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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 InGaAlAs 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, James G. Fujimoto, and Erich P. Ippen to develop the optical device application, characterization, and modeling aspects of this program, and with Professor Sylvia T. Ceyer to develop new in situ processing techniques.

1.2 Computer Controlled Growth of Lattice-Matched InGaAlAs Heterostructures on InP

Sponsors

Charles S. Draper Laboratories
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Project Staff

James C. Vlcek, Professor Clifton G. Fonstad, Jr.

In electronic and optical semiconductor devices, the need for both graded-composition and hyper-abrupt metallurgical junctions frequently arises. The use of graded-composition junctions allows for precise control of the confinement of charge carriers and optical fields through spatially varying bandgaps and refractive indices, respectively. On the other hand, hyper-abrupt junctions may be

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desired in some devices, most notably quantum effect devices, where a sharp interface is desired to reduce fluctuations in the confinement energy which might arise from graded interfaces due to shutter transients.

In this work, we have grown the quaternary $In_xGa_yAl_{1-y}As_{1-x}$, lattice-matched to InP substrates. The need to lattice-match, such as to an InP substrate, further constrains the ratio of constituent fluxes.

We have implemented a computer-automated MBE control system whose aim is to provide precise control of the constituent and dopant fluxes such as is necessary to achieve graded-composition lattice-matched alloys and maintain uniform lattice-matched compositions in the presence of shutter events. Key to this system are accurate models of the characteristics of the effusion cells, including not only the static flux versus temperature relationship, but also the time-dependent behavior of the cell in the presence of changes in either setpoint and/or shutter status. These models approximate the temporal response of the effusion cells to a setpoint change with a single-pole system function, with the location of the pole being determined by a direct measurement of the flux profile generated by a step change in the cell setpoint temperature.

In the case of graded-composition layers, the thermal lag time of the cell requires modification of the time-dependent effusion cell setpoint temperature profile, most notably to eliminate the over- and undershoot effects at the endpoints of the graded layer which would result if the effects of cell response time were neglected. With such modifications, we have achieved linearly graded flux profiles whose deviation from the desired profile can be held within one percent.

To remove flux transients which arise from the operation of the cell shutters, we have structured the control system so that it seeks to maintain the flux in the effusion cell at a constant value, irrespective of the shutter status. In practice, this entails maintaining the setpoint temperature of the cell at a lower value with the shutter closed than with it open and performing an exponential ramp sequence upon change of shutter status. Using this technique, we have reduced cell shutter transients from as high as 30 percent to one percent or less.

1.3 Molecular Beam Epitaxy of InGaAlAs Strained-Layer Heterostructures on 111 GaAs and InP

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Joint Services Electronics Program
Contract DAAL03-89-C-0001
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Project Staff

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The issues associated with the molecular beam epitaxial (MBE) deposition of $In_x(Ga_yAl_{1-y})_{1-x}As$ upon (111)B InP have been extensively explored. As a result, a reproducible growth algorithm has been developed whose execution has resulted in bulk n and p-type InGaAs and InGaAlAs of comparable crystallinity to simultaneously grown (100) oriented epilayers.

When epitaxial layers are pseudomorphically deposited upon a (111) zincblende substrate, a piezoelectric field is generated due to the ionic character of the chemical bond between the constituent elements and the lack of inversion symmetry in the (111) orientation. Recently, this strain-generated electric field has been demonstrated in a GaAs based p-i-n modulator whose absorption edge was in the vicinity of 0.9 μm.

Growth on (111) InP is especially difficult because of the volatility of the InP surface and the problems attendant to (111) surface chemistry. Not surprisingly, initial attempts to grow epitaxial layer of InGaAs on (111)B InP according to the proven methods of (100) orientations were unsuccessful. Moreover, reflection high-energy electron diffraction (RHEED) patterns, which usually provide essential in situ information about the condition of a growing surface, are unclear in this material system. As a result, the most critical step in the MBE growth process—the synchronization of the desorption of the substrate's native oxide layer with the initiation of growth—is performed "in the dark."

