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P. L. Mattern, Director

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We hope you find value in our Research Briefs - we welcome your inquiries.

Peter L. Mattern
Director

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Research Briefs

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Formation of Nanoscale Defects for Enhanced Critical Current Density in TlBaCaCuO Thin Films via Furnace Annealing

by E. L. Venturini, M. P. Siegal, and P. P. Newcomer

Motivation -- Several promising applications of high-temperature superconducting (HTS) thin films require large current densities in high magnetic fields at liquid nitrogen temperatures. Under these operating conditions, the magnetic field penetrates the film in discrete, quantized flux bundles termed vortices which move due to strong Lorentz forces (current density $\times$ magnetic field) and significant thermal energy. Such motion causes energy dissipation which limits the operating current density. The solution to this problem is to create controlled, nm-sized lattice defects which produce strong vortex pinning and suppress the motion. Surprisingly, simple furnace anneals produce defect structures in TlBaCaCuO thin films which enhance the vortex pinning and operating current density.

Accomplishment -- Highly-oriented, 600 nm-thick TlBa₂CaCu₂O_{7- δ} (Tl-1212) films are grown on LaAlO₃(100) substrates by a two-step process: sputter deposition of amorphous Ba₂CaCu₂O_x precursor followed by an 800 °C thallination anneal in a two-zone furnace to grow the superconducting phase. These films are composed mostly of near-perfect crystalline regions as seen by high-resolution transmission electron microscopy (HRTEM) in Figure 1a. A post-growth furnace anneal in nitrogen at low temperatures (~ 250 °C) raises the superconducting transition temperature (T_c) from 70 to 92 K without altering the structural integrity as seen by HRTEM. Anneals at 600 °C maintain

the high T_c while greatly enhancing the vortex pinning, and therefore, the operating current density. HRTEM has identified nanoscale defects in these annealed films which could be a source of enhanced pinning. Figure 1b reveals stacking faults in a 600 °C annealed film. The density, size-scale and orientation of these faults are appropriate for strongly enhanced pinning. Figure 2 demonstrates the improvement in the effective vortex pinning potential U_{eff} versus operating current density J in an annealed film versus an as-grown Tl-1212 film. A higher U_{eff} translates directly to lower loss under a given set of operating conditions.

Significance -- Maximizing vortex pinning is one of the major challenges in the application of HTS materials. Correlating defect structures with changes in pinning provides physical insight into this issue. We have identified the creation of useful defects through a simple nitrogen furnace anneal and demonstrated utility for enhanced pinning.

The most promising application for HTS thin films is microwave device components including oscillators, filters, delay lines, switches and antennas. The low microwave surface resistance of HTS films, where TlBaCaCuO films excel, enables substantial reductions in both the size and weight of these components. Increased operating current density via controlled defects should permit higher microwave power handling capability, making these films more useful.

Keywords: superconductivity, flux pinning, microwave surface resistance, power handling

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Figure 1: HRTEM images of the [100] zone axis. A) As-grown Tl-1212 films show continuity of the symmetry of the bright double layers which sandwich single bright spot layers with undisturbed cross-fringe patterns. B) Following the 600°C nitrogen post-anneal, there are discontinuities in the bright double layers (arrows) while the single bright spot layers are undisturbed. Other regions of the disordered structure show the same disturbance in the bright double layers and the single bright spots show a linear pattern rather than a cross-fringe.

Figure 2: Effective flux pinning energies at $H = 1$ T vs. current density for a Tl-1212 film grown in oxygen (squares) and for a film following 600 °C nitrogen post-anneal (triangles).

Semiconductor Nanoclusters as Potential Photocatalysts

by J. P. Wilcoxon, D. E. Bliss, P. P. Newcomer and G. A. Samara

Motivation -- There is strong interest in using small semiconductor particles as photocatalysts for solar fuel production and solar detoxification. In such applications these particles would absorb light creating electron-hole pairs and thus could catalyze specific chemical reactions. To be effective as a solar photocatalyst, the semiconductor must have a bandgap that is matched to the solar spectrum, and the energies of the valence and conduction band edges must be compatible with the oxidation and reduction potentials for the reactions involved. Additionally, the material must be resistant to photochemical degradation, and the carrier diffusion time to the surface must be shorter than the electron-hole recombination time. Nanometer-size semiconductor clusters (or nanoclusters) are in principle ideally suited to meet these requirements. Their small size allows fast carrier diffusion to the surface, and they possess the ability to continuously tune the bandgap (by up to 1 eV or more) by changing cluster size as a consequence of quantum confinement of the charge carriers.

Accomplishment -- Using our patented inverse micellar synthesis approach, we have successfully grown high quality, crystalline, monodisperse nanoclusters of PbS, FeS₂, MoS₂, CdS and WSe₂ and studied their structural and optical properties. Their bandgaps, which are typically in the mid to near infrared in the bulk, can be shifted to the near ultraviolet by reducing cluster size. Using PbS as a model system, we have demonstrated that most of the absorbed

light energy is channeled into a non-radiative process. We observed surface-related emission but little bulk recombination, features that bode well for potential applications of these nanoclusters in photocatalysis. Depending on the sign of the change in charge state of the surface recombination sites (or traps), the excited nanoclusters are capable of initiating either reduction (electron trap) or oxidation (hole trap) reactions. Results on gold capping the nanoclusters (see the figure) show that surface related states of one material can be excited through states of a different interior material. This effect has extremely important ramifications for photocatalysts since the functions of energy absorption and energy transfer can be separated. Materials for the interior of the nanocluster can be chosen to be efficient absorbers of light energy, while materials on the surface can be chosen to be efficient at transferring energy to reactants.

Significance -- This research has demonstrated significant progress toward the ultimate goal of using nanoclusters as efficient photocatalysts. The ability to successfully cap the clusters with metals is an important step. The specific direction of our work was guided by a practical consideration - the need for inexpensive, disposable photocatalysts; hence our emphasis on sulfides. Much more work is needed to develop these materials and apply them for such important reactions as the solar decomposition of H₂O and H₂S and the solar detoxification of chlorinated hydrocarbons in water.

Keywords: nanoclusters, optical absorption, emission, quantum confinement, photocatalysts

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Figure: (a) The photoluminescence emission (PL) and excitation (PLE) spectra of 3.0 nm PbS clusters. A strong emission band occurs at 520 nm. The PLE spectrum for the 520 nm emission exhibits two peaks at 270 and 300 nm. Since the emission occurs at a much lower energy than either the excitation or absorption features, it is interpreted to result from a surface state or defect. (b) Coating the clusters by a monolayer of gold has a dramatic effect on the PL spectrum. The emission at 520 nm is completely killed off and a new emission occurs at 350 nm. This indicates that the 520 nm emission is indeed a surface emission of the PbS cluster. The new 350 nm emission is due to Au-related levels on the surface and is stimulated through the excitation of PbS-related levels in the interior of the clusters as indicated by the fact that the PLE spectrum is essentially unchanged from Fig. (a).

Heavy Ion Backscattering Spectrometry (HIBS) User Facility

by J. C. Banks, J. A. Knapp, and B. L. Doyle

Motivation -- Measurement of metallic surface contamination on silicon wafers is of vital importance to semiconductor technology. Metal contamination present in starting material and arising from processing and cleaning operations is detrimental to devices because it results in defects which limit wafer yields and compromise circuit operation. The 1994 SIA roadmap indicates that metallic contamination in starting material must be $< 1 \times 10^{10}$ atoms/cm² for 0.18 μ m technology by the year 2001. HIBS, a Sandia patented ion beam analysis tool, is able to measure this ultra-trace level of surface contamination on Si wafers. HIBS is accomplished by taking advantage of the increased backscattering yield from a low energy C⁺ beam focused onto a Si wafer surface. By measuring the time-of-flight (TOF) of the backscattered C with a detector array having a large solid angle (see Fig. 1), the near-surface impurities are identified and quantified. HIBS is standardless, unlike Total-reflection X-Ray Fluorescence (TXRF) and Secondary Ion Mass Spectroscopy (SIMS), and also has no matrix effects such as found using SIMS. HIBS measures all elements above Ar in a single spectrum and can be used to analyze rough samples.

Accomplishment -- A HIBS User Facility, allowing measurement of ultra-trace levels of surface contamination on Si wafers, has been constructed this year under a CRADA with

SEMATECH. This facility houses a compact accelerator coupled to a Sandia/Vanderbilt designed TOF system installed in a high vacuum chamber. Wafers are inserted into the chamber via a load lock enclosed in a Class 10 mini-environment and mounted onto an in-situ four axis goniometer for analysis. The system has been designed to optimize the sensitivity for surface heavy-metal contamination and the present detection limits are $\sim 6 \times 10^9$ atoms/cm² for Fe and $\sim 3 \times 10^8$ atoms/cm² for Au on Si, without preconcentration. This is much better than TXRF for most elements (see Fig. 2). The sensitivity is improved $\sim 100\times$ with preconcentration using vapor phase decomposition (VPD).

Significance -- The HIBS User Facility is a national resource, providing Sandia, companies, laboratories and universities with a place to conduct ultra-trace level contamination studies. The facility is helping advance the state of microelectronics fabrication, having been used in studies of incoming wafer quality, gate oxide contamination, plasma processing, wet processing, and also to verify calibration standards for TXRF and SIMS. Collaborations have been started with DEC, Motorola, Sumitomo Sitix Silicon, Charles Evans & Associates, SEMATECH, Los Alamos National Laboratory, and Sandia National Laboratories-Contamination Free Manufacturing.

