REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
3/21/95

3. REPORT TYPE AND DATES COVERED
Final Technical: 12/15/92-12/14/94

4. TITLE AND SUBTITLE
Pseudomorphic Heterostructure Materials for High Performance Devices

5. FUNDING NUMBERS
N00014-90-J-1536

6. AUTHOR(S)
Wen I. Wang, Professor and Principal Investigator

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Trustees of Columbia University
Columbia University in the City of New York
Dept. of Elec. Eng., 500 W. 120th St.
New York, NY 10027

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Scientific Officer: Max Yoder
800 North Quincy St.
Arlington, VA 22217-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

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

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

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Using the planar-doping technique, Si has been shown to be amphoteric on (311)A InAlAs/InGaAs/InP grown by molecular beam epitaxy and excellent modulation-doped field effect transistors have been demonstrated. Through the use of an AlN/GaN strained superlattice buffer layer, high quality GaN layers were obtained. Crystalline SiC thin layers have been grown on 125 mm silicon-on-insulator (SOI) substrates. These two techniques have also been combined to synthesize the first GaN on SiC on SOI structure. Normal incidence infrared photodetectors using intersubband transitions in GaSb L-valley quantum wells have been demonstrated. Enhancement of normal incidence intervalence subband absorption in GaSb quantum wells coupled to a neighboring InAs has been observed.

14. SUBJECT TERMS

15. NUMBER OF PAGES
11

16. PRICE CODE

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

OFFICE OF NAVAL RESEARCH

FINAL TECHNICAL REPORT

FOR

15 December 1992 through 14 December 1994

****

CONTRACT: N00014-90-J-1536

R&T NO: 414 s 006

TITLE OF CONTRACT: Pseudomorphic Heterostructure Materials for High Performance Devices

NAMES OF PRINCIPAL INVESTIGATORS: Wen I. Wang, Professor

NAME OF ORGANIZATION: Electrical Engineering Department, Columbia University

ADDRESS OF ORGANIZATION: Electrical Engineering Department, Columbia University, 500 West 120th Street, New York, N.Y. 10027

****

The research performed under this contract started on December 15, 1992 and ended on December 14, 1994. The emphasis of our research under this program is to obtain high quality pseudomorphic (strained) heterostructure materials for high performance device applications.During the past two years, many strained-layer electronic and optical devices have been conceived and developed, including the growth of GaN on compliant substrates. The achievements are summarized in the following:

An approach to obtain high quality GaN on Si and SiC-on-SOI compliant substrate by molecular beam epitaxy

In recent years there has been significant progress in the growth of GaN layers and several GaN-based high temperature electronic and light-emitting devices have been demonstrated with promising properties. One of the critical issues in the development of III-V nitrides for device applications is the lack of a good substrate. At present, GaN is generally grown on sapphires, SiC or Si. Among them, Si substrates offer the potential for integration of mature Si MOS devices with nitride-based optoeletronic devices. Many methods have been implemented to obtain crystalline GaN on Si substrates despite their poor structural and thermal mismatches. In order to minimize the structural and thermal mismatch, SiC is an ideal substrate for GaN and it can be overgrown on Si substrates or silicon-on-insulator(SOI) substrates. The incorporation of high quality GaN, SiC and Si layer together will certainly result in a new generation of heterojunction devices.

During the last year of this program we have been developing high quality III-V nitrides on large area SiC for device applications. The SiC can be grown compliantly on SOI wafers up to 125 mm in diameter by molecular beam epitaxy (MBE). The close lattice-match between the SiC-SOI substrates and III-V nitrides will facilitate the overgrowth of high quality III-V nitrides with minimal structural defects. We have achieved the growth of GaN on Si(111) and SiC-on-SOI by molecular beam epitaxy.

High quality 2000Å GaN epitaxial layers on Si(111) have been achieved through the use of an AlN/GaN strained superlattice buffer. The x-ray rocking curve of these GaN layers exhibited a linewidth as narrow as 25 arcmin. A dominant bound-exciton peak at 3.472eV with an FWHM of 8 meV was observed in the associated low temperature photoluminescence spectra.

