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III-V Compound Semiconductors and High Speed Devices

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III-V COMPOUND SEMICONDUCTORS AND HIGH SPEED DEVICES REVIEW

November, 1986

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III-V COMPOUND SEMICONDUCTORS AND HIGH SPEED DEVICES

OBJECTIVES

The III-V Compound Semiconductors and High Speed Devices program is a coordinated project combining synthesis, characterization, and modeling of advanced semiconductor materials with applications in device development.

Devices and integrated circuits based on GaAs and related materials have emerged as strong contenders for the superfast solid state technologies of the 1990's. Ring oscillator delays close to 10 ps at 77 K have already been obtained and even shorter delays are posssible. Integrated circuits of several thousand gate complexity have been fabricated, and monolithic microwave integrated circuits have been produced in economically feasible yields opening new opportunities for satellite broadcasting applications.

Moreover, large scale computer companies have expressed interest in using GaAs technology for the next generation of supercomputers. In addition, the field of optoelectronics continues to develop with challenging scientific, processing, and device modeling problems.

This program's objectives are to incorporate new methods of surface and interface preparation of GaAs and related III-V semiconductors into new solid-state devices which will have an impact on high speed integrated circuits. The research team consists of experts in fundamental materials science and in device modeling and technology who have established internationally recognized research programs. Students, postdocs, and visitors participating in this team research are developing a broad-based expertise in microelectronics materials and device technology.

Coordinated research thrusts involving physics, chemistry, electrical engineering, and chemical engineering have been established which integrate basic materials research with device fabrication and device performance:

1. Studies of metal-GaAs interface properties which are scientifically fundamental and technologically relevant, with emphasis on electronic and structural modifications as interfacial chemical and physical parameters are changed, to lead to new methods of surface/interface control.
2. Investigations of III-V interfaces and thin film formation by molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD) with emphasis on fundamental physical and chemical rate processes, to result in improved film morphology, uniformity and impurity control.
3. Characterization, modeling and performance evaluation of III-V field-effect devices incorporating the advances made possible by interface modification and synthesis.

The group has identified five research projects for the team research program. These are outlined in the following text.

The combination of novel fundamental interface research with device fabrication and processing techniques (MOCVD) place the research group in the forefront of III-V research. By concentrating on compound semiconductors, the group has several options for future expansions in the sensor and optical device areas.

METAL OVERLAYERS ON SEMICONDUCTOR SURFACES

This component emphasizes chemical reactions occurring at metal/GaAs interfaces. These are being studied by advanced and unique interface and surface characterizationn techniques, including synchrotron radiation photoemission, LEED, angle resolved Auger, inverse photoemission, small-spot high-resolution XPS, and electron microscopy.

Progress

We have examined the electronic interactions and structural modifications which occur when metal overlayers are deposited onto clean semiconductor surfaces. We have examined these interactions as the physical and chemical parameters of the surface/interface are changed, have assessed atomic interdiffusion and overlayer reaction, and have determined whether clusters form and how they affect the properties of the interface. We have sought fundamental information describing interface evolution from the initial adatom on a surface through the growth of the extended, fully-reacted, microscopic interface.

We have been able to show that reactions at surfaces are highly heterogeneous, both parallel and perpendicular to the surface. The degree of lateral heterogeneity varies with the details of the initial interactions of atoms on the surface with epitaxy observed in some cases (e.g. Fe/GaAs and Co/GaAs) and microcrystallites in others (e.g. Ti/GaAs, AuGaAs, Ce/GaAs, V/Ge). We have examined the thermochemistry of these reactions, applying bulk concepts where possible and investigating the limits of bulk thermodynamics. We have made significant progress in understanding the reaction products themselves by advancing the state-of-the-art of high resolution synchrotron radiation photoemission and using that technique to investigate chemical shifts. These core level studies have lead to a much improved picture of heterogeneity perpendicular to the surface. In particular, we have shown that well defined and distinct chemical phases form at interfaces, even though the spatial extent of the interface is only a few atomic layers. These layers can be polycrystalline or single crystal, and the morphology that they exhibit determines the scale over which they form. Room temperature studies have shown the formation of very narrow, metastable germanides or arsenides whose properties enhance or restrict further atomic intermixing. We have been able to demonstrate that subsequent interface growth gives rise to second phases which resemble compounds in some cases or solid solutions in others. With this chemical information, we believe we have developed general pictures for interface formation. We have then taken the next step of seeking to quantitatively model these interfaces. These quantitative models, as they are further developed, will ultimately lead to predictive capabilities. Finally, we have undertaken investigations of the temperature dependence of interfaces, testing our room temperature models and extending the limits of our mathematical modeling.

Planned Work

Planned studies for the upcoming year include the following:

1. Studies of metal overlayers on InSb and InP. The purpose of this work is to investigate the chemistry of reaction for representative metals so

that a broader base can be built for the modeling of interface formation. In addition to studies of the evolving chemistry, we will undertake studies of the atomic profile of the interface to investigate surface segregation, the formation of solid solutions, and concentration gradients near the buried interface.

2. Temperature dependent studies of metal overlayers on GaAs. The purpose of this work is to investigate interface stability and reliability as a function of temperature. In particular, we will be investigating diffusion and reaction in the interfacial zone, seeking quantitative information concerning effective activation energies and diffusion coefficients.

3. Influence of native oxides on chemical reactivity. This program will investigate the ability of the overlayer to reduce the native oxide, the distribution of the rsulting species in the interfacial zone, and the influence of the oxide on interface morphology.

4. Diffusion barriers. The purpose of these studies will be to examine diffusion and reaction in the presence of thin layers of adatoms whose purpose is to block reaction and stabilize the interface.

In these studies, we will use synchrotron radiation at our now-commissioned beamline at Brookhaven National Laboratory, and the facilities at the Wisconsin Synchrotron Radiation Center. In our home laboratory, we will use our high resolution x-ray photoelectron spectrometer, the angle resolved Auger spectrometer, and the inverse photoelectron spectrometer. We have also undertaken the construction of a scanning tunneling microscope, and expect preliminary data late in the year.

NEW GATE AND INSULATING MATERIALS FOR GaAs

This project focuses on controlling the chemical reactions that take place at semiconductor surfaces and interfaces through the exploitation of catalytic effects. The main goal of our program is to investigate the microscopic mechanisms which determine these effects, characterize the electronic and structural modifications that accompany the surface reactions, determine the stoichiometry of the reaction products and/or the interface composition profile, and ultimately obtain an enhanced control of the kinetics of surface reactions with gaseous species and metals.

