Characterization of InSb quantum dots in InAs matrix
grown by molecular beam epitaxy for
infrared photodetectors

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Abstract

Materials for the generation and detection of long wavelength IR radiation continue to be of considerable interest for many applications such as night vision, defense and security, rescue, life sciences, industrial processing etc. For this purpose photodetection based on InSb is a well known technology in mid wavelength (3-5 µm) range. One of the ongoing projects in IMAGIC centre has been working on the development of technologies for the next generation long wavelength infrared (LWIR) photodetector focal plane arrays (FPAs) based on a ‘dot to bulk’ concept. A promising potential of this type photodetector exists to extend the detection wavelength to LWIR by using InSb QDs in InAs matrix, which also enable the device to operate at higher temperatures. Although, it is a novel and promising concept but still some challenges like optimization of material quality and device dark current etc are to be addressed.

This project work has been focused on the optical and structural characterization of various size InSb QDs embedded in InAs matrix grown on InAs substrate by molecular beam epitaxy (MBE). The InSb QD’s base diameter, height and density have been revealed and evaluated by Atomic force microscopy (AFM) and transmission electron microscopy (TEM). Strong QDs related photoluminescence (PL) signals in IR range have been observed which can be attributed to interband transition between the InSb QDs (holes) and their InAs matrix (electrons). The absorption measurement results show that high absorbance is in the corresponding IR wavelength range which is in agreement with PL measurement results.

The experimental results concluded from this work provide valuable information to optimize the InSb QDs materials for designing and fabricating desired LWIR photodetectors with low dark current and high photoresponsivity.
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Chapter 1

1 Introduction

1.1 Background, IR detectors

The infrared (IR) light is a type of radiations that exists within the electromagnetic spectrum which covers the range of 0.7 μm to about 1000 μm [1] in the electromagnetic spectrum. This part of electromagnetic spectrum is divided into its subparts, given below.

- Near infrared (NIR): 0.7-1 μm
- Short wavelength (SWIR): 1-3 μm
- Medium wavelength (MWIR): 3-5 μm
- Long wavelength infrared (LWIR): 8-14 μm
- Very long wavelength infrared (VLWIR): longer than 14 μm

![Figure 1.1. The electromagnetic spectrum with major spectral regions of interest (especially, infrared) is shown with their limits in terms of wavelength and frequency [1]](image)

The Infrared (IR) radiation which existed outside the visible spectral region was discovered by Sir William Herschel in 1800 [3] when he was conducting an experiment by using a thermometer as a detector to measure the distribution of energies in the solar spectrum. Infrared (IR) photodetectors have numerous important applications in many areas. They can be used both for military and commercial imaging application purposes, such as night vision cameras, satellite imaging, astronomy, medical thermography, chemical spectroscopy [4], air traffic control, medical diagnostics, all weather vision, missile tracking, recognition, chemical monitoring, target tracking [5, 6] etc.
Figure 1.2 shows, history of the infrared detectors. The development of infrared (IR) imaging initiated in 1950’s and the first imagers used the scanned single-element detectors and in a linear array. The second generation infrared (IR) imaging began in 1980’s with photovoltaic Mercury Cadmium Telluride (HgCdTe) array in a parallel scanned system. In the early 1990’s fully two dimensional second generation arrays provided with 256 x 256 formats were used. In the new millennium, the defining and development of the third generation of the infrared detectors has evolved. The main features focused in the third generation of the IR detectors are high performance cooled detectors with the potentials of multicolour imaging, higher operating temperatures and large format focal plane arrays [7]. The challenges at that time to be addressed, were pixel and chip size issue with two and three colour formats, sensitivity constraints and dynamic range, high operating temperatures etc.

The research and development work on infrared photodetectors is a prominent part of IMAGIC centre at Acreo. It includes quantum wells infrared photodetectors (QWIP) focal plane arrays (FPAs), quantum dots infrared photodetectors (QDIP) and type-II superlattice photodetectors. In recent years, IR detector research work at Acreo has been focused on development of technologies for next generation FPAs (focal plane arrays) based on the ‘dot to bulk’ (D2B) concept. The D2B photodetector is composed of InSb quantum dots embedded in an InAs matrix. A key advantage of this device is that it will enable higher operating temperatures.

