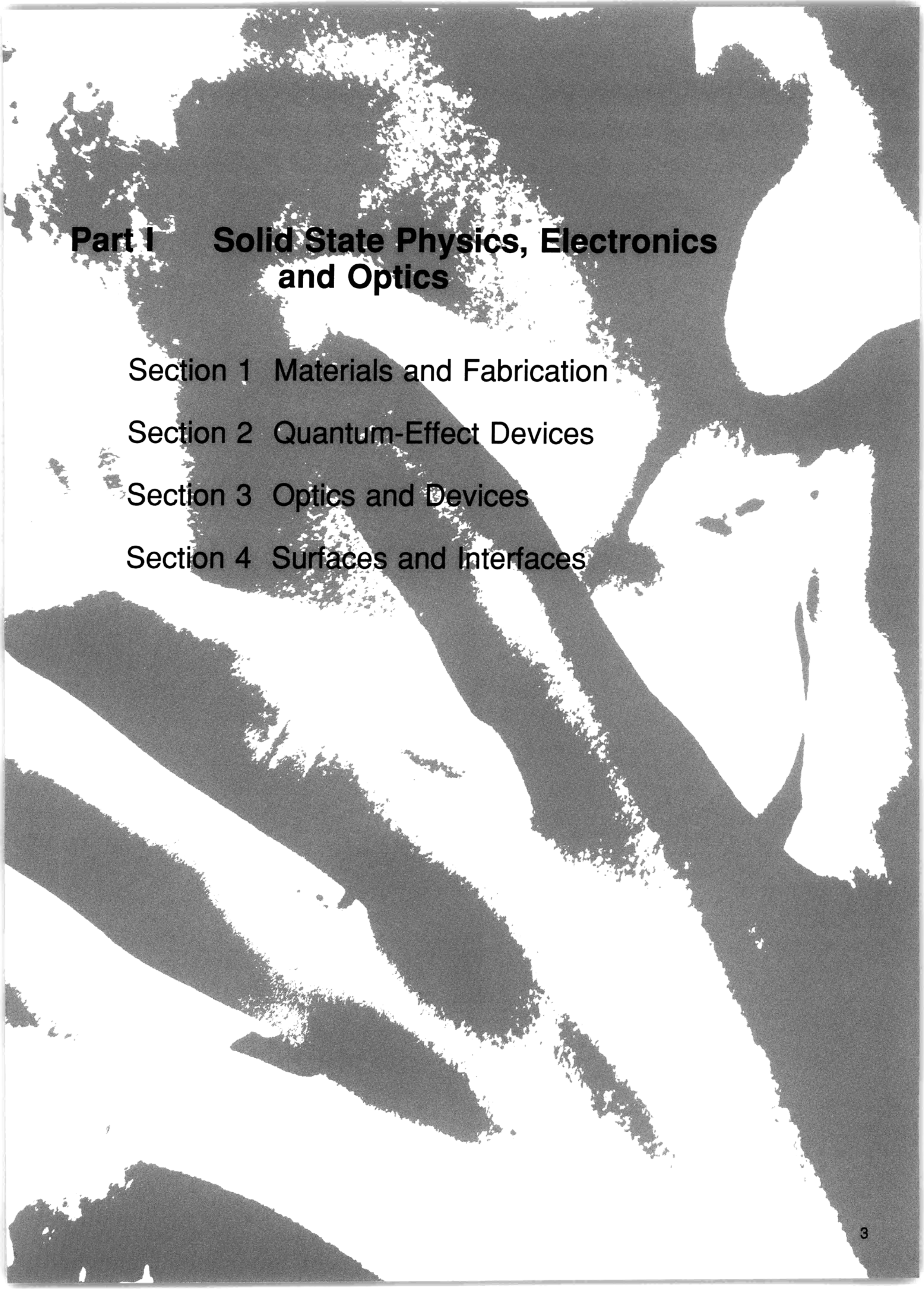

Part I Solid State Physics, Electronics and Optics

Section 1 Materials and Fabrication

Section 2 Quantum-Effect Devices

Section 3 Optics and Devices

Section 4 Surfaces and Interfaces

Section 1 Materials and Fabrication

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, Erich P. Ippen, and James G. Fujimoto to develop the optical device application, characterization, and modeling aspects of this program, with Professor Henry smith to develop a novel distributed feedback laser structure, and with Professor Sylvia T. Ceyer to develop new in situ processing techniques.