Progress

Our interest in GaAs stems from both technological and fundamental reasons. The possible use of catalysts to promote the formation of new stable insulating layers on GaAs surfaces would have substantial impact on device technology, if the reacted layers would exhibit inversion and accumulation characteristics suitable for MOS fabrication. From a fundamental point of view, our understanding of the microscopic mechanisms that determine interface catalytic effects could be greatly improved by considering GaAs-metal interfaces.

We have conducted a number of synchrotron radiation photoemission studies of the effect of different metal overlayers on the oxidation rate of GaAs surfaces. We have concentrated on low pressure, low temperature reaction with oxygen or water, and on semiconductor substrates cleaved _in situ_, in order to simplify the experimental procedures and to expedite the build-up of a substantial systematics. The objective was to establish correlations between the specific catalytic activity of a given overlayer, the chemistry of the metal and the properties of the semiconductor surface.

Investigation of the interaction of surfaces with oxygen in the presence of Ag, Au, and Cr overlayers, and of GaAs-water reaction in presence of Cr overlayers shows that the magnitude of the oxidation promotion effect depends on the chemistry of the overlayer, on the local morphology of the interface region, and on the nature of the gaseous reactants. We find that the promotion effect in the series is maximum in the presence of Cr overlayers, and that the nature of the surface reaction products changes if oxygen or water is employed.

In all of the catalytic studies performed in our program, the oxidation of the interface species resulted in their decomposition into stable oxide phases. If this process would lead to saturation of the chemisorption process, then the technological implications would be minor. However, in all cases we have examined thusfar we did not observe saturation at the highest exposures explored at room temperature.

The evidence that the chemistry of the metal is of primary importance in determining the promotion effect is unambiguous, but the metal overlayers mentioned so far have relatively high electronegativity. We speculated that metals with low electronegativity and intermixed interface morphology might give rise to unprecedented oxidation enhacement effects, since they would play the double role of "catalyst" and electronic "promoter" of the oxidation reaction.

We found evidence of dramatic oxidation promotion effects induced by Cs and Sm overlayers. The magnitude of the effect is smaller for Na overlayers. The unprecedented magnitude of the promotion effect for Sm overlayers is consistent with our model, since Sm is a low electronegativity metal that exhibits an intermixed interface morphology with GaAs substrates. The chemisorption of Sm atoms on GaAs surfaces follows a peculiar two-step process, with Sm atoms in a divalent state at submonolayer coverage, and in a mixed valent state at higher concentration. A most striking result is that the onset of the promotion effect appears related to the formation of trivalent Sm species. This result may give us invaluable insight on the connection between local bonding and interface catalytic effects.

In our present view the observation of a critical threshold coverage for oxidation promotion due to Cr and Sm overlayers is the most important element in favor of the "reactive interface" picture of oxidation promotion. Our results for Cs and Na, however, strike a definitive blow against the general applicability of this model to all promotion effects. Both Cs and Na overlayers ar found to give rise to large oxidation promotion although they do not intermix with GaAs. We proposed that at least a partial explanation may be connected to another aspect of alkali-metal chemisorption, namely the establishment of a substantial surface dipole layer.

Planned Work

We plan to concentrate on oxidation reactions of GaAs in the presence of oxygen and water. Our results for Ag, Au, Cr and Sm on Si and GaAs support a picture in which metallic silicide-like phases act as "promotion layers" for the oxidation reaction. However, our results for Cs and Na are in contrast with such a model and suggest that an electrostatic overlayer-oxygen interaction mediated by a "metallized" substrate should be examined to explain catalytic promotion. To reconcile (if possible) the two pictures we need more data on: 1) the catalytic activity of transition metal overlayers with different interface morphology, such as V, Mo, Ti and the early rare earth metal series; 2) in-depth analysis of the morphology of GaAs-alkali metal interfaces as a function of metal coverage and metal electro-negativity (Na, K, Rb, Cs): 3) an analysis of the catalytic activity of metal overlayers which exhibit both alkali and transition metal character (Cs, Ba, Sc, Y).

The low-pressure room temperature reaction parameters employed so far have been sufficient to synthesize thin (10-30Å) insulating layers. We plan to further extend the systematics, but we emphasize the importance of ultimately obtaining device-grade materials and test MOS structures. To do that we have to synthesize thick insulating layers (1-5 μm), characterize these layers for composition and structure, and examine the inversion and accumulation characteristics for practical MOS application. Since the catalyst atoms are not removed from the reaction products (the insulating layer) after the reaction is completed, they may, in principle, yield interface states in or below the insulating layer and give rise to junction parameters unsuitable for device applications. New thermal procedures would then have to be used in order to disperse the ultrathin catalyst layer in the semiconductor matrix without perturbing the insulating layer. The growth of MOS test structures for electrical characterization is the

most effective way of examining these problems. We will focus on some of the metal overlayers most effective in promoting low-pressure and low-temperature reactions (Sm, Cs, Cr) and perform chemisorption studies of oxygen and water at pressures up to 1-10 torr and temperatures up to 500-700°C. For this purpose we will construct a high pressure reaction cell where the sample can be heated through back-surface irradiation. The cell will be connected through a differentially pumped transfer stage to the existing electron spectrometer. X-ray photoemission and XPS-AES depth profiling will give information on layer composition. Ex-situ electron microscopy and Rutheford backscattering studies will provide information on the structures and composition of the thicker layers. Special emphasis will be given to examining the final distribution of catalyst atoms in the reaction products, and the influence of thermal processing on this distribution.

A positive conclusion of the thin film processing stage should enable us to start the preparation of MOS test structures for electrical characterization by the end of year 2. Having identified the most promising catalytic process, we will proceed to form insulating layers and suitable contact patterns on wafer samples. Our existing spectrometers are still suitable for our purpose, provided that suitable metallization patterns can be obtained beforehand on the wafers and kept stable during the following processing steps. Automated electrical testing equipment is availble to us through external collaborations with the Minnesota Microelectronic community (Honeywell, Department of Electrical Engineering).

