for a realistic treatment of the atomic motion and bonding. Even efforts to employ three body potentials for semiconductors have had only limited success. We have developed a new technique in which atomic forces are computed from the electronic energies of the entire system, rather than from interatomic potentials. A major reduction in the computational complexity has been achieved through the use of the subspace Hamiltonian technique [1-4]. Here we report studies of various chemical species impinging on the (110) surfaces of GaAs and other III-V semiconductors, with subsequent chemisorption in various bonding sites - - or, in some case, indiffusion. The results exhibit nontrivial variety in both the dynamics and final bonding sites. We have also looked at time-dependent relaxations of these surfaces. The chemisorption has been found to disturb the relaxed GaAs (110) surface, removing the relaxation for those surface atoms which are bonded to the adsorbate. The surface vibrational frequencies observed in our simulations are in satisfactory agreement with estimates based on measured bulk phonon frequencies. The systems studied up to the present include Ga, As, In, B, N, O, S, Br, C, Cd, Al, Cu, Zn, Si, Ge, Sn, P, Te, Se, Au, Hg on GaAs (110) and InP (110).

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Structure of Heteroepitaxial GaAs on Si: A Glancing Angle Synchrotron X-Ray Study

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Abstract

The current interest in GaAs grown on nonpolar substrates, such as Si and Ge has been stimulated by the potential technological advantages of these systems. The successful growth of GaAs on miscut Si and Ge (100) surfaces reported recently by Fischer et al.[1], implies that two major obstacles impeding progress so far have been overcome. These are the lattice mismatch between GaAs and Si and the formation of antiphase domain boundaries.

The microstructural mechanism of GaAs on Si or Ge is, however, not well understood. Recent x-ray scattering experiments[2] on 0.2 μm and 2 μm thick GaAs films confirm that if antiphase domain boundaries are present they should be at least 4000Å apart. We have extended these studies to 0.05 μm thick GaAs layers on miscut Si (100) and by using glancing angle synchrotron x-ray techniques. This technique allows to probe a range of penetration depths by varying the angles of incidence and exit beams to the surface. We have observed a pronounced gradient of the in-plane (400) peak position and width from the interface to the near surface region. In all cases the GaAS lattice parameters is contracted at the interface and relaxes towards the surface, in contrast to our previous observations at 2 μm thick GaAs films. The in-plane contraction induces a Poisson-expansion parallel to the growth direction. The thickness dependent in-plane lattice parameter yields new insight into the interfacial relationship of the heteroepitaxial structure and on the limits of strain and strain relaxation as the film grows.

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Analysis of Electron Propagation through narrow n^+ GaAs wires.

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Starting from the Schroedinger equation and using Landauer's multiple channels formula, we have calculated the resistance of narrow n^+ GaAs wires at zero temperature. The presence of impurity scattering is modeled by delta functions for the scattering potentials. For low impurity concentration ($10^{17}cm^{-3}$) and after averaging over many samples, we find an ohmic behaviour of the samples in the weak localization regime and an exponential increase of the resistance in the strong localization limit. For higher impurity concentration ($10^{19}cm^{-3}$), the resistance shows tendency to saturation as the length of the sample increases. This is related to the absence of phase randomization (between scatterers) of the different propagating modes in the GaAs wires contrary to what is observed in metals.

Shubnikov-De Haas Oscillations and Universal Conductance Fluctuations in Quasi-One Dimensional GaAs-AlGaAs heterostructures

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Narrow conducting channels have been fabricated in the two dimensional electron gas (2DEG) in a GaAs-AlGaAs heterostructure, using a recently developed shallow mesa etch technique which is described in ref. [1]. Material grown by Metal-Organic Chemical Vapor Deposition (MOCVD) was employed, with a mobility (for wide channels) of 10 $m^2 V^{-1} s^{-1}$ and a sheet carrier concentration of 5 $10^{15} m^{-2}$

Four terminal high and low field magnetoresistance measurements at temperatures down to 2 K have been performed on samples with etched width between 8 μm and 0.5 μm. The effective widths of the conducting channels are smaller as a consequence of sidewall depletion. This is especially significant in the case of the 0.5 μm sample, where the effective width estimated from low field weak localization modified by boundary scattering is 100 nm. In this contribution we will concentrate on the magnetoresistance oscillations observed at higher fields (above 0.2 T)

At fields above a critical value which depends on the sample width clear Shubnikov-de Haas oscillations are observed. Plots from the Landau level index versus B^{-1} show a straight line as expected for a 2DEG. Deviations from this behavior are observed in channels with etched width of 1.5 μm and 0.5 μm at high values for B^{-1}. This is interpreted as a manifestation of the transition to a regime of magnetic depopulation of one dimensional subbands.

At even lower fields aperiodic oscillations are observed in the narrow channels, which are thought to be universal conductance fluctuations. Some subband depopulation effects may still be important in this regime, however. The temperature dependence and typical field scales of the fluctuations is discussed

The angular dependence of the magnetoresistance clearly shows that the conductance fluctuations depend on the perpendicular component of the magnetic field only. This demonstrates the orbital origin of the fluctuations. The transverse magnetoresistance is negligible, which indicates the absence of spin related effects

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Polarization Dependent Absorption Spectra in Quantum Wire Structures

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Recently,the interest in quantum wire structures(QWS) or quantum box structures is increasing due to several attractive features, such as the capability to realize lower threshold current and less temperature dependent laser structures. In addition to these active optical properties, the absorption related properties of the QWS may have several advantages; quantum well(QW) waveguides integrated with QW laser sources are reported to have lower absorption loss with about 1/4 of the loss in a DH structure waveguide due to larger energy gap shrinkage in the QW laser source. The addition of another lateral quantization in the QW waveguide, i.e., QWS may further reduce the absorption loss in the waveguide. Also, regarding waveguide phase modulators and swiches, the increase of the oscillator strength of the exciton in QWS may further increase the refractive index change due to exciton absorption. Toward these directions, the fundamental properties, especially excitonic absorption properties in QWS must be clarified.

In this paper, we introduce a formula to take into account the polarization dependence of exciton absorption as well as interband absorption in QWS based on k·p perturbation theory. In the excitonic absorption, the k-space broadening due to the spatial localization must be taken into account in the calculation. The binding energies of excitons were calculated by a variational method. It is shown that the excitonic absorption spectra predominate over the interband absorption for all possible polarizations of the incident photon. In part due to the increase of the exciton oscillator strength and in part due to the decrease of the density of states in QWS.

For the polarization of the incident photon electric field perpendicular to the quantum wire (z) direction, the oscillator strength of the exciton absorption is shown to be controlled by changing the aspect ratio of the wire cross section. For example, aspect ratios of 2 and 4 (i.e., 200Å/100Å and 200Å/50Å) give a variation ratio of the conduction to heavy-hole band (c-hh) exciton oscillator strength by 2.6 and 6.4, respectively, depending on the polarization. This phenomena, in addition to the energy gap increase, may be in favor of realizing low-loss waveguides integrated with laser sources, considering the increase of the binding energies of excitons in QWS.

The calculated maximum refractive index change due to c-hh exciton absorption in a 100Å×100Å GaAs surrounded by $Al_{0.4}Ga_{0.6}As$ is about 4% for the photon electric field parallel to the wire direction assuming Gaussian lineshape function, which is on the same order as the corresponding QW structure. This is because the exciton spatial localization due to the Coulomb interaction is on the same order as the effective well width defined by the heterobarrier in the calculated structure. However, a larger refractive index change is expected with the use of higher barrier heights and smaller structures, although the latter depends on the development of fabrication techniques.

QUANTIZATION OF THE HALL EFFECT IN A 3-DIMENSIONAL QUASIPERIODIC SYSTEM

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The observation of the Quantum Hall effect in an electronic system that has electronic dispersion in all three spatial dimensions[1] has shown that the assumed criterion of two-dimensionality can be relaxed as long as the conductivity of the system in the magnetic field direction vanishes (i.e., $\sigma_{zz} \to 0$). This condition can be acheived in a superlattice when the Landau level spacing exceeds the zero-field miniband width of the superlattice, thus creating gaps in the electronic excitation spectrum. With the recent achievement of quasiperiodic systems,[2] it is now possible to test whether this condition still applies to a system in which the Bloch theorm is invalid. We have experimentally realized such a system utilizing a 1-D quasiperiodic modulation-doped GaAs-AlGaAs arranged in a Fibonacci sequence. We will present low temperature magnetotransport data, which is significantly different from that of a periodic modulation-doped GaAs-AlGaAs of nominally the same miniband width. Suprisingly, there is no evidence for the collapse of quantized resistance values and vanishing magnetoresistance due to the quasi-1D density of Landau levels

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The Microstructures of Solitons in One-Dimensional Conductors with Quarter Filled Band

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In some one-dimensional conductors such as orthorhomic TaS_3 and vanadium bronze, the energy bands are quarterly filled. Due to the instability of one-dimensional lattice caused by the electron-lattice interaction, there appears quadrimerization in the lattice, and the ground state becomes four-fold degenerate with four different phases $\varphi_m = m \cdot \pi/2$ ($m = 1,2,3,4$). The domain wall between two different phases m and m' is a soliton. There are two types of solitons S_I and S_{II}, the former has phase shift π and the later $\pi/2$. The microstructures of the deformed lattice and the electron states for both the ground state and solitons are obtained. The soliton S_I can be neutral or charged with $\pm e$, but the soliton S_{II} is charged with $\pm e/2$.

ABSTRACT SUBMITTED
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Optical transition and recombination lifetimes in quasi-zero dimensional electron system in CdS_xSe_{1-x}--Kai Shum, G. C. Tang, M. R. Junnarkar and R. R. Alfano, Institute for Ultrafast Spectroscopy and Lasers, Physics and Electrical Engineering Departments, The City College of New York, New York, NY 10031--We report on the observation of optical transitions between quantized levels (1S, 1P, 1D) in the conduction band and the valence band in quasi-zero dimensional electron system in CdS_xSe_{1-x} by steady-state photoluminescence measurements. Picosecond luminescence studies of the transitions reveal a significant influence of three-dimensional confinement on the transition probabilities of photoexcited carriers. The recombination lifetime of electrons and holes within the quasi-zero dimensional system decrease with the diameter (d) of system from 210 ps for d=10.2 nm to 70 ps for d=7.4 nm. The ratio of recombination lifetime for 1S-1S transition and 1P-1P transition is independent of diameter of system, and is measured to be about 3.5.

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InGaAs/InP Quantum Boxes and Wires Through use of Atmospheric OMVPE and Holographic Photolithography

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By use of atmospheric OMVPE and holographic photolithography, we have been able to make quantum dots and wires of approximately 200-300Å dimensions. OMVPE was used to initally grow a single GaInAs quantum well of 100Å on an InP substrate followed by a 30Å cover of InP. The wires were fabricated by a single exposure of a diffraction grating on a dilute photoresist. For the boxes a double exposure at right angles was used. The patterns were then etched using a weak Hydrobromic-Nitric acid solution. The resulting structure was roughly a triangular grating with a 2000Å period and ~ 600Å depth, resulting in an approximately 200-300Å dimension at the quantum well near the surface. Shifts in the photoluminescent wavelength corresponding to these dimensions have been observed at room temperature and were typically ~200Å for both the quantum boxes and wires. The photoluminescent intensity only decreased by a factor of 10X with the boxes and 2X with the wires, although the area was reduced by 50 and 5 respectively for the boxes and wires. We have then regrown these structures with a 1000Å thick layer of InP by OMVPE resulting in a completely planar surface. We have observed that the photoluminescent intensity increases in many cases by as much as 2X from the uncoated structures. This indicates that the wet chemical etch and careful regrowth does little—or no—damage to the boxes or wires and that any electron-hole pairs created by the optical excitation can easily migrate to a box or wire where recombination can take place.

We have made electrial conductivity and photoconductivity measurements both parallel and perpendicular to the regrown quantum wires and have observed a large anisotropy in these properties. These and other measurements will be shown.

Large Absorption Modulation in InGaAs/InAlAs Quantum Well Field Effect Structure

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The optical properties of quantum well (QW) structures can be strongly modified by generation of photo-carriers or by application of electrostatic fields. In this paper we demonstrate for the first time that even larger changes in the absorption spectrum can be produced by electrically driving carriers in and out a single QW in a field effect gated structure. We observe deep and broad quenching of the absorption ($\Delta\alpha > 10^4 cm^{-1}$ over $\Delta\hbar\omega > 90 meV$) near the band-edge and significant changes at higher energies. We present experimental data for lattice temperature $T_L = 10K \sim 300K$ and photon energy from below the QW gap to above that of the barrier material thus scanning the $n_e = 1, 2$ & 3 intersubband transitions. We discuss the physical mechanisms involved at each transition and we find good agreement with self consistent band structure calculation including correction for band gap renormalization. Finally we comment upon the potential applications of this novel effect.

The experiment performed on modulation doped field effect transistor (MODFET) which conduction channel is a single InGaAs QW ($L_z = 100\mathring{A}$ $Eg \sim 0.78eV$). The $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ microstructure was grown by MBE on an InP:Fe substrate. The gate electrode (1.6 μm long by 100 μm wide) was extended to a 100 μm × 100 μm optical test pad contiguous to the FET mesa. By varying the gate-source voltage the MODFET state is changed from pinch-off (empty channel) to conducting (full channel), and the electron density in the well is thus varied continuously from $N \sim 0$ to $1.6 \times 10^{11} cm^{-2}$. These changes

are probed by sending a light beam through the transparent InP substrate and AlInAs layers through the (absorbing) QW and reflecting off the metallic gate, while modulating the gate-source voltage ($-0.5V$~$-1.5V$). The reflected beam is monitored by a photo-detector in a conventional lock-in detection.

The mechanism governing the absorption quenching at the first intersubband transition is the filling of the phase-space by the electrons injected into the channel and gradually populating the $n_e = 1$ conduction subband according to a Fermi distribution f_e at the electron temperature T_e. The occupied states cannot contribute to absorption which is thus reduced by $(1-f_e)$. At the higher subband transitions changes of absorption are seen, although the population is low, because the electrons in the first subband produce an electrostatic field in the QW that shift the higher levels. We obtained a good quantitative description of the shifts by solving Poisson and Schroedinger equations self-consistently, and correcting for the band gap renormalization. From this analysis we also obtain the electron density N and temperature T_e in the QW-conducting channel for various gate-source voltages and lattice temperatures.

This novel effect is extremely efficient, it can be used for optical determination of the logic state of a FET thus serving as an optical interconnect. It can also be used as an efficient light modulator at wavelength ($\lambda \sim 1.5\mu m$) compatible with light wave communication systems.

DUAL-GATE SILICON PERMEABLE BASE TRANSISTOR WITH HIGH TRANSCONDUCTANCE

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Permeable base transistors (PBTs) are new high-speed devices with a predicted frequency performance of up to 1000 GHz. PBTs are suitable for three-dimensional integration by stacking several devices on top of each other. In this paper we present etched-grooved PBTs with a new dual-gate structure. Using an alternating grid, the vertical channels are connected to two independent gates.
Starting materials are (100) 1mOhm-cm n+ substrates with a 2um thick, 4×10^{16} cm^{-3} n-epilayer grown by LPVPE at 820°C. The top 100 nm are n+ doped for good ohmic contacts to the TiPtAuPt source-metallization which is patterend by lift-off. The metal acts as a mask in the subsequent RIE where 0,7um Si are removed in a SF_6 plasma resulting in a slight undercut. This is necessary to form a discontinuous metal film during the following 100 nm Pt gate-metallization. A special meander-shaped form of the source and rectangular gate pads provide a self-aligned formation of the alternating gate structure without critical alignments. Finally, the surface is planarized with PIX-1400 polyimide, a part of which is removed in a subsequent O_2 plasma etch. The top side contacts are thus revealed and reinforced with an additional Au pad. A AuSb metallization on the back side of the wafers forms the drain contact.
Several single and dual-gate PBTs have been fabricated with channelwidths between 0,5 and 2um and groove depths from 0,6 to 1,4um. Threshold voltages vary between -0,5 and -0,7V. The gate Schottky diodes have ideality factors less than 1,1. Breakdown occurred at about -10V. The maximum transconductance is 45mS/mm, the highest value ever reported for Si PBTs. The dual-gate devices may be controlled independently and switched off by each of the two inputs. Used as a mixer in RF application the transconductance can be varied from its maximum value to zero by one input. The advantage over dual-gate MESFETs or MOSFETs are the two identical gates. This should allow a very simple formation of two input NAND gates in dual-gate PBT integrated circuits.
PBTs suffer from a large drain-voltage influence on the characteristics leadig to triode-like instead tetrode-like behaviour. We expected a lowering of the output conductance by applying a constant voltage at one gate of the dual-gate PBT, however no reduction was found. Presently two-dimensional numerical simulations are beeing performed to evaluate the influence of different gate configurations.

Analytical Formulation of Nonstationary Electron Dynamics in the AlGaAs/GaAs High Electron Mobility Transistor.

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A self-consistent and analytical formulation of the carrier transport in the two-dimensional conducting channel of the AlGaAs/GaAs high electron mobility transistor (HEMT) is developed. A model is also advanced to account for the pinchoff region. It has previously been shown that important non-stationary effects such as velocity overshoot are reasonably well described within the framework of the relaxation time approximation of the Boltzmann transport equation. Here it is shown that, within the same approximation, a theory for non-uniform transport in the HEMT can be formulated on the basis of the transient behaviour of the average carrier velocity in the homogeneous case. Such "generic" transient responses to step changes in the electric field can readily be obtained from the space invariant Boltzmann equation by more advanced methods such as Monte Carlo technique. Specific calculations have been performed on current-voltage characteristics and on the spatial variation of the electric field and the average electron velocity along the conducting channel.

Band-Edge Electroabsorption in GaSb/AlGaSb Multiple Quantum Wells(MQWs) and its Application to Optical Modulators

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Optical modulators based on the Quantum-Confined Stark Effect in semiconductor MQWs have been attracting considerable attention. Large on/off ratios are achievable in short devices as a result of the large electroabsorption effect seen in these structures. Almost all previous work has been in the GaAs/AlGaAs material system, with an operating wavelength of about 0.85 μm. The GaSb/AlGaSb system is an interesting one for these devices, because its gap is close to the 1.55 μm wavelength used in lightwave systems.

Here, we report a waveguide optical modulator made from GaSb/$Al_xGa_{1-x}Sb$ MQWs. We observe clear shifts of the exciton peaks with applied field in photocurrent spectra, and, for the first time, report modulation with this material system. Fig. 1 shows the layer structure of our wafer, which was grown by MBE. It contains 16 MQWs, in the center of the i region of a pin diode. The length and width of the device were 83 μm and 175 μm, respectively. A leaky waveguide, consisting of a core of MQWs and superlattice, and a cladding of pure GaSb, confines the light perpendicular to the layers.

Fig. 2 shows the transmission-vs.-voltage characteristic for this device at a wavelength of 1.547 μm. The light was polarized perpendicular to the MQW layers. The device has an on/off ratio of 10.5 dB, implying a field-induced change in the absorption coefficient of 3[illegible] cm^{-1}. The air-to-air insertion loss is approximately 12 dB. Measurement of the polarization properties of this device at various wavelengths should provide information on the relative energies of the heavy and light hole transitions.

Finally, we measured the small-signal, swept-frequency response of a narrower device 28 μm wide and 78 μm long. The 3-dB rolloff frequency of this narrower device is approximately 3.7 GHz. By measuring the electrical reflection coefficient of the device, we calculate that this response is RC limited, with a slight increase in 3-dB rolloff frequency due to a resonance between the device capacitance and the 3 mm long bond wire.

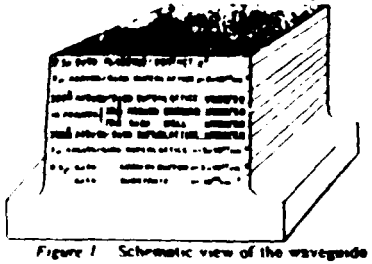

Figure 1 Schematic view of the waveguide modulator used for transmission experiments

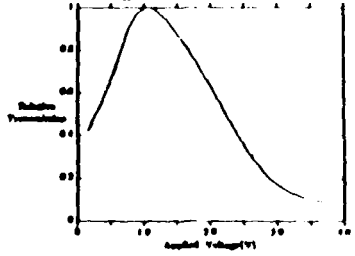

Figure 2 Relative transmission-vs.-voltage for the device of Fig. 1

Field spectrum anisotropy in multiple quantum well semiconductor lasers subjected to high magnetic fields

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Pasadena, California 91125

Yasuhiko Arakawa
University of Tokyo
Roppongi Minato-ku
Tokyo, Japan

Abstract

High magnetic fields are applied to a multiple quantum well laser. When the magnetic field is applied normal to the quantum well plane three dimensional electronic confinement effects are observed in the laser field spectrum linewidth and luminescence. When the field is parallel to the quantum well plane, these effects are not observed. This anisotropy can be interpretted to result from the frustration of the carrier cyclotron motion by the quantum well barrier.

SURFACE ACOUSTIC WAVE - SUPERLATTICE INTERACTION IN SEPARATE-MEDIUM STRUCTURE

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The acoustoelectric effect in GaAs and AlAs superlattice is investigated using a separate medium convolver structure. The acoustoelectric interaction in the superlattice is of fundamental interest and that it may provide the basis for nondestructive characterization of the superlattices and novel devices. The magnitude and polarity of the acoustoelectric voltages exhibit strong temperature and surface acoustic wave (SAW) frequency dependencies; a phenomena that is not observed in homogeneous semiconductors. SAW-superlattice interaction models that tentatively explain the observed data are discussed.

Abstract submitted for 3-rd Int.Conf. on Superlattices, Microstructures & Devices; Chicago August 17-20 1987

PROSPECTS OF THREE DIMENSIONAL ISOTOPIC SUPERLATTICES

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Spontaneous ordering of voids, gas bubbles and precipitates has been observed in metals under neutron irradiation [1,2]. The latter is essential as it provides energy for migrations of defects towards energetically favorable ordered configurations. According to [1] such ordering exemplifies self-organization (order-disorder transition) in non-equilibrium system in the sense of Prigogine-Haken synergetics.

Most elements have two or more stable isotopes. It is usually taken for granted that distribution of different isotopes of the same element over lattice sites is perfectly random. However, all the basic ingredients which lead to the spontaneous ordering of impurities or voids could be identified in isotopic case as well.

The non-zeroness of the isotopic ordering interaction results from the anharmonicity of zero-point vibrations [3]. The weak net repulsive interaction between the minority isotope in majority matrix was modelled by the power-law form $V(r) = A/(r/d)^p$ where d is interatomic spacing and $p \leq 5$ [4]. Small differences in bond lengths between various isotopic pairs result in random strains varying from site to site. An estimate for the favorable case of large mass difference (CaO crystal with Ca-40 and Ca-48 stable isotopes) gives about 20 meV for the net isotopic strain which is sufficient to produce a noticable isotopic ordering in experimental conditions similar to [1,2]. Other candidate materials to be discussed are carbon (diamond) films (C-13 vs C-12 ordering) and Si-28/Si-30 combination. Various device applications of 3-dimensional isotopic superlattices are possible. One such application (isotopic information storage) was discussed in [5].

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Nonlocal effects in helicon wave propagation in a superlattice.
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Dispersion relations have been obtained on the basis of linear response theory for helicon waves propagating in a superlattice represented by a Kronig-Penney model. The wave vector as well as the applied static magnetic field are assumed to be along the axis of the superlattice. Numerical applications are made to a model originally used by Tsu-Esaki and Quinn and the nonlocal effects are clearly brought out. These include the severe restriction of the wave vector in the Brillouin zone and the possible occurence of high frequency helicon modes.

Dependence of Lifetime on Design Parameters of an nipi Doping Superlattice: Results of Self-Consistent Calculations

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Our investigation on the possible use of a superlattice to design a high-efficiency, radiation-tolerant solar cell has led us to invent a solar cell structure using an nipi doping superlattice. In this structure, the photo-generated minority carriers are quickly ($< 10^{-10}$ sec.) separated by an electric field resulting from the periodic band bending. After separation into regions where they become majority carriers, they move parallel to the superlattice layers to the nearest selective ohmic contacts. Thus, our cell structure avoids the problem of carrier transport normal to the superlattice layers, a direction of difficult current flow. However, even after separation, the photogenerated carriers would be subject to recombination across the indirect gap in real space. Thus, in order for our structure to work, the carrier lifetime for recombination across the indirect gap in real space would have to be longer than the transit time to the nearest selective contact.

In order to verify theoretically the viability of our structure and to optimize its design, we have calculated the lifetime, at room temperature, for recombination across the indirect gap in real space as a function of the thicknesses of the n, p and i layers and of the dopings in the n and p layers. This was done using a computational algorithm for obtaining the self-consistent solutions of Schrodinger's and Poisson's equations for electrons and holes. The algorithm converged for a much wider range of design parameters, i.e. layer thicknesses and dopings, than in previously published work. The lifetime was calculated using overlap integrals. In this paper, we present the results of a systematic study of how the lifetime in a GaAs nipi doping superlattice, under a forward voltage of 1.0 V, varies with layer thickness and doping. This voltage corresponds to the expected maximum-power operating point of a nipi doping superlattice solar cell under a sunlight concentration of 20X. Our results give room temperature lifetimes as high as 27 ms for n and p layer thicknesses of 750 A each, i-layer thickness of 50 A, and dopings in the n and p layers of 2E18 cm^{-3}.

