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Chapter 1. Heterostructures for High-Performance Devices

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1.1 Introduction
The broad objective of our research effort is to develop III-V quantum heterostructures for high-performance electronic, optoelectronic, and photonic devices for applications in high-speed optical communications and signal processing. To this end, we are developing: (1) new, higher performance materials systems including InP-based InGaAs heterostructures and <111> oriented strained layer superlattices; (2) novel approaches to integrate laser diodes on VLSI-level electronic integrated circuits; (3) a new family of quantum-well-base, tunnel-barrier n-n-n transistors and near- and far-infrared optoelectronic devices; and (4) new damage-free in situ processing techniques for fabricating advanced quantum structure and embedded heterostructures.

The following sections describe our progress during the past year in the above research areas. Our group works closely with Professors Hermann A. Haus, Erich P. Ippen, and James G. Fujimoto to develop the optical device application, characterization, and modeling aspects of this program, with Professor Henry I. Smith to develop a novel distributed feedback laser structure, and with Professor Sylvia T. Geyer to develop new in situ processing techniques.

1.2 Growth Optimization of MBE-Grown InAlAs on InP

Sponsors
Advanced Research Projects Agency/NCIPT
Joint Services Electronics Program
Contract DAAL03-92-C-0001

Project Staff
Woo-Young Choi, Professor Clifton G. Fonstad, Jr.

InAlAs grown on InP is of great importance for many electrical and optical devices that utilize semiconductor heterostructures. The material quality of InAlAs, however, still leaves much to be desired. It suffers from high reactivity of aluminum with oxygen-containing residual species and alloy clustering due to the large difference in In-As and Al-As bond energies. Consequently, great care must be taken to establish growth conditions that minimize these degrading effects.

In growing InAlAs with an MBE machine that has ultraclean vacuum and high-source purity, there are two controllable growth parameters that significantly affect the resulting material quality: substrate temperature and As overpressure. The task is, then,
obtaining the optimal combination of these two that gives the best material quality. For this goal, we performed a systematic study in which InAlAs samples were grown on InP by MBE with different combinations of growth temperature and As overpressure and characterized by double crystal x-ray diffraction (DCXRD) measurements for the evaluation of crystalline quality, Hall measurements for electrical quality, and photoluminescence (PL) for optical quality.

Figure 1 shows different growth conditions under which five InAlAs samples were grown. These samples were all grown below the RHEED 2x to 4x transition temperature, as shown in the figure, above which the required As-stable surface condition cannot be maintained. Figure 2 shows the results of depend on MBE growth conditions. Particularly, high-As overpressure provides better quality than low As overpressure, probably because it minimizes alloy clustering. In addition, under a given As overpressure, higher growth temperature provides better quality because it most likely reduces impurity incorporation. If the temperature is too high, As deficiency may degrade the material quality. The similar trend is also shown in photoluminescence.

![Figure 1. Five different InAlAs growth conditions investigated. Also shown is the As-rich to Group-III-rich transition temperature measured at different values of As overpressure.](image)

1.3 Fabrication of Ridge Waveguide Distributed Feedback Lasers by X-ray Lithography

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Joint Services Electronics Program
Contract DAAL03-92-C-0001

Project Staff

Woo-Young Choi, Professor Clifton G. Fonstad, Jr., in collaboration with V. Wong, Professor Henry I. Smith, Kathy Meehan, Paul Gavrilovic, P. Whitney

We are developing novel InP-based ridge waveguide distributed feedback (RWG DFB) lasers which do not require any epitaxial regrowth or growth on corrugated substrates. Conventional DFB lasers have gratings buried within semiconductor materials, and this necessitates the complicated and often yield-limiting step of epitaxial overgrowth on top of gratings. Our approach relies on high-quality laser materials whose device performance, even with the ridge waveguide confinement scheme, is adequate for many applications. We simply add gratings next to the ridge waveguide after the formation of the waveguide; consequently, no complicated overgrowth step is needed and the simple and mature RWG fabrication technology can be fully utilized. Figure 3 schematically shows the structure of our RWG DFB device.
Numerical calculations show that the coupling coefficient values in the range of 10 to 100 cm\(^{-1}\) can be easily achieved if gratings are made as close to the ridge as possible and grating etching depth is about 0.3 μm. To achieve these, we are utilizing x-ray lithography and CH\(_4\)/H\(_2\)-based RIE. X-ray lithography, with its large depth-of-focus and minimal proximity effect, can provide gratings of the required period on non-planar structures. RIE patterning of gratings as well as waveguides gives waveguides with vertical side-walls and gratings with large aspect ratios. With these techniques, we have successfully fabricated RWG DFB structures on monitor InP wafers as shown in the figure 4, and we are now in the process of fabricating complete RWG DFB devices.