1.2 MBE-Grown InGaAlAs Laser Diodes for Optical Fiber Communication Applications

Sponsors

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

Project Staff

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

Semiconductor laser diodes with the lasing wavelength of 1.3 to 1.5 μm are an essential element of long-distance optical fiber communication systems that have revolutionized modern telecommunication networks. The material system of InGaAsP is most often used for laser diodes for such applications. We are investigation the feasibility of alternate material system of InGaAlAs for the same application.

The main advantage of InGaAlAs over InGaAsP is that quantum wells based on InGaAlAs have larger conduction band and smaller valence band offsets. For high speed modulation the hole transport can be a limiting factor; over-confinement of holes in

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InGaAsP quantum wells is undesirable. The other advantage of this material is that, unlike InGaAsP, InGaAlAs can be successfully grown by solid source MBE without toxic gases. This "environmental" factor will undoubtably become increasingly important as the price of disposing of environment pollutants grows.

The advantages listed above are not realized without a few challenges. First, the high percentage of aluminum in the device structure can trap impurities that can reduce the optical quality of the resulting materials. To reduce this posibility as much as possible, we have investigated the optical quality of materials obtained under various growth conditions and have determined optimal growth conditions for each device structure desired. Although we plan to do more growth-related studies, so far we have demonstrated device performances of InGaAlAs quantum well laser diodes that are comparable to those produced with InGaAsP.

Second, it is essential that laser devices for long-distance optical fiber communication applications operate with single longitudinal modes. Since InGaAlAs is not suitable for regrowth, techniques that are commonly used to achieve single mode selection cannot be applied to MBE-grown InGaAlAs. We are developing a novel ridge-grating distributed feedback (DFB) process in which gratings are made on the side walls of ridges, removing the need for regrowth (see following section). For this process, we are collaborating with Professor Henry I. Smith's group at MIT since the x-ray lithography technique he and his colleagues have developed are particular applicable for this process.

In addition to the above issues, we are also investigating the optimal use of strained multiple-quantum wells for the laser diode applications and reliable ridge waveguide processing techniques.

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

Sponsors

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

Project Staff

Woo-Young Choi, Professor Clifton G. Fonstad, Jr. in collaboration with Professor Henry I. Smith

It is essential that laser diodes for optical fiber communications 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 pursuing a DFB device structure in which gratings are formed entirely after complete epitaxial growth. Our motivation for this approach stems from the fact that we are working on laser diodes grown by conventional solid-source molecular beam epitaxy (MBE) technology. Ddue to its growth kinetics, successful MBE growth on the corrugated surface is very difficult. The present structure is also more suitable for use with the InGaAlAs system (see preceeding section).

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 the single mode selection.

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

1.4 Feasibility Study of 1.55 μm Intersubband Transition in InGaAs/AlAs Quantum-Well Heterostructures

Sponsors

Joint Services Electronics Program
Contract DAAL03-92-C-0001
National Science Foundation
Toshiba Corporation Ltd.

Project Staff

Yuzo Hirayama, Jurgen H. Smet, Professor Clifton G. Fonstad, Jr. in collaboration with Professor Erich P. Ippen and Professor Qing Hu

Realization of a 1.55 μm intersubband transition using InGaAs/AlAs quantum wells is an interesting topic for basic physics as well as for its potential applications. Very fast relaxation times and large optical nonlinearlities, which are useful for advanced photonic devices such as a high speed photonic switch, are expected. A wavelength of 1.55 μm is most suitable for optical communication systems. We plan to study carrier dynamics in these quantum well structures using femtosecond pump and probe techniques.