THE GROWTH OF COMPOUND SEMICONDUCTORS BY MOLECULAR BEAM EPITAXY

This work emphasizes the growth of compound semiconductors and the formation of interfaces by molecular beam epitaxy. At present, despite the pervasive role of materials preparation in device performance, there is little fundamental understanding of the growth of compound semiconductors. One cannot predict how to adjust growth parameters to influence the properties of materials. One cannot even predict which materials will grow epitaxially on another. The goals of this work are to use in situ electron diffraction to measure basic quantities important to MBE growth, to understand the stability of ternary systems, and to develop new techniques for application to nonultrahigh vacuum crystal growth.

Progress

Funding for this component of the III-V Compound Semiconductor and High Speed Device project began in July 1986. At that time Dr. Sharat Batra and Mr. Gale Petrich joined our group. Since July we have been working on three aspects of the project: (1) antiphase suppression in the growth of zincblend on diamond lattices; (2) measurement of the surface diffusion of Ga on GaAs; and (3) critical stability of AlGaAs surfaces as a function of temperature and Al mole fraction. Results of the first two will be presented at the International MBE Conference in York, England in September. The AlGaAs work will be presented at the MBE Workshop in Boston in October.

It is now possible to grow epitaxial GaAs films on Si with quality comparable to what can be grown on GaAs substrates. This means that one can now combine direct bandgap, electro-optical materials with indirect bandgap materials for which processing is a mature technology. At this point the growth process is purely empirical with no microscopic model. There are two main aspects to be understood. First, there is a severe lattice mismatch between GaAs and Si that must be accommodated. Second, since there are two identical sublattices of a diamond lattice, two domains of GaAs can be present in the epitaxial layer. We have separated these two issues by studying the lattice matched system of GaAs on Ge. In this case we find that there are two distinct classes of steps on the Ge surface and that the adsorption kinetics for each are very different. The result is that on surfaces misoriented in specific directions, the kinetics alone can force single domain growth of GaAs.

To develop a theoretical model for the growth of compound semiconductors, the most fundamental parameters must still be determined. This includes surface structure, adsorption geometries, dissociation processes, and most importantly the rates of surface diffusion of the adsorbed species. We are using reflection high-energy electron diffraction to determine the diffusion of Ga on GaAs. We have found that the diffusion coefficient is a sensitive function of As flux and substrate temperature. A hidden dependence is that there is a sharp change in the diffusion coefficient, depending upon the surface reconstruction.

Finally, we have found that not all AlGaAs(100) surfaces are equal. Real surfaces are never perfectly cut parallel to the (100) plane, with the result that the surface is comprised of steps with (100) terraces and sufficient monatomic risers to give the appropriate macroscopic misorientation. Surfaces mis-

oriented towards the <111> direction can have (111) risers with either Ga or As termination. We have found that surfaces misoriented with As termination are unstable and give poor growth morphology. Those with Ga termination are more stable and give better growth morphology. We are measuring the roughening rates of these surfaces as a function of growth conditions.

Planned Work

The ongoing effort is to measure the diffusion of surface species, to determine the role of surface structure, and to understand the kinetics of surface processes. The major goal is to develop a microscopic model of the growth of GaAs and AlGaAs.

Preliminary measurements of the growth of GaInAs indicate that the growth of this lattice mismatched material depends crucially on surface structure. We intend to determine the surface phase diagram and the interplay of structure with surface diffusion and stability.

A major effort will be begun to study the mechanism by which impurities are incorporated into these compound semiconductors during growth. We expect that they may pin steps affecting the morphology in a detectable way.

A spectroscopic ellipsometer will be designed for use in conjunction with electron diffraction in our MBE system. By comparison to what we can learn from electron diffraction we hope to be able to understand this old, surface sensitive technique. If successful, the next step will be to use ellipsometery by itself in a high pressure MOCVD reactor, where electron diffraction is not applicable.

MOCVD SYNTHESIS OF AlGaAs AND GaAs HETEROJUNCTIONS

This project focuses on the chemical and physical rate processes underlying the growth of compound semiconductor heterojunctions by metal-organic chemical vapor deposition (MOCVD). This process is a promising technique for large scale production of III-V device structures. However, critical aspects of the underlying chemistry and reactor design need to be understood to achieve large area film uniformity, low background impurity levels, and sharp heterojunctions.

Progress

A new MOCVD reactor for AlGaAs has been tested in the growth of GaAs from $(CH_3)_3Ga$ and $(CH_3)_3As$. Single crystalline films with good surface morphology have been deposited at low pressures (15 torr) and near atmospheric pressure (500 torr). The films were p-type and showed carbon incorporation because of the choice of an organometallic As source compound. However, $(CH_3)_3As$ is much less toxic than AsH_3. Work is continuing on identifying an organometallic As compound that will maintain this advantage while giving reduced carbon incorporation.

The MOCVD reactor system incorporates several new features including well controlled flow fields, short residence times, radiant heating and mass spectrometer effluent monitoring. It serves a dual purpose by producing III-V materials, whose electronic properties can be investigated as a function of growth conditions, and by allowing careful studies of chemical mechanisms and physical rate processes underlying MOCVD. The latter experiments will be augmented with detailed surface and gas phase investigations in two new specialized MOCVD systems. A MOCVD system with molecular beam mass spectrometer sampling has been constructed and leak tested. The sampling arrangement makes it feasible to identify reactive fragments arriving to the growth surface without confounding effects of wall reactions. This has not been done previously in MOCVD and the results are important for understanding growth and impurity incorporation. The second reactor system used a microbalance for *in situ* measurement of growth rates. It has been constructed and is being tested. We intend to study the intrinsic surface kinetics of MOCVD GaAs/AlGaAs growth. The kinetic data from the three reactor systems are crucial to both reactor scale-up and to the solution of special MOCVD problems, e.g. increased uniformity and reduced impurity levels.

The experimental effort has been complemented by MOCVD reactor analysis. Since convection and diffusion regulate the supply of reactant to the growing film, fluid flow phenomena strongly influence MOCVD processes. Large temperature gradients can generate buoyancy driven secondary flows leading to severe variations in film thickness and composition as well as smeared heterojunctions. Large scale finite element computations on the University of Minnesota's Cray-1 and Cray-2 have been used to investigate the formation of buoyancy driven roll patterns in horizontal reactors and recirculation cells in vertical reactors. These phenomena are nonlinear and highly sensitive to reactor boundary and inlet conditions. The effect of recirculations on interface abruptness in superlattice growth has also been studied by simulations. The results show that without special stop growth procedures two-three monolayer abruptness cannot be achieved in conventional vertical reactors. Finally, a flow visualization experiment has been set up to demonstrate the various flow phenomena.