Our approach to large area GaN-SiC materials is based on "pseudomorphic" (or compliant) growth starting with large area SOI wafers with a thin Si top layer (less than 50 nm). This layer was converted to a SiC on SOI structure, and III-V nitrides were subsequently grown on the SiC-SOI substrate. A thin layer (less than 50 nm) of Si (on

SiO_2) can be partially or completely converted into SiC by exposing the substrate to a flux of acetylene or carbon beam at 900 °C. We have performed experiments on the growth of SiC on SOI. The related X-ray photoelectron spectroscopy(XPS) spectra clearly show the characteristic 2S peak of Si in SiC at 99.5eV and the associated plasmon loss peak at 122eV, which agrees with the 22.5eV separation of SiC reported in the literature.

The growth of GaN on Si(111) was carried out in an EPI Gen II MBE system. Nitrogen plasma was introduced from a commercial RF-radical plasma source, which was fed with ultrahigh-purity (99.999%) nitrogen gas through a nitrogen purifier. The Ga and Al were generated by Knudsen cells, and the growth rate for GaN and AlN was 600Å/hr and 700Å/hr respectively. Due to the large difference of chemical bond strength between Si-N (9.5 eV) and III-V nitride (i.e. Al-N 2.98 eV), it is easier to form amorphous silicon nitride on the Si substrate surface than GaN or AlN. In order to avoid the formation of silicon nitrides at the Si substrate surface, a thin layer of Al was first deposited before the introduction of nitrogen plasma, since Al is less mobile and more reactive with nitrogen than Ga. The substrate temperature was in the range of 500°C to 740°C. After the ignition of the nitrogen plasma, a nucleation layer of 100 Å AlN followed by 100Å GaN was grown. A 10 period AlN/GaN superlattice with 40 Å periodicity was formed. Finally, a 2000 Å GaN layer was grown on the AlN/GaN superlattice.

The crystal quality of 2000 Å GaN layers was characterized by a standard x-ray diffraction (XRD) pattern and rocking curve. The rocking curve of GaN (0002) reflection indicates an FWHM of 25 arcmin, which is smaller than the 42 arcmin of the 3000 Å GaN grown under the same condition without the AlN/GaN strained superlattice buffer.

The 10 K PL spectrum exhibits a dominant bound-exciton peak at 3.472 eV with an FWHM of 8 meV, indicating a superior material quality. This peak was much weaker for GaN films grown without a strained superlattice buffer layer. Thus both XRD and PL results indicate that the AlN/GaN strained superlattice buffer significantly improves the crystalline quality of the GaN layers.

Combining the two technologies of growth of SiC on SOI and GaN, we have grown GaN on SiC on SOI wafers. From the RHEED patterns and the XRD measurements, the GaN films were of similar qualities as those grown on bulk SiC substrates in our laboratory.

In summary, an AlN/GaN strained layer superlattice was incorporated as a buffer layer to achieve high quality GaN layers on Si(111) substrates. SiC has been successfully grown on large area(125mm) SOI substrates. We have also performed first experiments on the growth of GaN on SiC/SOI substrates. Multilayer devices with nitride-, SiC- and Si-based materials can be achieved from the GaN/SiC/SOI structures.

Resonant tunneling of L-valley electrons in GaSb-based double barrier heterostructures

Intraband resonant tunneling is a strictly quantum phenomenon in which charged carriers tunnel between the two electrodes of a double barrier heterostructure through the quantized quasi-bound state of a potential well. The process is governed by the rules of conservation of energy and crystal momentum parallel to the interfaces and is characterized by a distinctive negative differential resistance (NDR) region. In this process, we clearly observed the first resonant tunneling of L-electrons in semiconductors and the intrinsic bistability in resonant tunneling structures.