Structures in which the energy separation between the first and fourth subband corresponds to a wavelength of 1.55 μm were designed and fabricated on InP substrates by MBE techniques. Strain compensated structures were also fabricated. To reveal subband structures in these quantum well samples, a conventional optical absorption measurement system and a newly developed photomodulated transmission measurement system were built. The latter system is basically a modulation spectroscopy method, having a high signal-to-noise ratio. Therefore, it is suitable for measurements of very narrow single quantum well structures.

A careful study of InGaAs/AlAs quantum well samples revealed the following facts: (1) Samples show many unidentified optical signals unless thick InGaAs or InGaAlAs buffer layers are used. (2) Dislocations due to strain relaxation are observed unless growth is performed at low-substrate temperature. (3) Transitions from the first to the second subband were observed. However, transitions from the first to the fourth subband were too weak to be detected. (4) Peak positions in the transmission spectra are difficult to predict so that simple effective mass approximation cannot be applied. A modified theory including other effects such as band bending or electron-electron exchange interactions cannot account for the results.

To realize a 1.55 μm intersubband transition, we have redesigned our quantum well structure using our previous experimental data. First observation of 1.55 μm intersubband transition will be in the near future. Theoretical work is also on going. To measure time resolved optical spectra, a new pump and probe system using white probe light is being built. In this system, strong optical pulses which are amplified in a NaCl color center crystal go into a nonlinear material and generate white light. It is expected that, with the use of this setup, the carrier dynamics in these new quantum well structures will become clear.

1.5 Growth and Characterization of High Quality InGaAlAs Multiple Quantum Wells

Sponsor

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

Project Staff

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

Use of strained layers in heterostructure device research is one of the most significant developments in the past decade. Strained layers are now routinely utlitized for enhancing the performance of optical and electrical devices, yielding lower threshold currents and faster modulation speeds for quantum well laser diodes and higher electron mobilities for heterostructure FET devices. However, this enhanced performance can be obtained only if the strained layers do not have any dislocation caused by strain relaxation. Consequently, understanding the strain relaxation mechanism and a careful control of epitaxial growth parameters are required for successful utilization of strained layers in heterostructure devices. With this in mind, we have performed intensive studies in which MBE-grown InGaAlAs strained multiple-quantum-wells on InP are characterized by double crystal x-ray diffraction, transmission, and photoluminescence measurements. The strained quantum wells under study have great potential for applications in laser diode and modulator devices.

Because the wavelength of x-rays is shorter than the lattice constants of materials being studied and the high beam quality obtained in the double crystal configuration, double crystal x-ray diffraction is the best characterization method for obtaining structural information of strained quantum wells. The degree of strain relaxation can be qualitatively determined by the sharpness of satellite peaks caused by the well and barrier periodicity. For coherent strained layers without major strain relaxation, we have developed a systematic method of determining layer composition and thickness in strained multiple quantum wells based on the amount of satellite peak separation and other growth information.

From the room temperature transmission measurements on strained multiple-quantum-well samples, we routinely observe excitonic transitions, indicating the high quality of strained quantum wells that are achieved in our lab. In addition, from the careful analysis of the spectra, we have estimated important parameters such as exciton binding energy and radius, in-plane reduced effective mass, etc.

From careful analyses of photoluminescence spectra, we have determined qualitative differences in the nature of luminescence peaks that are due to strain-relaxed quantum wells, bound or free excitons, and free carriers. These identifications and their characteristic dependence on temperature have enabled us to correctly interpret the photoluminescence spectra.

These characterization methods are exciting research techniques from which insight into the physics of strained multiple quantum wells can be obtained. Furthermore, they allow us to make an easy and early determination of quality of strained multiple quantum wells in actual device structures and provide material parameters that are of great importance in designing and analyzing devices.