Planned Work

We will continue to investigate the growth kinetics of GaAs and to evaluate finite element reactor models. Film morphology, uniformity, electronic properties and impurity concentrations will be examined as a function of growth conditions. Various organometallic source compounds, including methyl and ethyl compounds, will be used to investigate the effect of the alkyl on growth kinetics and impurity incorporation, in particular carbon. Because of the lower toxicity of organometallic As compounds compared to AsH_3, there is considerable incentive to find a suitable source compound. However, we also intend to begin growing with AsH_3 to produce device quality material and to compare to the chemistry of the As hydride and organometallic processes. Spatial growth rate variations will be monitored and related to model predictions. The effect of different inlet nozzle designs on uniformity will also be explored.

The gas phase decomposition kinetics of Ga and As organometallic source compounds will be investigated in the new molecular beam mass spectrometer sampled system. We will be particularly interested in differences in mechanisms between methyl and ethyl compounds and implications for GaAs growth and impurity levels. The microbalance system will be used to measure surface growth kinetics at low pressures which will be essential in the design of MOCVD reactors. The experimental data will continue to provide valuable feedback for the modeling approach. Flow visualization will also support the modeling effort. Emphasis will be given to match experimental and theoretically predicted results, to three-dimensional flow phenomena and to simulation of superlattice growth.

The next set of investigations are to be focused on the growth of AlGaAs on GaAs with the ultimate goal of depositing quantum well structures. The kinetics of Al incorporation are to be investigated and the feasible level of junction abruptness and minimum layer thickness is to be established. The deposition of composition graded layers are also to be considered. The electrical and optical properties of the grown structures are to be examined through collaboration with researchers at MEIS companies.

In addition to thermally driven MOCVD, the feasibility of producing special III-V structures by Laser assisted MOCVD is to be pursued in collaboration with Professor R. W. Carr in Chemical Engineering and Materials Science. These studies are also expected to include laser spectroscopy of MOCVD gas phase reactions. Finally, depending on the success of the MBE ellipsometer studies, ellipsometry will be investigated as an *in situ* surface/film characterization tool for MOCVD.

CHARACTERIZATION, MODELING AND SIMULATION OF III-V DEVICES AND CIRCUITS

This project focuses on the development of novel device concepts and analytical and computer models for simulation of ultra-high speed compound semiconductor devices and integrated circuits.

Progress

Four new device types have been proposed and developed (jointly with N. C. Cirillo, J. K. Abrokwah, D. K. Arch, R. R. Daniels and O. Tufte):

1. Complementary Heterostructure Insulated Gate Transistors with the highest ever observed transconductance and the shortest gate delay for p-channel devices. These devices are very stable with respect to the temperature variation and for the first time open up an opportunity for complementary GaAs logic.
2. A new inverted MODFET with the highest transconductance ever observed at 300 K and at 77 K for any FET.
3. A novel hot electron transistor with small parasitics.
4. Superlattice Modulation Doped transistor.

We have also proposed a new transistor: Tunneling Emitter Bipolar Transistor.

Studies of the device physics of modulation doped devices and heterojunction bipolar junction devices have progressed significantly. A new theory for scattering by impurities in modulation doped structures has been developed. It demonstrates that much higher mobilities may be obtained than previous research has indicated. A new theory for the current injected into the two-dimensional gas across the barrier is being developed. A Monte Carlo program for hot electron simulation has been implemented on the University of Minnesota's Cray-1 and Cray-2 and used to study electron velocity in compensated material. A new theory of a planar doped barrier diode has also been developed. Finally we have proposed and observed a new mechanism for the gate current in heterostructures.

Device models for GaAs and AlGaAs/GaAs circuits have been implemented on a variety of computers (IBM PC, PC/XT and Cray) for computer-aided circuit design. These models include MODFET, GaAs MESFET, GaAs ion-implanted MESFET and ungated saturated transistor descriptions. In addition, a model has been developed for GaAs and AlGaAs/GaAs logic gates (DCFL) and used to optimize ultrahigh speed circuits. A charge control model has also been proposed for our new device structures, in particular HIGFETs and inverted MODFETs.

In the area of device characterization, we have developed (jointly with A. Peczalski and H. Chung) new characterization technique for GaAs MESFETs and explained the threshold voltage variation with temperature. By using new GaAs and AlGaAs/GaAs circuit simulator on IBM PC, IBM PC/XT and Cray, we contributed to the development of the fastest integrated circuits ever made (8.5 ps at 77 K and 11.6 ps at 300 K (fabricated by N. Cirillo and J. Abrokwah of Honeywell).

INVESTIGATORS

Klavs F. Jensen, Associate Professor of Chemical Engineering and Materials Science, is Coordinator of the III-V Compound Semiconductors and High Speed Devices program. He presently supervises a group of 12 graduate students and 2 research associates working on metalorganic chemical vapor deposition, plasma processing, reaction and transport in porous structures, and nonlinear dynamics of chemical systems. He has coauthored more than 30 refereed publications. He received the 1983 Young Authors' Award in Solid State Science and Technology from the Electrochemical Society. He has been an invited speaker at international conferences on chemical vapor deposition. He is the recipient of a Dreyfuss Teacher Scholar Grant and an NSF Presidential Young Investigator award.

Philip I. Cohen, Associate Professor of Electrical Engineering heads a group of five graduate students and two post-doctoral associates. He joined the faculty at Minnesota in September 1978. He completed his Ph.D. at the University of Wisconsin in Madison and was a post-doctoral associate at the University of Maryland. His research program has focused on using electron diffraction to study surfaces during epitaxial growth.

Alfonso Franciosi, Assistant Professor of Chemical Engineering and Materials Science, heads a group of four students and one postdoc. He has authored more than 30 refereed publications. he joined the faculty at Minnesota in September 1983 as part of the microelectornic materials thrust. He completed his Ph.D. in physics at the University of Rome and has been active in research on metal-semiconductor interfaces, first at the Polytechnic of Milan and then at the University of Wisconsin Synchrotron Radiation Center. During 1981 he was a visiting professor at the University of Calabria. His research program focuses on semiconductor interface reactivity and interface catalysis.