To address these issues, an alternative growth algorithm, called quasi-migration enhanced epitaxy, was developed and named for the unusually low intensity of As overpressure, low substrate temperature, and slow growth rate which comprise its parameter set. It was learned that an intense group III overpressure, expressed in a rapid rate of growth, is needed to stabilize the (111) growth front: a $\sqrt{19} \times \sqrt{19}$ surface reconstruction that is rich in group III atoms. This is quite different from the case of (100) materials whose c(2x8) surface reconstructions are As stabilized. Another important modification was the elimination of the traditional 5: 1: 1 $H_2SO_4H_2O_2$-H_20 etching step in the pre-growth substrate preparation procedure. As a result, the thickness of the residual oxide layer was reduced which, in turn, allowed growth to be successfully initiated without the need of a risky high temperature desorption cycle.

1.4 Monolithic Fabrication of Strain-free GaAlAs Laser Diodes on Silicon Substrates

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DARPA/NCIPT
IBM Corporation Fellowship

Project Staff

Geoffrey F. Burns, Anton Failla, Professor Clifton G. Fonstad, Jr.

Prospects for monolithic integration of III-V electrical and optical devices with Si circuits have fueled vigorous research in direct heteroepitaxial growth of these compounds on Si substrates. Developing III-V optical sources useful for VLSI optical interconnects is one goal which has been pursued by several groups. Along these lines we have focused upon the laser diode due to its capacity for high speed modulation and efficient electrical to optical power conversion.

In this work molecular beam epitaxy of (Al,Ga)As heterostructures directly on silicon substrates has been investigated for use in fabricating semiconductor lasers for monolithic optoelectronic integration. A base laser process was developed and evaluated using homoepitaxy of (Al,Ga)As on GaAs substrates, incorporating a graded-index separate confinement heterostructure (GRINSCH) quantum well active region. Etched ridge waveguide lasers were fabricated from these layers, achieving continuous wave threshold currents of 19 mA and differential quantum efficiency of 66%. This same laser process was adopted to GaAs-on-Si growth initiation layers to produce monolithic (Al,Ga)As laser on silicon substrates. High dislocation density and residual thermal tension in the laser epitaxial layer degraded threshold currents and slightly degraded external quantum efficiency, with threshold currents as low as 40 mA and differential efficiencies as high as 60 percent. In addition, the same problems precluded continuous wave operation for these devices.

To address residual thermal tension, a technique for monolithic epitaxial separation and reattachment was developed to produce strain-free GaAs-on-Si. Rapid thermal annealing of these layers was also investigated for alleviating defect density imposed by the heteroepitaxial growth process. Photoluminescence studies demonstrated that epitaxial separation, along with rapid thermal annealing 600°C, produced strain-free material. In addition, these layers could be annealed at temperatures up to 800°C without reintroducing thermal stress and demonstrated further material improvement as indicated by photoluminescence intensity. Epitaxial separation and annealing was also applied to (Al,Ga)As laser epitaxy layers to produce the first strain-free lasers fabricated monolithically on Si substrates, an important achievement for advancing heteroepitaxy as a viable optoelectronic integration strategy.

1.5 Integration of Vertical Cavity Surface Emitting Lasers on GaAs Integrated Circuits

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DARPA/NCIPT
IBM Corporation Fellowship
National Science Foundation Fellowship
Vitesse Semiconductor

Project Staff

Krishna V. Shenoy, Geoffrey F. Burns, Professor Clifton G. Fonstad, Jr. in collaboration with J. Mikkelson[5]

There exists a long history of interest in the integration of high performance optoelectronic devices, particularly lasers and detectors, on high density electronic integrated circuits, and considerable attention has been focused on GaAs-on-Si processes because silicon has traditionally been the only source of VLSI circuitry. However, with the recent availability of GaAs-based VLSI, realized using refractory-metal gate processes, we feel that this picture has changed significantly. It is the purpose of this program to demonstrate that the growth of optoelectronic heterostructures on partially processed GaAs-VLSI wafers is a viable alternative to GaAs-on-Si for applications requiring the

[5] Vitesse Semiconductor, Camarillo, California.

integration of high density electronic circuitry and optoelectronic devices. Such applications include in-plane (on-chip and chip-to-chip) and plane-to-plane optical communication, computation, and signal distribution.