1.6 New Three-Terminal Laser Diodes with Dynamic Control of Gain and Refractive Index

Sponsor

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. We call these devices independently addressable asymmetric quantum well laser diodes (IAADQW - LDs). By designing structures in which the current injection into these two quantum wells can be independently controlled, we are gaining a new, as yet unutilized, degree of freedom in controlling light output from the device.

Wavelength division multiplexing (WDM) is an area in which we believe this new class of devices can have an important impact. An alternative approach to a single very fast laser diode 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. Since the low loss region of currently installed silica fiber is very broad, this technique has the potential to dramatically increase single fiber data rates into the terabit per second range for the installed fiber base. Essential for realizing practical WDM systems are dynamically tunable laser diodes for adjusting the wavelength of each signal channel and narrow line-width channel. Simulations we have done show that InP-based IAADQW-LDs can have tuning ranges in excess of 20 nm (2 THz) within the 1.5 μm low-loss window of Silica fiber. If realized, this would be a significant improvement over current multisection distributed Bragg reflector (DBR) type lasers which typically have usable tuning ranges of only a few nm. Also important for practical applications is the change in output power as the LD is tuned. Since the wavelength of the IAADQW is determined only by the ratio of the currents injected into the two active regions, the magnitude of current injection can be used to control power output, making it possible to keep power output constant over the entire tuning range. The ability to electrically tune output wavelength over a broad range while keeping output power constant makes the IAADQW device ideal for WDM.

To implement the IAADQW-LD we have developed a self-aligned process that uses a single metalization layer to define the ridge waveguide through $SiCl_4$-based reactive ion etching (RIE). This layer defines the current injection region for the lower quantum well through H+ ion implantation and contacts the upper quatum well. One subsequent photolithography step and metalization will then complete processing for the device.

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 bandwith filters and light modulators.

1.7 Laser Diode Modeling and Design for Narrow Linewidth Operation

Sponsor

Charles S. Draper Laboratories

Project Staff

Yakov Royter, Professor Clifton G. Fonstad, Jr. in collaboration with J.H. Hopps[5]

Many of the current laser applications require narrow linewidth output characteristics. Unfortunately, semiconductor lasers, possessing such advantages as small size, direct modulation capa-

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

bility, and integrability with other optical and electronic devices, have broad linewidths in comparison to almost all 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 was to investigate and help in the reduction of 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 was to investigate theoretically the intrinsic linewidth broadening effects. In particular, we concentrate on the alpha parameter, the largest intrinsic linewidth broadening factor, which describes the coupling of gain and refractive index fluctuations in the gain medium via carrier density fluctuations. For this purpose, we calculated the carrier energy bands of the active region semiconductor material, using the $k \bullet p$ approximation. From the energy bands, we obtained gain and refractive index profiles and linewidth broadening parameter.

To test our models, we plan to compare the calculated laser characteristics, such as threshold current, gain, refractive index and linewidth, with experimental results obtained from measurements done in our laboratory, as well as those quoted in the literature. Measurements of the CW semiconductor laser subthreshold spectrum are being conducted from which gain profile can be deduced. The shifts in the mode spectrum due to the change in the pumping provide information on the gain-refractive-index coupling, and thus the alpha parameter. To reduce the effect of thermal variations, gain measurements of pulsed laser spectra will also be done. Finally, from the comparison between experimental and theoretical results, we will attempt to establish systematic ways of obtaining parameters for our semiconductor laser models.

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.

