Chapter 9. Heterostructures for High Performance Devices

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9.1 Introduction

The broad objective of our research effort is to develop III-V quantum heterostructures for high performance electronic, optoelectronic, and photonic devices for 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) a new family of quantum-well-base, tunnel-barrier n-n-n transistors and near- and far-infrared optoelectronic devices; and (3) 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, Eric P. Ippen, and James G. Fujimoto 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.

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

Sponsors

Charles S. Draper Laboratory
  Contract DL-H-418483
DARPA/NCIPT
  Subcontract 542383
Joint Services Electronics Program
  Contract DAAL03-89-C-0001

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 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. Thus, optimal device designs can place tight constraints on the molecular beam epitaxial growth procedures – in particular, the ratios of the constituent and dopant fluxes during the growth — which will implement these complicated epitaxial layer structures.

The need to lattice-match, as to an InP substrate, further constrains the ratio of constituent fluxes. If the alloy composition is not sufficiently close to the lattice-matching composition, strain effects can significantly alter the electrical and optical properties of the material, and, in the extreme case, dislocations can be seeded. Thus, the constraints imposed by the need to lattice-match may be more stringent than those imposed by the composition gradients dictated by the device design. In this work, we have grown the quaternary $In_xGa_yAl_{1-y}As_{1-s}$, lattice-matched to InP substrates. This quaternary, which may be viewed as a binary alloy of the two ternaries IngGaAs and InAlAs, spans the bandgap range of 0.75 – 1.5 eV and is better suited to solid-source MBE techniques than the $In_{1-x}Ga_xAs_yP_{1-y}$ alloy system, which spans a similar bandgap range.

We have implemented a computer-automated MBE control system (1) to provide precise control of the constituent and dopant fluxes necessary to achieve graded-composition alloys and (2) to maintain uniform 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 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. This modification is necessary to eliminate the over- and undershoot effects at the endpoints of the graded layer which would result if the effects of cell response time are neglected. With such modifications, we have achieved linearly graded flux profiles with deviations from the desired profile which can be held within one percent. The gradient of material composition in these layers corresponded to a conduction band gradient of 33 kV/cm.

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 open and performing an exponential ramp sequence upon change of shutter status. Using this technique, we have reduced cell shutter transients from 15 - 30% to one percent or less.

9.3 InGaAlAs Strained-Layer Heterostructures on 111 GaAs and InP for Optoelectronic Device Applications

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  Subcontract 542383
Joint Services Electronics Program
  Contract DAAL03-89-C-0001

Project Staff

Richard A. Singer, Professor Clifton G. Fonstad, Jr.

We have been interested in (111)-oriented strained-layer heterostructures because of the large piezoelectrically generated built-in electric fields that are present in these materials, as well as because of the possibility of enhanced optical effects in (111)-oriented quantum structures. We have been very successful in growing layers on (111)B GaAs, routinely grow on these substrates, but we have had considerably more difficulty on InP substrates.

Mirror surfaces for both bulk InGaAs and InAlAs layers, grown by molecular beam epitaxy (MBE) on (111)B InP substrates, have recently been achieved. These materials have been characterized by photoluminescence (PL), Hall measurement, and double crystal diffraction, and, in the latter case, exhibit linewidths which compare favorably to both the InP substrates and to concurrently grown (100) epilayers. Nevertheless, the Hall mobilities of the (111) InGaAs samples are consistently an order of magnitude lower than their (100) counterparts, while the PL intensities are extremely weak. The InAlAs is essentially semiinsulating and shows no PL. These results, of course, indicate that the electrical and optical quality of these materials is still relatively low and, as a result, epilayers grown on (111)InP are not acceptable for use in p-i-n devices yet.

