

Research Summary

Modern integrated electronic and optoelectronic devices are practical examples of the spectacular advances in condensed matter physics, materials science and device engineering. The Electronic Materials Engineering (EME) Department contributes to these advances by undertaking world-class research in areas involving the growth, structure, properties and applications of electronic materials. Individual projects range from fundamental, curiosity driven studies of novel solid-state phenomenon to strategic or application-driven device engineering. Indeed, the diversity of the Department's research is one of its key strengths, underpinning its broad collaborative base and its ability to attract students and researchers from a range of disciplines.

This was an exciting and eventful year for EME with many significant personal and scientific achievements and many new developments and changes. The year also involved a degree of uncertainty, introspection, anticipation and exhilaration, as staff changes and full entry into the ARC competitive grants scheme had their impact. On the research front, productivity remained impressive, with over 58 papers published in peer-reviewed journals and around 15 invited or keynote talks presented at national or international conferences. The Department's extraordinary success in the 2003 competitive grant scheme (a success rate of over 85% compared to a national average of around 25%) was another major highlight of the year which clearly reflected the quality and strength of its research program. This success will see several new early-career researchers joining the Department in 2003, adding further to its vitality and energy. It will also see the total income from ARC competitive grants exceed that of recurrent funds from ANU, a situation that presents exciting new opportunities as well as interesting challenges.

As in previous years, the outstanding contributions of EME staff and students have been recognised by a range of promotions, appointments and awards. These are detailed later in this report but several are worth noting here. In particular, the promotion of C. Jagadish to academic level E2 and his election to Fellowship of the Australian Academy of Technological Sciences and Engineering (ATSE), together with the promotion of H.H. Tan to academic level C and P.N.K. Deenapanray to academic level B were well deserved. On the student front, Jodie Bradby was awarded a highly-regarded Australian-American Fellowship for study in the USA and was additionally awarded the Materials Research Society (MRS) Gold Medal for the best oral presentation at the 2002 MRS Fall Meeting. COMMAD 2002 poster awards were garnered by Christine Carmody and Penny Lever. In addition, three EME students were awarded PhDs (Michael Cohen, Stephanie Cheylan and Sergei Kucheyev), and three others submitted their theses for examination (Jodie Bradby, Chris Glover and Tessica Weijers). Sergei subsequently accepted a prestigious Lawrence Fellowship to work at Lawrence Livermore National Laboratory in the USA.

The year also saw several staff changes, including the departure of Laura Walmsley, our Departmental Administrator, and of two experienced technical staff, Alan Hayes and Tony Watt. Having worked in EME for around 5 years, Laura has now been appointed as Personal Assistant to the Director of the School. During her time in EME her contribution to the smooth and efficient operation (and social well being) of the Department was much appreciated. Renee Vercoe will take over Laura's role early in 2003. Other staff changes were precipitated by a review of EME's technical staff, together with a University-wide voluntary redundancy scheme. This resulted in Tony Watt and Alan Hayes taking redundancy packages. Tony and Alan were responsible for the maintenance and development of EME's high-profile accelerator laboratories and had accumulated around 20 years of total experience in this area. The loss of their skill and expertise will certainly impact on the operation of the accelerator laboratories throughout 2003 and beyond.



Professor Rob Elliman
- Head of Electronic Materials
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The Department of Electronic Materials Engineering conducts interdisciplinary research on the physics and engineering of electronic and optoelectronic materials and devices.

<http://wwwrphysse.anu.edu.au/eme>

The strength of EME's research program continues to be underpinned by the performance and reliability of its extensive suite of experimental equipment and associated facilities and infrastructure. These continue to grow each year, with a new photoluminescence laboratory and extensive clean-room suite being installed during 2002. The latter owes much to Michael Aggett who was largely responsible for the technical design and management of the project. The fact that the Department's equipment and facilities continue to operate at peak performance and with minimal down-time is a great credit to the Department's technical staff (M. Aggett, T. Halstead, A. Hayes, B. King, and A. Watt), technical assistants (M. Conway and A. Williams) and associated research assistant (D.J. Llewellyn). Their expertise, commitment and professionalism are much appreciated. The crucial role played by the School's workshops and service areas is also gratefully acknowledged in this context.