1.8 Evaluation of GaAs MESFET VLSI Circuits as Substrates for III-V Heterostructure Epitaxy

Sponsors

DARPA/NCIPT
Hertz Foundation Fellowship
Vitesse Semiconductor

Project Staff

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

Commercially available VLSI GaAs metal semiconductor field effect transistors (MESFETs) are potentially very useful in optoelectronic integrated circuits (OEICs). Direct epitaxy of photonic devices on fully processed MESFET circuitry is a viable approach to realizing monolithic OEICs if MESFETs are thermally stable at elevated temperatures. Ohmic contact and Schottky gate degradation, caused by thermally induced interdiffusion to the source or drain and channel, respectively, are the major modes of failure in GaAs MESFETs with Au metallization. In this research, we are examining the performance of commercial refractory-metal VLSI GaAs MESFETs after 3 h, high-temperature anneals, which duplicate the molecular beam epitaxy (MBE) growth sequence for an in-plane surface-emitting laser (IPSEL).

Vitesse Semiconductor Corporation HGaAs2 technology, a self-aligned VLSI GaAs MESFET process with tungsten-based refractory-metal Schottky gates, nickel-based refractory-metal ohmic contacts, and aluminum interconnection metallization, was selected for this study. Enhancement mode MESFETs (EFETs), depletion mode MESFETs (DFETs), and transmission line model (TLM) structures were selected from standard production process control monitor test bars. Partially processed wafers (with neither aluminum interconnection nor passivation dielectric deposited), as well as fully processed wafers, were tested.

MESFET and TLM parameter trends as the maximum anneal temperature was increased from 400°C to 600°C are as follows: (1) The partially processed wafer trends are similar to the fully processed wafer trends but are less pronounced. (2) EFET and DFET parameter trends are in agreement. (3) V_T, Schottky diode ideality, Schottky barrier voltage, and R_{SH} show no significant trends while I_D^{sat} and g_m decrease, and R_{GS} increases. (4)

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[6] Vitesse Semiconductor, Camarillo, California.

g_m and I_{DS} decrease significantly above 525°C ± 10°C; R_{GS} increases significantly above 525°C ± 10°C. Most significantly, Schottky gate and ohmic contact resistance degradation modes are absent. The increase in R_{GS}, which is the sum of the Schottky gate resistance, channel resistance, source implant sheet resistance, and ohmic contact resistance, can be attributed to an increase in the channel resistance component, and is responsible for the apparent decreases in g_m and I_{DS}.

These results indicate that if we can limit the temperature during the major portion of a growth sequence to 525°C or below, we will be able to grow heterostructures on pre-processed GaAs integrated circuits without effecting the performance of the underlying circuitry, and therefore not requiring any modification of existing design rules and circuit simulation models.

1.9 Low Temperature Growth of GaAlAs Laser Diodes

Sponsors

DARPA/NCIPT
GTE Laboratories
Hertz Foundation Fellowship
National Science Foundation Fellowship
Vitesse Semiconductor

Project Staff

Krishna V. Shenoy, Professor Clifton G. Fonstad, Jr. in collaboration with J. Mikkelson[6] and B. Elman[7]

Direct epitaxy of photonic devices on fully processed GaAs VLSI circuits to produce OEICs will require that lasers are grown at 525°C or less. The effect of lowered temperature AlGaAs epitaxial quality on laser performance is currently under investigation. Because conventional AlGaAs is grown at 700°C, which violates the thermal constraint imposed by the electronic circuitry.

To investigate lowered molecular beam epitaxy (MBE) growth temperatures on laser performance, single quantum well, step-confinement, strained-layer (Al,Ga,In)As laser diode heterostructures were optimized for growth at low temperatures. Low Al mole fraction cladding layers (1.4μm of $Al_{0.22}Ga_{0.78}As$) were used to minimize oxygen incorporation at heterojunction interfaces and allowed ridge waveguide lasers to be fabricated using a selective succinic acid etch and an AlAs etch-stop layer. 200 nm GaAs waveguide layers were used to maximize the optical confinement factor and optimize the quantum well-to-AlGaAs cladding layer separation which is critical with lowered temperature AlGaAs.