The difficulties associated with MBE grown on (111)InP arise because of the highly reactive (111) surface and the volatilty of the InP substrate and the indium alloys of the epitaxial layers. Unfortunately, the growth conditions, which address the issues described above, inhibit the surface mobility of the group III constituents. This results in material of poor surface morphology. To circumvent this problem, a quasi-migration enhanced epitaxy procedure was developed in which growth takes place at low substrate temperature, low As overpressure, and slow growth rate. We have, in fact, observed an increase in Hall Mobility when the growth rate was slowed. Therefore, this is a promising direction for continuing in our efforts to optimize the growth parameters for (111) epilayers.

9.4 Molecular Beam Epitaxy of GaAlAs Laser Diode Heterostructures on Silicon Substrates

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DARPA/NCIPT
  Subcontract 542383
IBM Corporation Fellowship

Project Staff

Geoffrey F. Burns, Dr. Herve Blanck, 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. Using molecular beam epitaxy (MBE), we have developed a process for routine fabrication of (Ga,Al)As laser heterostructure lasers directly on Si substrates.

Unfortunately, active optical devices such as the laser exhibit degraded luminescent efficiency and reliability when fabricated in heteroepitaxial GaAs-on-Si; threshold currents and lifetimes presently obtained are insufficient for Si integration. These shortcomings are imposed primarily by limitations in the quality of heteroepitaxial GaAs-on-Si currently produced, including dislocation densities above 10^6 per square cm and residual strains above 10^9 dynes per square cm, resulting from the 4.2% lattice mismatch and $\sim 40\%$ thermal expansion mismatch between GaAs and Si.

The thermal strain problem can be attacked by reducing the area of the III-V epitaxial layer in contact with the Si substrate during growth, as well as by significantly reducing the maximum growth temperature of the laser device. Following the first approach, we are evaluating lasers grown on substrates structured with oxide windows and ridges. Initial working devices have been produced on structured substrates and reduced threshold currents have been observed. Further evaluation of these devices will determine the degree of strain relief and reliability improvement. Additional process measures currently in development include an MBE growth process which lowers the laser device growth temperature in addition to post fabrication thermal annealing to reduce the residual dislocation density.

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

Sponsors

DARPA/NCIPT
  Subcontract 542383
IBM Corporation Fellowship
National Science Foundation Fellowship
Vitesse Semiconductor

Project Staff

Krishna Shenoy, Geoffrey F. Burns, Professor Clifton G. Fonstad, Jr., in collaboration with James Mikkelson

Vertical cavity surface emitting lasers (VCSELs) offer many advantages over in-plane lasers, both as discrete and integrated devices. Monolithic fabrication, on-wafer testing, inherent single longitudinal mode operation, low threshold currents, and low divergence angles (suitable for optical fiber coupling) are among VCSEL attributes. VCSELs can also form high-density two-dimensional arrays for high-speed parallel optical processing, and large-scale integrated circuit optical interconnections as a result of their vertical emission and small in-plane dimensions.

It is the purpose of this program to demonstrate that VCSELs can be integrated with state-of-the-art refractory metal gate GaAs VLSI integrated circuits by growing GaAlAs heterostructures selectively in windows, i.e., openings cut through the dielectric covering the electronic circuitry down to the underlying GaAs substrate. Solid source molecular beam epitaxy (MBE) is being used to grow the structures, and standard etchants and metalization procedures are being followed. The laser emission will occur normal to the wafer plane, either through the substrate or from the processed surface.

The basic low-threshold VCSEL design incorporates a single quantum well (SQW) active region between two distributed bragg reflector (DBR) mirrors. High mirror reflectivities (>95%), a thin active region (<10 nm), and adequate current confinement are crucial for low-threshold lasing. An InGaAs active region with alternating GaAs/AlAs DBRs is yielding the lowest threshold currents.