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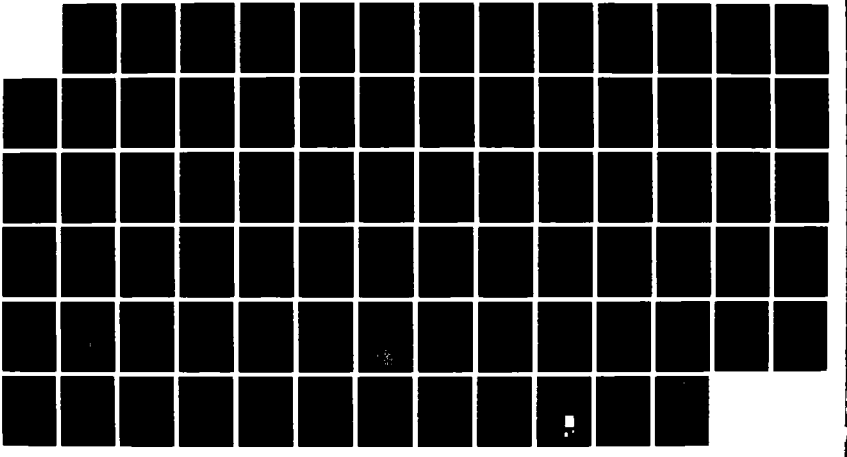

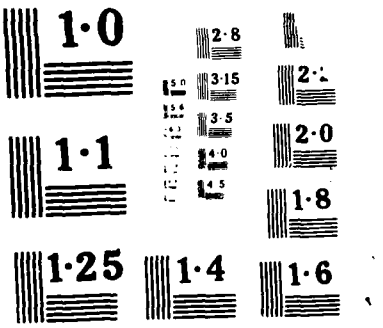
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Calculation of Transition Temperatures of Superconductor-Metal Sandwiches and Superlattices

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The transition temperatures of superconductor-metal sandwiches and superlattices have been calculated. We employ the eigenfunction expansion of the De Gennes[1] kernal near the critcal tempe ature as developed by Takahashi and Tachiki[2]. We have improved the calculation by approximately diagonalizing the eigenvalue equations rather than keeping only the lowest energy term. In agreement with physical measurements, our results show a much steeper decrease of the transition temperature with layer thickness that the Werthamer[3] one mode approximation. We have also considered the effects of magnetic impurities and calculated upper critical magnetic fields.

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Hydrogen in Niobium - Tantalum Superlattices

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Abstract

Hydrogen in Nb/Ta superlattices represents a novel way of investigating the properties of a lattice gas in a modulated field, and to study details of strained superlattices, including the interfacial relationship with the substrate.[1] We have found that H induces a strain modulation exhibiting a Curie-Weiss type temperature dependence. The Nb/Ta-H superlattice thus provides a first example of a strained layer superlattice which can be strained after the growth of the structure. In addition, we have observed a lattice-gas lattice-liquid phase transition where critical fluctuations exist only for wavelengths longer than the superlattice periodicity. The absence of short wavelength fluctuations prohibit complete phase separation and constitutes a novel manifestation of a coherent phase transition. The suppression of an incoherent phase boundary between the Nb and Ta sublattice yields new insight into the interplay between interfacial strain and discommensuration.

Supported by DOE-MRL-DE-AC02-76ER01198

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Structure and Low-Temperature Interdiffusion of Nb-Ti Superlattices

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Superlattices of Nb and Ti with periods from 15Å to 1000 Å have been fabricated by magnetron sputtering. X-ray analysis indicates that, the samples with shorter wavelengths ($\lambda < 20$Å) are generally compositionally modulated alloy of b.c.c. structure and those with longer wavelengths are of Nb(b.c.c.)-Nb/Ti alloy (b.c.c.) - Ti (b.c.c.) structure. α-Ti (h.c.p.) appears only when $\lambda > 160$ Å. The theoretical simulation is in agreement with the experiment. The low-temperature interdiffusivity between Nb and Ti was measured by the X-ray diffraction method. The tendency of variation of the effective interdiffusivity D_λ versus λ agreed with the theoretical result based on the microscopic theory. The measured interdiffusivities were in agreement with the extrapolation of high-temperature results made with tracer technique.

Many-Electron Edge Singularity at the Fermi Cutoff in the Photoluminescence Spectrum of Modulation-doped Quantum Wells

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We report the first observation of a Fermi energy edge singularity in the recombination spectrum of a semiconductor. This many-body effect has only been observed previously in the X-ray emission spectra of metals. It arises from multiple electron-hole scattering processes to empty electron states above the electron Fermi energy E_F. The photoluminescence (PL) experiments are carried out on $In_{0.53}Ga_{0.47}As/InP$ n-type modulation doped single quantum wells. We have shown elsewhere[1] that in low-temperature PL experiments on these QWs with low excitation intensity, the photocreated holes are localised on a 10Å to 30Å length scale, which we attribute to binding by alloy fluctuations. The hole localisation permits all electrons up to E_F to recombine without restriction of crystal momentum. This contrasts with the situation for modulation doped QWs in the GaAs/(Ga,Al)As system, in which the holes are not localised and k-restriction strongly reduces the intensity of low-temperature PL from electrons at E_F, thus precluding the observation of any Fermi energy singularities.

The PL spectrum is broad, comparable in width to E_F (up to 45meV). The lineshape is strongly skewed towards higher photon energies. In magnetic field, the PL spectrum consists of a discrete line associated with each occupied electron Landau level, showing that the unusual lineshape at zero magnetic field does not arise from disorder-induced modification of the electron density of states, or from the overlap of two bands of different origin, but from a dependence of the recombination rate on the electron state that is involved in PL.

The two-dimensional density of occupied electron states is a constant from the bottom of the lowest electron subband up to E_F. The constant or slowly varying oscillator strength found without consideration of many-particle effects is modified by the screened electron-hole interaction, which produces a singularity at E_F. This phenomenon explains the qualitative form of the PL spectrum.

Further support for this interpretation is given by the temperature dependence of the PL spectrum. The Fermi energy edge singularity disappears at temperature ~60K, i.e. when kT is of the order of the exciton Rydberg in these QWs, as anticipated theoretically[2]

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Excitations of Superlattice with a Complex Unit Cell and Effect of Background Dynamics in an External magnetic Field

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In this paper,the hydrodynamic model is used to investigate the spectrum of a type-I superlattice (SL) in which the repeat unit is comprised of two electronic layers instead of just one.The scheme is of the type ab-ab-.....,where a is the distance between the two layers in the unit cell,and d=a+b is the superlattice spacing. The reason to introduce such a slight complication lies in the fact that this new kind of type-I semiconducting SL is as easy to fabricate as the usual type,and this SL has a rich excitation spectrum that admits acoustic plasmon. The most obvious feature of such a system is that the relevant parameters determining the spectrum are simply of geometrical character ratios (a/b). Since hydrodynamic theory gives the results equivalent to SCF approach. If the compressibility or the hydrodynamic pressure term is empirically chosen[1].Our approach is patterned after Fetter's prescription [2] and Das Sarma's treatment in the presence of an external magnetic field [3].

A rigid uniform positive charge background is assumed while each layer contains a 2D electron fluid with mean surface density n. For the absence of an external magnetic field we have obtained the dispersion relation for the plasmon excitation

Band Structure of Non-Ideal Semiconductor Superlattices

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Center for Fundamental Materials Research and

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An ideal superlattice is a array of two (or more) alternating layers of materials with a single period, fixed barrier height and infinitely abrupt interfaces. A real superlattice differs from an ideal one in at least three aspects and this affects the miniband structure. They include unsharp interfaces, small fluctuations in the length of the superlattice period and in the potential barrier height. The miniband structure of superlattices in these realistic cases have been investigated in this paper. We have assumed that the potential formed in the interface regions are linear and that the fluctuations in both the period length and barrier height are random of Gaussian distribution. Under these assumptions the miniband structure as a function of the shape of the Gaussian distribution (which depends on the quality of growth) and on thickness of the interfaces has been calculated. Their effects on the miniband structure are quite significant. The relevance of these non-ideal cases to the shifting of the ground state energy of the electron, and the effective energy gap are also discussed.

Mean-Field Calculations of Electronic States in Optically Excited CdMnTe-CdTe Quantum Wells

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Martin Marietta Laboratories

Baltimore, Maryland

ABSTRACT

Because the mean-field Hamiltonian for a paramagnetic semiconductor is a local function of $|\psi|^2$, it is possible to find the exact electronic eigenstates of an optically-excited quantum well with paramagnetic cladding (such as CdMnTe-CdTe) by reducing to quadratures. The magnetic effects are mediated by the free electrons and holes optically injected into the well, which give rise to spin-induced polarization of the magnetic ions in the cladding layers. Results are presented for electron and hole states in CdMnTe-CdTe quantum wells as a function of magnetic field, injected carrier density, and Mn composition. From this model, it is possible to prove that no asymmetric mean-field states are possible for such a quantum well (i.e., all states in the well have definite parity). The implications of this fact for bound-magnetic-polaron theories are discussed.

An Improved Tight Binding Band Structure Calculation of III-V Semiconductor Superlattices

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The electronic band structure of III-V semiconductor superlattices is investigated by means of an improved tight binding method. The essence of method and results of the calculation are as follows. (1) In fitting the bulk band structures to the pseudopotential calculation, the overlap integrals up to the second nearest neighbor atoms, including new parameters, are explicitly taken into account in order to improve the fitting of the lowest conduction band dispersion, and resulting in the good improvement. (2) In the examples of GaAs-AlAs superlattices, the two cases of band offset values based on Dingle's rule, Miller's rule (Kroemer's rule) are employed and the resulting band structures are compared. (3) $(GaAs)_n/(AlAs)_n$ (n = 1-10) are investigated with paying an attention to the asymptotic approach to the Kronig-Penny model of a quantum well. (4) $(GaAs)_m/(AlAs)_1$ and $(AlAs)_m/(GaAs)_1$ (n = 1-10)are investigated with paying an attention to the band folding effect and to a possibility of transforming an indirect-gap material to a direct-gap material. (5) The estimated optical oscillator strength between the valence band top and a few of the lower conduction band minima at Γ-point for the cases of (3) and (4) indicates that the folded states are less effective for the optical absorption or emission but their quantitative characters depend on each superlattie structure, so that the further calculation is desirable in order to make an indirect-gap material be applicable to a "light emitting device".

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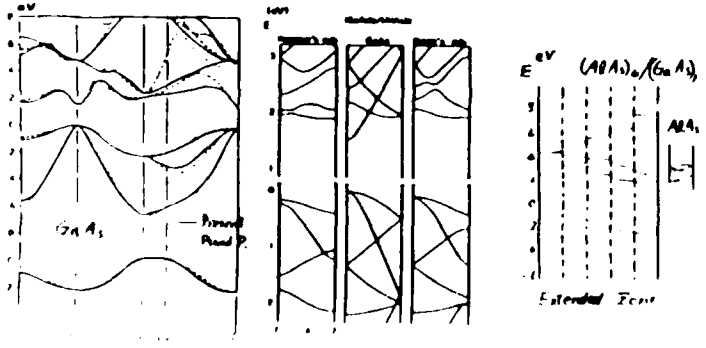
*ATR : Advanced Telecommunications Research Institute International

**On leave from Central Research Laboratory, Mitsubishi Electric Corporation



Exchange Correlation Energy in the Subbands of a Doping Superlattice

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Dept. of Elect. Eng., University of Alberta, Edmonton, Canada T6G 2E1.

Early calculations of the electronic subband energies in a doping superlattice were based on the Hartree approximation for the self-consistent potential [1]. Subsequent calculations included the exchange-correlation energy based on the local density functional method [2] by adding to the Hartree potential an additional exchange term, the Kohn-Sham potential. In our calculations, we make use of a more explicit form of the exchange term which includes the Kohn-Sham potential modified by a correlation enhancement factor [3]. Calculations using this method are done for both (100) silicon and GaAs and in three different cases of doping superlattice: pn^+p, pnpn and nipi.

Our numerical results show that the exchange-correlation term plays a more important role in silicon than in GaAs doping superlattices in all three cases. For the same doping levels, layer thicknesses and electron concentrations, the shift in the lowest subband energy from the value given by the Hartree approximation is 30 - 50% greater in silicon than in GaAs. This is due to the fact that while the higher valley degeneracy in silicon tends to reduce the Kohn-Sham potential, it is more than offset by stronger localized wavefunction due to the greater effective mass. In addition, the higher value of the effective mass and multiple valley degeneracy combine to give a larger correlation enhancement factor in silicon than in GaAs. Typically, when the correlation enhancement factor is included, the shift in the lowest subband energy from the value given by the Hartree approximation is about 30% more, whereas the corresponding number for GaAs is 10%.

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Abstract Submitted
for the Third Int'l Conference on
Superlattices, Microstructures and Microdevices
August 17 - 20, 1987

Γ-X Mixing in GaAs/$Al_xGa_{1-x}As$ and $Al_xGa_{1-x}As$/AlAs Superlattices. †
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- We have made a systematic study of the conduction bands of the (001) GaAs/$Al_xGa_{1-x}As$ and $Al_xGa_{1-x}As$/AlAs superlattices using a one-band Wannier orbital model. The parameters in the Wannier model are fitted to correctly describe the lowest bulk conduction band over the entire Brillouin zone, including the correct effective masses as a function of pressure. Using this model we have examined the dependence of the superlattice conduction band energy levels on layer thicknesses, alloy composition, wavevectors, as well as external hydrostatic pressure. We have found that there can be substantial mixing between the Γ-valley states and the (001) X-valley states. Mixings between the (100) and (010) X-valleys, and between the $(\frac{1}{2}\frac{1}{2}\frac{1}{2})$ and $(\frac{1}{2}\frac{1}{2}\frac{-1}{2})$ L-valleys are also studied. It is found that these mixings depend critically on the layer thicknesses. Our calculations also show that the pressure coefficient associated with the Γ-like quantum well states decreases with well width, the results are in good agreement with experimental data[1].

† Work supported by ONR N00014-81-K-0430.

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1

Effect of Collisional Broadening on the Polarizability of a Two-Dimensional Electron Gas. S. K. LYO. Sandia National Laboratories. -- The effect of the collisional damping (Γ) of the electronic levels on the Lindhard polarizability is studied for a degenerate two-dimensional electron gas interacting with ionized impurities by using an effective mass approximation. A specific wave-vector dependence as well as the Γ-dependence of the correction Δπ to the polarizability is obtained. In particular we find a significant reduction of the polarizability in the vicinity of the back-scattering regime: $\Delta\pi = -\sqrt{2}\Gamma[(k+k')^4+\Gamma^2]^{-1/4}$ where Δπ is given in a dimensionless unit. The initial (k) and the final (k') wave vectors are in units of twice the Fermi wave number and Γ is in units of four times the Fermi energy. The consequence of this result on the low-temperature mobility will be discussed.

*Supported by the U.S. Department of Energy under Contract DE-AC04-76-DP00789.

Third International Conference on Superlattices, Microstructures & Microdevices

Optical Studies of Unconfined Transitions in $GaAs/Al_xGa_{1-x}As$ Superlattices*

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J.N. Schulman, Hughes Research Labs.,
C.W. Tu, AT&T Bell Labs.,
and H. Morkoç, University of Illinois

We recently reported the observation of optical transitions between *unconfined states* in $GaAs/Al_xGa_{1-x}As$ superlattices at 5K using photoexcitation spectroscopy[1]. It was found that the transition strengths are a sensitive function of the *barrier width*. We have confirmed our previous observations with a new series of superlattices in which the well width and the aluminum concentration in the barrier are fixed. Further, we have found that the unconfined transition peaks are, in fact, doublets[2]. The origin of the doublet is attributed to optical resonances formed at the Brillouin-zone (BZ) center and the BZ edge. The separation of the doublet peaks depends on the barrier layer thickness, L_b. As L_b increases, the energy separation between the doublet peaks decreases. In some cases, the splitting changes at a rate equivalent to ~0.8meV for one atomic layer difference (2.83Å) in L_b. We also found that the splittings are hardly dependent upon the aluminum concentration. The experimental results will be compared with theoretical calculations based on a two-band tight binding model. They will also be compared with confined transitions exhibiting the subband energy dispersion along the sample growth direction.

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*Supported by ONR and AFOSR.

Optical Study of the Electronic Structure of $In_xGa_{1-x}As$-GaAs Strained-Layer Quantum Wells

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R. C. Miller, A. Y. Cho and D. L. Sivco

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ABSTRACT

We report a light scattering investigation of the electronic structure of $In_xGa_{1-x}As$-GaAs quantum wells lattice-matched to GaAs. We find that the valence band offset in this system is much larger than the value usually accepted.[1] This result has important consequences for the valence band structure. In particular, it means that the light holes remain localized in the $In_xGa_{1-x}As$ quantum wells, in contradiction with previous reports of a type II superlattice for light holes.[2] We confirm our new assignment by photoluminescence experiments with circular optical polarization.

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ABSTRACT SUBMITTED
for the Third International Conference on
Superlattices, Microstructures & Microdevices

August 17-20, 1987

Photoluminescence from GaAs under the Picosecond-Laser-Driven Shock Compression--X. Z. Lu, R. Caruthara, S. Lee and R. R. Alfano, **Institute for Ultrafast Spectroscopy and Lasers, The City College of New York, New York, N.Y. 10031**--Shock waves in GaAs semiconductors were generated by intense picosecond laser pulses. A pump-and-probe technique was used to investigate the shock effects on the photoluminescence spectra (~ 813 nm) at T ~ 80 K due to the direct transition from the Γ_6 conduction band to the Γ_8 4-fold degenerate top valence band in GaAs. Under the shock loading condition, the photoluminescence peak was observed to split into two components, corresponding to the transitions from the Γ_6 conduction band to the valence heavy- and light-hole-subbands, due to symmetry breaking by the uniaxial shock compression along the [001] direction. Both components were blue-shifted owing to the shock-pressure-induced band gap expansion. From the photoluminescence peak blue shift of up to 80 meV of the electron-heavy-hole recombination we deduced our picosecond-laser-driven shock pressure P ~ 14 kbar.

This research is supported by AFOSR and ONR

†Prefer Standard Session

Submitted by

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Optical Absorption in a Silicon Doping Superlattice

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Optical absorption at wavelengths greater than 1 μm is calculated for a silicon doping superlattice with a periodic internal potential. When the scale-length of the variation in the internal electric field is larger than the region in which the electron and hole wavefunctions overlap, the absorption coefficient may be calculated locally (Franz-Keldysh effect), and the total absorption may be found by averaging over one superlattice period. Absorption beyond the fundamental edge for large period GaAs has been calculated using this approach [1], however the calculation for silicon is more complicated due to its indirect bandgap structure which requires the creation or destruction of a phonon during optical absorption. Our calculations include the contribution from all six phonon branches using an expression for absorption in a constant electric field derived by Penchina [2].

Detailed calculations were carried out for the case of narrow n-type layers with doping levels up to $10^{19}/cm^3$ between broad p-type layers. For $\lambda \sim 1.3\mu m$ an absorption coefficient higher than 0.1 cm^{-1}, may be achieved for field strengths less than the breakdown value. This implies an absorption efficiency of 10% in a device one centimeter long with optical guiding parallel to the superlattice layers. We also examine the tunability of the absorption by variation of the internal field. In some cases, a two-fold increase in the field will increase the absorption coefficient by more than an order of magnitude.

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VALENCE BAND OFF-SET AND EFFECT OF STRAIN IN HgTe/CdTe SUPERLATTICES

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A theoretical calculation is made to explain our far-infrared magnetoabsorption data on a HgTe/CdTe superlattice (SL), published earlier[1]. The model which is used to determine the energy levels in this SL, first described by Smith and Mailhiot[2], is generalised to include the effect of an external magnetic field. Optical transition selection rules are then derived. By fitting the theoretical results to the experimental data, we obtain the value of the valence band off-set V_p between the interfacing HgTe and CdTe layers, as well as some knowledge of the effect of strain in the SL.

In the calculation we assume that the "cut-off" energy at zero magnetic field in Fig.3 of Ref.1 is the energy difference δE between the heavy-hole and the light-hole subbands of the SL at the zone center, and the magnetoabsorption spectra[1] are the results of the interband optical transitions between the heavy-hole and the light-hole Landau levels. As a first approximation, we obtain V_p from δE by assuming that strain exists *only* in HgTe layers, since the substrate of this SL is CdTe. Using this value of V_p, the Landau levels are then calculated as a function of the magnetic field, and are compared with the experimental results. The calculated results fit the data reasonably well. To further improve the fit we assume that after several (say 10) layers have been grown on the substrate the lattice constants of the subsequent layers are no longer those of the substrate. Strain will then exist in layers of *both* constituent materials, the degree of the strain being unknown. Using the degree of the strain, together with V_p, as adjustable parameters, we are then able to optimize the fit of the theoretical results. Our best fit value of V_p is about 10 meV, consistent with other magnetoabsorption results[3].

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Phonon-Polariton Density of States in Semiconductor Superlattices

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Abstract. An interesting property of modulated semiconductor materials is that their reflectance and absorption spectra can nearly be chosen at will by adjusting the layer geometry. Introducing the concept of phonon-polariton density of states, this paper is aimed at investigating spectral properties of multilayered materials in the infra-red frequency range. Then, using powerful analytical methods, we will successively consider the cases of finite thickness layered structures and semi-infinite superlattices.

The local density of states of polariton modes is obtained using a Green's function technique. Complete information is then available on allowed radiative and non-radiative electromagnetic excitations, (as a function of frequency and wavelength), at any depth in the stratified material. This approach will depict the essential role played by the surface, which changes significantly the polariton density of states as compared to ideal unbounded materials. The appearance of surface modes results from this modification. In multilayered materials, in addition to the effect induced by the surface, one can similarly investigate the influence of the internal interfaces on the polariton local density of states and, from these, on the optical properties of those systems. In the case of semi-infinite superlattices, the local density of states for both TM and TE polarizations allows us to clarify the respective importance of the interfaces and of the artifical anisotropy on the spectral properties. Electromagnetic eigenmodes arising from the accumulation of interfaces are crucial to assess the spectral properties involving TM-polarized radiations. Effects related to the TE-polarized radiations are explained from the macroscopic anisotropy due to the alternate growth of different semiconductors. These results will be used to discuss recent reflectance experiments and simulated ATR spectra.

Auger Decay of X Point Excitons in a Type II GaAs-AlGaAs superlattice

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Abstract

The nature of the cross-interface and cross-k-space recombination in a type II GaAs/AlGaAs superlattice (SL) created by the application of hydrostatic pressure (0-45kbar), is investigated. Optical measurements were made in a diamond-anvil-cell, at liquid He temperatures, on a variety of SL and multi-quantum-well structures. The observation of "fast", direct-gap quantum well (Γ) luminescence at long (10-100ns) delays after the exciting laser pulse is evidence for the Auger decay of the X-point excitons. The weak, direct-gap luminescence was found to decay at the same rate as the (50 meV at 35kbar) lower energy, cross-interface (X) luminescence. The X luminescence lifetime was reduced by an order of magnitude by raising the temperature from 6 to 30K but in all cases the Γ luminescence decay tracked the X luminescence decay. These observations are indicative of the feeding of the higher energy Γ luminescence by the Auger decay of the X luminescence. The observed intensity of the photoluminescence is a sub-linear function of the excitation density and is pressure independent, consistent with an increasing Auger decay. The Auger rate is thermally enhanced with an activation energy of 1 meV. This is interpreted as due to an increased free-X-exciton mobility, thereby increasing the capture rate on neutral donors and hence the Auger mediated recombination. Understanding the exact nature of the cross-interface luminescence in a type II superlattice is important for the direct optical determination of the band offsets, and for the detailed description of indirect-gap spatially quantized electron states.

Photoreflectance, Raman Scattering, Photoluminescence and Transmission Electron Microscopy of MOCVD GaAs/GaAlAs Multiple Quantum Wells

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Photoreflectance (PR), Raman scattering, low temperature Photoluminescence (PL) and transmission electron microscopy (TEM) have been performed on MOCVD grown GaAs/GaAlAs multiple quantum wells (MQW) with 100A and 200A well widths. In PR, which was performed in the range 300K and 77K, we have observed a number of allowed and forbidden quantum well transitions (including miniband dispersion effects) as well as features from the GaAs buffers. The large number of observed PR features, combined with a theoretical Bastard model calculation enables us to completely characterize the physical structure of the MQW's, i.e., well and barrier width in addition to barrier height (consistent with Raman data). We designate the quantum transitions as mnH(L), where m is the conduction subband and n is the valence subband of heavy (H)- or light (L)-hole character. In comparison with theory both the 11H and 11L experimental peaks occur at higher energies, a discrepancy that can be explained by assuming about 1% mole fraction of Al in the GaAs wells. This is confirmed by the PL, Raman and TEM measurements. For the higher lying transitions the agreement between PR experiment and theory indicates that the interfacial grading is less than about 10% of the well width, consistent with the TEM data. Interesting lineshape changes with temperature will also be discussed.

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Measurement of Superlattice Optical Properties from 1.45-4.5 eV by Variable Angle of Incidence Spectroscopic Ellipsometry.* P.G. SNYDER, J.A. WOOLLAM, U. Nebraska Lincoln, D.W. LANGER, C.F. STUTZ, R. JONES, Avionics Lab, WPAFB, A.K. RAI, K. EVANS, Universal Energy Systems.

Variable angle of incidence spectroscopic ellipsometry (VASE) [1] is a sensitive, nondestructive technique for determining optical constants, layer thicknesses, microstructure, and other parameters. It has been used recently to characterize layer thicknesses and composition [1], built-in electric fields [2], and implantation induced Al redistribution [3] in GaAs Al(x)Ga(1-x)As heterostructures.

