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13. ABSTRACT *(Maximum 200 words)*

The goal of this research was to improve our understanding of MBE growth and to apply this understanding to practical devices for electronic and optoelectronic applications. We studied semiconductor quantum wells (QWs), achievable through control of layer thickness with monolayer accuracy, and distributed Bragg reflectors (DBRs) with high reflectivity designed for specific wavelengths. We developed microcavities for both light emitters and detectors, which have resonant cavities on the order of a single wavelength of light. The resonant-cavity photodiode structure in effect decouples the quantum efficiency from the transit-time. Lasers and detectors employing such resonant cavities on the wavelength scale will play an important role in a variety of future optoelectronic applications, and for optical interconnects.

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MBE Growth for Electronic and Photonic Device Applications

Final Report

Ben G. Streetman

July, 1995

U.S. ARMY RESEARCH OFFICE

DAAL03-91-G-0334

The University of Texas at Austin

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A. Statement of the Problem Studied

The goal of this research was to improve our understanding of MBE growth and to apply this understanding to practical devices for electronic and optoelectronic applications. Modern crystal growth methods allow multilayer heterostructures to be incorporated in a variety of novel structures, and we were able to exploit these structures for potentially useful device applications.

For example, semiconductor quantum wells (QWs), achievable through control of layer thickness with monolayer accuracy, have been a rich source of insight into semiconductor physics and have led to novel structures for electronic and photonic device applications.

In the area of optoelectronics, the use of distributed Bragg reflectors (DBRs) with high reflectivity designed for a specific wavelength has allowed us to develop microcavities for both light emitters and detectors. The use of microcavities has revolutionized the design of semiconductor lasers, which now have resonant cavities on the order of a single wavelength of light. Photodetectors also have been changed by incorporating DBRs to form microcavities for absorption. The resonant-cavity photodiode structure in effect decouples the quantum efficiency from the transit-time. It is also possible to introduce additional periodicities in the mirror design to achieve reflectivity at two (or four) separate wavelengths. These wavelength-selective mirrors should have a variety of applications in wavelength division multiplexing. Lasers and detectors employing resonant cavities on the wavelength scale will play an important role in a variety of future optoelectronic applications, and for optical interconnects.

In this research we have grown multilayer heterostructures which allow us to examine these phenomena and have applied many of these structures to devices which have considerable promise for application in electronic and optoelectronic systems.

B. Summary of the Most Important Results

Growth Studies

We have carefully examined the interfaces between multilayer structures grown by MBE, using a combination of RHEED studies and low temperature photoluminescence of quantum well devices. We have studied the influence of substrate temperature and As/Ga incorporation ratio on RHEED dampening, and find a clear correlation between the extent of dampening and the PL linewidths of quantum wells, both increasing with As/Ga ratio. We developed an As flux monitor for use with our As cracking cell, and this new capability allows us to study the influence of As flux on a variety of growth parameters. We studied the influence of As overpressure on GaAs and AlGaAs grown at low temperatures, the evaporation of layers and resulting loss or buildup of impurities, and the efficiency of delta doping.

We studied the effects of changing As_4/As_2 flux ratio from our As cracking source on Si and Be δ-doped GaAs grown by MBE. We found that the carrier concentration increases as the As_4/As_2 flux ratio increases. The spatial confinement of carriers in the induced potential well is also enhanced using high As_4/As_2 flux ratio. These effects were attributed to the enhancement of dopant incorporation by As_4 during the δ-doping growth period. We extended this study using the real-time flux monitoring system mentioned above for control of our valved arsenic source. We studied the influence of growth temperature and As/Ga ratio on RHEED dampening and quantum well photoluminescence. These studies build on earlier work we have done relating RHEED and PL to AsO contamination, growth interruption, and growth of quantum wells on low-temperature grown buffer layers. In collaboration with Wright-Patterson AFB, we have applied *in-situ* ellipsometry to study the As capping of GaAs surfaces and the subsequent removal of the As cap. We also found that this method could be used to assist in accurately controlling the growth conditions of LT GaAs layers. We have applied this technique to the study of critical thickness, relating the ellipsometric response to the formation of submicron polycrystalline regions, as shown by low angle thin film x-ray diffractometry. This technique appears promising for studying semi-insulating layers grown at reduced temperatures.