1.4 Numerical Calculation of Coupling Coefficients in Ridge Waveguide Distributed Feedback Lasers

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Joint Services Electronics Program
Contract DAAL03-92-C-0001

Project Staff
Woo-Young Choi, Professor Clifton G. Fonstad, Jr., in collaboration with Jerry C. Chen and Professor Hermann A. Haus

As a part of our efforts in fabricating novel ridge waveguide (RWG) distributed feedback (DFB) lasers that do not require any epitaxial regrowth, we performed systematic numerical studies in which the coupling coefficients were calculated against many RWG structural parameters. In order to calculate the coupling coefficients, we used the coupled-mode theory which takes gratings as perturbation to grating-free two-dimensional waveguides. This requires an accurate two-dimensional field intensity profile, especially around the bottom parts of the ridge side-walls where most coupling between gratings and the evanescent fields occurs. Since simple two-dimensional waveguide solvers fail to provide accurate field intensity profile around this critical region, we used the newly developed imaginary-distance beam propagating method (IDBPM) for calculating accurate two-dimensional field intensity profiles. Figure 5 shows schematically the RWG of interest along with the parameters whose influences on the coupling coefficient were investigated. Figure 6 shows an example of guided mode intensity profile calculated by the IDBPM.

The investigation shows that, among the investigated parameters, the ridge width, the proximity of the gratings to the ridge, and the grating duty cycle have the most significant effects on the coupling coefficient. In addition, the coupling coefficients in the range of 10 to 100 cm\(^{-1}\) are easily achieved,
clearly demonstrating the feasibility of the proposed RWG DFB structure. Furthermore, calculations show that the proposed structure has advantage over the conventional DFB structure because it has more stable Bragg wavelength against the ridge width variations and the spatially-varying coupling coefficient DFB structure can be easily achievable.

**Figure 5.** A schematic drawing of a ridge waveguide distributed feedback laser with various parameters whose influences on the coupling coefficients are investigated.

**Figure 6.** A contour plot of a typical guided mode intensity profile calculated by the imaginary-distance beam propagation method.
1.5 Measurement of Excited-state Lifetimes in Narrow Quantum Wells

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Joint Services Electronics Program
Contract DAAL03-92-C-0001

Project Staff
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Recent achievement of 1.55 μm intersubband transitions using three-monolayer wide InGaAs/AlAs/InAlAs pseudomorphic quantum wells on InP has opened up a venue to study the carrier dynamics and time resolved optical spectra of such transitions in this important optical communication wavelength window. Fast relaxation times and large optical nonlinear behavior are the major merits expected from such quantum-well structures.

The 1.55 μm intersubband transition was observed in a single quantum well structure measured in a waveguide geometry to benefit from multiple passes through the quantum well and to increase the absorption to 5 percent. Nevertheless, to successfully carry out femtosecond pump probe measurements, modifications of the sample may be required. Current work is directed toward:

1. Improving the confinement of the incident light to the active region by incorporating the single quantum well structure into a ridge waveguide.
2. Attempting to grow a stack of these pseudomorphic single quantum wells using strain compensation techniques.
3. Adding quantum wells on both sides of the thin quantum well to improve carrier confinement in the upper level and prevent carrier leakage to the InAlAs barrier region.
4. Exploring the AlGaAs/InAs system on GaAs. The barriers are preferably thick and in this material system they are unstrained.

1.6 Tunable Semiconductor Lasers

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Project Staff
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Wavelength division multiplexing (WDM) applications such as the channel dropping filter proposed by Professor Hermann A. Haus and Bobby Y. Lai require tunable lasers and/or optical amplifiers. We have proposed a new three-terminal independently addressable asymmetric double quantum well (IAADQW) structure (figure 7) in which current injection into two quantum wells located within a single mode rib waveguide can be independently controlled. Simulations we have done show a continuous tuning range of more than 20 nm about a center wavelength of 1.5 μm for the structure shown below with one 95 Å well and one 100 Å well (figure 8). This is significantly larger than the continuous tuning range of both three-section distributed Bragg reflector (DBR) and tunable twin-guide (TTG) lasers that are competing for use in WDM systems. Furthermore, because the IAADQW laser is a three-terminal device, light output power can be held constant over the entire tuning range, making the IAADQW an important candidate for WDM applications.

