Self-organized growth of In(Ga)As/GaAs quantum dots and their opto-electronic device applications

P BHATTACHARYA, K KAMATH, J PHILLIPS and D KLOTZKIN

Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109, USA

Abstract. The self-assembly technique of forming three-dimensional islands in the growth of highly strained semiconductor heterostructures has emerged as a powerful technique for the realization of an ordered array of quantum dots. Such quantum dots have been incorporated into the active region of optoelectronic and microelectronic devices in the hope of improving device performance or engineering new ones. Here we present the growth, optical characterization, and device applications for self-assembled InGaAs/GaAs quantum dots.

Keywords. Quantum dots; lasers; optoelectronics.

1. Introduction

Three-dimensionally quantum confined semiconductor heterostructures, or quantum dots, are desirable for optoelectronic and electronic applications due to the formation of atomic like energy levels. The realization of a high density of small (~ 100 – 200 Å) and uniform quantum dots has been elusive. The most direct approach, with epitaxial growth of a quantum well followed by controlled etching, provides the requisite size and uniformity. Unfortunately, surface defects produced by the etching process, and interface states introduced during subsequent regrowth, reduces the material quality to unacceptable levels. Recently, self-organized quantum dots (Goldstein *et al* 1984; Berger *et al* 1988; Guha *et al* 1990; Whaley and Cohen 1990; Leonard *et al* 1993; Grundmann *et al* 1995a; Bimberg *et al* 1998) have been proven to be the structures which best approach the desired properties, and almost all groups actively pursuing quantum dot device development are utilizing self-organized growth. The use of strain to produce self-assembled quantum dot structures has now become a well accepted approach and is widely used in III–V semiconductors and other materials systems. Much progress has been made in the area of growth (Guha *et al* 1990; Moison *et al* 1994; Kobayashi *et al* 1996)—where the focus has been size control, and optical characterization (Marzin *et al* 1994; Grundmann *et al* 1995b; Ledentsov *et al* 1996; Kamath *et al* 1997a, b)—where the goal has been the application to quantum dot lasers and detectors.

There is a need for semiconductor lasers which have low threshold currents, high output power and efficiency, little or no temperature dependence of the threshold

current, large modulation bandwidth, and little or no chirp. These are important attributes for a host of applications, from lightwave communication to pump sources. Many of these characteristics are determined by the density of states and electronic properties of the gain medium. The use of gain media of reduced dimensionality, in particular quantum wells, have greatly enhanced laser performance, particularly due to the modification of the band density of states and the resulting gain and differential gain (Arakawa and Sakaki 1982; Arakawa and Yariv 1985).

Far-infrared (5 – 20 μm) semiconductor detectors are desired for applications involving chemical analysis, night vision, thermal imaging, and space applications. Low bandgap materials, particularly HgCdTe (Arias *et al* 1994; Destefanis *et al* 1997; Tribolet *et al* 1998), are the current state of the art in long wavelength detectors. Material and device quality have advanced tremendously for HgCdTe, however there are still severe problems in epitaxial growth, device fabrication, and non-uniformities. An alternative solution is devices based on intersubband transitions in quantum confined heterostructures. The optical transitions in these devices involve subband to subband or subband to continuum absorption. These devices enable the use of common III–V materials, such as GaAs- and InP-based alloys, which have the advantages of mature epitaxial and fabrication technologies, higher uniformity in structures, and generally lower cost. The use of intersubband transitions in quantum wells (Esaki and Sakaki 1977; West and Eglash 1985) has led to the development of quantum well infrared photodetectors (QWIPs) (Levine *et al* 1987; Hasnain *et al* 1990; Gunapala and Bandara 1995). QWIPs have demonstrated good detector performance, however there are still limitations such as low quantum efficiency, large dark current, narrow bandwidth, and off-normal incidence. The main

*Author for correspondence

advantages of QWIPs are their advanced process technology and uniformity which is illustrated by the demonstration of 640×486 focal plane array cameras (Gunapala *et al* 1997), which has not been achieved using HgCdTe. Quantum dots are being looked to as a method of advancing intersubband detectors. One advantage of quantum dots is that they are intrinsically sensitive to normal incidence photoexcitation, where quantum wells only absorb in-plane photoexcitation due to the polarization selection rules. A second advantage lies in the carrier capture and relaxation times in quantum dots. The discrete nature of the bound energy states of the quantum dots is expected to inhibit phonon scattering and therefore increases carrier capture and relaxation times in quantum dots (Benisty *et al* 1991; Vurgaftman *et al* 1994). By increasing these relaxation times, efficient detection is predicted since photoexcited carriers are less likely to be captured into the quantum dots or to relax to the ground state before being swept away as a photocurrent, leading to increased extraction efficiency and increased operating temperatures. The self-assembly technique using the Stranski–Krastanow growth mode (Goldstein 1984; Berger *et al* 1988; Guha *et al* 1990; Whaley and Cohen 1990; Leonard *et al* 1993; Grundmann *et al* 1995a; Bimberg *et al* 1998) has proven to be an excellent quantum dot fabrication technique, and is therefore of interest to examine the possibility of using these quantum dots for intersubband detectors. Recently, far-infrared absorption (Drexler *et al* 1994; Pan *et al* 1997; Phillips *et al* 1997) and photoconductive detectors (Berryman *et al* 1997; Kim *et al* 1998; Pan *et al* 1998; Phillips *et al* 1998) have been reported for self-assembled quantum dots. Here we present the characteristics of InAs quantum dot intersubband detectors.