In conventional double barrier heterostructures, such as GaAs-AlGaAs-GaAs-AlGaAs-GaAs, resonant tunneling takes its simplest form, since the states in the electrodes and the well have the same symmetry origin, i.e., the Γ-point of the Brillouin zone, and the electrons participating in the process have isotropic transport properties (isotropic effective masses). More interesting is the situation in GaSb-AlSb-GaSb-AlSb-GaSb double barrier heterostructures, due to the proximity in energy of the Γ and the eight equivalent (111)-oriented L-points at the electrodes and the presence of additional quasi-bound L-states in the well. The possibility may exist for electrons to tunnel resonantly from the Γ-valley of the electrodes through a L-state in the well, a process in which the states participating have different symmetries and the conservation of crystal momentum parallel to the interface can be tested. In addition, since the pressure coefficients of the Γ and L-points of GaSb are quite different, the application of hydrostatic pressure to the heterostructure can alter the relative band ordering of the Γ and L-profiles. Once this situation is reached, electrons will no longer populate the Γ-valley of the electrodes, but rather the L-valley. The possibility, then, arises of resonant tunneling via a completely new path entirely defined by the L-point profile, which, in view of the anisotropic character of the L-states, should exhibit an orientation dependent behavior.

To test these two tunneling possibilities, we have carried out transport experiments on samples grown by molecular beam epitaxy (MBE) on (100) and (111)B. At atmospheric pressure (P=0 kbar), the I-V characteristic of the sample grown along the (100)-direction, displays only a single NDR feature, at about 0.5 V. As pressure increases from 0 to 9 kBar, the following occurs: First, the NDR region at 0.5 V decreases and eventually disappears, without significantly altering its voltage. Second, a new NDR emerges and continuosly increases in peak current and bias (from I=2 mA, V=0.8 V at P< 3.2 kBar to I=15 mA, V=1.4 V at P=9 kBar). And third, a new, less evident NDR feature rises at high pressure (P=8 kBar), at 0.15V, without apparently altering its bias position with pressure.

In spite of their apparently different behaviors, these two pressure-induced NDR regions are the result of L-valley electrons tunneling, respectively, through the second and first L-confined state in the well.

As pressure is applied, electrons in the GaSb electrodes gradually transfer from the Γ to the L-valley. Consequently, the peak current of the Γ-based-NDR region decreases, while the one due to L-electrons through the second L-quantized state increases. Due to the lower mobility of the L-electrons, an increase of resistance is also induced, which explains the pressure dependence of the L-based NDR voltage. As the pressure-induced transfer of electrons is complete, the Γ-based NDR region disappears and the NDR region due to L-electrons tunneling through the first L-confined state in the well is observable. At this pressure, the overall resistance has already reached its maximum and therefore there is no further shift of the voltage peak.

The results on the (111)B samples support this explanation. The I-V characteristic at atmospheric pressure shows a strong NDR region at about the same voltage as the (100) sample, thus confirming the isotropic Γ-nature of the NDR region. On the other hand, in contrast with the (100) samples, the (111)B samples show no additional L-related feature in the 0.7 V - 1.4 V range. This is consistent with the anisotropic character of L-valley transport. No additional features due to Γ-electrons tunneling through L-states in the quantum well (or L-electrons tunneling through Γ-states in the well), have been observed, confirming the requirement of conservation of parallel momentum to obtain NDR behavior.

The novel possibility of observing resonant tunneling from electrons with different transport properties in a single device opens new opportunities for solving old controversies in the physics of the resonant tunneling process. One of these is the extrinsic versus intrinsic bistability. Through a careful design of the device parameters, we have been able to enhance the bistability in a NDR with low current, while supress it in the NDR region with a high current. This experiment, consequently, rules out the possibility of extrinsic bistability in favour of the intrisic mechanism. The variation of the NDR features with the magnetic field has confirmed this model.

In summary, we clearly observed the first resonant tunneling of L-electrons in semiconductors and the intrinsic bistability in resonant tunneling structures.

