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13. ABSTRACT *(Maximum 200 words)*

The aim of this research is to examine the structural and optical properties of strained InGaAs/GaAs quantum wells, quantum wires (QWRs) and dots (QDs) using new spatially, spectrally, and temporally resolved electron probes. The presence of defects will degrade the nonlinear optical properties and impact the performance of spatial light modulators and lasers. The carrier recombination dynamics and nonlinear optical properties in nipi-doped InGaAs/GaAs quantum wells were studied using a new approach called electron beam induced absorption (EBIA) modulation. Time-resolved cathodoluminescence (CL) was used to study InGaP and GaAs based QDs and QWRs. Carrier thermalization, ambipolar diffusion, and phase-space filling were studied with CL and EBIA, in an attempt to understand the interrelationship between the optical, transport, and structural properties in strained quantum heterostructures and nanostructures. These findings are expected to influence the design and implementation of these materials in light modulators and lasers, which can be used for digital optical communication, pattern recognition, and target tracking applications.

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Principal Investigator: Prof. Daniel H. Rich

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37. Y. Tang, D.H. Rich, A.M. Moy and K.Y. Cheng, An Optical Method for Studying Carrier Diffusion in Strained $(InP)_2/(GaP)_2$ Quantum Wires, Appl. Phys. Lett., in press.
36. X. Zhang, D.H. Rich, C.K. Lin, and P.D. Dapkus, Cathodoluminescence study of disordering of GaAs/AlGaAs quantum wells using an AlAs native oxide and thermal annealing technique, submitted to J. Appl. Phys.
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In-situ fabrication of three-dimensionally confined GaAs and InAs volumes via growth on non-planar patterned GaAs(001) substrates, J. Cryst. Growth **150**, 311 (1995).

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1. R.S. Goldman, K. Rammohan, A. Raisanen, M. Goorsky, L.J. Brillson, D.H. Rich, H.H. Wieder, and K.L. Kavanagh, Anisotropic Structural and Electronic Properties of InGaAs/GaAs Heterojunctions, Mater. Res. Soc. Symp. Proc. **340**, 552 (1994).

Description of Primary Projects:

A. Development of Electron Beam-Induced Absorption (EBIA) Modulation

The results of this work during this period are described in the submitted and published manuscripts as listed above. Briefly, the nonlinear optical and transport properties of *nipi*-doped InGaAs/GaAs multiple quantum well samples have been studied using a novel approach called electron beam-induced absorption-modulation (EBIA). The absorption in the samples is modulated as a result of screening of the built-in electric field in the *nipi* structure due to excess carrier generation. The change in field causes a Stark shift of the first quantized optical transitions in QWs which are situated in the intrinsic layers. In EBIA, a scanning electron probe is used to locally generate an electron-hole plasma that is used to study the spatial distribution of defects that impede excess carrier transport and reduce the lifetime of spatially-separated carriers. The local plasma serves as a probe that evaluates the way in which defects change the screening of the bulit-in field. The Stark shift in the MQW structure is imaged with μm-scale resolution and is compared with cathodoluminescence (CL) imaging results which show dark line defects resulting from strain-induced misfit dislocations. Theoretical calculations using Airy functions in the transfer-matrix method were used to determine the energy states, wavefunctions, and carrier recombination lifetimes of the MQW as a function of the built-in field. A quantitative phenomenological analysis is employed to determine the built-in field, excess carrier lifetime, and ambipolar diffusion coefficient as a function of the excitation density. The defects are found to create potential barriers and recombination centers which impede the transport and markedly reduce the excess carrier lifetime.

B. Implementation of polarized CL to study local strain variations

We have also investigated local variations in the optical properties of InGaAs/GaAs using linearly polarized cathodoluminescence imaging and spectroscopy. The influence of substrate misorientation on the polarization anisotropy of excitonic luminescence in the InGaAs films was examined. Local variations in excitonic polarization anisotropy and emission energy are found to correlate spatially with dark line defects which result from the formation of interfacial misfit dislocations. These findings could have significant ramifications on the designs of future SLM devices. The ability to tailor the polarization properties by varying the substrate misorientation, film thickness, and growth conditions could enable the development of light modulators based on polarization modulation. This would be a novel approach for SLM applications with the InGaAs/GaAs system, and we are just beginning to explore this possibility.

