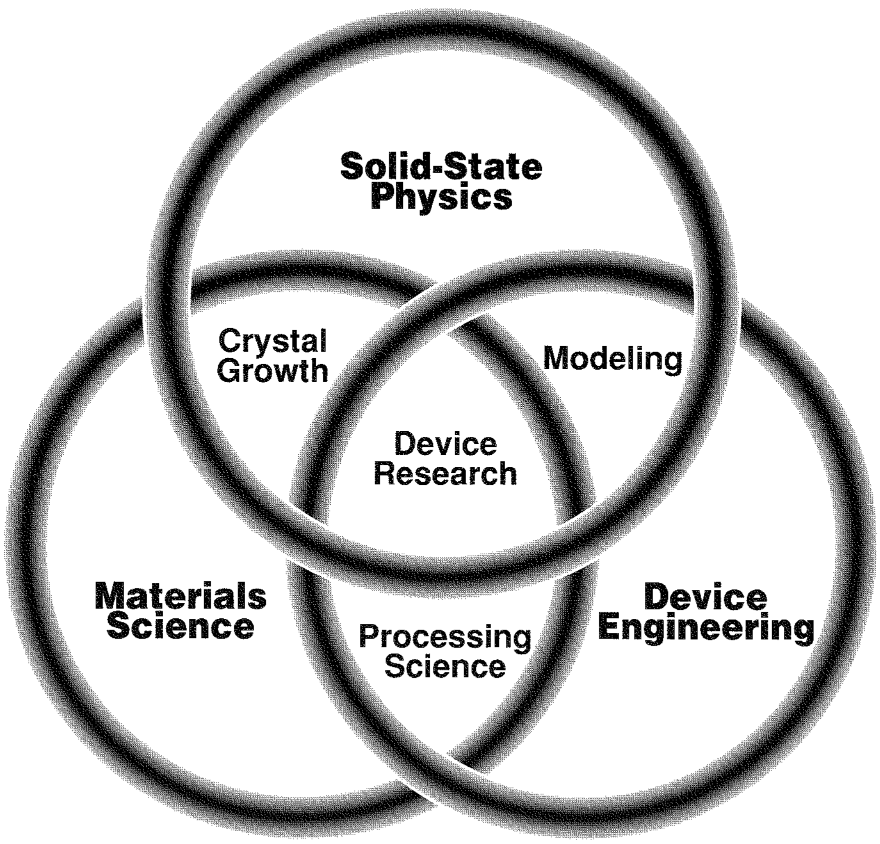
2/21-90 JS(1)

CENTER FOR COMPOUND SEMICONDUCTOR TECHNOLOGY

CCST RESEARCH BRIEFS

Volume 1, Number 2

December 1989



Compound Semiconductor and Device Research Department

Sandia National Laboratories
P.O. Box 5800, Albuquerque, NM 87185

SAND--89-2784

DE90 006446

Foreword...

The Center for Compound Semiconductor Technology (CCST) was formed within the Solid-State Sciences Directorate at Sandia National Laboratories in 1988, culminating a long-term thrust into compound semiconductor research and technology that began about ten years ago. At that time, it was realized that electronic and optoelectronic devices based on compound semiconductors would be necessary for photonic applications, and that they could provide greater radiation hardness, higher speed, and higher operating temperatures than comparable silicon devices and circuits. It was also realized that a successful program would require the development and integration of materials growth and processing capability, solid-state physics research, and device engineering. The program at Sandia grew steadily from the purchase of the first molecular beam epitaxy (MBE) system in 1981, and the discovery of strained-layer superlattices in 1982, to the completion of the Compound Semiconductor Research Laboratory in 1989. To more formally organize this effort, the CCST was established in 1988, aided by $10M of funding from DARPA. The CCST comprises most of the compound semiconductor research and development activities in the Solid-State Sciences Directorate. Ongoing programs are funded by the DOE Office of Military Application, DOE Basic Energy Sciences, DOE Conservation and Renewable Energy, and the Department of Defense.

Frederick L. Vook
Director, Solid-State Sciences

About the Center...

The Center for Compound Semiconductor Technology (CCST) at Sandia National Laboratories encompasses the full range of required activities—theoretical and experimental solid-state physics, materials science, crystal growth, device design, and fabrication—to develop the next generation of electronic and optoelectronic devices. Semiconductor electronics are vital to the communications and computer industries and to the nation's defense. Compound semiconductors offer very high speed electronics and integrated optical and electronic capabilities not available with silicon, and will underlie future electronic, optoelectronic, and photonic technologies.

The purpose of the CCST is to perform collaborative research generic to electronic and optoelectronic technologies in compound semiconductors. Facilities in the CCST include extensive Molecular Beam Epitaxy (MBE) and Metal-Organic Chemical Vapor Deposition (MOCVD) crystal growth capabilities, a 400-keV ion implanter, and a new 3700 net sq. ft. class 1000/100 clean room with state-of-the-art processing equipment. Addition of an e-beam lithography system to permit fabrication of devices with feature sizes below 100 nm is planned for the near future.

Research in the CCST includes numerous collaborative programs with scientists and engineers from universities, industry, and government laboratories. The number of collaborative programs is increasing rapidly, and additional collaborations are welcome.

Paul S. Peercy,
Director, CCST

(505)844-4309

About the CCST Research Briefs...

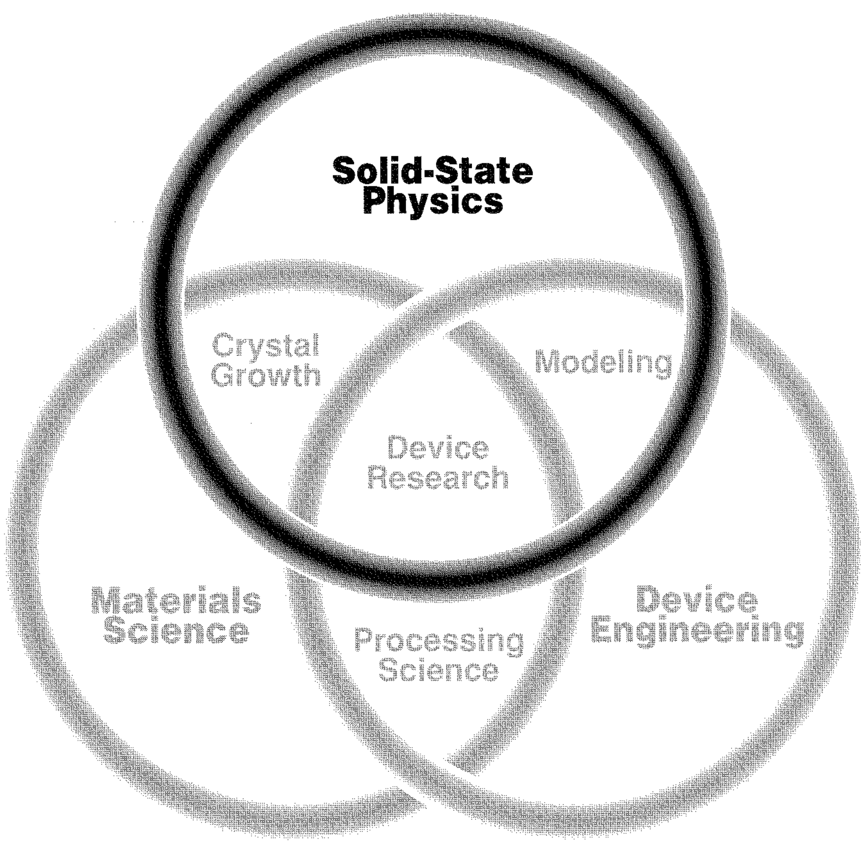
This booklet contains selected highlights of recent research accomplishments at the CCST. If you wish additional information on selected topics, please contact the authors directly. For information on the CCST or to inquire about a joint program with the CCST, please contact the Director.

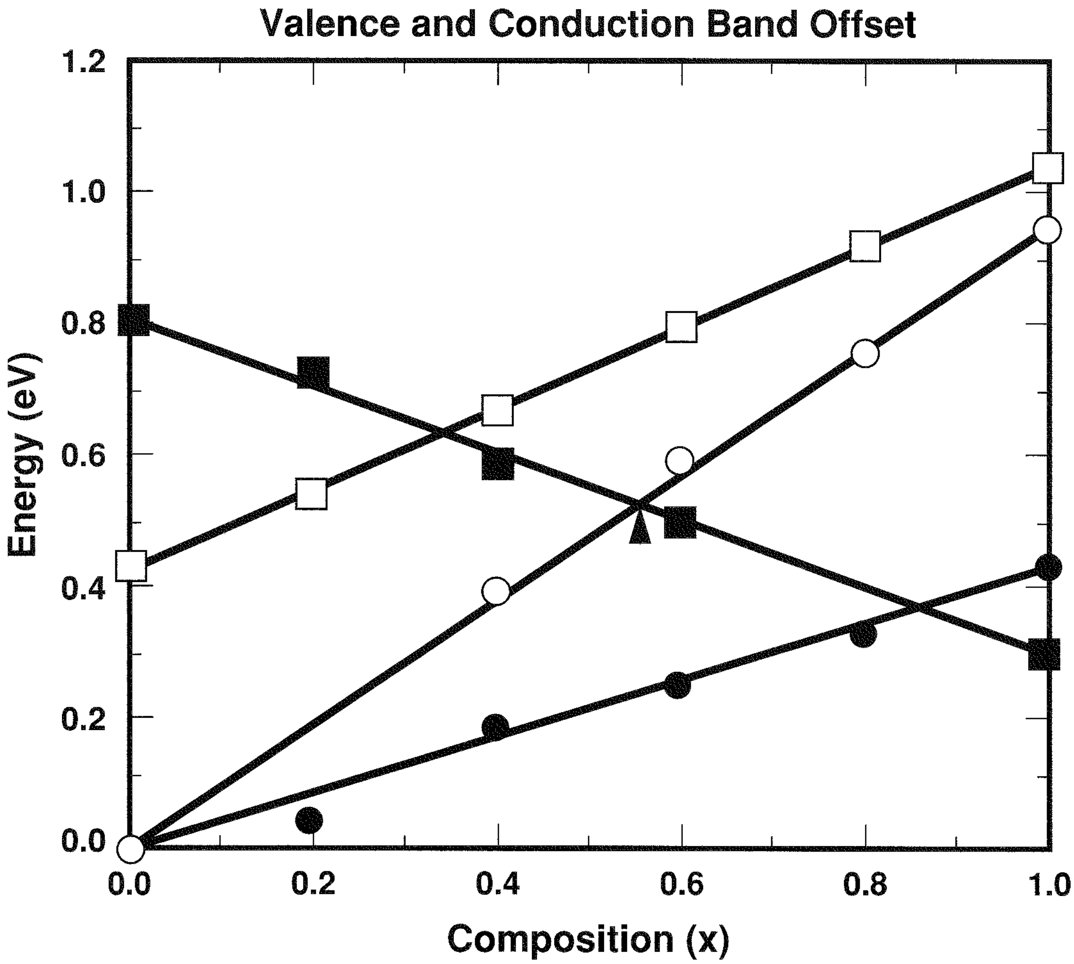
Commonly Used Abbreviations and Acronyms

AlAs	aluminum arsenide
AlAsSb	aluminum arsenide antimonide
AlGaAs	aluminum gallium arsenide
CCST	Center for Compound Semiconductor Technology
CdTe	cadmium telluride
EPI	electron-phonon interaction
ER	electroreflectance
FET	field-effect transistor
GaAs	gallium arsenide
HgCdTe	mercury cadmium telluride
HTS	high-temperature superconductor
InAlAs	indium aluminum arsenide
InAsSb	indium arsenide antimonide
InGaAs	indium gallium arsenide
InP	indium phosphide
InSb	indium antimonide
IR	infrared
MBE	molecular beam epitaxy
MOCVD	metal-organic chemical vapor deposition
MQW	multiple quantum well
PDTEP	phonon-drag thermoelectric power
PL	photoluminescence
QW	quantum well
REMS	reflection mass spectrometry
Si	silicon
SQW	strained quantum well
SLS	strained-layer superlattice

Index to this issue

SOLID - STATE PHYSICS





First-principles, self-consistent pseudopotential calculations of the valence and conduction band offsets of $Al_xGa_{1-x}As$ disordered alloys. The calculated valence band offset of GaAs/AlAs is 0.44 eV. The arrow in the figure indicates the Γ-X crossover of the conduction band. The filled circles, open circles, filled squares, and open squares represent the Γ_{15v}, Γ_{1c}, X_{1c}, and L_{1c} states, respectively.