Fabrication of the IAADQW devices has begun using a self-aligned technique we developed in which a single photolithography step defines a photoresist/silicon diode layer. We use this layer as: (1) an etch mask for the definition of an optical waveguide using reactive ion etching (RIE); (2) an ion implant mask that we use to confine the current injection in the lower quantum well; and (3) a lift-off stencil for defining the N-type contact to the center well region. Use of this technique eliminates critical photolithographic alignments that can make the fabrication of three-terminal devices prohibitively complex.

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IAADQW Process Summary

1) SiO₂ Deposition
2) Photolithographic Definition of Ridge Waveguide
3) RIE of SiO₂ and P AlGaAs Clad
4) Ion Implantation of Hydrogen Current Confinement Layer
5) AuGe Evaporation and SiO₂ Assisted Lift-off
6) SiO₂ RIE Planarization
7) AuZn P Contact Evaporation

![IAADQW Process Diagram](image)

Figure 7. IAADQW process description.

![Tuning Curve](image)

Figure 8. IAADQW simulated tuning range.
1.7 Integration of Vertically-emitting, In-plane Cavity Laser Diodes on GaAs VLSI Circuitry

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Advanced Research Projects Agency/NCIPT
Hertz Foundation Fellowship

Project Staff
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We have demonstrated for the first time key components of a fabrication sequence for manufacturing monolithic optoelectronic very large scale integration (OE-VLSI) circuits and systems. Commercially available refractory-gate metal VLSI GaAs MESFETs have recently been shown to be stable after more than three hours at 500°C. Thus, it is now possible to regrow optical sources, detectors, and modulators on fully processed MESFET circuitry. VLSI circuits and systems can, therefore, be built with optical inputs and optical outputs without electronic circuit design rule modification. Such OE-VLSI circuits and systems are useful for high-speed optical communication and optical computing (smart pixels).

An OE-VLSI circuit can be fabricated in four steps: (1) foundry fabrication of the electronic circuit design, (2) selective epitaxial regrowth of photonic heterostructures in window regions (GaAs substrate exposed), (3) removal of inter-window polycrystalline material and photonic device processing, and (4) photonic and electronic device interconnection. By cascading these mature technologies, high-performance OE-VLSI circuits are immediately available.

An OE transceiver (generic smart pixel) was designed, regrown, and is nearing completion to demonstrate the high-density integration of LEDs, ridge lasers, and in-plane surface emitting lasers (IPSELS) with state-of-the-art VLSI GaAs MESFET transceiver designs. IPSELS are attractive for the following reasons: (1) \( V_n < 2V \) is compatible with DCFL MESFET logic levels; (2) heterostructure thickness; \( \sim 4 \mu m \) is planar with electronics, (3) low divergence angles \( (13^\circ \text{FWHM}) \), and (4) \( \eta_d \) as high as 66 percent pulsed and 48 percent cw.

Figure 9 is a cross-section of a selectively grown strained-layer (Al,Ga,In)As laser heterostructure in which vertical mirror facets, a parabolic deflection mirror, and a ridge waveguide have been fabricated using chlorine ion-beam-assisted etching. Figure 10 is a scanning electron micrograph of a completed monolithically integrated IPSEL on a transceiver chip. Preliminary optoelectronic characterization is currently underway.

Figure 9. Cross-section of OE-VLSI transceiver chip with selectively grown strained-layer (Al,GaIn)As laser heterostructure in which vertical mirror facets, a parabolic deflection mirror, and a ridge waveguide have been fabricated using chlorine ion-beam-assisted etching.

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1.8 Thermal Stability of GaAs MESFET VLSI Circuits

**Sponsors**

Advanced Research Projects Agency/NCIPT  
National Science Foundation Fellowship  
Hertz Foundation Fellowship

**Project Staff**

Eric K. Braun, Krishna V. Shenoy, Professor Clifton G. Fonstad, Jr., in collaboration with J. Mikkelsen\(^\text{14}\) with G. Hansell,\(^\text{15}\) and A. Harton\(^\text{16}\) and C. Wyatt\(^\text{16}\)