Three VCSEL integration issues are currently being investigated: (1) selective growth of GaAs/InGaAs/AlGaAs VCSEL heterostructures in insulator windows on GaAs substrates, (2) low temperature AlGaAs growth, and (3) VCSEL design optimization. As a first step, crystalline GaAs/AlGaAs layers have been successfully grown in a variety of window geometries on GaAs wafers provided by Vitesse Semiconductor. These initial growths look excellent. However, high optical quality AlGaAs is conventionally grown above 700°C, and even with refractory metal gates, GaAs electronic circuitry can not tolerate these growth temperatures for the times involved in MBE growth. Hence, we are growing lower temperature AlGaAs and characterizing it both electrically and optically to understand the lower acceptable bound on the growth temperature. At the same time, tests of Vitesse circuitry are planned to quantify its thermal tolerance. Given this information, VCSEL designs will be optimized to reach a balance between growth temperature-time demands and the device limitations, while, at the same time, meeting the necessary threshold, power output, and emission specifications.

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

Sponsor

Charles S. Draper Laboratory
Contract DL-H-418483

Project Staff

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

Semiconductor lasers emitting at a wavelength of 1.3 to 1.5 μm 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 1.5 μm range. Significantly, the InGaAs/InAlAs heterojunction has a larger conduction band discontinuity than the InGaAs/InP heterojunction. This enhances the quantum confinement of elections, affording the device designer greater latitude in choosing layer structures for optimizing electrical and optical confinement profiles. This enhanced design latitude, in turn, can be used to achieve lower threshold currents, lower temperature variation (T_0), and narrower spectral line-width.

Using MBE, we have grown InGaAs/InAlAs double heterostructure (DH) 1.3 μm and 1.55 μm InGaAlAs graded-index separate confinement (GRIN-SCH) multiple quantum well (MQW) laser diodes. From these laser materials, we have fabricated broad-area and ridge-stripe laser diode devices. We have also characterized threshold currents, emission spectra, and far-field patterns. Our initial data indicate that our devices are comparable to other laser diodes of the same material system reported in the literature. Currently, we are focusing our efforts on the optimization of the GRIN-SCH MQW laser structure in terms of the optical confinement structure, barrier height and width, and the number of quantum wells. With these optimizations, we believe that our device performance will be greatly enhanced.

In addition, we are investigating the possibility of additional performance enhancement with strained quantum wells. Strained quantum well devices have demonstrated exciting results in GaAs-based laser diodes, and we believe we can achieve similar improvements in InGaAlAs long-wavelength laser diodes with the excellent capacity of MBE to grow precisely-controlled strained layers.

9.7 Applications for New Three Terminal Laser Diodes with Dynamic Control of Gain and Refractive Index

Sponsor

DARPA/NCIPT
Subcontract 542383

Project Staff

Paul 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 sets of quantum wells with different optical gain profiles. By designing structures in which the current injection into these two sets of quantum wells can be independently controlled, we gain a new, previously unexploited, 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, which is the ratio of refractive index change to gain change associated with an injected current density change. Since the linewidth of a semiconductor laser diode is proportional to one plus alpha squared, a reduction in alpha from a typical value of three for QW laser diodes to near zero would give a reduction in laser linewidth on the order of ten. 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 erbium-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 erbium-doped fiber communications systems thus makes this application especially timely.

Other possible applications for these devices include pure FM laser diodes with reduced AM noise, pure AM laser diodes with reduced chirping, laser diodes easily tunable over a wide band, and other non-laser devices like tunable narrow bandwith filters and light modulators.

The list of possible device applications shows that developing the basic idea of wells with different optical gain profiles and accessing them independently within a single device is quite general. Once the above narrow linewidth laser diode and the associated theory have been demonstrated, we expect this list to continue to grow.

9.8 Use of Graded Profiles to Improve InGaAlAs/InP Heterojunction Bipolar Transistor Performance

Sponsor

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

Project Staff

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

Heterojunction Bipolar Transistors (HBTs) fabricated in the $In_xGa_yAl_{1-y}As_{1-x}$ alloy system, lattice matched to semi-insulating InP substrates, are emerging as promising candidates for microwave applications. By utilizing the advantages of the material properties of this alloy system, in particular the properties of the ternary alloy InGaAs, HBT device performance superior to that of GaAlAs HBTs may be realized. The $In_xGa_yAl_{1-y}As_{1-x}$ 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 matches to InP.

