Chapter 9. Heterostructures for Optical Devices

Academic and Research Staff

Professor Clifton G. Fonstad, Jr., Dr. Elias D. Towe

Graduate Students

Richard Singer, James Vlcek

Undergraduate Students

Melissa Frank

The broad objective of our research effort is to develop the use of III-V quantum heterostructures as high performance guided wave optical devices and circuitry for high speed optical communications and signal processing. To this end, we are developing: 1) new, higher performance materials systems including <111> oriented strained layer superlattices and InP-based InGaAlAs heterostructures; 2) new techniques for integrating heterostructure active sections within passive planar waveguide circuitry; and 3) new damage-free in situ processing techniques for fabricating advanced quantum structures and embedded heterostructures.

The following report describes our progress during the past year in the above research areas. Our group works closely with Professors Hermann Haus, Erich Ippen, and James Fujimoto to develop the device application, characterization and modelling aspects of this program, and with Professor Sylvia Ceyer to develop new in situ processing methods.

9.1 Integration of GaAlAs and InGaAlAs Multiple Quantum Well Heterostructures in Guided Wave Optical Circuits

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Richard Singer, James Vlcek, Professor Clifton G. Fonstad, Jr., in collaboration with Kristen K. Anderson, Mary Phillips, and Professor Hermann A. Haus

In this project, we are examining methods for integrating multiple quantum well (MQW) heterostructures into planar guided wave optical circuits. In addition, we are considering the replacement of the much studied GaAlAs/GaAs system with alternative materials systems such as InGaAlAs MQW lattice-matched to InP system for these applications.

Defining multiple quantum well regions in an essentially one-dimensional environment can be addressed either: 1) at the stage of growth by selective area growth or 2) subsequent to growth by etching away, or otherwise removing, the undesirable MQW regions. Using the latter approach, we are employing compositional interdiffusion to homogenize the area outside of the desired MQW regions. Our initial efforts to use furnace anneals with silicon nitride masks to intermix the MQW layers were unsuccessful. The quality of the protected MQW regions degraded to the point that they were no longer useful. Kristen Anderson, working with J. Donnelly at MIT Lincoln Laboratory, is successfully using heavy ion bombardment (implantation) at elevated temperatures to achieve the desired selective intermixing (see also Part I, Section 2, Chapter 1, section 1.5 "Multiple Quantum Well Semiconductor Waveguide Optical Devices").

Because the GaAlAs/GaAs system has definite limitations for planar waveguide applications, we have directed our attention to the InGaAlAs/InP system (see also section 9.2, "Molecular Beam Epitaxy (MBE) Growth of Graded Composition InGaAlAs Heterostructures on InP Substrates" on page 54). The low refractive index, wide bandgap substrate in this system facilitates work with both window and planar waveguide structures. Also, the large bandgap and band-edge discontinuities yield accentuated excitonic structure. Larger non-linear and electro-optic effects are also anticipated. At this stage in our research on the InGaAlAs/InP system, Mary Phillips is measuring and characterizing the effects in InGaAlAs MQW heterostructures (see also Part I, Section 2, Chapter 1, section 1.5, "Multiple Quantum Well Semiconductor Waveguide Optical Devices"). Based on this system, optimized MQW heterostructures in the system will be developed and incorporated into planar guided wave optical circuitry similar to that now envisioned in the GaAlAs/GaAs research.

As our research on three-dimensional MBE and kinetic beam processing advances (see sections 9.5, "Molecular Beam Epitaxy (MBE) Growth on Textured Substrates: Three-Dimensional MBE" on page 56 and 9.7 "Kinetic Beam Processing of III-V Heterostructures" on page 57), techniques for embedding planar MQW regions within waveguide layers will be studied as alternatives to compositional interdiffusion. This process offers the most attractive long-term solution to the problem of monolithically integrating different optoelectronic devices.

9.2 Molecular Beam Epitaxy (MBE) Growth of Graded Composition InGaAlAs Heterostructures on InP Substrates

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Project Staff

Melissa Frank, James Vlcek, Professor Clifton G. Fonstad, Jr.

Graded-composition alloys have proven to be very useful in such devices as heterojunction bipolar transistors and laser diodes. Unlike the GaAlAs/GaAs system, however, which is virtually lattice-matched over the entire alloy range, InP-based alloy systems require precise control over the composition to maintain the lattice mismatch below 0.1 percent. As a result, relatively little work has been done on graded-composition InP-based alloys.

Recently, we have grown uniform and graded composition InGaAlAs quaternary alloys (lattice-matched to InP) spanning the entire available wavelength range. Compositional grading was achieved entirely by varying the effusion cell temperatures, under control of an interactive computer program utilizing the flux versus temperature characteristics of the constituent cells. The In cell was held at a constant temperature, resulting in a nearly constant growth rate, while the Ga- and Al-cell temperatures were varied to achieve the grading.

Results obtained to date indicate that graded composition alloys can be grown lattice-matched virtually as easily as uniform-composition alloys, and that the spread in lattice constant over the range of the graded layer can easily be held below 0.1 percent. This indicates that the use static flux versus temperature data is sufficient for the growth of compositionally graded material, and that the of sticking coefficients of the group III elements are indeed close to unity. Characterization of the graded composition materials was performed using single- and double-crystal x-ray diffraction and Auger electron spectroscopy.