Semiconductor materials have had a profound impact in everyday life through their application in micro-electronics. Semiconductor process technology has dramatically increased the number of transistors in one chip from several thousand in 1970 to several million today. With this increase in devices per chip, the power consumption must be kept to a manageable level. One method of doing so is through single-electron charging effects in nanostructures. Interesting electronic properties related to the transport of carriers through the bound states and the trapping of electrons and holes can be used to realize a new class of devices such as the single-electron transistor (Kastner 1992; Ahmed and Nakazato 1996) which may be used for a multi-level logic element which may be used for a multi-level logic element (Asahi *et al* 1997; Iwamura *et al* 1998), memory element (Nakazato *et al* 1993; Tiwari *et al* 1996), etc. Single-electron devices are one answer to the problem of increasing device density on a chip without sacrificing power consumption. Self-assembled quantum dots have demonstrated a large degree of quantum confinement

with electron intersubband separation much larger than the thermal energy at room temperature. Therefore, they are a good candidate for single-electron devices operating at room temperature. Here we present a novel modulation doped field-effect transistor with a layer of quantum dots near the conducting channel in the interest of demonstrating the possible use of self-assembled quantum dots in single-electron transistor applications.

Nonlinear optical materials are attractive for their use in optical devices such as switches and electron-optic and electro-absorption modulators. Bulk III–V compounds such as GaAs and GaAlAs exhibit a linear electro-optic (Pockels) effect since they are non-centrosymmetric and lack inversion symmetry. However, the effect is weak compared to that in crystals such as lithium niobate. From the point of photonic integrated circuits, it would be very useful to realize non-linear electro-optic devices, which could be integrated with other active and quasi-active devices such as lasers, detectors, and interferometers. A great deal of work has therefore been done to investigate the optical properties of quantum wells and superlattices. Quantum wells demonstrate enhanced electro-optic effects due to two features: a built-in birefringence due to the layered structure and quadratic electro-optic (Kerr) effect arising from the quantum confined Stark effect (QCSE) near the excitonic absorption edge (Miller *et al* 1984). Low-dimensional quantum confined structures such as quantum wires and dots are expected to exhibit enhanced optical non-linearities and enhanced electro-optic effects (Schmitt-Rink *et al* 1987; Takagahara 1987; Bryant 1988; Davis *et al* 1993). It is therefore of interest to examine the use of self-assembled quantum dots in electro-optic modulators, as presented here.

2. Self-organized growth of quantum dots

It has been shown that highly lattice-mismatched Ga(In)As epitaxially grows on GaAs in the so-called Stranski–Krastanow growth mode, where self-organized islands are formed after a few monolayers of layer-by-layer growth. From RHEED measurements during molecular beam epitaxial (MBE) growth of InGaAs on GaAs and from energy minimization considerations in a unit cell of the growing layer, we had shown for the first time that for a misfit > 0.018 , the island mode of growth is preferred (Berger *et al* 1988). For typical growth parameters used in MBE or metal-organic vapour phase epitaxy (MOVPE), an array of pyramidal islands of lateral size 10–40 nm and heights 5–8 nm are formed. Elastic relaxation on the facet edges, renormalization of the surface energy of the facets, and interaction between neighbouring islands via the substrate are the driving forces for self-organized growth. There are considerable strain fields within the pyramidal dots, in the substrate

underneath, and in the overlayer, if the latter is grown. *In situ* atomic force microscope (AFM) studies (Kobayashi *et al* 1996) during growth of InAs on GaAs have given valuable insight into the evolution of the size distribution between dots, as growth proceeds, and a tendency for eventual size equalization. Careful studies of growth in the InAs-GaAs system (Leonard *et al* 1993) have also shown that there exists a relatively narrow range of deposition parameters, where the islands are small (~ 10 nm), have very similar size and shape and form dense arrays. Interaction of the islands via the substrate also makes their lateral ordering favourable. By virtue of their size and shape, the self-organized islands best approach the desired properties of zero-dimensional quantum dots. It is important to realize for device applications that the pyramidal quantum dots are defect-free. An AFM image of an array of $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{GaAs}$ dots grown by MBE at 530°C at a rate of 0.25 monolayer/sec is shown in figure 1a. From this image, the dot density is estimated to be $3 \times 10^{10} \text{ cm}^{-2}$.

If a layer of In(Ga)As dots is covered with a thin layer of GaAs and another In(Ga)As growth cycle is initiated, the dots in the second sheet are formed exactly on top of the dots in the first layer and this trend continues, resulting in a 3-D array of vertically aligned and electronically coupled dots (Xie *et al* 1995; Solomon *et al* 1996). Multiple layer quantum dots (MLQD) are very useful for laser and detector applications. The cross-sectional transmission electron microscope (TEM) image of a 4-layer stack of InAs dots grown by MBE at 500°C is shown in figure 1b. The strain driven alignment of the dots is evident. The optimum growth conditions for multi-dot layers have been described in detail in previous publications by us (Kamath *et al* 1997a, b).