While, in its simplest form, an HBT needs to have only an emitter of a wider bandgap material than its base, such single heterojunction devices suffer from a number of drawbacks. Most important of these drawbacks is that 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 $In_xGa_yAl_{1-y}As_{1-x}$ 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 $In_xGa_yAl_{1-y}As_{1-x}/InP$ emitter-up, doubly-graded heterojunction bipolar transistor. By using parabolic compositional gradings in the pn junctions, made possible by precise computer control of the constituent fluxes during the epitaxial growth, successful devices with characteristics much improved over abrupt single-heterojunction devices fabricated in this same material system. In particular, the "offset voltage" from which many single heterojunction devices suffer has been reduced from ≥ 500, mV to ≤ 20, mV; the Early voltage has been increased from < 5, V to 25, V; the collector breakdown voltage has been increased from $BV_{CEO} < 5$, V to $BV_{CEO} > 10$, V.

9.9 Applications of Delta-Doping to Heterojunction Bipolar Transistors

Sponsors

AT&T Bell Laboratories
Hertz Foundation Fellowship

Project Staff

Tanni Y. Kuo, Professor Clifton G. Fonstad, Jr., in collaboration with Jack Cunningham

In our research, we have grown heterostructure bipolar transistors (HBTs) by gas source molecular beam epitaxy in which the base is delta-doped with Be to concentrations ranging from $5 \times 10^{13}/cm^2$ to $6 \times 10^{14}/cm^2$. Transmission electron microscopy studies revealed that the Be is spatially confined to within 1.5 nm. To fabricate the HBT without inducing Be redistribution and avoid critical emitter mesa etching, we have developed a new low-temperature base-contacting procedure ($T_{max} = 420°C$) which requires no base emitter etching. We use a non-alloyed emitter contact facilitated by a delta-doped n-layer placed on the surface of the sample, eliminating the need for a doped cap layer. The base is contacted by depositing Au-Zn or Au-Be on the surface and alloying at 420° C for 10 seconds. This results in ohmic contact with the base, rectifying contact with the emitter. A 50 μm diameter delta-HBT shows a current gain of 20. After reducing the size of the emitter 3 x 8 μm, the current gain of the delta-HBT increases to 30. This is due to the fact that we have eliminated the critical base-emitter etch which reduces surface recombination. In order to completely planarize the HBTs, we grew and fabricated HBTs in holes which were pre-etched into the substrates. High quality material has been achieved in the holes.

We have also demonstrated the growth of the complete structure of high quality AlGaAs/GaAs heterostructure bipolar transistors (HBTs) by chemical beam epitaxy (CBE). This includes a non-alloyed delta-doped ohmic emitter contact and *in situ* Al emitter metalization which are accomplished by CBE using a new precursor, trimethylamine alane, as the Al source and trimethyl-Ga as the Ga source. Devices with both graded AlGaAs and uniform GaAs bases doped with carbon to the high $10^{19}/cm^3$ using trimethyl-Ga have been fabricated. A current gain of 10 at a current density of 2.5 kA/cm^2 is obtained for the uniform base HBTs. The DC performance of the grade base HBTs is comparable. Both types of devices display excellent output characteristics.

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

Sponsors

National Science Foundation[8]
TRW

Project Staff

Dr. Sheila Prasad, Professor Clifton G. Fonstad, Jr., in collaboration with Bahman Meskoob, Michael Kim

Emitter-down InGaAs/InAlAs/InP heterojunction bipolar transistors have been characterized at microwave frequencies and small-signal equivalent circuit models have been obtained using the commercial Touchstone software. A comparison of the measured S-parameters and gain characteristics with the modeled values showed an error of about 5%. Since such a large percentage of error was

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[8] Support of Dr. Prasad at Northeastern University.

not considered acceptable for optimization, other methods of optimization were considered.