A 60 $In_{0.2}Ga_{0.8}As$ active region was used to minimize the threshold current; the corresponding emission is nominally at 0.98 μm. A strained layer quantum well active region yields lower threshold currents than unstrained quantum wells because compressively straining InGaAs decreases the effective mass in the parallel direction, thus reducing the density of states and number of carriers required to reach population inversion. Such laser diodes were MBE grown with a maximum substrate temperature of 530°C and had threshold current densities only 2.4 times higher than lasers grown under more optimal growth conditions. This demonstrates for the first time that practical laser diodes can be grown using standard MBE techniques at temperatures compatible with direct epitaxial growth on fully processed VLSI GaAs circuitry.

Further reduction in threshold currents are anticipated. More exploratory 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 ($<$ 600°C) AlGaAs. Phosphide based optoelectronic devices, grown by gas-source MBE, are also being considered because they provide both lower growth temperatures (typically $<$ 500°C) and shorter wavelength emission.

1.10 Optical Input and Output Circuitry for High Density, High Speed GaAs MESFET-based OEICs

Sponsors

DARPA/MOSIS
DARPA/NCIPT
Hertz Foundation Fellowship

Project Staff

Krishna V. Shenoy, Professor Clifton G. Fonstad, Jr. in collaboration with P. Nuytkens

Optoelectronic signal processors have become major components of advanced communication

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[7] GTE Corporation, Waltham, Massachusetts.

systems, real-time signal processors, and high-performance sensing systems. Integrated optics offers the potential to significantly advance these systems. To fully exploit the potential of optoelectronic devices, semiconductor processes and technology must be designed to integrate photodetectors, transimpedance amplifiers, laser diodes, and VLSI transistor circuits. Such integrated optoelectronic device technology results in lower cost, reduced power consumption, higher bandwidth, lower weight, increased reliability and increased performance of optoelectronic systems.

An optoelectronic integrated circuit (OEIC) transceiver has been designed, thoroughly simulated with HSPICE, and fabricated in the Vitesse HGaAs2 technology (MOSIS). The OEIC transceiver accepts either electrical or optical signal inputs and generates corresponding electrical or optical signal outputs. The OEIC incorporates an ECL electrical input receiver and output driver, MSM photodetector, with a companion transipedance amplifier, laser diode driver, and opening to the substrate for epitaxial growth, cross point switch, and control logic. The OEIC transceiver demonstrates four possible signal conversions: (1) electrical signal at ECL level input, through intermediate DCFL electrical level, to ECL level output; (2) electrical signal at ECL level input through intermediate DCFL electrical level to optical signal output (via regrown in-plane surface emitting laser diode); (3) optical signal input through intermediate DCFL electrical level to electrical signal at ECL level output; and (4) optical signal input through intermediate DCFL electrical level to optical signal output.

Ninety-six processed chips 5 mm by 5 mm on a side, each with 24 OEIC tranceiver cells, have been received through the MOSIS service. Each chip contains numerous 100μm by 400μm opennings etched through to the substrate into which laser diode heterostructures are now being grown.

1.11 High Density GaAs MESFET-based OEIC Neural Systems

Sponsors

Hertz Foundation Fellowship
National Science Foundation Fellowship

Project Staff

Krishna V. Shenoy, Professor Clifton G. Fonstad, Jr. in collaboration with A. Grot[8] and D. Psaltis[8]

Two components required for implementation of a neural network are neurons and connections. In an optical implementation, neurons are typically arranged as two-dimensional arrays interconnected via the third dimension. The interconnections are realized with holograms or spatial light modulators. Use of GaAs optoelectronic circuits provides the flexibility of implementing complex neuron response functions and fine tuning properties of the neurons as required by the neural network algorithm that is being implemented.