Material Growth, Synthesis and Processing

MOCVD Growth of III-V Semiconductor Structures

The growth of epitaxial III-V semiconductor structures by metal-organic chemical vapour deposition (MOCVD) is an active area of research with several new material systems and structures being investigated this year. Highlights included the growth of highly strained InGaAs and InGaAsN structures for long wavelength (1.3 and 1.55 μm) optical communications, which resulted in InGaAsN quantum wells having room-temperature optical emission at 1.21 and 1.320 μm , respectively, and a novel scheme of inserting InAs monolayers in GaAsN quantum wells to increase luminescence efficiency, a process that looks

promising for device applications. Work also continued on the growth of high-In content quantum dots and stacked dot layers. In order to reduce the strain in stacked quantum dot structures a strain-compensating scheme was proposed and implemented, in which, InGaAs dots were grown on a thin buffer layer of pseudomorphic GaP. It was found that there was substantial improvement in the uniformity, size and thermal stability of the dots although a blueshift in the emission wavelength due to intermixing of the InGaAs and the GaP layer was observed. These layers are now being investigated for their suitability in device structures which require higher temperature growth.

Intermixing for Optoelectronic Device Integration

Impurity-free disordering (IFD) of III-V semiconductors is a promising candidate for the monolithic integration of optoelectronic and photonic devices. The underlying operative mechanisms of this apparently simple process are, however, not well understood. Our recent studies of bulk GaAs, InP/InGaAs heterostructures and InGaAs/GaAs quantum dot structures have provided insight into these mechanisms, showing, for example, that stress-induced conversion of gallium vacancies into arsenic anti-sites can reduce the efficiency of IFD in bulk GaAs. Related studies of ion implantation-induced intermixing in InP/InGaAs quantum well and InGaAs/GaAs quantum dot structures further revealed that the degree of intermixing/interdiffusion was influenced by the surface capping layer. The use of other capping layer treatments with a wide range of thermal expansion coefficients were also shown to influence the luminescence emission, providing strong evidence that stress plays a major role in controlling interdiffusion in these systems.



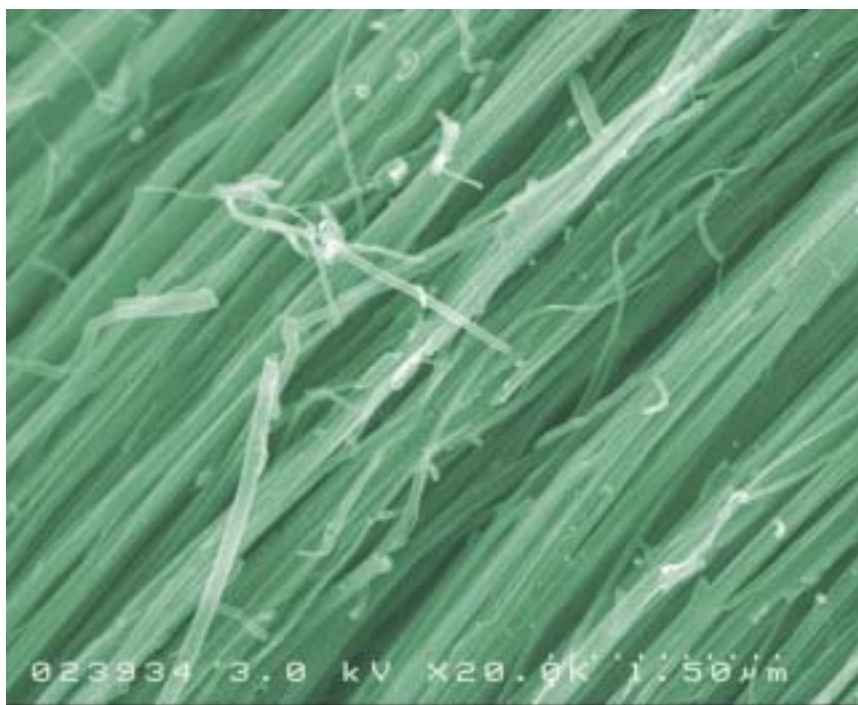
PhD student, Christine Carmody, working with the high energy ion implanter