A modification of the Touchstone program was suggested by Professor R. Trew at North Carolina State University. The technique uses the device cut-off frequency f_T, determined by the current gain h_{21} characteristic to establish the total emitter-to-collector delay time from the experimental data. This information was used to establish an equation that is then used to constrain the circuit elements, thereby facilitating the procedure for parameter extraction. The error between measured and modeled parameters was reduced to 0.05%. The simulated annealing algorithm has been used successfully in other modelling applications. Since it does not depend on good starting values for the elements, the error should be minimized further. Optimization using the simulated annealing method is now in progress.

Large signal-modeling of the HBT is also in progress. Small-signal S parameter measurements are being made for a large number of bias points on-wafer probing of the transistors using the Hewlett-Packard 8510B automatic network analyzer and the Cascade Microtech microwave probe station. The bias-dependence of each of the elements in the equivalent circuit will be determined so that an accurate large-signal model will obtained. Measurements are also in progress to determine the optimized model for high frequency third-order intermodulation product.

9.11 AlAs Etch-Stop Layers for InGaAlAs/InP Heterostructure Devices and Circuits.

Sponsor

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

Project Staff

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

Wet chemical etching solutions have been developed that allow the selective etching of InP lattice-matched InGaAlAs quaternary compounds using thin pseudomorphic AlAs layers as etch stops. The best results have been obtained for etchants consisting of succinic acid, ammonia, and hydrogen peroxide. The etchant is well buffered and can be used over a wide pH range, 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. At a pH of 5 and higher, the InAlAs etch rate becomes very small while the InGaAs etch rate remains about the same, enabling the selective etching of InGaAs over InAlAs with a selectivity of better than 100 to 1. A typical AlAs stop layer is about 10 monolayers (m.l.) thick (2.73 nm). Stop layers as thin as 3 m.l. can also be used, however, the pH must be increased to at least 6.2 and the selectivity decreases to 25 to 1.

Buffered HF can be used to remove the AlAs stop layer, while it does not etch InGaAlAs to any significant degree.

These selective etchants have enabled us to measure the conductance and mobility of a directly contacted quantum well in a resonant tunneling structure for the first time and have opened up the possibility of fabricating a whole new set of novel quantum devices (see the following section).

9.12 Three-Terminal n-n-n Quantum-Well-Base, Tunnel-Barrier Devices

Sponsors

Belgian American Education Foundation (BAEF)
Fellowship
Joint Services Electronics Program
Contract DAAL03-89-C-0001
National Science Foundation
Grant ECS 90-08485

Project Staff

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

We have attained the ellusive goal of making direct electrical contact to a populated conduction band quantum well in a resonant tunneling heterostructure. In a significant breakthrough (see preceeding section), we have recently succeeded in selectively and controllably etching away the layers above the quantum well in an AlAs/InAs/InGaAs resonant tunneling diode. This result is a major advance that opens the way to a whole new class of ultra-high performance electronic, optoelectronic, and photonic devices. We have begun an aggressive program of research utilizing this advance to investigate quantum-well-base, tunnel-barrier (QT) n-n-n transistors, and (see Section 9.15) tunnel-barrier infrared photodiodes and optotelectronic modulators.

The basis for these devices is the AlAs/InAs/InGaAs double barrier resonant tunneling diode (RTD) structure, which we have used successfully in the past to produce two-terminal RTDs with room temperature peak-to-valley current ratios of 30 to 1, peak current densities in excess of 450kA/cm^2, and characteristics displaying three resonant peaks.

There are at least three unique features of this structure which make it ideally suited for these devices. First, the AlAs tunnel barriers are unusually high relative to the InGaAs injectors and the InAs well, which yields multiple confined well states and sharp quantum structure at room temperature. Second, the InAs well lies below the band edges of the InGaAs injectors so that when it is suitably wide and doped, the first well level will be populated, providing all-important lateral conduction in the plane of the well and the ground-state population necessary for detector and optical modulator applications. Third, the very wide range of materials in these structures has allowed us to develop a selective etch which, in turn, makes electrical contact to the very thin quantum well layer possible.

