Introduction

The infrastructure of the Information Age has to date relied upon advances in microelectronics to produce integrated circuits that continually become smaller, better, and less expensive. The emergence of photonics, where light rather than electricity is manipulated, is posed to further advance the Information Age. Central to the photonic revolution is the development of miniature light sources such as the Quantum dots(QDs). Today, Quantum Dots manufacturing has been established to serve new datacom and telecom markets.

Recent progress in microcavity physics, new materials, and fabrication technologies has enabled a new generation of high performance QDs. This presentation will review commercial QDs and their applications as well as discuss recent research, including new device structures such as composite resonators and photonic crystals

Semiconductor lasers are key components in a host of widely used technological products, including compact disk players and laser printers, and they will play critical roles in optical communication schemes. The basis of laser operation depends on the creation of non-equilibrium populations of electrons and holes, and coupling of electrons and holes to an optical field, which will stimulate radiative emission. . Other benefits of quantum dot active layers include further reduction in threshold currents and an increase in differential gain-that is, more efficient laser operation.

Since the 1994 demonstration of a quantum dot (QD) semiconductor laser, the research progress in developing lasers based on QDs has been impressive. Because of their fundamentally different physics that stem from zero-dimensional electronic states, QD lasers now surpass the established planar quantum well laser technology in several respects. These include their minimum threshold current density, the threshold dependence on temperature, and range of wavelengths obtainable in given strained layer material systems. Self-organized QDs are formed from strained-layer epitaxy. Upon reaching such conditions, the growth front can spontaneously reorganize to form 3-dimensional islands. The greater strain relief provided by the 3-dimensionally structured crystal surface prevents the formation of dislocations. When covered with additional epitaxy, the coherently strained islands form the QDs that trap and isolate individual electron-hole pairs to create efficient light emitters.

Semiconductor Laser

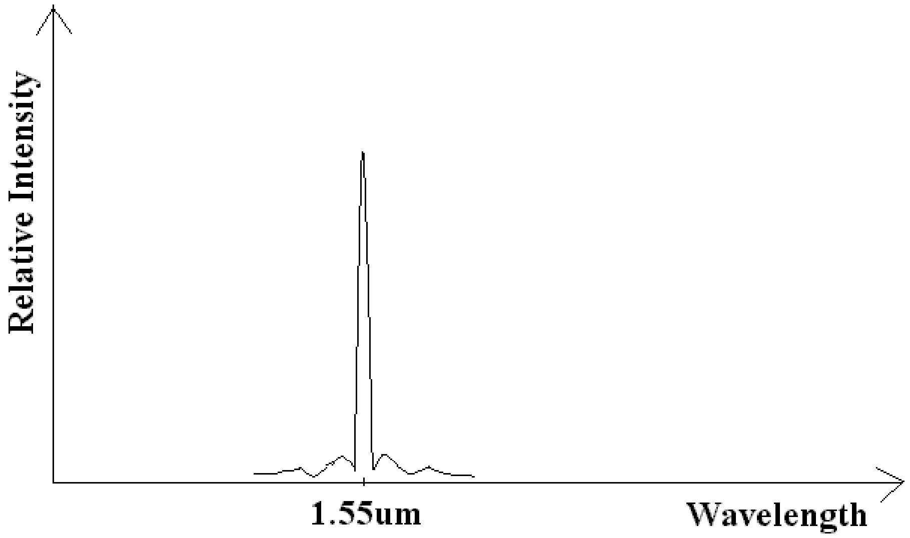


Figure 1: single longitudinal mode output spectrum

The central objective of the present day optical engineers is the development of lasers and amplifiers based on innovative gallium arsenide (GaAs) based 'quantum dot' technology, that operate at the 1300 and 1500 nm emission wavelengths used in broadband fiber optic communications. The fabrication of such lasers using GaAs will deliver a considerable cost advantage over the Indium Phosphide (InP) technology that is currently the state-of-the-art for manufacturing devices at these wavelengths. The program is targeting the fabrication of quantum dots using standard and well understood wafer fabrication systems.

The figure above shows a typical single longitudinal mode output spectrum from a single mode injection laser. Single mode injection lasers are lasers that transmit a single mode of radiation. Maximum relative intensity is obtained at a wavelength of 1.55µm, which is also the permitted wavelength for optoelectronic communication. Low optical loss and low dispersion of light can be achieved at this wavelength. Low Hydroxyl loss in the optical fiber cable can also be obtained at this wavelength. Hence this wavelength is of considerable importance and all the optical engineers are trying to develop a laser having the same characteristics.

Quantum Dots

Optimizing the QD characteristics for use as practical, commercial light sources is based on controlling their density, shape, and uniformity during epitaxy. In particular, the QD's shape plays a large role in determining its dynamic response, as well as the temperature sensitivity of the laser's characteristics. Their density, shape, and uniformity also establish the optical gain of a QD ensemble. All three physical characteristics can be engineered through the precise deposition conditions in which temperature, growth rate, and material composition are carefully controlled.

Thus, the challenge in realizing quantum dot lasers with operation superior to that shown by quantum well lasers is that of forming high quality, uniform quantum dots in the active layer. The most widely followed approach to forming quantum dots was through electron beam lithography of suitably small featured patterns (~300 Å) and subsequent dry-etch transfer of dots into the substrate material. The problem that plagued these quantum dot arrays was their exceedingly low optical efficiency: high surface-to-volume ratios of these nanostructures and associated high surface recombination rates, together with damage introduced during the fabrication itself, precluded the successful formation of a quantum dot laser.

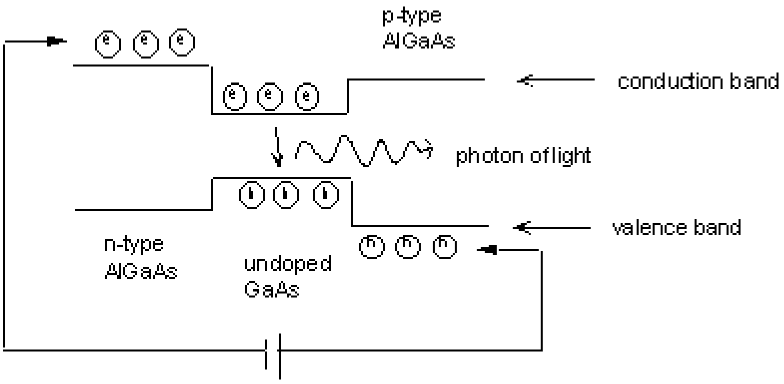


Figure 2: Schematic of a semiconductor laser

Quantum dot lasers should exhibit performance that is less temperature-dependent than existing semiconductor lasers, and that will in particular not degrade at elevated temperatures. Other benefits of quantum dot active layers include further reduction in threshold currents and an increase in differential gain-that is, more efficient laser operation. Figure2 illustrate some of the key concepts in the laser operation.