Theoretical Predictions of Valence and Conduction Band Offsets in III-V Semiconductors

The experimental search for new semiconductor heterostructures for novel device applications can be costly and time-consuming. Theoretical predictions of the electronic properties of III-V heterojunctions can help narrow the search to material systems with the most potential for success. Two of the most important electronic parameters for device design are the valence and conduction band offsets. Values of these parameters obtained from simple physical arguments can often be erroneous and misleading. Recently, *ab initio* self-consistent pseudopotential calculations were developed that can predict band offsets in good agreement with experiment. These calculations rely only on the atomic number of the elements that form the heterostructure.

A new program developed by CCST researchers has made it possible to calculate the valence and conduction band offsets for disordered III-V semiconductors, $A_xB_{1-x}C$. Presently, we are investigating the lattice-matched indium arsenide (InAs)/aluminum arsenide antimonide (AlAsSb) alloy system for possible applications as III-V memory devices. Preliminary calculations suggest that ~93% of the bandgap difference occurs in the conduction band, making this system a good candidate for electron storage. We also found that interfacial strain can have a significant effect (>0.1 eV) on the band offsets, even in lattice-matched alloys.

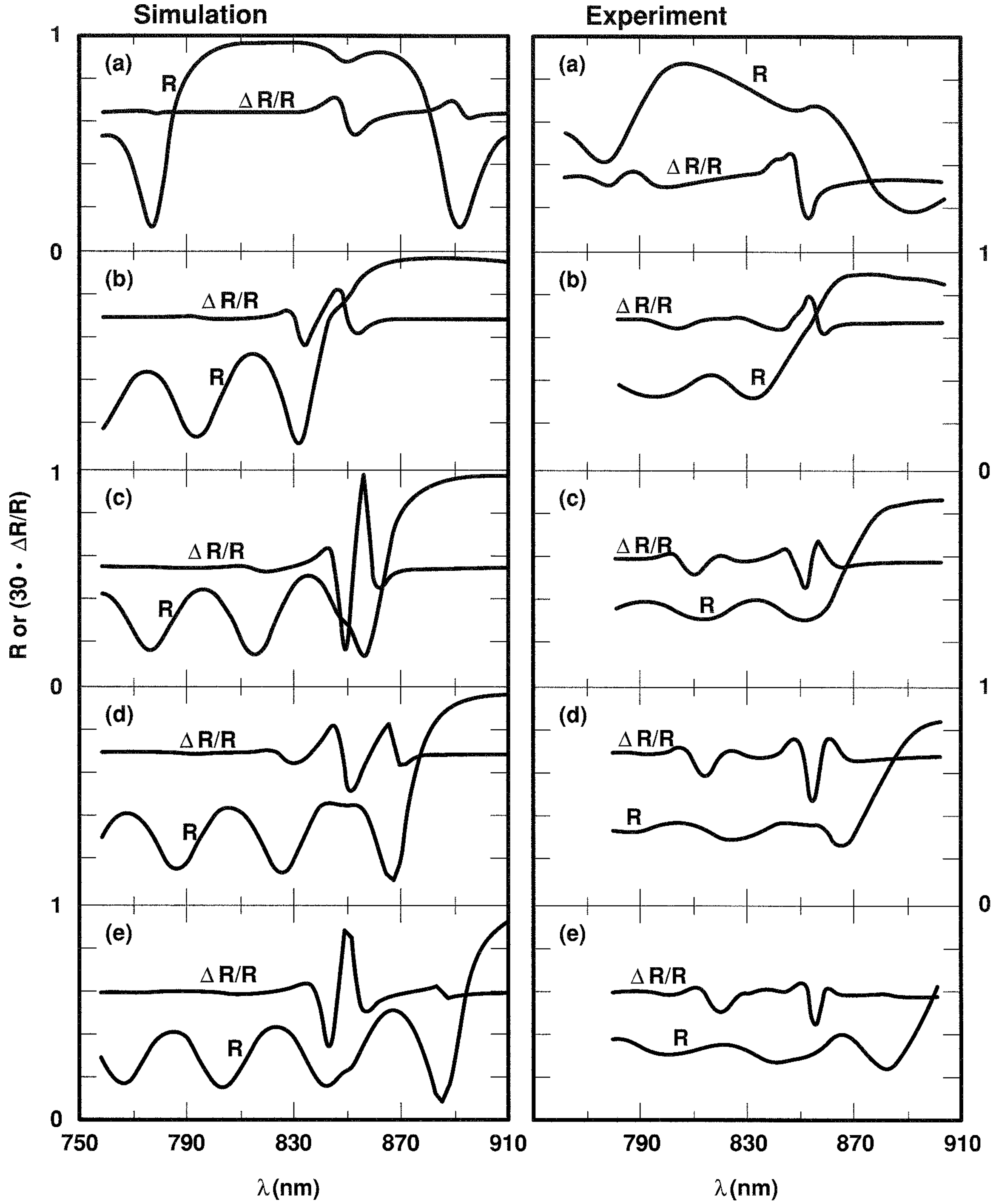
This research will allow more efficient searches for optimum material systems for particular optoelectronic device applications.

For further information:

I. P. Batra, S. Ciraci, and J. S. Nelson, "Confined States and Stability of GaAs-AlAs Superlattices," J. Vac. Sci. Tech. B 5, 1300 (1987).

Principal investigator:

J. S. Nelson, (505)846-7388



Computer simulations and experimental results for reflectance (R) and electroreflectance (ΔR/R) spectra in a semiconductor mirror structure containing quantum wells. The mirror is made up of alternating blocks of AlAs/AlGaAs and AlGaAs/GaAs multiple-quantum-well layers. The band-edge excitonic transition is located at λ = 850 nm. Panels (a) through (e) represent structures with progressively increasing layer thickness. The simulations and data both show complicated lineshapes resulting from the interaction of the exciton line with the spectrum of the mirror.

Reflectance Modulation of a Semiconductor Superlattice Optical Mirror

Modern epitaxial techniques of crystal growth allow fabrication of high-quality, all-semiconductor multilayered structures exhibiting strong and electrically controllable optical interference effects. Such structures include stacked quarter-wave "plates" to form mirrors, Fabry-Perot etalons, and interference filters. These multilayers have potentially important applications in integrated optoelectronic devices such as reflectance or transmission modulators, surface-directed emitters, and selective wavelength photodetectors.

Researchers at the CCST are developing novel experimental and theoretical tools to study the effects of electric fields on the optical properties of these complicated multilayered structures. One technique, electroreflectance (ER) spectroscopy, studies the small-signal electric field response of semiconductor mirror structures. The mirror consisted of a stack of quarter-wave plates of alternating high and low refractive index material, with each plate actually being a multiple-quantum-well (MQW) structure. Because of an interaction of the MQW excitonic response with the multilayered mirror response, the ER spectra exhibit unusual features not predicted by standard ER theory. The spectra were successfully modeled by recently developed computer simulations of the overall optical response.

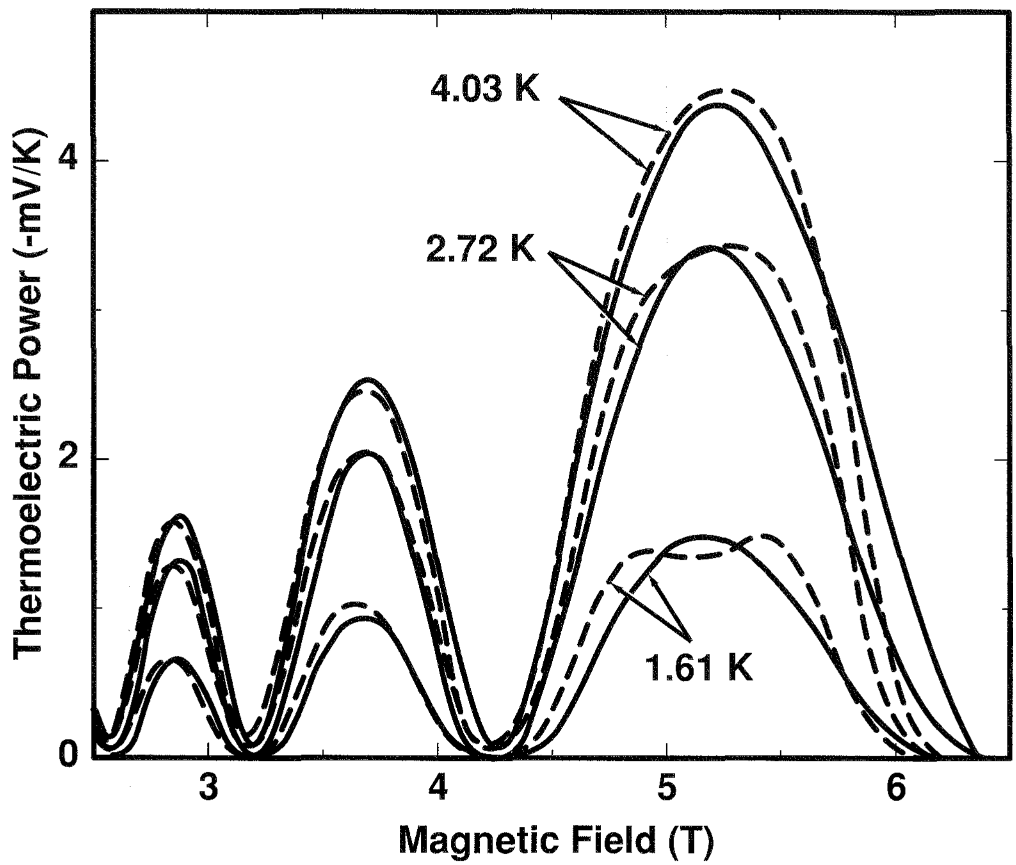
The computer simulations of ER spectra in a complicated multilayered structure provide, for the first time, a description of the interplay between field-tunable electronic properties (e.g., the quantum-confined Stark effect) and the overall reflectance/transmittance of the multilayer. This work provides a framework for studying the characteristics of various field-tunable optoelectronic devices made from complex, multilayered semiconductor structures.

For further information:

I. J. Fritz, P. L. Gourley, and T. J. Drummond, "Electric Field Response of a Semiconductor Superlattice Optical Mirror from Electroreflectance Spectra," Appl. Phys. Lett. 55, 1324 (1989).

Principal investigators:

I. J. Fritz, (505)844-7789; and P. L. Gourley, (505)846-6291



Comparison of the theoretical (solid curves) PDTEP with experimental data (dashed curves; R. Fletcher, et al., J. Phys. C 21, 2681 (1988)) at three temperatures.

Magnetoquantum Oscillations of the Phonon-Drag Thermoelectric Power in Quantum Wells

Electron-phonon interactions (EPIs) profoundly affect the transport properties of modulation-doped semiconductor quantum wells (QWs). Structures of this sort are used in high-performance field-effect transistors (FETs) for high-frequency analog and digital integrated circuit applications. EPIs couple aspects of the electron transport (e.g., mobility) in QWs to the phonon dynamics and determine the ultimate speed of carriers (and hence of devices). EPIs are also responsible for a complex transport effect called the phonon-drag thermoelectric power (PDTEP), which provides a powerful method to probe and analyze EPIs.