3. Photoluminescence under applied pressure

The bandstructure of self-assembled quantum dots needs to be better understood to properly design quantum dot devices. One technique used to obtain deformation potentials in strained systems and information on bandstructure is measurement under applied pressure. Here we report a study of the photoluminescence of $\text{In}_{0.5}\text{Al}_{0.5}\text{As}/\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ self-assembled quantum dots under hydrostatic pressure in the effort to further understand the bandstructure and strained nature of the quantum dots.

Heterostructures were grown by molecular beam epitaxy. The grown structure consists of a GaAs buffer layer followed by a 200 nm $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ barrier, both grown at 630°C . The $\text{In}_{0.5}\text{Al}_{0.5}\text{As}$ quantum dots were then grown at 540°C with a nominal thickness of 10 ML. The quantum dot growth was monitored by reflection high energy electron diffraction (RHEED) and 3-D island growth was found to commence after ~ 8 ML, which is

in agreement with other reports (Leon *et al* 1995). A 15 sec growth interruption at this point allowed further dot formation and was followed by the growth of 200 nm of $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ at 630°C . A layer of $\text{In}_{0.5}\text{Al}_{0.5}\text{As}$ quantum dots was then grown on the surface under conditions similar to the buried dots for AFM measurements, which reveal a density of $\sim 1 \times 10^{11} \text{ dots/cm}^2$. In addition, a reference $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ sample was grown under similar conditions, but without the quantum dot layers.

Photoluminescence measurements were performed using an Ar^+ ($\lambda = 488$ nm) laser, a 1-meter monochromator, and a photomultiplier with photon counting. Excitation was less than 30 mW for all measurements with a diameter of ~ 50 μm , corresponding to a region containing an estimated 2×10^6 dots. A Merrill-Bassett-type diamond anvil cell and a closed cycle helium cryostat were used for the high pressure measurements at low temperature. A 4 : 1 methanol-ethanol solution served as the pressure transmitting medium and the pressure calibration was done using fluorescence from a small piece of ruby mounted with the sample. Pressure was adjusted at room temperature for all measurements.

The low temperature photoluminescence (PL) spectra of the quantum dot sample for varying pressures are shown in figure 2. At 1 bar, three peaks at $E = 1.5$, 1.705, and 1.845 eV are observed corresponding to luminescence from the GaAs buffer, InAlAs quantum dots, and AlGaAs bulk, respectively. The PL peak energy

Figure 1. (a) AFM image of a single layer of InGaAs quantum dots and (b) cross-sectional TEM image of 4 layers of InAs quantum dots separated by nominally 5 nm GaAs spacers.

shifts with pressure are shown in figure 3. The underlying GaAs buffer peak was observed for all pressure measurements, with a linear pressure coefficient of 10.6 meV/kbar, serving as a good reference for verifying pressure calibration. Other PL peaks shift linearly with applied pressure up to 8 kbar with pressure coefficients for AlGaAs and InAlAs quantum dots of 11.5 meV/kbar and 9.0 meV/kbar, respectively. The pressure coefficient of InAlAs quantum dots is smaller than that expected for InAlAs bulk, but is consistent with that reported for self-assembled InAs/GaAs quantum dots (Itskevich *et al* 1997). We believe that the reduced pressure shifts is due to the highly confined energy levels in the dots, similar to the reduced pressure coefficients reported for increasing confinement in InGaAs/AlGaAs quantum wells (Wilkinson *et al* 1991). Between 8 and 20 kbar, there is no significant energy shift (or a small red shift of ~ 1 meV/kbar) in the quantum dot peak with pressure. Above 20 kbar, there is a gradual red shift in peak energy with pressure, and finally the quantum dot luminescence is quenched above 26 kbar.

The energy states in self-assembled quantum dots are quite different from those in the corresponding bulk material because of quantum confinement and the built-in strain between the quantum dot and barrier material. Application of external pressure modifies the strain field in and around the quantum dots due to the differences in the bulk moduli of the two materials. In addition, pressure-induced energy level crossings also influence the pressure coefficient of the quantum dot PL peak. The true cause of the photoluminescence peak shift with

pressure cannot be deduced from these measurements alone; however, a possible explanation is schematically shown in figure 4 for the three distinct pressure regions.

4. Lasers

Separate confinement heterostructure (SCH) lasers, shown in figure 5, were grown by MBE on semi-insulating (001) GaAs substrates. The structure consists of an $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ outer clad, GaAs inner clad, and a single or multiple layers of $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ self-organized quantum dots as the active region. Broad area lasers with dimensions of $50\text{ }\mu\text{m}$ by 1 mm were fabricated for material characterization. Room temperature lasing was observed at $\sim 1\text{ }\mu\text{m}$ with threshold current density of 650 A/cm^2

Figure 3. Photoluminescence peak intensity shift with pressure for the quantum dot sample. GaAs data points are not shown between 22 and 28 kbar to avoid confusion with quantum dot data.

Figure 2. Photoluminescence from the quantum dot sample for various pressures showing luminescence peaks for the InAlAs quantum dots, AlGaAs barrier, and GaAs buffer.

Figure 4. Schematic of proposed band alignment for quantum dots and AlGaAs barriers for the three pressure regions observed. The levels denote the AlGaAs band edge or quantum confined ground state in the quantum dots.

and 280 A/cm² for single- and 4-layer dot lasers, respectively. 3 μ m wide ridge waveguide lasers of variable length were made by standard photolithographic, wet and dry etching, and metallization techniques. They were fabricated in a ground-signal-ground configuration to facilitate microwave probing.