Normal incidence infrared photodetectors using intersubband transitions in GaSb L-valley quantum wells

We have demonstrated normal incidence infrared detectors based on inter-conduction subband transitions in narrow GaSb/AlGaSb multiquantum wells (MQWs) in which L-valley is the ground state. Strong IR absorption at 7.8 μm with an absorption coefficient of 9100 cm^{-1} and good photodetector response covering a wide spectrum region have been achieved. This is the largest absorption ever reported for this wavelength range. We also studied the orientation dependence of the absorption. Our results indicate the potential of this novel structure for use as normal incidence IR photodetectors.

Indirect-gap semiconductor quantum well systems can achieve normally incident IR detector structures. For L-valley materials, absorption of normal incidence radiation is allowed for the (100) orientation. We observed normal incidence IR absorption in GaSb (100) and (311) multiquantum wells. An absorption coefficient as large as 9100 cm^{-1} was observed, which represents the largest ever reported for this wavelength range. Good photodetector response covering a wide spectrum region 5-15 μm has also been achieved.

In bulk GaSb the conduction band minimum is at the Γ-point, with the L-valley minimum located only 63 meV above the Γ-minimum. Due to the much smaller effective mass of the Γ valley than that of the L-valleys, the Γ valley can be easily pushed above the L-valley by quantum confinement in narrow GaSb QWs. As a result, for narrow GaSb quantum wells the L-valleys will become the ground state. For the GaSb MQWs designed in our experiments, the L-valleys become the ground state for a GaSb well thickness of about 5 nm. While the conventional (100)-oriented QWs can be grown with high structural quality, there is an increasing interest in QWs with non-conventional growth directions for the exploration of orientation dependent absorption properties. We have calculated the absorption coefficients for a given sheet doping concentration of 1.5×10^{12} cm^{-2}, and found that absorption coefficients greater than 10^4 cm^{-1} can be easily achieved for normal incident radiation at the wavelength range of 8-20 μm. From our calculation we also found that the absorption of the conventional (100) QWs is smaller than QWs in other growth directions such as (311) and (511).

We performed normal incidence IR absorption measurements at 68K and room temperature, and observed that the (311) sample exhibited a stronger absorption than the (100) sample. The spectra of the (311) GaSb MQWs at 68K have an absorption peaks at 7.8 μm with an absorption coefficient of 9100 cm^{-1}. This is the strongest absorption ever reported in this wavelength range. The spectra of the (100) sample showed a similar absorption peak at 7.4 μm with an absorption coefficient of 8100 cm^{-1}.

We have also grown photodetector structures similar to that used in the absorption experiments. Responsibility peak was observed at 8.3 μm with a photoresponsivity of 310 mA/W. The photocurrent threshold was seen at about 5 μm and the responsivity spectrum covered a wide region of 5-15 μm. Our results indicate the potential of this novel structure for use as normal incidence infrared photodetectors.

Normal incidence intervalence subband absorption in GaSb quantum well enhanced by coupling to InAs conduction band

Under this program, we proposed and demonstrated normal incidence *p*-type QW detectors which utilize intervalence subband absorption. Due to the inverse relationship between the effective mass of free carriers and the absorption coefficient, QWs with a small effective mass are preferred. Among III-V semiconductors GaSb has the smallest heavy hole effective mass which will lead to a large intervalence subband absorption. We have previously proposed IR detectors based on the intervalence subband absorption in p-doped GaSb quantum wells. In order to further improve the intervalence subband absorption, we demonstrate in our work a novel IR detector structure based on the type-II InAs/GaSb multiquantum well system. By utilizing the coupling of the valence band states in the GaSb quantum well to the conduction band states in the neighboring InAs, the intervalence subband absorption in the GaSb quantum well is greatly enhanced. We have previously explored this interband coupling mechanism between GaSb and the neighboring InAs for tunneling device applications. Our present experimental results show that a normal incidence IR absorption coefficient as large as 6500 cm^{-1} can be obtained through this novel mechanism in the wavelength range of 8-17 μm. This is the strongest absorption ever observed among all the IR materials in this wavelength range.