The growth techniques for InGaAlAs alloys are now being exploited to achieve the same advantages of graded layers in electrical and optical devices which have been demonstrated in the GaAs/AlGaAs system. These, coupled with intrinsic properties of the InGaAlAs system such as the optical emission wavelength range of 0.85 to 1.65 μm and the large bandgap difference and conduction band discontinuity, make this graded quaternary system an ideal candidate for device applications.

9.3 Molecular Beam Epitaxy of Pseudomorphic InGaAlAs Quantum Wells on (111) Oriented GaAs and InP Substrates for Optical Modulators

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Project Staff

Richard Singer, Professor Clifton G. Fonstad, Jr., Dr. Elias D. Towe, in collaboration with Stuart D. Brorson, and Professor Hermann A. Haus

A major motivation for our MBE effort on (111) substrates (see section 9.4, "Characterization of Strained Layer InGaAlAs Heterostructures on (111) Oriented GaAs Substrates") is the potential importance of these layers for optical modulators. Quantum wells have been shown to exhibit much larger refractive index and absorption edge changes under the influence of an electric field than are observed in uniform "bulk" materials. Such changes may form the basis for a variety of possible optical modulator structures if the changes are sufficiently large. Our work on (111)-oriented pseudomorphic layers is directed at enhancing these effects.

Specifically, the major electro-optic effect of interest, the quantum confined stark effect, yields a quadradic refractive index variation with applied electric field. Thus the change in index is greater at higher electric fields, and any modulator based on this effect will be more effective if a large dc bias voltage is applied along with any incremental voltage signal. Our goal is to use the large internal electric fields generated in (111)-oriented strained layers to provide this dc bias. With fields at least as great as 10^5 V/cm available, these devices will be able to operate at a fraction of the external voltages now required and will be significantly more sensitive and efficient. Viewed externally, the quadradic electro-optic effect of the conventional quantum well heterostructure will have been converted to a much stronger, essentially linear electro-optic effect with wider interest for applications. With the purpose of producing modulators based on this effect, we worked with our collaborators to supply GaAs-based heterostructures. We are now working to develop techniques for MBE growth on (111) InP to investigate InP-based devices. Window type devices are being produced initially, but the longer range goal is to develop guided wave optical circuits (planar waveguide type) incorporating these devices.

9.4 Characterization of Strained Layer InGaAlAs Heterostructures on (111) Oriented GaAs Substrates

Sponsors

Xerox Corporation Fellowship
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Project Staff

Richard Singer, Kimberly Elcess, Professor Clifton G. Fonstad, Jr., in collaboration with B. Laurich,[1] B.D. McCombe,[2] Chrishen Mailhoit,[3] Richard Singer, Daryl Smith,[1] B.A. Weinstein[2]

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[1] Los Alamos National Laboratory.

[2] State University of New York at Buffalo.

[3] Xerox Corporation.

After developing unique capabilities to grow InGaAlAs strained-layer heterostructures on <111> oriented GaAs substrates last year, we have been extending this work to InP substrates and have collaborated with several groups interested in doing fundamental characterization of these materials. Of primary interest in these structures are the large internal electric fields expected to be generated piezoelectrically by the strain. Fields in excess of 10^5 V/cm are predicted.

B.D. McCombe and his colleagues at the State University of New York at Buffalo have used low temperature far infrared magnetotransmission, near infrared magnetoreflectivity, and photoluminescence measurements to provide direct evidence for the predicted electric fields. B.K. Laurich and D.L. Smith at Los Alamos National Laboratory have measured luminescence spectrum as a function of excitation intensity to compare (100) and (111) oriented strained layer superlattices and have also demonstrated the existance of high internal electric fields.

We will continue these collaborations including supplying material for researchers interested in fundamental properties of these structures. However, our emphasis will be on exploiting these structures in optoelectronic devices.

9.5 Molecular Beam Epitaxy (MBE) Growth on Textured Substrates: Three-Dimensional MBE

Sponsors

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Project Staff

Thomas Broekaert, Professor Clifton G. Fonstad, Jr., in collaboration with Professor Carl V. Thompson III

In an important new frontier of MBE research, we recently began to study and model heterostructures grown on various three-dimensionally patterned substrates by molecular beam epitaxial (MBE) techniques. Liquid phase epitaxy (LPE) and chemical vapor deposition (CVD) techniques had been used for years to produce devices and structures with unique characteristics.

A mask set has been prepared to etch straight grooves from 1 to 25 μm wide separated by 1 to 25 μm, and oriented at 0, 45 degrees, and 90 degrees to a reference. Using this mask on a (100) substrate with an isotropic etch produces v-grooves with approximately (111)A, (111)B, and (110) walls while an anisotropic etch revealing (111)A planes v-grooves creates dove-tail and near-vertically walled grooves. Depending on the width of the groove, the distance to its neighbor, and the etch depth, a variety of surface areas are formed on which to study the effects of surface atom mobility, orientation and inclination.