We are presently developing a fabrication process for QT transistors. Particular attention is being given to the amount and placement of the dopants in the well. Our objective is to simultaneously maximize the lateral sheet conductance while not increasing the scattering experienced by the carriers resonantly tunneling vertically through the structure significantly. Intitial results indicate that moderate levels of carriers introduced using delta doping techniques will be optimal. Overall, the basic details of the fabrication process have been established, and the first devices will be available shortly.

9.13 Self-Consistent Modeling of Biased Quantum-Well-Base, Tunnel-Barrier Structures

Sponsor

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

Project Staff

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

A numerical model has been developed that solves the Schrodinger equation self-consistently with Poisson's equation for a resonant tunneling structure. The numerical model was implemented as a computer program. The program enables us to calculate the conduction band diagram and the emitter to collector current of a biased resonant tunneling structure with a heavily charged well, as a function of base-emitter and collector-emitter voltage. The goal of this program is to facilitate choice and optimization of device parameters for resonant tunneling structures that are grown by molecular beam epitaxy and processed into resonant tunneling transistors. The most critical parameters that need to be optimized are the well thickness and composition and the doping profile in the well, since they most directly affect the position of the resonant levels, and therefore, any transistor action in the structure.

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

Sponsors

Harvard University. Division of Applied Physics
National Science Foundation
Grant ECS 90-08485

Project Staff

Lung-Han Peng, Thomas P.E. Broekaert, Professor Clifton G. Fonstad, Jr., in collaboration with R. Victor Jones and Victor Ehrenrich

As a first step to the realization of quantum-well-base, tunnel-barrier (QT) infrared detectors, we have been studying the infrared absorption spectra of InAs/AlAs/InGaAs quantum wells on InP. We have made the first measurements of intersubband absorption in populated pseudomorphic InAs/InGaAs/AlAs quantum wells on InP and demonstrated that very strong absorption can be obtained in this materials system from a single quantum well in a waveguide geometry. Furthermore, we have demonstrated both experimentally and theoretically that TE, as well as TM mode, intersubband absorption can be strong in this system. Finally, we have identified for the first time the "extrinsic" features in the absorption spectra and 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 in these structures, open the way to realizing high performance QT optoelectronic devices.

Using a fast Fourier transform infrared spectrometer with a microscope attachment, we have measured the absorption spectra of a variety of samples with the light propagating parallel to the heterostructure planes. This geometry has important advantages over the more common Brewster angle configuration including longer path length, good optical confinement, excellent polarization purity, and immunity from Fabry-Perot effects. In measurements in which light is guided in the substrate as well as the epilayers, we have measured over 8% intersubband absorption (n = 1 to n = 2) for a single populated quantum well, compared with less than 1% per well typically reported for GaAs. By extrapolation, structures designed to confine the light only to the epilayers are expected to show near total absorption. There is little polarization dependance of the transmission spectra, whereas conventional theory says that only TM polarization should be absorbed. It can be shown, however, that, in a narrow bandgap alloy system, band mixing effects and random potential fluctuation-induced tetragonal distortion (local field) effects relax the polarization selection rules.

Additional features noticed in the absorption spectra have been identified for the first time with multiphonon absorption in the InP substrate and absorption at the interface between the substrate and InGaAs buffer layers. These features can be eliminated by using InAlAs buffer layers and structures in which the light is confined to the epilayers away from the substrate.

Work has now begun on fabricating detector structures and preparations are being made to perform a variety of electrical characterization and optical response measurements on them.