Integration of optical devices with VLSI GaAs circuits by MBE regrowth has recently been demonstrated. The time temperature budget of the epitaxial layers is constrained by the thermal stability of the GaAs MESFET circuits. Investigations to date have demonstrated that commercially available GaAs VLSI discrete devices exhibit stable characteristics for three hour thermal cycles at temperatures up to 500°C. In this research we are continuing to evaluate the DC and AC performance of commercial VLSI GaAs MESFETs after thermal cycles of varying time and temperature. DC tests on refractory-gate metal MESFETs, from Vitesse Semiconductor Corporation's HGaAs\(_2\) process and Motorola Corporation's CS-1 process, show reduced MESFET performance, after three hour thermal cycles, for temperatures above 500°C (figure 11). DC parameters were extracted from enhancement mode MESFETs (EFETs), depletion mode MESFETs (DFETs) and transmission line model structures on the standard process control monitor test bars. It is observed that the EFET and DFET parameter trends are in agreement. Threshold voltage, Schottky diode ideality, Schottky barrier voltage, contact resistance, and sheet resistance all show no significant trends. However, with increasing cycle temperature, transconductance and saturation current decrease as the channel series resistance increases.

Future work on the thermal cycle response of VLSI GaAs MESFET circuits will be directed in the following three areas: (1) Additional DC tests of the latest refractory-metal gate processes from Vitesse and Motorola spanning a wider time and temperature range. (2) AC tests of the Motorola and Vitesse processes including the measurement of ring oscillators. (3) Testing of a gate-less process flow provided by Vitesse to isolate the mechanism for the increasing channel resistance.

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1.9 Gas Source MBE of InGaAsP Laser Diodes on GaAs Substrates

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Advanced Research Projects Agency/NCIPT

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The collaborative effort between Professors Clifton G. Fonstad, Jr., and Leslie A. Kolodziejski is aimed at the development of Al-free compound semiconductor lasers as part of a program to develop commercially viable OptoElectronic VLSI circuit (OE-VLSI) technology. Lasers are ultimately to be regrown on commercially fabricated GaAs MESFET VLSI circuits. These VLSI circuits have been found to withstand temperatures up to 500°C for several hours without degradation. While this condition counterindicates the use of conventionally grown AlGaAs based lasers, which traditionally require growth temperatures greater than 600°C to achieve high-quality material, the InGaAsP system is normally grown at a substrate temperature of approximately 500°C.

At present, multiple quantum well InGaAs/GaAs/InGaP lasers are under development. The lasers are to be grown by GSBME in Professor Kolodziejski's laboratory. To date, high-quality InGaP epilayers on GaAs substrates have been achieved, and doping studies are underway. Phase I, the growth of a preliminary double heterostructure laser structure, began in February 1994. Phase II will involve growth of quantum well active regions and Phase III will build on this structure to achieve state-of-the-art graded index, quantum well performance.

1.10 High-Density OEIC Neural Systems Produced by Monolithic Integration of GaAlAs Light Emitting Diodes on GaAs MESFET VLSI Circuits

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Advanced Research Projects Agency/NCIPT

Project Staff
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Recently it has been shown that commercially available, self-aligned VLSI GaAs MESFETs are stable after more than three hours at 500°C. Thus, it is now possible to use molecular beam epitaxy techniques to regrow optical sources, detectors, and modulators on fully processed, high-density MESFET circuitry without electronic design rule modifications. Such optoelectronic arrays are potentially extremely useful in optical neural systems where planes of electronic "neurons" are optically interconnected in the third dimension.

A first generation optoelectronic "bump" neuron was fabricated to demonstrate the integration of two phototransistor for optical inputs (E-MESFETs), nonlinear thresholding electronics (E/D-MESFETs),

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and a regrown AlGaAs LED for optical output. The desired optoelectronic thresholding function was achieved while maintaining good electronic circuit performance and LED efficiencies.

Based on this initial success, three additional generations of optoelectronic neural chips have been designed, regrown, and fabricated incorporating increasingly complex neural circuits and more refined processing techniques. These techniques include regrowth in dielectric windows as small as $10 \mu m \times 10 \mu m$, bottom side n+ LED contacts made by regrowth on n+ source/drain ion-implanted regions, and monolithic LED-probe pad interconnect metallization. Figure 12 shows a cross section of a Generation 4 neural chip with an LED regrown on a source/drain ion implanted region in a dielectric window. Winner-take-all (WTA) circuits, where the only LED that is on is the output associated with the neuron in an array with the largest optical input signal, were successively demonstrated. Figure 13 shows the output power of two competing branches when the optical power on unit 1 was fixed at 30 nW while the power on unit 2 varied from 0 to 100 nW. A Generation 5 neural chip is in progress, which will demonstrate a 100-element optoelectronic WTA array and will provide a significantly higher speed alternative to spatial light modulator arrays currently used in optical neural systems.