Keywords: ion beam analysis, time-of-flight, metallic surface contamination, user facility

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Figure 1: A Sandia/Vanderbilt designed TOF detector array, built under a cooperative research and development agreement with SEMATECH, is seen to the right of a sample insertion load lock. The load lock is inside a Class 10 mini-environment. Samples ranging from 1 cm² up to 200 mm wafers may be inserted for HIBS analysis.

Figure 2: HIBS has better sensitivity (<10¹⁰ atoms/cm²) than TXRF for most elements. Measurements are standardless and quantitative, even for rough samples.

*Optically Imprinted Refractive Index Modulations
in Photosensitive Glass Thin Films*

by K. Simmons-Potter and B. G. Potter, Jr.

Motivation -- Multi-functional, integrated optical devices are the foundation for technologies commanding a significant high-tech market share. Areas such as telecommunications, information processing, remote sensing and data storage benefit from devices based on patterned refractive index modulations. Typically device structures are produced via multi-step processing, relying on complex chemical and/or mechanical procedures. Photosensitive materials exhibit a permanent refractive index change when exposed to optical radiation. Thus, the use of photosensitive materials allows the fabrication of a broad range of complex integrable optical devices using a single, optical, direct-write process. Potential applications areas include waveguide devices, integrated optical interconnects, diffractive, refractive and reflective optical elements, sensors, and optical data storage.

Accomplishment -- We have produced large refractive index modulations ($\Delta n \sim 10^{-3}$) in germanosilicate thin-film waveguides by exposure to UV radiation. The films were produced using a reactive-atmosphere, rf-sputtering technique which represents an innovation in the production of these photosensitive materials. Currently our films demonstrate a photosensitive response which is > 100x greater than that typically observed in

commercially available materials. Only through hydrogen exposure at elevated temperature and pressure, has similar photosensitivity been obtained in comparable materials systems. Such post-fabrication activation of the material, however, is unstable and is accompanied by deleterious hydrogen incorporation into the glass structure. Our technique offers in-situ control and long-term stability of the glass photosensitivity. We are now investigating microscopic mechanisms responsible for the photosensitivity with the goal of producing new materials capable of enhanced refractive index modulation and broader wavelength response.

Significance -- Photosensitive glasses, enable the fabrication of discrete optical elements possessing tailored functionality within the material using a single, post-synthesis, direct-write process. From a manufacturing standpoint, a material "blank" could be synthesized and "programmed" later for a specific purpose. Our photosensitive materials can, thus, address a range of application areas where agile configurability and integrability of refractive index device structures are crucial to the successful development of working optical systems. In addition, the technology enables low-cost processing of structures in materials which are robust, reliable and directly integrable with optical fiber technologies.

Keywords: photosensitivity, integrated optics, glass thin films

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UV-induced change in the refractive index of photosensitive glass. The dashed line is typical of commercially available photosensitive germanosilicate glasses. The solid line depicts data taken from germanosilicate thin films produced at Sandia.

Compact optical system. Reflective gratings produced by photosensitivity form cavity for active source element. Optical channels and wavelength selective grating elements in spectrometer chip arise from an optically induced refractive index in the photosensitive material.

Boron Carbides' Unusual Thermoelectric Coefficients

by T. L. Aselage, D. Emin and S. S. McCready

Motivation -- The unexpectedly large Seebeck coefficients reported for boron carbides generated interest in their use for thermoelectric energy conversion. In particular, both existing theory and experience with conventional materials indicates that materials with large carrier concentrations have small Seebeck coefficients ($\ll 100 \mu\text{V/K}$). However, large Seebeck coefficients are reported to coexist with large carrier concentrations in boron carbides. Irreproducible aspects of these reports made it unclear if these reports were to be trusted. In this work we endeavored to ascertain whether the boron carbides truly had large Seebeck coefficients. Presuming some truth to the published reports, careful measurements of the Seebeck coefficients as functions of temperature and carrier concentration would facilitate unearthing the cause of boron carbides anomalously large Seebeck coefficients.

Accomplishment -- Well-characterized samples of boron carbides were prepared with carbon contents that span boron carbides' full range. Three apparatus were also built so that the Seebeck coefficients could be measured over an unusually wide temperature range, 15 K to 900 K. The Seebeck coefficients of a few representative boron carbides are shown in Figure 1. Unlike the Seebeck coefficients of conventional materials with large carrier densities, these rise with temperature to large near-temperature-independent values. Boron carbides' Seebeck coefficients also have a fractionally small variation with carbon

concentration and hence carrier concentration. These findings show prior works to contain significant errors. For example, some prior measurements of boron carbides' Seebeck coefficients were strongly affected by shorting out of boron carbides' transport by graphite inclusions.

The large contribution to the Seebeck coefficient that is independent of carrier concentration is a novel effect. We explain this effect as arising from the carrier-induced softening of sites upon which carriers reside, twelve-atom boron-rich icosahedra. We have shown that carriers added to multisite structural units generally soften these units. This softening lowers the vibrational frequencies and thereby increases the vibrational entropy. As illustrated in Figure 2, the Seebeck coefficient produced by this effect rises with increasing temperature to saturation above the temperature corresponding to the molecular vibrations with which the carriers interact, Θ .

Significance -- Large Seebeck coefficients can result when carriers added to atomic clusters soften these units. Thus, solids based on atomic clusters should be the focus of searches for especially efficient thermoelectrics. Indeed, the large cage-like structures of Si- and Ge-based clathrates may be key to these materials having the large Seebeck coefficients that has generated recent interest in their use in thermoelectric cooling. Carrier-induced softening is also an essential element of both conventional (BCS) and large-bipolaronic superconductivity.

Keywords: Seebeck coefficients, thermoelectrics, boron carbides, atomic vibrations

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Figure 1

Figure 2

A Pseudomorphic InAsSb Multiple Quantum Well Injection Laser Emitting at 3.5 μm .

by S. R. Kurtz, R. M. Biefeld, A. A. Allerman, and M. H. Crawford

Motivation -- Strained InAsSb/InAs heterostructures offer the promise of new III-V based, infrared detectors and emitters for use in mid-wave, 3-5 μm infrared optoelectronic and heterojunction devices. Mid-infrared (3-6 μm) lasers and LEDs are being developed for use in chemical sensor systems and for defense countermeasures. With the prospect of reduced Auger rates in compressively strained heterostructures, InAsSb-based midwave infrared (3-5 μm) lasers have attracted renewed interest in recent years, and a variety of electrically injected, strained InAsSb semiconductor laser structures have been examined. Usually, these devices consist of molecular-beam epitaxy (MBE) grown AlAsSb claddings with InAlAsSb/InAsSb or InGaAs/InAsSb strained active regions. Ideally, the claddings and active regions are lattice-matched to InAs or GaSb substrates. The best of these strained injection lasers exhibit characteristic temperatures (T_0) $\approx$ 30 K. However, material quality, turn-on voltage, and carrier diffusion and confinement in the active region potentially limit the performance of injection lasers, and the essential Auger problem has been obscured. To place some of these issues in perspective, we present results for a midwave injection laser that is fundamentally different from current MBE devices.

Accomplishment -- We have prepared a pseudomorphic, compressively strained InAs_{0.94}Sb_{0.06} multiple quantum well injection laser, emitting in the 3.5-3.6 μm range. Our laser was grown by metal-organic chemical

vapor deposition (MOCVD) and contains InPSb cladding layers. The active region consists of InAs with pseudomorphic, compressively strained InAsSb quantum wells. With this laser design, hole confinement and carrier diffusion are enhanced while ensuring high material quality in the strained active region. X-ray and optical characterization indicate that the active region has a very low dislocation density. In pulsed mode, the laser operated at 135K and displayed a characteristic temperature of 33 K, equaling the highest value reported for molecular-beam epitaxy-grown, InAsSb/InAlAsSb active region lasers of comparable wavelength. Lasing, electroluminescence, and photoluminescence spectra are displayed in Figure 1.

Significance -- The InAsSb multiple quantum wells in InAs should ensure carrier diffusion/uniformity in the active region, and the InPSb cladding has a type I band offset with the active region, producing good electron-hole confinement. The operational characteristics (output power and temperature of operation) of this laser are equal to or better than other lasers working in this wavelength range. To increase the characteristic temperature of strained InAsSb lasers, we believe that the heavy-light hole splitting in the InAsSb wells needs to be increased by using barrier materials which produce larger valence band offsets (InAlSb for example) and increasing the compressive strain of the wells. Such modifications would result in improved hole confinement to the quantum wells and reduced Auger rates.

Keywords: metal-organic chemical vapor deposition, strained-layer superlattice, infrared emitter

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Photoluminescence, electroluminescence (LED emission), and laser emission spectra. The LED was driven with a current density of 200 A/cm^2 . The $40 \times 1000 \text{ }\mu\text{m}$ laser stripe was driven at 275 A/cm^2 ($1.1 \times I_{\text{th}}$).

In Situ Growth Monitor has Revolutionized the Manufacturing of Complex Compound Semiconductor Thin Film Structures

by W. G. Breiland and K. P. Killeen

Motivation -- The fabrication of semiconductor thin films has traditionally been accomplished through a tedious set of preliminary calibration runs that establish growth rates and materials properties of interest before an actual device structure is grown. Unfortunately, these calibration runs must be repeated whenever a new chemical source is added or some part of the deposition equipment fails. Day-to-day variations must also be accounted for in critical device structures. A large portion of the time and expense of thin film fabrication is thus spent in calibration and post-process failure analysis. This problem may be addressed with real time, *in situ* monitors that measure the materials properties of the films directly during growth. We have developed a simple and robust method that can perform the necessary calibrations in a single run using *in situ* normal incidence reflectance.