Stimulated recombination of electron-hole pairs takes place in the GaAs quantum well region, where the confinement of carriers and of the optical mode enhances the interaction between carriers and radiation. The population inversion (creation of electrons and holes) necessary for lasing occurs more efficiently as the active layer material is scaled down from bulk (3-dimensional) to quantum dots (0-dimensional). However, the advantages in operation depend not only on the absolute size of the nanostructures in the active region, but also on the uniformity of size. A broad distribution of sizes "smears" the density of states, producing behavior similar to that of bulk material.

Quantum dots (QDs) make up the structure of a material at maximum quantization. When the space, at any side, around a material shrinks to 100Å (one millionth cm), quantization of the energy levels at the reduced side will occur. Comparing with bulk, quantum well is one-dimensionally quantized, quantum wire being two-dimensionally quantized, and QD is three-dimensionally quantized. However, from the three-dimensional perspective, the order of dimensionality of the three is reversed: quantum well being two-dimensional, quantum wire one-dimensional, and QD being zero dimensional.

When quantization reaches its maximum, the energy levels of QDs are highly discontinuous. Theoretically, under such a condition, electrons in the energy levels have the least sensitivity to temperature changes. Thus, QDs should produce lasers of better quality than that of quantum well and quantum wire. Another advantage of a QD laser is that they can be turned on at very low threshold current. Not only is the potential of a QD amazing, it is also important to the studies of fundamental physics. Given that research on QDs has become rather popular around the world, it is not surprising that QDs will play a critical role in the nanotechnology of the 21th century.

However, with further advances in the understanding and development of QD lasers, we may see that much of the future laser diode technology convert to this zero-dimensional active region, similar to the conversion in the last 10 years to planar quantum wells from bulk material.

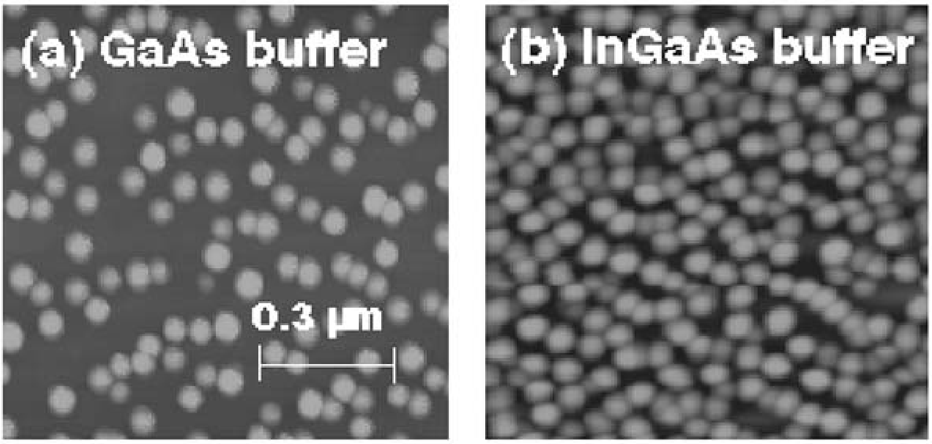


Figure 3. Atomic force microscope images showing the control of the QD density using a strained buffer layer. (a) shows InGaAs QDs grown directly on GaAs, and the QD density is ~10^{10} cm^{-2}. (b) shows similar InGaAs QDs grown with a strained layer buffer, which increases the QD density to ~2x~10^{10} cm^{-2}.

The atomic force microscope images shown in Fig. 3 illustrate how a strained buffer layer can be used to control the density of InGaAs QDs. In Fig. 3 (a) the InGaAs QDs are deposited directly on GaAs, and alternating depositions of In, Ga, and As are used to achieve high surface atom mobility and slow growth rates to form the efficient 1.3 µm QD emitters. Their density is ~1010 cm-2. In Fig. 3 (b) the same strained-layer deposition is performed on a thin, strained InGaAs buffer layer of less In content, and the QD density increases to ~2x1010 cm-2. The increase in the QD density significantly improves laser performance. Because of the novel physics associated with the QD ensemble, the active material shown in Fig. 3 (b) has resulted in the lowest threshold current density yet reported (19 A/cm2) for any semiconductor material system for continuous-wave (CW) room temperature operation. Even lower threshold current densities could be possible in the future. At a slightly lower temperature of ~200 K the threshold current density of the InGaAs QD material of Fig. 2 (b) reduces to 5 A/cm2, and generates lasers with threshold currents of ~400 µA.

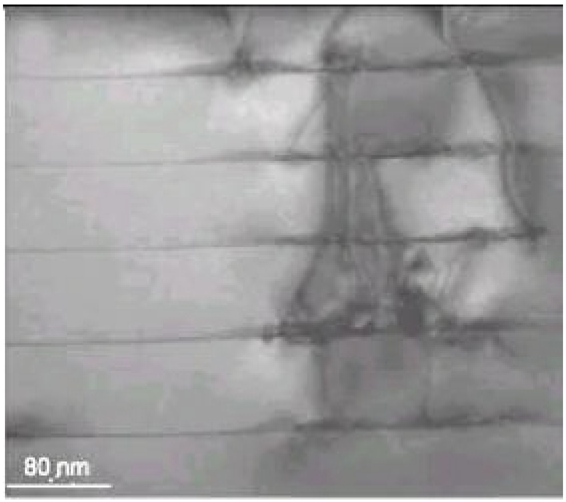
The interest in quantum dots was initially driven by a desire to create a material with electronic density of states strongly modified by quantum confinement effects (a reduction in size to less than tens of nanometers) and approaching a delta-like density of states for a truly zero-dimensional system. Such a medium was perceived to offer significant advantages for example in ultra-low threshold semiconductor diode lasers, and also presented interesting opportunities for fundamental research in the area of light-matter interaction.