C. Studies of $(InP)_2/(GaP)_2$ quantum wires

The nonlinear optical properties of $(InP)_2/(GaP)_2$ bilayer superlattice (BSL) structures have been examined with linearly polarized cathodoluminescence (LPCL) spectroscopy. Transmission electron microscopy showed a composition modulation with periods of 100 to 800 Å along the [110] direction, which occurs spontaneously during the growth, resulting in coherently strained quantum wires. The strong excitation dependence of the polarization anisotropy and energy of excitonic luminescence from the quantum wires was found to be consistent with a band filling model, that is based on **k·p** and 2D quantum confinement calculations. A temperature dependence of the QWR luminescence decay time reveals that thermal activation of carriers in the QWR and transfer to and from $In_{0.49}Ga_{0.51}P$ barriers play an important role in determining the measured lifetimes. The presence of disorder in the QWRs was found to induce inhomogeneous regions which exhibit large variations in carrier capture and band-filling.

D. Carrier kinetics of AlGaAs/GaAs quantum boxes

The kinetics of carrier relaxation in GaAs/AlGaAs QWs, QWRs, and QDs have been studied with time-resolved CL. In the cases of QWRs and QBs, the nanostructures were grown via a size-reducing growth approach on pre-patterned GaAs(001) substrates composed of stripes and mesas, respectively. The growth involved deposition of multiple GaAs/AlGaAs layers in order to establish both structural and optical markers which facilitated the identification of important features in transmission electron microscopy (TEM) and CL experiments. In TEM measurements, the lateral dimensions of the top most GaAs layers in typical stripe and mesa structures comprising the QWRs and QBs delineate GaAs regions expected to exhibit 2D and 3D quantum confinement effects, respectively. Time-delayed CL spectra of all three structures reveal that the initial capture of carriers in the active regions occurs on a time scale less than the temporal resolution of the CL system, ~100 ps, during the onset of luminescence. Hot carriers, as a result of re-emission out of thin QWs surrounding the QWRs and QBs, exhibit diffusive transport followed by relaxation into laterally-confined regions which exhibit confined states of lower energy. This thermalization gives rise to a relatively slow onset and decay of luminescence attributed to the lowest energy optical transitions. By comparing time-resolved CL transients in these three structures, we find that the average luminescence onset and initial-decay rates both decrease as the dimensionality of the system reduces from 2D to 0D. These results demonstrate that the rate of carrier relaxation, including the re-emission and diffusive transport of carriers, will depend on details of the *total* surrounding structure which comprises the excitation region.

E. Studies of heterojunction phototransistors under operating conditions

We have studied the influence of misfit dislocations on hole accumulation in the base layer of *n*-AlGaAs/*p*-GaAs/*n*-InGaAs heterojunction phototransistors (HPTs). Spatially and temporally resolved cathodoluminescence (CL) measurements reveal that variations in the hole accumulation is caused primarily by strain-induced defects which impede the transport of holes in the collector. The lifetime of holes in the InGaAs/GaAs collector is found to be negligibly affected by the underlying misfit dislocations in the InGaAs/GaAs collector. The reduction in the local electron-beam-induced current (EBIC) signal by the dislocations is less than ~20%, indicating that these defects have a minor impact on the overall device performance.

F. Optical properties of strained high electron mobility transistor (HEMT) samples

We have also examined the influence of strain relaxation on the excitonic recombination and diffusion in $In_{0.2}Ga_{0.8}As/Al_xGa_{1-x}As$ quantum well (QW) samples designed for high-electron mobility transistors, using spectrally and spatially resolved polarized cathodoluminescence (CL). Six molecular beam epitaxial grown samples, with varying channel thicknesses ranging from 75 to 300 Å, were examined at various temperatures between 87 and 300 K. An increase in misfit dislocation density occurred with increasing channel thicknesses and resulted in changes in the dark line defect (DLD) density, polarization anisotropy, QW excitonic luminescence energy, and luminescence activation energy, as observed in CL. The influence of misfit dislocations on the ambipolar diffusion of excess carriers in a direction parallel to the dislocation line, in varying proximity to the DLDs, was examined with a CL-based diffusion experiment. The temperature dependence of the CL imaging was examined, enabling a study of the spatial variation of the activation energies associated with thermal quenching of the $GaAs/Al_{0.25}Ga_{0.75}As$ multiple QW and $In_{0.2}Ga_{0.8}As$ QW luminescence.

In short, we have studied the interplay of structure and recombination dynamics in a variety of heterostructure and nanostructure systems. An essential theme that has emerged in these studies is that the use of novel probes in the SEM can facilitate the observation and measurement of fundamental quantities that shed light on the way defects and structure influence the optical and electronic properties. These results are expected to impact current thinking in the implementation of light modulators and lasers.

Description of Actual Expenditures from 7/15/94 through 11/14/1997

1) Salary for P.I., Prof. D. Rich	18,409.72
2) Fringe Benefits	5,735.21
3) Salaries for Research Assistants	48,068.88
4) Materials and Supplies	5,420.33
5) Equipment	10,229.86
6) Travel Expenses	3,152.00
7) University Services	1,553.00
8) Overhead	52,431.00
TOTAL	145,000.00