Michael Shur, Professor of Electrical Engineering, presently supervises a group of seven graduate students and one research associate working on different aspects of device physics, characterization, modeling and simulation as well as IC simulators. He has coauthored more than 200 refereed publications. He has been involved in research on semiconductor devices and integrated circuits for almost twenty years. He has been a visiting scientist at IBM Thomas J. Watson Research Center, he has served as a reviewer for many IEEE and AIP publications, NSF, ARO and other governement agencies and has been a technical consultant to many industrial firms.

John H. Weaver, Professor of Chemical Engineering and Materials Science, presently heads a group of ten Ph.D. students, six post-docs, two senior research fellows, and two visiting professors focusing on electronic and structural interactions at metal/semiconductor and metal/metal interfaces. He is Director of the MEIS synchrotron radiation beamline project at the National Synchrotron Light Source at Brookhaven National Laboratory, Director of Graduate Studies in Materials Science, author of over 150 refereed papers, chapters, and reviews, and holds appointments with both Ames Laboratory and Argonne National Laboratory. He joined the faculty at the University of Minnesota in 1982 and has established the microelectronic materials thrust at Minnesota.

Analytical models for GaAs and AlGaAs/GaAs logic gates (DCFL) have also been developed which allowed us to optimize the performance of the ultrahigh speed circuits and to contribute to the development of 2 K GaAs gate arrays (work joint with Tho Vu and others of Honeywell). One of the major practical benefits from this project has been the contribution to the development of the fastsest integrated circuits made so far.

Planned Work

Future plans include the design and optimization of high speed integrated circuits. Based on circuit simulations and analytical considerations, a set of design rules is to be developed for SSI, MSI, LSI circuits. In addition, further advancement of integrated circuit simulation on the Cray is planned. This should make it possible to link process parameters with circuit yields, reliability and performance.

The team members plan to continue the studies on the device physics of heterojunctions with emphasis on improving the current heterojunction device model. Finally, complementary GaAs heterojunction logic will be considered with the goal of developing complementary heterojunction devices and circuits.

Post-Doctoral Researchers

S. Batra, F. Boscherini, R. A. Butera, C. Capasso, S. A. Chambers, S. H. Chen, L. D. Cheng, M. del Giudice, D. Dong, Y. L. Gao, K. Jamison, S. Kieda, F. Ku, Z. Lin, H. Mayers, Y. Shayira, B. Smandek.

Graduate Students

Z. Abid, C. Aldao, S. B. Anderson, S. G. Anderson, J. Baek, O. E. Berger, B. Bernhardt, Y. Byun, S. Chang, C. H. Chen, J. Conger, D. Fotiadis, D. Hill, P. Jenkins, J. Joyce, S. Krahn, P. Lee, D. McKenna, H. Moffat, M. Nikaido, T. Omstead, D. O'Neill, M. Pedio, G. Petrich, P. Philip, P. Pukite, K. S. Rae, A. Raisanen, D. Skouby, B. Trafas, N. Troullier, I. Vitomirov, T. Wagener, A. Wall, G. Whaley, A. Wowchak, J. Xu, N. Zhou.

Matching Funds

$900,000 from Army Research Office, Department of Defense, National Science Foundation, Office of Naval Research, Honeywell, Amoco, CDC, Ford and the University of Minnesota Graduate School.

Equipment Built or Acquired

- Angle resolved Auger spectrometer (NSF, MEIS)
- Inverse photoemission spectrometer (DOD)
- Small spot x-ray photoelectron spectrometer (ONR, ARO, University of Minnesota)
- Reflection electron energy loss fine structure spectrometer (ONR, University of Minnesota)
- MOCVD system (NSF, MEIS)
- Molecular beam sampled MOCVD system (NSF, MEIS)
- Microbalance MOCVD reactor (NSF)
- Laser equipment for MOCVD (NSF, University of Minnesota)
- HP Characterization system (MEIS)

REFEREED PUBLICATIONS AND PAPERS RELATED TO TEAM PROGRAM

1. G. Margaritondo and A. Franciosi, Synchrotron Radiation Photoemission Spectroscopy of Semiconductor Surfaces and Interfaces, Annual Review of Materials Science 14, 67 (1984).

2. K. F. Jensen, Modelling of CVD Reactors, invited review for the 9th Int. Conf. CVD, Electrochem. Soc., 1984, pp. 3-20.

3. T. J. Drummond, R. Fisher, D. Arnold, H. Morkoc and M. S. Shur, Current-Voltage and Capacitance-Voltage Characteristics of a Metal/$A_{0.5}Ga_{0.5}As$/GaAs Capacitor, Appl. Phys. Lett. 44, No. 2, 214-216 (Jan. 1984).

4. K. Lee, M. S. Shur, T. J. Drummond and H. Morkoc, Parsitic MESFET in (Al,Ga)As/GaAs Modulation doped FET, IEEE Trans. Electron Devices ED-31, No. 1, 2935 (Jan. 1984).

5. T. Vu, P. C. Roberts, R. D. Nelson, G. M. Lee, B. R. Hansal, K. W. Lee, N. Zafar, D. R. Lamb, M. J. Helix, S. A. Jamison, S. A. Hanka, J. C. Brown and M. S. Shur, GaAs Gate ARRAY, IEEE Transactions on Electron Devices ED-31, No. 2, 144-156 (Feb. 1984). Also reprinted in IEEE Journal of Solid-State Circuits SC-19, No. 1 (Feb. 1984).

6. N. C. Cirillo, J. K. Abrokwah and M. S. Shur, Self-Aligned Modulation Doped (Al,Ga)As/GaAs Field-Effect Transitor, IEEE Electron Device Letters EDL-5, No. 4, 129-131 (April 1984).

7. K. Lee, M. S. Shur, K. W. Lee, T. Vu, P. Roberts and M. Helix, A New Interpretation of "End" Resistance Measurements, IEEE Electron Device Letters EDL-5, No. 1, 5-7 (Jan. 1984).

8. T. J. Drummond, R. Fisher, W. Kopp, D. Arnold, J. Klemm, H. Morkoc and M. S. Shur, Temperature Dependence of Al/Undoped $Al_{0.5}Ga_{0.5}As$/GaAs MIS Capacitors, IEEE Trans. Electron Devices ED-31, No. 9, 1164-1168 (1984).

9. K. Lee, M. S. Shur, K. W. Lee, T. Vu, P. Roberts and M. Helix, Low Field Mobility in GaAs Ion-Implanted FET's, IEEE Trans. Electron Devices ED-31, No. 3, 390-393 (March 1984).