LEDs and laser diodes are the choices for on-chip light sources. Laser diodes have higher quantum efficiency and a more directed beam than LEDs, which means a higher light efficiency. Unfortunately, electrical power dissipation is a limiting factor for high density circuits. For typical laser diode values of $V_D = 2$ Volts and $I_{th} = 500\mu\text{Å}$ and a maximum power dissipation of 1 W/cm^2, the maximum integration density is 1000/cm^2. Because of the absence of a threshold current, LEDs can operate with very small currents allowing a density of up to 10^5/cm^2. Thus, if one is interested in high density arrays that operate with relatively slow switching times then LEDs are the preferred choice.

A neuron calculates a simple nonlinear function, thereby mapping its input signals to the output signal. A commonly used nonlinearity is the "bump" function, simply the derivative of a sigmoidal function, which is used in backward error propagation algorithms for calculation of the interconnection weight updates. In the most simplistic approach to implementing the "bump" function, the output should be low whenever the two inputs are not equal and high when the two inputs are matched. In this realization, the input is a photodetector current, which is converted to a voltage in a differential input circuit, and the output is a current through an LED. This differential circuit acts as a thresholding circuit if the detectors have I-V characteristics where the current saturates quickly. An optoelectronic integrated circuit (OEIC) neural chip with arrays of GaAs MESFET neurons and photodetectors has been designed, simulated, fabricated by Vitesse, and tested by Grot and Psaltis at the California Institute of Technology. Monolithic integration of LEDs in dielectric windows is the final fabrication step.

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[8] California Institute of Technology, Pasadena, California.

The Vitesse refractory-metal GaAs MESFET circuitry can withstand three hour molecular beam epitaxy (MBE) growths at temperatures up to 525°C ± 10°C. GaAs-AlGaAs LEDs are being grown by MBE at MIT on fully processed neural chips in dielectric windows, regions where the interlevel and passivation dielectrics have been removed to expose the semi-insulating GaAs substrate. Processing of the LEDs is then completed at Caltech. After planarizing the neural chip by stripping the poly-crystalline material deposited everywhere but in the dielectric windows, LEDs are fabricated and metallically interconnected with the electronic neurons. The culmination of this research will be the demonstration of high-density, monolithic opto-electronic neural systems.

1.12 Applications of Resonant Tunneling Diodes in GaAs MESFET VLSI

Sponsors

Texas Instruments, Inc.
U.S. Army Research Office
Grant DAAL03-92-G-0251

Project Staff

Rajni J. Aggarwal and Professor Clifton G. Fonstad Jr. in collaboration with P. Nuytkens

We are investigating the integration of resonant tunneling diodes (RTDs) with GaAs MESFETs. Our intent is to use epitaxial regrowth techniques to integrate RTDs with commercially available GaAs MESFET technology. We have considered both the development of a logic family as well as a SRAM. RTDs can provide stable, low current, voltage states, and both applications are designed to take full advantage of these properties. Additionally, the small area of tunnel diodes gives the potential for increasing integration densities. Using experimental techniques as well as HSPICE simulations to evaluate the circuits, we have concluded that only the SRAM presents a commercially viable technology.

We compared the performance of the RTD logic family to that of direct coupled FET logic (DCFL). We considered 23 stage ring oscillators using 1, 2, 3, and 4 input NOR gates. The RTD logic consistently dissipated an order of magnitude less power than DCFL, however, much of this advantage was lost when the delay per stage was considered. Overall, the power-delay product of the RTD logic was on average only a factor of four times smaller than that of DCFL. This does not represent enough of an improvement over DCFL to be a commercially viable logic family.

The SRAM cell consists of an enhancement mode FET connected to two RTDs. An integrated RTDs and FET static memory cell has two main advantages over present GaAs SRAMs. Using epitaxial regrowth, RTDs can be grown directly on top of the driver FET, reducing the memory cell size to that of a single transistor. This design has the possibility of obtaining DRAM densities in a static memory. Additionally, proper diode design will result in both the "1" and "0" states being low power states.