4.1 DC characteristics

Light-current characteristics of single- and 4-layer dot lasers have slope efficiencies of 0.29 and 0.4, respectively and threshold currents of 14.4 and 6.9 mA, respectively. The room-temperature electroluminescent spectra of broad-area single-layer and 4-layer In_{0.4}In_{0.6}As/GaAs quantum dot lasers, both in the spontaneous and stimulated emission regimes, are shown in figure 6a and b, respectively. Several significant features are observed in the spectra. First, multiple peaks (at least 3), corresponding to ground and excited state transitions, are observed in figure 6. The lasing of single dot layer lasers from an excited state and that of multi-dot layer devices from a ground state transition have been observed before (Kamath *et al* 1996; Mirin *et al* 1996; Bimberg *et al* 1997). This behaviour is related to the saturation of the ground states in single dot layer devices. The energy difference between the emission peaks in figures 6a and b is $\sim$ 65 meV, which is very close to the theoretically calculated values (Jiang and Singh 1998). The respective transitions are most likely *e1-hh1* and *e2-hh2*.

4.2 Dynamic characteristics

The small signal modulation response of ridge-waveguide lasers were made with a cryogenic system. The optical frequency response was measured as a function of temperature using a photoreceiver, amplifier and network analyzer. Light was collected with a cleaved fibre and the measured response was corrected for the measured frequency dependence of the cables and amplifier, and for the manufacturers reported frequency dependence of

the photoreceiver. Measurement of the frequency response characteristics was made at several intermediate temperatures between 300 K and 40 K and at each temperature the measurement was repeated at several injection currents above threshold, till a saturation behaviour of the response was observed. Figure 7 shows the modulation characteristics at three temperatures, 80 K, 155 K and 245 K, under DC bias conditions. Room temperature measurements have already been reported with the maximum measured bandwidth (f_{-3dB}) varying between 5 and 7.5 GHz (Kamath *et al* 1997c; Klotzkin *et al* 1997), agreeing with the observations of other researchers (Bimberg *et al* 1997). However, with lowering of measurement temperature, the bandwidth increases monotonically, up to a maximum value of > 20 GHz at 80 K.

There is a clear, qualitative change in the device response at about 150 K. The responses at 80 K and 155 K do not differ greatly, even to the drive current necessary to achieve a particular resonance frequency. However, the measured response at 245 K is much reduced. We believe that this change is due to the increase in carrier capture time with temperature.

(a)

Figure 5. Schematic of the quantum dot laser heterostructure. This is a conventional SCH-quantum well laser structure where quantum wells are replaced by quantum dots.

Figure 6. Room temperature spontaneous emission and lasing emission spectra from (a) single layer and (b) 4-layer quantum dot lasers.

Two additional experiments, performed with similar quantum dot lasers, help us to understand the results obtained from the optical response measurements. In the first, the electrical impedance of the laser diode is measured at room temperature as a function of frequency with the help of a Network Analyzer. The measured high-frequency electrical impedance data is fit to the expression for impedance derived by Weisser *et al* (1994) from rate equations. The quantum capture time of injected carriers, determined in this way, varies from ~ 40 ps for single-layer QD lasers to ~ 30 ps for multi-dot layer lasers (Klotzkin *et al* 1997). The capture time decreases with increase of injection current. In a separate experiment, Sosnowski *et al* (1998), have performed low-temperature femtosecond differential transmission spectroscopy (DTS) with a 4 In_{0.35}Ga_{0.65}As/GaAs dot-layer sample using the pump-probe technique. From their analysis of the data with rate equations, the relaxation times of electrons from the GaAs barrier to the excited and ground state are determined to be 2.8 and 8 ps, respectively. Therefore, in a laser with such an active region,

the total capture time of injected carriers will be of ~ 10 ps. From the results of these two measurements it appears that the capture time of electrons at 300 K and 18 K are ~ 30 ps and 10 ps, respectively. These numbers translate to modulation bandwidths of ~ 5 GHz and 16 GHz, almost identical to those measured directly. The capture time at low temperature is also in fair agreement with the calculated $e-h$ scattering time of 10 ps, done by Jiang and Singh (1998).

We therefore believe that the carrier relaxation, or capture times, limit the maximum modulation bandwidth achievable in quantum dot lasers. It may be noted that in quantum well lasers, where optical phonon scattering rates are quite high, the relaxation times are $\sim 2-5$ ps. Due to requirements of energy and momentum conservation, the phonon scattering rates are very small in quantum dots. With lowering of temperature, the rate of electron-hole scattering is expected to increase since there will be more empty hole states at higher (hole) energies. That helps to explain the value of 8 ps carrier relaxation time obtained from the pump-probe measurements (Sosnowski *et al* 1998) and the corresponding > 20 GHz modulation bandwidth.

Figure 7. Small signal modulation characteristics of a 4-layer quantum dot ridge laser at 80 K, 155 K, and 245 K.