In this research, the integration of high-density laser diodes on production GaAs electronics (Vitesse Semiconductor) is being investigated. Thermal studies have been conducted on refractory metal gate enhancement and depletion mode MESFETs and their tolerance to extended periods of time at molecular beam epitaxy (MBE) growth temperatures has been determined. While device performance is observed to decrease for anneal temperatures greater than 550°C, performance is modestly enhanced for anneal temperatures between 400°C and 550°C. Thus, the electronic thermal constraint is that lasers must be grown on the GaAs circuitry at a temperature less than 550°C. Work on lasers compatible with this constraint is described in the next section.

Surface emitting lasers, or lasers with radiation emitted normal to the wafer plane, will be fabricated by etching a total internal reflection mirror using ion beam assisted etching (IBAE) (MIT Lincoln Laboratory) and standard III-V processing techniques. Growth of lasers, compatible with the underlying GaAs VLSI circuitry, directly on the partially processed circuitry will then be conducted. We are currently determining the optimal step in the electronic fabrication sequence for lasers to be grown as well as the optimal shape of the sidewalls etched through the electronics down to the GaAs substrate. This project will culminate by demonstrating an interconnected optoelectronic system.

1.6 Low Temperature Growth of GaAlAs Laser Diodes

Sponsors

DARPA/NCIPT
GTE Laboratories
IBM Corporation Fellowship
National Science Foundation Fellowship
Vitesse Semiconductor

Project Staff

Krishna V. Shenoy, Professor Clifton G. Fonstad, Jr. in collaboration with J. Mikkelson[5] and B. Elman[6]

Reducing the temperature at which laser diodes are grown is of interest for several reasons. The first reason is our interest in growing lasers on GaAs MESFET wafers (see preceding section). A laser diode heterostructure, compatible with the electronic thermal constraint, has been designed and grown using conventional MBE techniques. The laser incorporates a 60Å strained layer $In_{0.2}Ga_{0.8}As$ single quantum well active region, a GaAs waveguide, low aluminum fraction $Al_{0.22}Ga_{0.78}As$ cladding layers, and an AlAs etch-stop layer. The strained layer quantum well active region yields lower threshold currents than unstrained quantum wells because compressively strained InGaAs decreases the effective mass in the parallel direction, thus reducing the density of states and the number of carriers required to reach population inversion. A GaAs waveguide, GaAs on either side of the InGaAs, confines the optical mode and by varying the thickness of this material, the proximity of the AlGaAs cladding layers to the active region can be altered, thus AlGaAs dependent laser characteristics may be studied. The effect of low temperature AlGaAs epitaxial quality on laser performance is currently under investigation (GTE Laboratories) and is central to this research because conventional AlGaAs is grown at 700°C, which violates the electronic thermal constraint. Low aluminum fraction AlGaAs can be grown at temperatures as low as 600°C without significant degradation. Exotic growth techniques such as migration enhanced epitaxy (MEE), variable duty cycle As cell shuttering, and precisely controlled low As overpressure are all being pursued to achieve high quality, low temperature ($\leq 600°C$) AlGaAs. An AlAs etch-stop layer is placed 1400Å above the top GaAs waveguide to provide a selective etch barrier. This increases the reproducibility of the ridge etch depth.

Lasers grown between 600°C and 530°C have been fabricated as ridge lasers. Preliminary optical and electrical characterization of the higher temperature material has demonstrated close to state-of-the-art lasers while the lower temperature material (grown conventionally) appears promising.

[6] GTE Laboratories, Waltham, Massachusetts.

1.7 MBE-Grown InGaAlAs/InP Long-Wavelength Laser Diodes for Narrow Linewidth Applications

Sponsor

Charles S. Draper Laboratories
Contract DL-H-418483

Project Staff

Woo-Young Choi, Yakov Royter, Professor Clifton G. Fonstad, Jr.

Semiconductor lasers emitting at the wavelength of 1.3 to 1.55 mm are a key element of low-loss optical fiber communication systems. The material system most often used for such laser diodes is the quaternary alloy InGaAsP lattice-matched to InP substrates. Liquid phase epitaxy (LPE) and metal-organic chemical vapor deposition (MOCVD) are the usual growth techniques for this material system.

The InGaAlAs material system, grown by conventional solid-source molecular beam epitaxy (MBE), is another promising candidate for laser diodes emitting in the 1.3 to 1.55 mm range. Significantly, the InGaAs/InAlAs heterojunction has a larger conduction band discontinuity than the InGaAs/InP heterojunction (approximately, 0.5 eV versus 0.22 eV). This enhances quantum confinement of electrons and results in the stronger optical transitions which, in turn, can result in better laser diode device performance.