---Semi-insulating GaAs substrate-----

Figure 12. Cross-section of a Vitesse/MOSIS chip with LED grown in the dielectric via.

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Figure 13. Output power of two competing branches of a winner-take-all circuit.

Figure 14. Transceiver block diagram (above) showing ECL input and output levels, a MSM detector with transimpedance amplifier, a MBE regrown laser diode, and a cross point switch.
1.11 Surface-Normal Optical Input and Output Cells for High-Density, High Speed GaAs MESFET-based OEICs

Sponsor
Advanced Research Projects Agency/NCIPT

Project Staff
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Optoelectronic signal processors have become major components of advanced communication systems, real-time signal processors, and high-performance sensing systems. Integrated optoelectronics offers potential to significantly advance these systems as well as to enable the commercialization of board-to-board optical interconnects. In order to fully exploit the potential of optoelectronic devices, semiconductor processes and technology must be designed to monolithically integrate photodetectors, laser diodes, optical modulators and VLSI transistor circuits. Such monolithic optoelectronic device technology results in lower cost, reduced power consumption, higher bandwidth, lower weight, increased reliability and increased performance of optoelectronic systems.

An optoelectronic integrated circuit (OEIC) transceiver has been designed (Nuytkens, MIT), fabricated in the Vitesse Semiconductor, Inc. HGaAs technology through MOSIS, molecular beam epitaxially regrown, and in-plane surface-emitting laser diodes (IPSELs) have been fabricated.\textsuperscript{20} The OEIC transceiver accepts either electrical or optical signal inputs and generates corresponding electrical or optical signal outputs. The OEIC incorporates an ECL electrical input receiver and output driver, an MSM photodetector, a transimpedance amplifier, cross point switch, and control logic. The OEIC transceiver demonstrates four possible signal conversions (figure 14): (1) Electrical signal at ECL level input, through intermediate DCFL electrical level, to ECL level output; (2) Electrical signal at ECL level input, through laser current driver, to optical signal at 0.98 µm wavelength output (via regrown IPSELs);\textsuperscript{21} (3) Optical signal at 0.86 µm wavelength input, through transimpedance amplifier, to electrical signal at ECL level output, and (4) Optical signal at 0.86 µm wavelength input, through transimpedance amplifier and laser current driver, to optical signal at 0.98 µm wavelength output. Figure 15 shows the layout of the transceiver circuitry and the dielectric windows in which the IPSELs are regrown. Preliminary optoelectronic characterization is underway.

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1.12 Fiber-coupled GaAs MESFET-based OEICs

**Sponsor**
Advanced Research Projects Agency/NCIPT

**Project Staff**
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Recently, due to the fiberoptic telecommunications boom, much work has been done in the area of integration of semiconductor optical devices, such as modulators, detectors, and lasers, with driving electronics made up of MESFETs, MODFETs, and HBTs. However, the necessity to optimize both the optical and electronic devices simultaneously make this approach slow. Our project is to integrate mature GaAs electronic ICs with optical components, by selectively growing using MBE optical devices on open areas of commercial quality IC chips. This has already been successfully achieved for integrating surface emitting laser diode array with such electronics.\(^\text{22}\) Our goal is to demonstrate a working optical switching circuit fabricated on and integrated with a GaAs IC chip (figure 16). The basic optical components of this system are passive waveguides, waveguide couplers and Y-junctions, phase modulators, and detectors. The electronics will consist of driving and amplifying circuit for the modulators, and detectors, as well as signal detection and routing decision digital circuits.

The first version of the circuit will consist of conventional double heterostructure waveguides and electro-optic modulators, with total internal reflection mirror coupled MSM detectors. A schematic of integrating a waveguide with a modulator or a detector is shown in figure 17. A quantum well heterostructure version of the system will also be attempted in order to take advantage of the strong electro-optic effect in QW structures. Finally, a structure with an InGaAs detector layer will be attempted, which will enable the system to operate at the industry standard wavelength of 1.35 m.

One of the biggest challenges of this project is the fabrication of the optical circuits on the exposed areas of the chip without causing drastic deterioration of the IC performance. According to recent studies performed on the ICs, this means that all of epitaxial growth has to be performed at temperatures below 520°C. Thus, to quantify the effect of low temperature grown AlGaAs, we are performing a study of waveguide loss in this material. At the same time, we are working on the optimization of our optical circuit using BPM simulation software. Finally, we are addressing the issues of size reduction of the optical system, as well as the waveguide-fiber coupling issue.