The quantum dot (QD) based infrared photodetectors have potential of offering higher operating temperature and more isotropic IR absorption, which is caused by the less available paths for the dark current due to the lower dimensionality and carriers’ confinement in all spatial directions. In order to detect the photocurrent, the dark current must be low. The possible sources of dark current in the QD based IR detectors are surface leakage current, Ohmic leakage current, thermal generation of carriers in the 3D quantum dots barrier layers.
thermionic emission from the quantum dots (QDs), impact ionization in the active region and field assisted tunneling emission from QDs [9].

1.2 Project goals and task
This project aims to compare and analyze different ‘dot to bulk’ (D2B) quantum structures with each other. An optimized structure will then be processed into IR detectors, and the photoresponse and dark current of fabricated IR detectors will be characterized.

- Basic concept study on IR detector, type-II and type-III quantum dots, and epitaxy growth technology
- Learn material and device characterization techniques, AFM, TEM, low-temperature and room-temperature absorption and PL measurements, and also photoresponse of IR photodetectors at 77K
- Learn and follow detector fabrication process in clean-room
- Characterization and analysis of the D2B materials and fabricated IR detectors
- Written report

1.3 Thesis outline
This thesis is organized as:
Chapter 1. The basic information about this master thesis work
Chapter 2. Quantum structures for infrared photodetectors
Chapter 3. Different epitaxial growth techniques
Chapter 4. Characterization techniques
Chapter 5. Fabrication processes of the infrared photodetectors
Chapter 6. Experimental results and discussions
Chapter 7. Summary and future work
Chapter 8. References
Chapter 2

2 Quantum structure for infrared photodetectors

2.1 Quantum Wells, Quantum wires and Quantum dots

Quantum well (QW) is a heterostructure of two different types of semiconductor materials grown almost layer by layer on an atomic scale. It consists of a thin layer of semiconducting material A with a smaller bandgap between thick layers of another type of semiconductor material B with a larger bandgap. The QWs fabricated in this way act as a potential barrier in which the electrons and holes are confined to material A in the growth (or z-) direction and can move only in x and y directions. This restriction on the movement of the charge carriers in this plane also affects the energy of these carriers compared to the free charge carriers in a 3D case. This quantization will conclude in allowed energy levels, whose energy positions depend on the width and height of the well. The corresponding allowed energy levels can be calculated by using the Schrödinger equation,

\[-\frac{\hbar^2}{2m^*} \frac{d^2 \phi_n}{dz^2} + V(z)\phi_n = E_n \phi_n \quad (1)\]

Where \( V(z) \) is the structural (quantum well) potential along the z-direction, \( m^* \) is the effective mass of the particle, \( E_n \) and \( \phi_n \) are the energy eigenvalue and eigenfunction respectively. The simplest case as shown in Figure 2.1 is the “infinite QW” where for simplicity, we assume that barrier height is infinite, so the wave function is zero at the walls of the QW.

The solution of the above equation (1) is then,

\[ E_n = -\frac{\hbar^2}{2m^*} \left( \frac{n\pi}{L_z} \right)^2 \quad \text{Where, } n = 1, 2, 3… \]

And \[ \phi_n = A \sin \left( \frac{n\pi z}{L_z} \right) \quad (2) \]

The confinement energies (or the energy levels) are spaced quadratically and the wave functions are the sine waves. The energy here is referred to the energy of the bottom of the well and \( n=1 \) is the first allowed energy level above the bottom of the well [10].

The QWIPs technology has emerged an alternative for the accomplishing of high performance focal plane arrays (FPA) detectors which showed better performance than that of bulk material detectors, such as InSb and HgCdTe. The use of QWIPs have also some very important limitations. Some of them are, (i) the infrared radiations incident normally to the electric field, in parallel direction to the quantum well (QW) cannot be absorbed. (ii) The
noise source of the QWIPs hinders the extension of the operating wavelength into the far infrared region of the spectrum, and (iii) the low operating temperature [11].