To achieve this goal, we first did an extensive MBE growth study in which the optical quality of InGaAlAs materials were optimized. We then investigated, theoretically and experimentally, various device structures that were suitable for our MBE growth. From these studies, we were able to demonstrate 1.55 mm InGaAlAs graded-index separate confinement (GRIN-SCH) multiple quantum well (MQW) laser diodes whose device performances are comparable to those of the best-reported InGaAsP laser diodes.

Currently, we are working on strained quantum well devices in the hope of achieving further device improvements as well as obtaining a deeper understanding of strained quantum well laser diodes.

1.8 New Three-Terminal Independently Addressable Asymmetric Laser Diodes (IAADQW-LD) with Dynamic Control of Gain and Refractive Index

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DARPA/NCIPT

Project Staff

Paul S. Martin, Professor Clifton G. Fonstad, Jr. in collaboration with Professor Hermann A. Haus

We are investigating a new class of devices in which the active region consists of two quantum wells with different widths and therefore different optical gain profiles. By designing structures in which the current injection into these two quantum wells can be independently controlled, we gain a new, as yet unutilized, degree of freedom in controlling light output from the device. The immediate goal of this program is to use this new degree of freedom to design a ridge-type laser diode with reduced alpha-parameter; the ratio of refractive index change to gain change associated with an injected current density change. We expect narrow-linewidth lasers incorporating this scheme to find application in many optical communications systems where linewidth of the signal laser limits the transmission bit rate-distance product. New systems based on Er-doped fiber are particularly sensitive to signal laser linewidth because optical signals are amplified but not regenerated or retimed. The recent explosion of interest in Er-doped fiber communications systems makes this application especially timely.

Wavelength division multiplexing (WDM) is another area in which we believe this new class of devices can have an important impact. As modulation frequencies for individual laser diodes move into the multi-gigabit per second range, dramatic increases in data rates become increasingly more difficult to achieve through increases in modulation frequency. An alternative approach is to use many slower and, thus, simpler, less expensive and more reliable laser diodes all transmitting down the same fiber but at slightly different wavelengths. Two devices that are essential for realizing practical WDM systems are (1) dynamically tunable laser diodes for adjusting the wavelength of each signal channel, and (2) narrow linewidth channel dropping filters for routing of individual channels to their respective detection circuits. Both of these devices can be much improved over existing designs by exploiting the advantages of the IAADQW-LD.

Other applications for these devices include pure FM laser diodes with reduced AM noise, two wavelength integrated but independently controlled laser diodes and other non-laser devices like tunable narrow bandwidth filters and light modulators.

1.9 Design and Fabrication of Distributed Feedback (DFB) InGaAlAs Laser Diodes Grown by Molecular Beam Epitaxy

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DARPA/NCIPT
Joint Services Electronics Program
Contract DAAL03-89-C-0001
Contract DAAL03-92-C-0001

Project Staff

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

It is essential that laser diodes for optical fiber communication applications operate with a single oscillation frequency. Typically, schemes of distributed feedback (DFB) or distributed Bragg reflector (DBR) are used in which gratings above or below the active layer (DFB) or outside the active layer (DBR) perform the act of frequency selection. To make such a device structure, either epitaxial growth is initiated on a corrugated substrate, or regrowth is performed on the epitaxial material onto which gratings have been formed.

In this project, we are in the pursuit of a DFB device structure in which gratings are formed entirely after the complete epitaxial growth. Our motivation for this approach stems from the fact that we are working on laser diodes grown by the conventional solid-source Molecular Beam Epitaxy technology and, due to its growth kinetics, successful MBE growth on the corrugated surface is very difficult to achieve.

We have proposed a ridge stripe structure in which gratings are made on the side walls of the ridge as well as on the bottom channels next to the ridge. According to our initial calculation, there is enough coupling between the optical wave and gratings to result in single mode selection.

To realize such a device structure, we are collaborating with Professor Henry I. Smith's group at MIT and utilizing their x-ray lithography technology. Currently, we are in the process of combining x-ray lithography technology with the ridge-stripe laser diode fabrication technology.