Recently, CCST researchers obtained a theoretical understanding of the PDTEP by solving coupled electron and phonon Boltzmann equations with and without quantizing magnetic fields. This new theory describes the momentum and energy transfer between the electrons and phonons that occurs through screened deformation-potential and piezoelectric interactions. Excellent agreement is obtained between theory and experiment for the temperature and field dependences of the PDTEP. The theory also explains recent observations of anomalously large quantum oscillations of the thermoelectric power in gallium arsenide (GaAs)/ aluminum gallium arsenide (AlGaAs) heterojunctions.

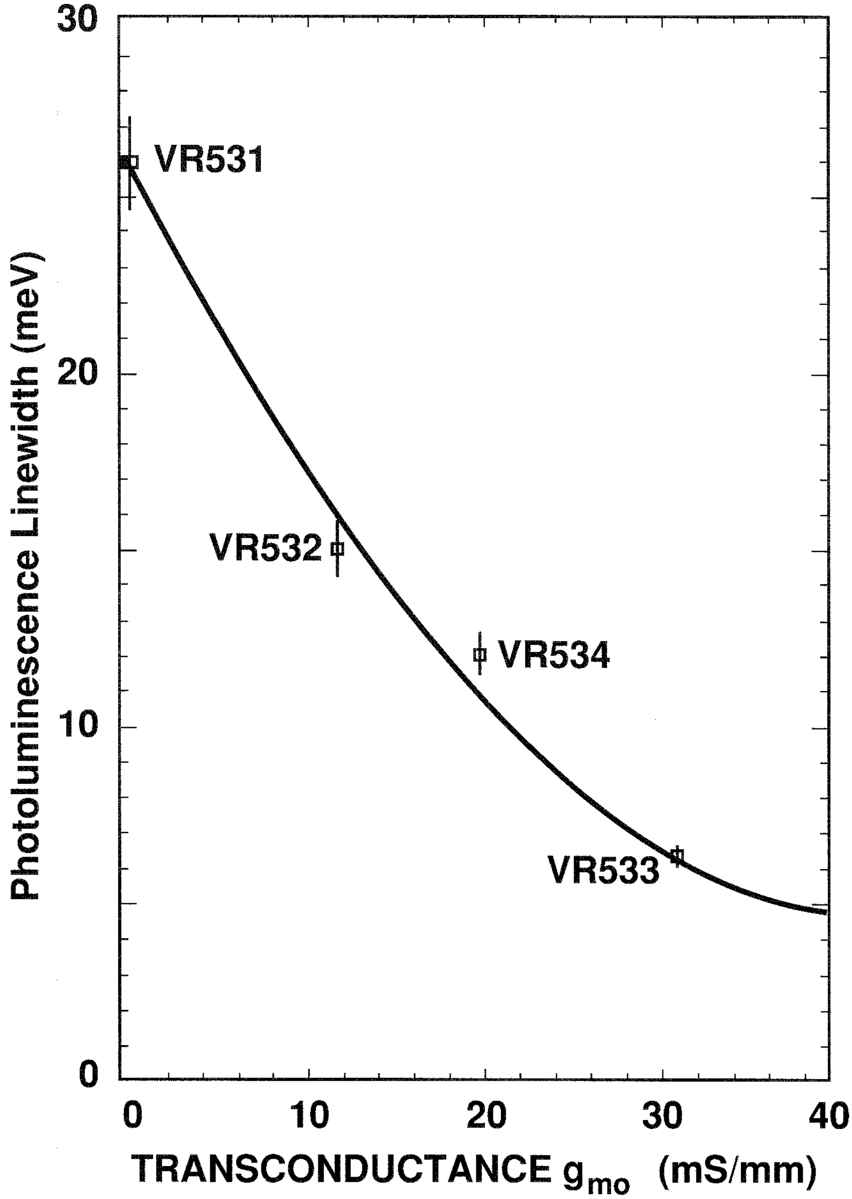
Insights into details of EPIs given by this new theory offer interesting possibilities. The large PDTEP effect may be used to enhance the intrinsic mobility of carriers in QWs, thus possibly significantly increasing the speed of FETs. The PDTEP effect may also be useful for developing phonon detectors.

For further information:

S. K. Lyo, "Magnetoquantum Oscillations of the Phonon-Drag Thermoelectric Power in Heterojunctions," Phys. Rev. B 40 (Rapid Commun.), 6458 (1989).

Principal investigator:

S. K. Lyo, (505)844-3718



Low-temperature photoluminescence linewidth from GaAs/$In_{0.2}Ga_{0.8}As$/GaAs p-channel strained-quantum-well field-effect transistors plotted as a function of the room-temperature normalized extrinsic transconductance, g_{mo} (V_{DS} = -2.0 V).

Correlation Between Photoluminescence Line Shape and Device Performance of p-Channel Strained-Layer Materials

In the development of new devices and circuits from artificially structured solid-state materials, significant costs in both time and money are associated with device processing and delays between material growth and the feedback of information about the initial material quality. In conventional development protocol, samples must undergo a full device fabricational sequence and must be electrically tested before such information is available. In these situations, diagnostic techniques for screening materials before device fabrication are extremely valuable.

CCST researchers have developed a photoluminescence (PL) diagnostic technique for material characterization and screening of p-type strained-quantum-well (SQW) structures in the indium gallium arsenide (InGaAs)/gallium arsenide (GaAs) heterojunction system. The new technique uses the observation of correlation between the low-temperature (4 K) PL linewidth and the room-temperature extrinsic transconductance, g_{mo}, of field-effect transistors (FETs) fabricated from these materials. The 4 K photoluminescence linewidth in heavily doped p-type materials decreased from ~30 to 6 meV for structures whose extrinsic transconductance increased from 0.4 to 31 mS/mm. Besides providing a screening technique for SQW materials, these techniques also permit identification and optimization of the material parameters responsible for changes in the PL linewidth and the terminal characteristics of FETs.

This new technique provides a valuable tool for materials characterization and optimization before FET device fabrication in SQW GaAs/InGaAs structures. Furthermore, these procedures can be extended to n-type SQW structures.

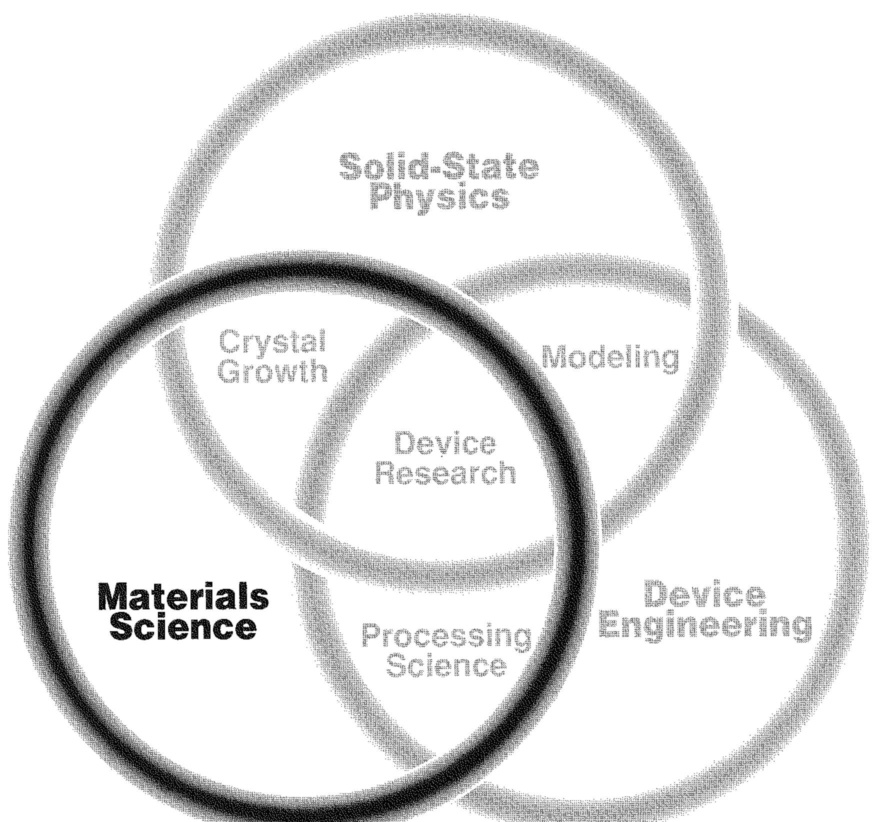
For further information:

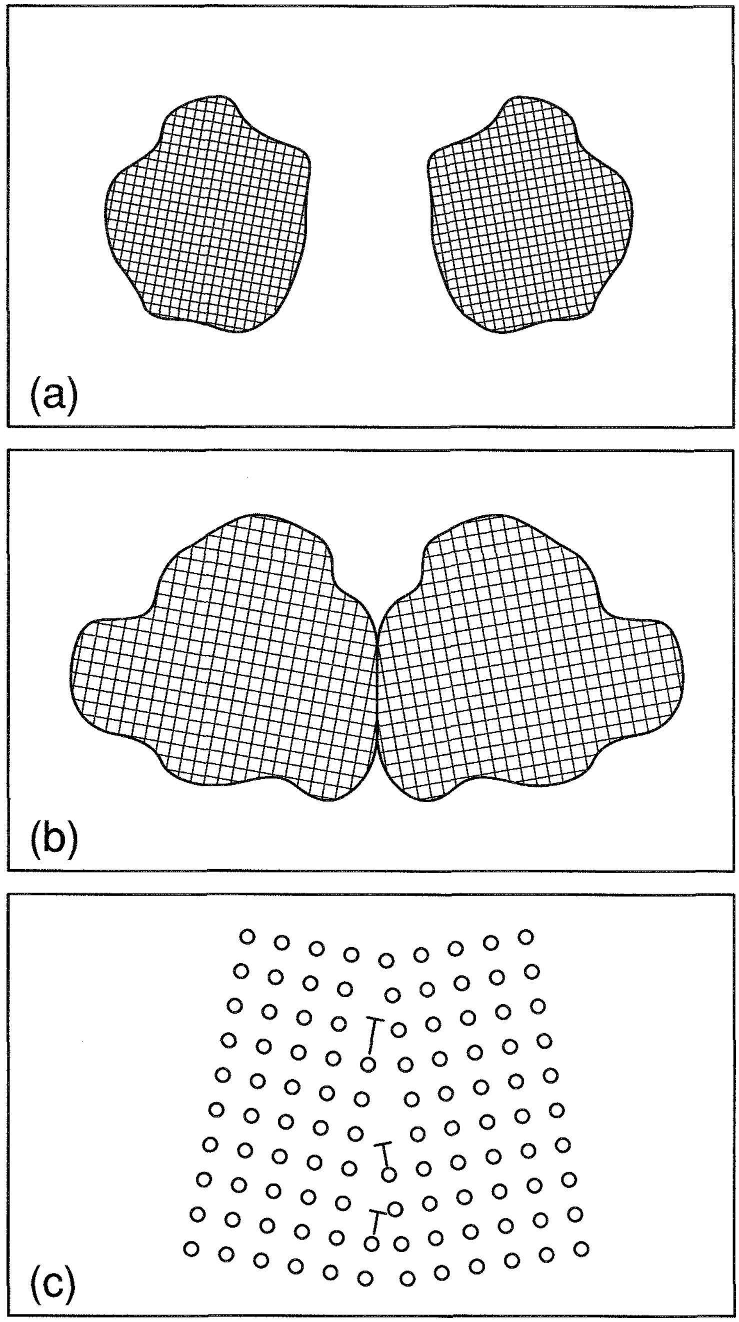
E. D. Jones, T. E. Zipperian, S. K. Lyo, J. E. Schirber, and L. R. Dawson, "Correlation Between Photoluminescence Data and Device Performance of p-Channel Strained-Layer Materials," accepted for publication in J. of Electr. Mat. (1990).