10. K. Lee, M. S. Shur, T. J. Drummond and H. Morkoc, Charge Control Model of Inverted GaAs-AlGaAs Modulation Doped FET's (IMODFETs), J. Vac. Sci. Tech. B2(2), 113-116 (1984).

11. K. Lee, M. S. Shur, A. Valois, G. Y. Robinson, X. Zhu and A. Van der Ziel, A New Technique for Characterization of the "End" Resistance in Modulation Doped FETs, IEEE Trans. Electron Devices ED-31, No. 10, 1394-1398 (October 1984).

12. A. A. Grinberg, M. S. Shur, R. Fisher and H. Morkoc, An investigation of the Effect of Graded Layers and Tunneling on the Performance of AlGaAs/GaAs Heretojunction Bipolar Transistors, IEEE Trans. ED-31, No. 12 (Dec. 1984).

13. K. Lee, M. S. Shur, J. Klem, T. J. Drummond and H. Morkoc, Parallel Conduction Correction to Measured Room Temperature Mobility in (Al,Ga)As-GaAs Modulation Doped Layers, Japanese Journal of Applied Physics 23, No. 4, L230-L231 (April, 1984).

14. A. A. Grinberg and M. S. Shur, Density of Two-Dimensional Electron Gas in Modulation Doped Structure with Graded Interface, Appl. Phys. Lett. 45(5), 573-574 (Sept. 1984).

15. K. W. Lee, M. S. Shur, T. T. Vu, New Technique for Measurmeent of Electron Saturation Velocity in GaAs MESFETs, IEEE Electron Device Letters EDL-5, No. 10, 426-427 (Oct. 1984).

16. M. S. Shur, Folded Gate — A Novel Logic Gate Structure, IEEE Electron Device Letters EDL-5, No. 11, 454-455 (1984).

17. N. C. Cirillo, A. Fraasch, H. Lee, L. F. Eastman, M. S. Shur, S. Baier, Novel Multilayer Modulation Doped (Al,Ga)As/GaAs Structures for Self-Aligned Gate FETs, Electronics Letters 20, No. 21, 854-855 (Oct. 1984).

18. N. C. Cirillo, J. K. Abrokwah and M. S. Shur, A Self-Aligned Gate Process for ICs Based on Modulation Doped (Al,Ga)As/GaAs FETs, IEEE Trans. Electron Devices (Dec. 1984).

19. S. A. Chambers, T. R. Greenlee, G. A. Howell and J. H. Weaver, Characterization of Intermixing in Metal-Semiconductor Interfaces by Means of Angle-Resolved Auger Electron Emission: Cu/Si(111)7x7, Phys. Rev. B 31, 6402-6410 (1985).

20. M. Grioni, J. J. Joyce and J. H. Weaver, Temperature Dependent Growth Morphology of a Semiconductor/Metal Interface: Ge/Ta(110), Phys. Rev. B.

21. A. Fujimori, M. Grioni and J. H. Weaver, Thermoreflectance Investigation of Zirconium Hydrides in the Face Centered Tetragonal Phase, Phys. Rev. B.

22. J. H. Weaver, Metal/Semiconductor Interfaces, Physics Today 39, 24-30 (1986) and cover photo.

23. J. H. Weaver, M. Grioni and J. J. Joyce, Critical Development Stages for the Reactive Cr-GaAs(110) Interface, Phys. Rev. B 31, 5348-5354 (1985).

24. M. Grioni, J. J. Joyce and J. H. Weaver, Reactions at a Rare-Earth/GaAs Interface: Ce/GaAs, Phys. Rev. B 31, 5290-5296 (1985).

25. A. Fujimori, M. Grioni, J. J. Joyce and J. H. Weaver, 4f Photoemission from Ce/Si and Ce/GaAs Interfaces, Phys. Rev. - Rapid Commun. B 31, 8291-8294 (1985).

26. M. Grioni, M. del Giudice, J. J. Joyce and J. H. Weaver, Modeling of Interface Reaction Products with High Resolution Core Level Photoemission, J. Vac. Sci. Technol. A3, 907-910 (1985).

27. M. Grioni, J. J. Joyce and J. H. Weaver, Room Temperature Reaction at a Refractory Metal-Semiconductor Interface: V/GaAs(110), J. Vac. Sci. Technol. A 3, 918-921 (1985).

28. M. Grioni, J. J. Joyce and J. H. Weaver, Adatom Aggregation, Reaction, and Chemical Trapping at the Sm/GaAs(110) Interface, Phys. Rev. B 32, 962-968 (1985).

29. A. Fujimori, M. Grioni and J. H. Weaver, Rare-Earth-Metal/Semiconductor Interfacial Reactions: Thermodynamic Aspects, Phys. Rev. B 33, 726-735 (1986).

30. M. W. Ruckman, M. del Giudice, J. J. Joyce and J. H. Weaver, Photoemission Study of the Development of the Ti/GaAs(110) Interfaces, Phys. Rev. B 33, 2191-2197 (1986).

31. M. W. Ruckman, J. J. Joyce and J. H. Weaver, Interdiffusion and Reaction at the Fe/GaAs(110) Interface, Phys. Rev. B 33, 8039-8047 (1986).

32. M. Grioni, J. J. Joyce and J. H. Weaver, Metal-Anion Bond Strength and Room Temperature Diffusion at Metal/GaAs Interfaces: Transition vs. Rare-Earth Metals, J. Vac. Sci. Technol. A 4, 965-968 (1986).

33. J. J. Joyce and J. H. Weaver, Characterization of an Extended Reactive Noble-Metal/III-V Semiconductor Interface: Cu/GaAs(110), Proceedings of the Materials Research Society (Boston 1985) (in press).

34. M. W. Ruckman, J. J. Joyce, F. Boscherini and J. H. Weaver, Ga and As Interdiffusion and Reaction at Epitaxial Fe/GaAs(110) and Co/GaAs(110) Interfaces, J. Vac. Sci. Technol. (submitted).

35. A. Franciosi, Shu Chang, P. Philip, C. Caprile and J. Joyce, Microscopic Control of Semiconductor Surface Oxidation, Journal of Vacuum Science and Technology A 3, 933 (1985).