1.10 Laser Diode Modeling and Design for Narrow Linewidth Operation

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Charles S. Draper Laboratories

Project Staff

Yakov Royter, Professor Clifton G. Fonstad, Jr. in collaboration with J.H. Hopps[7]

Many of the current laser applications require narrow linewidth output characteristics. Unfortunately, semiconductor lasers, possessing such advantages as small size, direct modulation capability, and integrability with other optical and electronic devices, have broad linewidths in comparison to most other kinds of lasers. The relatively broad linewidths are due to the low Q of the cavity and to the intrinsic effects specific to the semiconductor gain medium. Since most of the linewidth reduction methods have involved the increase of the cavity Q, our goal is to investigate and to help in the reduction of the intrinsic linewidth broadening effects. Reduction of these effects, in conjunction with the increase of the cavity Q, would produce semiconductor lasers with narrowest possible linewidths.

The first step in our research is to investigate theoretically the intrinsic linewidth broadening effects. In particular, we concentrate on the linewidth broadening parameter, α, the largest intrinsic linewidth broadening factor, which describes the coupling of gain and refractive index fluctuations in the gain medium via carrier density fluctuations. Also, due to their apparent promise over conventional diode lasers, we consider only quantum-well semiconductor lasers. We begin the investigation of the α parameter by first calculating the carrier energy bands of the active region semiconductor material, using both parabolic band and $k \bullet p$ approximations. From the energy bands, we can obtain gain and refractive index profiles and the linewidth broadening parameter. Thus, the energy band calculations are the first major task in our investigation.

To test our models, we plan to compare the calculated laser characteristics, such as threshold current, gain, refractive index and linewidth, with

[7] Charles S. Draper Laboratories, Cambridge, Massachusetts.

experimental results obtained from measurements done in our laboratory, as well as the ones quoted in the literature. Moreover, we will work on establishing systematic ways of obtaining parameters for our models. Finally, we hope to be able to use our modeling to help in the fabrication of narrow linewidth semiconductor lasers.

As an extension of our modeling efforts, we will also investigate strain layer quantum-well lasers. Furthermore, we intend to improve our models by including calculations of energy dependent carrier lifetimes, different loss mechanisms, and other sources of linewidth broadening.

1.11 Growth and Processing of Improved InGaAlAs/InP Heterojunction Bipolar Transistors

Sponsor

Electronics and Telecommunications Research Institute (ETRI) Fellowship

Project Staff

Jae-Jin Lee, Woo-Young Choi, James C. Vlcek, Professor Clifton G. Fonstad, Jr.

HBTs fabricated in the $In_xGa_yAl_{1-x-y}As$ alloy system, lattice matched to semi-insulating InP substrates, are emerging as promising candidates for microwave applications. By utilizing the advantageous material properties of this alloy system, in particular the properties of ternary alloy InGaAs, HBT device performance superior to that of GaAlAs HBTs may be realized. The $In_xGa_yAl_{1-x-y}As$ system is also better suited to the solid-source molecular beam epitaxial (MBE) growth techniques typically employed in HBT fabrication than the $In_{1-x}Ga_xAs_yP_{1-y}$ system, which also lattice matched to InP.

While, in its simplest form, an HBT need only have an emitter of a wider bandgap material than the base, such single heterojunction devices suffer from a number of drawbacks. Most notably, the base-collector junction of such a device will have a lower turn-on voltage than the base-emitter junction, resulting in an "offset" voltage in the output characteristics. A single heterojunction HBT which uses the ternary InGaAs for both base and collector will also suffer from a high output conductance and low collector-emitter breakdown voltage due to the narrow gap collector material. Finally, the use of abrupt heterojunctions, at either of the two pn junctions in the device, introduces "spikes" in the band edges at the junctions which could lead to carrier trapping and degraded device performance. For these reasons, an HBT fabricated in the $In_xGa_yAl_{1-x-y}As$ alloy system is best achieved with graded base-emitter and base-collector junctions.

Using advanced computer-controlled MBE growth techniques, we have successfully fabricated and characterized an $In_xGa_yAl_{1-x-y}As/InP$ emitter-up, doubly-graded heterojunction bipolar transistor. By using parabolic compositional gradings in the pn junctions devices have been realized with dc characteristics much improved over abrupt single-heterojunction devices fabricated in this same material system. We are continuing this work with the objective of now optimizing microwave, as well as dc performance.