Accomplishment -- The method, called ADVISOR for Analysis of Deposition using Virtual Interfaces and Spectroscopic Optical Reflectance, can extract growth rates and optical constants from the topmost layer of a growing thin film. Because the method uses a virtual interface approach, it may be applied to any film grown on an arbitrarily complicated multiple

layer film structure. This feature allows one to change process conditions within a single run and collect all necessary calibration information. The figure shows an example of such a calibration run used to set up the growth of a 140-layer structure for a vertical cavity surface emitting laser (VCSEL). To produce this complex structure, growth rates are needed for two aluminum sources, two gallium sources, and two different carbon doping conditions. Carbon doping with CCl_4 results in an etchback reaction that is highly non-linear in CCl_4 concentration and aluminum content. The ADVISOR method allows one to measure this etchback as well as determine all other growth rates in a single calibration run.

Significance -- Application of the ADVISOR method to VCSEL growth has eliminated many weeks of tedious calibration runs and has produced devices with very high yield and world-record threshold currents. In addition to this pre-growth calibration tool and fault-detection monitor, it will be possible to use the method to provide real time process control. Full-spectrum implementations of the method will allow one to measure thickness and composition in real time.

Keywords: reflectance, in situ monitor, semiconductor thin films, real-time control

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ADVISOR pre-growth calibration run using 633 nm light for a vertical cavity surface emitting laser (VCSEL). In a single run, growth rates for two aluminum sources, two gallium sources, and two carbon doping conditions are determined.

X-Ray-Diffraction Reciprocal-Space Analysis Measures the Dislocation Density in Strained Heterolayers at the Onset of Strain Relaxation

by S. R. Lee and J. A. Floro

Motivation -- Dislocations in semiconductors often have an adverse effect on device performance -- for example, by providing undesirable carrier recombination centers or leakage current paths. Even if as-fabricated device performance is acceptable, the multiplication of existing dislocations is a likely pathway to premature device failure. The limited lifetime of present-day II-VI lasers is a timely example illustrating this point. Thus, there is a continuing need to develop and maintain processes which produce dislocation-free epitaxial materials. This implies the ability to routinely characterize the dislocations -- particularly at low densities where their presence is undesirable but difficult to detect. Dislocations and other defects in crystals produce diffuse-x-ray-scattering intensity in regions of reciprocal space adjacent to the Bragg peaks of the crystal. The diffuse-scattering intensity depends on the strain field, the microstructural arrangement, and the density of the defects. We have made detailed measurements of the diffuse-x-ray scattering produced by 60° misfit-dislocation arrays in strained SiGe heterolayers in order to characterize the evolution of dislocations during the earliest stages of strain relaxation.

Accomplishment -- Metastable $\text{Si}_{78}\text{Ge}_{22}$ films were grown by MBE on Si (001) substrates and annealed to promote varying degrees of partial relaxation. X-ray-diffraction reciprocal-space

analysis was then used to monitor the structural evolution of the dislocation array with increasing misfit density. The change in the (113) diffuse-scattering pattern with dislocation density is shown in Fig. 1. In Fig. 1(a), the pair of "disks" and the asymmetrical broadening of the pattern about [001] are diffuse-x-ray-scattering features produced by dislocations. In Figs. 1(b) and 1(c), the diffuse intensity increases with dislocation density and changes in shape as the strain fields of adjacent dislocations move together. The integrated-diffuse intensities of the dislocated heterolayers are compared with lineal-misfit densities determined by defect etching in Fig. 1(d). The data demonstrate that the diffuse-x-ray-scattering intensity of the strained layer can be used to accurately measure lineal misfit-dislocation densities from 400 to 20,000 lines/cm.

Significance -- Quantitative measurements in this low-density regime previously required either destructive defect-etching; time-consuming, device-based EBIC; or, resolution permitting, x-ray topography. Our technique, based on the off-Bragg diffuse intensity, offers an alternative approach. We will continue to improve and apply this technique in the development of $\text{Si}_{1-x}\text{C}_x$, $\text{Si}_{1-x}\text{Ge}_x$, and strained-Si heteroepitaxial materials. CRADA partners intend to integrate these materials with standard Si processes with the ultimate goal being higher-performance ULSI devices.

Keywords: x-ray diffraction, reciprocal space analysis, strain relaxation, dislocations, heteroepitaxy

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Figure 1: (a) 748 Å-thick $\text{Si}_{78}\text{Ge}_{22}$, 1400 dislocation-lines/cm, (b) 748 Å-thick $\text{Si}_{78}\text{Ge}_{22}$, 6600 dislocation-lines/cm, (c) 748 Å-thick $\text{Si}_{78}\text{Ge}_{22}$, 18,000 dislocation-lines/cm, and (d) measured dislocation density versus measured diffuse-x-ray-scattering intensity.

World Record Mobilities in MOCVD Growth and Applications to New Quantum Tunneling Transistors

by J. A. Simmons, H. C. Chui, B. E. Hammons, M. E. Sherwin,
H. Q. Hou, N. E. Harff, and W. E. Baca

Motivation -- Molecular beam epitaxy (MBE) has long been the growth technique of choice for quantum transport devices based on III-V semiconductor heterostructures. Quantum tunneling is considered the most promising basis for a new generation of electronic devices, due to (1) its inherently high speed, and (2) its increased functionality. Recently, we have developed a novel concept for a quantum transistor, the double electron layer tunnel transistor (DELTT). The DELTT (Fig. 1) operates by resonant tunneling between layers of two-dimensional electron gas (2DEGs). Such 2DEGs require exceptionally low disorder (high mobility), and thus in the past has been grown primarily by MBE. However, an alternative growth technique, metal-organic chemical vapor deposition (MOCVD), has various advantages over MBE. These include low defect density, high quality regrowth capability, and rapidly varying alloy compositions, important for the DELTT's backgating scheme. More importantly, MOCVD is recognized as a key technology for manufacturing, due to its higher throughput, shorter downtimes, and scalability to very large reactors. To date there have been two primary disadvantages of MOCVD: lower material purity, and severe safety concerns due to the high toxicity of the arsine precursor gas.

Accomplishment -- We have shown that the use of tertiarybutylarsine (TBA), a much safer liquid arsenic precursor, results in nearly a factor of two increase in 2DEG mobility over those grown with arsine. The improvement occurs because TBA reduces the incorporation of both

carbon and donor impurities, despite TBA itself containing carbon. These 2DEGs were the first MOCVD-grown structures in which the fractional quantum Hall effect was observed, and exhibited 2DEG mobilities of $2 \times 10^6 \text{ cm}^2/\text{Vs}$ at densities of $3.2 \times 10^{11} \text{ cm}^{-2}$, nearly doubling the previous MOCVD world record (Fig. 2). Indeed, these mobilities are competitive with current state-of-the-art MBE. We have also used MOCVD to grow several prototype DELTT transistors and also double quantum well structures for studies of 2D-2D tunneling. The quality of these structures are also comparable to MBE. Rapid variation of alloy composition is being used in novel schemes for backgating, incorporating barriers of high Al content to reduce leakage currents.

Significance -- Our demonstration that the use of TBA in place of arsine produces 2DEG mobilities that are quite difficult to obtain even by MBE, is extremely significant. Because of the added advantage of tremendous gains in safety, we expect that our work will cause TBA to become the standard arsenic precursor for MOCVD. Further, since relatively little effort has been spent on high-mobility MOCVD growth, further mobility gains can likely be achieved via improvements in structure design and source purity, much as occurred with MBE in the 1980s. Thus we have made significant advances in the growth of MOCVD ultra-high quality materials and in their important application to nanoelectronics through new quantum transport device structures.

Keywords: MOCVD, epitaxial growth, MBE, tunneling, quantum transport, transistors

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Figure 1: Illustration of concept for Sandia's new double electron layer tunneling transistor (DELTT). The restricted dimensionality of tunneling from 2D to 2D produces exceptionally sharp resonances and allows control by a third terminal.

Figure 2: Mobility versus carrier density for record mobility 2D electron gas layers grown by MOCVD. The use of tertiarybutylarsine (TBA) rather than arsine produces nearly a factor of two increase in mobility, while simultaneously providing increased safety.

Experimental Program Provides Basis for Advanced Concepts Describing Shock Compression of Highly Porous Solids

by R. A. Graham, M. U. Anderson and G. T. Holman

Motivation -- It is widely recognized that modeling of the deformation of highly porous solids under rapid impulsive loading is essential to a wide range of critical applications including deflagration-to-detonation events as might be encountered in accident scenarios, in use of porous materials for shock attenuation, in shock-induced chemical synthesis, and for use of chemical transformations in porous ballotechnic energetic materials. Unfortunately, scientific knowledge of the deformation processes is limited largely to first-order descriptions based on thermodynamic equilibrium or modest modifications describing isolated pores.

Accomplishment -- Our program has provided quantum advances in materials-response data based on new experimental techniques. The data on materials behavior demonstrates the need and provides the foundation for advanced modeling of the deformation of highly porous solids. One of the techniques uses PVDF piezoelectric *stress-rate* gauges to measure input stresses and propagated stresses in samples under controlled loading. In a second major advance, the PVDF stress-gauge technique has been combined with the VISAR particle-velocity technique to provide the first nanosecond time-resolved stress-volume data on the kinetics of powder deformation. The experimental arrangement for the combined technique as applied to porous high explosive HMX is shown in Figure 1. As shown in the figure, the VISAR mirror and the PVDF film are placed in close proximity to monitor the wave transmitted through the sample which has been

subjected to precise, controlled loading. The measured stress-versus-particle velocity data determined from correlating the measurements in time are shown in Figure 2. The results provide the first description of the viscous, three-dimensional deformation of a porous solid. Completing an extensive scientific investigation, the PVDF stress-rate technique has been applied to the study of the single-component powders, HMX explosive and titanium dioxide, as well as the two-component powder mixtures, aluminum-hematite, and titanium-silicon. Data are in hand which systematically show the influence of powder morphology and mixture ratios.