We have simulated the basic memory cell and are developing its driver circuitry. We have experimentally demonstrated the bistable nature of diode chains. Using both the experimental and simulation results, we have determined a series of design constraints for both RTDs and FETS. In the coming year we will be designing and growing suitable RTDs for these cells both in stand alone form as well as integrated with circuits. An integral part of the integration of these devices is the process flow required for manufacturing them, and these issues will also receive attention in the coming year.

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

Sponsors

National Science Foundation
U.S. Army Research Office
Grant DAAL03-92-G-0251

Project Staff

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

In this work, we are studying the possibility of achieving population inversion between two quantum well subbands, with an electrically pumped intersubband laser as the ultimate goal. A triple quantum well structure consisting of two narrow filter wells and a wide center well appears to be a promising structure to achieve this goal. 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. In addition, the required population inversion imposed by the gain needed to overcome optical losses should be sufficiently low to prevent the energy difference between the quasi-Fermi level in the upper subband and the ground state from being larger than the LO-phonon energy. These stringent requirements can only be met in wide quantum well structures.

To test the feasibility of population inversion, the I-V characteristics at low temperature of triple quantum well structures with varying barrier thickness and well thickness are being studied to verify that injection and removal of the electrons from the inner well is not the current limiting factor, but that the intersubband relaxation processes determine the current and therefore that population inversion might be achieved.

As the width and the number of the quantum wells increases, and thus the characteristic energy scales reduce and the number of possible transmission channels increase, the assignment of various transmission channels to the currents peaks in the I-V characteristics becomes considerably more difficult and ambiguous. Of the techniques used to analyse the I-V characteristics, magneto-quantum oscillations observed in the tunnel current as a function of applied bias when sweeping the magnetic field have proven to be the most powerful. Using Fast Fourier Transform algorithms, we are able to determine the transmission channel responsible for a certain current peak, the energy seperation between the lowest subbands, and the charge present in the subbands of the first well. We can also determine that the GaAs-like LO-phonon emission process is the dominant inelastic process over InAs-like inelastic scattering. This is in agreement with reports on bulk $In_{0.53}Ga_{0.47}As$.

Our interest in applying a magnetic field parallel to the current goes beyond its use as a diagnostic tool. The magnetic field reduces the dimensionality of the originally 2D quantum well to a OD system and should suppress inelastic scattering processes if the spacing between Landau levels in different subbands differs from the LO-phonon energy and may thus aid in achieving population inversion. We are currently performing experiments to verify and demonstrate this suppresion of inelastic scattering.

1.14 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[9]

The application of III-V single quantum well (SQW) C1-to-C2 intersubband transitions for mid (2 ~ 5 μm) and far (8 ~ 10 μm) infrared (IR) detection, owing to their fast response speed, high detectivity, and reliance on more mature growth and process technologies, have advantages over conventional interband transition materials such as mercury cadmium telluride (MCT), which suffers serious problems of device uniformity and yield rate.

By devising angle- and polarization-resolved IR spectroscopy techniques, we have shown that conventional wisdom forbidding normal incidence (TE) quantum well intersubband transitions is incorrect. In fact, we have consistently measured equally strong TE- and TM-active intersubband QW absorption peaks and have seen a strain-dependent splitting between these peaks. These results enable us to develop a new theory that considers the symmetry effects on subband Bloch states, which leads to the explanation of polarization selection rules, absorption strength, and splitting in our experimental work (see next section).

By engineering the composition and width of InGaAs quantum well and the InAlAs barrier height, we have successfully measuring the intersubband absorption in the 2 to 5 μm wavelength region based on InGaAs/AlAs/InAlAs SQW the resonant tunneling diode structures. Future work involves using MQW structures to increase photocurrent and applying selective etches to contact the QW directly to realize high performance IR detectors.

1.15 Analysis of the Symmetry Properties of Quantum Well Subband Energy Levels

Sponsors

National Science Foundation
U.S. Army Research Office
Grant DAAL03-92-G-0251

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[9] Harvard University, Cambridge, Massachusetts.

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