Anodic Oxidation

Anodic oxidation of Al creates an oxide layer that is characterised by a hexagonally close-packed ordered array of pores with nanometer dimensions, the size and density of which can be controlled by changing the anodising conditions and pre/post-anodising treatment. Interest in porous alumina has increased recently due to its potential as a template for the synthesis of nano-sized materials. The simplicity of the electrochemical fabrication process only serves to increase this appeal. Work is currently being undertaken to maximise pore ordering in systems consisting of Al layers deposited on semiconductor substrates, as well as investigating avenues for the use of alumina as a template for the growth of semiconductor nanostructures.

Mechano-Thermal Processing of C and BN Nanotubes

Significant progress has been made in the synthesis of C and BN nanotubes using the mechano-thermal process, which consists of high-energy ball milling and thermal annealing. This includes an improved understanding of the formation mechanism for C nanotubes and a significant improvement in the control of the size and structure of BN nanotubes. In the former case, mechanical grinding of graphite creates a precursor for nanotube growth with subsequent annealing activating the growth of two types of multi-walled nanotubes, thin nanotubes (diameter <20 nm) which are formed via crystallisation of disordered carbon, and thick nanotubes (diameter >20 nm), which are formed through a metal catalytic solution-precipitation process. In the latter case, annealing conditions and specific catalysts were used to control the growth of BN nanostructures. This enabled the growth of BN nanotubes with diameters as small as two atomic layers at low temperatures where thick nanotubes are prevented from forming. It was also found that BN nanotubes with novel shapes and structures (bamboo or cone) could be prepared for special applications.



Scanning electron microscopy image of nanotubes synthesised by mechanochemical process

Ion Beam Modification of Materials

Radiation Damage

With the ever increasing scale of device integration, and the widespread use of ion-implantation as a processing tool, the understanding of irradiation-induced defects, their structure, mobility and interactions has become increasingly important. Studies of ion-irradiated silicon using extremely sensitive carrier lifetime measurements have shown that irradiation-induced defects can penetrate well beyond the range of the implanted ions. In contrast, studies of ion-irradiated compound semiconductors, including ZnO, GaAlAs, InP, and SiC, have concentrated on structural changes, including the influence of dynamic annealing on the evolution of disorder, and defect-annealing phenomena.

In a very different study, in-situ transmission electron microscopy was used to explore the effect of ion-irradiation on the structure and evolution of nano-scale cavities (nanocavities) in Si. The nanocavity diameter was found to decrease as a function of ion dose in both the crystalline and amorphous phases and mechanisms for such changes have been investigated. The observed rate of nanocavity diameter decrease, as a function of ion dose, was found to be consistent with a ballistic process.

Implant Isolation

Because of its potential for device applications, irradiation-induced electrical isolation of semiconductors has been studied in several material systems. In one such study, both n- and p-type InGaAs epilayers grown on InP were implanted with H, Li, C and O ions. The thermal stability of the isolation was investigated as a function of annealing temperature with the production of shallow donors in the InP substrate found to be an important factor regulating isolation in this system. Similar experiments conducted on GaAsN layers with different N compositions showed that the isolation process was independent of the N fraction in the layer. The thermal stability of the defects responsible for carrier compensation in GaAsN was also investigated. In the case of ZnO, sheet resistivities were shown to be increased by up to seven orders of magnitude as a result of ion irradiation. However, due to extremely efficient dynamic annealing processes in ZnO, the ion doses needed for isolation of this material were about two orders of magnitude larger than those required doses in GaN. The defect-induced electrical isolation of ZnO was further found to be unstable to rapid thermal annealing at temperatures above ~300°C.