Significance -- Study of the behaviors of highly porous solids with both the PVDF stress-rate technique and the combined PVDF-VISAR technique show presently available models are inadequate. All experiments provided detailed, quantitative data on the rate of initial deformation of powders at the loading interface. The results also show highly dispersive waves propagating in the samples with considerable detail in the stress-rate plane. Present materials models do not reflect these behaviors. The stress-versus-particle velocity results will permit development of a fully constrained deformations model. The present work demonstrates that present models of shock-compression processes in highly porous solids are inadequate to describe the observed behaviors. This work provides a basis for the substantial advances in materials models needed for realistic description of the deformation of porous solids under rapid impulsive loading.

Keywords: shock compression, porous solids, deformation, PVDF, VISAR

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Figure 1: The new experimental arrangement makes possible simultaneous measurement of rate-dependent materials responses under high pressure shock-compression loading. By combining PVDF stress and VISAR particle-velocity data both stress and volumetric data are independently obtained.

Figure 2: The time-resolved stress versus particle velocity record shown is the first obtained with the combined PVDF-VISAR technique. The experiment on highly porous HMX explosive shows a measured relationship which differs from the one-dimensional line shown as PMMA-Schuler. The deviation is due to the two-dimensional stress field in the porous sample and indicates that a time of about 150 nanoseconds is required to crush the materials to solid density. The late time record indicates the beginning of a chemical reaction.

Light Scattering Studies in Oscillatory Shear Lead to a Theory of Electrorheology

by J. E. Martin

Motivation -- Electrorheological fluids (ERFs) are particle suspensions that undergo dramatic rheological changes when subjected to strong electric fields, because of the formation of particle chains along field lines. These fluids solidify in milliseconds when a field is applied, and liquefy nearly instantly when the field is removed. This rapid rheological control makes ERFs promising candidates for electro-mechanical devices such as automotive and robotic clutches. A curious aspect of these materials is that flow can be induced in the solid by a small stress; the fluidized solid then has a viscosity nearly inversely proportional to the flow rate, and proportional to the square of the field, so ERFs can be used as field-controllable vibration damping fluids. In this application the fluid would be subjected to rapidly varying stress. Our goal is thus to obtain an understanding of how the ERF viscosity depends on particle concentration, temperature, applied field, flow rate, and flow history. This knowledge can then be used to develop effective control algorithms for active ERF-based devices.

Accomplishment -- We have conducted extensive time-resolved, two-dimensional light scattering studies of ER fluids in oscillatory shear flow. From the orientation of the scattering lobes we are able to determine how

the chain angle θ varies with the applied strain γ . Sample data are shown in the figures. The light scattering data can be understood by thinking of the particle chains as over-damped oscillators that are driven by the imposed flow. A typical oscillator has a fixed characteristic frequency, but particle chains fragment and aggregate during each cycle and thus have a characteristic frequency that is time dependent. We have developed an accurate microscopic model of the nonlinear rheology of ERFs that is in good agreement with rheological data.

Significance -- Our microscopic theory is applicable to steady, oscillatory, and nonperiodic shear flows and is a demonstrative advance over the phenomenological Bingham plastic model previously used. A major issue in the engineering of active devices such as shock absorbers is the development of active control algorithms. These algorithms use variables such as the shaft velocity to compute the viscosity the fluid should have to obtain optimal damping. Algorithm development relies on having an accurate constitutive equation for the fluid, and our research provides this. We are now discussing using our new constitutive equation with several groups developing control algorithms. This will give a much better idea of actual device performance and will be a significant aid in device engineering.

Keywords: electrorheology, electrorheological fluids, light scattering, oscillatory shear

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Figure 1: Light scattering pattern from an ERF in oscillatory shear. The tilted lobes indicate the chain orientation and the position of the spot in the lower left tells us the strain phase.

Figure 2: Lissajous plot of the chain orientation as a function of the applied strain (data on left axis). A linear response would give an ellipse oriented along a diagonal. The model describes the non linear response of the fluid to good accuracy, even with only one free parameter.

Plasma Synthesis of Low Dielectric Constant Interlevel Dielectric

by J. C. Barbour, D. R. Denison (Lam Research Corporation),
J. H. Burkhart (Idaho State University) and C. A. Applebitt

Motivation -- Microelectronics are important to the U.S. Department of Energy technologies for both energy and defense applications. Further, the development of commercially available microelectronics for defense applications is becoming increasingly important. Sandia has taken a lead role among the National Laboratories in the research and development of materials for microelectronics. As device size shrinks to the 0.1 μm level and the density of devices on a chip increase, a material of particular importance identified by the Semiconductor Industry Association national technology roadmap is a low-dielectric-constant (K) material for interlevel isolation. A low-K dielectric is required for reduced power consumption in high frequency devices, reduced crosstalk between metallic interconnects, and reduced circuit RC time constants. The reduction in time constants is necessary for increased speed and functionality on a chip. We have taken a major step toward developing a stable material with a dielectric constant below that for SiO_2 ($K=4$), which is currently used as an interlevel dielectric.

Accomplishment -- Low-K, fluorine-doped silicon dioxide films have been deposited at 270 $^{\circ}\text{C}$ using an electron cyclotron resonance plasma system (as depicted in Figure 1). The silicon supply for these SiO_2 films was provided from a mixture of SiH_4 and SiF_4 gases, in which the % SiF_4 was varied from 0 to 100%. In order to maximize the F content in the films, the Ar

flow rate, the microwave power, and the O_2 to Si-bearing gas ratio were varied using a constant ratio $\text{SiF}_4/\text{SiH}_4 = 3$. The concentration-depth profiles were measured using nuclear reaction analysis and Rutherford backscattering spectrometry, and the fluorine concentration was found to be uniform with depth. The dielectric constant, film stress, index of refraction, and infra-red absorption for Si-F and Si-O bonds were measured as a function of F content. Figure 2 shows that K decreases linearly from 4.0 to 3.55 with increasing fluorine concentration from 0 to 10.5 atomic %F. In addition, the film stress and index of refraction decreased linearly with increasing F content.

Significance -- A low temperature process for the deposition of fluorine-doped silicon dioxide was developed in conjunction with one of the leading U.S. suppliers of equipment for microelectronic-device fabrication. The low temperature of this process and the commercial availability of this equipment is important to rapid integratability and compatibility with current semiconductor processing. A high-density plasma source produced SiO_2 films with uniform and controllable concentrations of fluorine. By increasing the F concentration, the dielectric constant of the films was decreased and this work indicates that $K \approx 3.5$ could be achieved for 11-12 atomic %F. Further work is in progress to decrease the dielectric constant below 3.5.

Keywords: low dielectric constant, electron cyclotron resonance plasma, interlevel dielectric

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Figure 1: Schematic layout of the electron cyclotron resonance plasma system used to deposit low dielectric constant SiO_xF_y films from a commercially available reactor. This low temperature process produces films with compressive stresses of only 70-150 MPa (decreasing with increasing F content).

Figure 2: The dielectric constant decreased linearly with increasing F content over the composition range from 0 to approximately 10.5 at.% F. In this way, the dielectric constant was successfully lowered to 3.55.

Theory of Group-III Nitride Lasers

by W. W. Chow, A. F. Wright, and J. S. Nelson

Motivation -- Semiconductor lasers based on the wide direct band gap group-III nitrides have substantial application potential because they can provide output with wavelengths covering the range from blue-green to ultraviolet. Light emitting diodes with InGaN-AlGaIn heterostructures are commercially available, and lasing in bulk GaN has been achieved.

The determination of gain properties in group III-nitride quantum wells is complicated by the incomplete knowledge of band structure properties. Variations in material quality hamper experiments for investigating band structure properties. As a result, some important parameters necessary for determining and understanding laser gain medium behavior are unknown and discrepancies exist in others.

A second complication, is the need for a consistent treatment of many-body Coulomb effects. Coulomb effects are expected to be important because of the large exciton binding energies in wide-band gap compounds, such as the group-III nitrides. Neglecting them, as is the case for a free-carrier theory, will likely result in errors in the magnitude and spectral extension, as well as the temperature and carrier density dependences of the optical gain and absorption.

Accomplishment -- We have developed an approach that involves a first-principles band structure calculation, the results of which are incorporated into a microscopic laser theory, where many-body Coulomb effects are treated in

a consistent manner. Using this approach, we investigate bulk and quantum well structures composed of alloys of GaN, AlN and InN, in particular, the quantum well structure, GaN-AlInN, which has high confinement potentials in both strained and unstrained configurations.

Significance -- By using a single analytical model to compute the group-III nitride material properties, we ensure consistency in the values for the different band structure parameters. Having a consistent set of material parameters allows us to investigate the effects of strain in a nitride based quantum well gain medium. The computed spectra show gain peaks that are red shifted relative to the exciton resonance by several tens of meV, and the simultaneous appearance of an absorption resonance and gain at high carrier densities. Both phenomena have been observed in II-VI lasers (which like the group-III nitrides have large exciton binding energies), and are indications of strong Coulomb interactions. Our investigations show that a GaN-AlInN quantum well structure has the attractive property of having high confinement potentials. Since the structure may be grown unstrained, with tensile strain, or with compressive strain, a wide wavelength range can be accessed. Band structure calculations are ongoing to obtain better estimates of the elastic constants, band offsets and dielectric constants. Work is also continuing to apply the approach presented in this paper to other quantum well structures of group-III nitride alloys, including those having the wurtzite structure.

Keywords: visible and uv semiconductor lasers, wide bandgap lasers, bandstructure calculations, laser theory

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Gain and absorption spectra for bulk GaN at 77K. The higher density spectrum shows two features unique to wide-bandgap lasers: the red shifted gain peak relative to the exciton resonance, and the presence of an absorption resonance at high densities.