**Figure 16.** A schematic representation of the proposed OEIC network signal router.

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1.13 Low-temperature, Selective-area MBE Growth of GaAlInAs Laser Diodes and Optical Waveguides on Semi-insulating GaAs Substrates

Sponsor
Advanced Research Projects Agency/NCIPT

Project Staff
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Integration of optical devices on commercially available VLSI GaAs circuits requires MBE growth of heterostructures at temperatures at or below ~500°C to avoid electronic device and circuit performance deterioration. AI containing MBE grown lasers at lowered growth temperatures (< 600°C) exhibit substantially reduced performance with threshold current densities typically an order of magnitude or more higher than at optimal growth temperatures (~ 700°C). However, a mechanism for the reduced performance has not been clearly isolated. This research is intended to identify, as either optical or electrical, the nature of the dominant degradation mechanism.

To decouple the electrical and optical contributions to the increasing threshold current density as growth temperature is lowered, waveguide loss measurements on the same structure have been proposed. The experimental setup for measuring waveguide loss is shown in figure 18. A narrow linewidth laser (17 MHz) is focused into one end of the waveguide cavity and the transmitted beam is collected at the other end by microscope objectives. A heat lamp is used to modulate the index of refraction and length of the waveguide resulting in Fabry-Perot oscillations of the transmitted intensity. The ratio of the maximum to minimum intensity in the oscillation pattern can be related to the waveguide loss coefficient, as shown in figure 19. Using this setup the waveguide loss can be determined to an accuracy of 0.5 dB/cm. Waveguide loss measurements will be performed on GaAlInAs strip loaded waveguides, with both doped and undoped cladding layers, over the growth temperature range of 350°C to 700°C. Laser diodes, fabricated from the doped waveguides, will then be characterized. Using this information, it will be possible to design new heterostructure and doping profiles to improve lowered-temperature MBE grown AlGaAs laser performance. These proposed experiments will also be essential for the proper design of integrated passive optical components, including waveguides and modulators.
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1.14 Applications of Resonant Tunneling Diodes in GaAs MESFET VLSI

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Project Staff
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We are investigating the integration of Resonant Tunneling Diodes (RTDs) with GaAs MESFETs. Our focus is on the determination of the optimum diode electrical characteristics for RTD based the SRAM cell shown in figure 20. Based on previous theoretical work, the desired diode has a low reso-
nance voltage, a high peak to valley current ratio (PVCR), and an extended low current valley.

Using molecular beam epitaxy, we have grown GaAs/AlAs, GaAs/InGaAs/AlAs and relaxed buffer InGaAs/AlAs resonant tunneling structures. In these structures, the smaller bandgap of InGaAs is used to reduce both the resonance voltage and valley current of the devices. The relaxed buffer devices use thick InGaAs layers of increasing indium fraction to change the lattice constant of the substrate, enabling the growth of higher percentage indium containing diodes. We have successfully demonstrated working diodes using all three structures. The 7:1 @ 300K (17.5:1 @ 77K) PVCR obtained on a relaxed buffer diode is the highest obtained for such a structure.

Diodes were tested in the SRAM configuration. Initial tests were performed to verify the bistable nature of a series diode chain. In these measurements, the diode supply voltage was varied as the node voltage was measured. Subsequent measurements focused on understanding the memory cell switching process. In these measurements, a programmable current source was used to simulate the MESFET. Figure 20 (right) shows a trace of a cell going through a write HI, hold HI, write LO, hold LO cycle. For a given cell, the maximum current necessary for switching will be the difference in the peak and valley currents for the diode with the largest PVCR. However, the switching current is a function of the supply voltage and can be reduced by adjusting the bias of the cell. There is an inherent tradeoff between switching and static current. Future work will involve examining the dynamics of the switch in an effort to quantify more specifically the influence of diode current density, capacitance, and resistance on the switching process.

Resonant Tunneling Diode Based Memory Cells

Figure 20. (left) Schematic of RTD based SRAM cell. (right) Operation of RTD based SRAM cell with simulated MESFET input.

1.15 Polarization-resolved Infrared Spectra of Very Narrow AlAs/InGaAs/InP Quantum Wells

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Project Staff

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The application of III-V quantum well (QW) C1-to-C2 intersubband transitions for far (8 ~ 10 μm) and mid (1 ~ 5 μm) infrared (IR) detection have, owing to their quantum structure-enhanced dipole transition, fast response speed, and reliance
on more mature growth and process technologies, substantial advantages over the bulk mercury-based materials, which are known to suffer serious problems of device uniformity and yield.