In InAs/GaSb multiquantum wells, the Γ band edge lines up in a type-II configuration, i.e. the quantum well for the conduction electrons is in InAs while that for the valence holes is in GaSb. Previous work on InAs/GaSb superlattices indicated that the InAs conduction band edge lies 150 meV lower than the GaSb valence band edge. The intervalence subband transitions from the heavy-hole to light-hole subbands in the GaSb quantum wells are used to absorb the IR signal. The novelty of our structure is that a strong coupling exists between the InAs conduction band and the GaSb valence band: the electrons in InAs couple to the light-hole states of GaSb at the zone center, and they couple to both the heavy-hole and light-hole states away from the zone center due to band mixing. We have previously demonstrated the interband coupling between the electrons in InAs and the holes in GaSb. By using the same mechanism, i.e., when the quantum states associated with electrons in InAs are tuned close in energy to those associated with holes in GaSb, the GaSb valence subband structure is significantly modified due to the induced strong mixing with the InAs conduction band. As a result the optical matrix elements for the heavy-hole to light-hole intervalence subband transitions are tremendously enhanced, which is the mechanism for our observed large absorption.

Enhancement of intersubband Stark effects in L-valley step quantum wells for infrared modulation and voltage tunable detection

We have proposed a new type of infrared optical modulator employing two-step $Ga_{1-x}Al_xSb/Ga_{1-y}Al_ySb/Ga_{1-z}Al_zSb$ L-valley quantum wells to enhance the Stark shifts of the intersubband transition energy and therefore to achieve large absorption spectral changes with applied bias. Due to the effective-mass anisotropy of electrons in the L-valleys and the tilted growth direction with respect to the valleys, this novel structure can intrinsically absorb normal incidence light. Under an electric field of 50 kV/cm, a blue shift of the absorption peak from 10.9 to 9.8 μm was found from our calculations in a $Ga_{0.7}Al_{0.3}Sb/Ga_{0.5}Al_{0.5}Sb/Ga_{0.4}Al_{0.6}Sb$ structure. The ability to achieve significant Stark effects with bias makes this structure an attractive choice as vertical infrared light modulators and voltage tunable photodetectors.

Normal incidence infrared absorption in AlAs/AlGaAs X-valley multiquantum wells grown on GaAs and Si substrtates

We have carried out theoretical analysis of the AlAs/AlGaAs X-valley system. The conduction subband structure was obtained by the transfer matrix method within the effective-mass approximation. The calculation also takes into account a realistic conduction-band offset. We found that the (112) and (113) orientations have stronger normal incidence absorption than QWs with the other growth directions. This is due to the complicated orientation dependence of the reciprocal effective-mass tensor. We have also calculated the absorption coefficient as a function of the general growth direction for the AlAs/AlGaAs X-valley system, and found that normal incidence absorption for (210) and (320) is as strong as that for (112) and (113), as expected on symmetry grounds because the tilting angle for the (113) orientation is similar to that for the (210) and (320) orientation

Experimentally, we demonstrated normal incidence infrared absorption due to inter-conduction subband transitions in AlAs/AlGaAs X-valley multiquantum wells. Infrared absorption measurements were performed on samples grown on (111), (113), (115), and (001) substrates with normal incidence radiation at wavelengths of 5-20 μm. Two absorption peaks were observed in (113) and (115) multiquantum wells with well widths of 4 nm and sheet doping concentrations of 10^{12} cm^{-2}. One peak, due to transitions between the ground state and the continuum band occured at 7.1 μm, a second peak originating from inter-conduction subband transitions between the ground state and the first excited state occured at 17 μm.

To summarize, we have experimentally investigated infrared absorption properties of inter-conduction subband transitions at normal incidence in AlAs/AlGaAs X-valley X-valley MQWs grown in the (113) direction. Substantial absorption coefficients of 2000 cm^{-1} have been measured for normal incidence radiation at the wavelengths of 5-20 μm in these quantum wells. The peak detectivity D^* can be obtained from $D^*=R_p(A\Delta f)^{1/2}/i_n$, where R_p=0.54A/W and A is the detector' active area. By simple calculation $D^*=5.4 * 10^{10}$ $cm(H_z)^{1/2}/W$ from our detectors operation parameters (g=0.30, $I_D=10^{-6}A$, $i_n=4.3*10^{13}$, at 68K and V_b=1V).