Dr Ying Chen and Dr Jun Yu demonstrate the strength of nanotubes using a model. Nanotubes have many potential applications in structural engineering one of which is sporting equipment such as tennis racquets

Ultrafast Photodetector Materials

Earlier studies examined the effect of ion-implantation on the carrier lifetime in InP. Recent studies have extended these measurements to look at the effect of Fe implantation on carrier lifetimes in InP and InGaAs. Hall effect measurements determined the evolution of electrical characteristics with ion dose and annealing temperature, and double-crystal X-ray diffraction (DCXRD) and transmission electron microscopy (TEM) measurements were used to glean detailed information about damage and strain in the samples. Time resolved photoluminescence measurements, performed by collaborators at the Royal Institute of Technology in Sweden, showed that both implantations of p-InP with P ions and semi-insulating InP with Fe ions could produce a material with sub-picosecond response times.

Si-Based Photonics and Light Emission from Si Nanocrystals

Research has continued into the properties and applications of Si-nanocrystal-based photonic materials and structures with recent studies examining: a) the effect of impurities on the luminescence intensity and lifetime, b) the effect of materials

structure on measured luminescence spectra, c) the fabrication and properties of optical waveguides containing Si nanocrystals, and d) the photoresponse of Si nanocrystals and the prospect of optical gain from such materials.

Passivation and depassivation kinetics were determined by studying the effects of isochronal and isothermal annealing schedules and modeling the results with a generalised reaction rate model. This enabled activation-energy distributions and reaction rates to be determined for both the passivation and depassivation reactions. An important outcome of this study was the fact that there is an optimum passivation annealing temperature, with the efficiency of passivation falling for temperatures above about 500°C due to the increasing significance of the depassivation reaction. The Si nanocrystal luminescence efficiency and spectral distribution were also found to be sensitive to annealing ambient, with significant differences being observed for samples annealed in Ar or N₂, and to the presence of metallic impurities, such as Cu, Au and Fe.

The effect of sample structure on the measured photoluminescence emission from Si nanocrystals, including the role of optical microcavities, was explored. This included

studying the effect of simple layered structures, such as single SiO_2 layers grown on Si, as well as deliberately engineered microcavity structures consisting of a nanocrystal-rich layer sandwiched between wavelength-specific Bragg mirrors. The study highlighted the fact that photoluminescence emission spectra can be dramatically influenced by the sample structure, with both the intensity distribution of the excitation source and the spectral distribution of the emitted light being sensitive to such structure.

The optical properties of nanocrystal-containing slab- and rib-waveguide structures were investigated and the structures used to study the prospects for optical gain in such systems. These structures were fabricated either by using plasma-enhanced chemical vapour deposition (PECVD) to grow alternate layers of SiO_2 and silicon-rich oxide (SRO) or by ion-implantation of Si into SiO_2 . Nanosecond optical pump-probe measurements were performed by guiding an 800 nm probe beam within the nanocrystal-rich layer and optically pumping the nanocrystals with 25 ns pulses of 355 nm radiation. Initial measurements suggest that induced absorption (pseudo-free carrier absorption) is the dominant mechanism on this time scale.

Materials Processing and Characterisation

Atomic Scale Structure and Surface Properties

Studies of semiconductor materials, using techniques such as perturbed angular correlation (PAC) and extended X-ray absorption fine structure (EXAFS) provide important insight into atomic-scale phenomena. A broad range of such studies have been undertaken over the past few years, many using international synchrotron facilities. This has included studies of the structure and structural relaxation of amorphous compound semiconductors produced by ion-implantation, which has shown that relaxation proceeds via the annihilation of