In the self-assembled growth the quantum dots are created from ultrathin layers (typically about 2 monolayers thick) which spontaneously break up due to strain between the substrate and the grown film, and minimize their energy by forming small scale islands. Size quantization in such islands has been demonstrated.

Self-assembled growth has proven to be an extremely fruitful technique which is now widely used. At Macquarie University scientists have made significant advances in material growth and understanding of the self-assembly growth process and its control. We deposit GaSb quantum dots on GaAs using atmospheric pressure metalorganic chemical vapour deposition. The GaSb dots (islands) self-organise due to lattice mismatch of several percent between GaAs and GaSb. The dots can be visualised using a technique called Atomic Force Microscopy producing photographic imges.

Studies of quantum dots attract significant interest worldwide, because of their fascinating new physics and unique potential for innovative electronic and optoelectronic devices. Actually, these innovative applications are just beginning to emerge. One of them involves using quantum dots for the detection of infrared light in devices similar to the previously explored quantum well intersubband detectors. Other interesting applications include use in quantum gates at the centre of a quantum computer.

Devices being investigated utilise both standard and non-standard bandedge profiles and are being used as transmission and reflection irradiance modulators. Individual modulators are being combined into the common self electro-optic effect device (SEED) configuration for implementation of logical functions. The operation of symmetric SEED's is being investigated for application to optical oversampled analog-to-digital conversion applications.



The figure shown in here is the pictorial representation of the GaSb, which is the counterpart of the conventional GaAs structures which is the mai subject that has been dealt in the seminar and a whole lot of information is given in the coming sections.

The aim of the research on GaSb quantum dots was to establish a technology to fabricate a three dimensional quantum dot composite material, a building block for future electronic and optoelectronic devices. This is achieved by depositing multiple layers of quantum dots interspersed with quantum barriers of a different material. Interestingly, the dots show some degree of vertical correlation.

A lure demonstration of feasibility of QD growth using atmospheric pressure MOCVD can be easily expained using the GaSb structures. This is significant, because of an extremely rapid turnover time possible in such systems. Scientists working in the university could complete the growth process (from loading the chamber to taking the sample out) within 1 hour, while the actual QD growth takes several seconds. Such short times indicate a process which may be industrially relevant.

Theory of GaInNAs materials and optoelectronics devices:

GaInNAs exhibits a remarkable band-gap bowing, enabling optical emission at 1.3 and 1.5 microns on a GaAs substrate. The first theory which explains qualitatively and quantitatively the origin of this strong bowing in bulk GaInNAs has been developed. The theory is based on and confirmed by tight-binding calculations that have been performed. The model will be validated and refined by comparison with experimental data from collaborators and from the literature. Calculations will then be undertaken to investigate how the unique features of GaInNAs/GaAs quantum wells change laser gain characteristics compared to conventional GaInAsP/InP and AlGaInAs/InP QW lasers. These unique features include an extremely large conduction band offset, comparable conduction and valence effective masses, and significantly reduced optical transition matrix elements, due to strong mixing with an N-related resonance level. Our modelling provides the first clear understanding of the electronic properties of GaInNAs materials, and will enable us to predict optimum GaInNAs quantum-well laser structures

Assessment of InGaAsN materials and optoelectronic devices:

The III-V alloy InGaAsN shows quite remarkable band structure properties that raise exciting possibilities for optoelectronic applications. Although GaN has a much larger band gap than GaAs, when a low concentration of N is incorporated into GaAs there is a very strong decrease in the optical band gap. This is very interesting both theoretically and practically: theoretically, because the behaviour cannot be explained by standard models of III-V alloys and so new approaches are clearly needed; practically, because the lower band gap makes accessible in the GaAs system the 1.3um and 1.55um wavelengths of interest for optical fibre communications. If we can achieve a good theoretical understanding of the band structure and optical properties of InGaAsN, the possibility exists that we may be able to propose novel and superior optoelectronic device structures, (eg with mc*=mv*). To temperature dependences of I. The optical and electrical properties of InGaAsN/GaAs quantum wells and II. The gain and loss processes in laser diodes. The results will be used to refine our new theoretical model which then will be used to predict optimum laser structures.

Long wavelength quantum dot lasers

Trunk communications using silica optical fibres at 1.55um have grown enormously in recent years. However, all 1.55um lasers are very temperature sensitive and require expensive control modules. Therefore, if such systems are to be extended into the home and into the workplace, cheaper, simpler to operate devices are required. InAs on InP quantum dots promise lasers ideal for this purpose. This proposal aims to develop these devices starting from basic growth through to working laser diodes. Edge-emitting lasers will be fabricated and studied in detail using a variety of experimental and theoretical techniques developed recently at Surrey for 1.55um quantum well lasers. This will involve novel high pressure and low temperature techniques.

Theoretical models will address

1) the electronic band structure including strain effects
2) radiative and non-radiative transitions and optical gain,
3) the waveguide structure and lasing characteristics.

Self-organized QDs based on strained layer epitaxy have pushed semiconductor lasers nearly to the ultimate in terms of their quantum dimensionality. Lasing is obtained from truly zero-dimensional energy levels, and the novel quantum physics and nanostructure material features open new avenues for future semiconductor laser device research and development. Through use of microcavities, new types of light emitters and lasers can be envisioned that also make use of a zero-dimensional photon field. QD lasers exhibit both important new performance features that are unmatched by previous semiconductor lasers based on planar quantum wells or bulk active materials that include ultra-low threshold current densities, regimes of temperature insensitive lasing, reduction of the linewidth enhancement factor, and a greater range of lasing wavelengths for a given material system**.** On the other hand, they also have problems that must be overcome to advance to the status of commercial products, such as their small room temperature modulation bandwidth and poor temperature sensitivity above room temperature.