5. Intersubband detectors

Self-assembled InAs/GaAs quantum dot heterostructures were grown by molecular beam epitaxy (MBE) on semi-insulating GaAs (100) substrates for study. A set of heterostructures were grown for photoconductive intersubband detectors consisting of ten layers of silicon-doped quantum dots (2.2 ML nominal InAs thickness) with 100 nm undoped GaAs barriers sandwiched between n^+ GaAs contact layers. The grown heterostructures are shown in figure 8. Each InAs quantum dot layer was grown at 510°C at a growth rate of 0.1 ML/s with a background arsenic pressure of 1×10^{-5} T. A 10 sec pause was used after the InAs growth to further promote quantum dot formation. The growth of InAs layers was

Figure 8. Schematic of MBE grown heterostructures and devices for photoconductive intersubband detectors.

monitored by reflection high energy electron diffraction (RHEED) where the transition from 2D to 3D island growth was observed after ~ 1.8 ML of InAs growth. The InAs quantum dot layers were uniformly and directly silicon-doped to a level of $n = 0.5 - 1 \times 10^{18} \text{ cm}^{-3}$. Atomic force microscope (AFM) measurements on samples with quantum dots grown on the surface under similar growth conditions indicate a dot density of 10^{10} – 10^{11} dots/cm². The doping level then corresponds to ~ 0.5 – 1 dopant atoms/dot. The GaAs regions were grown at 630°C with temperature ramps before and after quantum dot growth. Circular mesa structures of 400 μm diameter were patterned to contact top and bottom n^+ -GaAs regions. Ni/Ge/Au ring contacts were then deposited and annealed for ohmic contacts. The devices were wire bonded to a chip carrier for measurement. The device structure is shown schematically in figure 8.

Current–voltage measurements were performed to determine the dark current and photocurrent. Low temperature current–voltage characteristics are shown in figure 9 for the device in the dark and under illumination from a $T = 500$ K blackbody source with a 2.5° field of view. The dark current is symmetric for positive and negative bias indicating good doping uniformity in the heterostructure. The characteristics are slightly asymmetric with bias under illumination which is attributed to the asymmetric dot shape.

The normalized responsivity spectrum of the detector is shown in figure 10. The measured signal has a series of sharp spikes which is determined to be from absorption lines in the epoxy used to mount the samples on a chip carrier. Incident light that is not absorbed on the first pass reaches the chip carrier and reflects back to the detector structure. The sharp dips in the responsivity are then observed at the sharp epoxy absorption lines which suppress light reflected back to the device at particular wavelengths. This light reflection problem may be avoided by using a doped substrate. A signal averaged responsivity spectrum is shown to give a better idea of the detector

response shape. Through comparison to FTIR measurements and theoretical calculations (Jiang and Singh 1998), we believe the absorption is from bound state to continuum transitions in the quantum dot. A notable feature of the detector response spectrum is the broad linewidth $\Delta\lambda/\lambda = 0.7$. This value is larger than reported for QWIPs using varying quantum well thicknesses (Bandara *et al* 1998), and is due to the distribution in quantum dot size and energy levels. The broad linewidth is useful for broadband detection applications such as in space science missions (Bandara *et al* 1998). The peak responsivity for varying bias is shown in figure 11. There is no significant change in the responsivity spectra with applied bias. The measurements were performed on the detector left alone and with a glass cover slide surrounding the device. The glass cover slide is opaque in the wavelength region of measurement and serves as a better indication of the true responsivity of the device. The larger responsivity values for the measurement without the cover stem from light incident outside the detector which reflects in the substrate and is incident on the backside of the detector.

Figure 10. Normalized responsivity of InAs/GaAs quantum dot detector measured at $T = 40$ K with a FTIR spectrometer.

Figure 9. InAs/GaAs quantum dot detector current–voltage characteristics measured at $T = 40$ K in the dark and with a 2.5° field of view.

Figure 11. InAs/GaAs quantum dot detector peak responsivity at varying bias for a device with and without a surrounding opaque cover slide.

The detectivity, D^* , a measure of the signal-to-noise ratio, is in the range $D^* = 1\text{--}10 \times 10^9 \text{ cm Hz}^{1/2}/\text{W}$ for varying bias. In spite of the dark current, reasonably good detectivity is observed at $V_B = \pm 1 \text{ V}$. An interesting feature of these detectors is the existence of photoconductive gain (Liu 1992; Beck 1993). A gain of greater than one is possible for long carrier lifetimes since these detectors are unipolar majority carrier devices. The photoconductive gain of the quantum dot detector under varying bias is in the range 0.15–12.

6. Transistors

The self-assembled growth of In(Ga)As/Ga(Al)As quantum dots has proven to be an excellent method of forming semiconductor nanostructures and has an advanced GaAs process technology for producing high performance electronic devices. These self-assembled quantum dots have demonstrated single-electron charging effects in modulation doped field effect transistor (MODFET) structures (Horiguchi *et al* 1997; Yusa and Sakaki 1997). These results are similar to single-electron transistor devices, with low current levels. However, these effects were only reported near liquid helium temperatures.