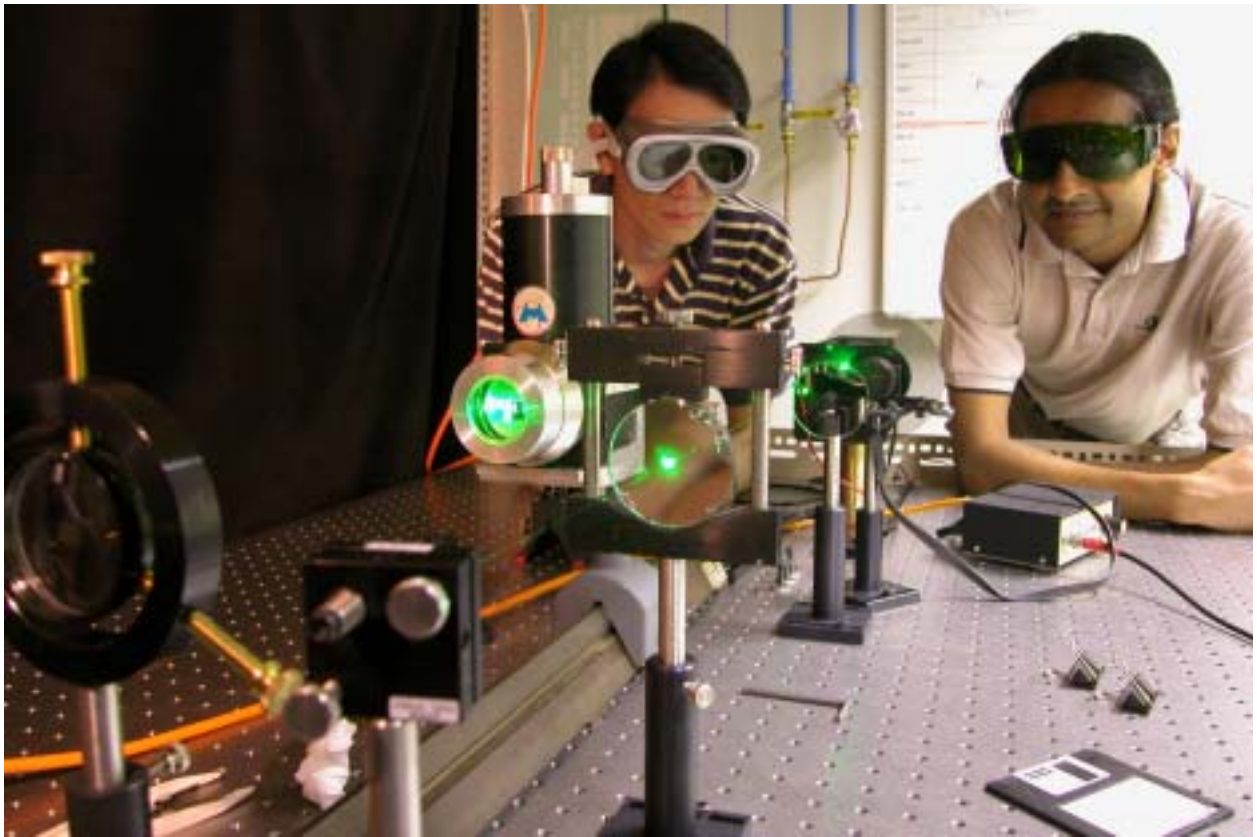
homopolar bonds, as well as characterisation of semiconductor and metallic nanocrystals embedded in a silica matrix. Structural information is readily apparent from changes in the atomic radial distribution function and can be used to study the effects of the nanometre-size dimensions, strain at the nanocrystal/matrix interface and matrix-induced compression.

A range of complementary characterisation techniques, including EXAFS and PAC, were employed to study the atomic scale structure and mechanisms associated with metallic-impurity gettering mechanisms in Si. The efficiency of implantation-induced nanocavities as gettering sites for Pd impurities was measured as a function of implantation dose and annealing temperature. It was shown that nanocavities effectively trap Pd impurities and an attempt was made to identify the gettering sites and reconstruction processes for Pd impurities on nanocavity inner surfaces.

Work has also continued on the application of synchrotron radiation to the characterisation and modification of compound semiconductor surfaces (GaAs and III-V nitrides). In recent work synchrotron-based high-resolution core-level photoemission and valence-band emission measurements have been used to characterise H chemisorption on non-polar GaAs (110) and polar GaAs (100) and GaAs (001) surfaces. Chemisorbed atomic H forms both Ga-H and As-H bonds on all three surfaces causing chemical shifts of core-level binding energies and changing the valence band emission. For low H exposures, As desorbs from all surfaces. However, at higher exposures, the (110) surface transforms into a Ga-rich structure with traces of metallic Ga, while the (100) surface transforms into an As-rich structure. Additional changes in the binding energy of bulk components of Ga and As core levels have also been observed as a function of H exposure, which were explained by hydrogen-induced changes in band bending.