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

Sponsors

AT&T Bell Laboratories Fellowship
DARPA/NCIPT
Subcontract 542383
National Science Foundation
Grant ECS 90-07745

Project Staff

Isako Hoshino, Professor Clifton G. Fonstad, Jr., in collaboration with Professor Sylvia T. Ceyer and Professor Herbert H. Sawin[9]

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 to do this involve relatively high energy ion beams (100 eV and above) which cause substantial subsurface damage, much of which is impossible to remove.

As a solution to the problem of process-induced damage, we have begun 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) anisotopically etch-pattern III-V heterostructure wafers with no damage; (2) clean surfaces allowing epitaxial growth on wafers which 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 builds on the work of Professor Sylvia T. Ceyer, an expert on using supersonic beams to probe surface reactions and to etch silicon, and that of Professor Herbert H. 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. Initial designs for the etcher using a methane-hydrogen gas mixture and a supersonic beam source are currently being investigated.

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[9] MIT Department of Chemical Engineering.

9.16 Publications

Published Journal Articles

Bagwell, P.F., T.P.E. Broekaert, T.P. Orlando, and C.G. Fonstad. "Resonant Tunneling Diodes and Transistors with a One, Two, and Three Dimensional Electron Emitter." *J. Appl. Phys.* 68: 4634-4646 (1990).

Broekaert, T.P.E., and C.G. Fonstad. "InGaAs/AlAs Resonant Tunneling Diodes with Peak Current Densities in Excess of 450kA/cm^2." *J. Appl. Phys.* 68: 4310-4312 (1990.)

Burns, G.F., H. Blanck, and C.G. Fonstad. "Low-threshold GaAs/AlGaAs Graded-index Separate-confinement Heterostructure Lasers Grown by Molecular Beam Epitaxy on Oxide-masked Si Substrates." *Appl. Phys. Lett.* 56: 2499-2501 (1990).

Kuo, T.Y., J.E. Cunningham, K W. Goosen, W.Y. Jan, C.G. Fonstad, and F. Ren. "Monolayer Be S-doped Heterostructure Bipolar Transistor - Fabricated Using Doping Slecting Base Contact." *Electron. Lett.* 26: 1187-1188 (1990).

Kuo, T.Y., T.H. Chiu, J.E. Cunningham, K.W. Goosen, C.G. Fonstad, and F. Ren. "Heterostructure Bipolar Transistor Employing Carbon-Doped Base Grown with Trimethyl-Ga and Arsine." *Electron. Lett.* 26: 1260-1262 (1990).

Prasad, S., W. Lee, and C.G. Fonstad. "Reply to 'Comments on Unilateral Gain of Hetrojunction Bipolar Transistors at Microwave Frequences.'" *IEEE Trans. Electron. Dev.* 37: 826 (1990).

Sato, H., J.C. Vlcek, C.G. Fonstad, B. Meskoob, and S. Prasad. "InGaAs/InAlAs/InP Collector - Up Microwave Heterojunction Bipolar Transistors." *Electron Dev. Lett.* 11: 457-459 (1990).

Venkateswsan, V.D., L.J. Cui, M. Li, B.A. Weinstein, K. Elcess, C.G. Fonstad, and C. Mailhoit. "Strain Mapping in (111)- and (100)-InGaAs/GaAs Superlattices." *Appl. Phys. Lett.* 56: 286-288 (1990).

Venkateswasan, V.D., T. Burnett, L.J. Cui, M. Li, B.A. Weinstein, J.M. Kim, C.R. Wie, K. Elcess, C.G. Fonstad, and C. Mailhoit. "Comparison and Spatial Profiling of Strain in [001] and [111] InGaAs/GaAs Superlattices from Raman and X-ray Experiments." *Phys. Rev. B* 42: 3100-3108 (1990).

Journal Articles Accepted for Publication

Vlcek, J.C., and C.G. Fonstad. "Precise Computer Control of the MBE Process - Application of Graded InGaAlAs/InP Alloys." *J. Cryst. Growth.* Forthcoming.