In the effort to observe more macroscopic device characteristics and at room temperature, a different device structure and larger device dimensions are used in these experiments. In this case, a typical quantum well delta-doped transistor is used with the modification of placing a layer of quantum dots between the doping layer and the 2-dimensional channel. The device heterostructure, grown by molecular beam epitaxy, is shown in figure 12a and the conduction band diagram in figure 12b. The GaAs buffer layer, top $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ layer and the n^+ -GaAs contact layer were grown at 620°C . The

$\text{In}_{0.19}\text{Ga}_{0.81}\text{As}$ quantum well channel layer, InAs quantum dot layer and the $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ spacer layer were grown at 510°C . The quantum dot layer consists of 2.5 ML of InAs grown at a rate of 0.1 ML/sec. The density of dots formed under these growth conditions, measured by atomic force microscopy (AFM) on similar samples, is $\sim 5 \times 10^{10} \text{ cm}^{-2}$. Due to the small separation (2.5 nm), the electronic states in the quantum well and the quantum dot layer are coupled. A transistor heterostructure without the quantum dot layer was also grown for comparison. Single recess FETs (0.2–0.3 μm -gate) were fabricated using electron beam lithography and standard metallization and wet chemical etching. The gate widths were in the range 50–100 μm .

At room temperature, the output current–voltage ($I_D - V_{DS}$) characteristics of QD transistors, shown in figure 13a, exhibit weak current steps, nonlinear behaviour with varying gate voltage, and a strong negative differential resistance (NDR) region observed for certain values of gate bias. The observed unique characteristics are a result of the additional conduction via the confined conduction band states of the quantum dots contributing

Figure 12. The (a) epitaxial heterostructure and (b) conduction band diagramme under varying gate bias of the quantum dot MODFET.

Figure 13. (a) Output characteristics ($I_D - V_{DS}$) and (b) transfer characteristics ($I_D - V_G$) of a quantum dot MODFET measured at room temperature.

to conduction in the quantum well channel. This additional dot conduction is controlled by the gate bias, which changes the energy position of the Fermi level with respect to the bound states in the dot. The NDR region occurs where the Fermi level crosses the excited quantum dot energy level and is believed to be due to the carrier escape from the excited state to the lower mobility AlGaAs barrier layer. The minimum NDR observed is 570Ω . NDR is not observed for gate voltages where the Fermi level coincides with the ground state of the quantum dots.

The current steps and the NDR are observed over a wide range of gate voltages, which is a result of the inhomogeneous distribution of dot energy levels that stems from the size distribution of the quantum dots. The transfer (I_D-V_G) characteristics, shown in figure 13b, exhibit steps corresponding to the output characteristics at two distinct values of V_G and are observed only at particular V_{DS} . The maximum transconductance of the devices, without including the current steps, is $g_m(\max) = 120 \text{ mS/mm}$. In comparison, all of the features mentioned above are not observed in a normal InGaAs/AlGaAs MODFET without the quantum dot layer.

The device described in these experiments are of much larger dimensions than a single-electron transistor and include an additional conducting channel. The characteristics described above can be made to approach those of a true single-electron transistor with partial or complete removal of the quantum well channel conduction. The removal of the quantum well channel will result in only conduction through bound states in the quantum dots. Additionally, through reduction in device size where only a few dots lie under the active region, few active electrons will be controlled, as is the case in a single-electron transistor.

Figure 14. Phase retardation and refractive index change as a function of reverse bias. The curve is a fit to the measured data.

7. Electro-optic modulators

A quantum dot heterostructure, similar to those grown for the quantum dot lasers, was grown by MBE. The active layer consists of a single layer of self-organized $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ quantum dots with a GaAs layer grown over it. The grown heterostructure, in fact, forms an edge emitting laser which is suitable for electro-optic measurement. Single mode ridge waveguides $3 \mu\text{m} \times 840 \mu\text{m}$ with both p- and n-contacts on the top surface were fabricated by standard photolithography, wet and dry-etching and contact metallization techniques.

Measurement of the electro-optic coefficients was carried out by coupling $1.15 \mu\text{m}$ light from a He-Ne laser onto one end of a $840 \mu\text{m}$ long waveguide with a focusing lens. The polarization of the light is oriented, through use of an input polarizer, at 45° to the direction of the diode electric field with an applied reverse bias. The phase retardation of the transmitted light was measured with an analyzer and a Ge detector at the output end. The measured phase retardation and refractive index change as a function of reverse bias, as shown in figure 14, are seen to vary with field in a non-linear manner. The linear and quadratic electro-optic coefficients are obtained by fitting the measured phase retardation with the relation (Bloemer and Myeni 1993).

$$\Delta\Phi = \pi L n_0^3 \lambda^{-1} [\Gamma_l r E + \Gamma_q s E^2], \quad (1)$$

where n_0 is the average refractive index in the active region, E the average electric field, r and s are the linear and quadratic electro-optic coefficients, respectively, and Γ_l and Γ_q are the linear and quadratic confinement factors, taking into account the fill factor of the quantum dot array. The confinement factors themselves are separated into those for the quantum dot, the GaAs layers, and the $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ guiding layers which are respectively, 1.25×10^{-2} , 0.415 and 0.456. The fill factor of the dots is estimated to be 0.242 using the technique described by Kamath *et al* (1997c). The values of r and s obtained for the quantum dots are $2.58 \times 10^{-11} \text{ m/V}$ and $6.23 \times 10^{-17} \text{ m}^2/\text{V}^2$, respectively. Note that the linear electro-optic coefficient is larger than that of GaAs (Lee *et al* 1991) or of GaAs and InP-based multiquantum wells (Glick *et al* 1986; Nagai *et al* 1986; Zucker *et al* 1988; Pamulapati 1991). Similarly, the quadratic electro-optic coefficient is also very large compared to the quantum wells, in spite of a small fill factor. A multiple dot layer active region, commonly used in lasers, may yield even larger electro-optic coefficients.