To date, the IR device application of QW intersubband transitions has been hindered by the inappropriate geometry used to study their optical selection rules. Our group has developed a polarization-resolved IR techniques for Fourier transform infrared (FTIR) and near infrared grating (NIR) spectroscopic study of QW optical transitions in the wavelength range from 400 nm to 20 μm.

Figure 21 shows the device structures, experimental setup, and polarization-resolved IR absorption data used in our study of AlAs/InGaAs QW intersubband transitions. By engineering the composition and width of the InGaAs QW, we have succeeded in bringing the intersubband absorption peak wavelength into the NIR (1.55 μm - 3 μm) regime. Our data also shows that by employing strained InGaAs/AlAs QWs, intersubband transitions exhibit (1) equally strong TE- and TM-polarization activity and (2) strain-induced polarization splitting.

Future work in strain InGaAs/AlAs QW waveguide devices will focus on their applications in integrated optics by using (1) linear intersubband absorption for fast IR detectors and modulators in the 1.55 μm spectral region for fiber optics communication systems and (2) nonlinear effects of QW intersubband and interband transitions for surface emitting of visible sum-frequency generation.

Figure 21. Polarization-resolved IR absorption data for strain InGaAs/AlAs single quantum wells measured in a waveguide configuration. Samples (a) ~ (h) are n⁺ InGaAs wells of 3, 4, 5, 6, 10, 15, 17, and 22 monolayers in thickness.
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InGaAs/AlAs Intersubband Strain Splitting

Figure 22. Linear dependence of QW intersubband polarization splitting with QW strain.

1.16 Symmetry Properties of Quantum Well Subband Energy Levels and Selection Rules for Intersubband Transitions

Sponsor
National Science Foundation

Project Staff
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According to an oversimplified picture of a double-barrier quantum well (DB-QW) structure in the energy-position space, it is widely assumed this DB-QW is of inversion symmetry in the growth direction as well as in the QW plane. The eigen wave functions of DB-QW subbands are typically written as a product of sin or cos functions in the growth (z) direction with those of plane waves solutions in the QW plane (x-y directions). As a result, the intersubband transitions in DB-QW are believed to be active only for light polarized with electric field along the z direction (TM-polarization).

Our polarization-resolved intersubband data on DB-QW (figure 21), however, clearly resolved (1) equally TE- and TM-polarized intersubband activity and (2) strain induced polarization splitting. Intersubband data of multiple quantum wells measured in the conventional Brewster angle configuration were confirmed to be corresponding to the TE-active signals measured in the polarization-resolved waveguide configuration. The experimental discrepancy in the Brewster angle configuration was caused by the large index of refraction in the semiconductors, as a result, 90 percent of the refracted light were TE-polarized into the QW plane.

We consider the DB-QW intersubband optical selection rules from the symmetry point of view. Near the k=0 point in the Brillouin zone, DB-QW of zinc blende III-V materials has D2d symmetry that does not include an inversion center. The Bloch states of C1 and C2 QW conduction subbands are S- and P-like at k=0 instead of being both S-like in the old theory. The corresponding wavefunction at k=0 point reduces to those of Bloch states and can be written as \( \cos X \cos Y \cos Z \), and \( p(\sin X \cos Y \cos Z) \), where p stands for the permutations of the X,Y,Z coordinates in the parenthesis.

Our model analysis leads to the conclusions that C1-to-C2 intersubband transitions (1) are of equal absorption strength for both polarizations (parallel and perpendicular to the QW plane) and (2) have strain induced polarization splitting. The later prediction was confirmed in figure 22, where a linear dependence of intersubband polarization splitting versus QW strain was clearly demonstrated.

Our model further predicates the possibility of using counter-propagating TE- and TM-active intense coherent intersubband nonlinear excitations to generate surface-emitting sum-frequency. Experimental work is underway to confirm this proposal.

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23 Harvard University, Cambridge, Massachusetts.
1.17 Investigation of Infrared Intersubband Emission from InGaAs/AlAs/InP Quantum Well Heterostructures

Sponsor
U.S. Army Research Office
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Project Staff
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In this work, we study the possibility of achieving population inversion between two quantum well subbands in the conduction band, with an electrically pumped far infrared intersubband laser as the ultimate goal.