We have applied VASE to the study of AlAs-GaAs and Al(x)Ga(1-x)As GaAs superlattices. Sharp spectroscopic features were observed at the first electron to heavy hole, e-hh(1), first electron to light hole, e-lh(1), and second electron to heavy hole, e-hh(2) transition energies. To our knowledge, these are the first observations by spectroscopic ellipsometry of quantized level transitions near the fundamental gap. Cross sectional transmission electron microscopy (XTEM) showed these superlattices to be of good quality. VASE data for two other samples did not contain any sharp features due to quantized level transitions, and XTEM of these samples revealed poor quality superlattice structure. This confirms the direct correlation between superlattice quality and VASE measurements. A comparison of VASE, XTEM, and also photoluminescence and photoreflectance results will be presented.

An advantage of ellipsometry over other techniques is that the complex refractive index, N, can be obtained without Kramers-Kronig analysis. Experimentally determined values of the effective N for a superlattice are useful both for optoelectronic device design, and for comparison with theory [4]. The effective N for a 20 period superlattice was solved using VASE data at three angles of incidence, near 74°. Re(N) is increased by about 3% at the e-hh(1) peak, and the imaginary part (extinction coefficient) is increased by 0.05.

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PHOTOREFLECTANCE OF GaAs DOPING SUPERLATTICES

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Room temperature photoreflectance (PR) of molecular beam epitaxy (MBE) GaAs doping superlattices were measured.6328A line of a 1mW He-Ne laser,chopped at 125 Hz was used as the pump beam.It is found that much more fine structures appear when pump beam intensity decreases by several magnitudes.Analysis show that this is not third derivative spectrum,and it is not easy or simple to distingrish the optical transitions corresponding to the PR spectrum.We thought PR of doping superlattices having mainly first derivative linashape caused by modulatted built-in potential from photon injection.Theoretical calculations based on a simple model and effective mass approximation (EMA) give a good explanation to all the experiments.

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PbTe-SnTe Superlattices

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The PbTe-SnTe superlattice has potential as an infrared material. 1) The symmetry reversal of the valence and conduction bands between SnTe and PbTe ($L_2' - L_1$ and $L_1 - L_2'$, respectively) can be exploited to obtain arbitrarily small energy gaps. 2) As in the HgTe-CdTe system, calculations indicate that superlattice layer thickness affords better control of the gap than does alloy composition. 3) The unusual toroidal constant energy surface at the band edge of SnTe might be used to optimize quantum efficiency. 4) A PbTe-SnTe superlattice may be more stable than HgTe-CdTe against layer interdiffusion. The expected band gap as a function of repeat distance and thickness ratio has been calculated for a small period superlattice. Useful band gaps should be obtained with realizable layer thicknesses. Superlattices with 60 A PbTe and 60 A SnTe layers have been produced by vacuum deposition on BaF_2 substrates, but are strongly p-type due to Sn vacancies. Doping with Bi reduced the hole density in isolated SnTe films by two orders of magnitude (from 10^{20} cm^{-3} to 10^{18} cm^{-3}) but failed to completely compensate the material. Attempts to Bi dope only the SnTe layers of the superlattices produced n-type SL's, suggesting the presence of Bi in the PbTe layers. This may be a result of the accumulation of Bi on the SnTe surface during growth.

Dielectric Function Due to Carrier Confinement in Semiconducting Quantum Well Systems

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We have calculated the real part of the dielectric function from the interband optical absorption in semiconducting quasi-one and two dimensional structures by using the Kramers-Kronig dispersion relations. The real part of the dielectric function, which is related to the index of refraction, is found to be strongly effected by the confinement of the carriers. In Q2D quantum well structures, logarithmic singularities are found at photon frequencies such that interband transitions can occur between new pairs of subbands in the conduction and valence bands. In Q1D quantum well wire structures, sharp peaks occur at such photon energies. Below the lowest energy for interband transitions, the confinement of the carriers causes a reduction of the index of refraction below its value in a bulk semiconductor with the same material parameters with the reduction being greater for Q1D quantum well wire structures than for Q2D quantum well structures. Therefore, the confinement of the carriers in such structures should dramaticly change the index of refraction in the vicinity of the band gap

Exciton Linewidth Due to Scattering From Free Carriers in Semiconducting Quantum Well Structures

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The contribution to the exciton linewidth in semiconducting quantum well structures due to the scattering of excitons by free carriers is calculated. It is found that this contribution becomes very important in limiting the exciton linewidth when a high density of free carriers is present or at low temperatures where the scattering of the excitons by optical and acoustic phonons is reduced. This contribution to the linewidth in quantum well structures is compared with the contribution due to the same mechanism in bulk semiconductors. It is found that the exciton linewidth due to this scattering mechanism is enhanced in quantum well structures over its value in a bulk semiconductor of the same material parameters.

EFFECTS OF UNIAXIAL STRESS ON HOLE SUBBAND IN QUANTUM WELLS

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ABSTRACT

The hole subbands in a quantum well with a finite potential barrier under a uniaxial stress are calculated by solving the Luttinger-Kohn Hamiltonian (including the warping of the valence band but ignoring the spin-orbit interaction) plus the strain energy Hamiltonian in the spin J=3/2 basis. The boundary conditions are obtained by integrating the total Hamiltonian across the interfaces of the well. The hole subbands are investigated as functions of the wave vector $\vec{k}$ parallel to the interface, the uniaxial stress $\vec{X}$ along various directions, the thickness L of the well and the potential barrier height V_h. We compare the stress dependence of some of our calculated band edge energies with experimental results. We report on the variations of the effective masses at $\vec{k} = 0$ with $\vec{X}$, L, V_h and the angle between $\vec{k}$ and $\vec{X}$. The effective masses are shown to vary strongly and to differ from the results obtained by using infinite well model.

Electronic properties of pseudomorphic InGaAs/AlGaAs (on GaAs) and InGaAs/InAlAs (on InP) MODFET structures.

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Recently, there has been a considerable interest, with remarkable success, in pseudomorphic (strained channel) modulation doped field effect transistors. The motivation for these studies has been the potential for higher carrier mobility, band discontinuity, peak and saturation velocity, as well as the ability to tailor compositions to avoid problems such as the DX center in the $GaAs/Al_{0.3}Ga_{0.7}As$ MODFET. To fully utilize the potential of these devices and to select the ideal In composition for the channel, it is important to understand the effects of the strain on the electronic properties of the channel. To study this, we have used a tight binding method coupled with deformation potential theory. This technique is capable of accurately fitting the bandstructure, including the electron and hole effective masses, of semiconductors in the presence of strain. We will report results on the channel effective mass tensor, intervalley separations, and bandgaps for both electron and hole states for $In_xGa_{1-x}As/Al_yGa_{1-y}As$ on GaAs and $In_xGa_{1-x}As/In_yAl_{1-y}As$ on InP MODFETS as a function of strain. In the table below, we present the electron effective masses in a direction parallel to the interface for varying In compositions in the materials shown both when they are unstrained, and when they are biaxially strained to match the substrate indicated.

$In_xGa_{1-x}As$ on GaAs			$In_{0.53+x}Ga_{0.47-x}As$ on InP	
x	$m^*_{\parallel unstrained}$	$m^*_{\parallel strained}$	$m^*_{\parallel unstrained}$	$m^*_{\parallel strained}$
0.00	0.0655	0.0655	0.0451	0.0451
0.03	0.0643	0.0651	0.0439	0.0446
0.06	0.0631	0.0647	0.0427	0.0441
0.09	0.0619	0.0643	0.0415	0.0436
0.12	0.0607	0.0639	0.0403	0.0430

Since at this time the bandedge lineups of strained systems are not well known, we will discuss the effect of band lineup on the channel properties. Consequences for charge transport will be discussed and comparisons made with existing data. Channel properties can be improved by the addition of In, and predictions for the optimum strain for different configurations will be made.

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ENSEMBLE MONTE CARLO SIMULATION OF VELOCITY MODULATION (VMT) AND REAL SPACE TRANSFER (NERFET/CHINT) DEVICES

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We study in detail the dynamics of electron transport in velocity modulation transistors (VMT)[1], and devices based on real space transfer[2] (NERFET/CHINT)[3].

For this analysis, a self-consistent particle-field ensemble Monte Carlo model has been used. The model incorporates the Γ−L−X band structure for both GaAs and AlGaAs. Polar optical phonon scattering, equivalent and non-equivalent intervalley scattering, ionized impurity scattering, impact ionization and real space transfer are included.

The velocity-modulation concept attempts to capitalize on the extremely short perpendicular transit times between two adjacent channels with different transport properties (i.e., mobility). Our analysis shows that current switching can be achieved by the velocity modulation concept, and the calculated switching speeds compare favorably to that of the conventional GaAs field effect transistors.

The simulations performed for real space transfer devices (NERFET/CHINT) are in agreement with experiments and reproduce all prominent features of these structures such as negative differential resistance (NDR) in the drain current, saturation of drain and substrate (injection) current at high source-to-drain voltages, and the negative transconductance ($\Delta I_{D,sat}/\Delta V_{sub} < 0$) in the saturated drain current.

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THE MOBILITY OF ELECTRONS IN STRAINED SILICON STRUCTURES

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Developments in Si molecular beam epitaxial growth techniques have lead to the formation of abrupt junction Si/SiGe heterostructures on Si substrates. In these layers the conduction band offset between the Si and SiGe layers is determined by both the Ge concentration in the SiGe layers and the strain distribution within the structure. This strain distribution may be controlled by growing the films commensurately on a range of SiGe buffer layer compositions. By appropriate choice of buffer layer the electrons may be confined in the Si layer, and HEMT structures have been produced using this effect (1). An increased understanding of the transport properties of electrons confined within the triangular wells of these structures can be obtained by considering the effect of strain on the electron mobility of bulk silicon, the subject of this paper.

Strain has the effect of splitting the bulk 6-fold degeneracy of the conduction band minimum into 2-fold and 4-fold symmetric components. In this work it is assumed that the shape and position of the band minima in k-space are changed little with strain, and that bulk values may be used for effective mass corrections for non-parabolicity. To study the transport properties of these layers a Monte Carlo technique has been used to simulate the movement of an electron in thin but bulk-like layers of Si under various strains. In these calculations larger fields than those normally encountered in devices were used to reduce computational times while retaining precision.

Results from these calculations show two phenomena. At fields <1E6 V/cm and low strain levels the in-plane mobility increases with strain, whereas at higher fields and strain levels mobility decreases with strain. The increase in mobility with strain can be explained by appreciating that the effect of increasing strain is to reduce the energy of the 2-fold minima with respect to the 4-fold minima and thus increase their population. But within the plane, the 2-fold minima also have a lower effective mass than the 4-fold minima, thus increasing the electron velocity between collisions, and hence mobility. At large fields and strain levels the mobility decreases as the rate of inter-valley scattering involving optical phonons decreases, reducing the ratio of the energy loss rate to total scattering rate and thus lowering the electron drift velocity.

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RESONANT TUNNELING THROUGH GaAs/AlGaAs HETEROSTRUCTURES

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Vertical transport in a finite GaAs-AlGaAs superlattice is studied in terms of the resonant tunneling process.The multibarrier transmission probability is determined using an iteration matrix formalism within the effective-mass approximation and assuming a uniform electric field with Airy function solutions and appropriate boundary conditions at the interfaces.The current-voltage(I-V)characteristics of double-barrier devices are computed at selected temperatures and the results are compared with recent tunneling-current measurements.It is shown that the features in the I-V curves at high bias observed by E.E.Mendez et al(Phys.Rev.B 33, 7368(1986))can be explained by assuming intra-valley tunneling of Γ states without invoking transmission via high energy states at the point X of the Brillouin zone.

EQUIVALENT CIRCUIT OF THE BARRIER-CONDUCTOR STRUCTURES

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Novel heterostructure devices are comprised of potential barriers connected by short conductors. Typically the conductor is longer than the de Broglie wavelength of the electron. This means that the conductor part can be treated by the semiclassical Boltzmann equation. On the other hand, a general solution of the Boltzmann equation is needed since the conductor length can be less than the electron mean free path. Particle transport through the potential barriers is described by the quantum mechanical wave transmission. The solution of the Boltzmann equation can be fitted to account for the reflection and transmission phenomena occurring at barriers. This provides a complete solution for the whole system.

The equivalent circuit is determined from the small signal analysis of the barrier-conductor chain. As an application the high frequency properties of the single barrier, double barrier, ballistic transistor and the infinite periodic chain are discussed.

NEGATIVE RESISTANCE IN STRAINED LAYER DOUBLE BARRIER HETEROSTRUCTURES

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We have grown, processed and tested several different strained layer GaAs–AlAs–$In_xGa_{1-x}As$–AlAs–GaAs double barrier resonant tunneling structures with both quasi-stationary resonant states and bound states. An advantage of the strained layer approach is that by varying only the depth of the InGaAs well the voltages associated with the peak current can be adjusted (reduced) while holding constant all other thickness and compositions.[1,2]

The thrust of this work is to investigate the limits of tunneling with respect to the indium composition x and the presence of energy states below the energy level through which the tunneling occurs. Room temperature negative differential resistance has been observed for indium compositions as high as $x = 0.18$. For samples with both resonant and bound states negative differential resistance has been observed for the $n = 2$ resonant state while only weak tunneling resulting in a zero conductance feature has been observed for the $n = 1$ "bound" state at 77K. The bias voltages at which resonant tunneling[1] and tunneling through the bound state should occur, $V_r = 2(E_n - \Delta E_c)/e$ and $V_b = 2(\Delta E_c - E_n)/e$, respectively, is in qualitative agreement with a simple quantum mechanical model that includes strain effects.

Negative differential resistance has been observed over a large range of indium compositions in pseudomorphic InGaAs-AlAs-GaAs double barrier tunnel structures, and for the first time in structures that have both resonant and "bound" states. Qualitative agreement for the observed features are consistent with a simple quantum mechanical model. Tunneling associated with "bound" states appears to be inelastic (tunnel-scatter-tunnel) where as tunneling through resonant states is elastic.

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Electronic properties of InAsP/InAs strained-layer superlattices prepared by hydride vapor phase epitaxy

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The electronic properties of strained-layer superlattices of $InAs_xP_{1-x}$/InAs prepared by hydride vapor phase epitaxy are reported for the first time. The InAsP/InAs system is potentially useful for both microwave and optoelectronic device applications. For these superlattices x = 0.63-0.83, which correspond to bandgap differences of E_g = 0.13 - .31 eV. The superlattices were grown on semi-insulating Fe-doped InP using a single barrel horizontal reactor. The superlattice consisted of n periods of alternate InAsP and InAs layers with equal thicknesses of 50 nm. The net carrier concentrations for these structures at 295K are in the low 10^{16} cm^{-3} range with electron mobilities between 8130 and 12,100 cm^2/V-sec. The highest electron mobility was obtained for an $InAs_{0.7}P_{0.3}$/InAs superlattice, which has a lattice misfit strain of 0.95%. The observed mobilities are comparable to lattice matched systems involving InAs. The highest liquid nitrogen mobility observed for the InAsP/InAs structure was 4.7×10^4 cm^2/V sec for a net carrier concentration of $1.15 \times 10^{16} cm^{-3}$. Further improvement in mobility is expected using modulation doping.

Electronic conduction mechanisms in the superlattices were studied from their magnetoresistance properties at 1.6K. For these measurements the van der Pauw configuration was used. Highly anisotropic magnetoresistance was noted for magnetic fields perpendicular and parallel to the layer. For low fields a negative magnetoresistance that was proportional to the square of the magnetic field was observed. For high magnetic fields on samples with high mobilities, oscillations in the magnetoresistance were noted. Moreover for the highest mobility sample, well defined plateaus in the magnetoresistance along with other anomalous structures were observed. From the observed Shubnikov-deHaas oscillations the effective carrier density was calculated to be 1.8×10^{11} cm^{-2}.

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WARM ELECTRON COEFFICIENT OF TWO DIMENSIONAL ELECTRON GAS IN A GaAs-AlGaAs HETEROJUNCTIONS AT LOW TEMPERATURES

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In the presence of a moderate electric field, F, the deviation of the mobility from its ohmic value is proportional to F^2. The values of the proportionality constant B : the warm electron coefficient for 2DEG in GaAs has been reported and the values of inelastic scattering time have been estimated from the measured power loss /1/.

In the present work, the theory of warm electron coefficient has been developed by assigning an electron temperature to the 2DEG and considering screened potentials for interaction between 2DEG and deformation potential and piezoelectric phonons, and remote and background impurities. All the states are assumed free so that the density-of-states is constant. This model has been successful in explaining the mobility behaviour of 2DEG in heterojunctions /2,3/ and has been employed in /1/ to obtain the values of inelastic scattering time.

The calculated mobility using the impurity density and spacer width reported in /1/ is about one order higher. The experimental values can only be reproduced by assuming too high a value of background impurity density ($10^{16} cm^{-3}$). However even with this value the calculated B are two order lower and in contrast to the reported ones, increase with temperature. It is likely that localised states are present giving rise to activated behaviour for the mobility and warm electron coefficient. The effect of deviation of DOS from constancy on B and mobility is estimated.

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THE TRANSIENT AND STEADY-STATE RESPONSE OF THE TWO-DIMENSIONAL ELECTRON GAS IN HETEROJUNCTIONS SUBJECT TO AN EXTERNAL ELECTRIC FIELD

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Abstract The time-dependent linearized Boltzmann equation is solved accurately by a new self consistent algorithm to obtain the time dependent subband distribution functions in response to a step-wise electric field applied parallel to the AlGaAs GaAs heterojunction interface. The scattering mechanisms included in the calculation are remote ionized impurity scattering, acoustic, piezoelectric and polar optical phonon-electron scattering. Both intra- and inter subband scattering are included. The transient and steady state transport properties of the two dimensional electron gas are studied. In particular, it is discovered that the energy dependent relaxation time plotted against energy oscillates with a characteristic period equal to the optical phonon energy of 36meV. The oscillations are more enhanced at low temperature than at high temperature. Inbetween the peaks of the optical phonon mode oscillations are small peaks due to intervalley scattering. The order of magnitude of the relaxation time is around 10^{-11} and 10^{-12} seconds.

Complex band structure calculations of the electric field dependence of the reflection and transmission of valence band states from a (100) GaAs/AlGaAs quantum well (barrier)

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A pseudopotential complex band structure approach is used to investigate the transmission and reflection of heavy hole (hh) light hole (lh), and spin-split-off (sso) states from a (100) GaAs/AlGaAs quantum barrier (well) that has a constant electric field applied across it. Large deviations are observed from a simple postion-dependent effective mass theory (EMT), even for $k_{\parallel} = 0$. In particular, for an incident lh state there is a large barrier (well) induced mixing with the sso states at the three electric-field dependent sso band edges, which drastically reduces the transmission of the lh states and excites the transmission of sso states. Incident hh states mix only very weakly with the lh and sso states and in this case the main deviation from EMT is due to electric-field dependent nonparabolic effects. We investigate the differences between the well and barrier that are due to the bound sso well states. We also discuss more complicated structures and external fields (e.g., double wells and external magnetic fields etc.).

NUMERICAL EVALUATION OF FEYNMAN INTEGRALS OVER PATHS IN REAL AND IMAGINARY TIME

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Abstract

New techniques are described for Monte Carol evaluation of quantum mechanical systems in the Feynman "integral over paths" formulation. Path translation, a simple yet powerful technique, is introduced in imaginary-time calculations. It is demonstrated that path translation allows the imaginary-time propagator to be accurately evaluated using Monte Carlo techniques even when multiple potential minima are present. Examples considered include a symmetric double finite square well potential and a symmetric double barrier potential. In real-time calculations, a "windowed action" with both real and imaginary components is obtained from an analytical averaging of the exponential in the action over a small range of paths. The imaginary component of the windowed action, by creating an exponentially decaying probability for selecting paths, allows the propagation of the density matrix in real-time to be evaluated using Monte Carlo techniques.

(This work is supported by the Office of Naval Research, Arlington, VA).

SHUBNIKOV-DE HAAS MEASUREMENTS OF THE 2-D ELECTRON GAS IN PSEUDOMORPHIC $In_xGa_{1-x}As$ ($x \leq 0.20$) GROWN ON GaAs*

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Thin layers (~200 Å) of pseudomorphic $In_xGA_{1-x}As$ ($x \leq 0.20$) have been grown by molecular beam epitaxy on a GaAs buffer layer. A Si-doped overlayer of $Al_{0.15}Ga_{0.85}As$ was used as the electron supply material. Shubnikov-de Haas (SdH) measurements were taken as a function of temperature ($1.8 \leq T \leq 7$ K) and in Concentration x ($0 \leq x \leq 0.20$) at magnetic fields below 1.4 T. Effective mass m^* and quantum scattering time τ_{SdH} were calculated using the procedure of Ando et al. [1]. The value of m^* shows a steep drop with increasing x. For example, we obtained $m^*=0.059\ m_o$ for x=0.18 at a 2-D electron gas (2DEG) density of $5.3 \times 10^{11}/cm^2$. We also found a small apparent magnetic field dependence of m^*, of order $0.003\ m_o/T$. Hall effect measurements were also performed as a function of temperature ($2 \leq T \leq 300$ K) and x. The low temperature mobility vs. x shows a peak of $10^5\ cm^2/(V\text{-}s)$ at x=0.18. This value is high compared to InGaAs lattice-matched to InP, but it is very low compared to AlGaAs/GaAs 2DEG material. This result is probably due to alloy scattering in InGaAs. The Hall mobilities were used to calculate the classical scattering time τ_H. The ratio τ_{SdH}/τ_H in InGaAs is of order unity compared to 0.1-0.2 measured by us in AlGaAs/GaAs. A theoretical estimate of τ_{SdH}/τ_H was performed, showing that a value of 1 is consistent with alloy scattering.

* work performed at NASA Lewis Research Center
† NASA Summer Faculty Research Participant
† Work supported by NASA grant NCC3-25
†† Work supported in part by NASA grant NNE3-613

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Resonant Tunneling Transistors

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This paper presents several new structures of resonant tunneling transistors (RTT's), the computer simulation results of the I-V characteristics for these RTT's, and the fabrication for some of the proposed RTT's using MBE and ultra-high resolution e-beam lithgraphy. The RTT's, which are different from that proposed by Capasso et al, have a gate electrode(s) which can tune the bottom of quantum well continuously. The devices operate by varying gate voltage at fixed source-drain voltage. The gate voltage moves the metastable quantum levels down, and tunneling current results whenever a resonant condition is satisfied. In the lateral surface RTT's, not only can the bottom of quantum well be adjusted, but also the barrier height and Fermi level can be adjusted continuously. Formalism and computer simulation programs have been developed for these devices. Simulation results show that, in RTT's, because the source-drain voltage is fixed and can be kept rather small, the leakage current is very small, while the resonant tunneling current, on the other hand, is very large, because the symmetry of the barriers in RTT is nearly preserved for a low source-drain voltage. Hence, the peak-to-valley ratio of RTT's is orders of magnitude larger than that of a resonant tunneling diode (RTD). Simulation shows that for an AlAs/GaAs/AlAs (5nm/5nm/5nm) double barrier quantum well RTT, a peak-to-valley ratio of 600 is predicted at 300K and 2,500 at 77K. These values are two orders of magnitude higher than that for a RTD with same quantum well structure and whose peak-to-valley ratio is calculated 3 at 300 K, and 15 at 77 K by our simulation.

Resonant Tunneling of Electrons of 2 or 1-Degrees of Freedom

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Although resonant tunneling of electrons of 3-degrees of freedom (DOF) through an 1-dimensional (confined) double barrier quantum well has been studied extensively, very little has been reported for the cases in which additional quantum confinement perpendicular to the direction of electron tunneling is introduced; and as a result, electrons have 2-DOF and tunnel through a 2-dimensional quantum well, or have 1-DOF and tunnel through a 3-D quantum well. This paper presents the formalism for the tunneling of the electrons of 2- and 1-DOF which are very different from that for electrons of 3-DOF, and computer simulation for the I-V characteristics of Resonant Tunneling Diodes (RTD's) of 2- and 1-DOF electrons. The simulation shows that at low temperatures, the reduction of the degree of freedom of tunneling electrons results in a much higher the peak-to-valley ratio and much narrower peak width in tunneling current. The paper also will address the effects of scattering for electrons of reduced degrees of freedom, and other quantization effects due to the additional confinement on the tunneling current. The fabrication technology of the RTD's for electrons of 2- and 1-DOF is based upon MBE growth and ultra-high resolution e-beam lithography, and it will be presented.

Simulation of Charge Transport in a GaAs MESFET Using the Time Dependent Schrodinger Equation

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ABSTRACT

Preliminary results of a quantum mechanical simulation of electron transport in a submicron scale GaAs MESFET are reported. The simulation is carried out through the solution of the time-dependent Schrodinger equation. The Poisson equation is simultaneously solved self consistently with the charge concentration to obtain the electrostatic potential. Charge transport in two different types of conduction band valleys is considered. The electron-phonon interaction (equivalent and non equivalent intervalley as well as acoustic and optical intravalley) is simulated in an approximation which is consistent with the results of first order perturbation theory.

WIGNER FUNCTION SIMULATION OF QUANTUM TUNNELING*

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The quantum mechanical phenomenon of tunneling time has been the subject of much debate. We have used a Wigner function description of a Gaussian wave packet (of neutral particles) to study the tunneling process. The parameters of the barrier and the energy spread of the packet are adjustable, enabling studies of many varied cases. From the time-evolution of the Wigner packet, we can determine the times of entry into and exit from the barrier, and thus determine the tunneling time. From the Wigner formalism, the tunneling probability and the phase shift of the packet are readily available. We note a tunneling time proportional to 1/k, and a constant tunneling delay associated with energies less than the barrier. We have extended the study to electrons, and have included self-consistent potentials. Self-consistency greatly affects the propagator for the Wigner functions through a non-local potential in the forcing term. The 1/k tunneling time is thus disrupted. Finally, we study resonant tunneling of a double quantum barrier problem. From this study, we show a peak in the tunneling probability, as in theoretical calculations, but not as sharp due to the energy spread of the incident packet. We also note persistence within the well at energies corresponding to bound states. This gives rise to sudden peaks in the tunneling times at the energies corresponding to the bound states.