1.3 µm InGaAs QD Lasers and Selective Oxidation

The central objective is the development of lasers and amplifiers based on innovative gallium arsenide (GaAs) based 'quantum dot' technology, that operate at the 1300 and 1500 nm emission wavelengths used in broadband fiber optic communications. The fabrication of such lasers using GaAs will deliver a considerable cost advantage over the Indium Phosphide (InP) technology that is currently the state-of-the-art for manufacturing devices at these wavelengths. The program is targeting the fabrication of quantum dots using standard and well understood wafer fabrication systems.

Quantum dots (QDs) are nanometer-sized objects that are fabricated by deposition of a thin semiconductor layer on a substrate with a different lattice constant (a materials technology generally known as compound semiconductors). Due to their small dimensions, QDs confine trapped carriers in all three spatial directions, combining the advantages of semiconductors with the defined behaviour of atoms. This supports the creation of novel optical communications devices with very stable performance that are much less prone to problems suffered by today's devices, such as distortion.

A wealth of studies on InGaAs QDs now show that the emission wavelength in 3-dimensionally, coherently-strained III-V epitaxy can be extended well beyond that possible with 2-dimensionally coherently strained heterostructures of the same materials. This feature has been convincingly demonstrated with GaAs-based InGaAs QD lasers that operate beyond 1.3 µm wavelength that now operate at CW threshold currents close to 1 mA and threshold current densities less than 20 A/cm2. The development of long-wavelength nano-structured materials could lead to GaAs- based light sources that cover the entire wavelength range of ~0.7 µm to beyond 1.55 µm important for data-communication and telecommunication technologies. Creation of a phonon bottleneck in the QDs might also be used to significantly reduce thresholds for intraband quantum-cascade lasers that operate in the 10 µm to 20 µm wavelength range.

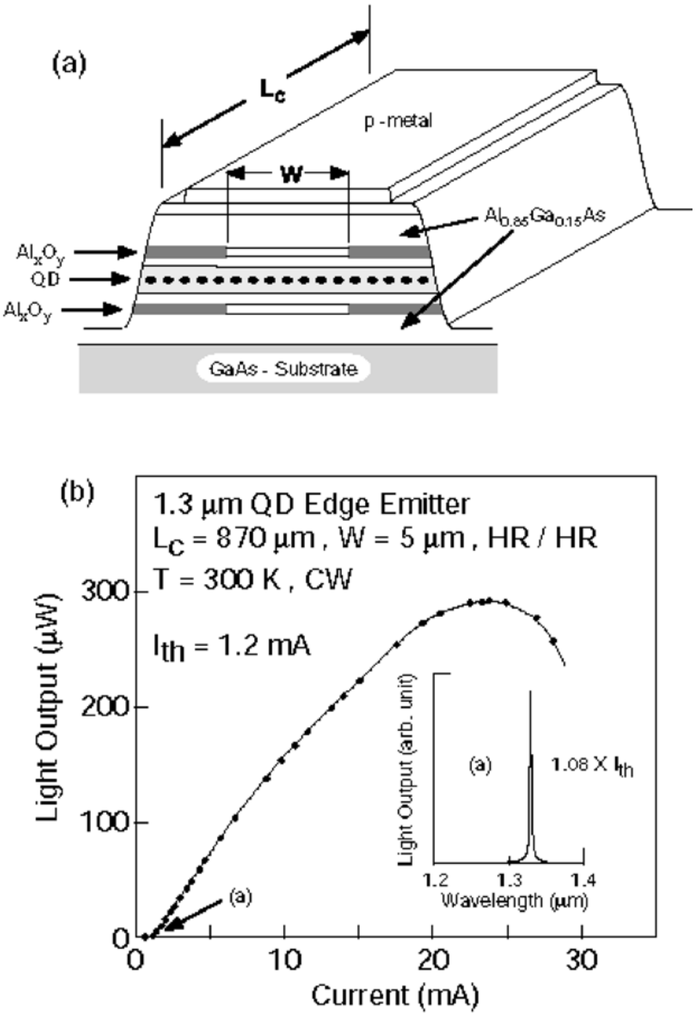


Figure 4. (a) Schematic illustration of the oxide-confined QD laser. Two oxide layers have been placed 0.25 µm above and below the waveguide layer, and the laser uses a single InGaAs QD active region with a ground state emission at 1.3 µm. (b) Lasing characteristics of the 1.3 µm, oxide-defined QD laser.

An advantage of 1.3 µm GaAs-based lasers is their ability to be oxidized to form buried low refractive index insulators. An example is shown in Fig. 4, where the selective oxidation scheme for planar quantum well edge-emitting semiconductor lasers are applied to a 1.3 µm InGaAs QD laser. The oxide simultaneously channels electrical current due to electron-hole injection into the laser's active region, and laterally confines photons of the lasing mode. Figure 4 (b) shows that this type of laser can operate at low CW, room temperature power levels with threshold currents approaching 1 mA. More recent results show that 1.3 µm QD lasers can exhibit characteristic temperatures as high as 80 K even above 300 K. The 80 K characteristic temperature exceeds that of commercial InP-based 1.3 µm lasers, so that 1.3 µm GaAs-based QD lasers may eventually compete with commercial InP-based lasers.

Shape-Engineering and Control of the QD Electronic Structure

A major limitation in today's QD lasers is poor temperature performance at and above room temperature. In the presence of inhomogeneous broadening, ground state QD lasers can potentially offer a characteristic threshold temperature, commonly called T_o, of several hundred Kelvin at wavelengths of 1.3 µm and beyond. This is well in excess of planar quantum well InP-based lasers. The temperature insensitive threshold has been measured in several studies for below room temperature operation of QD lasers.

With the work described here, QDs are formed using strained layer epitaxy of InAs on a GaAs surface in which a 7% lattice mismatch exists between the 2 materials. A small amount of strained material can be grown while maintaining dislocation free planar surface this is called pseudomorphic growth. When a critical thickness is surpassed, the 3-D islands form spontaneously in order to reduce the surface free energy of the strained material. Some strained 2-D material remains after the formation of the QDs and is called the wetting layer. The critical thickness is dependent upon the lattice mismatch, growth temperature, and other growth condition. Interestingly, the modified optical properties also can arise in larger nanostructures (that is not quantised in the growth plane) due to stress gradients in the quantum dots, these lead to normal incidence operation of quantum dot light detectors.