Plasma Synthesis of Nanostructured Aluminum Alloys With Exceptional Strengths

by D. M. Follstaedt, J. A. Knapp, J. C. Barbour, S. M. Myers and M. T. Dugger

Motivation -- Aluminum alloys are important as light-weight materials in transportation and energy applications. However aluminum has two serious limitations: relatively low strength, and strong adhesion to other metals during sliding contact. We previously showed that ion implanting aluminum with oxygen overcomes both deficiencies. Surface layers with 5 to 20 at.% oxygen exhibited yield stresses of 1.4 to 2.9 GPa, and "stick-slip" adhesion was reduced during sliding contact with a steel pin, lowering the coefficient of friction from ~1 to 0.2. For comparison, the yield stress of pure aluminum is 0.041 GPa, and that of aerospace 7075 alloy is 0.5 GPa. Transmission electron microscopy (TEM) showed a high density of nanometer-size γ -Al₂O₃ precipitates in the implanted layer that are responsible for the high strengths. In spite of these improvements, uses of implantation are limited by the oxygen penetration depth (<1 μ m) and relatively high cost.

Accomplishment -- We have synthesized aluminum alloys with up to 30 at.% oxygen using two new methods: pulsed-laser deposition (PLD) and electron-cyclotron resonance (ECR) plasma deposition. PLD forms very fine-grained aluminum layers (5 to 25 nm) with ~1 nm oxides dispersed throughout (Figure 1). The ECR plasma is used with aluminum evaporation to form layers of larger aluminum grains (10 to 100 nm) having 1 to 2 nm oxide precipitates. We have also developed methods for evaluating the strength of these layers by depositing them on silicon and using ultra-low load indentation to

measure the force required to penetrate into the 0.3 to 1.2 μ m-thick layers. This mechanical response was modeled with the ABAQUS finite-element code using the known properties of the substrate and diamond indenter tip, while adjusting the yield stress and elastic modulus of the alloy layer to fit the observed response (Figure 2). The PLD alloys exhibit the highest yield stress that we have observed for aluminum, 5.1 GPa for 20 at.% oxygen. The ECR alloys are also quite strong, 1.3 GPa; additional results indicate that actively cooling the substrates to maintain low temperatures during deposition may result in even higher-strength alloys.

Significance -- These new nanostructured Al materials exhibit extreme strengths for Al alloys. The techniques are further important because the two methods are "scalable" (i.e., greater thickness and area can be attained with a larger apparatus). The techniques can thus form much thicker layers than ion implantation and are expected to be more economically viable. These alloys may be used as hard coatings on aluminum components, and might be considered for metallizations with greater resistance to stress- and electromigration-induced voiding on microelectronic devices. More generally, our work shows that aluminum can be strengthened far beyond the levels of conventional alloys, and fine γ -Al₂O₃ precipitates are very effective for hardening. It may be possible to extend these techniques for forming nanostructured alloys with extreme levels of dispersion strengthening to other metals as well.

Keywords: aluminum, electron-cyclotron resonance plasma, pulsed laser deposition, yield stress

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Figure 1: Dark-field TEM image of $\text{Al}_{0.80}\text{O}_{0.20}$ alloy layer deposited with PLD. Larger white areas are aluminum grains in contrast; fine white spots are ~ 1 nm $\gamma\text{-Al}_2\text{O}_3$ precipitates in other grains.

Figure 2: Indentation response curve for a PLD alloy layer on a silicon substrate, and ABAQUS finite element simulation fitting the data using a yield stress of 5.1 GPa and an elastic modulus of 160 GPa. Note two step indentation to 100 nm followed by 200 nm.

Group V Inhibition of GaAs and AlAs MOCVD Growth Rates

by H. K. Moffat, K. P. Killeen, K. C. Baucom

Motivation -- MOCVD of III-V materials has rapidly been moving into the high-production manufacturing environment, where process control and reactor optimization are critical needs. In order for the theoretical low-cost, scalability advantages of MOCVD to be realized, all inputs to the reactor, plus the reactor itself, must be monitored and put under control. Currently, they are not. This requires a predictive model of the behavior of the reactor to be used in a process control loop. Accurate experimental growth rate data for MOCVD systems, which is in short supply under well-defined fluid and thermal environments, has been identified as the major need for numerical models, in order for them to be used for this purpose and for reactor design studies.

Accomplishment -- We have used the in-situ reflectance monitor, ADVISOR, to obtain accurate and reproducible growth rates for a number of III-V MOCVD systems in a research rotating disk system. Evidence for a group V inhibition of the growth rate has been demonstrated for the first time for the MOCVD of GaAs and AlAs from TMGa, TMAI, AsH₃, and tBuAs precursors. A surface mechanism, wherein As atoms occupy group III lattice sites on the surface partially creating the c(4x4) surface reconstruction and blocking group III surface reactions, has been incorporated into a

simplified kinetics model of the process. Rate constants for the stability of these As surface atoms are in agreement with TPD measurements by Banse and Creighton. Figure 1 demonstrates the agreement of this blocking mechanism with experimental data at 640°C. The model calculations were carried out using the 1-D code, SPIN, based on the CHEMKIN suite of gas and surface kinetics/transport library.

Figure 2 shows the agreement of several experiments against the 1-D model (solid line) and a 3-D model (dashed line), SALSA, an MP reacting flow code. Agreement of the 1-D model is good at the matching flow conditions, where the spinning of the disk masks the 2-D effects of the side walls. A 2-D transport code, however, is needed to model the stagnation point flow limit, due to the breakdown in the Von-Karmon similarity transformation.

Significance -- The group V inhibition effect has important ramifications for the concept of what types of surface ligands are present during normal growth conditions. Such behavior is also not presently incorporated into detailed kinetics models of III-V growth behavior, necessitating their reevaluation. These accurate growth rates are being used now to construct detailed kinetics models, which will be used in reactor scale-up.

Keywords: CVD, III-V MOCVD, reflectance monitor, advanced materials, CHEMKIN, finite element method

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Figure 1: Model (—) vs. experiment at 640°C, using TMGa and tBuAs, three different TMGa inlet flow rates.

Figure 2: 1-D and 3-D Model vs. experiment at 640°C, using TMGa and AsH₃, 70 torr total pressure.

Site-Independent Decomposition Rates Observed in TEOS-Based SiO₂ Chemical Vapor Deposition

by M. E. Bartram and H. K. Moffat

Motivation -- TEOS (tetraethylorthosilicate, Si(OCH₂CH₃)₄) is used in numerous microelectronics processes for the critical step of conformal SiO₂ film deposition. Good conformality is achieved only if the SiO₂ growth rate is uniform over the entire deposition surface. However, if the reaction kinetics are highly dependent on a specific type of site, growth rates and uniformity will be determined by the local coverage of the reactive sites on the surface. For this reason, identification of the reactive sites and precise measurements of the their reaction kinetics are required for the development of a predictive CVD (chemical vapor deposition) model.

Accomplishment -- We have determined that the TEOS decomposition rate is independent of specific surface sites on SiO₂ at 1000K. This was achieved using FTIR (Fourier transform infrared spectroscopy) and isotopic labeling techniques. TEOS reactions were carried out on a series of surfaces which were first annealed at progressively higher temperatures. This allowed the initial coverages of silanols and siloxane bridges (Si-O-Si) in three-membered siloxane rings to be systematically varied. The initial silanols were labeled with deuterium (SiOD) so that SiOH formation, which we used as a measure of TEOS decomposition, could be measured with FTIR. The data are shown in Fig.1 for 20mTorr of TEOS reacting at 1000K. The constant slopes signify that the SiOH formation rate is independent of silanol coverages on SiO₂. This implies that TEOS

reaction rates are also independent of siloxane bridge coverages, since the annealing preparation which decreased the initial silanol coverage also increased the three-membered siloxane ring coverage. It is important to note that TEOS can react preferentially with siloxane bridges in two-membered rings. However, they are of minor concentration and their rate of formation is quite slow. Therefore, we expect that their participation is insignificant under CVD processing conditions.

Significance -- These surface specific studies have demonstrated for the first time that TEOS reactions on SiO₂ at 1000K are not site-specific. This is an important new understanding since it has been postulated from low temperature studies that silanols were an important reaction site for promoting TEOS decomposition in SiO₂ CVD. Since our determination was achieved at temperatures and pressures used commonly in CVD processes, our data can be applied to predictive CVD models. Specifically, the site-independent decomposition rate suggests that a precise knowledge of the coverages of functional groups on SiO₂ is not required for modeling TEOS surface reaction rates. From the standpoint of deposition uniformity and conformality, our results predict that deposition rates will be insensitive to the relative coverages of siloxane bridges and silanols on the SiO₂ surface. Therefore, it is likely that non-uniform SiO₂ depositions in TEOS CVD are due to thermal gradients and/or depletion of TEOS in the gas-phase.

Keywords: CVD, FTIR, microelectronics, SiO₂, silanols, SiOH, siloxane, Si-O-Si, surfaces, TEOS, tetraethylorthosilicate

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FTIR measurements in a series of TEOS reactions which show that the rate of SiOH formation (TEOS decomposition) is independent of silanol and siloxane bridge coverages (in three-membered siloxane rings). ($\square$) and ($\circ$) are raw data points above which corrections for reactions with two-membered siloxane rings are plotted.