Principal investigators:

E. D. Jones, (505)844-8752; and T. E. Zipperian, (505)844-6407

Materials Science





Growth of heterostructures often occurs by means of 3-D island formation. In this case, isolated islands are produced on the surface (a) that twist slightly (exaggerated in figure) to reduce energy. These islands then merge to form a continuous layer (b) producing low-angle grain boundaries and a dense network of threading dislocations. Schematic atomic structure (c) shows that these dislocations are intrinsic to the global structure and hence are difficult to remove. Growth techniques are required that force 2-D growth in such material systems.

Control of Threading Dislocations in Heteroepitaxial Structures

A major obstacle in applying semiconductor heterostructures to new classes of electronic devices is that large densities of threading dislocations (dislocations terminating on the growth surface) often appear after crystal growth. This is particularly true in structures formed from materials with large amounts of lattice mismatch. Such dislocations provide effective centers for both strain relaxation and electron-hole recombination, making impractical many strained-layer and/or minority-carrier devices. Considerable effort has gone into developing dislocation filtering techniques to address this problem.

An ongoing CCST project on structural breakdown of heterostructures recently focused on this little-understood phenomenon. Past models, based on quasi-equilibrium processes driven by excess stress, disagree significantly with experimental observations. CCST researchers have developed a fundamentally new model for dislocation filtering based on trapping of nonequilibrium configurations encountered during crystal growth. The new model is consistent with all experiments to date. A new mechanism was also identified that is responsible for the failure of dislocation filtering in high-mismatch structures. In these systems, misaligned 3-D islands appear during growth and coalesce to form low-angle grain boundaries. These boundaries are composed of special threading dislocations that require very rapid atomic diffusion for effective filtering.

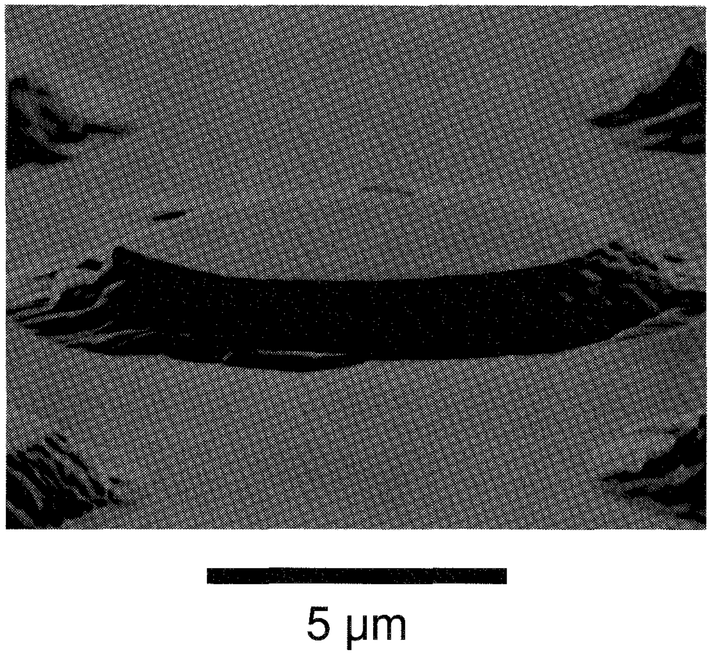
Understanding sources of threading dislocations and dislocation filtering mechanisms is vital to the future of high-quality semiconductor heterodevices. Examples of such applications include gallium arsenide (GaAs)-on-silicon (Si) epitaxy for integrated GaAs and Si devices, heterostructural complementary logic circuits, and strained-layer laser arrays. Our new understanding of this important process will provide a foundation for developing such novel applications.

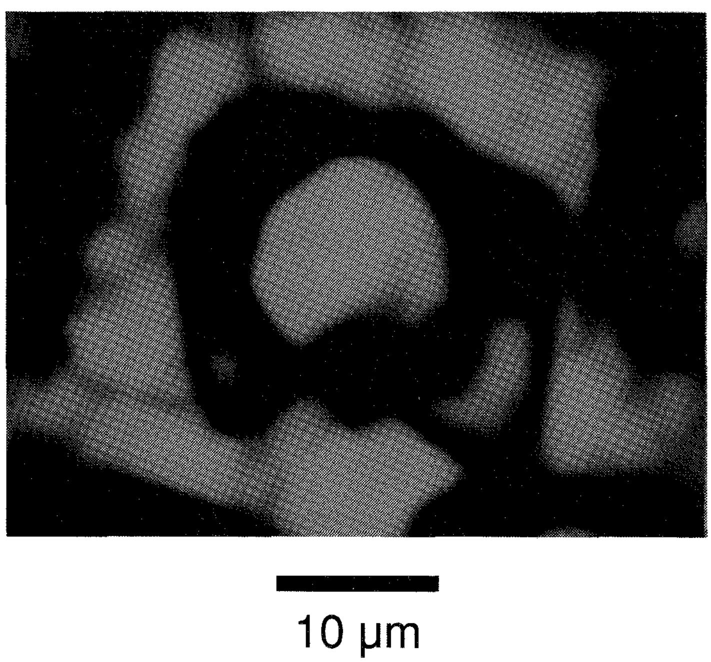
For further information:

B. W. Dodson, "On the Erratic Nature of Dislocation Filtering in Semiconductor Heterostructures," submitted to J. Mat. Res. (1989).

Principal investigator:

B. W. Dodson, (505)844-5459





Scanning electron microscope (SEM) picture (top) and photoluminescence micrograph (PLM) (bottom) of 5.5 µm of CdTe (111) epitaxially deposited on a prepatterned GaAs substrate. Dislocations are imaged by PLM as dark areas. The CdTe exhibits very dark rings resulting from the high number of dislocations at the mesa edge. The low number of dark spots on the mesa tops (inside the dark rings) indicates the high quality of the CdTe.

Improved Growth of CdTe on GaAs by Patterning

Infrared detectors that operate in the range of 8 to 12 μm are of great technological and military importance. One material of interest for this application is mercury cadmium telluride (HgCdTe). Development of this system has been severely hampered by material problems, including the lack of an appropriate substrate. Cadmium telluride (CdTe), the most obvious choice, is quite fragile and expensive. The use of gallium arsenide (GaAs) as a substrate would alleviate these problems, but the large mismatch (~14.5%) with CdTe and HgCdTe produces many dislocations in the layers.

To reduce the dislocation density of CdTe grown on GaAs, researchers within the CCST patterned the surface of the GaAs substrates before growth of CdTe by molecular beam epitaxy (MBE). Mesas were etched on the GaAs using standard photolithography techniques and reactive ion etching. In initial experiments with 12-μm-diameter mesas located 22 μm apart, CdTe grown by MBE on the mesa tops was found to be free of twin boundaries and to contain only a few dislocations. This yielded a reduction in the dislocation density of about one order of magnitude compared to growth directly on the unpatterned substrate.

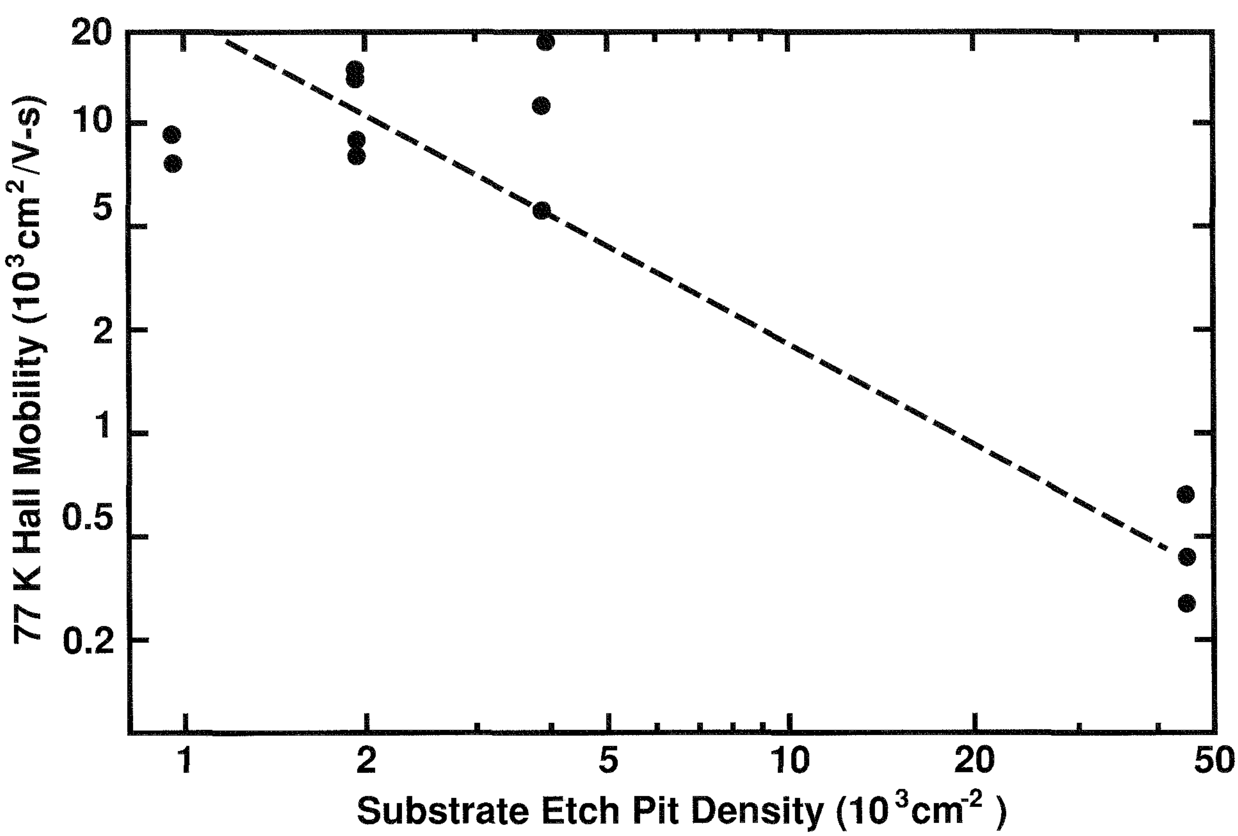
This work demonstrates that high-quality CdTe can be grown on GaAs substrates, making possible the growth of large areas of HgCdTe on a relatively strong substrate. Optimization of the patterning and growth technology is in progress.

For further information:

J. L. Reno, M. J. Carr, and P. L. Gourley, "The Growth of High Quality CdTe on GaAs by Molecular Beam Epitaxy," Proc. of the U. S. Workshop on the Physics and Chemistry of HgCdTe and Related Compounds, San Diego, CA, October 1989.

Principal investigators:

J. L. Reno, (505)844-9677; and P. L. Gourley, (505)846-6291



Hall mobilities at 77 K for 140-Å-thick, $In_{0.26}Ga_{0.74}As$ quantum-well structures grown on GaAs substrates as a function of the substrate etch-pit (threading dislocation) density. The structure grown on a moderate defect-density substrate (~45,000 cm^{-2}) has undergone a catastrophic degradation because of the formation of misfit dislocations at the strained interface.

Role of Substrate Threading Dislocations in Relaxation of Highly Strained Single-Quantum-Well Structures

The inclusion of strained layers in semiconductor device structures allows a new degree of flexibility in tailoring the characteristics of these devices through choice of alloy compositions, layer thicknesses, and strain. Limitations exist, however, on the degree of strain and thickness of strained layers that may be used in coherent, stable structures. When these limits are exceeded, the structure degrades by the formation of misfit dislocations at the strained interfaces.