However, even in QDs thermal excitation of electrons and holes can occur to higher energy levels associated with either zero-dimensional states of the QD or the QD wetting layer. Thermal excitation to the wetting layer is a particularly serious problem, because of the wetting layer's relatively large density of levels. Therefore, the best room temperature performance has been obtained with InGaAs QDs that have deep potential wells, with ground state light emission beyond 1.2 µm. Since these deep QDs are also typically rather large (several hundred angstroms in diameter), they contain multiple discrete electron and hole levels. For the deep QDs, these higher energy zero-dimensional quantum states in large part control the lasers threshold sensitivity to temperature. For the 1.3 µm InGaAs QDs, the energy separation between the ground and first excited radiative transitions is ~66 meV.

By engineering the QD shape to be narrow in lateral size, the ground state energy can still be deep with respect to the wetting layer, but also have a wide energy separation between the ground and first excited radiative transitions.

The temperature dependence of the lasing threshold for both a 1.3 µm InGaAs QD laser and a 1.24 µm InAs QD laser are shown in Fig. 5. Some differences in the laser structures give different minimum threshold currents for low temperatures, and the 1.3 µm InGaAs QD laser reaches lower threshold current density at low temperature. However, the difference at room temperature and above is set mainly by the energy separation between the ground and first excited radiative transitions. The QD's electronic levels also control its dynamic response. Larger QDs show shorter spontaneous lifetimes at low temperatures, and very fast capture times. Many experimental studies attempting to characterize capture times for electrons and holes have been flawed by transport time delays of charge carriers. However, more accurate experiments are now being performed, and show that larger QDs can respond faster than smaller QDs in both their capture time and spontaneous emission rate. Initial experiments on the QD modulation response suggest that QD lasers are slower than planar quantum well lasers at room temperature, but become comparable in speed below room temperature. The precise reasons are not yet known, and show that there is much research yet to be done on QD lasers to fully understand and optimize their performance.

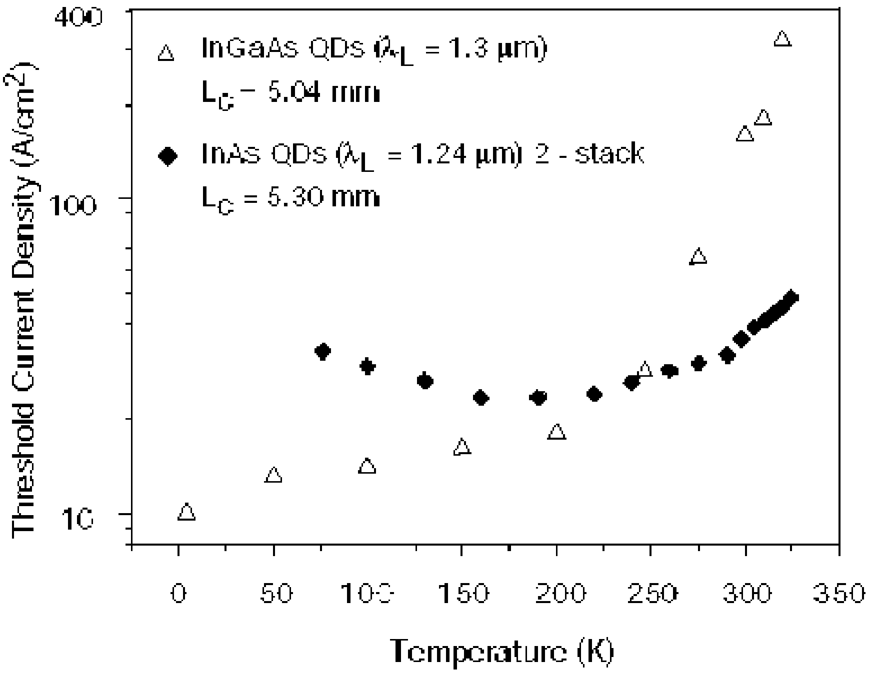


Figure 5. Plot of threshold current density versus temperature for either a 1.3 μm InGaAs QD laser, or a 1.24 μm InAs QD lasers. For room temperature operation and above, the temperature dependence of the threshold current density is set by the energy separation between the ground and first excited radiative transitions. These are ~66 meV for the InGaAs QD laser, and ~104 meV for the InAs QD laser.

An increasing need for sources and detectors for mid and far infrared applications such as infrared spectroscopy for chemical analysis, remote sensing and atmospheric communications provides the driving force to develop improved infrared light detectors. At present, commercial infrared light detectors are principally based on HgCdTe, and while their performance parameters such as detectivity and responsivity remain excellent, their deficiencies such as nonuniformity of HgCdTe wafers, important for imaging, as well as difficult manufacturing technology remain well known. Therefore the motivation arose to seek alternatives, preferably based on GaAs-type materials where advanced growth technology such as the molecular beam epitaxy (MBE) is widely available. Since over ten years the quantum well intersubband detectors (QWIPS) based on GaAs-type materials are being developed, and while this work still continues, much of the underlying science has been well established.

Because the InGaAs QDs form self-buried heterostructures, they are ideal for use with the most sophisticated III-V laser device processing aimed at microcavity devices. The ability to convert high Al content AlGaAs layer to oxide makes the GaAs-based AlGaAs/GaAs/InGaAs strained layer QD system ideal for microcavities. Such devices offer an unprecedented control over a spontaneous emitter's lifetime through the mechanism known as the Purcell effect. The Purcell effect is generated by phase-coherent electromagnetic feedback due to closely spaced reflecting boundaries. The reflecting boundaries both modify the amplitudes of the quantum fluctuations that exist in the electromagnetic field and drive the spontaneous emitter, as well as the amplitude of the emitter's radiated spontaneous field. Either increase (or decrease) the emitter's spontaneous emission rate by equal amounts. Because the phase-coherence time is short for spontaneous emission, microcavities are required that place the electromagnetic reflectors as close as possible to the light emitter.