1.12 Microwave Characterization, Analysis, and Modeling of Emitter-Down Heterojunction Bipolar Transistors

Sponsors

National Science Foundation/Northeastern University
TRW Systems

Project Staff

Sheila Prasad, Professor Clifton G. Fonstad, Jr. in collaboration with B. Meskoob[8] and M. Kim[9]

Emitter-down InGaAs/InAlAs/InP heterojunction bipolar transistors have been characterized at microwave frequencies. Small-signal equivalent circuit models were obtained using the commercial Touchstone software. The simulated annealing (SA) algorithm, which does not depend on good initial conditions, has been applied to the modeling problem. The results obtained with SA and Touchstone were consistent. However, continuous human intervention was required to obtain the results with Touchstone, whereas SA yielded the results automatically. SA was therefore proved to

[8] Northeastern University, Boston, Massachusetts.

[9] TRW Systems, Redondo Beach, California.

be the superior method for optimization because of its speed and convenience.

Small-signal S parameter measurements were made by on-wafer probing of the devices using the Hewlett-Packard 8510B automatic network analyzer and the Cascade Microtech microwave probe station for 39 different bias points. The bias dependence of elements of the small-signal equivalent circuit was determined and it was found that five of the elements of the circuit were highly bias dependent. These results are being used for the large-signal modeling of the HBT which is in progress. Measurements are also in progress to determine the third-order intermodulation product (IP3). The optimized model for high IP3 which is related to device linearity is to be determined.

1.13 Analysis of Three-Terminal n-n-n Quantum Well Base, Tunnel-Barrier Transistors

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Project Staff

Thomas P.E. Broekaert, Professor Clifton G. Fonstad, Jr.

Three-terminal n-n-n quantum-well base, tunnel barrier transistors, consisting of a resonant tunneling structure with an ohmic contact to the quantum well have been fabricated. Although an ohmic contact to the quantum well was successfully achieved by heavily doping the quantum well, it was found that all such structures exhibit strong leakage currents from base to emitter.

The conductance of surface quantum wells in such transistor structures has been measured successfully, and the dependence of sheet carrier concentration, sheet conductance, and carrier mobility as a function of temperature has been measured. No transistor action was seen for the tested temperature range of 10 to 300 K. The lack of transistor action is tentatively attributed to fast hot carrier relaxation, resulting in large base currents and small collector currents. Possible mechanisms for the hot carrier relaxation are impurity scattering, polar optical phonon scattering, and electron-electron scattering.

Several non-idealities that hamper the active behavior of the resonant tunneling transistor have been analyzed. First, electron-polar optical phonon and electron-electron scattering from second to first subband in the quantum well are believed to be the dominant mechanisms at low temperatures that limit the ultimate gain of the resonant tunneling transistor. Second, due to the fact that this device only has a single dipole layer, it follows that the emitter accumulation region is not completely shielded from the collector potential, which results in a low output impedance and a low voltage gain.

A novel device structure is introduced, in which the hot carrier relaxation, which is prevalent in InGaAlAs resonant tunneling structures, is reduced. This reduction in hot carrier relaxation rate is obtained by having a quantum well in which the quantum-well level for base potential modulation and the quantum-well level for emitter to collector tunneling are located at different points in the Brillouin zone, e.g., direct vs. indirect valley quantum well. A possible material system for this novel device structure would be GaAs/AlAs/Ge/AlAs/GaAs for emitter/barrier/base/barrier/collector respectively. This material system would also improve the performance of the bipolar quantum-well resonant tunneling transistor and the hot electron transistor.

1.14 Applications of AlAs Etch-Stop Layers in InGaAlAs/InP Heterostructure Electronics and Optoelectronics

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Project Staff

Thomas P.E. Broekaert, Woo-Young Choi, Professor Clifton G. Fonstad, Jr.

We have used wet chemical etching solutions that allow the selective etching of InP lattice-matched InGaAlAs quaternary compounds using thin pseudomorphic AlAs layers as etch stops to explore new device concepts.