Journal Articles Submitted for Publication

Broekaert, T.P.E., and C.G. Fonstad. "AlAs Etch-Stop Layers for InGaAlAs/InP Heterostructure Devices and Circuits." Submitted to *IEEE Trans. Electron. Dev.*

Peng, L.-H., T.P.E. Broekaert, W-Y. Choi, C.G. Fonstad, and V. Jones. "Defect Activated Infrared Multi-phonon Excitation in Fe-doped Semi-insulating InP." Submitted to *Appl. Phys. Lett.*

Meeting Papers Presented

Blanck, H. "Characterization of GaAs Grown Patterned Si-substrates for Photoelectronic Devices." Fifth New England MBE Workshop, Cambridge, Massachusetts, April 17, 1990.

Broekaert, T.P.E., and C.G. Fonstad. "AlAs Etch-Stop Layers for InGaAs/InP Heterostructure Devices and Circuits." *Technical Digest of the 1990 International Electron Devices Meeting.* Piscataway, New Jersey: IEEE, 1990, pp. 339-342.

Broekaert, T.P.E., P.F. Bagwell, T.P. Orlando, and C.G. Fonstad. "Resonant Tunneling Diodes and Transistors with One, Two, or Three Dimensional Emitter." American Physical Society, Anaheim, California, March 12-16, 1990. Abstract in *Bull. Am. Phys. Soc.* 35: 298 (1990).

Kuo, T.Y., K.W. Goossen, J.E. Cunningham, W.Y. Jan, C.G. Fonstad, and F. Ren. "Monolayer Be d-doped Heterostructure Bipolar Transistor Fabricated using Doping Selective Base Contact." Forty-eighth Annual Device Research Conference, Santa Barbara, California, June 25-27, 1990.

Kuo, T.Y., K.W. Goossen, J.E. Cunningham, C.G. Fonstad, F. Ren, and W. Jan. "Elimination of Emitter-Mesa Etching and Complete Planarization of Heterojunction Bipolar Transistors via Doping Selective Base Contact and Selective Hole Epitaxy." International Confer-

ence on Solid State Devices and Materials, Sendai, Japan, August 23-26, 1990.

Meskoob, B., J.C. Vlcek, H. Sato, S. Prasad, G. Fonstad, and M-K. Vai. "Characterization of InGaAs/InalAs/InP Emitter-Down Heterojunction Bipolar Transistors at Microwave Frequencies." EES of Users's Group Meeting, Dallas, Texas, May 8, 1990.

Ranganathan, R., J. Kaminsky, B.D. McCombe, K. Elcess, and C.G. Fonstad. "Free Electron Laser Studies of the Saturation of Cyclotron Resonance in a <111>-InGaAs/GaAs Strained Layer Superlattice." American Physical Society, Anaheim, California, March 12-16, 1990. Abstract in *Bull. Amer. Phys. Soc.* 35: 346 (1990).

Singer, R.A., and C.G. Fonstad. "MBE Growth of InGaAs and InAlAs on (111) B InP." Sixth International Conference on Molecular Beam Epitaxy, San Diego, California, August 27-31, 1990.

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Vlcek, J.C. "Control of Compositional Grading and Abruptness in InGaAlAs Heteroepitaxy." 5th New England MBE Workshop, Cambridge, Massachusetts, April 17, 1990.

Vlcek, J.C., and C.G. Fonstad. "Precise Control of Time-dependent MBE Flux Profiles — Application to InGaAlAs/InP Alloys." Electronic Materials Conference, Santa Barbara, California, June 27-29, 1990.

Vlcek, J.C., and C.G. Fonstad. "Precise Computer Control of the MBE Process — Application to Graded InGaAlAs/InP Alloys." Sixth International Conference on Molecular Beam Epitaxy, San Diego, California, August 27-31, 1990.

Thesis

McCann, P. *Heteroepitaxial Growth of IV-VI Semiconductors on Barium Flouride.* Ph.D. diss. Dept. of Mater. Sci. and Eng., MIT, 1990.