Observation and Theory of Phonon Side Bands in the Magnetoluminescence from Doped Quantum Wells

by E. D. Jones and S. K. Lyo

Motivation -- Landau level (LL) spectroscopy offers a powerful probe of electronic structures and interactions in semiconductor quantum wells (QWs). In a magnetic field perpendicular to the QW plane, the carriers are quantized into the LLs with quantum numbers $n_e, n_h = 0, 1, \dots$. Zero-phonon electron-hole recombinations $n_e \rightarrow n_h$ occur through selection-rule allowed direct transitions with $n_e = n_h$ or through weaker zeroth-order forbidden indirect off-diagonal transitions with $n_e \neq n_h$ in direct-gap QWs. At low temperatures with most of the holes in the ground LL $n_h = 0$, the allowed $0 \rightarrow 0$ direct transition is dominant, while the zeroth-order forbidden $n_e (> 0) \rightarrow 0$ off-diagonal transitions are weaker. At high temperatures with higher hole LLs populated, recombinations occur through the allowed direct transitions. This crossover between direct and indirect transitions was utilized to determine the conduction- and valence-band energy dispersion curves. While the zero-phonon processes have been fully investigated and utilized, there have been no theoretical or experimental studies of *phonon-assisted* optical transitions in QWs possibly due to the weak intensities of the lines. Study of the phonon side bands (SBs) in the luminescence lines is expected to yield rich information about the phonon structures.

Accomplishment -- We have observed the LO-phonon SBs for transitions between the electron and hole LLs in the n-GaAs/ $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}/\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ QWs and developed a microscopic theory. The SBs appear

about 37 meV below the zero-phonon lines, corresponding to the GaAs LO phonon energy. Contrary to intuition, however, the relative intensities of the SBs are inverted from those of the zero-phonon lines. Namely, the SBs of the primary $n_e = 0 \rightarrow n_h = 0$ line is absent at low temperatures, while the SBs of the secondary $n_e (> 0) \rightarrow n_h = 0$ lines are relatively strong, growing with n_e (see Fig. 1), yielding excellent agreement with our theoretical predictions as shown in Fig. 1. The suppression of the intensities from small $\Delta n (= |n_e - n_h|)$ SBs is due to the cancellation in the amplitudes of the electron-phonon and hole-phonon recombination channels in the presence of the magnetic quantization in two dimensions. The degree of the cancellation decreases with increasing Δn .

Significance -- This is a new phenomenon established theoretically and experimentally for the first time to our knowledge. Currently, phonons in alloy QW structures are poorly understood although they affect transport and relaxation properties significantly. Luminescence studies of the phonon SBs provide an important tool to investigate the LO phonon structure and the carrier-phonon coupling. For GaAs/ $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}/\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ QWs, our data indicate that the phonon modes are not much different from those of bulk GaAs because of the low In and Al concentrations. Recent tunneling data indicate that Al begins to affect the phonon modes in the AlGaAs barrier significantly above 20% Al concentration.

Keywords: magnetoluminescence, quantum well, heterostucture, phonons, phonon side band

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The 4K- PL spectra at (a) 5 tesla and (b) 9 tesla from $n\text{-GaAs/In}_{0.15}\text{Ga}_{0.85}\text{As/Al}_{0.15}\text{GaAs}_{0.85}$ excited with an argon-ion laser (514.2 nm) source. The spectral resolution is 1 meV. The $0 \rightarrow 0$ peak energies are 1390 and 1396 meV for 5T and 9T, respectively. The peak energies of the phonon side bands " $n_e \rightarrow 0\text{ p}$ " are about 37 meV below the $n_e \rightarrow 0$ zero-phonon peaks. Calculated oscillator strengths of the side bands are spread out into Gaussian line shapes (dashed curves) with a full width at half maximum of 4 meV. The $1 \rightarrow 1$ and $1 \rightarrow 1\text{ p}$ peaks in (b) are from unrelaxed holes in $n_h = 1$. The position of the peaks identified here rises nearly linearly with the field. The peak "?" in (b) is independent of the field.

Direct Measurement of Surface Diffusion Using Atom-Tracking STM

by B. S. Swartzentruber

Motivation -- The evolution of surface morphology during growth or etching depends on the detailed interplay between a myriad of atomic-scale kinetic processes. To study surface morphology evolution many investigators utilize rate equation analysis, Monte Carlo, or molecular dynamics simulations which require the input of specific atomic-scale energy parameters, which are derived in a variety of ways ranging from first-principles total energy calculations to purely empirical values chosen to reproduce particular measured morphological features. Of course quantitative experimental measurements of particular system-specific atomic-scale processes are ideal. The quantitative measure of individual atomic-scale energy parameters not only serve as inputs to realistic simulations and model calculations, but also enable the validation and refinement of such calculations.

Accomplishment -- We invented a technique called "atom tracking" that we employed to quantitatively measure the diffusion kinetics of Si ad-dimers on the Si(001) surface at temperatures between 25 and 130C. In atom-tracking mode, the STM tip is locked onto a selected ad-dimer using lateral feedback. Once locked, the feedback electronics maintain the tip over the cluster as it diffuses over the substrate tracking its coordinates. The feedback maintains a lateral position of zero local slope--the top of the ad-dimer is tracked by continually "climbing uphill". In the atom-tracker mode, the STM spends *all* of its time measuring the

kinetics of the selected ad-dimer. When a diffusion event occurs the atom tracker quickly relocates to the ad-dimer's new position. The atom-track data consist of the X, Y and Z feedback coordinates as a function of time. In Figure 1a) we show a scatter plot of the complete set of lateral coordinates of the ad-dimer in the middle of Figure 1b), acquired at 65C over 540 sec. During the course of the measurement the ad-dimer visited 7 lattice sites along the top of the substrate dimer row, making 41 hops. The individual site visitations are easily distinguishable in the scatter plot and are separated by the Si(001) lattice spacing of 3.84Å. The data points at each lattice site group to <1Å, indicating how well the atom tracker locates the "top" of the ad-dimer. Utilizing atom tracking we increase the time response of the instrument by about three orders of magnitude over conventional STM imaging techniques. The average hop rate of the ad-dimers increases from 0.001 sec⁻¹ at 25C to 10 sec⁻¹ at 130°C. Analyzing the hop rate as a function of temperature yields the activation barrier for diffusion, $E_a = 0.94 \pm 0.09$ eV (Figure 2).

Significance -- By increasing the capability of the STM to yield quantitative measurements of surface kinetic processes that were previously inaccessible, we provide additional insight into the complicated interplay between atomic-level processes that control growth, corrosion, and etching of materials surfaces. We can also identify and measure new dynamic mechanisms that exist on the surface.

Keywords: scanning tunneling microscopy, kinetics, Si(001), surface diffusion, ad-dimer

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Figure 1: (a) Scatter plot of atom-track data acquired at 65C (540 sec.) of the diffusion of the ad-dimer in the middle of the 100Å image (b).

Figure 2: Arrhenius plot of the ad-dimer diffusion rate measured at temperatures between 25 and 130°C from which the activation energy barrier is extracted.

Nucleation and Evolution of Film Structure in Chemical Vapor Deposition Processes

by T. M. Mayer, D. P. Adams, B. S. Swartzentruber

Motivation -- The structure and properties of a thin film are highly dependent on the conditions employed during growth. In particular, nucleation is known to be an important rate limiting step, and responsible for the evolution of the macroscopic structure of many materials. For many examples of film growth by evaporation or molecular beam epitaxy, surface morphology, growth mode and film microstructure is dominated by adatom surface mobility. In contrast, chemical vapor deposition processes (CVD) are often dominated by chemical reaction kinetics. The effect of such processes on film structure is not understood. We have designed and carried out a project to investigate atomic scale kinetic processes important in nucleation of a film and evolution of structure of the film during chemical vapor deposition.

Accomplishment -- We have used the scanning tunneling microscope to investigate the initial, or nucleation, stage of iron growth on Si (100) surfaces by pyrolysis of $\text{Fe}(\text{CO})_5$. Density and size distributions of nuclei are obtained for varying doses, temperature and coverage. This is contrasted to similar measurements obtained for evaporation of iron atoms onto Si(100) at the same conditions. Qualitative and quantitative differences in nuclei size and density are evident and attributable to the chemical reaction processes active in CVD. We observe fewer, larger islands for CVD, and marked temperature dependence to the growth rate. Kinetic Monte-Carlo simulations lend support to our conclusion

that the morphology observed in CVD is due primarily to an autocatalytic process, in which precursor molecules dissociate preferentially at existing nuclei sites. More subtle effects on morphology can potentially be extracted from analysis of island size distributions. Through a scaling analysis (carried out by D Chrzan, S Bales) we see evidence for a second order process in formation of new nuclei, and possible effects of anisotropic precursor diffusion on morphology of islands. The second order process may be the result of surface site poisoning by dissociated ligands or other impurities, preventing formation of new nuclei as coverage increases. We (with E. Chason) have also carried out *in-situ* measurements of surface roughness as the film grows to multilayer thickness. We see evidence for the autocatalytic growth and nuclei coalescence at higher coverage.

Significance -- This study represents the most complete experimental investigation to date of nucleation and morphology development in a CVD process. We have directly identified important chemical kinetic parameters that control film growth. We have also shown that dynamic scaling theory analysis is appropriate for this class of problems, and is able to extract useful information from the detailed experimental data. This study contributes to our understanding of nucleation processes and lays the foundation for manipulation and control of surface kinetic process for high quality film growth and nanostructure fabrication.

Keywords: chemical vapor deposition, nucleation, scanning tunneling microscopy, nanostructures

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Figure 1: 30 nm x 30 nm STM images of Fe nuclei grown by CVD and evaporation at 215 C on Si (100). CVD results in fewer, larger island at similar total coverage.

Figure 2: STM images of a) H-passivated Si (100) surface which has been patterned by H desorption. Bright areas are where H has been removed by electron stimulated desorption; b) Fe crystallites selectively deposited in areas where H has been removed.