Recently, CCST researchers investigated the mechanisms by which highly strained, metastable indium gallium arsenide (InGaAs)/ gallium arsenide (GaAs) single-quantum-well structures relax. Because the GaAs substrates on which these structures are grown contain moderate densities of threading dislocations, these dislocations are suspected to be sources of misfit dislocations at the strained interfaces. Identical layers, with thicknesses nearly 50% greater than the established critical thickness for stable structures, were grown on substrates with both moderate (5×10^4 cm^{-2}) and low (1 to 4×10^3 cm^{-2}) densities of threading dislocations. Characterization of these structures reveals that a moderate density of substrate dislocations leads to catastrophic degradation of the optical and electrical properties of the layers, while samples grown on substrates with low dislocation densities show much less degradation.

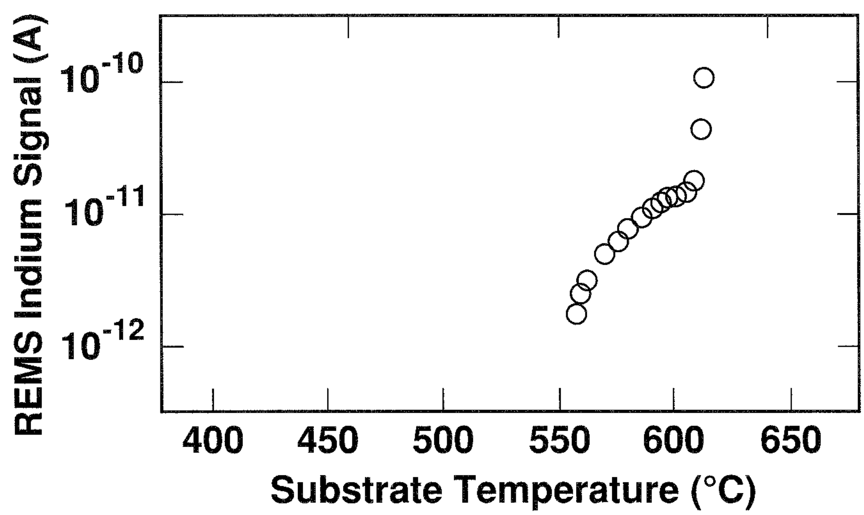
These results have important implications for the successful growth of metastable strained layer devices. Metastable structures are desired when device performance can benefit from the use of thick, highly strained layers, and when high-temperature processing is not necessary. In these situations, the use of low threading dislocation substrates is crucial to obtaining high-quality strained-layer material.

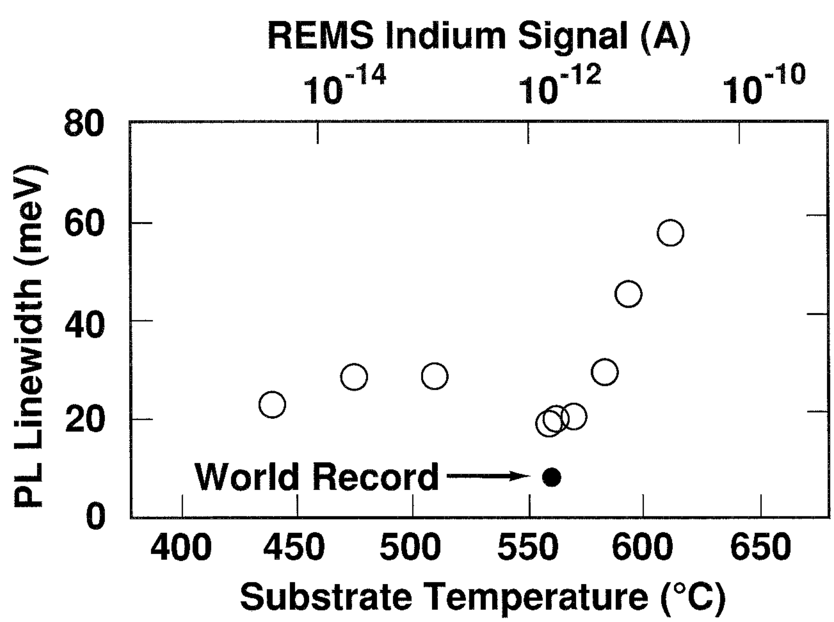
For further information:

J. F. Klem, W. Fu, P. L. Gourley, E. D. Jones, T. M. Brennan, and J. Lott, "Role of Substrate Threading Dislocation Density in Relaxation of Highly Strained InGaAs/GaAs Quantum Well Structures," submitted to Appl. Phys. Lett.

Principal investigators:

J. F. Klem, (505)845-8225; and P. L. Gourley, (505)846-6291





Plots of the REMS indium signal (top) and photoluminescence linewidth (bottom) as functions of the crystal growth (substrate) temperature during MBE of lattice-matched InAlAs on InP. The growth temperature can be measured and optimized using REMS. With increasing temperature above 425 °C, the photoluminescence linewidth widens initially as increased surface mobility enhances clustering, narrows as the miscibility gap narrows, then widens again as indium desorption results in lattice mismatch between the InAlAs and InP. InAlAs with the narrowest photoluminescence linewidth measured to date were grown at very high As overpressures and growth rates, as indicated by the solid data point at 550 °C. As the substrate temperature approaches 615 °C, the indium signal rises dramatically as the InP substrate begins to decompose.

InAlAs Growth Optimization Using Reflection Mass Spectrometry (REMS)

There is significant interest in the molecular beam epitaxial (MBE) growth of indium aluminum arsenide (InAlAs)/indium gallium arsenide (InGaAs) heterostructures for high-speed electronic and optoelectronic devices. The optical and electrical properties of such ternary III-V compound semiconductors, however, are strongly influenced by the uniformity of the group III constituents in the crystal. Because of the size difference between In and Al atoms, the InAlAs system is expected to have a miscibility gap, and hence a tendency to "phase separate" into In-rich and Al-rich clusters.

Recently, CCST researchers developed and applied REflection Mass Spectrometry (REMS) to monitor and optimize growth conditions during MBE of InAlAs and InGaAs on indium phosphide (InP). REMS involves using a cryo-shrouded and apertured mass spectrometer to measure line-of-sight chemical species leaving the surface of a semiconductor during crystal growth. Monitoring the indium desorption as a function of substrate temperature permitted significant improvements in the optical and electrical properties of lattice-matched InAlAs on InP. We have achieved electron concentrations as low as $3 \times 10^{15}/cm^3$, electron mobilities as high as 4000 $cm^2/(V\text{-}s)$ at 77 K, and photoluminescence linewidths as narrow as 10 meV.

REMS is an *in situ*, real-time diagnostic that can be used to characterize and optimize surface chemistry during the MBE growth of many semiconductor alloys. In the present work, REMS was used to improve materials grown on InP for advanced electronic and optoelectronic devices.

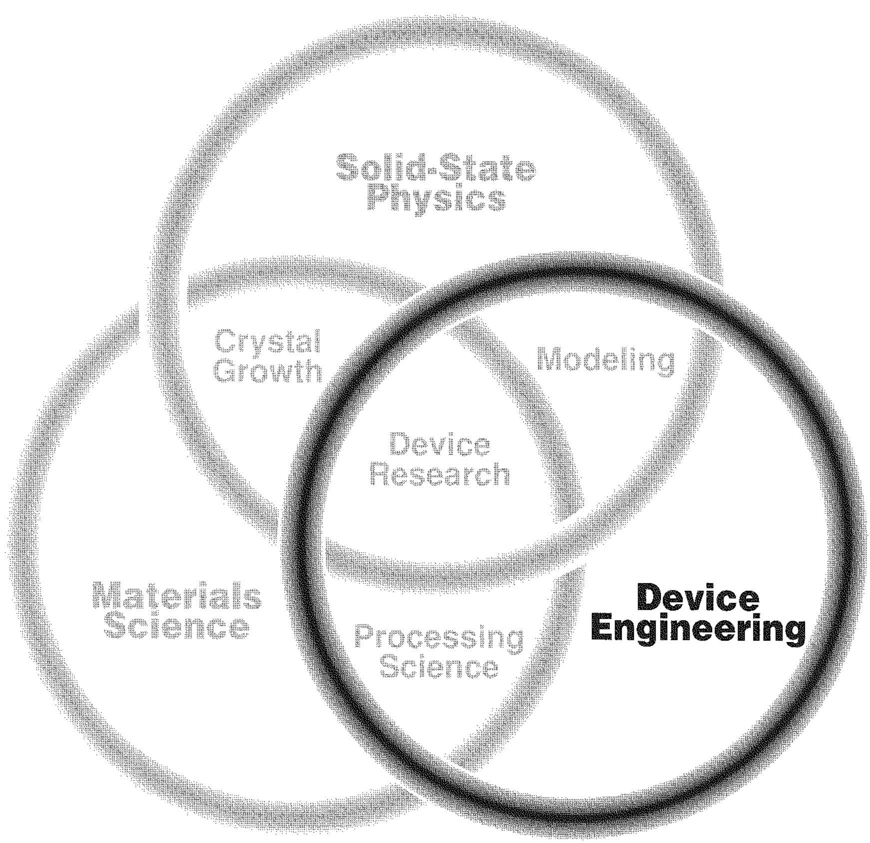
For further information:

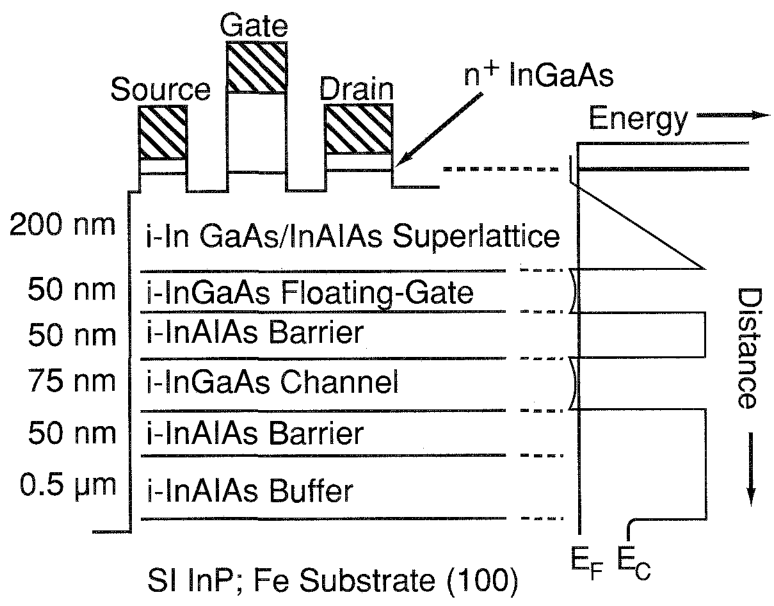
T. M. Brennan, J. Y. Tsao, B. E. Hammons, J. F. Klem, and E. D. Jones, "Application of Reflection Mass Spectrometry to Molecular-Beam Epitaxial Growth of InAlAs and InGaAs," J. Vac. Sci. Tech. B 7, 277 (1989).

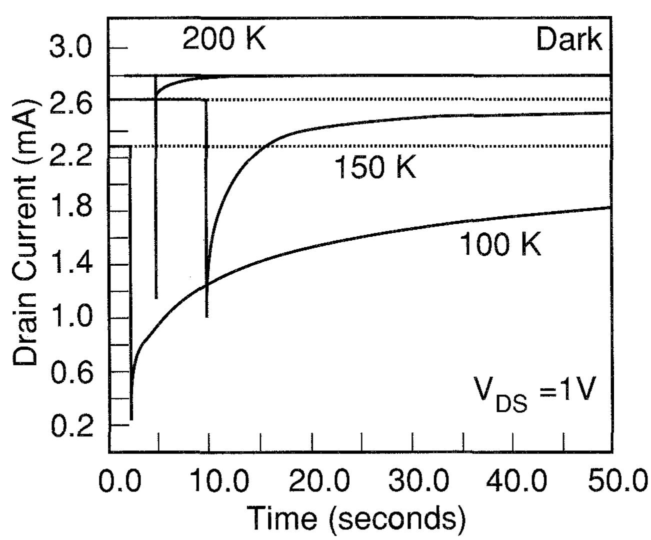
Principal investigators:

T. M. Brennan, (505)846-8192; and J. Y. Tsao, (505)844-7092

DEVICE ENGINEERING







Schematic cross section and typical drain current transients for a prototype nonvolatile memory element. This InGaAs/InAlAs device was grown lattice-matched to semi-insulating (SI) InP substrates by molecular beam epitaxy. The drain current transients begin when charge is injected into the floating gate by pulsing the gate with a negative voltage. The drain current then decays as the confined charge escapes.