The QWs are usually grown by using advanced epitaxial growth techniques like molecular beam epitaxy (MBE), metal organic vapour phase epitaxy (MOVPE) and their variants. In order to address the limitations in QWIPs, significant interest has been taken in the lower dimensions quantum structures, such as quantum wires (QWR) for infrared photodetectors. Quantum wire is a structure in which the charge carriers are confined in the two spatial dimensions and allow free propagation only in the third dimension. A schematic structure of the QWR is shown in Figure. 2.2. This confinement of charge carriers in nanostructures allows the absorption of the infrared radiations incident normally. Moreover, the discrete bound energy states in these nanostructures (1D, 0D) give rise to more carrier capture and relaxation time due to reduced phonon scattering [12].

Quantum dots (QDs) are 0D structures in which the electrons or holes are confined in all directions for the purpose to quantize in all the space degrees of freedom. In QDs, we can say that, there is no possibility for free particle like motion. The energy spectrum of the QDs is discrete because its wave function is confined in all directions. The QDs are surrounded by a potential barrier, which restricts the carriers energy and trapped them inside the dot and hence
their energy levels become discrete ($E_n$, \(n=1,2,3,\ldots\)), which is similar to that of the energy levels in an atom. Therefore, the QDs are sometimes called artificial atoms. Their density of states (DOS) is given by a series delta functions located at the energies of the eigen states, shown in Figure 2.3. The electrons and holes are strongly localized in the QDs [13].

![Figure 2.3](image)

*Figure 2.3. Low dimensional qualitative behavior of density of states (g(E)) for (a) bulk, (b) Quantum well (c) Quantum wire (d) Quantum dot.*

Significant interest has been taken by using the QDs in the infrared photodetectors in the last decade. QDIPs can be considered as the extrapolation of the QWIPs and are expecting to offer high operating temperature and more isotropic infrared radiations absorption. It is also expecting that the dark current is less in QDIPS due to its less dimensionality. Several variations of the QDs concept are used and the most prominent is the “Dot-in-Well” (DWELL) detector. This concept is more flexible for detection wavelength characteristics and for reducing the dark current of the detectors. It is reported that, to increase the operating temperature greater than 77K, the size of the quantum dots is to be reduced in order to reduce the dark current in infrared photodetectors as predicted [13].

### 2.2 Type of quantum structures

When one semiconductor is grown on the top of another semiconductor, we obtain a semiconductor heterostructure and their relative positions of the energy gaps constitute the band offset. This band offset not only depends on the bulk material properties but also on the microscopic properties of the material surfaces. The semiconductor heterostructure provides a novel electronic and/or optical properties to the material. Beside the band offset, band bending also takes place to line up the Fermi levels of these substances combined to form the heterostructure [10]. Figure 2.4 shows the three different types of band gap alignments; type I, type II & type III. The alignment of the band gap introduces potential barriers and traps for
the charge carriers, which hinders the motion of the charge carriers. In type I band alignment; a narrower bandgap is within the wider bandgap material and both electrons and holes are trapped in a narrow bandgap material. In type II band alignment, one type of charge carrier is trapped and the other is free to move. Moreover, in this type of alignment the valence and conduction bands go in the same direction while in type III, the heterojunction have broken bandgap and no overlap. In the last case, the valence band edge of one semiconductor has higher energy than the conduction band edge of the other semiconductor.

**Figure 2.4. Different types of bandgap alignments formed (a) type-I, (b) type-II & (c) type-III bandgap alignment [14]**

### 2.3 Sb-based QDs

Antimonide based QDs such as InSb, GaSb etc represents a promising active means for the optoelectronic devices especially for those operating in the mid infrared (3-5 µm) region for the detection of the explosives, various chemicals, biological agents etc which have noticeable absorption in this wavelength range. It is realized that, in order to get high performance QDs devices, it is essential to have high density quantum dots with a small size and uniform distribution [15]. It is reported that, the formation of large area of InSb, AlSb and GaSb quantum confinement islands with sufficiently high densities has made possible. It has also reported that the size of the islands and their densities depend mainly on the amount of the materials deposited [16].