Until recently, proposals in the literature favored intra-well transitions between the first two levels of the quantum wells in superlattices or the middle quantum well of triple quantum-well structures to achieve this goal, because these transitions account for 96 percent of the total available oscillator strength. The adjacent quantum wells in these superlattices or triple quantum wells ensured selective injection into the second level and selective removal from the bottom subband. However, obtaining a sufficiently large population inversion and current density while maintaining all energy levels in resonance conditions appears difficult in both schemes.
Recent spontaneous emission experiments in the 45 m wavelength range reported by Faist et al. exploited inter-well intersubband transitions between off-resonance ground levels of double quantum wells. At the expense of a lower oscillator strength and uncertainty in the lasing wavelength, this approach is more suitable to attain a large population inversion and current density and is being explored for our wavelength of interest (50 μm).

1.18 High-Frequency/High-Speed Characterization, Analysis and Modeling of Heterojunction Bipolar Transistors, Laser Diodes, and m-s-m Photodetectors

Sponsor
National Science Foundation

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Emitter-down InGaAs/InAlAs/InP heterojunction bipolar transistors have been characterized at frequencies up to 40 GHz and small-signal equivalent circuit models have been obtained using the commercial Touchstone software as well as the simulated annealing (SA) algorithm. The bias dependence of the small-signal equivalent circuit elements was determined by measuring the scattering parameters at 39 different bias points. These results were used for the large-signal modeling of the HBT. The model obtained was based on first-order device physics and this was verified experimentally. When standard large signal modeling techniques such as the Harmonic Balance method are used, it was observed that the first-order model was sufficiently accurate for medium power levels with respect to the device under consideration.24 At higher power levels where the transistor is driven into hard saturation and cutoff, a more elaborate model is necessary to obtain a high third-order intermodulation product (IP3) and hence device linearity.25 Representative results are shown in Figure 23. Work on model improvement is in progress. Optimization of the HBT for high third-order intermodulation product is the goal of this work. Characterization of laser diodes and m-s-m photodetectors using the automatic network analyzer and on-wafer probe station is planned and modeling methods which have been effectively applied to HBTs will be used.

1.19 Damage-Free In-Situ UHV Etching and Cleaning of III-V Heterostructures Using Molecular Beams

Sponsors
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The development of damage-free ultrahigh vacuum (UHV) etching, cleaning, and regrowth techniques compatible with molecular beam epitaxy (MBE) and ex-situ processing of III-V heterostructures is a major challenge facing device researchers. The ability to selectively pattern, etch, and overgrow quantum heterostructures is crucial to the effective realization of integrated optical circuitry and quantum effect electronic structures. Present techniques to do this involve relatively high-energy ions or plasma sources which cause substantial subsurface or structural damage, much of which is impossible to remove or repair, especially on compound semiconductors which are more susceptible to such damage than silicon.

As a solution to the problem of process-induced damages, we have begun a project investigating the use of molecular beam (hot neutral beam, or also known as kinetic beam) techniques to etch and clean III-V substrates and heterostructures with a minimum of surface damage and allowing maximum flexibility in attaining various etch profiles. Depending on the etchant gas, it is anticipated that low energy (0.5 to 30 eV) kinetic beams can be used to (1) both directionally and isotropically etch-pattern III-V heterostructure wafers with no damage; (2) clean surfaces allowing epitaxial growth on wafers that have been removed from the UHV environment for external processing; and (3) selectively remove masking materials and clean surfaces suitable for subsequent overgrowth.


Currently, the construction of the differentially pumped UHV Kinetic Beam Etch (KBE) system designed to use a methane-hydrogen gas mixture using a supersonic beam source is near completion. The system is designed such that it can be connected to the existing Riber 2300 solid source MBE system in the future through a transfer mechanism of special design.

The initial function tests of the KBE system are scheduled to be performed in the near future. Subsequently, a full-scale characterization of the ability of the KBE system will be performed, mainly concentrating on etch rate, etch profile, and surface damage assessment. The extent of surface damage, if any, will be determined through photoluminescence and carrier mobility measurements using various III-V heterostructures grown by MBE.

![Figure 24. Photo of KBE system. Riber 2000 MBE system can be seen in the background.](image)

**1.19.1 Publications**

**Journal Articles**


Chapter 1. Heterostructures for High-Performance Devices


Smet, J.H., C.G. Fonstad, and Q. Hu. "Magnetotunneling Spectroscopy in Wide In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As Double Quantum Wells." Appl. Phys. Lett. 63: 2225-2227 (1993).


Meeting Paper