Although we have studied only a limited number of growths so far, the strong orientation dependence of the profile is clearly indicated. It is possible to achieve large lateral thickness variations that are important for applications. The growth temperature and III-V flux ratio affect the structure so that one can begin to qualitatively compare the growth rates of the various major planes. Guided by work by Ohtsuka et al., at Canon, reported in August 1988, we are developing a model that simulates the growth profiles with the ultimate goal of achieving quantitative design control over the profiles grown.

9.6 Molecular Beam Epitaxial Growth on (n 11) Vicinial Surfaces

Sponsors

MIT Funds

Project Staff

Dr. Elias D. Towe, Clifton G. Fonstad, Jr., in collaboration with H.Q. Lee[4] and J.V. Hryniewicz[4]

Traditionally, III-V compound semiconductors have been synthesized on (100) subtrate surfaces. The need to fabricate devices on structured (100) surfaces processed chemically and the fundamentally different molecular beam epitaxial growth characteristics on high-index surfaces has made it necessary to develop an understanding of the materials properties on high-index planes vicinal to the (100) surface. The particular planes of interest are those denoted by {h11}.

We have conducted preliminary studies on two of the {h11} planes: the (211) and (511) surfaces. GaAs and (Al,Ga)As layers grown on the (211) and (511) surfaces indicate differences in the growth conditions for similar structures on the (100) substrates. Specifically, photoluminescence and excitation studies show that unintentional residual background impurities behave differently on the (511) surface compared to the (100) surface. In the same study, we have also found that the splitting between the heavy hole and light hole exciton energy is larger in quantum well structures grown on (511)B surfaces than those on (100) surfaces. A simple Luttinger-Kohn analysis indicates that this is due to the anisotropy of the valence band.

The differences in epitaxial growth conditions and optical properties are significant enough to require further study of other members of the {h11} family of planes.

9.7 Kinetic Beam Processing of III-V Heterostructures

Sponsors

Joint Services Electronics Program
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Project Staff

Professor Clifton G. Fonstad, Jr., in collaboration with Professor Sylvia T. Ceyer

The development of damage-free UHV etching, cleaning, and regrowth compatible with molecular beam epitaxy and ex situ III-V heterostructure processing is the main challenge facing the optoelectronic compound semiconductor materials community. The ability to selectively pattern, etch, and overgrow quantum heterostructures is crucial to the effective realization of integrated optical circuitry. Present-day techniques involve relatively high energy ion beams (20 to 200 eV, and above) that cause substantial surface and sub-surface damage, much of which is essentially impossible to remove. These high energies are necessary to maintain a well directed ion beam; the actual etching reactions require only a few electron volts of energy.

Recent research by Professor Sylvia Ceyer has shown that molecular beams with as little as 0.5 eV of kinetic energy can efficiently etch semiconductor surfaces. This energy is below the threshold for creating damage. Upon learning of these results, Professor Fonstad initiated a collaboration with Professor Ceyer to exploit "supersonic," or "kinetic," beam techniques to ansitropically etch-pattern MBE-grown III-V heterostructures, to clean their surfaces after masking and/or ex situ processing, and to prepare them for overgrowth. Reactants have been identified (the first work will use methane/hydrogen mixtures) and a preliminary design for a kinetic beam etching system has been completed. Funds are being sought for its assembly and for a research program to develop it to anisotropically etch III-V heterostructures, to selectively remove etch mask materials, and to clean surfaces returned to the UHV environment after external processing. This effort will be closely coupled to the programs on 3D-MBE, quantum well, wire, and box heterostructures, and optoelectronic integration.

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[4] MIT Lincoln Laboratory.

9.8 Diffraction Coupled Heterostructure Diode Laser Arrays

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Project Staff

Dr. Elias D. Towe, Professor Clifton G. Fonstad, Jr., in collaboration with A. Chin[5] and K. Meehan[5]

We have continued developing our novel phase-locked diode laser array, the mixed-mode phase-locked (M^2PL) laser array. This array achieves phase locking and operation in the fundamental, single-lobed super-mode by diffraction in a region introduced into the middle of the array. The radiation is not laterally confined on either side of this mode mixing region. Thus, a small fraction of the radiation in each element of the array is coupled in this region to the adjacent elements. If the length of the mode-mixing region is properly designed, coupling will occur in phase, the radiation in the adjacent guides will be locked in phase, and a narrow, single-lobed output beam will result.

The M^2PL laser concept has been successfully demonstrated in our earlier work. Because its structure routinely produces stable, single-lobed, far-field patterns, this laser concept appears to be unique among the multitude of array structures tested. It is also one of the simplest to produce.

In the past year, we began to collaborate with researchers at Polaroid who are interested in applying the M^2PL concept to their work. To further confirm the value of M^2PL concept, and provide data for more complete modeling of the device performance, a mask set having a variety of coupling region lengths and net phase shifts ranging from 2π to 3π has been designed. Arrays are being built with this mask set at Polaroid. The results will be used to further refine the theory and optimize the arrays.

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[5] Polaroid Corporation.