Intracavity Microlasers: A New Approach to Microparticle Analysis and its Application to Cell-Structures

by P. L. Gourley, K. E. Meissner, and M. F. Gourley (National Institutes of Health)

Motivation -- Research on semiconductor microstructures and vertical cavity surface-emitting lasers at Sandia has made remarkable progress in recent years and is finding new applications. One application exploits the 2-dimensional surface emission from these microlasers to permit a revolutionary method for analyzing biological cells and microparticles. The laser imager (called a biological microcavity laser or biocavity laser) provides the basis for a new kind of biomedical analysis of cell structure. Both living and fixed cells can be analyzed and the technique doesn't require the customary cell-perturbing staining procedures. This intracavity laser technique has the potential for advancing cell microbiology, immunology, DNA fragment sizing, and provides a new clinical technique for early diagnosis of disease.

Accomplishment -- Using vertical cavity surface-emitting laser technology, we have demonstrated that the biocavity laser can quantify the size and shape of sickled and normal red blood cells. By intracavity spectroscopy, we find the laser light corresponds to electromagnetic modes defined by the cell structure and depends sensitively on the size and shape of the cells (Fig.). This sensitivity arises because the laser operates at resonant frequencies established by the dielectric properties of the cells. By using a high resolution spectrometer, these lasing frequencies

were resolved into narrow spectral peaks. The spacing and intensity distribution between peaks provide a unique spectral signature for each cell. A simple analysis of cylindrical optical modes of red blood cells in the biocavity shows the spacing of lateral mode wavelength is proportional to the inverse square of the cell diameter.

Significance -- An important area of biomedical research is the understanding of cellular and molecular events during blood cell production. Quantitative measurements of blood cells and precursor stem cells would help assess the effectiveness of gene therapy or bone marrow transplants in the treatment of leukemia. Currently, there is no assay for human stem cells. The biocavity laser has the potential to probe 10^5 - 10^6 cells per second making such an assay possible.

Further, this microlaser technique of intracavity sensing may have additional broad implications. It represents a new approach to detecting trace amounts of microparticulate and chemical species at very rapid rates. Micro-instruments based on such concepts may hold potential for such diverse applications as sensitive monitoring of environmental species or quality control of microphase materials in manufacturing.

Keywords: semiconductor lasers, microcavity laser, biological cell analysis, intracavity spectroscopy

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TRANSVERSE OPTICAL MODES OF RED BLOOD CELLS IN LASER CAVITY

Experimentally observed biocavity laser images corresponding to the six lowest order transverse optical modes in a normal red blood cell. The vertical bars mark the wavelength positions computed for lateral modes of a $7.5 \mu\text{m}$ diameter cell of refractive index 1.4 at wavelength $0.85 \mu\text{m}$. Above the line, the modes indices mn are given.

*Multispectral Ultraviolet Fluorescence Lidar System Identifies
Chemical Mixtures in Field Tests*

by P. J. Hargis, Jr., G. C. Tisone, T. D. Raymond, J. G. Taylor, J. S. Wagner, I. S. Shokair,
R. D. Mead, J. D. Daniels, T. J. Sobering, M. S. Johnson, M. W. Trahan,
B. F. Clark, C. Wakefield-Reyes, and F. R. Franklin

Motivation -- Highly sensitive ultraviolet (UV) measurements are generally thought to be of limited use in lidar systems designed to detect chemical species in the atmosphere. Recent work at Sandia National Laboratories has changed this perception and led to the development of a new multispectral UV fluorescence lidar system designed for remote chemical analysis. Briefly, a broadly tunable UV laser is used to transmit multiple laser wavelengths, some of which are selectively absorbed and subsequently excite fluorescence in specific chemical species. The resulting fluorescence spectra at each excitation wavelength are compared to a database of fluorescence spectra from individual species to determine species concentrations. The comparison is carried out using a unique multivariate analysis algorithm developed at Sandia to determine species concentrations from multispectral UV fluorescence measurements.

Accomplishment -- Sandia's multispectral UV fluorescence lidar system was tested in July 1995 at the Nevada Test Site. Measurements were made on vapor plumes consisting of mixtures of benzene, m-xylene, p-xylene, and toluene ranging in concentration from 1 to 500 ppm. All measurements were made at a standoff distance of 0.5 km. Atmospheric attenuation

coefficients derived from elastic backscatter measurements were used in the multivariate analysis algorithm to correct measured fluorescence spectra for distortions due to transmission of the fluorescence radiation through the atmosphere. The analysis algorithm was then used to determine species concentrations and time-dependent concentration profiles. Almost 95% accuracy was achieved in identifying species in chemical plumes containing up to four species. Fluorescence detection limits for individual species ranged from about 5 to 10 ppm-m for all measured species. Highlights of the field test results include the first multivariate analysis of multispectral absorption and fluorescence data and the capability of UV fluorescence lidar measurements to map species concentrations in chemical plumes.

Significance -- Data obtained at the July 1995 field test demonstrates the potential of multispectral UV fluorescence measurements to detect nuclear, chemical, and biological proliferation activities. Other areas of national importance that benefit from the new technology are counterterrorism, drug interdiction, environmental monitoring, and global climate change.

Keywords: remote sensing, ultraviolet lidar, fluorescence, absorption, chemical analysis

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Figure 1: Configuration of the multispectral UV fluorescence lidar system.

Laser:

250 to 400 nm wavelength range
 3 to 15 mJ/pulse
 30 Hz pulse repetition rate
 2 to 4 cm^{-1} bandwidth

Receiver:

Multichannel fluorescence (250-600 nm)
 Elastic backscatter (250-400 nm)
 Time-resolved fluorescence

Measurement Modes:

Analog and photon counting
 Multispectral scan
 Continuous data acquisition
 Gas plume mapping

(a)

(b)

Figure 2: Multispectral UV fluorescence signals measured at a standoff distance of 0.5 km from vapor plumes containing representative mixtures of benzene, m-xylene, p-xylene, and toluene.

Quasi-Ballistic Transillumination Spectral Imaging Using Optical Parametric Amplification

by S. M. Cameron, D. E. Bliss, and M. W. Kimmel

Motivation: Light-based imaging through turbid media is possible because variations in absorbance and scattering properties influence photon diffusion. The nature of transmitted light from such a medium ranges from the quasi-coherent properties of the minimally scattered component to the random incoherent light of the diffuse component. Implementation of optical imagery in a diffuse scatterer is therefore premised on an understanding of photon migration dynamics and multiple scattering processes which act to randomize pathlength, to invalidate direct geometrical correlation between incident and detected light, and to degrade resultant image quality. Compensation for these “fog-like” effects will require dynamic path-sensitive imaging methods which rely on spatial, temporal, and phase signatures to actively discriminate against diffusely scattered background. One experimental approach designed to circumvent interpretational difficulties associated with connecting photon trajectory and image reconstruction is ballistic imaging which seeks to isolate the fast image-bearing component from the slow incoherent noise background using a subpicosecond optical gate superimposed on the transmitted or reflected photon time-of-flight distribution.

Accomplishment: We have demonstrated a novel broadband (450-800 nm), high gain ($>10^4$), ultrashort (<200 fs) amplifying gate for

trans-illumination imaging based on optical parametric amplification in a nonlinear crystal. We have used this system to reconstruct and enhance images with absolute feature sizes of 65 μm and an overall resolution approaching 10:1 in optically limited environments exhibiting attenuations exceeding 10^{12} . The gate simultaneously amplifies and temporally isolates the weak ballistic image component at a 250 KHz repetition rate and can be angularly tuned in wavelength space by virtue of the crystal phase matching conditions. In our system, we successfully cascaded two parametric amplifier stages, one as a polychromatic light source (signal and/or idler), and the second as a temporal gate after the object. By upconverting and amplifying the near-infrared idler rather than the visible signal, we can suppress background effects, reduce diffuse scattering, and improve the dynamic range for image formation. In future experiments, a wavefront sensor and a gain-modulated camera will be used in conjunction with the current gating scheme to obtain phase images.

Significance: This spectral imaging technique is an important new extension of nonlinear optics to image processing and the visualization of stationary and transient phenomena in turbid media, with important applications to medical tomography, subsurface metrology, and optical ranging.

Keywords: optical ballistic imaging, parametric amplification, optical ranging

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Ballistic Image Formation Using Optical Parametric Amplification

Acquired grayscale ballistic image of resolution chart feature (65 μm) through opal diffusers with O.D. 10.

— *Diagnostics and Characterization* —

Materials Characterization

Our capabilities in this area include optical microscopy, scanning, electron microscopy, analytical transmission electron microscopy, double crystal x-ray diffraction, ion beam analysis of materials (RBS, channeling, ERD, PIXE, NRA), Hall measurements, photoluminescence, light scattering, electronic transport, deep level spectroscopy, magnetization, and dielectric and magnetic susceptibilities.

Chemical Vapor Deposition (CVD)

We have a wide range of experimental tools for investigating CVD which include optical probes for gas-phase and surface processes, a range of surface analytic techniques, molecular beam methods for gas/surface kinetics, and flow visualization techniques. Carefully chosen experiments provide the critical information on chemical species, gas temperatures, and flows necessary for model development and validation.

Surface and Interface Spectroscopies

We maintain strong capabilities in auger electron spectroscopy (AES), x-ray photoelectron spectroscopy (XPS), low energy electron diffraction (LEED), ultraviolet photoelectron spectroscopy (UPS), thermal desorption spectroscopy (TDS), infrared reflectance-absorption spectroscopy (IRAS), and quantum state resolved laser surface probes.

Sandia Nuclear Microprobe

The Sandia Nuclear Microprobe is used to study and evaluate the radiation hardness of microelectronic devices using two new advanced diagnostic techniques invented at Sandia: Single-Event-Upset Imaging and Ion-Beam-Induced-Charge-Collection Imaging.