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RESONANT TUNNELING TRANSISTORS

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We report an experimental project to incorporate double-barrier tunnel structures into three-terminal devices. These devices have the negative-differential-resistance (NDR) features of the double barrier, with the added flexibility of a third controlling electrode. One device concept involves the integration of a double-barrier tunnel structure with a field-effect transistor. This concept has been realized in several samples grown by metalorganic chemical vapor deposition. The devices consist of a GaAs-$Al_xGa_{1-x}As$ double-barrier tunneling heterostructure, the current through which is controlled by an integrated vertical field-effect transistor. All samples exhibit NDR in their source-drain current-voltage characteristics at 77 K, with peak-to-valley current ratios ranging between 3 and 5.3. One sample exhibits NDR at room temperature. The position and peak-to-valley current ratio of the NDR can be controlled by gate voltage. Due to asymmetry in the doping levels of the two GaAs cladding layers, resonant-tunneling peaks occur at larger voltages in reverse bias than in forward bias. Devices of this type may find application as oscillators, amplifiers, signal processing components, and logic elements. This work was supported in part by the Defense Advanced Research Projects Agency under contract No. N00014-84C-0083.

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Screening of the Exciton-LO Phonon Interaction in $In_{0.53}Ga_{0.47}As/InP$ Quantum Wells

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The Fröhlich interaction of an exciton with longitudinal optic (*LO*) phonons gives rise to phonon satellites 'X_{LO}' of the exciton photoluminescence (PL) line 'X'. We report the effect of free carrier screening of the Fröhlich interaction on the strength of X_{LO} in a modulation doped $In_{0.53}Ga_{0.47}As/InP$ quantum well (QW) grown by atmospheric pressure metal-organic chemical vapour deposition (MOCVD).

The sheet carrier density, n_s, in the QW could be varied from zero to ~10^{12} cm^{-2} using Schottky barrier depletion. X_{LO} has 5% of the intensity of X when *no carriers* are present in the well ($n_s = 0$). This unusually high intensity arises because, in these low temperature PL experiments, the hole thermalises into a very compact state which we propose is bound by alloy fluctuations. The ratio of X_{LO} to X is found to decrease linearly with n_s up to ~3×10^{11} cm^{-2}, when it is very weak, and is unobservable for $n_s > 5\times10^{11}$ cm^{-2}.

These results will be compared with the effect of screening on other manifestations of the Fröhlich interaction. Calculations of the polaron mass enhancement[1] Δm^* predict only a factor of two reduction in Δm^* at $n_s = 5\times10^{11}$ cm^{-2}, compared to the complete screening observed in our experiments at these carrier densities.

1. e.g. Das Sarma S and Mason B 1985 *Phys. Rev. B* 31 5536

Abstract withdrawn

EXCITONS AND OPTICAL PHONONS AS STUDIED BY RESONANT RAMAN SPECTROSCOPY IN CdTe/(Cd,Mn)Te QUANTUM WELLS

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Resonant Raman scattering (RRS) has been recently employed in semiconductor quantum wells and supe lattices to yield much insight into either the electronic or vibronic properties of these new artificial microstructures. A particularly useful case has been that of excitonic resonances in III-V quantum wells where RRS from optical phonons has yielded detailed information about nature of quasi-2D excitons in this system. We report on resonant Raman studies of excitons and exciton-LO phonon interaction in a II-VI strained layer superlattice based on (100) oriented CdTe/(Cd,Mn)Te heterostructures. While this superlattice has been the subject of a number of recent optical studies (1), many details of its electronic structure remain quantitatively uncertain. Among other things, magneto-optical spectroscopy has strongly suggested that the (valence) band offset of the CdTe/(Cd,Mn)Te system is small. This projection is directly verified in our Raman experiments by the presence of LO-phonon modes from both the CdTe well and (Cd,Mn)Te barrier layers with an incident photon energy near the n=1 quantum well exciton. The exciton is composed of a quasi-2D electron and a quasi-3D hole. From the details of the RRS excitation spectra we can obtain an approximate value for the valence band offset and the exciton binding energy for a given superlattice. Well defined ingoing and outgoing resonances are seen which agree with the results of luminescence excitation spectroscopy for the strain split heavy and light hole exciton ground state energies. A striking new aspect in our RRS spectra at low temperatures is the broadening of the Raman lines under resonant excitation of the n=1 excitons, thereby indicating the presence of anomalously large exciton-phonon interaction effects. This coupling which involves the Frohlich interaction appears to be characteristic of diluted magnetic semiconductor (DMS) superlattices with weak hole confinement. Additional information about the exciton-phonon interaction is obtained from the 2 LO phonon spectra which contains only particular overtones and combination terms.

(1) e.g. A.V. Nurmikko, R.L. Gunshor, and L.A. Kolodziejski, IEEE J. Quant. Electr. QE 22, 1785 (1986).

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FAR-INFRARED REFLECTANCE AND ANISOTROPY OF PHONON MODES IN GaAs-AlAs SUPERLATTICES*

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We report infrared reflectance spectra in the range 100-480 cm^{-1} for three GaAs-AlAs superlattices[1] with layer thicknesses of 50A/50A, 100A/100A, and 150A/150A. In the superlattice with 150A/150A layers we observed one peak at 360 cm^{-1} and a second unexpected peak at 380 cm^{-1}. We analyze this spectrum with long wavelength superlattice response theory[2] and find that the peaks correspond to phonon modes parallel to and perpendicular to the growth direction of the superlattice. Similar anisotropy has been observed in Raman scattering measurements[3], and explained theoretically[4], but we report the first infrared observation.

1. Samples were supplied by T. J. Drummond, Sandia National Laboratory.

2. V. M. Agranovich and V. E. Kravtsov, Solid State Commun. 55, 85 (1985).

3. R. Merlin, C. Colvard, M. V. Klein, H. Morkoc, A. Y. Cho, and A. C. Gossard, Appl. Phys. Lett. 36, 43 (1980).

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ABSTRACT SUBMITTED
for the Third International Conference on
Superlattices, Microstructures & Microdevices

17-20 August, 1987

Direct measurement of ultrafast electron-hole plasma expansion at high density in an asymmetric GaAs quantum well--Kai Shum, M. R. Junnarkar, M. S. Chao, and R. R. Alfano, Institute for Ultrafast Spectroscopy and Lasers, Physics and Electrical Engineering Departments, The City College of New York, and N. Morkoc, University of Illinois--The ultrafast spatial expansion of photoexcited electron-hole plasma created by a femtosecond laser pulse excitation in an asymmetric GaAs single quantum well at 8.3K was directly measured using a 3ps time resolution streak camera system. The experimental results show that the diffusion D is four orders of magnitude larger than the conventional ambipolar diffusivity (about 10^4cm/sec) and the ballistic velocity of the plasma is about four times larger than its Fermi-velocity. The mechanism which causes the photoexcited carriers to be so diffusive will be discussed.

†This work was supported by the Air Force Office of Scientific Research.

†Prefer Standard Session

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ABSTRACT SUBMITTED
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17-20 August, 1987

Nonequilibrium carrier phonon effect on the time-dependent relaxation of hot carriers in GaAs quantum wells--Kai Shum, M. R. Junnarkar, M. S. Chao, and R. R. Alfano, Institute for Ultrafast Spectroscopy and Lasers, Physics and Electrical Engineering Departments, The City College of New York, N. Morkoc, University of Illinois--The temporal evolution of photoexcited carrier temperature and carrier density in GaAs quantum wells (55A) is measured from the time-resolved photoluminescence measurements with 3ps time resolution. The energy loss rate for electrons $\left[\frac{d\langle E\rangle_e}{dt}\right]$ and for holes $\left[\frac{d\langle E\rangle_{hh}}{dt}\right]$, and the average phonon emission time τ_{avg} were experimentally determined as a function of carrier temperature (2300K-250K) and carrier density (10^{16}cm^{-3} for 5.5×10^{15}cm^{-3}). It is found the nonequilibrium phonon effect plays an essential role on time dependent energy relaxation of hot carriers. The existence of nonequilibrium phonons is further substantiated from the measurement of the lattice temperature dependence of the integrated luminescence spectra excited by fs pulses where a nonequilibrium-phonon-enhanced phonon replica emission band appears.

†This work was supported by the Air Force Office of Scientific Research.

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Phonon Dispersion Curves of GaAs/AlAs Superlattices†

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We present calculations of Phonon dispersion curves of GaAs/AlAs superlattices using an eleven-parameter rigid-ion model[1]. The parameters for GaAs are fitted to the latest experimental data of Neuman et. al [2] and the parameters fo AlAs are fitted to the existing experimental data [3] The slab method is used to compute the phonon frequencies and displacement vectors, and the long range Coulomb interaction is included almost exactly (within numerical errors). The effect of Coulomb interaction on the dispersions for both normal ($k_{\parallel} = 0$) and oblique ($k_{\parallel} \neq 0$) propagations are examined. It is *found* that the optical phonons have different frequencies as the wave vectors approch zero from different directions. Such anisotropic behavior was previously reported by Merlin et. al.[4] and they interpreted it with a macroscopic model. Our microscopic model predicts the same phenonmenon, and we can explain it in terms of the singular behavior of the summation of long range Coulomb interactions between atoms in the the superlattice (a tetragonal crystal)

† Work supported by ONR N00014-81-K-0430.

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Raman Scattering from Periodic and Nonperiodic GaSb/AlSb Strained-Layer Lattices

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Lattice dynamics measurements have been performed on a series of periodic and nonperiodic strained-layer GaSb/AlSb lattices using Raman scattering. In the optical frequency region for periodic lattices quantum confined longitudinal optic phonons have been observed in GaSb layers with widths less than 25Å. Spatially extended interface modes lying within the LO-TO regions for both GaSb and AlSb have also been observed. The interface mode frequencies we have observed are not particularly well fit by current macroscopic theories. The confinement-induced Γ to L crossover in GaSb manifests itself in our spectra via the observation of a scattering structure which resembles the optical phonon density of states. In the acoustic regime of periodic lattices, the phonons display zone folding and are relatively insensitive even to the presence of misfit dislocations in these structures. Samples have also been grown with certain types of deliberately broken symmetry wherein one of the layer widths contains ±15% variation and the sequencing of these altered layers has been arranged in either a random or periodic fashion. The most general affect of this process has been to introduce new scattering peaks rather than to merely broaden the peak widths. Finite length quasiperiodic structures with the individual layers sequenced according to the Fibonacci series have also been examined and compared to periodic lattices with (ABAAB) and (ABAABAAB) repeat units. We have found that both the peak frequencies and relative intensities of our finite length Fibonacci lattices are reasonably modeled by the latter periodic lattice.

The effect of inelastic scattering on resonant and sequential tunnelling through double barrier heterostructures.

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In this work we demonstrate that the current through a double barrier heterostructure is independent of whether the electron tunnelling mechanism is sequential or Fabry-Perot like. By considering how a wave packet is moving through the system we determine in an illustrative manner the time needed to establish a full resonance. In most cases this resonance time is much longer than the inelastic scattering time. Hence we find that the transmission through the double barrier is strongly affected by inelastic scattering. This means that the tunnelling through the double barrier structure is sequential rather than Fabry-Perot like. However, we show that the tunnelling current does not depend on which of the two mechanisms dominate.

Abstract pending

LPE grown $A^{III}_{B}{}^{V}$ QW heterostructures spontaneous radiations and laser parameters, Zh. I. Alferov, D. Z. Garbuzov, A. F. Ioffe Physico-Technical Institute (USSR)

Poster Session 2

Structural Studies

2-1 **Raman scattering study of Al/Ga interdiffusion in ion-implanted and annealed GaAs-$Ga_{1-x}Al_xAs$ superlattices**, J. Sapriel, E. V. K. Rao, F. Brillouet, J. Chevignon, P. Ossart, Y. Gao, P. Krauz, CNET (France)

2-2 **Selective intermixing of $Al_xGa_{1-x}As$/GaAs superlattices using pulsed lasers**, J. Ralston, A. L. Moretti, R. K. Jain, F. A. Chambers, Amoco Corporation

2-3 **Surface migration study of atoms and formation of truly-smooth top and bottom heterointerfaces in GaAs-AlAs quantum wells by temperature-switched technique in molecular beam epitaxy**, M. Tanaka, H. Sakaki, University of Tokyo (Japan)

2-4 **Improvements in narrow bandgap MCT heterojunctions made by MBE**, M. Boukerche, I. K. Sou, S. Yoo, J. P. Faurie, University of Illinois at Chicago

2-5 **Low temperature characterization of Al-Si diffusion kinetics**, M. P. Dugan, RCA Microelectronics Center; T. Tsakalakos, Rutgers University

2-6 **Ion implantation damage and annealing effects in (InGa)As/GaAs strained-layer semiconductor systems**, D. R. Myers, L. R. Dawson, R. M. Biefeld, G. W. Arnold, C. R. Hills, B. L. Doyle, Sandia National Laboratories

2-7 **Multilayer roughness evaluated by x-ray reflectivity**, D. L. Rosen, Sachs/Freeman Assoc. Inc.; D. Brown, J. Gilfrich, P. Burkhalter, Naval Research Laboratory

2-8 **Electronic conductivity and electromigration in metallic microstructures**, R. S. Sorbello, C. S. Chu, University of Wisconsin at Milwaukee

2-9 **Crystallinity and interdiffusion in InP/InGaAs quantumn wells grown by hydride VPE**, K. Makita, K. Taguchi, NEC Corporation (Japan)

Microstructures and Microdevices

2-10 **Suspension of small silver particles in epitaxial silicon**, Q. Y. Chen, L. Wang, Applied Detector Corporation

2-11 **Emission of thermal radiation from Planckian modes in microstructured surfaces: I**, P. J. Hesketh, J. N. Zemel, B. Gebhart, University of Pennsylvania

2-12 **Emission of thermal radiation from Planckian modes in microstructured surfaces: II**, T. K. Wang, J. N. Zemel, University of Pennsylvania

2-13 **Light and heavy holes in one-dimensional systems**, M. Sweeny, Unisys Corporation; J. Xu, M. Shur, University of Minnesota

2-14 **Patterned GaAs/AlGaAs superlattice heterostructures by epitaxial growth on nonplanar GaAs substrates**, E. Kapon, D. M. Hwang, R. Bhat, M. C. Tamargo, Bell Communications Research

2-15 **Conductance fluctuations in microstructures for a four-probe geometry**, H. U. Baranger, AT&T Bell Laboratories; D. P. DiVincenzo, IBM T. J. Watson Research Center; A. D. Stone, Yale University

Devices and Novel Properties

2-16 **Light-induced metastable state in doping-modulated amorphous silicon superlattices**, B.-S. Yoo, S.-H. Choi, C. Lee, Korea Advanced Institute of Science and Technology; J. Jang, Kyung Hee University, (Korea)

2-17 **Thermal conductivity of AlAs/GaAs superlattices**, T. Yao, Electrotechnical Laboratory (Japan)

2-18 **Field and geometry dependence of the electron ionization rate in multiple quantum well structures**, K. F. Brennan, Y. Wang, A. Torabi, C. J. Summers, Georgia Institute of Technology

2-19 **P-type ohmic contacts to GaAs/AlGaAs heterostructures**, J.-H. Reemtsma, K. Heime, Universitat Duisburg; W. Schlapp, G. Weimann, Forschungsinstitut der Deutschen Bundespost (FRG)

2-20 **The spatial-dispersion, the optical nonlinearity and the coherent propagating phenomena in the vicinity of excitonic resonance**, Z. Gan, Peking University (PRC)

Metallic Superlattices

2-21 **Critical modulation amplitude in monocrystalline Nb/V and Ta/V superlattices**, R. H. M. van de Leur, A. J. G. Schellingerhout, F. Tuinstra, J. E. Mooij, Delft University of Technology (The Netherlands)

2-22 **Magnetic properties of Fe/Mn Superlattices**, Y. Motomura, J. B. Ketterson, Northwestern University

2-23 **Superconducting tunneling through NbTi/Ge multilayers**, S. N. Song, B. Y. Jin, J. B. Ketterson, Northwestern University

2-24 **Structural determination of ultra-thin epitaxial overlayers, sandwiches, and superlattices by auger electron diffraction**, S. A. Chambers, Boeing

2-25 **Microstructure of Fe film on Si grown by MOCVD**, Z. Youdou, Z. Rong, Nanjing University (PRC); T. K. Kim, B. D. McCombe, State University of New York at Buffalo (USA)

Spectroscopy and Band Structure

2-26 **Extended electronic density of states in semiconductor heterostructures**, S. Colak, North American Philips Corporation

2-27 **Stark effect in quantum wells: Effect of Coulomb interaction**, J.-W. Wu, Indiana University; A. V. Nurmikko, Brown University

2-28 **Exciton ground state and binding energy in semiconductor quantum wells with small valence band offsets**, J.-W. Wu, Indiana University; A. V. Nurmikko, Brown University

2-29 **Magneto-reflectance of GaAs/GaAlAs quantum well structure**, X. L. Zheng, D. Heiman, B. Lax, National Magnetic Laboratory, Massachusetts Institute of Technology; F. A. Chambers, Amoco Research Center

2-30 **Confinement effects on Be acceptors in GaAs/AlGaAs multi quantum well structures,** B. A. Reader, B. D. McCombe, SUNY at Buffalo; F. A. Chambers, G. P. Devane, Amoco Corporation

2-31 **Magnetoreflectance study of Be acceptors in selectively doped GaAs/AlGaAs multiple quantum wells,** X. Liu, A. Petrou, SUNY at Buffalo; A. L. Moretti, F. A. Chambers, G. P. Devane, Amoco Corporation

2-32 **Emission spectroscopy of GaSb/AlSb quantum wells in the 1.6eV - 2 eV energy range,** A. Forchel, U. Cebulla, G. Trankle, Universitat Stuttgart (FRG); T. L. Reinecke, Naval Research Laboratory; G. Griffiths, H. Kroemer, S. Subbanna, UCSB (USA)

2-33 **Electronic structure of strained-layer $Si/Si_{1-x}Ge_x$ superlattices from tight-binding calculations,** H. Rucker, Humboldt-Universitat zu Berlin; F. Bechstedt, Friedrich-Schiller-Universitat; R. Enderlein, D. Hennig, Humboldt-Universitat zu Berlin (GDR); S. Wilke, Czechoslovak Academy of Science (USSR)

2-34 **Optical investigations of highly strained InGaAs-GaAs multiple quantum wells,** G. Ji, D. Huang, U. K. Reddy, T. S. Henderson, H. Morkoc, University of Illinois at Urbana-Champaign

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2-74 **Monte Carlo particle investigation of photo-excited electron-hole plasma transport in submicron structures,** D. Junevicius, S. Kersulis, A. Reklaitis, Lithuanian Academy of Sciences (USSR)

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RAMAN SCATTERING STUDY OF Al/Ga INTERDIFFUSION IN ION-IMPLANTED AND ANNEALED GaAs-$Ga_{1-x}Al_xAs$ SUPERLATTICES

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The formation of compositionaly disordered $Ga_{1-y}Al_yAs$ layers for lateral confinement of light in a laser active region composed of a GaAs-$Ga_{1-x}Al_xAs$ multiquantum-well structure (superlattice) can be obtained using adequate treatments of the superlattice. In certain conditions, an ion-implantation followed by a thermal annealing provoke the inter-diffusion of the Al/Ga atoms in the bombarded zone of the superlattice.

Raman scatterning from the phonons is an useful and non destructive tool to characterize each stage of this complex process. The LO and TO of GaAs, the LO and TO of GaAlAs of both the GaAs and AlAs types, and the so-called folded acoustic modes have been investigated in detail. Ion implantation of 10^{15} cm^{-2} P ions at 100 keV have been performed at two temperatures (25°C and 250°C). An estimate of the implantation induced defects is obtained through the comparison of the Disorded Activated Transverse Acoustic modes (DATA) and the Disorded Activated Transverse Optical modes (DATO). The interdiffusion of Ga/Al was then obtained after heat treatment at 850°C using close contact conditions. The composition as well as the crystalline quality are then deduced from the Raman spectra. The frequency, width and intensity variations of the folded longitudinal acoustic modes is used for the first time as a finger-print of the transformations brought out by the different treatments.

Secondary ion mass spectroscopy (SIMS) and Auger electron spectroscopy characterizations on the same samples are briefly presented. They confirm and complement the Raman results. The combination of all these techniques allowed us to discriminate between the respective contributions of the P impurities and the implantation induced defects to the interdiffusion process.

Selective Intermixing of $Al_xGa_{1-x}As$/GaAs Superlattices using Pulsed Lasers

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The ability to tailor properties of semiconductors by epitaxial growth of multilayered structures such as GaAs/$Al_xGa_{1-x}As$ multiquantum wells and superlattices has spurred a revival in the fields of optoelectronics and integrated optics. However, monolithic integration of electronic, optoelectronic, and optical components requires a capability for selective lateral and vertical modification of the doping, mobility, bandgap and refractive index of such epitaxially grown compound semiconductor layers.

Such modification has previously been performed via localized diffusion or implantation of impurities. However, it is not feasible to obtain intermixed alloys with these techniques without introducing free carriers into the material. A need has existed for a complementary process whereby intermixing is accomplished without doping the semiconductor crystal, particularly for applications requiring some degree of electrical isolation. We present here results which demonstrate such a complementary process, in which a pulsed laser is employed to selectively intermix GaAs/$Al_xGa_{1-x}As$ superlattices.

In our experiments pulsed KrF excimer and frequency doubled Nd:YAG lasers of a few nanoseconds pulse duration were used to irradiate various superlattice samples. In order to obtain a nondestructive indication of whether intermixing has occurred, Raman measurements were performed on both the irradiated and "as-grown" regions of the samples. The Raman signal from the "as-grown" region shows two distinct peaks, one due to the longitudinal optical (LO) phonons of the GaAs layers (281 cm^{-1}), and the other due to the LO phonons of the $Al_{0.3}Ga_{0.7}As$ layers (281 cm^{-1}). In contrast, the Raman spectrum from the laser irradiated region (dashed curve) shows a single peak at 286 cm^{-1}, indicating that extensive intermixing of the original superlattice layers into an $Al_xGa_{1-x}As$ alloy with a medium composition $x = 0.15$ has occurred.

The nature and characteristics of the intermixing process have been confirmed with sputter-Auger depth profiling. Simple analysis indicates that a thermal melting model is adequate for describing the physical process involved in the laser intermixing process. Both of these features will be elaborated on in the talk.

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Surface Migration Study of Atoms and Formation of Truly-Smooth Top and Bottom Heterointerfaces in GaAs-AlAs Quantum Wells by Temperature-Switched Technique in Molecular Beam Epitaxy

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ABSTRACT:

Our recent study on the migration process of atoms on MBE-grown GaAs and AlAs surfaces has revealed that, at particular growth conditions (substrate temperature Ts=580℃), growth interruption significantly enhances the migration of GaAs, and thereby smooth out the roughness of top (AlAs-on-GaAs) interfaces, while bottom (GaAs-on-AlAs) interfaces are pseudo-smooth with the lateral size of atomic step (L_{step} being much smaller than exciton size D_{ex}. This is due to much less efficient migration of Al, which is little affected by growth interruptions[1],[2]. In this paper, we extend our study to more generalized growth conditions, and clarify the temperature dependence of the diffusion length of Ga and Al atoms on the interrupted and uninterrupted growth front. We develop, in particular, a novel temperature-switched technique to form GaAs-AlAs quantum wells (QWs) with both top and bottom interfaces being truly-smooth (L_{step}>>D_{ex}).

Multi-QWs consisting of 17 monolayers of GaAs and 18 monolayers of AlAs were grown on (001) GaAs at various Ts (550℃≦Ts≦700℃) with and without growth interruptions (GI) prior to the interface formations. The flux ratio As_4/Ga was fixed at 3.5. The behavior of RHEED intensity and PL results at 77K revealed that the surface migration process and the effect of GI at 550℃≦Ts<650℃ is almost the same as the case of Ts=580℃[1],[2]. In contrast, when Ts>660℃, the RHEED data suggest that Al atoms migrate well at high Ts and the surface roughness of AlAs can be smoothed by growth interruption as in the case of GaAs surface at 580℃. This interruption at high Ts, however, does not smooth out the roughness of GaAs surface, probably because the re-evaporation process of GaAs becomes noticeable. Hence, the PL linewidth gets broad because of the roughening of top interfaces although the bottom interface can be truly smoothed. The optimum growth condition to achieve truly-smooth surface of GaAs is, therefore, different from that of AlAs.

To make both interfaces of QWs truly-smooth, we have adopted a switched Ts technique, in which the bottom interfaces are formed at Ts=680℃ while the top interfaces at Ts=580℃. To confirm that the bottom interfaces are truly smoothed by GI at 680℃, we have grown and compared two types of QWs; type-A' QW was grown with GI at both top and bottom interfaces whereas type-B' QW was grown with GI only at the top interfaces. PL spectrum of type-B' QW at 77K is Gaussian-like and broad with the linewidth of 20-30meV, indicating that the bottom interface prepared continuously is rough with L_{step} being comparable to D_{ex}. In contrast, PL of type-A' QW has a splitting of two peaks, the linewidth of each peak is narrower than the PL peak of type-B' QW. This indicates that the AlAs surface continuously grown at Ts=680℃ is no more pseudo-smooth but rough sensed by excitons, and such roughness can be smoothed by growth interruption. Hence, type-A' QW grown by temperature-switched MBE has two truly-smooth interfaces.