We have developed techniques for regrowing layers on patterned and etched substrates, to allow more complex device structures to be designed. Epitaxial growth and regrowth on patterned substrates is a useful technique for the development of optoelectronic device structures. There is considerable interest in selective area epitaxy for the planar lateral definition of device structures, but MBE regrowth over patterned substrates has presented difficulties in obtaining good quality epitaxial layers. Air-exposed AlGaAs and even some processed GaAs surfaces can lead to poor regrowth. Therefore, the techniques developed here for regrowth can be applied in a variety of device designs.

Quantum Wells

The interaction between photons and carriers in a quantum well, the optical transition, is governed by the fact that only discrete energy states are allowed for electrons and holes in the well. Not only do quantum wells provide transition energies different from the bulk material, but also population inversion is achieved at a lower threshold current in a QW laser. Confinement of carriers can be substantial in δ-doped quantum wells. For example, we have reported confinement of holes on a scale of about 5 Å in a 50Å QW δ-doped with Be. Carrier confinement can lead to a number of interesting low-dimensional effects including those related to quantum wires and quantum boxes. In the usual quantum well structure, where electrons and holes are well-confined in the potential well region, transition energies occur near the energy gap of the well layer. From the earliest days of MBE, there has been an interest in artificial periodicities available by growth of multilayer heterostructures. Both compositional and doping periodicities can lead to new "miniband" or "subband" conduction of electrons and holes. Superlattice quantum wells (SLQWs) were used in this work to achieve high-energy transitions, which can be varied over a few hundred meV using different AlAs and GaAs layer thicknesses in the SLQWs. We also employed aperiodic layer thicknesses, including random-period superlattices, to further tailor the properties of the quantum wells. Our work on superlattice quantum wells has led to a better understanding of band alignments in these structures and electronic transitions involved in luminescence.

Novel Bragg Mirrors

An extension of the periodic growth of heterostructures is the ability to grow alternating layers of thicknesses corresponding to fractions of a wavelength of light (e.g., $\lambda/4$) in the material. It is therefore possible to simulate mirrors within the device by incorporating distributed Bragg reflectors (DBRs) with high reflectivity designed for a specific wavelength. Recently, mirrors have been made with additional periodicities to achieve the proper phase change and/or delay such that the DBR exhibits reflectivity at two separate wavelengths. We have also achieved two- and four- wavelength mirrors in this work. These wavelength-selective mirrors should have a variety of applications in wavelength division multiplexing. Of particular interest is the use of DBRs to form microcavity structures in which the cavity length is adjustable on the scale of a wavelength of the light being used. This has revolutionized the design of semiconductor lasers, and has led to the use of microcavities in both lasers and detectors, as discussed below.