The bias-dependent transmission of the quantum dot phase modulator is depicted in figure 15. A large change in transmission, almost by a factor of 2, is obtained for a small applied bias of 3 V. The change in the absorption coefficient of the phase modulator due to changes in

Figure 15. Normalized transmitted light as a function of reverse bias. The dashed line is shown as a join of the measured data.

the applied electric field is obtained by fitting the power transmission with

$$T = e^{-\Gamma\Delta\alpha L} \cos^2(\Delta\Phi/2).$$

The estimated value of $\Gamma\Delta\alpha$ is less than 7 cm^{-1} .

8. Conclusion

Self-organized growth of strained In(Ga,Al)As/Ga(Al)As quantum dots have been described. $\text{In}_{0.5}\text{Al}_{0.5}\text{As}/\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ quantum dots exhibit unique changes in PL spectra under applied pressure. The PL peak energy shows three distinct regions with different pressure coefficients which are attributed to energy level crossovers.

Room temperature SCH quantum dot lasers have been demonstrated. Measurement of the modulation bandwidth of single-mode ridge waveguide lasers, together with comparison to theoretical calculation (Jiang and Singh 1998), electrical impedance (Klotzkin et al 1997), and pump-probe measurements (Sosnowski et al 1998), indicate that the modulation bandwidths are limited to $\sim 6 \text{ GHz}$ and $> 20 \text{ GHz}$ at 300 K and 80 K, respectively, by electron-hole scattering.

Photoconductive quantum dot intersubband detectors were fabricated and detector responses in the far-infrared were observed. A broad detector response was observed due to the size distribution of the quantum dots. Subband-continuum quantum dot intersubband detectors show decent normal incidence performance characteristics at $T = 40 \text{ K}$, with $R_p = 10\text{--}100 \text{ mA/W}$, $D^* = 1 - 10 \times 10^9 \text{ cm}^2\text{Hz}^{1/2}/\text{W}$, and large photoconductive gain up to $g = 12$ for a 10-layer quantum dot heterostructure.

Self-assembled quantum dots are an excellent candidate for single-electron transistors and novel devices operating

at room temperature. A novel InGaAs/AlGaAs modulation doped field effect transistor with the inclusion of a layer of InAs self-assembled quantum dots near the conducting channel has been demonstrated and shows unique non-linear $I-V$ characteristics and NDR due to electron charging into quantum dot conduction band energy levels.

We have measured the linear and quadratic electro-optic coefficients and phase and amplitude modulation characteristics of $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ single-layer self-organized quantum dots. Both electro-optic coefficients are significantly larger than those measured in quantum wells, with very small absorption loss. The results indicate that low-voltage modulators can be made with quantum dots.

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References

- Ahmed H and Nakazato K 1996 *Microelectron. Eng.* **32** 297
- Arakawa Y and Sakaki H 1982 *Appl. Phys. Lett.* **40** 939
- Arakawa Y and Yariv A 1985 *IEEE J. Quantum Electron.* 1666
- Arias J M et al 1994 *Proc. SPIE* **2274** 2
- Asahi N, Akazawa M and Amemiya Y 1997 *IEEE Trans. Electron. Dev.* **44** 1109
- Bandara S V et al 1998 *Appl. Phys. Lett.* **72** 2427
- Beck W A 1993 *Appl. Phys. Lett.* **63** 3589
- Benisty H, Sotomayor-Torres C M and Weisbuch C 1991 *Phys. Rev.* **B44** 10945
- Berger P, Chang K, Bhattacharya P, Singh J and Bajaj K 1988 *Appl. Phys. Lett.* **53** 684
- Berryman K W, Lyon S A and Segev M 1997 *Appl. Phys. Lett.* **70** 1861
- Bimberg D et al 1997 *IEEE J. Sel. Topics Quantum Electron.* **3** 196
- Bimberg D, Grundmann M and Ledentsov N N 1998 *Mater. Res. Soc. Bull.* **23** 31
- Bloemer M J and Myeni K 1993 *J. Appl. Phys.* **74** 4849
- Bryant G W 1988 *Phys. Rev.* **B37** 8763
- Davis L et al 1993 *Appl. Phys. Lett.* **62** 2766
- Destefanis G, Audebert P, Mottin E and Rambaud P 1997 *Proc. SPIE* **3061** 111
- Drexler H, Leonard D, Hansen W, Kotthaus J P and Petroff P M 1994 *Phys. Rev. Lett.* **73** 2252
- Esaki L and Sakaki H 1977 *IBM Tech. Disc. Bull.* **20** 2456
- Glick M, Reinhart F, Weimann G and Schlapp W 1986 *Appl. Phys. Lett.* **48** 989
- Goldstein L, Glas F, Marzin J Y, Charasse M N and LeRoux G 1984 *Appl. Phys. Lett.* **47** 1099