As the size of the microcavity shrinks, the control over both the directionality and the rate of the spontaneous emission increases. The directionality is strongly dependent on the microcavity geometry. Fabry-Perot type microcavities can radiate a collimated, single lobed beam, and therefore achieve high efficiency coupling with the simplest optical interconnects. Figure 6 shows the emission characteristics from such a QD oxide-confined microcavity when the QDs are inhomogeneously broadened. The microcavity is formed by selectively oxidizing AlGaAs layers, as shown in the inset, to form an intracavity aperture of approximately 1 μm diameter. The QDs that emit on resonance with the micro- cavity show a spontaneous emission rate that is increased by 250 % over those QDs that emit at wavelengths either shorter or longer than the microcavity resonance peak. Other reports based on etched-pillar microcavities show up to 500 % lifetime change for the smallest pillar sizes. Because the increase in the spontaneous emission rate can be used to fabricate high speed, high efficiency lasers, as well as extremely low power high efficiency spontaneous light emitters, this type of QD microcavity technology may be useful for ultra-low power optical interconnects and displays. Microarrays of high efficiency microcavity light emitters may also compete with higher power VCSELs and light emitting diodes.

Recently, new fundamental optical properties of nanostructures have been discovered. These include significant changes in the energy level assignment and in the selection rules for optical absorption. The relaxed selection rules, and particularly absorption at normal incidence (forbidden in most commonly used n-type GaAs/AlGaAs quantum wells.

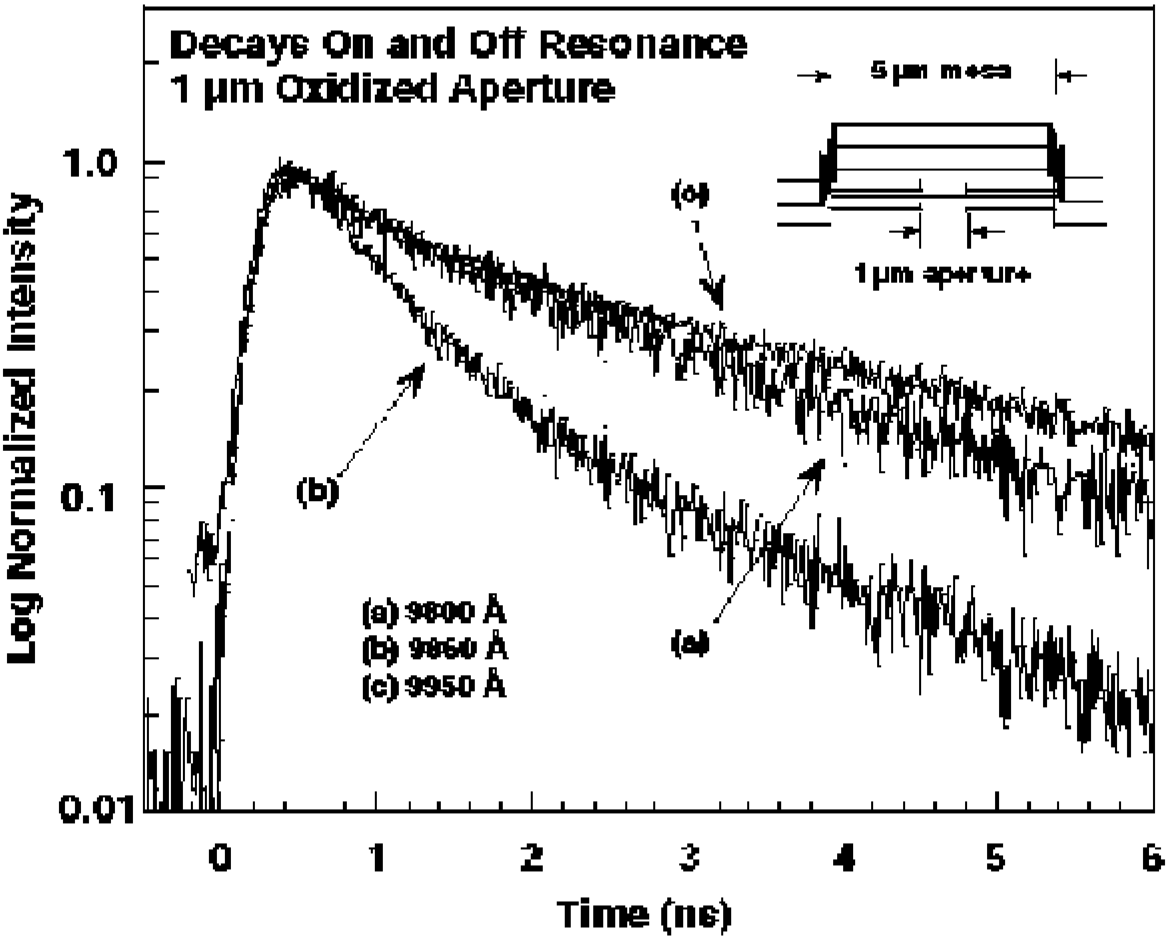


Figure 6. Spontaneous lifetime change due to placement of QDs in an oxide-confined microcavity. The lifetime of QDs on-resonance with the microcavity is increased by ~250% over those QDs with emission off-resolnance with the microcavity.

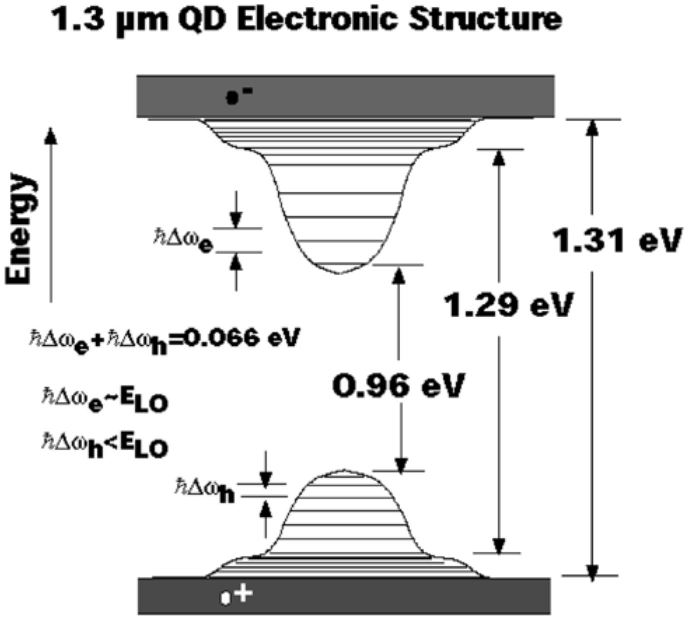


Figure 7. Threshold current and current density measured for various oxide-confined stripe widths. The minimum threshold current density under CW operation is 26 A/cm2 for the oxide-confined stripe width of 13 µm.