VCSELs

A major goal of this research has been to apply the results of our ARO-supported materials studies to solve important device problems. The results of our materials studies and MBE growth research have allowed us to make substantial progress in electronic and optoelectronic device development. We have accomplished this goal in the development of vertical cavity surface-emitting lasers (VCSELs). We have made a number of advances in VCSEL development in collaboration with Prof. Dennis Deppe. Our work on VCSEL structures is particularly interesting in that we have been able to incorporate a number of novel MBE growth techniques into these devices. A common problem with VCSEL structures is that current is injected through the same region light is emitted from, unlike edge emitters in which current and light emission are along different directions. Thus, optimizing the top Bragg reflector mirror has in the past led to high series resistance for the current, and a resulting high bias voltage at the threshold for lasing. In addressing this problem, we have succeeded in incorporating a layer of AlGaAs grown at a reduced temperature as a semi-insulating region to allow current funneling from the top contact to the active region of the laser. This AlGaAs region is lattice-matched to the rest of the structure, and we have developed methods allowing selective etching and regrowth to provide the buried semi-insulating current funneling region in these devices. We have reported VCSEL devices employing this structure with CW output power of 5.7 mW at room temperature. The lasers exhibit threshold currents for lasing of 1.9 mA for 10μm diameter devices, with a bias voltage at threshold of only 1.8V. Since high bias at threshold has been a major drawback of most VCSEL structures, this result is considered to be a major advance. We have demonstrated optical switching and memory in a bistable vertical-cavity surface-emitting laser (VCSEL), in which two modes of optical switching are possible by optically addressing different regions of the device. These functions may be important for use in two-dimensional arrays and in future applications in optical computing. The background developed in this ARO-supported research on growth of quantum wells and superlattices, pseudomorphic growth, regrowth on layers after photolithography and etching, and growth of semi-insulating GaAs and AlGaAs, has made these device applications possible.

We have extended the technology of regrowth in lithographically-defined regions by performing an undercutting etch of the semi-insulating AlGaAs layer, leaving an overhanging GaAs layer as a shadow mask for regrowth. As a result, we are now able to grow isolated structures with a buried etched void surrounding the device. We have applied this technology to the VCSEL structure and achieved CW lasing thresholds of 470μA in a device having a diameter of 4μm. We believe this etched-void regrowth technology will have a number of applications in electronic and optoelectronic devices.

Detectors

We have investigated various p-i-n structures which show promise for detectors and other optoelectronic applications. We have done theoretical calculations of the speed and efficiency of multiple p-i-n photodetectors and have studied experimentally the influence of growth temperatures on the photoresponse of low-temperature grown GaAs for use in p-i-n detectors. Recently we have applied the Bragg reflectors available by MBE growth to take advantage of resonant absorption of photons in microcavities, in collaboration with Prof. Joe Campbell. Such resonant cavities can have enormous impact on traditional photodiodes.

The PIN photodiode is the most widely deployed photodetector for photonic applications. The light that enters the photodiode is attenuated exponentially with distance into the absorbing layer, and photogenerated electrons and holes give rise to a photocurrent that is proportional to the incident intensity. There is a tradeoff between the responsivity and the bandwidth of the PIN structure, since to achieve high quantum efficiency a relatively thick absorption layer is required, which in turn requires a longer time to collect the photogenerated carriers. This is the origin of the transit-time limit to the bandwidth.

We have demonstrated a novel resonant-cavity photodiode that circumvents the quantum efficiency-bandwidth tradeoff due to transit time effects. This structure increases the absorption through multiple reflections between two parallel mirrors in a Fabry-Perot cavity whose length is typically a few wavelengths. The lower mirror is an integrated Bragg reflector consisting of alternating $\lambda/4$ epitaxial layers, having a reflectivity >99%. The top mirror is usually a high reflectivity dielectric stack that can be deposited after fabrication and initial characterization.

For resonant-cavity photodiodes having device areas ~ 50 μm^2, bandwidths greater than 100 GHz can be achieved without sacrificing responsivity. The photon buildup time in such a short cavity corresponds to a bandwidth in excess of ~10^{12} Hz and poses no limitation on the speed. This illustrates one advantage of the resonant-cavity approach, namely, that the quantum efficiency can be effectively decoupled from the transit-time. While the improved bandwidth is accomplished at the expense of a narrower spectral response, almost all photonic systems operate within a very narrow wavelength range. In fact, this may be used to advantage for applications such as wavelength-division multiplexing in fiber optic systems. Resonant-cavity structures offer the potential for performance enhancements in several photodetector applications.

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Advanced Degrees Earned While Employed on this Project

MS in Materials Science and Engineering:	Anand Srinivasan
BS in Electrical Engineering:	Andy Tang, Nabeel Atique
MS in Electrical Engineering:	Chad Hansing
PhD in Electrical Engineering:	Thomas J. Rogers, Albert Shih