Nonvolatile Charge Storage in III-V Heterostructures

Charge storage devices (memories) are essential to high-density integrated circuits. Long-term or "nonvolatile" memories in silicon technology are based on the storage of charge in silicon "floating-gate" layers or by the trapping of charge in silicon nitride layers. Recently, long-term charge storage was demonstrated in heterojunction structures constructed from III-V semiconductor materials. Charge is placed in a confining potential well formed by tailored large- and small-bandgap III-V semiconductor material. The quantity of confined charge that may be stored and its escape rate are measures of the practicability of the structure as a memory element.

CCST researchers recently demonstrated an aluminum arsenide (AlAs)/ gallium arsenide (GaAs) nonvolatile memory cell with significantly improved characteristics. This device uses a spatially graded superlattice for charge injection. Charge in the potential well is held in place by heterojunction energy barriers in the growth direction and by Schottky energy barriers in the other directions. The storage times are temperature-dependent and extrapolate from seconds at 300 K to hundreds of years at 77 K. CCST researchers also demonstrated nonvolatile charge storage in indium gallium arsenide (InGaAs)/indium aluminum arsenide (InAlAs) heterostructures. The conduction band offsets (potential energy barriers) in these materials are larger than in AlAs/GaAs, and even longer storage times were measured.

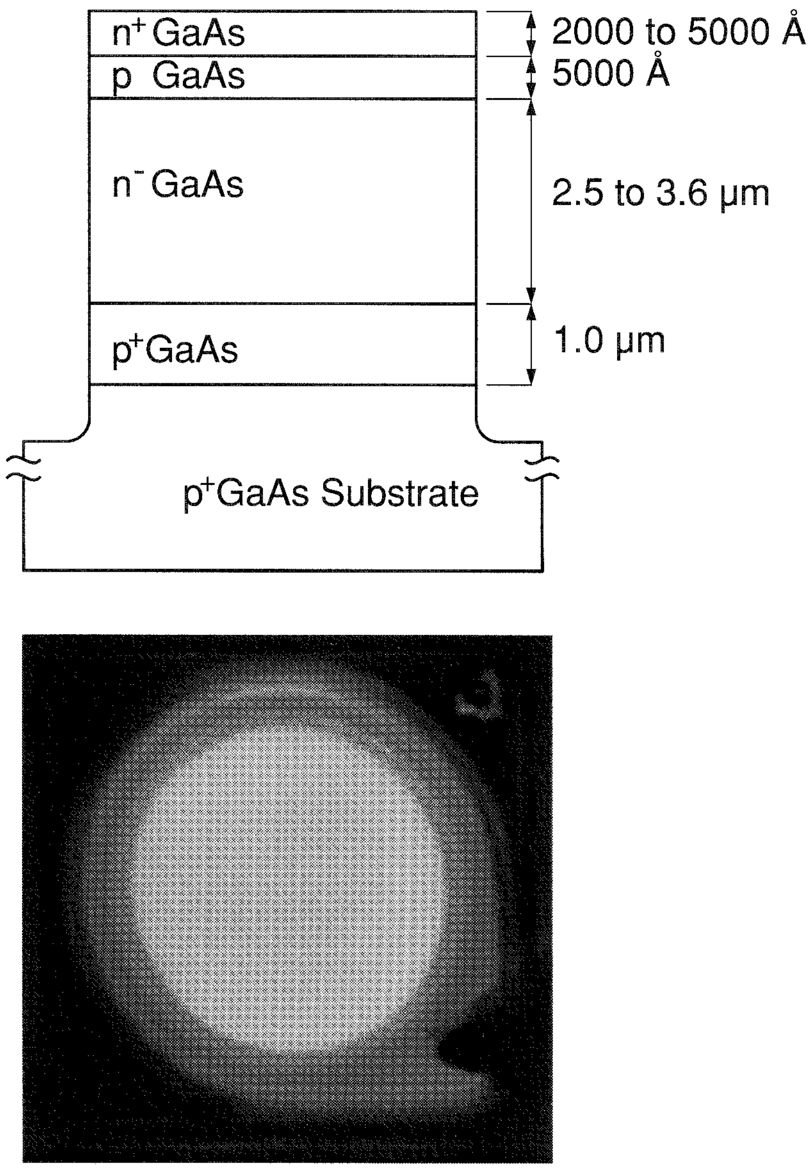
Based on the performance of prototype memory elements demonstrated in this work, III-V charge storage devices show promise for future nonvolatile memory applications. In contrast to silicon technologies, III-V devices have increased writing speed, reduced writing voltages, unlimited writing cycles, improved radiation tolerance, and simultaneous fabrication with other III-V devices.

For further information:

J. A. Lott, J. F. Klem, and H. T. Weaver, "Anisotropic Thermionic Emission of Electrons Contained in GaAs/AlAs Floating Gate Structures," Appl. Phys. Lett. 55, 1226 (1989).

Principal investigators:

J. A. Lott, (505)844-1097; and H. T. Weaver, (505)844-8979



Typical structure for the GaAs light-activated two-terminal thyristor. A thinner n^- blocking layer results in a switch with a lower dark breakover voltage that is harder to trigger by transient ionizing radiation. Also shown is a photomicrograph of a thyristor structure in its turned-on state. Light is emitted from the surface within the metal contact annulus because of current-induced carrier recombination in the device.

Optically Triggered Thyristor Switches

In radiation environments, optically activated switches offer potential advantages in safety, reliability, and resistance to electromagnetic pulses. Radiation-induced switching, however, is a well-known phenomenon in conventional four-layer semiconductor switches. For radiation "hard" devices, this undesirable effect must be prevented while permitting reliable optical triggering. Radiation hardness in this context is achieved by increasing the triggering sensitivity of the device to light and by decreasing the sensitivity to ionizing radiation. Both of these features are enhanced by devices based on gallium arsenide (GaAs) instead of on silicon (Si).

Optically triggered GaAs thyristors that exhibit tolerance to high x-ray dose rates were recently fabricated in the CCST. With no radiation or light applied, these two-terminal epitaxial devices exhibit breakover voltages of 18 to 55 V. The dark breakover level is controlled by the thickness of a low-doped blocking layer. All devices trigger at <2 V with <1 mW of laser power. When tested with dose rates up to 2×10^9 rad (Si)/s, the 38-V (2.5-µm blocking layer) devices do not switch at applied voltage levels that are 40% to 60% of dark breakover. Thicker (3.6 µm) devices with dark breakover levels of 55 V switch at lower voltages at 1×10^9 rad (Si)/s because of larger radiation-induced carrier generation and the thicker active region.

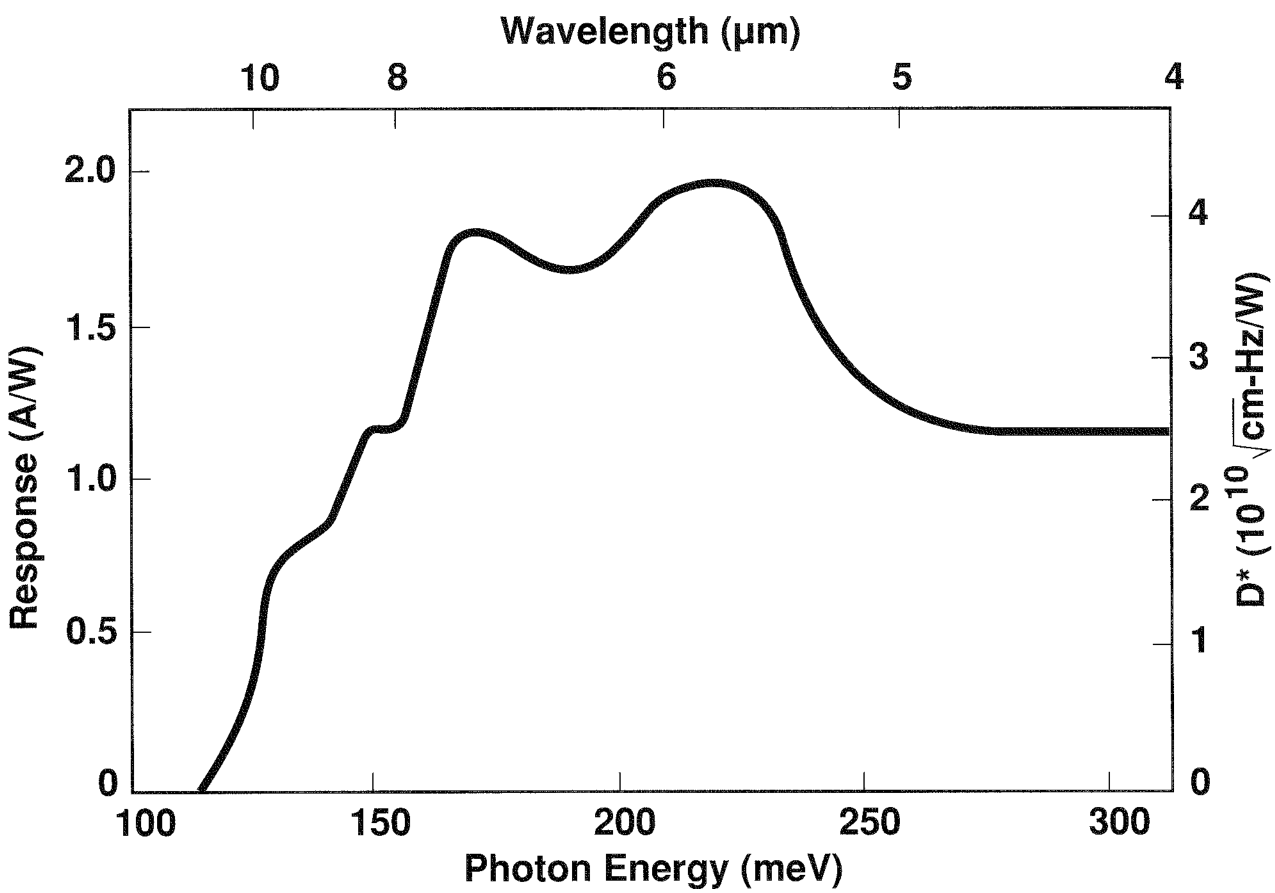
These studies have established the limits of radiation tolerance for optically triggered GaAs thyristor switches. Devices <2.5 µm thick are hard to levels >2 x 10^9 rad (Si)/s. Additional hardening of thicker devices with higher breakover voltages is being pursued by the use of advanced, integrated device structures.

For further information:

R. F. Carson, R. C. Hughes, T. E. Zipperian, H. T. Weaver, T. M. Brennan, B. E. Hammons, and J. F. Klem, "Radiation Response of Optically-Triggered GaAs Thyristors," accepted for publication in IEEE Trans. Nucl. Sci., December 1989.

Principal investigators:

R. F. Carson, (505)844-4127; and H. T. Weaver, (505)844-8979



The current responsivity and detectivity (100 kHz) for an SLS photodiode grown by molecular beam epitaxy. The SLS consisted of equal, 150-Å-thick, $InAs_{0.15}Sb_{0.85}$ and InSb layers.

InAsSb Strained-Layer Superlattice Infrared Detectors with High Detectivities

Numerous military and civilian imaging applications exist in the far infrared (IR) 8- to 12-μm spectral range. As an alternative to the difficult II-VI materials used in conventional imaging systems, indium arsenide antimonide (InAsSb) strained-layer superlattices (SLSs) were developed to extend the photoresponse of III-V materials to long wavelength. High-quality InAsSb SLSs were demonstrated using both molecular beam epitaxy and metal-organic chemical vapor deposition. This capability, together with recently demonstrated InAsSb doping and device processing technologies, has resulted in the development of both photovoltaic and photoconductive SLS IR detectors. InAsSb SLS photodiodes are the longest wavelength, III-V photovoltaic devices reported to date.