We developed the etchants used here last year, and they typically consist of succinic acid (or other dicarboxylic acids), ammonia, and hydrogen peroxide. The etchant is well buffered and can be used over a wide pH range including from 4.2 to 7.0 by varying the amount of ammonia added. In addition, the etchant is compatible with Cr/Au contact metallization and standard positive photoresists. Typically, the InGaAs etch rate is about 100 nm/min. At a pH of 4.2, the etch rate of InGaAs is found to be over 1000 times the etch rate of AlAs, while the etch rate of InAlAs is over 500 times that of the AlAs. A typical AlAs stop layer is about 10 monolayers (m.l.) thick (2.73 nm). Buffered HF can be used to remove the AlAs stop layer without etching InGaAlAs to any significant degree.

These selective etchants have enabled us, for the first time, to measure the conductance and mobility of a directly contacted quantum well in a resonant tunneling structure, and they open up the possibility of fabricating a whole new set of novel quantum devices.

Also, we utilized the selective etchants in fabricating ridge-stripe InGaAlAs/InP GRIN-SCH MQW laser diodes. By inserting a thin pseudomorphic AlAs layer at a desired location during the epitaxial growth and then selectively etching away InGaAlAs materials up to the etch stop layer, we were able to fabricate laser devices with ridges whose heights are precisely and reliably controlled.

1.15 Electrical Transport Studies in Directly Contacted InGaAs Quantum Wells

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National Science Foundation Fellowship
U.S. Army Research Office

Project Staff

Rajni J. Aggarwal, Thomas P.E. Broekaert, Professor Clifton G. Fonstad, Jr.

Using a recently developed selective etch, we have been able to demonstrate direct electrical contact to the quantum well of an AlAs/InAs/InGaAs resonant tunneling structure. This contact serves as the base contact in our three-terminal, unipolar resonant tunneling transistor (RTT). Our devices incorporate high indium content materials in the quantum well. In addition to their favorable transport properties, these compounds have low Schottky barrier heights, enhancing our ability to make ohmic contact to them. We are limited in the indium fraction that we can use by the lattice mismatch of such compounds with the InP based lattice constant of the device.

We believe that the performance of our device is limited by two factors: (1) doping within the quantum well and (2) depletion of the well due to surface exposure. Neither of these problems has been overcome by the inclusion of high indium content materials alone. We feel that it is necessary to study the nature of the contact itself in order to engineer around the present limitations. Specifically, we are interested in elucidating the effect, if any, of quantization on Schottky barrier height. In addition, we would like to experimentally determine any potential barriers that may exist in electron transport from quasi-confined (contact) regions to confined (intrinsic base) regions within the device.

We are measuring the Schottky barrier height of a variety of quantum well contacts and comparing them to those obtained for comparable bulk materials. Among the experimental variables are quantum well and barrier thickness and well indium content. In addition, we are performing photoluminescence studies in hopes of experimentally observing the shift in energy of the n=1 quantum state within the well as one barrier is removed.

1.16 Investigation of Infrared Intersubband Emission from InGaAs/AlAs/InP Quantum Well Heterostructures

Sponsor

National Science Foundation Fellowship

Project Staff

Jurgen H. Smet, Professor Clifton G. Fonstad, Jr. in collaboration with Professor Qing Hu

Subbands in quasi-two-dimensional semiconductor structures exhibit a large electric dipole matrix element, making them attractive as the active medium in an infrared source. Triple quantum-well structures are proposed in which electrons are selectively injected into the second subband of a wide center quantum well. After relaxation to the first subband, electrons are selectively removed. Two important issues need to be addressed: the achievement of population inversion and the confinement of the emitted radiation.

To avoid fast relaxation through electron/LO-phonon scattering, it is desirable to design a structure for a lasing frequency smaller than the LO-phonon frequency. This requires a subband separation of less than 30 meV. This requirement fixes the center well width and the width of the side wells. The balancing of gain and losses determines the required population inversion. The threshold current density is then, in essence, this population inversion divided by the intersubband relaxation time, provided that population of the second subband and depopulation of the first subband do not limit the current density. Calculations indicate that for reported intersubband relaxation times in the regime below the LO-phonon threshold and for the necessary population inversion to balance the losses, the structure is not feasible unless coherent tunneling, giving rise to larger transmission coefficients than sequential tunneling, is invoked and thin barriers are used. We are in the process of measuring the I-V characteristics at low temperature of triple quantum-well structures with varying barrier thickness to verify that the current density at low applied bias voltages is not a strong function of the barrier thickness. That would support the hypothesis that injection and removal of the electrons is not the current limiting factor and thus that population inversion might be achieved.