Below: Panoramic view of the new RBS accelerator labs



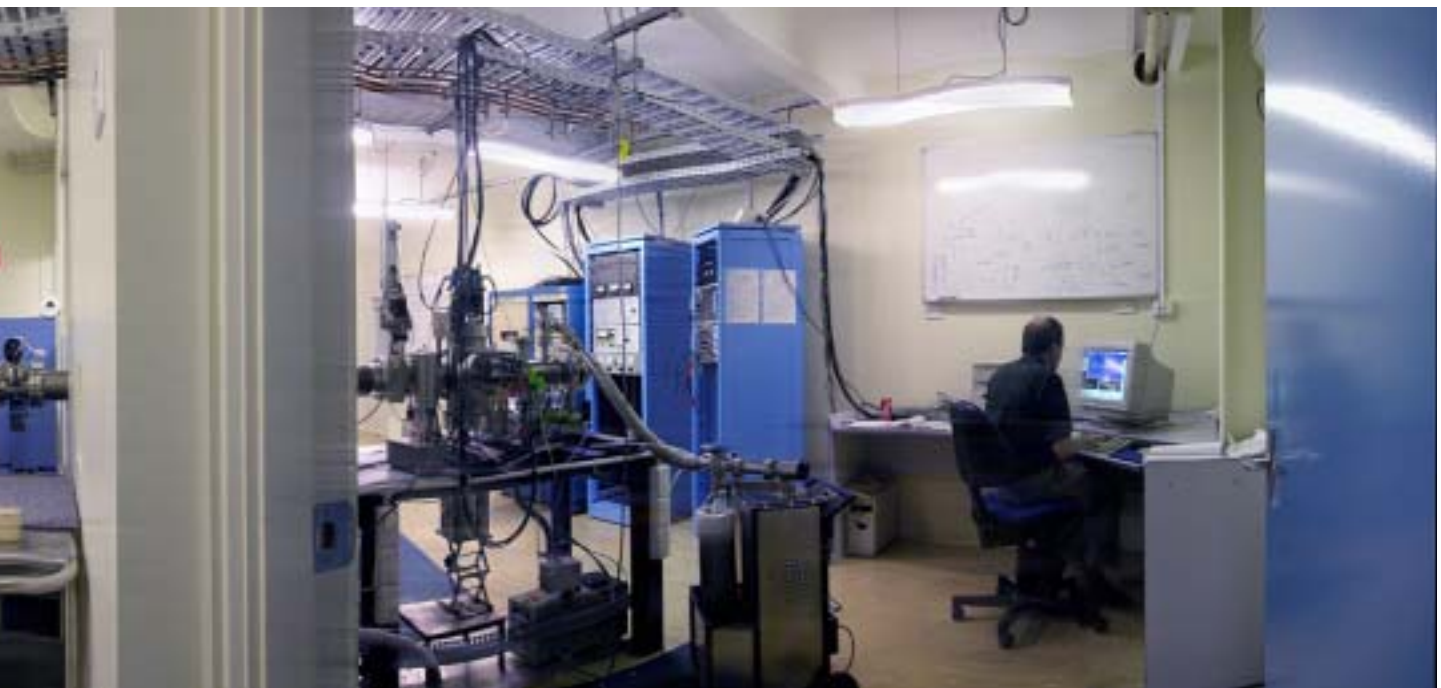


Dr Hoe Tan, ARC QEII Fellow and Dr Sanju Deenapanray, ARC Postdoctoral Fellow, in the optics laboratory

Post-ionisation experiments (the subsequent ionisation of neutral sputtered atoms) using the Free Electron Laser (FEL) at Argonne National Laboratory (ANL) have continued in collaboration with researchers from Newcastle University and ANL. A new analysis chamber and Time-of-Flight Spectrometer were constructed at the FEL facility to undertake the first post-ionisation experiments.