36. S. Chang, A. Rizzi, C. Caprile, P. Philip, A. Wall and A. Franciosi, Overlayer-Induced Enhanced Oxidation of GaAs Surfaces, J. Vac. Sci. Technol. A (in press).

37. A. Franciosi, D. W. Niles, G. Margaritondo, C. Quaresima, M. Capozi and P. Perfetti, Au-Si Interface Formation: The Other Side of the Problem, Phys. Rev. B 32, 6917 (1985).

38. C. Caprile, A. Franciosi, D. Wielickza and C. G. Olson, Experimental Determination of the Electronic Structure of Small Metal Particles J. Vac. Sci. Technol. A (in press).

39. S. Chang, C. Caprile, A. Franciosi and E. Colavita, Trapping Mechanisms in Diffusion Barriers: Al Interlayers at the GaAs(110)-Cr Interface, Sol. State Commun. (submitted).

40. H. Moffat, C. Houtman and K. F. Jensen, Large Scale Finite Element Computation of Reacting Flows in CVD Reactors, invited paper Proceedings 5th European Conf. CVD, June 1985, pp. 73-87.

41. D. W. Hess, K. F. Jensen and T. Anderson, Chemical Vapor Deposition — A Chemical Engineering Perspective, Reviews in Chemical Engineering 3, 97-186 (1985).

42. C. Houtman, D. B. Graves and K. F. Jensen, CVD in Stagnation Point Flow, An Evaluation of the Classical 1D Treatment, J. Electrochem. Soc. 133, 961-970 (1986).

43. H. Moffat and K. F. Jensen, Complex Flow Phenomena in MOVPE Reactors, J. Crystal Growth (in press).

44. P. Lee, D. McKenna, D. Kapur and K. F. Jensen, MOVPE in Inverted Stagnation Point Flow I: Deposition of GaAs from TmGa, TEGa and TMAs, J. Crystal Growth (in press).

45. M. S. Shur, Analytical Models of GaAs FETs, IEEE Trans. Electron Devices ED-32(1), 70-72 (1985).

46. T. H. Chen and M. S. Shur, Analytical Models of Ion-Implanted FETs, IEEE Trans. Electron Devices ED-32(1), 18-28 (1985).

47. T. H. Chen and M. S. Shur, Capacitance Model of GaAs MESFETs, IEEE Trans. Electron Devices ED-32(5), 987-992 (1985).

48. T. H. Chen, C. H. Hyun, P. N. Jenkins, M. S. Shur and N. Cirillo, Jr., Simulation and Design of Self-Aligned Modulation Doped AlGaAs/GaAs Integrated Circuits, accepted for publication in Proceedings of the International Solid State Circuit Conference, New York, Feb. 1985, pp. 264-265.

49. K. W. Lee, K. Lee, M. S. Shur, T. T. Vu, P. Roberts and M. Helix, Gate, Drain and Source Series Resistances of GaAs MESFETs, IEEE Trans. Electron Devices ED-32(5), 987-992 (1985).

50. A. A. Grinberg and M. S. Shur, Modulation Doped Structures with Graded Interfaces, J. Appl. Phys. 57(4), 1242-1246 (1985).

51. M. S. Shur, Novel GaAs Device Models, in Proc. 1985 Int. Conf. on Circuits and Systems, Kyoto, Japan, June 1985.

52. M. S. Shur, Device Models for High Speed GaAs Integrated Circuits, in Proc. 1985 Int. Conf. on Circuits and Systems, Kyoto, Japan, June 1985.

53. J. H. Baek, M. Shur, K. Lee and T. Vu, Current-Voltage Characteristics of Ungated FETs, IEEE Trans. Electron Devices ED-32(11), 2426-2430 (1985).

55. S. Baier, K. Lee, M. S. Shur, N. C. Cirillo, Jr., FET Characterization using Gated Transmission Line Model Structure, IEEE Trans. Electron. Devices ED-32(12), 2824-2829 (1985).

56. M. Shur, GaAs FET model, book section, in Circuit Analysis Simulation and Design, Advances in CAD, for VLSI series, ed. A. Ruehli, to be published.

57. M. Shur, GaAs Devices and Circuits, Plenum Publishing Co. (in press).

58. C. H. Hyun, M. S. Shur, J. H. Baek, N. C. Cirillo, Comparative Study of MODFET Integrated Circuits Operating at 77 and 300 K, to be published in Proceedings of IEEE Biannual Cornell Conference on New Device Concepts, July 1985. IEEE Cat. No. 85 CH2173-3, pp. 220-229.

59. M. S. Shur, Spill-Over Effects in Planar Doped Barrier Structures, Appl. Phys. Lett 47(8), 869-871 (1985).

60. C. H. Hyun, M. S. Shur, N. C. Cirillo, Simulation and Design Analysis of AlGaAs/GaAs MODFET Integrated Circuits, IEEE Trans. CAD CAD-5(2), 284-292 (1986).

61. A. Peczalski, M. Shur, C. H. Hyun, K. Lee and T. Vu, Design Analysis of GaAs Direct Coupled Field Effect Transistor Logic, IEEE Trans CAD CAD-5(2), 266-273 (1986).

62. C. H. Chen, M. S. Shur and A. Peczalsi, Trapping Enhanced Temperature Variation of the Threshold Voltage of GaAs MESFETs, IEEE Trans. Electron Devices, ED ED-33(6), 792-797 (1986).

63. M. S. Shur, D. K. Arch, R. R. Daniels and J. K. Abrokwah, New Negative Resistance Regime of Heterostructure Insulated Gate Transistor (HIGFET) Operation, IEEE Electron Device Letters EDL-7(2), 78-80 (1986).

64. N. C. Cirillo, M. S. Shur, P. J. Vold, J. K. Abrokwah, R. R. Daniels and O. N. Tufte, Complimentary Heterostructure Insulated Gate Field Effect Transistors (HIGFET's), IEDM Technical Digest, paper 12.2, pp. 317-320 (1985) Washington, published by IEEE.

65. N. C. Cirillo, M. S. Shur, P. J. Vold, J. K. Abrokwah and O. N. Tufte, Realization of n-Channel and p-Channel High Mobility (Al,Ga)As-GaAs Heterostructure Insulated Gate FETs on a Planar Wafer Surface, IEEE Electron Device Letters EDL-6(12), 645-647 (1985).

66. N. C. Cirillo, M. S. Shur and J. K. Abrokwah, Inverted GaAs/AlGaAs Modulation Doped Transistors with Extremely High Transconductances, IEEE Electron Device Letters EDL-7(2), 71-74 (1986).