We present comprehensive understanding on surface diffusion process which depends on materials, temperature and growth interruptions.

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Improvements in narrow bandgap MCT heterojunctions made by MBE

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The previously reported characterizations of the first n(x = 0.2) - N(x = 0.3) MCT heterojunctions showed a nearly non-rectifying behavior with a double "soft reverse breakdown." Current transport at medium and low temperatures was attributed to tunneling and Schottky barrier lowering accross an unexpected conduction band barrier between the two materials.

We suggested that this situation arised from the growth conditions. Abrupt changes in CdTe fluxes intentionally made to produce the compositional change at the interface could actually produce unexpected "bursts" of material bandgap, with long enough decay time constants to influence substantially the transport properties.

Several samples were grown recently, trying to avoid this problem. They give credit to this hypothesis. Several devices containing N - $10^{15}cm^{-3}$(x = 0.3)/n - 3 x $10^{16}cm^{-3}$(x = 0.2) heterojunctions showed strong rectification. Computer least square fitting to the Schottky model gives ideality factors varying from 2.0 to 2.5 between 250 and 80 K. The spectral response peaks around 8 μm wavelength at 80 K instead of 1.5 - 2 μm before. The barrier height tentatively deduced from the activation energy of the saturated current decreases from 0.10 eV at 250 K to around 60 meV at 80 K. We will discuss the problems involved in the interpretation of the measurements and present the preliminary results of the last samples grown with thicker layers and tighter growth controls.

Low Temperature Characterization of Al-Si Diffusion Kinetics

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The diffusion kinetics of the aluminum-silicon system at low temperatures has been characterized by a novel technique. Previously published studies used bulk samples (plates or wires) to determine bulk diffusivities, or thick films of 1 or 2 micrometers Al on a silicon substrate to investigate the diffusion kinetics; whereas our samples consist of thin films comprised of alternately deposited ultrathin layers of Al and Si. This approach permits the characterization of the diffusion kinetics at the Al-Si interface through the cummulative effects of several hundred interfaces while minimizing the effects of bulk material.

Composition modulated films with wavelengths of 1.3 to 6.0 nanometers were prepared by thermal evaporation of Al and Si from seperate sources and deposited on polished <1$\bar{1}$02> sapphire substrates held at room temperature. The incident flux was interupted by a rotating pinwheel shutter to achieve composition modulation. Films having a total thickness of several hundred nanometers were prepared in this manner.

The resistivity of these films was monitored by the "four-point-probe" technique during isothermal annealing at temperatures in the range of 75C to 150C. The resistivity was observed to increase initially and later decrease, eventually stabilizing at a value lower than the starting resistivity. The increase in resistivity is attributed to an increase in disorder caused by Si diffusing into the Al layers and the decrease in resistivity to stress relief in the film.

Analysis of the data has allowed the calculation of diffusion coefficients (D(75C)=1.9E-17, D(100C)=6.9E-17, D(150C)=35.8E-17 cm^2/sec), thermal activation energy of diffusion (0.48 eV) and the gradient energy coefficient (7.0 to 8.0E-11 J/cm). This contribution extends the database of the Al-Si system to lower temperatures than have been previously reported, and these results are in agreement with extrapolations of the previously reported data.

Ion Implantation Damage and Annealing Effects in (InGa)As/GaAs Strained-Layer Semiconductor Systems

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Abstract

In addition to its utility for the fabrication of electronic devices, ion implantation provides a demanding probe of the structural response of strained-layer semiconductor systems. Studies of ion damage production and annealing in strained-layer systems have elucidated the role of lattice mismatch in determining the response of implanted strained-layer systems and the nature of stress relief for heavily implanted composites.

We have applied cantilever beam measurements, ion channeling, transmission electron microscopy, and double crystal x-ray diffraction to examine defect production and annealing in (InGa)As strained-layer systems. Typical strained-layer superlattices (SLS) consisted of forty periods of $In_{0.2}Ga_{0.8}As$/GaAs (20nm/layer) grown over a 1.5μm $In_{0.1}Ga_{0.9}As$ buffer layer on GaAs, while single strained quantum wells (ssqw's) were grown with 300nm of GaAs over 20nm of $In_{0.15}Ga_{0.85}As$ over a 1.5μm GaAs buffer on semi-insulating GaAs substrates. Room temperature implants were performed using either 200 keV silicon or 300 keV argon, for fluences selected between $5x10^{12}$/cm^2 and $1x10^{16}$/cm^2. Anneals were performed in 2.5% arsine in hydrogen at 800°C. All the structures examined here had layer thicknesses below the limit of critical layer thickness for thermodynamic stability(1)

We find that silicon implantation at fluences of 10^{14}/cm^2 or less into the ssqw structures results in a broad strain distribution due to displacement damage. Similar to the behavior (2,3) in ion implanted SLSs for these ion fluences, annealing removes the damage-induced strain distribution and returns the interlayer strains to their as-grown values.

Higher fluence implants into strained-layer superlattices for compositional disordering produce dislocations, microtwins, and stacking faults near the mean ion range. These implants also induce a precipitous stress relief in the implanted composite structures (4). TEM indicates that this stress relief is localized at the interface between the buffer layer and the substrate (where the maximum in-plane lattice mismatch occurs), and that the defects induced by this stress relief degrade neither the buffer nor the superlattice on annealing. For the argon implants, defect clusters are preferentially located in the (InGa)As layers beyond the heavily dislocated layers; on annealing, these clusters form dislocation loops which remain localized within the (InGa)As layer and do not penetrate into surrounding GaAs layers. This behavior is remarkably similar to that observed for threading dislocation movement in SLSs, and suggests that the compositional modulation of the SLS acts on point defects as it does on dislocations.

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MULTILAYER ROUGHNESS EVALUATED BY X-RAY REFLECTIVITY

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Abstract

Crystal diffraction theory was used to model the integrated reflectivity of multilayer structures. Experimental measurements of integral reflectivity were analyzed using this theory, showing that the most important defect decreasing the integrated reflectivities of the multilayer structures studied was correlated roughness (rms about 7 Å), which was probably caused by the roughness of the substrate. The theory described correlated roughness as a probability distribution of the substrate displacement.

A computer simulation and an analytical solution were used to calculate the reflectivity of multilayer structures. The analytical solution showed that the probability distribution can be expanded in a Fourier series, with each diffraction order corresponding to a term in the series. Both the simulation and the analytical solution were used with the experimental data to find the probability distribution for the displacement of the substrate surface

A uniform distribution of correlated displacements was a good first order approximation of the multilayer roughness. A Gaussian probability distribution for the substrate surface displacement gave predictions inconsistent with the measured reflectivity data, although such a distribution has been assumed in other studies.

Although crystal diffraction theory was applied to defects other than correlated roughness, only roughness could explain the experimental data. The simulation showed that varying layer thickness can not greatly affect integral reflectivity. Macroscopic curvature of the substrate can not affect the integral reflectivity because of the small transverse coherence length of the X-ray source. Interfacial diffusion layers are too thin, in the refractory materials used to make the multilayers, to explain the large reduction in integral reflectivity.

Poster session requested.

Electronic Conductivity and Electromigration in Metallic Microstructures

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Electron transport in a metallic microstructure is characterized by microscopically inhomogeneous electric fields and currents. When the inelastic mean free path is longer than characteristic sample dimensions, the fields and currents are sensitive to quantum interference and resonance phenomenona involving defects and interfaces. A general theoretical approach is described for determining the microscopic electric field and current for a system with impurities and interfaces. The approach is based on ideas from the theory of low-energy electron diffraction and from the theory of electromigration. The local field and the electromigration driving force are calculated for an impurity near a surface and for an impurity in a wire of microscopic cross-section using the infinite-barrier model. The electromigration driving force is shown to be related to the residual resistivity, and also, to the viscosity experienced by an impurity moving through the microstructure. Multiple scattering between the impurity and the surfaces can lead to strong resonance effects. The long range fields (beyond an inelastic mean-free-path) are set-up by entities analogous to the residual-resistivity-dipoles obtained by Landauer for a single impurity in bulk.

Crystallinity and Interdiffusion in InP/InGaAs Quantumn Wells Grown by Hydride VPE

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The InP/InGaAs Quantumn Well (QW) structure is expected to improve device performance, for instance, low threshold current and high T_o in QW lasers and low noise in QW detectors. There have been no systematic reports about interdiffusion effect in InP/InGaAs QW. This paper reports results of a study on interfacial quality and thermal interdiffusion for InP/InGaAs QW grown by Hydride VPE. For the first time, interdiffusion coefficients for InP/InGaAs QW were estimated. A typical value was $2.5\times10^{-19}cm^2/sec$ for 700°C.

InP/InGaAs QW was grown by Hydride VPE with a multi-growth-chamber reactor[1]. The growth conditions were optimized with lowering growth temperature (600°C) and lowering growth rate (InP~10Å/sec; InGaAs~3Å/sec). In these methods, InP/InGaAs QW with as thin as 25Å well thickness has been obtained reproducibly. In 4.2K PL for different well thickness (Lz) samples, a marked increase in PL linewidth, especially for Lz<100Å, was observed. This tendency can be related with the geometric well fluctuation due to the interfacial roughness. Applying this result with Singh et.al.'s model[2], it was estimated that islands and valleys, whose height was one monolayer and whose lateral size was one third of exciton radius, existed at the interface. These interfacial roughness values are comparable to those grown by MBE and MOCVD.

The annealing process for InP/InGaAs QW was examined to determine the thermal stability of its optical properties. 77K PL spectra, after the annealing process, shifted to a shorter wavelength, which could be explained as deformation in QW with interdiffusion effect. The 4.2K PL linewidth dependence for Lz showed that the degree of increase, for Lz<100Å, in annealed samples was greater than that in as-grown samples. This indicates that the annealing process results in promoting interfacial roughness with interdiffusion effect. For the first time, interdiffusion coefficients for InP/InGaAs QW were estimated from 77K PL peak energy shift. Typical values were $2.5\times10^{-19}cm^2/sec$ and $1.5\times10^{-18}cm^2/sec$ for the annealing temperature of 700°C and 750°C, respectively. These values are over 10^2 times larger than that in AlGaAs/GaAs QW[3], and less 10^{-2} times smaller than that in InAlAs/InGaAs QW[4].

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Suspension of Small Silver Particles in Epitaxial Silicon

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Abstract

It is now well-known that small metal particles embedded in high refraction index dielectrics show great optical absorption in the infrared.[1,2] Microstructures of micro-metal-particles in dielectrics demonstrate surface-enhanced photoeffects which can be applied to photon detection. Theoretical studies have inferred material-design rules for this type of microstructure. [3,4]

In this work, efforts are made to grow single crystal silicon film embedding small silver particles using low temperature regrowth and solid phase epitaxy techniques. Photoelectronic devices based upon these materials include the short base p-n diodes, p-i-n photodiodes, sandwiched structure of Ag-Si composite-pure Si multilayers and n-MOSFET with Ag-p-Si composite substrate. X-ray diffraction, Auger spectroscopy and electron microscopy are used for material characterizations. Optical and electrical properties and their relations to the microstructures will be discussed.

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Emission of Thermal Radiation From Planckian Modes in Microstructured Surfaces: I

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An extensive series of measurements were conducted on the emission of thermal radiation from various types of micromachined silicon (110) surfaces. Gratings, rectangular pits and hexagonal pits were examined. The silicon was heavily doped after the micromachining to produce a near metallic surface condition. The measurements were carried out at 400°C[2,3,4]. The polarized spectral emittance of the microconfigured surfaces exhibited oscillatory behavior of a type never previously reported. Analysis of these experimental results established that electromagnetic standing wave states are produced in the gratings, and to some extent in the rectangular pits. The wedge shaped bottoms of these structures complicated the observations, particularly on the rectangular and hexagonal pits.

Perhaps the most unusual observations were made on the polar angular dependence of the polarized spectral emittance at an azimuthal angle where the emission plane was parallel to the walls of the grating slots. This is perpendicular to the customary observation direction for diffraction from gratings. It was found that the polar angle dependence also exhibited oscillatory behavior corresponding to coupling of the standing waves in the vertical direction to emission at an angle θ. The maxima are governed by the relation

$$m\lambda_p = 2H\cos\theta$$

where m is the mode number, H is the depth of the grating and λ_p is wavelength of the maximum in the emittance. Additional evidence for standing wave patterns were obtained from other polarizations and azimuths

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Emission of Thermal Radiation From Planckian Modes in Microstructured Surfaces: II

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Additional experiments on the polarized spectral angular emittance of the type described in the previous abstract will be reported on undoped silicon microconfigured surfaces. In these experiments, the silicon was left undoped in order to explore the role of wall conductivity on the character of the radiation. The emissivity of undoped silicon is approximately 0.8. The behavior induced by the presence of these microstructures on the emittance of the surface is considered. The most important information being sought is the degree of coupling between the standing wave states in the slots of the deep grating as modulated by the conductance of the walls. Control of the wall conductance is possible to some degree by varying the temperature of the sample. For lightly doped silicon, $N \leq 10^{15}/cm^3$, the intrinsic carrier concentration will dominate the conductance for temperatures in excess of 250°C. The results of a systematic polarized spectral emittance study conducted in the temperature range $300^{\circ}C \leq T \leq 600^{\circ}C$ will be presented.

Light and Heavy Holes in One-Dimensional Systems.

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Recently, complementary heterostructure compound semiconductor devices have emerged as leading contenders for high speed low power integrated circuits. The performance of these devices is strongly dependent on the mobility of holes which is much smaller than the electron mobility, primarily because of the large effective mass of heavy holes in compound semiconductors. In this paper we show that the band structure of holes in the one-dimensional systems is considerably different from the 3-d bulk case. We solve the band structures by the envelope function approximations and obtain exact solutions for the Hamiltonian of the envelope functions (neglecting the warping). The resulting band structure contains many overlapping subbands with subband splitting inversely proportional to the square of the radius of the one dimensional semiconductor wire. In fairly large energy range the dependence of the energy on the wave vector for lowest subbands is nearly linear. The effective mass of holes is smaller than the heavy hole effective mass. The prospect of having lighter hole effective mass and a possibility to change the band structure by varying the radii of one-dimensional semiconductor wires should have very important implications for the p-channel compound semiconductor devices.

Patterned GaAs/AlGaAs Superlattice Heterostructures by Epitaxial Growth on Nonplanar GaAs Substrates

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Patterning of semiconductor superlattice heterostructures in the substrate plane has been attracting considerable attention recently [1,2]. Such patterned superlattices are expected to exhibit new interesting and useful physical properties, especially those associated with reduced carrier dimensionality. In the present talk we describe a new superlattice patterning method which utilizes the thickness variations exhibited by epitaxial layers grown on nonplanar substrates [3]. When the grown layers are sufficiently thin ($\lesssim$ 500Å for GaAs/AlGaAs heterostructures), the strong dependence of the quantum size effects on the layer thickness translates into lateral patterning of physical properties which depend on these quantum size effects. In particular, the lateral variation in the carrier confinement energy due to the quantum well thickness variations should give rise to lateral, effective potential barriers which can be used to confine carriers in more than one dimension.

We have grown 100Å GaAs/100Å $Al_{0.3}Ga_{0.7}As$ superlattice heterostructures on periodically corrugated GaAs substrates using both molecular beam epitaxy (MBE) and organo-metallic vapor phase epitaxy (OMVPE). The periodic corrugations were ~2 μm deep and of 5 μm periodicity, and were prepared by using conventional photolithography and preferential (wet) chemical etching. The growth features and the crystal quality of the patterned superlattices were studied by using transmission electron microscopy.

It was found that the superlattice layers grow along a specific set of crystal planes. For MBE growth on $[01\bar{1}]$ oriented corrugations, the layer thicknesses decreased from 100Å at the bottom of the grooves to less than 50Å on their slopes. Furthermore, the width of the thick quantum well section was only 0.2 μm because of the V-shaped groove profile. The OMVPE growth features on the corrugated substrate, however, are significantly different. At the corrugation peaks, the quantum wells grow along the (100) plane and are thinner by a factor of ~4 than those at the adjacent groove slopes (30Å compared to 120Å). For both MBE and OMVPE, the transition between quantum well sections of different thickness is mostly abrupt and occurs within $\lesssim$ 100Å.

Our results suggest that growth of superlattice heterostructures on nonplanar substrates should provide a method for producing patterned superlattices of high crystal quality. Possible applications of such patterned superlattices in optoelectronics will be discussed.

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Conductance fluctuations in microstructures for a four-probe geometry

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Recent work[1] on conductance fluctuations in microstructures has revealed universal characteristics in the diffusive regime. However, quantitative microscopic calculations to date have dealt exclusively with the two-point conductance of a disordered region attached to two ordered leads. These calculations are appropriate only when the conductance is measured on a scale larger than an inelastic mean free path. However, recent experiments have probed length scales shorter than an inelastic mean free path and find significant new effects.

We calculate numerically the four-point conductance or resistance of a disordered region, a calculation more relevant to these new experiments. The disordered region we consider is a rectangular strip attached to four perfect leads and modelled by an Anderson Hamiltonian with on-site disorder. The Green's functions between all combinations of the four ordered regions follow from recursion relations. We derive the transmission and reflection coefficients from these Green's functions and then calculate the conductance or resistance using a multi-channel linear response formula which can be derived from a Kubo formulation. The resulting expression is identical in form to that obtained by Büttiker[2] but gives in addition a microscopic formula for the transmission and reflection coefficients. We find that such a derivation is only valid in the absence of a magnetic field.

Results for the conductance fluctuations and the energy correlation function are discussed for both the diffusive and ballistic regimes, with particular attention paid to the dependence of the fluctuations on the separation between the probes.

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LIGHT-INDUCED METASTABLE STATE IN DOPING-MODULATED AMORPHOUS SILICON SUPERLATTICES

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The light induced effect (Staebler-Wronski effect) has been observed for the first time in doping-modulated npnp.... type superlattices of hydrogenated amorphous silicon (a-Si:H) after prolonged illumination. The persistent photoconductivity(PPC) was observed to increase with illumination time until the overall illumination time reached 40 min. Then the PPC started to decrease with further illumination and finally dropped to value much lower than the original dark conductivity after 5 days of illumination. In fact, the PPC value dropped by several orders of magnitude from the initial value and becomes negative. The actual value of conductance after 5 days of illumination was one tenth of the original dark conductance. This metastable conductance after prolonged illumination was found to recover completely to the original value before illumination by 150°C annealing for 30 min. The recovery, however, was not monotonous : By 100°C annealing, the metastable conductance was found to decrease further showing negative recovery effect. The results will be discussed using models on PPC and Staebler-Wronski effect.

Thermal Conductivity of AlAs/GaAs superlattices

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Transport properties in semiconductor alloys are strongly affected by the presence of disorder scattering which is due to random distribution of constituent atoms at the sublattice sites. It is well known that the carrier mobility and the thermal conductivity of an alloy are strongly reduced because of the disorder scattering. Very recently, we have predicted the suppression of the disorder scattering in carrier transport in SL and suggested great enhancement of carrier mobility compared to semiconductor alloys[1]. Although there has been no theoretical prediction on thermal properties of SL, it is easily anticipated that the disorder scattering in phonon transport can be suppressed in SLs because of the coherently stacked layer. However, there has been no report on thermal conductivity of SL.

In this paper we report the first measurements of thermal properties of SL. We have found that the thermal conductivity in AlAs/GaAs SLs is strongly enhanced compared to AlGaAs alloy. This fact indicates the suppression of the disorder scattering in SLs.

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FIELD AND GEOMETRY DEPENDENCE OF THE ELECTRON IONIZATION RATE IN MULTIPLE QUANTUM WELL STRUCTURES

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We present theoretical and experimental results of the electron impact ionization rate in GaAs/$Al_xGa_{1-x}As$ multiquantum well structures as a function of applied electric field for various geometries, ie. well and barrier widths. It is found that the average ionization rate, determined by averaging over the GaAs and AlGaAs layers, depends critically upon the layer widths and the magnitude of the applied electric field. The average ionization rate in a symmetric structure of 500 Å well and barrier widths is found to be less than the corresponding GaAs bulk rate at very high electric fields, 500-600 kV/cm. The electron ionization rate within the well regions alone is still higher than that in the bulk GaAs but is insufficiently enhanced to compensate for the much lower rate in the AlGaAs layers. As the field is decreased to ~250 kV/cm the average ionization rate in the multiquantum well structure becomes larger than in the bulk. This field dependence can be explained in terms of the mean distance required for impact ionization, l_i. As the field decreases, l_i increases. When l_i becomes greater than the well width the average multiquantum well ionization rate becomes larger than that of the bulk. The ionization rate in different well and barrier width geometries is also investigated as a function of applied field. Again, the average ionization rate is found to decrease below the bulk rate at high electric fields.

P-type Ohmic Contacts to GaAs/AlGaAs Heterostructures

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P-type ohmic contacts to GaAs/AlGaAs heterostructures show a strong increase of both, absolute and specific contact resistance with decreasing temperature. They loose their ohmic behaviour at temperatures below 60K. Quantum mechanical calculations show the high effective hole mass to be responsible for this increase because of the lower tunneling probability through the metal-semiconductor-barrier. To reduce this effect one has to achieve a very high surface concentration below the contact. The normally used metallisation is AuZnAu containing Zn as a dopant source. The semiconductor between metallization and two-dimensional hole gas (2DHG) becomes highly doped by the alloying process (2 minutes, 450°C). Especially for p-type heterostructures it is very important to dope the contact area down to the 2DHG because the p-channel heterostructures often include thick undoped AlGaAs-spacer (40 nm) to achieve higher mobilities in the 2DHG. The spacer is an additional barrier of about 100meV height. Our calculations show a strong increase of specific contact resistance between 40K and 80K for such a barrier height. This temperature range is in good agreement with our experimental results.
Higher temperatures and/or longer times are necessary to achieve larger doping depths. The upper limits for the alloying-process are 450 °C and 2 minutes because of the outdiffusion of Zn through the Au cap-layer. To prevent the outdiffusion we sputtered an insulator layer to our samples after the evaporation of the AuZnAu film. With this protective layer we could increase the temperature and the time up to 650°C and 30 minutes without degradation of the contacts. We present the optimized conditions for the varied process. The results are compared with "normally" alloyed contacts and with contacts produced by selective diffusion from spin on films.

The Spatial-dispersion, the Optical Nonlinearity and the Coherent Propagating Phenomena in the Vicinity of Excitonic Resonance

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(Abstract)

A semi-phenomenological equation for the excitation of the polarization wave in the vicinity of excitonic resonances is introduced. The linear approximation of this equation is similar to the equation obtained by Hopfield and Thomas[1]. Some phenomena related to the spatial dispersion, the optical nonlinearity and the transient coherent propagating are discussed. In particularly, these phenomena in the hetero-interface, quantum well and super-lattice are discussed.

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Critical modulation amplitude in monocrystalline Nb/V and Ta/V superlattices.

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We have fabricated monocrystalline Nb/V and Ta/V superlattices. For both the difference in lattice constant of the constituent metals is 10%. Our superlattices have a simusoidal modulation of concentration. The average concentration of V is 50% for all samples. The amplitude and periode of modulation have been varied. The samples have been analysed by X-ray diffraction, including 4-circle diffractometer measurements. Monocrystalline growth is only obtained up to a critical value of the modulation amplitude, which corresponds to a maximum V concentration of 90% in the Nb/V and 75% in the Ta/V superlattices. At larger modulation amplitudes polycrystalline samples are obtained. The periode of modulation has been varied between 1 and 10 nm, no influence on the critical amplitude has been found.
The superlattices are grown on (012) sapphire substrates at moderate temperatures (~450 K) in an ultra high vacuum system with two electron beam evaporators. The simusoidally modulated deposition rates are controlled by a mass spectrometer.

MAGNETIC PROPERTIES OF Fe/Mn SUPERLATTICES

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Fe/Mn superlattices provide a unique opportunity to study the ferromagnetic/antiferromagnetic interface. Three series of superlattice films have been investigated: Fe(9Å)/Mn(XÅ), Fe(17Å)/Mn(XÅ) and Fe(37Å)/Mn(XÅ) (where X = 9, 19, 38, and 76). These films have been prepared by depositing alternating layers of Fe and Mn on the (0001) surface of sapphire substrates (nominally at room temperature) in a UHV evaporator[1]. The typical growth rate was 2Å/sec. The number of bilayers in the film was typically 50 ~ 100.

The microstructure of these films was characterized by X-ray diffraction. The α-Mn structure was dominant in the Fe(9Å)/Mn(XÅ) films. On the other hand, the bcc Fe structure was dominant in the Fe(37Å)/Mn(XÅ) films. The structure of the Fe(17Å)/Mn(XÅ) films changes from the bcc Fe structure to the α-Mn structure as the Mn layer thickness increases. All the films showed a strong (110) texture and the 50% half width of the rocking curve was 1-2 degrees. Films with a bilayer thickness of less than 60Å generally showed satellite peaks due to the superlattice structure.

Magnetic measurements have been performed with a SQUID magnetometer. The saturation magnetization (M_s) of the films depends strongly on the film microstructure. The M_s for the films with a dominant bcc Fe structure was 70% of the bulk Fe value. On the other hand, the M_s for the films with a dominant α Mn structure was 20% of the bulk. The reduction of M_s indicates that a large amount of interdiffusion takes place at the interfaces. The temperature dependence of the magnetic susceptibility shows ferromagnetic behavior for the thick Fe layers, and antiferromagnetic behavior for the thick Mn layers. Superimposed on these, a mictomagnetic like behavior is observed in most films, which can be attributed to the thick interdiffusion layer[2]. In-plane B-H hysteresis loop measurements on the Fe(37Å)/Mn(XÅ) films show a large increase in the coercive force and the anisotropy field at low temperature as the Mn layer thickness increases. Similar phenomena have been reported on another ferromagnetic/antiferromagnetic (Fe/Cr) superlattice[3] [4].