We have also successfully grown the same AlAs/AlGaAs detector structures on Si (113) and (115) substrates. Excellent detector results have been achieved with an absorption coefficient of $\alpha=1400$ cm^{-1} and quantum efficiency of η=13%. The absorption is due to inter-conduction subband transitions of electrons from the bound state to extended continuum state. The QWIPs on silicon substrates are of special importance since it is convenient to integrate the infrared detectors with Si signal processing circuits on the same wafer.

PAPERS PUBLISHED IN REFEREED JOURNALS

1. Z. Yang, F. Guarin, I.W. Tao, W.I. Wang, and S.S. Iyer, "An approach to obtain high quality GaN on Si and SiC-on-SOI compliant substrate by molecular beam epitaxy", J.Vac. Sci. Tech. B13, March/April issue (1995).

2. J.L. Jimendez, X. Li, W.I. Wang, and E.E. Mendez, "Resonant tunneling of L-valley electrons in GaSb-based double barrier heterostructures", Phys. Rev. B15, March (1995).

3. Y. Zhang, N. Baruch, and W.I. Wang, "AlA/AlGaAs X-valley quantum well normal incidence infrared detectors on Si substrates", J. Appl. Phys. 75, 3690-3692 (1994).

4. H. Xie, W.I. Wang, and J.R. Meyer, "Infrared electroabsorption modulation at normal incidence in asymmetrically stepped AlSb/InAs/GaSb/AlSb quantum wells", J. Appl. Phys. vol. 76, 92-96 (1994).

5. J.L. Jimendez, X. Li, and W.I. Wang, "Resonant tunneling in AlSb/GaSb/AlSb and AlSb/InGaSb/AlSb double barrier heterostructures", Appl. Phys. Lett. 65, 2068-2070 (1994).

6. Y. Hsu, W.I. Wang, and T.S. Kuan, "Molecular beam epitaxial GaAs/AlAs superlattices in the (311)A orientation", Phys. Rev.B50, 4973-4975 (1994).

7. Y. Hsu, W.I. Wang, and T.S. Kuan, "Molecular beam epitaxial heterostructures in the (311)A orientation", J. Vac. Sci. Tech. B12, 2584-2586 (1994).

8. H. Xie, W.I. Wang, J.R. Meyer, J.R., and L.R. Ram-Moham, "Normal incidence second harmonic generation in L-valley AlSb/GaSb/AlGaSb/AlSb stepped quantum wells", Appl. Phys. Lett. 65, 2048-2050 (1994).

9. E.E. Mendez, J. Nocera, and W.I. Wang, "Observation by spin-resolved magnetotunneling of oscillatory Lande factor in two-dimentional electron systems", Solid State Electron. 37, 779-782 (1994).

10. L. Munoz, L. Vina, N. Mestres, and W.I. Wang, "Free to bound exciton relaxation in (001) and (111) GaAs/GaAlAs quantum wells", Solid State Electron. 37, 877-880 (1994).

11. J. Katz, Y. Zhang, and W.I. Wang, "Normal incidence intervalence subband absorption in GaSb quantum well enhanced by coupling to InAs conduction band", Appl. Phys. Lett., vol. 62, pp 609-611 (1993).

12. Y. Zhang, J. Katz, and W.I. Wang, "Orientation dependence of normal incidence absorption in ellipsoidal-valley quantum wells", J. Vac. Sci. Tech. vol. B11, pp 1681-1684, (1993).

13. H. Xie, Y. Zhang, N. Baruch, and W.I. Wang, "Infrared devices based on antimonide quantum wells" (Invited paper), 20th International Symposium on GaAs and Related Compounds, Freiburg, Germany, 1993.