67. T. Vu, R. D. Nelson, G. M. Lee, P. C. T. Roberts, K. W. Lee, S. K. Swanson, A. Peczalski, W. R. Betten, S. A. Hanka, M. J. Helix, P. J. Vold, G. Y. Lee, S. A. Jamison, C. Arsenault, S. M. Karwaski, B. A. Naused, B. K. Gilbert and M. Shur, Low Power Logic Circuits and 2k Gate Array using GaAs Self-Aligned MESFETs, IEEE J. Solid State Circuits (submitted).

68. J. H. Weaver, Synchrotron Radiation Studies of Surfaces and Interfaces, Chapter 4 in Analysis and Characterization of Thin Films, K. N. Tu and R. Rosenberg, Eds., Academic Press, New York (in press).

69. P. R. Pukite and P. I. Cohen, Antiphase Suppression in the Growth of GaAs on Ge by Molecular Beam Epitaxy, J Cryst. Growth (submitted).

70. J. M. Van Hove, S. atra, P. R. Pukite and P. I. Cohen, Surface Diffusion of Ga on GaAs, J. Cryst. Growth (submitted).

71. A. Franciosi, P. Phip, S. Chang, A. Wall, A. Raisanen and N. Troullier, Catalysis of Semiconductor Surface Reactions, Proc. 18th Int. Conf. on Phys. of Semiconductors, O. Engstrom, ed., World Scientific Publishing Co. (1987).

72. K. F. Jensen, Micro-Reaction Engineering (invited review) Chem. Eng. Sci. (in press).

73. A. A. Grinberg and M. S. Shur, Effect of Image Charges on Impurity Scattering of Two-Dimensional Electron Gas in AlGaAs/GaAs, J. Appl. Phys. 58(1), 382-386 (1985).

74. J. Xu and M. S. Shur, Tunneling Emitter Bipolar Junction Transistor, IEEE Electron. Device Letters EDL-6(7) (1986).

75. M. S. Shur, K. Lee, R. Choe and K. Berger, Charge Collection by Drift during Single Particle Upset, IEEE Trans. Nuclear Sci. (accepted).

76. J. Xu, B. A. Berndhardt, M. Shur, C. H. Chen and A. Peczalsky, Electron Mobility and Velocity in Compensated GaAs, Appl. Phys. Lett. (submitted).

77. M. W. Ruckman, M. del Giudice and J. H. Weaver, Temperature Dependent Growth Morphology of a Semiconductor/Metal Interface: Ge/Ta(110), Phys. Rev. B 32, 1077-1084 (1985).

78. S. A. Chambers, F. Xu, H.-C. Chen, I. M. Vitomirov, S. B. Anderson and J. H. Weaver, Simultaneous Epitaxy and Substrate Outdiffusion at a Metal/Semiconductor Interface: Fe/GaAs(001)-c(8x2), Phys. Rev. B (submitted).

79. F. Xu, M. W. Ruckman, H.-S. Chen, J. J. Joyce, F. Boscherini, D. M. Hill, S. A. Chambers and J. H. Weaver, Epitaxy, Overlayer Growth and Surface Segregation for Co/GaAs(110) and Co/GaAs(100)-c(8x2), Phys. Rev. B (submitted).

80. P. R. Pukite, D. Saluja and P. I. Cohen, Roughening Rates and Critical Surface Stability of AlGaAs, J. Vac. Sci. Technol. (submitted).

81. P. I. Cohen, Application of Reflection Electron Diffraction to Epitaxial Growth Technology, J. Vac. Sci. Technol. (invited review) (submitted).

Patents

M. Shur, Folded Logic Gate — U.S. Patent 4,593,300, June 3, 1986
J. Xu, M. Shur, Tunnelling Barrier Bipolar Junction Transistor, pending

Selected Invited Presentations

A. Franciosi, "Surface and Interface Properties of Ternary Semiconductors for Infrared Applications," 1985 Annual Meeting of the Italian National Research Council, Surface Division, Modena, Italy, December 16-18 (1985).

M. S. Shur, "Novel MODFET Devices," NSF Symposium on Electromagnetics, Dallas, February 1986.

M. S. Shur, "Modulation Doped Transistors," American Physical Society, Las Vegas, April 1986.

M. S. Shur, "Modeling and Simulation of MODFETs," Workshop on Compound Semiconductor Devices, San Francisco, February 1986.

J. H. Weaver, "Modeling Homogeneous and Heterogeneous Metal/Semiconductor Interface Reactions with Photoemission and Angle Resolved Auger Spectroscopies," International conference on the Formation of Semiconductor Interfaces, Marseilles, France, June 1985.

J. H. Weaver, "Materials Science of Complex Systems: Microelectronics," Control Data High Technology Futures Workshop, October 1985.

J. H. Weaver, "High Resolution Core Level Photoemission Interfaces," Workshop on an Advanced Soft X-Ray and Ultraviolet Synchrotron Source, Berkeley, California, November 1985.

K. F. Jensen, "MOCVD of III-V Compounds," Sperry III-V Research Frontiers, June 1985.

K. F. Jensen, "Chemical Vapor Deposition," Control Data High Technology October Futures Workshop, 1985.

A. Franciosi, "Synchrotron Radiation studies of Ternary Semimagnetic Semiconductors," Annual Meeting Materials Reserach Society, Boston, Massachusetts, December 1986.

K. F. Jensen "Micro Chemical Reaction Engineering," Review Ninth Int. Symposium on Chemical Reaction Engineering, Philadelphia, May 1986.

K. F. Jensen, "CVD Reaction and Reactor Models," Gordon Conference on "Chemistry of Electronic Materials, August 1986.

J. H. Weaver, "High Resolution Photoemission Studies of Reactive Metal/ Semiconductor Interfaces," International Workshop on Physics of Interfaces by Synchrotron Radiation and Other High Energy Probes, Bad Honnef, West Germany, April 1986.

J. H. Weaver, Reactions at Metal/Semiconductor Interfaces," Materials Research Society Meeting, Boston, Massachusetts, December 1986.

In addition to the listed publications and selected invited presentations, the members of the Pinnacle have presented numerous papers at International conferences, other universities, and electronics companies. A. Franciosi and M. Shur have both organized III-V materials and device workshops at the University of Minnesota within the last two years.