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Superconducting Tunneling Through NbTi/Ge Multilayers*

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ABSTRACT

We have studied vertical transport in NbTi/Ge multilayers having the structure Nb/NbTi/Ge/NbTi/Ge ..... NbTi/Ge/Nb. The initial and final Nb layers serve as equipotential electrodes, and measurements are taken only in the temperature range below which the thick Nb electrodes are superconducting. In plane (parallel) transport studies were made on nearly identical NbTi/Ge multilayers deposited at the same time on a different part of the substrate using an appropriate mask. The layered structure was confirmed by low angle X-ray defraction. Depending on the transition temperature of the NbTi/Ge multilayers, the temperature-dependent junction resistance shows several interesting features. I-V characteristics and first derivative dI/dV were measured, yielding a sum gap of about 20meV for a 16 layer structure having a T_c of 7K. Possible interpretations of these resules will be presented.

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STRUCTURAL DETERMINATION OF ULTRA-THIN EPITAXIAL OVERLAYERS, SANDWICHES, AND SUPERLATTICES BY AUGER ELECTRON DIFFRACTION

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High-energy Auger electron diffraction is shown to be a highly accurate, atom-specific structural probe for ultra-thin epitaxial films. Coherent scattering of high-energy ($\geq$ 500 eV) Auger electrons by neighboring atoms leads to intensity modulations of the order of 50% in an angle-resolved measurement. These modulations are well accounted for by a straightforward kinematical scattering formalism in which trail geometries are employed and varied. Optimal agreement with experiment consistently results from a single geometry, leading to a unique solution to the structural problem. Atomic coordinates and elastic strain associated with lattice mismatch at the interface can be routinely determined with sub-Angstrom precision. Representative results will be given for the following systems: Cu/Ni(001), Fe/GaAs(001), Fe/Cu(001), Cu/Fe/Cu(001) Fe/Cu/Fe/Cu(001).

Microstructure of Fe Film on Si Grown by MOCVD

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In this paper we study the microstructure of the metalorganic chemical vapor deposition (MOCVD) grown Fe film on Si substrate. The Fe film is grown on Si(100) substrate by MOCVD using iron pentacarbonyl,$Fe(CO)_5$. We have undertaken x-ray diffraction studies using Rigaku D/max-B x-ray diffractometer to characterize the Fe film on Si. Careful x-ray studies have shown that in the thin film only single crystal Fe(200) peak appears,but in the thick film both single crystal iron and iron oxide appear. Using x-ray diffraction method we have determined the crystal structure and lattice constant of iron and iron oxide.

The result indicate that the Fe film grown on Si(100) by MOCVD is a single crystal deposited in the direction of (100), the layer near Si is Fe and its thickness is limited by the growth condition,the outer layer is iron oxide and its thickness depends on the total thickness of the film and growth condition. The result of XPS proved this conclusion. Therefore we have obtained a new multilayer structure (iron oxide-iron-silicon) by MOCVD using $Fe(CO)_5$,as iron oxide is also a semiconductor,i.e., the structure is a single crystal S-M-S (Semiconductor-Metal-Semiconductor) structure. It is very exciting because the structure can be used to manufacture new devices.

We have also discussed the relation between microstructure and MOCVD process.

Extended Electronic Density of States in Semiconductor Heterostructures

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Many applications of new semiconductor heterostructures require operation at near-room temperatures with heavy occupation of the bands by carriers. Therefore, knowledge of the extended electronic density of states (EDOS) away from the band edges is needed. In this work, we present the results of a study aimed at obtaining extended EDOS in heterostructures.

Our model for the study of EDOS is based on a continium solution of the heterostructure electronic states in the bound and resonance regions. This is done within the theme of an effective mass model using a simple nonlocal potential. The parameters of this potential are adjusted to represent the bulk band structures. We choose a plane wave basis set which is valid for the heterostructure as a whole. This avoids the use of complex k-vectors and wave function matching at the interfaces. This approach permits one to study arbitrarily shaped potential profiles.

We investigate several heterostructure geometries in detail. These involve both single heterostructure interfaces and quantum wells. We show that for some structures, extending the EDOS to higher energies is as important as a detailed electronic subband computation near the band edges. Initially, we assume cylindrical symmetry in the band structure perpendicular to potential variation. We will also present the results of our recent efforts to make the computations self consistent under an electrical or optical perturbation.

Stark Effect in Quantum Wells: Effect of Coulomb Interaction

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When an electric field is applied perpendicularly to the quantum well, the exciton luminescence or absorption peak position exhibits a shift analogous to the atomic Stark effects. At a finite applied field, the total perpendicular electric field acting on each of the carriers (electrons or holes) should be the sum of the applied field and the component of electron-hole Coulomb interaction in that direction. We generalize the variational calculation by D.A.B. Miller et al. (Phys. Rev. B32, 1043 (1985)) so the effect of Coulomb interaction on the exciton spectra is described more appropriately. This becomes important particularly in those heterostructures where either the conduction or valence band offset is small. Numerical results are presented for comparision with II-VI semiconductor heterostructures studied in recent experiments.

Exciton Ground State and Binding Energy in Semiconductor Quantum Wells with Small Valence Band Offsets

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Abstract

The ground state and binding energy of a Wannier Exciton in a quantum well with small valence band offset is calculated by generalizing the variational approach normally used to study excitons in GaAs/AlGaAs quantum wells. The central issue is to include the additional confinement of the hole caused by the electron-hole Coulomb interaction in the direction perpendicular to the quantum well interface. In addition to the relative motion part of the exciton wavefunction, the envelope function of the hole in that direction is also determined variationally. The accuracy of our method is tested and applications to II-VI compound semiconductor quantum wells studied in recent experiments are discussed.

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MAGNETO-REFLECTANCE OF GaAs/GaAlAs QUANTUM WELL STRUCTURE

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ABSTRACT

We have performed magneto-reflection and magneto-photoreflectance experiments on GaAs/GaAlAs quantum well structures, including single, double and multiple quantum wells, in magnetic fields up to 15 Tesla, and in the temperature range 4.2k - 17.3k, by use of the optical fiber techniques. We observed the Landau level interband transitions for all the subbands in the Faraday configuration, and the magnetotunneling effects in the double quantum well. At liquid helium temperature, the narrow derivative line width of 1 mev is measured.

From both reflectance experiments, we obtained the exciton binding energy, the reduced effective mass and information on the valence band mixing and crossing. Comparison of the results of the two techniques will be discussed, including the mechanism of the photoreflectance.

Our optical fiber apparatus provides a new method to perform photoreflectance without using optical dewar. Advantages are low cost and alignment-free access, which are especially important for measurements made in the superconducting magnets.

Confinement effects on Be acceptors in GaAs/AlGaAs multi quantum well structures

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We have measured the far infra red (FIR) absorption due to Be acceptors in bulk GaAs and several Multi Quantum Well structures.These structures have well widths between 50 and 200 A and were doped to 3E17 cm-3 over the center 1/3 or the end 1/3 of the well.A bulk sample 3um thick doped to 3E16 cm-3 has also been studied. Since the Bohr radius of the bulk acceptor is (40A) compareable to the quantum well width confinement effects are expected, similar to those that have been seen when donors are confined in quantum wells,Jarosik et. al.
The dependence of the FIR acceptor absorption on well width and the position of the acceptor in the quantum well has been examined. Magnetic fields up to 9.0T and temperature dependence up to 20K have been used to determine the symmetry of the states involved in the optical transitions.By studying the magnetic field splitting of the bulk acceptor as the well width is decreased a systematic trend due to the confinement can be seen. Previous workers, Masselink et.al.,have used Photoluminescence to determine the binding energy of the acceptor in the well.For the center doped well the agreement with their calculations was good.The only reported study of higher states was by Gammon et.al. who used Raman scattering to determine the separation of the 1S and 2S states.
Our results will be discussed in relation to the theoretical calculations and Photoluminescence measurments of Masselink et al. The acceptor confinment effects will also be discussed in relation to the donor confinement .

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Magnetoreflectance Study of Be Acceptors in Selectively Doped GaAs/AlGaAs Multiple Quantum Wells.

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We have recorded low temperature (T~5K) reflectivity spectra from p-type, Be doped GaAs/AlGaAs quantum wells in magnetic fields up to 8 Tesla. Doping was confined to either the center or "top" 1/3 of the GaAs wells. The reflectivity spectra exhibit three types of features:

(a) excitons (heavy and light hole excitons from the wells as well as the excitons from the buffer),
(b) interband transitions between conduction and valence band Landau levels, and
(c) transitions between the Be acceptors and the conduction band Landau levels.

Type (b) transitions, extrapolated to zero field, give the value of the heterostructure effective gap E_g^*, while type (c) transitions extrapolate at $E_g^* - E_B(Be)$, where $E_B(Be)$ is the Be-acceptor binding energy. Thus the difference between the two energy intercepts gives an accurate value of the Be acceptor binding energies in these quantum wells.

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Emission Spectroscopy of GaSb/AlSb Quantum Wells in the 1.6eV - 2 eV Energy Range

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We have investigated the optical emissions of MBE grown GaSb/AlSb multiple quantum wells with well widths L_z between 120Å and 12Å at energies highly above the bulk GaSb band gap (0.8eV). In the experiments the samples were excited only slightly above the first subband edge by a Nd-YAG or infrared dye laser. The study of such high energy emissions under these conditions is particularly interesting because i) it provides information on hot carriers which follow nonradiative recombination (Auger) processes and ii) because new quantization induced transitions have been observed in GaSb in this energy range.[1,2]

In addition to the previously investigated $E_o+\Delta_o$-emission[2] and $2E_g$-transitions[1] due to the simultaneous recombination of 2 electrons and 2 holes, we report here the observation of a new emission band in the energy range above 1.6eV for 30Å<L_z<70Å. The emission energy increases with decreasing L_z up to 1.95eV. The energetic positions of the emission imply very high subband energy contributions (0.8eV - 1.15eV) to the transition energies.

We have investigated the transitions as a function of well widths, excitation intensity and temperature. Our data imply that the conduction band level involved in the transition is occupied by an electron-electron-hole Auger process. The emission is most likely due to a parity allowed but forbidden transition from the 3rd conduction band subband to the 1st heavy hole valence band subband. This means that almost the entire quantization occurs in the conduction band potential well. In the conduction band dispersions of bulk GaSb (and AlSb) this corresponds to regions with negative mass. Model calculations which account for the well width dependence of the transition energies under these conditions will be discussed.

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ELECTRONIC STRUCTURE OF STRAINED-LAYER $Si/Si_{1-x}Ge_x$ SUPERLATTICES FROM TIGHT-BINDING CALCULATIONS

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The electronic structure, energy bands as well as layer- and wavevector-resolved local densities of states of strained $Si/Si_{1-x}Ge_x$ superlattices are calculated by means of the empirical tight-binding (TB) method. Two different types of TB Hamiltonians are applied, the so-called sp^3- and the sp^3s^*-Hamiltonians. We consider homogeneous strained superlattices grown in [001]-direction. The problem of band offsets is reflected in our calculations by a proper choice of the energy zero points for the bulk Si and Ge Hamiltonians. The mixed crystal is described by the virtual crystal approximation. In the present paper the following questions are studied for different layer thicknesses and chemical compositions:

(i) the subband structure,

(ii) the position of the lowest conduction band minima in the Brillouin zone, and

(iii) the influence of strain on the change of band offsets and on the energy gap.

Optical Investigations of *Highly Strained* InGaAs GaAs Multiple Quantum Wells

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Abstract

The low temperature optical transmission spectra of several $In_xGa_{1-x}As/GaAs$ strained multiple quantum wells (MQWs) with different *well widths and In mole fractions* have been measured. The excitonic transitions up to C3-HH3 between the electrons in the conduction bands and heavy holes in the valence bands are observed. Besides, step-like structures corresponding to band-to-band transitions are also observed, which are identified as C1-LH1 transitions. The calculated transition energies taking into account both the strain and the quantum well effects are in good agreement with the measured values. In these calculations the lattice mismatch between the GaAs buffer and the InGaAs/GaAs MQW is taken into account and the valence band offset Q_v is chosen as an adjustable parameter. By fitting the experimental results to our calculations, we conclude that the light holes are in the GaAs barrier region (type 2 MQW) and the valence band offset Q_v is determined to be 0.30. A possible system in which the transition from type 1 to type 2 for light holes might be observed is also discussed.

Intersubband optical absorption in superlattices†

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ABSTRACT

Phononless intraband absorption in superlattices has been investigated theoretically. The absorption coefficient for optical transitions between the conduction subbands has been calculated. In general, the absorption is small because the conduction states are almost entirely *s*-like. A small *p*-like component is mixed into the conduction subband states, giving rise to a non-zero but small optical matrix element. However at the zone center and zone boundary of the mini-Brillouin zone, we find that the absorption is enhanced because of singularities in the joint density of states. Near the singularities, the absorption is a few orders of magnitude greater than at points further away. The results suggest the possibility of utilizing intersubband absorption for long wavelength infra-red detection as an alternative to using narrow bandgap semiconductors. Interband absorption between the heavy hole and conduction subbands has also been computed so that the relative strengths of the two cases could be compared. Although GaAs-$Ga_{1-x}Al_xAs$ superlattices have been used as an example, the intersubband results are applicable to superlattices in general. Consequently superlattices having silicon as a host material could be used, thereby exploiting the good material properties of silicon.

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Photoluminescence Studies of Quasi-2D Electrons and Holes in a Magnetic Field

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We discuss the magnetic-field-dependence of the low-temperature photoluminescence (PL) spectrum of (In,Ga)As/InP quantum wells (QWs). Several novel results will be presented, including: the interpretation of the diamagnetism of bound excitons in quantum wells; a direct observation of the decreasing length scale, as magnetic field is increased, of the most localised states in the low-energy tail of a disorder-broadened Landau level; in an n-type modulation-doped QW, recombination of photocreated holes with electrons in all states below the Fermi energy, without restriction of electron crystal momentum; and a magnetic-field-induced quenching of the screening by the quasi-2D electron gas of the Frohlich electron-phonon interaction.

The diamagnetic energy shift of the exciton PL line 'X' enables information to be deduced on the length scale of exciton binding, and is discussed for QWs grown both by molecular beam epitaxy (MBE) and by metal-organic chemical vapour deposition (MOVCD).

The strength of the longitudinal optic (LO) phonon sideband 'X_{LO}' of X gives another measure of the length scale of the bound exciton which recombines. In a high-quality undoped QW grown by MBE, there is no measurable phonon sideband at zero magnetic field, showing that the length scale of exciton binding is very large. With increasing magnetic field, the phonon satellite strength increases, indicating a decreasing localisation length, as expected for an exciton formed from the most localised states in the low-energy tails of the lowest electron and hole Landau levels.

In MOCVD QWs the photocreated holes occupy very compact bound states which we interpret as arising from binding by alloy fluctuations. In n-type modulation-doped QWs with electron Fermi energy E_F as large as 45 meV, the spread of the hole wavefunction in k-space permits recombination processes involving electrons right up to E_F. In magnetic field this broad PL band splits into a series of lines arising from recombination involving different electron Landau levels. Study of the lineshape as a function of magnetic field leads to determination of the density of states of the quasi-2D electron gas in a magnetic field.

When the electron density in the QW is increased to ~5×10^{11} cm^{-2} by changing the bias on a Schottky gate, the LO phonon satellite X_{LO} is unobservable because the Frohlich interaction is screened out[1]. In a magnetic field, however, the phonon satellite is observed even for high sheet carrier densities. We discuss this quenching by the magnetic field of the screening of the Frohlich interaction.

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Effective Masses and Optical Matrix Elements in *Semiconductor Superlattices**

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A generalization of the well-known f-sum rule for periodic systems[1] is examined for three different types (I-III) of semiconductor superlattices (SL). Effective masses parallel ($m_\parallel$) and perpendicular ($m_\perp$) to the layers in each case are obtained analytically in terms of bulk band structure parameters, band offsets and layer thicknesses using the envelope function approximation and the Kane model. General features of $m_\parallel$, $m_\perp$, optical matrix elements and oscillator strengths are discussed. Calculated values of both electron effective masses in the Type I SL GaAs/GaAlAs agree well with recent cyclotron resonance measurements. The different behavior of $m_\parallel$ and $m_\perp$ is explained in terms of the repulsion from the next highest SL conduction band. The properties of Type II SL's (eg., InAs/GaSb) are investigated as a function of the staggered band alignment of the constituents. An application to the Type III SL HgTe/CdTe yields information on both the narrow gap regime, which is important for infra-red devices, and a wider gap regime in which $m_\perp$ exhibits an unusual non-monotonic dependence on HgTe layer thickness.

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Theoretical Studies of Polarization Dependent Electro Optical Modulation in GaAs/AlGaAs and InGaAs/GaAs Multi Quantum Well Structures

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We have studied the optical absorption process for excitonic and interband transitions in lattice matched (GaAs/$Al_{0.3}Ga_{0.7}As$) and strained ($In_xGa_{1-x}As$/GaAs) multi quantum well (MQW) structures in presence of a transverse electric field. The hole problem is solved by using the Kohn-Luttinger Hamiltonian which is solved by an eigenvalue method. The effect of strain on the splitting of light and heavy hole bands is also treated in the Kohn Luttinger framework. The exciton problem is then solved variationally and optical absorption is then calculated for different polarization orientations. For lateral coupling of light into the MQW structure the polarization effects are very strong and also strongly dependent on the applied electric field. Optical modulation depths are calculated by including realistic homogeneous and inhomogeneous line broadening for the excitonic transitions. Inhomogeous broadening due to structural imperfections(interface roughness + inter-well size fluctuation) is very sensitive to the applied field (e.g. $\acute{O}_{inhom}$ (E=60 KV/cm) / $\acute{O}_{inhom}$ (E=0) ~2.5 for a 100 Å GaAs/$Al_{0.3}Ga_{0.7}As$ MQW structure) and seriously affects the modulation depth. In the strained system, with a proper choice of composition and well size, the light hole exciton can be at a lower energy than the heavy hole exciton. Consequences of this on the polarization dependence of optical modulation will be discussed.

Absorption and Photoluminescence Studies of the Temperature Dependence of Exciton Lifetimes in Lattice-Matched and Strained Quantum Well Systems*

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ABSTRACT

We have carried out a systematic study of the temperature dependence of exciton transitions of lattice-matched $Al_xGa_{1-x}As$/GaAs and $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ and strained $In_xGa_{1-x}As$/GaAs quantum wells (QW) grown by molecular beam epitaxy. The experiments were done in the temperature range of 4-300 K. It is observed that the excitonic transitions remain dominant up to 300 K in all cases. The measured exciton linewidths at 6 K for the AlGaAs/GaAs, InGaAs/InAlAs and InGaAs/GaAs QW systems are 0.8, 6.4 and 4.1 meV, respectively, which are one of the narrowest observed for each system. The linewidths increased significantly with increase of temperature.

Our studies focussed on the lowest energy transitions which are attributed to heavy hole transitions in the lattice-matched systems and to light-hole transitions in mismatched systems. The finite exciton linewidth at the lowest temperature is attributed to inhomogeneous broadening due to interface roughness and well size fluctuations, while the temperature broadening results from homogeneous interactions of excitons with both acoustic and optical phonons. Based on this assumption we have calculated the homogeneous part of the linewidth and consequently the exciton lifetime at higher temperatures by careful fitting of experimental data with Gaussian and Lorentzian lineshapes. For example, the lifetimes at 77 and 300 K are 2.4 and 0.48 ps for a 120 Å lattice-matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ SQW. In the case of a 120 Å strained $In_{0.18}Ga_{0.82}As$/GaAs SQW, where the energy positions of the light- and heavy-hole exciton transitions are reversed, we calculate a lifetime of 0.15 ps at 300 K for the light-hole excitons. These results are interpreted in terms of exciton-phonon interactions and are expected to be very useful for the design of semiconductor optical devices operating at different temperatures. The effect of varying well size on exciton lifetimes are also being studied and will be discussed in the same context.

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PHOTOLUMINESCENCE STUDIES OF GaAs/AlAs SUPERLATTICES

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The results of low temperature pressure-dependent photoluminescence measurements on short and long period GaAs/AlAs superlattice structures will be presented and discussed. The experimental technique and apparatus for performing low-temperature hydrostatic-pressure optical measurements will be discussed. Measurements in short period structures show that the lowest energy conduction-band states are in the AlAs layers and the highest energy valence-band states are located in the GaAs layers. This conjecture is supported by the following three experimental observations: (1) the observed pressure coefficient of the conduction-band to valence-band transition energy is negative, (2) the magnetic mass of this transition is "heavy", and (3) the band-to-band absorption coefficient appears to be small. Additionally, the experimental observations are in agreement with predictions of tight-binding calculations. Finally, pressure-dependent pulsed-laser-excitation spectroscopy results at 4K will be presented.

DYNAMICS OF EXCITON TRANSFER BETWEEN MONOLAYER-FLAT ISLANDS IN SINGLE QUANTUM WELLS

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Single quantum wells of GaAs grown by Molecular Beam Epitaxy with growth interruption at hetero-interfaces exhibit multiple structure in the luminescence spectrum corresponding to excitons in monolayer-flat islands with N and N ± 1 monolayer thicknesses [1,2]. We have investigated the dynamics of carrier and exciton transfer between monolayer-flat islands within a single well, by using time resolved luminescence spectroscopy with sub-picosecond time resolution [3]. These first results on the dynamics of transfer between islands provide new insight into this interesting property of quantum wells.

Single quantum wells with N and N + 1 monolayer-flat islands were excited at 15 K with a carrier density of 2×10^{10} cm^{-2} using 300 fs dye laser pulses. Luminescence spectra at various time delays (τ) following photoexcitation were measured using sum-frequency-mixing technique with 400 fs time resolution [3]. For small τ, the higher energy luminescence corresponding to N monolayer-thick islands dominates. With increasing τ the luminescence corresponding to N + 1 monolayer-thick islands increases in intensity because of transfer of carriers and excitons from narrow to thick islands. Quantum wells with N = 6 and 10 were investigated and the data were analyzed in terms of three time constants (the time of formation of excitons, the transfer time between different islands and the exciton decay time) as well as the ratio of areas of islands of N and N + 1 monolayer thicknesses. We find that the exciton formation time is 20 ps while the transfer time is 250 ps, in good agreement with the estimated size of the islands.

*** on leave from Centre National d'Etudes des Telecommunications, Lannion, France**

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ELECTRIC-FIELD DEPENDENCE OF THE INTERSUBBAND OPTICAL ABSORPTION IN A SEMICONDUCTOR QUANTUM WELL

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ABSTRACT

We present theoretical results of intersubband linear optical absorption in the conduction band of a GaAs-AlGaAs quantum well structure with an applied electric field taking into account of the field-dependent intrasubband relaxation. Our analysis is based on the one electron density matrix formulation with intrasubband relaxation processes due to polar optical phonon scatterings. Previous calculations for polar optical phonon scatterings[1] in a quantum well did not consider the electric field dependance. We improved our previous calculation[2] for optical absorption by considering the electric field dependence of the polar optical phonon scattering as a main intrasubband relaxation process instead of a constant relaxation time employed before. It is shown that the electron-phonon scattering rate is increased by about 10% when field is 200 kV/cm for the well width of 126.5 Å at room temperature compared with zero field case. We show that for increasing electric field the absorption peak corresponding to the transition of states 1 → 2 is shifted higher in energy and the peak amplitude is also increased. The effect of the field broadening in the absorption spectrum is also demonstrated numerically. These features have the potential applications for novel far-infrared high speed optical modulators.

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Electron Energy Levels of Si/CoSi$_2$/Si Quantum Well Structures
M. S. Hybertsen, Physics Department, University of California, Berkeley, and Department of Electrical Engineering and Computer Sciences, California Institute of Technology -- An effective-mass theory is derived for estimating the behavior of the quantized energy levels of a semiconductor/metal/semiconductor epitaxial layered structure and applied to Si/CoSi$_2$/Si. Although this theory is very approximate, it provides insights into the quantum behavior of such thin layered structures. The results suggest that new quantum-well structures may be achievable. Only the electrons in the metal whose energies lie in the silicon band gap are confined. It is found that, for thin layers, there are only a few quantized levels, the energy difference between levels being large. In addition, the energy of a level varies rapidly with the thickness of the metal layer. The ability to engineer discrete, well-separated energy levels is of particular interest to quantum-well device applications such as resonant tunneling and optoelectronics. However, because of the sensitivity of the energy levels to the metal layer thickness, precise monolayer control will be necessary to utilize these effects, posing a serious challenge for the experimental approach.

FAR INFRARED CHARACTERIZATION OF III-V AND II-VI SUPERLATTICES*

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Intricate semiconductor microstructures require an array of measurement methods to examine fundamental properties and structural quality. Far infrared spectroscopy (10-400 cm^{-1}) is contactless and nondestructive; it can determine band, free carrier, phonon, impurity, and structural properties for most superlattices of current interest; it probes the entire structure from front to back; it has potential for in situ characterization and for the measurement of spatial inhomogeneity.

Our recent and emerging far infrared work in a variety of superlattices (SL) will be presented, complemented with Raman, photoluminescence and picosecond time-resolved analysis. Areas and SL's include: confirmation of SL infrared theory, observation of anomalous phonon modes and of possible strain effects in AlAs-GaAs (1); measurement of alloy effects, carrier concentration and effective masses in MBE- and MOCVD-grown HgTe-CdTe (2); verification of structural quality and observation of anomalous phonon behavior in $Cd_{1-x}Mn_xTe$-CdTe (3); determination of electronic parameters in $Cd_{1-x}Zn_xTe$-CdTe.