An energy level diagram for 1.3 µm InGaAs QDs is illustrated in Fig. 7. In nearly all III-V semiconductor self-organized QD's reported to date, the height of the QD is much less than its lateral dimension. Along with the In composition, the height and lateral dimension establish important traits of the QD electronic structure. Due to quantum size effects, the height mainly sets the energy difference between the wetting layer and the ground state and the lateral size mainly sets the energy separations between the ground and higher energy radiative transitions due to discrete levels.

Figure 8 shows electroluminescence from InAs QDs designed for such wide energy separations. As measured by atomic force microscope, their lateral size is ~250 Å. Figure 8 shows that the small lateral size results in an energy separation between the ground and first excited radiative transition of 104 meV. The ground state emission wavelength is ~1.24 µm. The energy separation between the ground and first excited radiative transitions is the largest yet reported for InAs or InGaAs QDs.

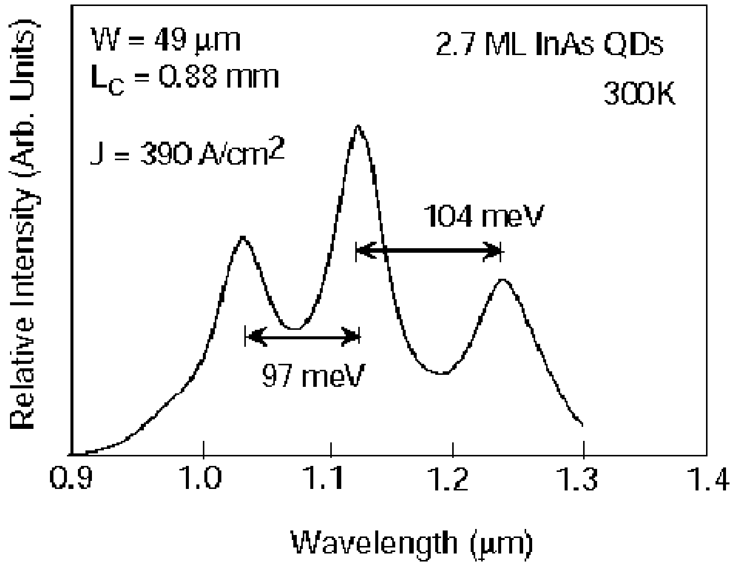


Figure 8. Spontaneous emission spectrum for an InAs QD light emitter engineered to have wide energy separations between the discrete radiative transitions.

Here the improvement due to the InAs QDs with the wider energy separations is apparent, with the InAs QD lasers showing much less temperature sensitivity with To > 80 K even above room temperature.

The QD's electronic levels also control its dynamic response. Larger QDs show shorter spontaneous lifetimes at low temperatures, and very fast capture times. Many experimental studies attempting to characterize capture times for electrons and holes have been flawed by transport time delays of charge carriers. However, more accurate experiments are now being performed, and show that larger QDs can respond faster than smaller QDs in both their capture time and spontaneous emission rate. Initial experiments on the QD modulation response suggest that QD lasers are slower than planar quantum well lasers at room temperature, but become comparable in speed below room temperature. The precise reasons are not yet known, and show that there is much research yet to be done on QD lasers to fully understand and optimize their performance.

Quantum Dots in the world of Optoelectronic communication

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Traditionally, network communication relied on copper cables, with both data loading and transmission being limited. Today, it is being replaced by fiber optic cable. For the latter, signal transmissions rely mainly on optical waves produced by lasers. Accordingly, lasers are becoming increasingly important in the era of fiber optic communication. Transmission in optical fiber has the lowest loss at wavelengths of 1.31μm and 1.55 μm, allowing fiber optic signal transmission to reach its maximum distance. Thus, the Opto-Electronics & Systems Laboratories (OES) research group, has emphasized its research on producing long wavelength lasers longer than 1 μm.

In the recent two years the quantum dot infrared detectors emerged at the forefront of light detector research, In comparison with QWIPS, the quantum dot detectors offer important advantages in regard to the performance parameters such as responsivity, detectivity and normal incidence operation. Standard quantum dot detectors, similarly to QWIPs respond to a single radiation wavelength or to a narrow spectral band.

Shortcomings of InGaAsP

The ultimate goal of each research teams is, of course, to provide the industry with a cost-effective solution and yet a feasible one using the most appropriate material and technology to grow lasers. The currently matured technology for lasers used in fiber optic communication involves the growth of InGaAsP edge-emitting lasers and vertical cavity surface emitting lasers (VCSEL) using InP substrate. However, two problems inherent to the InGaAsP lasers need to be addressed : poor temperature stability and low efficiency of the reflective mirrors made. For the latter, an alternative is to use the AlGaAs series for reflecting mirrors instead, and couple it with the InGaAsP active region through wafer bonding. This will obviously increase the complication in wafer manufacturing and therefore the cost. This, coupled with the low temperature stability, has aroused a vast search for new materials. "QDs is one of the technologies to replace InGaAsP. Another is the use of InGaNAs with 1-2% of nitrogen".

Advantages of QDs

"Laser requires a high temperature-stability so that it will not burn out when overheated. QD lasers are exactly the tool which could overcome the disadvantages of InGaAsP", said Dr. Chang. "Theoretically, a QD laser has a very high temperature-stability. It can also be grown directly on GaAs substrate, making use of the AlGaAs distributed Bragg reflector (DBR) in one single growth without the need of wafer bonding technique."

The central objective is the development of lasers and amplifiers based on innovative gallium arsenide (GaAs) based 'quantum dot' technology, that operate at the 1300 and 1500 nm emission wavelengths used in broadband fiber optic communications. The fabrication of such lasers using GaAs will deliver a considerable cost advantage over the Indium Phosphide (InP) technology that is currently the state-of-the-art for manufacturing devices at these wavelengths. The program is targeting the fabrication of quantum dots using standard and well understood wafer fabrication systems.