CCST researchers recently demonstrated an IR photodiode constructed from an InAsSb SLS with 15% arsenic that displayed a broad spectral response extending beyond 10 μm. A rudimentary surface passivation was implemented to decrease detector noise. The detectivity of this nonoptimized device was $>1 \times 10^{10}$ cm-Hz$^{1/2}$/W at wavelengths <10 μm. The performance of the photodiode was limited by the 300 K blackbody background, and this detectivity is comparable to that of commercially available mercury cadmium telluride (HgCdTe) IR detectors.

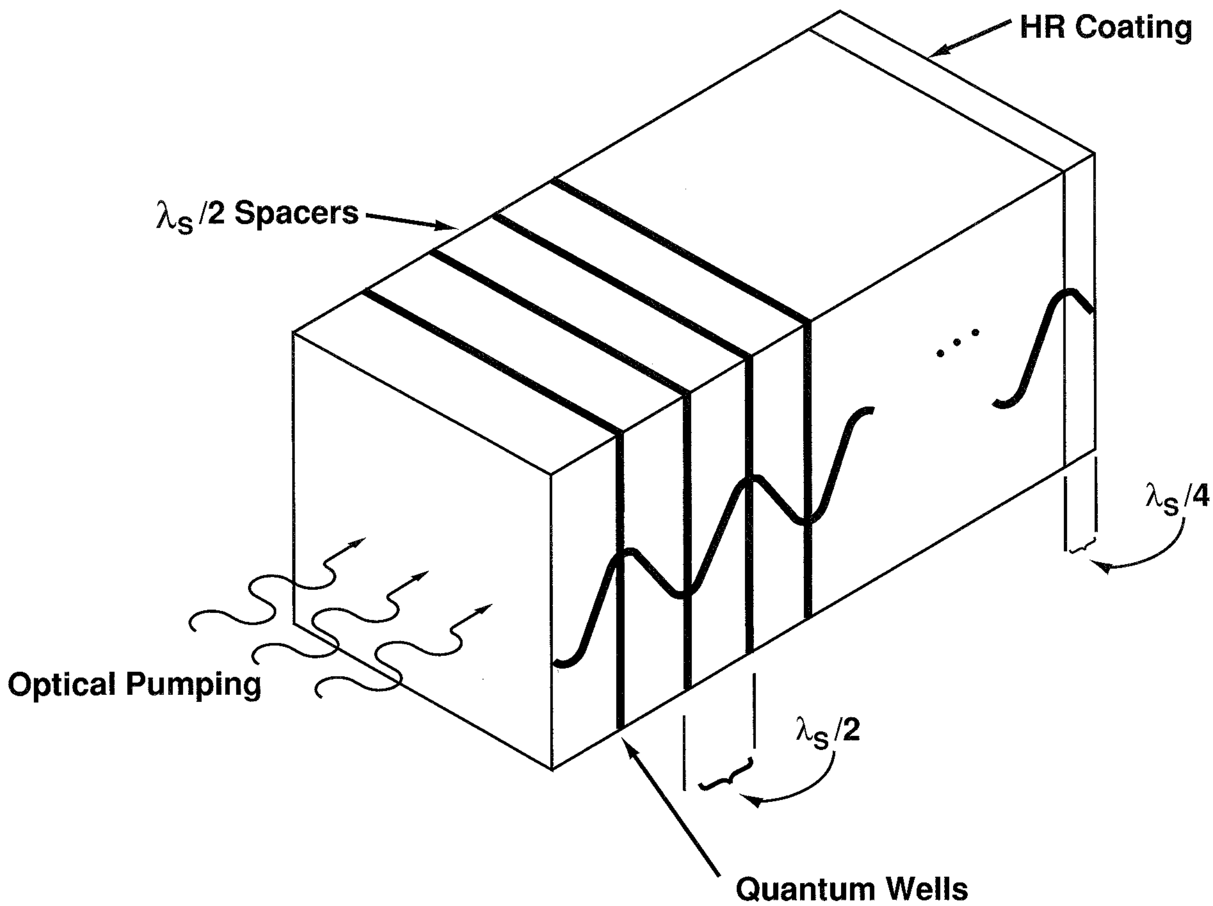
Based on the performance of prototype InAsSb SLS IR photodiodes, this new technology could lead to manufacturable, high-detectivity long-wavelength IR detectors. These devices will find widespread use in IR imaging focal-plane-arrays.

For further information:

S. R. Kurtz, L. R. Dawson, T. E. Zipperian, and R. D. Whaley, Jr., "High Detectivity ($>1 \times 10^{10}$ cm-Hz$^{1/2}$/W), InAsSb Strained-Layer Superlattice, Photovoltaic Infrared Detector," submitted to Elect. Device Lett.

Principal investigators:

S. R. Kurtz, (505)846-9821; and L. R. Dawson, (505)845-8920



Schematic diagram of a resonant periodic gain (RPG) structure designed to enhance the interaction between a standing wave optical field and a charge carrier distribution. The thick lines represent localized gain regions (quantum wells), and $\lambda_s = \lambda_r/\mu_s$ is the resonant wavelength in the spacer medium.

Resonant Periodic Gain Surface-Emitting Semiconductor Lasers

Vertical-cavity surface-emitting lasers are gaining attention for a variety of applications, including monolithic optoelectronic integrated circuits, optical chip-to-chip interconnects, optical logic devices, and high-power, 2-D laser arrays. In conventional designs, the active medium is either uniform in composition or contains closely spaced, multiple-quantum-wells (MQWs) without optimizing their position relative to the optical standing wave. These designs suffer from the requirement of high threshold power densities to initiate lasing.

Recently, CCST researchers in collaboration with scientists from the University of New Mexico developed a novel vertical-cavity, resonant periodic gain (RPG) surface-emitting laser. In this device, the active region consists of a series of quantum wells spaced at one-half the emission wavelength of a particular optical transition of the structure. This spatial periodicity allows maxima of the standing-wave optical field to coincide with the gain elements, increasing the gain in the vertical direction, enhancing the frequency selectivity, and substantially reducing amplified spontaneous emission. Optically pumped lasing was achieved in a gallium arsenide (GaAs)/aluminum gallium arsenide (AlGaAs) structure that demonstrated a gain medium of only 310 nm.

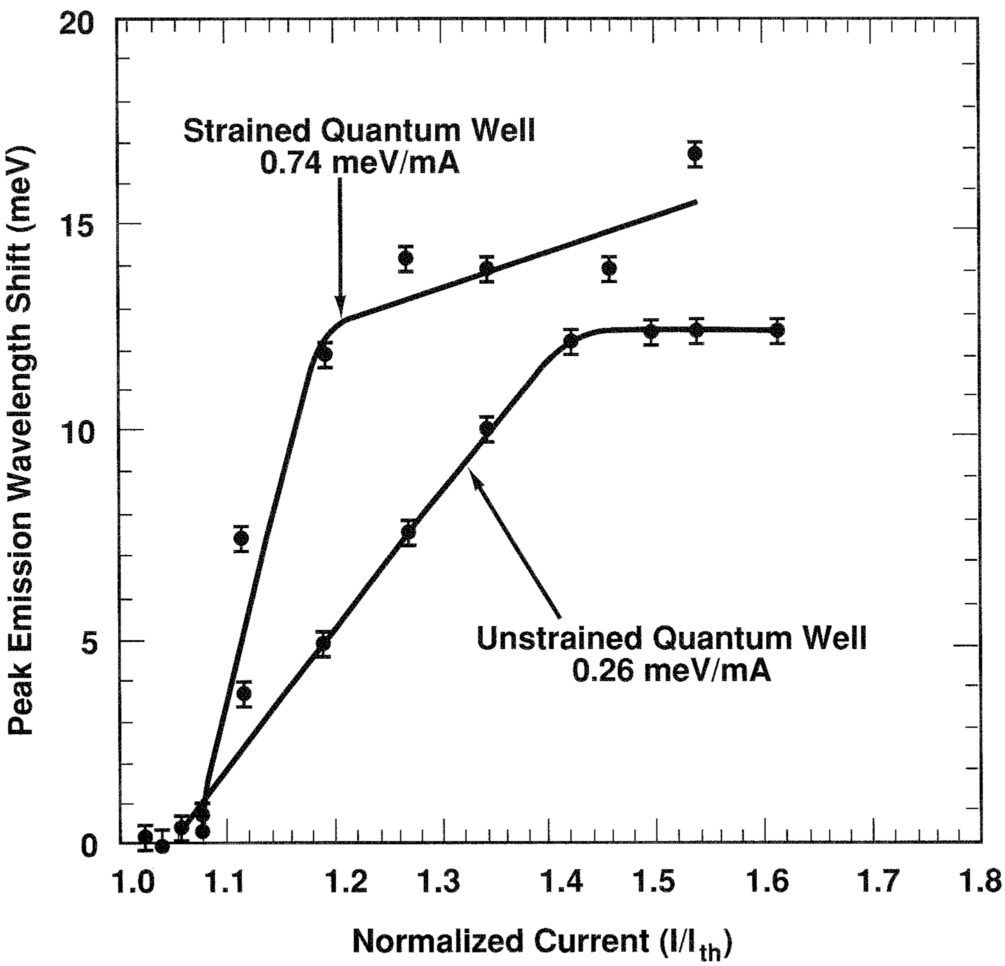
This new concept of surface emitters offers potentially higher packing density, larger emitting areas, better beam quality, unconstrained arrangement of emitters, and planar integration. The general idea of the RPG surface-emitting laser can be applied to other devices that depend on the interaction between an electromagnetic standing wave and a carrier population distribution.

For further information:

M. Y. A. Raja, S. R. J. Brueck, M. Osinski, C. F. Schaus, J. G. McInerney, T. M. Brennan, and B. E. Hammons, "Resonant Periodic Gain Surface-Emitting Semiconductor Lasers," IEEE J. Quant. Electr. 25, 1500 (1989).

Principal investigators:

T. M. Brennan, (505)846-8192; and M. Y. A. Raja, (505)277-3317



Measured shift of lasing energy versus injection current of lattice-mismatched single strained-quantum-well lasers and conventional unstrained control devices. Introduction of strain in the quantum-well active layer results in a nearly three-fold enhancement of the lasing energy shift as a function of injection current.

Performance Advantages of Strained-Quantum-Well Lasers in AlGaAs/InGaAs

Semiconductor lasers for optical communications should (1) operate at a single frequency for amplitude-modulation applications; (2) change wavelength rapidly with changes in laser current for frequency-modulation applications; and (3) operate at low power. Operating characteristics of semiconductor lasers made from lattice-matched materials suffer because of a high density of states in the valence band. The tetragonal lattice distortions of strained layers lower the crystal symmetry to reduce the density of states of the edge of the valence band. As a result, lasers made from strained-layer materials should have reduced threshold currents, increased modulation bandwidths, and greater spectral purity than those of their unstrained counterparts.

Recently a team of CCST researchers demonstrated CW, room-temperature operation of a novel strained-quantum-well (SQW), implanted-planar-buried-heterostructure, graded-index separate-confinement-heterostructure (IPBH-GRINSCH) laser in indium gallium arsenide (InGaAs)/aluminum gallium arsenide (AlGaAs). This structure exhibited the first direct evidence of strain-induced improvements in the performance of SQW injection lasers. The devices exhibited an enhanced lasing-energy shift (0.74 meV/mA) versus injection current compared to unstrained, reference gallium arsenide (GaAs)/AlGaAs devices (0.26 meV/mA). The lasing-energy shift saturated at ~13 meV from the wavelength at threshold for both structures.