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PICOSECOND SPECTROSCOPY OF $Cd_{1-x}Mn_xTe$-CdTe MICROSTRUCTURES*

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Picosecond relaxation times of excitons in three MBE-grown $Cd_{1-x}Mn_xTe$-CdTe microstructures[1] (x = 0.06, 0.23 and 0.45, CdTe well thickness L_z = 210 A, 16 A and 150 A respectively) at 7K have been measured by time-correlated single photon counting. These microstructures were previously examined by cw photoluminescence (PL) and Raman scattering, which established their excellent quality[1,2] and showed confinement effects.

Our time-resolved experiments give exciton lifetimes of several hundred picoseconds which decrease with L_z. This is in keeping with earlier measurements of the total excitonic luminescence decay using a monochromator/streak camera combination[3]. In addition, the high spectral resolution of our method allows us to see small PL peaks for the $Cd_{0.55}Mn_{0.45}Te$-CdTe sample which lie near confined subband energies predicted by a Kronig-Penney model, and to measure the lifetime at each peak. The resulting values (from <150 ps to 900 ps) and their energy dependence will be discussed.

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Dynamics of Field Control of Luminescence Intensities in GaAs/AlGaAs Quantum Well Structures

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High speed photoluminescence (PL) switching by electric field-induced carrier separation inside the Quantum Well (QW), combined with carrier escaping out from the well to the barrier layer is demonstrated to be free from carrier life time limitation. A new technique for evaluating radiative life time is also shown.

Figure 1 shows the PL response for a short pulsed voltage applied to a p-i-n diode with a GaAs(100Å)/AlAs(300Å) multi-QW structure. The 300psec delay of PL from the pulsed voltage was observed to be much shorter than the life time (30nsec). However, for a consecutive input pulse train, the PL response was degraded with the increasing number of the input pulses as shown in Fig.2(a) as long as the radiative recombination dominates over nonradiative processes under the condition of a constant generation rate. In order to solve this problem, we examined a modulation scheme in which a field-induced increase in radiative life time is combined with a field-induced decrease in nonradiative life time due to the carrier leakage at a high field. One of the examples of such a modulation is shown in Fig.2(b), indicating a significant improvement of the PL responses for the consecutive pulses. Figure 3 shows overall life time and radiative life time of the carriers obtained with the transient response of PL for pulsed electric field, as functions of the applied field. The new technique will be, in more detail, discussed at the presentation.

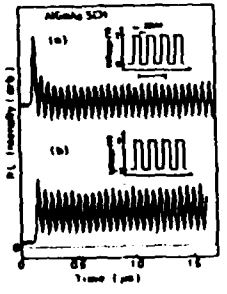

Fig.2

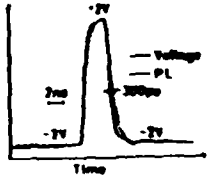

Fig.1

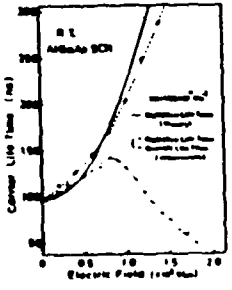

Fig.3

OPTICAL AND MAGNETO-OPTICAL STUDIES OF GaAs/AlAs QUANTUM WELLS

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Photoluminescence and reflectivity from several GaAs/AlAs quantum wells has been measured at 5K. The intensity of the emission spectra is one order magnitude smaller than that of the GaAs substrate. The main luminescence feature is attributed to transitions between the ground state conduction and valence subbands of the GaAs layers. In addition, weak luminescence associate with the X and L electrons of the GaAs has been observed. The reflectivity spectra shows a series of confined states. In the reflectivity spectra however, the intensity of the confined levels is similar to that of the substrate. The data suggests that the electrons in the GaAs layers are confined by the X (rather than the Γ) conduction bands of the AlAs barriers. In a magnetic field, in addition to the exciton, interband Landau level transitions are observed. The slopes of these transitions indicate that the electrons are in the GaAs layers. The zero field energy intercepts of the Landau transitions give the effective gap, thus allowing us to determine the binding energy of the ground state of the heavy hole exciton.

ELECTRON STATES IN InGaAs/InP HETEROSTRUCTURES

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Missing plateaus in the quantum Hall effect[1] and the high mobility of the two-dimensional electron gas are two characteristic features of InGaAs/InP heterojunctions. The small effective mass, essential for the mobility, is related to the small gap of InGaAs; this in turn determines via the nonparabolicity the crossing of Landau levels from different subbands for varying magnetic field. We have performed calculations of subband Landau levels for $In_{0.53}Ga_{0.47}As/InP$ heterojunctions based on self-consistent solutions of the subband problem without magnetic field. This calculation is based on a 2×2 conduction band Hamiltonian obtained from a 14×14 $\underline{k}\cdot\underline{p}$ Hamiltonian by higher order perturbation theory and includes the nonparabolicity of the bulk bandstructure by higher order terms in the electron wave vector $\underline{k}$.[2] These terms are all well defined by the bulk properties and do not introduce additional parameters. Moreover our subband Hamiltonian includes also the spin-orbit term connected with the interface electric field. Our calculations are performed for electron concentrations of about $5\cdot10^{11}cm^{-2}$, which correspond to the experimental situation of Ref. 1 with two occupied subbands, and yield subband separations and Landau levels. On the basis of these results and the magnetic field dependent Fermi energy we can correlate jumps of the Fermi energy and crossing of Landau levels with the observed QHE data. The influence of the magnetic field on the self-consistent potential is discussed.

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INTERVALENCE BAND ABSORPTION IN STRAINED LAYER SYSTEMS

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Intervalence band absorption (IVBA) is believed to be an important contribution to the temperature sensitivity of the threshold currents in some of the longer-wavelength semiconductor lasers used for optical fibre communications. Recent calculations of the IVBA coefficient α in bulk $Ga_{0.47}In_{0.53}As$ [1] show that there is significant absorption of radiation at the wavelength corresponding to the bandgap energy (α ≈ 39 cm^{-1} at λ = 1.6 μm and T = 300K).

There is now substantial interest in semiconductor lasers based on quantum well structures because of the advantageous properties of the gain spectrum of the quasi-two-dimensional system. However, IVBA is also a detrimental process in these devices and here we present theoretical results from a $\underline{k}.\underline{p}$ model for IVBA in quantum well structures based on the lattice matched GaInAsP/InP materials system. Recently Adams [2] has proposed that in strained layer quantum wells the valence bandstructure can be modified in such a way as to considerably reduce or effectively eliminate IVBA. In this paper we also present results for strained layers of GaInAs demonstrating the effect of strain on the IVBA spectrum and the reduction of α at the emission wavelength.

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A Tunneling Measurement of the Electronic Density of States of a Superlattice

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The optical and electrical properties of weakly coupled superlattices have been investigated extensively for many years. However, only recently has there been convincing *evidence of miniband transport in strongly coupled superlattices*, albeit limited to the bottom of the first miniband.

We report on electrical tunneling measurements between asymmetric, strongly coupled, superlattices which has allowed us to probe the full density of states. The samples grown by MBE, had superlattices formed from narrow (<30A) $Al_{0.3}Ga_{0.7}As$ barriers and GaAs wells of thickness chosen to form a desired number of minibands on either side of a 200Å $Al_{0.3}Ga_{0.7}As$ tunnel barrier. Pronounced negative differential resistance can be seen in the current-voltage characteristics associated with tunneling transitions between the two miniband structures. The data enables us to obtain information on the superlattice density of states, and the measured band structure is compared with various theories.

Vertical Transport in Superlattices: The Influence of Electron-electron Scattering

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Electrons injected into the continuum of a quantum well or superlattice system suffer collisions with the electrons residing within the bound states of the system below the band edge of the barrier material. Such collisions may be viewed as a dissipative loss mechanism for the injected electrons primarily resulting in energy loss and/or capture into the well states. Such effects are expected to be a major loss mechanism in hot electron transistors where carriers are injected above the base and must reach the collector without capture.

Calculations have been performed of the short range(single particle) interaction between continuum and bound electrons within the Born approximation. The form factor resulting from the overlap integral of the free and bound carriers shows that resonances as a function of the *normal wavevector may arise associated with* the bound state energies. For transitions in which the initial and final state of the injected electron is the continuum, scattering is peaked for q_z=0, where q_z is the difference between the initial and final wavevector normal to the well. This suggests that electrons over the well may undergo successive scattering events which dissipate the parallel component of the energy while leaving the normal component unchanged, resulting in a polarized beam of electrons arriving at the collector. Transport calculations of the injection of high energy carriers into the superlattice will be presented based on Monte Carlo simulation which includes interaction between bound and injected electrons.

PRESSURE DEPENDENCE STUDY OF THE EFFECTIVE MASS IN GaInAs/InP HETEROJUNCTION

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A study of the effective mass in GaInAs/InP heterojunction under hydrostatic pressure up to 15 Kbars is presented .Earlier results have showed the importance of hydrostatic pressure effects on the band parameters of the heterojunction to explain the experimental decrease of the carrier concentration with pressure at the interface.Here Magnetophonon Resonance experiments are performed to work out the increase of mass with pressure in our samples.The effective mass at atmospheric pressure is deduced from high temperature cyclotron resonance experiments and then used to work out the frequency of the phonon interacting with the 2D electron gas(Wo).The value of Wo is found to be dependent on the carrier concentration of the measured samples.The lowest value was found for the highest carrier concentration sample.
A band edge effective mass increase of 12.1%/kbar is found in the highest carrier concentration sample,two times smaller than the rate found experimentally in GaInAs bulk material(2) and slightly smaller than in AlInAs/GaInAs heterojunction .The experimental increase could be fitted with the multiband k.p theory assuming no pressure dependence for the interaction of Γ minimum with the higher conduction bands.

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SMMIII

NEGATIVE RESISTANCE SWITCHING IN SUPERLATTICES : RESONANT TUNNELING OR HOT ELECTRON TRANSFER ?

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The study of negative differential resistance (NDR) effects in semiconductor microstructures has received much attention in recent years, both for a fundamental interest in electrical transport physics, and for more practical reasons based on the possibility of designing novel fast electronic devices having new functions. Most works, however, have been devoted to double barrier structures, for which the interpretation of NDR relies on resonant tunneling of carriers through the barrier layers. On the other hand, little has been done on perpendicular transport in superlattices (SL), since ESAKI's pioneering work.

At low electric fields in SL, the effective medium approximation in fact generally is sufficient, and the main parameters characterizing perpendicular transport are effective mobilities for electrons and for holes (1). However, the small width of the minibands and the existence of secondary minima in the bulk material band structure may cause this approximation to fail at large fields, and eventually produce NDR effects.

We have, therefore, measured current-voltage (I-V) characteristics as a function of temperature on n^+-SL (GaAs-GaAlAs)-n^+ structures, which offer the advantage of allowing the application of large electric fields when the SL is undoped. At 77 K and below, two successive negative resistance switching (NRS) events were indeed found under large d.c. or pulsed applied biases. The abrupt character of the high conduction to low conduction transition, together with the absence of hysteresis, points to the formation of a high field domain located in the vicinity of the n^+ anode. Two possible mechanisms could account for this unusual behavior. In the first, a resonant tunneling effect (or miniband conduction) is quenched when the voltage drop per period becomes equal to the miniband width. In the second, hot electron transfer occurs between minibands originating from the Γ and L or X valleys. A convenient way to choose between those mechanisms is to apply a hydrostatic pressure, which is known to reduce the energy difference between the principal and the secondary minima. Our investigations up to 9 kbar give a strong support to the interpretation of NRS in terms of resonant tunneling quenching involving only the first miniband derived from the Γ minimum.

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18th Int. Conf. on the physics of semiconductors, Stockholm, August 1986

SM4III

PERPENDICULAR TRANSPORT IN SUPERLATTICE BIPOLAR TRANSISTORS (SBT)

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It has recently been shown that diffusive electron transport along the growth axis in superlattices (SL) could conveniently be studied through gain measurements in heterojunction bipolar transistors, whose p-type base is made of a superlattice (1). In these experiments, the base transport factor, or equivalently the current gain is a direct function of the electron diffusion coefficient, itself strongly dependent on SL parameters. The main advantage of this technique is that it gives access to pure diffusive transport, as opposed to more conventional current-voltage or time of flight measurements, which require the existence of an electric field.

In superlattices, diffusive perpendicular conduction can result from two main mechanisms (1) :
i) Bloch type conduction with a mobility essentially limited by phonon scattering at room temperature.
ii) phonon-assisted tunneling (hopping) from well to well.

It can be expected that the temperature dependence of those two processes should be markedly different. One may to gain further insight into perpendicular transport in SL is thus to study the effect of temperature on the electrical characteristics of SBT's. Such investigations have, therefore, been carried out with or without photoexcitation, on transistors with various barrier widths of the SL base, in conjunction with a quantitative modelling of the device characteristics. The main result is that the perpendicular electron mobility may remain large down to 77 K at least, which favors Bloch over hopping transport. It appears however, that polar optic phonon scattering is not the only mechanism which limits the mobility, even at 300 K.

This conclusion will be discussed in relation with calculations on the temperature dependence of perpendicular mobility in GaAs-GaAlAs superlattices. Finally, it will be stressed that with suitably chosen SL parameters, a full compatibility could be achieved, between a SBT and a laser using the same epitaxial structure, a prerequisite for the design of integrated transistor-laser circuits (2).

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Effect of Continuum Resonances on Electronic Transport in Quantum Wells

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The study of electronic transport in quantum wells and superlattices is of great current interest. In particular, the real-space transfer of hot electrons out of a quantum well is known to be an important process in microdevices, such as the high electron mobility transistor. At present, a good understanding of transport exists as long as the carriers reside inside the quantum well with an energy lower than the barrier height. For larger energies, which may lead to real-space transfer, no good picture exists which also includes virtual resonant states above the quantum well. The importance of such resonant states has recently been pointed out [1]. So far, several Monte Carlo models of HEMT-like structures have been developed [2,3] which include the transfer of carriers out of the quantum well into the barrier material. In these models, carriers are treated as free as soon as their energy becomes larger than the barrier height, thereby neglecting the influence of virtual states. Very recent experimental evidence [4] suggests that such resonant states influence ballistic transport across a quantum well by modulating the transmission probability. Here, we investigate the influence of these resonant states on transport in quantum wells, with particular emphasis on the real-space transfer of hot electrons out of a quantum well. We present results for a model system, consisting of a square quantum well, which compares transport with and without virtual states. Results for a HEMT-like quantum well are also presented.

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ON THE EINSTEIN RELATION IN HgTe-CdTe SUPERLATTICES IN THE PRESENCE OF A QUANTIZING MAGNETIC FIELD

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ABSTRACT

An attempt is made for the first time to investigate the Einstein relation for the diffusivity-mobility ratio of the electrons in HgTe-CdTe superlattices (SL) in the presence of a quantizing magnetic field along the superlattice direction by formulating a generalised dispersion relation under magnetic quantization . It is found that the ratio oscillates with the reciprocal quantizing magnetic field since the origin of the oscillations in the Einstein relation are the same as that of the SdH oscillations. Besides, the same ratio increases with increasing carrier degeneracy and the theoretical results are in qualitative agreement with the suggested experimental method of determining the Einstein relation in degenerate semiconductors having arbitrary dispersion law. The corresponding results for superlattices of relatively large bandgap semiconductors are also obtained from the expressions derived.

Double Base Hot Electron Transistor

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Abstract

We demonstrate that the performance of ballistic devices can be greatly improved if a focused beam of energetic electrons is injected into the active region of a ballistic structure. In particular, we propose a new device - a Double Base Hot Electron Transistor (DBHET) - where the first base focuses and accelerates the beam of electrons injected into the second base. The electrons propagating in the first base with large angles to the direction normal to the heterointerface are more likely to be scattered and hence are more likely to lose energy and be removed as the first base current. This effect is enhanced by the impurity scattering as less energetic electrons are more frequently scattered by impurities. By grading composition and doping in the first base the additional acceleration of the electrons is achieved. Hence, the first (doped and/or graded) base region acts as an "electron gun" accelerating electrons and as a "lens" providing a focused ballistic electron beam. This beam is injected into the second base where an input signal is applied. We present the results of the Monte Carlo simulation of such a device on a supercomputer (using an ensemble of 72,000 electrons) along with the results of a similar simulation for a single base hot electron transistor. This calculation clearly shows that focusing and acceleration of the electron beam in the first base can considerably reduce the transit time across the active region (up to a factor of 4). There is also a considerable increase in the fraction of electrons that cross the active region without collisions. In addition, we consider the effects of built-in field and temperature on the electron transport in DBHETs. Finally, we discuss different possible implementations of these new devices.

Scattering theory for quasi-one-dimensional tunneling structures*

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Quantum theoretical studies of semiconductor microstructures are most naturally done in terms of one-dimensional scattering states, which are characterized far from a structure by k-dependent reflection and transmission amplitudes. These states are usually computed by integration of Schroedinger's differential equation. We follow an alternative approach, beginning from integral forms such as the Lippmann-Schwinger equation. This is less practical for direct computation, but is used to obtain global properties of the states and provides the basis for a formal scattering theory of the kind that has been developed for the conventional problem of three-dimensional potential scattering. One very useful formal result is that scattering states obey the same orthonormality relations as related momentum eigenstates. This simplifies the calculation of thermodynamic and conduction properties, as well as the construction of many-electron states. The reflection and transmission amplitudes generalize the phase shifts of s-wave scattering in a central field, so we have generalized Wigner's constraint on the phase shift k-derivative. This arises from a casuality condition: a scattered wave cannot leave the scatterer before an incident wave arrives; thus in the 1-d case there are two constraints corresponding to outgoing waves in opposite directions. Levinson's theorem, giving the zero-energy phase shift, has also been generalized. We have studied the analyticity of the amplitudes, finding relations between poles and bound states that parallel those for the Jost function in conventional scattering.

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Tunneling by an electron packet with an initially sharp wavefront*

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We have studied the propagation of an electron pulse through various one-dimensional potentials. This pulse, as suggested by Stevens[1], is a plane wave state that has been cut off to give a sharp initial wavefront. For some simple barriers, exact solutions were found. These included single and double delta-function barriers, which elucidate the behavior of the delay time, and a potential step, which allows the wavefunction to be studied within a classically forbidden region. The general case was studied by writing the Green's function in terms of a complete basis of scattering eigenstates. In a classically allowed region, at constant potential, the wavefront propagates at the velocity of the unmodified plane wave state, while it broadens as $\sqrt{t}$. In the presence of a tunneling barrier, the transmitted wavefunction is the sum of two parts: a propagating wave and a dissipative precursor. The propagating portion is essentially the incident pulse, attenuated by a factor of the transmission amplitude and shifted. In contrast with Stevens, we find that the shift, or delay time, of the wavefront is comparable to that of a Gaussian wavepacket with the same momentum. By examining the general case, we show that this and other features of the pulse propagation are insensitive to details of the potential such as the sharpness of potential steps.

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* Work supported in part by the Office of Naval Research.

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Calculations of Channel Density in an AlGaAs-InGaAs-GaAs Pseudomorphic MODFET Structure

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ABSTRACT

We describe self-consistent space charge calculations of the low-temperature channel density of an AlGaAs-InGaAs-GaAs pseudomorphic MODFET structure as a function of material parameters, well width, and gate voltage. These calculations are based on a variational treatment of the wave function in the quantum well. For large well width, our results reduce to those of Stern[1] for a two-dimensional electron gas at the AlGaAs-InGaAs interface. We present plots of channel density versus several physical parameters (e.g. aluminum and indium fractions, well width).

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A COUPLED RAMAN-BRILLOUIN STUDY OF DIRECT AND FOLDED ACOUSTIC MODES IN LONG-PERIOD GaAs-AlAs SUPERLATTICES

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A new experimental set-up combining the advantages of both Brillouin and Raman techniques have allowed a systematical study of the direct (Brillouin) longitudinal acoustic (LA), transverse acoustice (TA) folded longitudinal acoustic (FLA) and folded transverse acoustic modes (FTA). All these modes, except the FLA, are investigated for the first time. Another interest of the study consist of the investigation of long period (GaAs-AlAs) superlattices (D = 500 A), thus allowing the observation of phonon corresponding to wave vectors in the z direction (perpendicular to the layers) whose magnitude is larger than the limit π/D of the Brillouin zone.

By using several excitation wavelengths belonging to both the Krypton and Argon-ion lasers, and by superposition of results corresponding to superlattices of varying periods but with the same aluminium concentration, very precise phonon dispersion curves are plotted in the first Brillouin zone ($0 < k_z < \pi/D$) and 2nd Brillouin zone ($\pi/D < k_z < 2\pi/D$) involving 20 values of the normalized phonon wavevector $k_z D$.

Several "anomalous" behaviours related to the frequency and the intensity of the Brillouin and folded acoustic modes are reported. An improved theory of propagation and interaction of light and acoustic waves, which explains the whole set of experimental results, is also presented here.

FREE CARRIER SCATTERING FROM QUASI-2D OPTICAL PHONONS IN SEMICONDUCTOR QUANTUM WELLS AND SUPERLATTICES

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The effect of the interfaces of semiconductor quantum wells and superlattices (SL's) on the long-wave optical phonons of such systems is twofold:

(i) the ordinary dispersion-free LO and TO phonons are changed to be confined modes in certain layers implaying that small wave-vectors are forbidden,

(ii) additionally, interface phonons arise, which can be regarded as the consequence of the small-wave-vector bulk phonons missing in such layered structures.

The free carriers are scattered from these interface as well as confined optical phonons via the polar Fröhlich and the deformation potential coupling. For the first time we calculate the total scattering rate, which is a sum of the four processes, in the case of a GaAs-$Ga_{1-x}Al_xAs$ double heterostructure (DHS) and a infinite SL. We find that interface phonons give rise to scattering rates which are comparable with those of confined bulk phonons, but which differ appreciable from the corresponding scattering rates from ordinary 3D bulk phonons. The scattering rates of the two types of quasi-2D optical phonons, however, sum up to a total scattering rate which is close to the 3D scattering rate, although deviations exist which become important for structures on the scale of a few atomic layers. Conclusions on reduced scattering rates of optical phonons in DHS's and SL's which take only confined bulk phonons into account have to be reexamined.

Raman scattering studies from periodic and quasiperiodic (Fibonacci) superlattices

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Excitation of zone-folded longitudinal acoustic phonons in GaAs/$In_xGa_{1-x}As$ strained layer superlattices, GaAs/AlGaAs Fibonacci superlattices, and in strained layer Si/Ge_xSi_{1-x} Fibonacci superlattices are reported. The main features of the experimental results are determined by the Fourier components of the dependence on position along the growth direction of the photoelastic coefficient. We discuss the interpretation of the experimental data and in particular the peak intensities, using simple analytical models as well as one-dimensional numerical calculations.

31GSMM - ELECTRIC FIELD EFFECTS ON INTERSUBBAND TRANSITIONS AND PHOTOLUMINESCENCE IN QUANTUM WELL STRUCTURES[**]

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The electric-field dependence of intersubband transitions of photoexcited electrons has been studied in a 264 Å GaAs-$Al_{0.3}Ga_{0.7}As$ quantum-well structure using Raman spectroscopy. The effect of the field on the photoluminescence spectrum has been also investigated. The width of the heavy-hole exciton increases rapidly with applied field while the intersubband linewidth remains nearly constant (see Figure 1). This feature is attributed to differences in the localization properties of excitons and free carriers for disorder due to interface roughness. Field-induced shifts of exciton and intersubband transitions agree well with theoretical predictions.

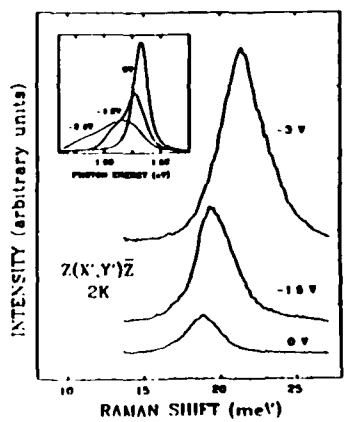

Fig. 1: Raman spectra of the quantum wells showing the $c_e \rightarrow c$, intersubband transition at different external voltages. The inset shows HH1 photoluminescence spectra.

[**] Supported by NSF Grant No. ECE-8610803

11CSMM - RAMAN SPECTROSCOPY OF ACOUSTIC PHONONS IN FIBONACCI SUPERLATTICES**

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We report on resonant and non-resonant Raman scattering by longitudinal acoustic (LA) phonons in Fibonacci GaAs-AlAs superlattices.[1] Spectra off-resonance are dominanted by doublets centered at frequencies that follow a power-law behavior, reflecting the self-similarity of the quasiperiodic ordering. Resonant data show a weighted density of states revealing the expected rich structure of gaps in the phonon spectrum (see Figure 1). It is proposed that the electronic excitation involved in the resonant process is an intrinsic surface state of the superlattice.

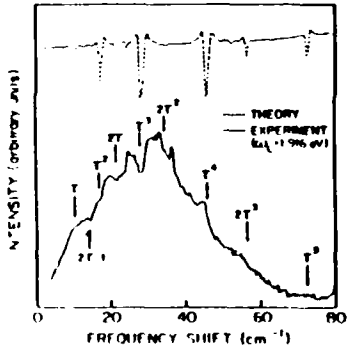

Fig. 1: Room temperature resonant Raman spectrum of the Fibonacci superlattice corrected for thermal factors, and calculated density of states of LA modes propagating along [001] (dashed curve). Arrows denote expected midfrequencies of main gaps in units of ωcd^{-1}; c is the average sound velocity.