Vision Science Laboratory

We have developed a vision science laboratory with state-of-the-art hardware and software

capabilities for carrying out video inspection, multi-spectral image analysis, and sensor-based pattern recognition. These capabilities can be applied to applications ranging from microsensor-based chemical detection and recognition to automated video/SEM inspection of semiconductor materials and circuits.

Xternal Micro Ion Beam Analysis (X-MIBA)

This unique facility is designed for the multi-elemental analysis and ion irradiation of samples which are vacuum incompatible or extraordinarily large. Detection of elements ranging from all three isotopes of hydrogen to the transuranics is possible with sensitivities of 0.01 to 100 ppm.

Growth Science Laboratory

We have unique capabilities for in situ characterization of materials during molecular beam epitaxial growth, low energy ion bombardment on ion beam simulated growth using intensity profile sensitive reflection high energy electron diffraction (RHEED) for surface structure, energy dispersive x-ray reflectometry for in situ surface and interface structure, multibeam wafer curvature for strain, and Auger electron spectroscopy for surface composition.

KMAP X-Ray Diffractometer

KMAP X-Ray Diffraction Analysis is used to determine the lattice constant, strain relaxation, composition, layer orientation, and mosaic spread of a large variety of advanced epitaxial semiconductor materials.

Tandem Van de Graaff Ion Accelerator

This 6 MV EN accelerator provides ion species from hydrogen to bismuth for quantitative ion beam analysis of materials containing light elements (hydrogen to fluorine) using elastic recoil detection (ERD) and heavy elements using Rutherford backscattering spectrometry (RBS).

This facility has also been used for high energy ion irradiation studies of high temperature superconductors.

Atomic-Level Imaging and Spectroscopy

We have developed unique capabilities in scanning tunneling microscopy (STM), field Ion microscopy (FIM), atom probe microscopy (APM), and interfacial force microscopy (IFM). Selected analysis is possible in both high temperature and ultra-high vacuum.

Nanoelectronics Laboratory

We have capabilities for characterizing nanoelectronic structures (also fabricated at Sandia by e-beam lithography) through electrical transport measurements at low temperatures and high magnetic fields.

Lasers and Optics

We have extensive capabilities in characterizing and advancing the understanding in the area of solid-state lasers and non-linear optics, especially as coherent sources of broadly tunable light in rugged, compact geometries. We have established expertise in long-term and transient radiation effects characterization of optical materials.

Laser Spectroscopies

We have extensive capabilities for characterizing semiconductor materials by photoluminescence and magnetoluminescence down to low temperatures by optical laser imaging and laser microscopy, by laser excitation spectroscopy, and by time-resolved measurements of optical emission.

— Synthesis and Processing —

Nanocluster Laboratory

We have developed and patented a process based on the use of inverse micelles for the synthesis of large quantities of monodisperse clusters of metals, semiconductors, and oxides.

Electron Cyclotron Resonance (ECR)

This plasma facility has been built for studying fundamental processes governing the growth of oxide and nitride dielectric films used in optoelectronics and used as hard coatings.

400 kV Ion Planter

This system is equipped with a variety of sources (gas, sputter, and metal vapor). This facility provides ion species from hydrogen to bismuth which can be used for studying fundamental irradiation mechanisms and selective chemical doping in semiconductors, ferroelectrics, and superconductors.

Molecular Beam Epitaxy

We have state-of-the-art commercial semiconductor growth laboratories for MBE

growth of III-V materials. In addition, we have research systems for Group IV semiconductor growth, including conventional and beam-enhanced epitaxial growth.

Metal-Organic Chemical Vapor Deposition (MOCVD)

We maintain state-of-the-art materials growth and characterization facilities with unique capabilities in MOCVD of compound semiconductor materials. Our facilities include commercial production MOCVD reactors as well as research reactors designed specifically for studies of CVD chemistry and for the development of advanced in situ diagnostics.

High Pressure and Shock Wave Physics and Chemistry Laboratories

Our capabilities in this area include large volume static high pressure apparatus which can be operated at temperatures ranging from 2° to 700° K and in magnetic fields; gas gun and explosive loading facilities with state-of-the-art, time-resolved diagnostics.

Shock Wave Synthesis

Recovery fixtures have been developed for use with gas gun and explosive shock loading facilities which allow unique material synthesis over broad ranges of shock pressures and temperatures.

Crystal and Thin Film Growth

Capabilities in this area include a pulsed laser deposition chamber, a thin film oxide deposition chamber, a diamond-like carbon deposition chamber, a hot filament chemical vapor

deposition chamber, and various apparatus for single crystal growth.

Low-Temperature Plasma Analysis

We have state-of-the-art capabilities for the analysis of low-temperature plasmas as found in commercial processing reactors. These include emission spectroscopy, electrical characterization, laser and microwave-based measurements of species concentrations, electric field measurements (in situ), and others.

— Theory and Simulation —

CVD Reactions

We have extensive capabilities to model complex chemically reacting flows such as occur in chemical vapor deposition manufacturing processes. Our numerical simulations can include the coupled gas-phase and gas-surface chemistry, fluid dynamics, heat, and mass transfer to provide predictive models of a chemical process.

Low-Temperature Plasmas

We have extensive capabilities in simulating the time and space evolution of low-temperature plasmas, focusing on new theoretical techniques for achieving rapid convergence and on direct comparisons with experimental results.

Optical Design

We have capabilities in novel optical designs, including resonators for application-driven laser geometries and in the application of binary optics. These capabilities are coupled to in-house micro-optics construction facilities and state-of-the-art optics testing.

Wave Propagation

We have developed advanced simulation codes for understanding wave propagation in optical parametric oscillators and amplifiers for the purpose of designing efficient, mission-oriented tunable laser sources.

Electronic Structure and Linear Scaling

We have developed state-of-the-art massively parallel electronic structure algorithms, based on ab initio pseudopotentials and plane-wave/gaussian basis functions. In close collaboration with experimental efforts at SNL, these codes are used to develop a fundamental understanding of new physical phenomena and materials-compound semiconductor band structure, point defects in semiconductors, surface electronic structure enhanced reactivity of nanoparticles, and adsorbate interactions on surfaces. To allow the investigation of more complex systems and phenomena, we are also developing new computationally efficient algorithms, e.g., self-consistent linear scaling density functional theory, and variable- and real-space gridding.

Semiconductor Calculations

Expertise in this area includes: Ab initio pseudopotential bandstructure, semi-conductor transport and photo-luminescence, Monte Carlo surface epitaxial growth and sputtering, and binary collision TRIMRC code to simulate ion-solid interactions. Workstations, CRAY-YMP, and massively parallel computational facilities are used.

—Recent Awards and Prizes in the Physical and Chemical Sciences Center—

1995 — Norbert J. Kreidl Award from the New Mexico Ceramics Society Glass Division to K. S. Simmons-Potter.

1994 — R&D 100 Award to J. E. Houston and T. A. Michalske for "*Interfacial Force Microscope*."

1994 — Department of Energy Materials Science Award for Sustained Outstanding Research in Solid State Physics to P. J. Feibelman for "*Surface Atom Energetics*."

1994 — Department of Energy Materials Science Award for Significant Implication for Department of Energy Related Technologies in Materials Chemistry to K. P. Killeen, S. A. Chambers, W. G. Brieland and T. J. Kerley for "*Real Time, In Situ Materials Growth Monitors Using Remote Optical Probes*."

1994 — Department of Energy Materials Science Award for Sustained Outstanding Research in Metallurgy and Ceramics to E. Chason, J. Y. Tsao, J. A. Floro, K. M. Horn, T. M. Mayer, P. Bedrossian, D. K. Brice, A. J. Howard, S. T. Picraux, D. L. Buller and K. J. Penn for "*Science of Surface Processes in Beam-Enhanced Growth*."

1993 — The American Physical Society International Prize for New Materials to G. C. Osbourn for "*Originating the Field of Strained-Layer Superlattice Electronics on Optoelectronics*."

1993 — Department of Energy Materials Science Award for Significant Implications for DOE Related Technologies in the Metallurgy and Ceramics Category to J. E. Houston and T. A. Michalske for "*Interfacial-Force Microscope*."

1993 — The American Physical Society Shock Compression Science Award to R. A. Graham.

1993 — Department of Energy Materials Science Award for Sustained outstanding Research in Metallurgy and Ceramics to P. L. Gourley for "*Strained-Layer and Artificially Structured Semiconductors*."

1992 — Department of Energy Materials Science Award for Sustained Outstanding Research in Metallurgy and Ceramics to B. L. Doyle, S. T. Picraux, J. A. Knapp and S. M. Myers for "*Advanced Ion Beam Techniques for Materials Analysis*."

1992 — Department of Energy Materials Science Award for Sustained Outstanding Research in Materials Chemistry to W. G. Breiland, M. E. Coltrin, G. H. Evans, P. Ho, and R. Kee for "*CVD Sciences*."

1991 — Department of Energy Materials Science Award for Significant Implication for DOE Related Technologies in Metallurgy and Ceramics to D. M. Follstaedt, R. J. Bourcier, M. T. Dugger and S. M. Myers for "*Exceptionally High-Strength Aluminum Alloys*."

1991 — Department of Energy Materials Science Award for Outstanding Science Accomplishment in Solid State Physics to G. L. Kellogg and P. J. Feibelman for "*Surface Diffusion by Atomic Substitution*."

1990 — E. O. Lawrence Award to S. T. Picraux.

1990 — Department of Energy Materials Science Award for Sustained Outstanding Research in Metallurgy and Ceramics to S. M. Myers, K. L. Brower, P. M. Richards and H. J. Stein.