- Grundmann M *et al* 1995a *Phys. Rev. Lett.* **74** 4043
- Grundmann M, Stier O and Bimberg D 1995b *Phys. Rev.* **B52** 11969
- Guha S, Madhukar A and Rajkumar K C 1990 *Appl. Phys. Lett.* **57** 2110
- Gunapala S D and Bandara K M S V 1995 *Thin Films* **21** 113
- Gunapala S D *et al* 1997 *Proc. SPIE* **3061** 722
- Hasnain G, Levine B F, Sivco D L and Cho A Y 1990 *Appl. Phys. Lett.* **56** 770
- Horiguchi N, Futatsugi T, Nakata Y and Yokoyama N 1997 *Appl. Phys. Lett.* **70** 2294
- Itskevich I E *et al* 1997 *Appl. Phys. Lett.* **70** 505
- Iwamura H, Akazawa M and Amemiya Y 1998 *IEICE Trans. Electron.* **E81-C** 42
- Jiang H and Singh J 1997 *Phys. Rev.* **B56** 4696
- Jiang H and Singh J 1998 *IEEE J. Quantum Electron.* **34** 1188
- Kamath K, Bhattacharya P, Sosnowski T, Norris T and Phillips J 1996 *Electron. Lett.* **32** 1374
- Kamath K, Bhattacharya P and Phillips J 1997a *J. Crystal Growth* **175/176** 720
- Kamath K *et al* 1997b *Appl. Phys. Lett.* **71** 927.
- Kamath K, Phillips J, Jiang H, Singh J and Bhattacharya P 1997c *Appl. Phys. Lett.* **70** 2952
- Kastner M A 1992 *Rev. Mod. Phys.* **64** 849
- Kim S *et al* 1998 *Appl. Phys. Lett.* **73** 963
- Klotzkin D, Kamath K and Bhattacharya P 1997 *IEEE Photon. Technol. Lett.* **9** 1301
- Kobayashi N P, Ramachandran T R, Chen P and Madhukar A 1996 *Appl. Phys. Lett.* **68** 3299
- Ledentsov N N *et al* 1996 *Solid State Electron.* **40** 785
- Lee S S, Ramaswamy R V and Sundaram V S 1991 *IEEE J. Quantum Electron.* **27** 726
- Leonard D, Krishnamurthy M, Reaves C M, Denbaars S P and Petroff P M 1993 *Appl. Phys. Lett.* **63** 3202
- Leon R, Fafard S, Leonard D, Merz J L and Petroff P M 1995 *Appl. Phys. Lett.* **67** 521
- Levine B, Choi K, Bethea C, Walker J and Malik R 1987 *Appl. Phys. Lett.* **50** 1092
- Levine B F *et al* 1990 *Appl. Phys. Lett.* **56** 851
- Liu H C 1992 *Appl. Phys. Lett.* **61** 2703
- Marzin J Y, Gerard J M, Izrael A and Barrier D 1994 *Phys. Rev. Lett.* **73** 716
- Miller D A B *et al* 1984 *Phys. Rev. Lett.* **53** 2173
- Mirin R, Gossard A and Bowers J 1996 *Electron. Lett.* **32** 1732
- Moison J M *et al* 1994 *Appl. Phys. Lett.* **64** 196
- Nagai H, Yamanishi M, Kan Y and Suemune I 1986 *Electron. Lett.* **22** 888
- Nakazato K, Blaikie R J, Cleaver J R A and Ahmed H 1993 *Electron. Lett.* **29** 384
- Pamulapati J, Loehr J P, Singh J, Bhattacharya P K and Ludowise M J 1991 *J. Appl. Phys.* **69** 4071
- Pan D *et al* 1997 *J. Crystal Growth* **175–176** 760
- Pan D, Towe E and Kennerly S 1998 *Electron. Lett.* **34** 1019
- Phillips J, Kamath K, Zhou X, Chervela N and Bhattacharya P 1997 *Appl. Phys. Lett.* **71** 2079
- Phillips J, Kamath K and Bhattacharya P 1998 *Appl. Phys. Lett.* **72** 2020
- Schmitt-Rink S, Miller D A B and Chemla D S 1987 *Phys. Rev.* **B35** 8113
- Solomon G S, Trezza J A, Marshall A F and Harris J S 1996 *J. Vac. Sci. Technol.* **B14** 2208
- Sosnowski T *et al* 1998 *Phys. Rev.* **B57** R9423
- Takagahara T 1987 *Phys. Rev.* **B36** 9293
- Tiwari S, Rana F, Chan K, Shi L and Hanafi H 1996 *Appl. Phys. Lett.* **69** 1232
- Tribolet P, Chatard J P, Costa P and Manissadjian A 1998 *J. Crystal Growth* **184–185** 1262
- Yusa G and Sakaki H 1996 *Electron. Lett.* **32** 491
- Yusa G and Sakaki H 1997 *J. Crystal Growth* **175/176** 730
- Vurgaftman I, Lam Y and Singh J 1994 *Phys. Rev.* **B50** 14309
- Weisser S *et al* 1994 *IEEE Photon. Technol. Lett.* **6** 1421
- West L and Eglash S 1985 *Appl. Phys. Lett.* **46** 1156
- Whaley G J and Cohen P I 1990 *Appl. Phys. Lett.* **57** 144
- Wilkinson V A, Prins A D, Dunstan D J, Howard L K and Emeny M T 1991 *J. Electron. Mater.* **20** 509
- Xie Q, Madhukar A, Chen P and Kobayashi N P 1995 *Phys. Rev. Lett.* **75** 2542
- Zucker J E, Hendrickson T L and Burrus C A 1988 *Appl. Phys. Lett.* **52** 945