** Supported in part by ARO Contracts No. DAAG-29-85-K-0175 and No. DAAL-03-86-6-0020

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11CSMM - ENHANCED AND QUENCHED RAMAN SCATTERING BY INTERFACE PHONONS IN QUANTUM WELLS: LOCALIZATION EFFECTS?*

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We report on the magnetic field and power density dependence of resonant Raman scattering by interface phonons in GaAs-$Al_xGa_{1-x}As$ quantum-well structures. Fields perpendicular to the layers lead to a dramatic enhancement of the scattering[1] (see Figure 1) while quenching is observed under strong photoexcitation. It is proposed that the resonances are due to excitons localized at the interfaces.

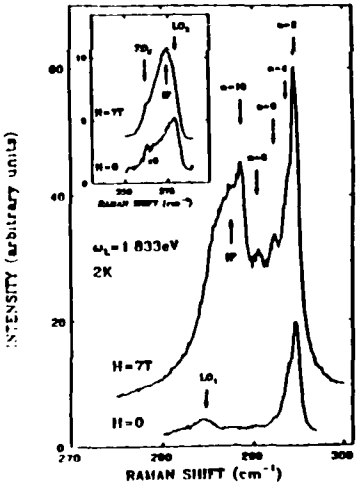

FIG. 1:
Raman spectra at 0 and 7T (field normal to the layers). ω_L is in the vicinity of the LH2 exciton. Labels n and IF denote, respectively, confined LO-phonons with $|\vec{q}|=n\pi L^{-1}$ and interface modes (L is the thickness of the well). The inset shows scattering by AlAs-like phonons. LO_1 (LO_2, TO_2) indicate the positions of GaAs(AlAs)-like modes in bulk $Al_{0.3}Ga_{0.7}As$.

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TICSMM - ELECTRONIC RAMAN SCATTERING IN QUANTUM WELLS COUPLED LEVELS IN TILTED MAGNETIC FIELDS*

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We report a magneto-Raman scattering investigation of free and donor-bound electrons in GaAs-$Al_xGa_{1-x}As$ quantum-well structures. For fields perpendicular to the layers, the spectra show intersubband transitions of photoexcited carriers, $1s \rightarrow 2s$ and $1s \rightarrow 1s'$ donor excitations.[1] Subband-Landau level and $1s'$-$2p^+$ coupling is observed in tilted fields. The latter results complement recent far infrared studies.[2,3] Experiments are in good agreement with theoretical calculations.

* Supported in part by ARO Contract No. DAAG-29-85-0175

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A Method for Making Shaped Layers on Spherical Substrates

by

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A combination of a secure, temporary mounting technique and laser photoablation produced a laser fusion target with an equatorial band of aluminum 30 μm wide on a spherical shell 400 μm in diameter. The temporary mounting technique utilizes a carbon fiber 10 μm in diameter and several millimeters long coated with silicone RTV which has been allowed to cure. Touched to the surface of a bare shell, this stalk holds the shell securely even in a vacuum environment. A nearly 4 π coating of aluminum is applied in a PVD coater equipped with a three axis rotater. Without removing the target from its temporary mount, the unwanted aluminum can be ablated away with a dye laser leaving a band of aluminum on the equator. The finished product may then be removed from the stalk with a vacuum fixture. There is no perturbation from temporary mounting.

The finished product is used to study the symmetry of laser implosions. The aluminum band absorbs light from an x-ray backlighter, thus, in a series of shots, progress of the layer containing the aluminum can be tracked as it implodes.

This method can be used with smaller substrates and different materials. Generalizations of the technique will be discussed.

GALVANOMAGNETIC PROPERTIES OF Ag/M (M = Fe, Ni, Co) LAYERED METALLIC FILMS†

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The zero field resistivity, magnetoresistance, and Hall effect have been measured at 4.2, 78, and 300K for a series of layered metallic films produced by sputtering. The magnetization at 4.2K was measured on a SQUID magnetometer. The sample periodicity Λ lay between 1.4 and 16nm. In each case the components of the sample were mutually insoluble and the thickness of the Ag layers was the same as the thickness of the M layers. The samples were characterized by high angle X-ray measurements which showed very clear satellite peaks, indicating for the Ag/Co system (which has been most thoroughly studied) coherence lengths ranging from 10nm for Λ = 2 to 20nm for Λ = 16nm. The zero field resistivity indicated a mean free path greater than the thickness of the individual layers. The data for the Ag/Co system could be fit to a simple extension of Fuch's theory involving a single, adjustable parameter--the transmission coefficient of an electron through a Ag/Co interface. Some measurements have also been made on the resistivity measured perpendicular to the layers, but in this paper we are mainly concerned with the galvanomagnetic properties and magnetization measurements.

The saturation magnetization at 4.2K is almost independent of Λ for Λ greater than 1nm, and is close to the value for bulk M. The negative magnetoresistance, on the other hand, varies strongly with Λ and passes through a maximum as Λ increases. This result cannot be understood if it is assumed that the magnetoresistance is the sum of independent contributions from the individual M layers. The magnetoresistance as a function of field direction is sharply peaked when the field is perpendicular to the sample. This is consistent with the experimental observation that this is a direction of hard magnetization. The Hall effect shows the usual normal and anomalous contributions associated with ferromagnetic materials. From a comparison of the anomalous Hall effect and the SQUID magnetization measurements we can deduce the existence of a surface anisotropy. For Ag/Ni this has the opposite sign from Ag/Co and Ag/Fe.

The effect of annealing temperature on the various physical properties will also be reported.

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INTERFACE PHENOMENA AT SEMICONDUCTOR HETEROJUNCTIONS:

LOCAL DENSITY VALENCE BAND OFF-SET IN GaAs/AlAs*

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Abstract

The valence band off-set ΔE_v at the lattice-matched GaAs/AlAs(001) interface is derived from highly precise self-consistent all-electron local density band structure calculations of the $(GaAs)_n/(AlAs)_n(001)$ superlattices (with $n \leq 3$). We calculate ΔE_v by using the core levels - available uniquely from an all- electron approach - as reference energies. Since these are experimentally accessible quantities, a direct comparison with experiment is, in principle, possible. We find that $\Delta E_v = 0.5 \pm 0.05$ eV, in very good agreement with recent experimental results ($\Delta E_v = 0.45 - 0.55$ eV). Calculated core level shifts are also compared with experiment. These results, which are closely related to changes in the charge density distribution at the interface, contribute to understanding the underlying mechanism of the band discontinuity.

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Effect of electric field on the transition energies and oscillator strengths of undoped GaAs-AlGaAs multiple quantum well structures determined by photocurrent spectroscopy.

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It is well known that an electric field in quantum wells changes the intrinsic transition energy and the transition oscillator strength. However, experimental details of the changes due to electric field, both for the ground and excited state excitons, have not been demonstrated well. The present work quantitatively determines the effects of electric field on the exciton transition energies and oscillator strengths for the n=1 and higher excitons. Photocurrents obtained with the use of a transparent Au Schottky structure were measured as a function of the photon energy for different externally applied biases perpendicular to the quantum-well interfaces. Photoluminescence and reflection spectroscopies were also used at liquid helium temperatures for the identification of the transitions. Nominally undoped GaAs-AlGaAs multiple quantum well structures were prepared by molecular beam epitaxy with the GaAs well thickness of 230-260Å and the AlGaAs barrier thickness of 100Å. A large number of excitonic transitions (as many as 14) of both allowed ($\Delta n=0$) and forbidden ($\Delta n\neq 0$) types are identified. The transition strengths of the allowed transitions of n=1, 2, and 3 usually decrease with the increase of electric field whereas those of the forbidden transitions tend to increase with the field. Two normally very weak transitions of the n=2 electron-n=1 heavy hole and the n=3 electron-n=2 heavy hole increased in strength by up to a full order of magnitude upon application of the electric field. In particular, the two superimposed excitons involving the n=2 electron-n=1 light hole and the n=2 electron-n=2 heavy hole transitions in the absence of the field were observed to split into the individual ones with the application of electric field. The variation of the transition energies and oscillator strengths with electric field makes the observation possible. These effects are caused by the variation of the degree of overlap between the electron and hole wave function. The experimental results are compared with theoretical values obtained using a theory incorporating valence-band mixing effects, and good agreement between experimental data and theory is found. This work represents the first such comparative study and demonstrates new features due to electric field.

Work performed at Wright-Patterson AFB, respectively, under contract F-33615-86-C-1062* and F33601-82-C-1716*.

RAMAN SCATTERING INVESTIGATIONS OF THE DAMAGE CAUSED BY REACTIVE-ION-ETCHING OF GAAS

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REACTIVE ION ETCHING IS AN IMPORTANT TECHNIQUE FOR THE FABRICATION OF STRUCTURES IN THE NANOMETER REGIME. IF SUCH STRUCTURES ARE TO PROVE USEFUL FOR DEVICE PURPOSES, THEN THE DAMAGE PRODUCED BY THE ETCHING PROCESS MUST BE KEPT TO A MINIMUM. AT PRESENT A NEW ETCHANT MATERIAL, CH(4)/H(2), IS UNDER INVESTIGATION FOR BETTER ETCH QUALITY AND LESS DAMAGE. RAMAN SCATTERING IS ONE OF THE TECHNIQUES USED TO ASSESS BOTH THE EXTENT AND THE NATURE OF THE DAMAGE INCURRED. THE ASYMMETRIC BROADENING OF THE OPTICAL PHONON MODES GIVES INFORMATION ON THE SPATIAL EXTENT OF ANY DAMAGE WHILE THE APPEARANCE OF SYMMETRY-FORBIDDEN PHONON MODES CAN TELL US ABOUT THE ORIENTATION OF SUCH DAMAGE.

WE REPORT RAMAN SCATTERING STUDIES OF SEVERAL REACTIVE-ION-ETCHED (RIE) GAAS SAMPLES IN WHICH WE COMPARE THE DIFFERENCES IN THE DAMAGE CAUSED BY THE TWO ETCHANTS, SICL(4) AND CH(4)/H(2). WE USE BOTH THE ASSYMETRY OF THE LO PHONON MODE AND THE VARIATION IN THE TO PHONON PEAK INTENSITY WITH ETCH POWER TO CALCULATE THE EXTENT OF THE DAMAGE. THESE SPECTRA ARE THEN COMPARED WITH THOSE OBTAINED FROM A SAMPLE ON WHICH QUANTUM DOTS HAVE BEEN ETCHED. WE OBSERVE SIGNIFICANT DIFFERENCES IN THE PHONON SPECTRUM WHICH WE ATTRIBUTE TO THE 300 TO 800A SIZE OF THE DOTS.

HgTe/CdTe Double Barrier Diode with 5:1 Peak-to-Valley Ratio at 300K

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Double barrier negative resistance resonant tunneling diodes consisting of HgTe and CdTe layers have been suggested as having superior room temperature peak-to-valley current ratios as compared with conventional GaAs/GaAlAs or other III-V materials systems.[1] The largest ratio published to-date is 3.5 to 1 with GaAs and pure AlAs barriers.[2] Calculations indicated that the large HgTe-CdTe conduction band discontinuity should minimize the thermal current over the CdTe barriers. The thermal current contributes to the valley current and thus degrades the peak-to-valley ratio. Negative resistance has been detected in HgTe/CdTe diodes, but not with peak-to-valley ratios enhanced compared to the III-V structures.[3] We have grown a series of HgTe/CdTe structures, all with 70A HgTe central wells, and CdTe barrier thicknesses of 25, 40, and 60A. The morphology was excellent as determined by SEM. The carrier concentration as determined by Hall measurements was close to intrinsic from 77K to room temperature. Diodes were fabricated with 25 to 200μm square sides and their current-voltage characteristics measured. The structure with the 60A barriers had a room temperature peak-to-valley ratio of 5:1, the largest ratio in any material system to-date. The current densities decreased with barrier width as expected, but much less than predicted by a simple theory which omitted space charge effects. The voltages at resonance were larger than predicted. The current-voltage characteristics versus temperature, and the implications concerning the value of the HgTe-CdTe valence band offset will be discussed.

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2. E.R. Brown, T.C.L.G. Sollner, W.D. Goodhue, and C.D. Parker, Appl. Phys. Lett. 50, 83 (1987).
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MONTE CARLO PARTICLE INVESTIGATION OF PHOTOEXCITED ELECTRON-HOLE PLASMA TRANSPORT IN SUBMICRON STRUCTURES

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It has been shown by the one-dimensional Monte Carlo particle simulation [1] that in photoexcited p^+-i-n^+ GaAs structure with short base at quasiballistic transport conditions current oscillations can occur. These oscillations are caused by the photoexcited charge carrier plasma instability in considerably disturbed applied electric field. A necessary condition for this instability to occur is the extraction of charge carriers from the base through contacts and associated with this redistribution of the electric field.

In this paper the results of further investigation of predicted instability are presented. The simulation was performed by Monte Carlo particle technique in three-dimensional momentum space and one-dimensional real space. The dependence of current oscillation frequency on base length, rate of photoexcitation, applied voltage, contact doping was estimated in the simulation. It was found also that the excitation of the charge carriers with non-zero initial energy slightly reduces the frequency and has little effect on amplitude of oscillations.

As the one-dimensional approach fails to account for some effects important for a performance of device, simulation in two-dimensional real space was carried out. The main result is that regularities obtained by the one-dimensional simulation take place in two-dimensional case.

The heterostructures of ternary III-V alloys such as $InP(p^+)$-$In_xGa_{1-x}As$-$InP(n^+)$ and $Al_xGa_{1-x}As(p^+)$-GaAs-$Al_xGa_{1-x}As(n^+)$ can be more suitable for a practical realisation of this instability. Simulation of such a device with heterojunction contacts was performed.

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HOT CARRIER PHOTOTRANSISTOR

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In this report the experimental investigations on the photoelectrical properties of the epitaxial p-n-p silicon structures under the CO_2 laser radiation are presented. The emitter p-n -junctions having thickness of 0.1μm were fabricated by boron diffusion. The hole concentration in the emitter was 10^{20} cm^{-3}. The base width was 0.2μm.

Phototransistor operation is based on the hot hole emission from the emitter into the base under the IR laser illumination. The current-voltage measurement on the emitter-base junction showed that the forward current across the emitter junction increased with the CO_2 -laser irradiation as in the usual germanium p-n junction [1]. The application of a reverse-bias increases the p-n junction potential barrier which decreases the photo-induced current. At high values of reverse-bias voltage U_{EB} the reverse current is independent of the CO_2 laser irradiation.

It is established, that the collector photocurrent I_c is strongly dependent on emitter-base bias. When the emitter is forward biased the photo-excited hole injection into the base increases and I_c is proportional to $\exp(U_{EB})$. The collector photocurrent vs the collector-base voltage characteristic is the same as the ordinary static collector current vs the collector voltage characteristic of the bipolar transistor in the common-base configuration.

Hot carrier phototransistor has advantage over the ordinary bipolar phototransistor since it can operate at room temperature even in far IR region. In addition, the sensivity of hot carrier phototransistor is larger at longer radiation wavelengths due to the increase of the hole absorption cross-section.

1. S.Ašmontas, E.Širmulis, S.Stonys.Liet.fiz.rink.24,76(1984).

DOMAIN INSTABILITY IN SEMICONDUCTOR SUPERLATTICE

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One of the most known effects leading to the electric field domain formation in semiconductors is the Gunn effect. The possibility of similar effect in semiconductor superlattices is shown in [1]. The drift-diffusion approach used in [1] is valid only at relatively low frequencies. On the other hand, the collective behavior of electrons at high frequancies can result in qualitatively new phenomena.

In the present paper the results of Monte Carlo particle simulation of time-dependent electron transport in the superlattice (SL) are presented. The electron dispersion relation in the first miniband of SL is assumed to be $\mathcal{E}(k) = \mathcal{E}_0(1 - \cos(kd))/2$, where k is the electron wave vector component parallel to SL axis, $\mathcal{E}_0$ is the miniband width and d is SL period. It is shown by the simulation and linear analysis that the electron flow in SL can be unstable with respect to the electron plasma waves. At the sufficiently high electron concentration the instability leads to the electric field domain formation. The effect is more pronounced in the collisionless plasma, on the contrary to the Gunn effect in SL which appears in collision dominate plasma only [1].

It is obtained by Monte Carlo particle simulation that the considered above instability leads to the current oscillations in the diode with the SL at $\mathcal{E}_0 \leq eU \leq 3\mathcal{E}_0$, where U is the voltage drop across the diode. The current oscillations are caused by the periodical formation and dissipation of the electric field domain. The oscillation frequency is of the order of $f = edU/hL$, where h is the Planck constant and L is the diode length.

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ICSMM Program Changes as of August 14, 1987

Withdrawn

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1-78
2-41
2-51

Additions--Poster Session 1

1-79 Optical study on band edge offset in strained MBE grown (InGa)As-GaAs and (InGa)As-(AlGa)As quantum wells, G. G. Andersson, V. Kulakovski, Z.-G. Chen, A. Uddin, J. Vallin, J. Westin, Chalmers University of Technology, Sweden

Additions--Poster Session 2

2-77 MBE growth and optical absorption of InAsSb strained-layer superlattices with 77K cutoff wavelength greater than 10 um, L. R. Dawson, G. C. Osbourn, S. R. Kurtz, H. J. Stein, R. E. Hibray, Sandia National Laboratories

2-78 High-speed 2x2 electrically-driven spatial light modulator made with GaAs/AlGaAs multiple quantum wells (MQWs), T. H. Wood, E. C. Carr, C. A. Burrus, J. E. Henry, A. C. Gossard, J. H. English, AT&T Bell Laboratories

2-79 Uniaxial-stress induced photoluminescence in Si/Ge [111] superlattices, S. Y. Ren, J. Shen, G.-L. Yang, J. D. Dow, University of Notre Dame

2-80 Tunneling through double-barrier heterostructures in small band-gap materials, J. Shen, G.-L. Yang, J. D. Dow, University of Notre Dame

2-81 Optical properties and deep levels of [001] superlattices, F. An, J. D. Dow, W. M. Hu, S. Y. Ren, J. Shen, D. A. Vasquez R. P. Wang, G.-L. Yang, University of Notre Dame

[pc-compaq--8/14/87]

OPTICAL STUDY ON BAND EDGE OFFSET IN STRAINED MBE GROWN (InGa)As-GaAs AND (InGa)As-(AlGa)As QUANTUM WELLS

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LATE NEWS PAPER

MBE Growth and Optical Absorption of InAsSb Strained-Layer Superlattices with 77K Cutoff Wavelength Greater Than 10 μm

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We report the successful growth and the first optical characterization of strained-layer superlattices (SLSs) in the InAsSb system. The results show that the tensile strain parallel to (100) interfaces in such superlattices is an efficient means of reducing the effective energy gap of the structure below that of unstrained alloy materials. FTIR absorption measurements on 5 μm-thick SLSs composed of 200Å $InAs_{.1}Sb_{.9}$/200Å $InAs_{.3}Sb_{.7}$ periods (equal strain in each layer) indicate cutoff wavelength, λ_c, of 10.1 μm at 77K. Similar structures with 400Å/200Å periods (2/3 of the total mismatch is accommodated in the narrow gap member) show additional shift to λ_c = 10.5 μm. By comparison, λ_c for unstrained, bulk $InAs_{.3}Sb_{.7}$ alloy material is 8.8 μm at 77K. Here energy gap is defined by $\alpha = 300cm^{-1}$. Additional weaker absorption in the second sample may indicate additional strain-induced shifts beyond 12 μm.

These SLS materials were grown by MBE using Sb_2 and As_2 sources at a substrate temperature of 450°C on InSb substrates with suitable intervening buffer layers. The entire epitaxial structure (buffer layers plus SLS) is in tension with respect to the thick InSb substrate, leading to extensive cracking of the material for average As composition, $\bar{x}$, greater than 0.10. The cracking problem has been overcome by the initial growth of a severely mismatched $InAs_{.35}Sb_{.65}$ buffer layer directly onto the InSb substrate. This high level of strain induces the nucleation of enough dislocations to relieve much of the strain in the ensuing epitaxial layer, avoiding the accumulation of strain energy sufficient to form cracks. Subsequent buffer layers with x = .27 and .20 are in compression and cracking does not occur. $InAs_{.1}Sb_{.9}$/$InAs_{.3}Sb_{.7}$ SLSs grown on such buffers are crack-free and show substantial reduction in dislocation density relative to that in the buffer layers. Surface morphology is excellent and TEM reveals smooth, abrupt interfaces.

This work, performed at Sandia National Laboratories, Albuquerque, NM, was supported by U. S. Dept. of Energy under Contract No. DE-AC04-76DP00789.

High-Speed 2x2 Electrically-Driven Spatial Light Modulator made with GaAs/AlGaAs Multiple Quantum Wells (MQWs)

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A variety of information processing applications require a 2-dimensional array of optical intensity modulators, usually termed a spatial light modulator(SLM). Semiconductor Multiple Quantum Well (MQW) devices have been shown to be useful for high-speed single-element optical intensity modulators. In this paper, we report a small-scale 2 dimensional array of individually-contacted, electrically-driven MQW intensity modulators.

The design of our device is shown in Fig. 1. The individual modulator elements each contain 50 GaAs quantum wells in the center of a back-biased p-i-n diode. To form the SLM, we etch a 2x2 array of 125 μm diameter mesas. A wire was individually contacted to each of the mesas and brought to the exterior of the package.

All devices provided an on/off ratio of approximately 1.45:1 when driven between 0 and 6 V. The insertion losses of the best devices are about 2.5 dB; however, two devices had an additional loss of approximately 3.5 dB due to incomplete removal of the absorbing substrate. Electrical isolation of the individual devices was excellent: the signal induced on a device adjacent to the one driven was at least 200 times less than that on the device being driven.

High speed response is critical to many SLM applications. Fig. 2 shows the pulse response of one of the devices. Rise and fall times of ~ 400 $psec$ are observed. We believe this is primarily limited by the speed of the electrical pulse generator. These speeds are far higher than those attainable with most other SLM technologies.

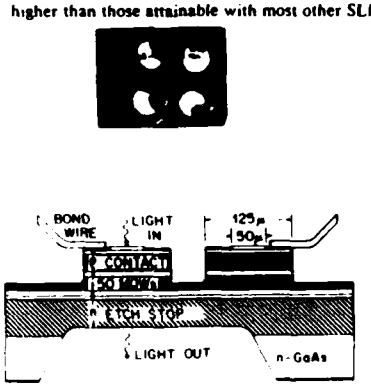

Figure 1: Schematic view of MQW spatial light modulator. The inset shows a photo of a top view of the array.

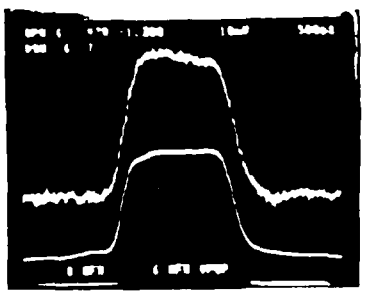

Figure 2: High-speed pulse response of one device. The lower trace is the electrical drive pulse, while the upper trace is the detected optical pulse. The horizontal scale is 500 $psec/div$

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Uniaxial-stress induced photoluminescence in Si/Ge [111] superlattices

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In Ge/Si [111] superlattices, one of the four conduction band minima at L in Ge is folded into the Γ point of the superlattice's mini-Brillouin zone, and has significant s-character -- raising the possibility of a direct-gap in the superlattice and efficient light-emission from the Ge layers (if the folded minimum lies at lower energy than the other L minima). We find that the condition of lower folded minimum never occurs in a (naturally) strained superlattice, but does occur in a superlattice under uniaxial stress of ~10 kbar, if the Ge layer thickness is greater than ~50Å.

Tunneling through double-barrier heterostructures in small band-gap materials

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In small band-gap materials such as $Hg_{0.8}Cd_{0.2}Te$, resonant tunneling through double-barrier heterostructures (of, say, CdTe) in the the conduction band can be dramatically enhanced by nearby valence bands, as proposed by Schulman and Anderson [1]. We show that: (1) The wavevectors of the resonances are determined largely by the separation of the two barriers; (2) The energies of the resonances are determined from these wavevectors by the band-structure of the well-material; (3) The transmission coefficient is determined by the evanescent waves in the barriers; and can be dominated by the band with the least quantum mechanical action (often neither the top valence band nor the bottom conduction band); (4) Interface states do not play a major role in the tunneling; (5) A sheet of deep levels in the centers of the barriers can *make the barriers appear to be half their natural thicknesses*; and (6) By using different materials inside and outside the wells, desireable negative differential resistance properties can be achieved. A new kind of "deep level superlattice" is also proposed, based on these ideas.

[1] J. N. Schulman and C. L. Anderson, Appl. Phys. Lett. 48, 1684 (1986).

Optical properties and deep levels of [001] superlattices

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We present the results of theoretical calculations for [001] superlattices, including the following: Si/Si_xGe_{1-x}, InAs/GaSb (Type II), GaAs/ZnSe, and $Al_{1-y}In_yAs/In_xGa_{1-x}As$. We calculate the band structures, optical absorption coefficients, imaginary parts of the dielectric functions, and deep levels as functions of layer widths and alloy compositions. Strain effects are included. We find many interesting results. For example, in Si/Si_xGe_{1-x} the optical matrix elements and hence the photoluminescence intensity are small. The deep levels in all superlattices, especially Type II superlattices, exhibit interesting behavior: shallow-deep transitions of donors and acceptors commonly occur as functions of layer thickness (for example, changing a dopant from being n-type to semi-insulating); and false valences sometimes occur as layer thicknesses vary, especially in Type II superlattices. When a false valence occurs, dopants that normally are p-type become n-type (or vice versa).

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