The traditional confinement of the generated radiation in a dielectric waveguide is not practical because of the long wavelength. Highly doped regions, with a plasma frequency higher than the light frequency will be used to confine the light.

Structures in which the energy separation between the fourth and first subband corresponds to a wavelength of 1.55 μm were designed taking the non-parabolicity of the bandstructure into account. Similarly resonant tunneling transistor structures were modified to make them suitable for pump and probe time resolved measurements. Both structures consist of pseudomorphic AlAs barriers and strained InGaAs wells on InP.

Wide quantum-well structures with energy separations smaller than the energy of an optical phonon are of interest to test the feasibility of far infrared emitting devices (14.0). Fast relaxation is undesirable since it prevents the achievement of population inversion. By going to subband separations smaller than the LO-phonon threshold energy one avoids fast relaxation by LO-phonon emission. However, so far, the intersubband relaxation times reported by different authors in this regime show considerable discrepancies. Therefore, pump probe measurements on these structures will be carried out and compared with existing data in the literature.

1.17 Investigation of Intersubband Relaxation Times in InGaAlAs Quantum Well Heterostructures

Sponsor

National Science Foundation

Project Staff

Jurgen H. Smet, Professor Clifton G. Fonstad, Jr.

The carrier dynamics in systems of reduced dimensionality is of great interest because of its implications on both electronic and optical quantum-well heterostructure devices. Intersubband transitions in multiple quantum-well structures with energy level separations larger than the LO-phonon energy have attracted considerable attention because of their large optical nonlinearities and fast relaxation times.

At the same time, three terminal unipolar quantum well base, tunnel barrier transistors (11.0), in which the subband separation is larger than the LO-phonon threshold, have been hampered by excessive base current due to fast electron relaxation from the second to the first subband in the quantum well.

1.18 Infrared Characterization of InGaAs/AlAs/InP Quantum Well Heterostructures

Sponsor

National Science Foundation

Project Staff

Lung-Han Peng, Professor Clifton G. Fonstad, Jr. in collaboration with R. Victor Jones and Victor Ehrenrich[10]

We have been successfully measuring the long wavelength infrared quantum well (LWIR) intersubband absorption in 2 to 5 μm wavelength region based on InAs/InGaAs/AlAs resonnant tunneling diode structures for the IR detectors application. Over 40 percent intersubband absorption can be achieved from a doped single quantum well through our dedicated designed waveguiding system, where IR is focused upon the sample edge and makes 20 times total internal reflection while it propagates along the samples and dramatically increases the aborption strength. We also demonstrate both theoretically and experimentally that TE as well as TM modes can excite the intersubband absorption. We also pointed out that the interface Fe interband absorption at 0.3 eV could seriously

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obscure the IR absorption spectra and have shown how they can be avoided. These results, applied in concert with recently developed selective etches that allow us to make electrical contact to the quantum well directly, open the way to realizing high performance LWIR detectors.

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

Sponsors

AT&T Bell Laboratories Fellowship
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National Science Foundation
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Project Staff

Isako Hoshino, Professor Clifton G. Fonstad, Jr. in collaboration with Professor Sylvia T. Ceyer and Professor Herbert H. Sawin

The development of damage-free ultra-high 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 involve relatively high energy (100eV and above) ion beams which cause substantial sub-surface damage, much of which is impossible to remove.

As a solution to the problem of process-induced damage, we have begun a program investigating the use of UHV kinetic molecular beam techniques (widely used to study atomic surface interactions) to etch and clean III-V substrates and heterostructures with a minimum of surface damage and maximum flexibility. Depending on the etchant gas mixture established, it is anticipated that low energy (0.5 to 2 eV) kinetic beams can be used to (1) anisotropically 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.

This program benefits from collaboration with Professor Sylvia Ceyer, an expert on using supersonic beams to probe surface reactions and to etch silicon, and with Professor Herb Sawin, an expert on the design of molecular beam and RF plasma sources and reactors as well as plasma reaction dynamics. Funding has been obtained to assemble a UHV chamber for kinetic beam processing which will be connected through a transfer mechanism of special design to the present Riber 2300 solid source MBE system. An etch chamber designed to use a methane-hydrogen gas mixture in a supersonic beam source is currently being assembled.

1.20 Publications

Journal Articles

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