14. X. Li, W.I. Wang, A.Y. Cho, and D.L. Sivco, "Planar-doped n-type InAlAs/InGaAs MODFETs on InP(311)A substrates by molecular beam epitaxy", IEEE Electron Dev. Lett. 14, 170-172 (1993).

15. X. Li, W.I. Wang, A.Y. Cho, and D.L. Sivco, "Amphoteric doping of Si in InAlAs/InGaAs/InP (311)A heterostructures grown by molecular beam epitaxy", J. Vac. Sci. Tech. B11, 912-914 (1993).

16. E.E. Mendez, J. Nocera, and W.I. Wang, "Oscillatory Lande factor of two-dimensional electrons under high magnetic fields", Phys. Rev. B47, 13937-19940 (1993).

17. H. Xie and W.I. Wang, "Normal incidence infrared modulator using direct-indirect transitions in GaSb quantum wells", Appl. Phys. Lett. 63, 776-778 (1993).

18. Y. Zhang, N. Baruch, and W.I. Wang, "Nornal incidence infrared photodetectors using intersubband transitions in GaSb L-valley quantum wells", Appl. Phys. Lett. 63, 1068-1070 (1993).

19. H. Xie, W.I. Wang, J. R. Meyer, C.A. Hoffman, F.J. Bartoli, "Enhancement of intersubband Stark effects in L-valley step quantum wells for infrared modulation and voltage tunable detection", J. Appl. Phys. 74, 1195-1198 (1993).

20. H. Xie, W.I. Wang, J. R. Meyer, C.A. Hoffman, F.J. Bartoli, "Normal incidence electroabsorption in GaAlSb/AlSb L-valley quantum wells for 3-5 micron optical modulation", J. Appl. Phys. 74, 2810-2812 (1993).

21. C.A. Hoffman, J.R. Meyer, F.J. Bartoli, and W.I. Wang, "Shubnikov-de Haas and Hall oscillations in InAs/GaInSb superlattices", Phys. Rev. B48, 1959-1962 (1993).

22. L. Vina, L. Munoz, F. Calle, N. Mestres, J.M. Calleja, and W.I. Wang, "Excitonic spectrum of [111] GaAs/AlGaAs quantum wells, Phys. Rev. B15, 13234-13243 (1992).

23. J. Katz, Y. Zhang, and W.I. Wang, "Normal incidence infrared absorption in AlAs/AlGaAs x-valley multiquantum wells", Appl. Phys. Lett. 61, 1697-1699 (1992).

24. H. Xie, J. Katz, and W.I. Wang, "Orientation dependence of intersubband absorption in AlAs/AlGaAs x-valley superlattices", J. Appl. Phys. 72, 3681-3685 (1992).

25. H. Xie, J. Katz, and W.I. Wang, "Growth orientation dependence of normal incidence absorption in ellipsoidal-valley quantum wells", Appl. Phys. Lett. 61, 2694-2696 (1992).

26. E.E. Mendez, J. Nocera, and W.I. Wang, "Conservation of momentum and its consequences in interband resonant tunneling", Phys.Rev. B45, 3910-3913 (1992).

INVITED PRESENTATIONS

W.I. Wang, "Molecular beam epitaxial antimonide quantum wells for infrared and high speed device applications", Fall Meeting of the Materials Research Society, December 9, 1994, Boston, MA.

W.I. Wang, "L-valley GaSb quantum wells for IR detector applications", University of Texas Workshop on III-V Antimonide Compounds, March 1, 1994, Austin, TX.

PROFESSIONAL HONORS

W.I. Wang was elected IEEE Fellow for "contributions to compound semiconductor devices through innovative crystal growth", 1994.

W.I. Wang was a Member of Conference Committee, 21st Conference on Physics and Chemistry of Semiconductor Interfaces, Mohonk, New York, Jan 24-28, 1994.

PATENTS FILED

none

GRADUATE STUDENTS WORKING UNDER CONTRACT

GRADUATE RESEARCH ASSISTANTS

Fernando Guarin

Jose L. Jimenez

Xiaoming Li

Z. Yang