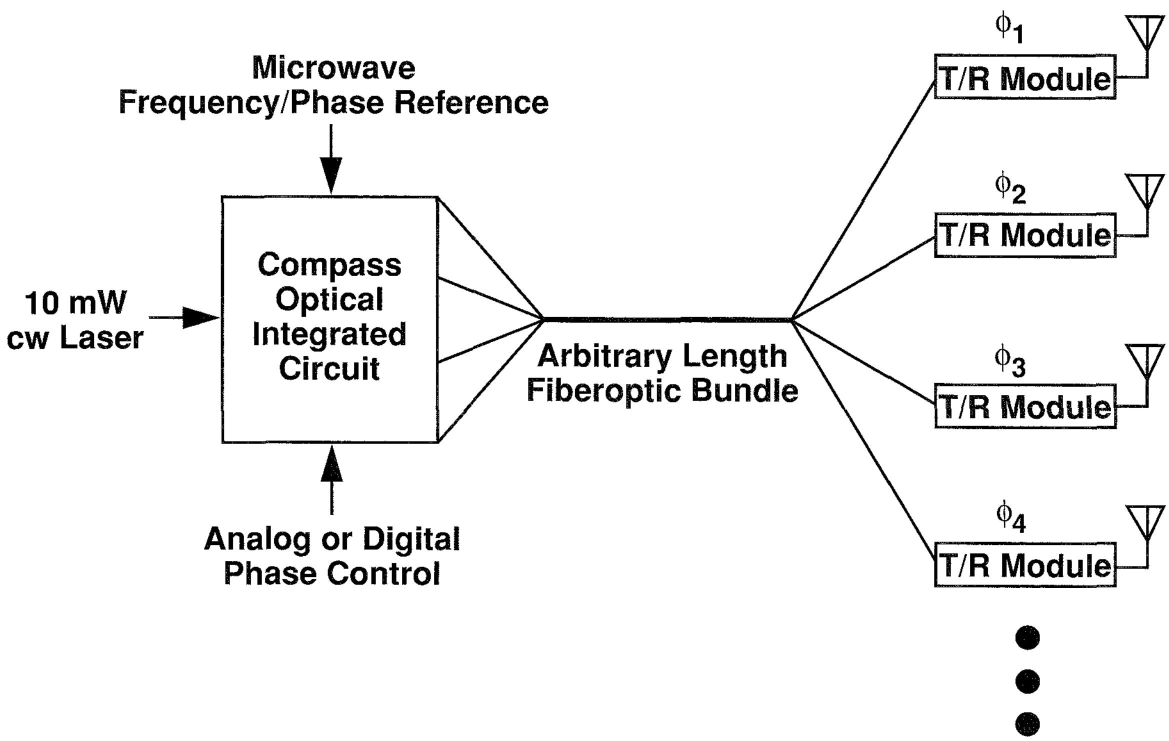
This first demonstration of the strain-induced improvement in SQW injection lasers supports the predicted superior performance of strained-layer lasers and may soon be exploited in a variety of devices for optical communication systems.

For further information:

G. A. Vawter, D. R. Myers, J. P. Hohimer, T. M. Brennan, and B. E. Hammons, "Characterization of Parabolic Light-Hole Effects on an Implanted-Planar-Buried-Heterostructure Graded-Index Separate-Confinement Heterostructure InGaAs-AlGaAs Strained-Layer Laser," Proc. Elect. Mat. Conf. April 1989.

Principal investigators:

G. A. Vawter, (505)846-8985; and D. R. Myers, (505)846-1393



Simplified block diagram of COMPASS. COMPASS is based on an optical integrated circuit that controls the microwave phase (ϕ_j) of the elements on a phased-array antenna. Appropriate phase settings on each element allow electronic steering of the antenna's beam. The only active optical component in the system will be a semiconductor diode laser. The Transmit/Receive (T/R) modules convert the modulated light into microwave phase-referenced signals. The T/R modules are connected to the optical integrated circuit with fiberoptic cables.

Optical Integrated Circuit for Phased-Array Radar Antenna Control

Phased-array antennas offer significant performance advantages over conventional antenna designs in radar and communication applications. A phased-array antenna comprises a large number of identical antenna elements with independently controllable relative phase. These elements are typically arranged in a 2-D grid on a flat surface or are mounted conformally on a curved surface (i.e., the body or wing of an aircraft). The phase of each element is controlled electronically, and by interference of the wave front of each element, the radiation pattern of the array is steered at high speed. This occurs without physical movement of any portion of the array. Unfortunately, though simple in concept, phased-array antennas are difficult to implement because of their complex phase-control electronics.

To address this need, a system named COMPASS (Coherent Optical Monolithic Phased-Array Steering System) was recently proposed by CCST researchers. COMPASS is based on optical heterodyning to produce microwave phase shifting. The heart of COMPASS is an optoelectronic integrated circuit (OEIC) that will be constructed entirely of passive components (optical waveguides, phase shifters, power splitters/combiners, and corners). The system translates optical phase shifts into microwave phase shifts. Since the optical wavelength is 10^4 times smaller than the microwave wavelength, this phase translation allows for physically small phase shifters. Only one semiconductor diode laser is required to power the entire optical system.

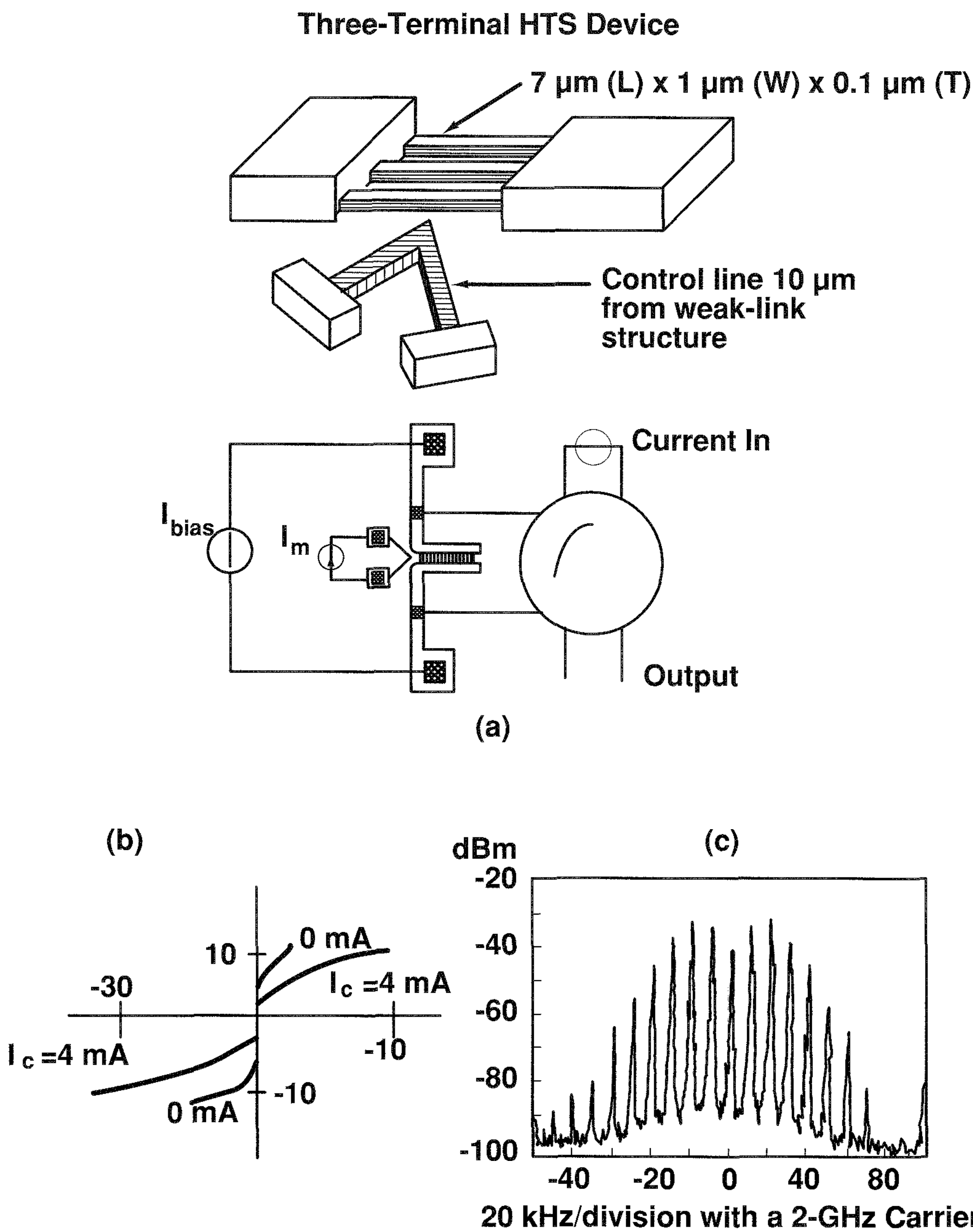
COMPASS promises to greatly reduce the complexity of the electronics and interconnects required for phased-array antennas. Wires for phase control and microwave power distribution will be replaced by lightweight optical fiber. COMPASS will be one of the largest OEICs ever built, requiring state-of-the-art fabrication and characterization technology for integrated optical components available in the CCST.

For further information:

R. A. Soref, "Voltage-Controlled Optical/RF Phase Shifter," J. Lightwave Tech. LT-3, 992 (1985).

Principal investigators:

V. M. Hietala, (505)844-5849; and S. H. Kravitz (505)846-2646



The structure and equivalent circuit of a three-terminal HTS device are shown in (a). This device operates as a current-controlled voltage source. The dependence of the critical current in the weak-link array as a function of current in the control line is shown in (b). This component has been used in AM and FM modulator circuits operating to frequencies as high as 30 GHz. Figure (c) shows the phase modulation spectrum for a 2-GHz carrier and a 10-kHz modulation signal on the control line. The measured bandwidth is presently detection limited.

Deposition and Novel Device Fabrication From $Tl_2Ca_2Ba_2Cu_3O_y$ Thin Films

The Tl-Ca-Ba-Cu-O high-temperature superconductor (HTS) system, with the highest documented critical temperature, T_c, to date, has considerable potential for device applications. Accomplishing these goals is complicated by the complexity of both the thin-film preparation and the patterning technologies. To achieve high-quality HTS films requires carefully controlling the partial pressures of both thallium and oxygen during deposition and annealing. Conventional lithographic sequences are difficult in the thallium-based system because of the complexity and reactivity of the constituent materials and also because of the large grain size and intricate topology of the films.

CCST researchers have grown epitaxial polycrystalline films of $Tl_2Ca_2Ba_2Cu_3O_y$ on a number of substrates with T_c's to 110 K and zero-field critical current densities, J_c's, at 77 K, of over 650,000 A/cm^2. Working collaboratively with scientists from the University of Wisconsin, we patterned these HTS films and demonstrated a three-terminal device (a flux flow transistor), which functions as a current-controlled voltage source. These devices have been used to make microwave oscillators operating at frequencies over 30 GHz (at 77 K) with output powers of approximately -45 dBm. AM and FM modulator circuits operating up to 30 GHz were also constructed.

These studies demonstrate that growth of high-quality thallium-based HTS thin films is possible and that interesting three-terminal device structures with novel characteristics can be formed. Other devices like far-infrared detectors and weak-link superconducting quantum interference devices (SQUIDs) are being constructed.

For further information:

D. S. Ginley, J. F. Kwak, E. L. Venturini, B. Morosin, R. J. Baughman, J. S. Martens, J.E. Nordman, J. B. Beyer, and G. K. G. Hohenwarter, "Thin Film Preparation and Single Device Fabrication in the Tl-Ca-Ba-Cu-O HTS System," Proc. Int. Symp. Superconducting Electr., Tokyo, Japan, June 1989.

Principal investigators:

D. S. Ginley, (505)844-8863; and J. S. Martens, (608)262-3893