Due to their small dimensions, QDs confine trapped carriers in all three spatial directions, combining the advantages of semiconductors with the defined behaviour of atoms. This supports the creation of novel optical communications devices with very stable performance, that are much less prone to problems suffered by today's devices, such as distortion Development of quantum dot lasers on GaAs substrates for the 980 nm and 1.3 µm wavelength range. While in the 980 nm wavelength range the emphasis is more on high power applications and single mode emitting lasers suitable for gas sensoric, the interest for 1.3 µm emitting quantum dot lasers is in the realization of low cost but high performance devices for optical communication which can eventually substitute InP based devices in future. Beside the extension of the wavelength range of the GaAs based material system quantum dot specific features will be investigated which can improve device functions as e.g. low threshold current, improved modulation behavior, reduced temperature sensitivity, reduced filamentation and mirror load for high power applications, etc..

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It has therefore been anticipated that the success achieved in using quantum well structures in novel optoelectronic and electronic devices may be extended by using quantum dots instead of quantum wells due to significant improvements in the infrared detector performance. The significance of quantum dot light detectors lies in the fact that they are an emerging class of infrared detectors that will complement the HgCdTe detectors and QWIPs with commensurate or higher detectivity and fast response time. HgCdTe are traditionally the only high detectivity far infrared detector on the market today. Investigations of quantum dot light detectors have just started to appear in the recent literature. These devices offer scope for improved performance compared to quantum well light detector devices (QWIPs), and hence they are significant, while relatively unexplored

The modified properties of quantum dots significantly influence the key light detector parameters, such as detectivity and responsivity. Compared to quantum wells used in QWIPs, quantum dots are characterised by slowing of the intersubband relaxation time due to a reduced electron-phonon interaction. The reduced phonon scattering due to a discrete density of states in a quantum dot leads to long lifetime and long dephasing time and therefore to an increased radiative efficiency. Quantum dot detectors are also expected to exhibit lower dark current and noise than a quantum well detector.

Research on GaSb quantum dots was to establish a technology to fabricate a three dimensional quantum dot composite material, a building block for future electronic and optoelectronic devices. This is achieved by depositing multiple layers of quantum dots interspersed with quantum barriers of a different material. Interestingly, the dots show some degree of vertical correlation. Identification and understanding of growth evolution was possible. The systematic studies of growth evolution with variation of growth parameters indicate a variety of different scenarios, where the dilution of precursors and the growth time both play a role, in addition to the commonly recognized influences of growth temperature and the lattice mismatch. Optical characterization and analysis of optical emission is the added advantage. In embedded films we have observed optical (photoluminescence and cathodoluminescence) emission at energies about 1.0 eV, with peak energies following the trend in dot sizes. We interpret this by a combined effect of quantum confinement and interface intermixing. Hence comparison of GaSb dots embedded in GaAs with an opposite system of GaAs embedded in GaSb, and with a II-VI system of ZnTe dots in CdSe was possible.

Quantum Dot Research - the future now

The remaining major division of the field of quantum electronics deals with the interactions of coherent light with matter and again leads to a wide range of all-optical and opto-electronic devices.

Advances in research into the quantum dot phenomena made by scientists at IMS have resulted in a recent article in Nature Magazine and have attracted international recognition.

The research, a collaboration between IMS and the University of Wurzburg, has led to the ability to probe a single quantum dot and gradually increase the number of electrons and holes populating it. This is equivalent to creating artificial atoms and building a man-made periodic table.

By carefully controlling the excitation, the scientists were able to study the interaction of many electrons and holes (excitons), observing the difference in their emission spectra and providing important insight into the physics of such quantum systems.

The nanostructures confining carriers will play a crucial role in future technologies with the miniaturization of semiconductor devices for electronics and photonics applications. . A more distant hope is the application of QDs in improved optical memory. GaN has a much larger band gap than GaAs and very expectant researches are going on the GaN and its alloys. When a low concentration of N is incorporated into GaAs there is a very strong decrease in the optical band gap. This is very interesting both theoretically and practically: theoretically, because the behaviour cannot be explained by standard models of III-V alloys and so new approaches are clearly needed; practically, because the lower band gap makes accessible in the GaAs system the 1.3um and 1.55um wavelengths of interest for optical fibre communications. If we can achieve a good theoretical understanding of the band structure and optical properties of InGaAsN, the possibility exists that we may be able to propose novel and superior optoelectronic device structures.

CONCLUSION

The infrastructure of the Information Age has to date relied upon advances in microelectronics to produce integrated circuits that continually become smaller, better, and less expensive. Traditionally, network communication relied on copper cables, with both data loading and transmission being limited. Today, it is being replaced by fiber optic cable. For the latter, signal transmissions rely mainly on optical waves produced by lasers. Accordingly, lasers are becoming increasingly important in the era of fiber optic communication. The remaining major division of the field of quantum electronics deals with the interactions of coherent light with matter and again leads to a wide range of all-optical and optoelectronic devices. Transmission in optical fiber has the lowest loss at wavelengths of 1.31µm and 1.55 µm, allowing fiber optic signal transmission to reach its maximum distance.

The emergence of photonics, where light rather than electricity is manipulated, is posed to further advance the Information Age. Central to the photonic revolution is the development of miniature light sources such as the QDs. Today, QDs manufacturing has been established to serve new datacom and telecom markets. Recent progress in microcavity physics, new materials, and fabrication technologies has enabled a new generation of high performance QDs. This presentation has reviewed commercial QDs and their applications as well as recent researches, including new device structures such as applications of 3-dimensional QD arrays.

For the any industry interested in entering fiber optical communication, being able to grow LED, is only the first step; the next will be producing edge-emitting lasers and then QDS and VCSELs. For the benefits of the domestic industry, now is the time to start R&D effort on the long wavelength QDs lasers. Due to the optimized growth approach, sub-monolayer deposits results in large, low density QDs. Besides 1.3 um emission wavelength, QDs demonstrate very low threshold current density due to low transparency current and low free-carrier absorption and temperatre-insenseitive threshold due to deep confinement potentials with large energy separation between states. This principle is used in the opto-electronic communication.