Secondary Ion Mass Spectrometry (SIMS)

Anomalous SIMS broadening of buried delta layers in Si was observed under O beam bombardment at angle of incidence close to 30° . Channelling effects have been proposed as a possible explanation for the effect with simulations using the Marlowe program revealing a channel in Si (100) at slightly higher impact angle (35°), while one weaker channel opens at





Victoria Coleman, PhD student, loading samples into the MOCVD reactor

55°. Careful SIMS measurements showed an additional small enhancement in broadening around 50° and experiments are now under way to explain this difference between simulation and experiment.

Microindentation and Mechanical Properties of Semiconductors

A comprehensive understanding of microindentation behaviour in a wide range of semiconductors has been obtained using a number of analytical techniques.

A particular highlight of research in 2002 was the use of in-situ electrical measurements to probe indentation-induced phase transformations in amorphous-crystalline Si structures.

Dramatic differences were observed between the deformation behaviour of relaxed and unrelaxed amorphous Si.

The former undergoes an amorphous-to-crystalline transformation on loading and can transform back to amorphous Si during some unloading conditions.

In comparison, unrelaxed amorphous Si deforms plastically under indentation and remains in the amorphous phase.

These intriguing, room temperature crystalline-to-amorphous and amorphous-to-crystalline transformations have been examined by ex-situ microscopy techniques.

Optoelectronic Devices and Integration

Preliminary work carried out in the growth of InP-based vertical-cavity surface emitting lasers (VCSELs) has been very encouraging. We have grown InP-AlGaInAs multilayers as the Bragg mirror due to the large refractive index difference between these two materials. By growing only 25 pairs, reflectivity in excess of 99% was achieved. Work is now in progress to grow the full VCSEL structure and fabricate and characterise these devices for 1.55 μm applications.

The use of Selective Area Epitaxy (SAE) was also investigated for the growth of quantum well structures. Patterning the substrates with oxide masks prior to growth enables tailoring of growth rates and compositions in the 'window' region. This has particular advantages for the integration of optoelectronic structures. GaAs has been grown with a growth rate enhancement of up to 1.4, yielding excellent quality material. InGaP (lattice-matched to GaAs) has also been grown with minimal ordering and growth rate enhancements exceeding a factor of two. InGaAs/GaAs quantum wells with emission differences of up to 90 nm between different parts of the wafer was achieved.

Impurity-free intermixing of quantum-well laser diode structures for optoelectronic integration was studied. It was found that when dielectric cap layers are used in order to promote intermixing, the intermixing process is accompanied by a significant Zn migration from the highly-doped regions of the device into unintentionally doped regions. This adversely affects the laser performance. To achieve high device

performance for optoelectronic integration, a good option would be to replace the commonly used Zn with C as the p-type dopant. Carbon is stable upon annealing at temperatures higher than 900°C. However, the role of different point defects in the intermixing process of laser diode structures needs to be further investigated, since C doping occurs by replacing a group V atom in the GaAs lattice, and not a group III atom, as is the case for Zn.

The influence of the thickness of the SiO₂ layer used as an insulator outside the ridge in high power 980 nm laser diodes was thoroughly investigated. It was found that the extra absorption that is provided by the extension of the optical field into the lossy Ti/Pt/Au metallisation gives selective absorption for the first-order lateral mode and thus improves the kink-free power output by 30-50%.

Quantum dot infrared photodetectors (QDIPs) with a 30-stacked-layer InAs/GaAs quantum dots grown by molecular

beam epitaxy have shown good device performance. High temperature annealing of QDIPs led to strain relaxation. Strain compensating QDIPs are under investigation.

Other Areas

Within the acoustics area, there is a major continuing ARC-funded cooperative project with the University of NSW and Melbourne University on the acoustics of the didgeridu – there is much interest in this instrument from musicologists around the world and it seems important that basic understanding be developed in Australia. There have also been some more applied interactions on microphone design and related subjects with CSIRO and industry, and in addition there are currently research interactions with several biologists on hearing and sound production in humans and other animals.

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