It is said that the most suitable heterostructure for the obtaining of the photoluminescence at wavelength exceeding 2µm is InSb/InAs and a heterojunction of type-II band alignment is formed [17]. In this system these two constituent materials do not overlap to each other where the holes are localized in the InSb and electrons in InAs. The energy of the transitions between the holes and electrons appear in the spectral range of infrared (IR) radiations. Publication [18] showed a heterostructure of InAs/InGaSb/InAs/AlSb with so called W-shaped band matching in the active region, which provides maximum overlap of the wave functions of the electrons and holes. They proposed nanostructures (type-II) QDs of InSb in and InAs matrix which are self assembled under elastic stress as a result of significant (~7%) lattice mismatch. The main features of these structures are; (i) the localization energy of the carriers become higher related to deeper potential well in heavily strained InSb/InAs QDs (ii)
the probability of the defects formation is low in the active region because of the elastic relaxation of the large part of the mismatch stresses during the InSb QDs formation (iii) larger overlap of the hole and electron wave functions, (iv) the possibility of changing wavelengths (3–5µm) in active region and as result, high PL quantum efficiency at room and lower temperature is achieved.
Chapter 3

3 Epitaxial growth

The performance of the semiconductor devices depend on the crystalline structure, defects of the material, grain boundaries etc. Single crystal solid thin films can be grown on a crystalline substrate through epitaxy in which atoms are deposited from the gaseous phase on the top of the existing layer on the solid substrate. The crystal growth in which the crystallinity and orientation of the grown layer is determined by the substrate, is called epitaxy. The growth process in epitaxy should be well controlled and not too rapid, so that the newly growing films adjust to the atomic arrangement of the substrate atoms, otherwise unwanted surface features, such as mounds may form. Hence, the fabrication process is heavily dependent on the monocrystalline growth of a single element [19]. The main techniques used for the epitaxial growth are molecular beam epitaxy (MBE), migration enhanced epitaxy (MEE) and metal organic vapour phase epitaxy (MOVPE).

3.1 Molecular beam epitaxy

Molecular beam epitaxy (MBE) is a versatile technique and a refined ultrahigh vacuum (UHV) evaporation method used for the preparation of high quality thin films and crystalline structures with monolayer (ML) control for fundamental studies as well as for the device applications. The elemental sources are evaporated in a control manner onto a heated substrate in an ultra high vacuum condition. In this technique, deposition process of thermally generated atomic or molecular beams take place and crystallized on a suitable oriented surface of a substrate. Since it is a slow process, it has extreme dimensional control over impurity incorporation and major compositional variations. Moreover, due to the extreme dimensional control of the MBE, it is possible to fabricate necessary new crystals with the periodicities that are not available in the nature and to make structures the properties of which depend on the confinement of electrons and holes to crystalline regions so small in a manner that their quantum confinement effects become more important [20].

![Image of molecular beam epitaxy growth chamber](image-url)
3.1.1 **Stranski-Krastanov growth mode**

The formation of quantum dots through Stranski-Krastanov mode occurs when lattice mismatched material is grown over a substrate or matrix layer. The first few deposited layers of the QDs material over the buffer layer grow in a flat and layer by layer fashion. Since, the QDs material is lattice mismatched, the thin deposited layer is pseudomorphically strained and the strained builds up with the growing of more layers over it. Beyond certain critical thickness limit, the thin deposited layer spontaneously reorganizes. If the growing layers are still continued, the material results in the growth of three dimensional dot features. This process is depicted in Fig. 3.2.

![Figure 3.2, Fabrication of InSb QDs through Strnski-Krastanov growth mode](image)

3.2 **Migration enhanced epitaxy**

Migration enhanced epitaxial technique has been developed to grow automatically controlled surfaces and interfaces, prevent islands growth and provide a uniform prelayer with only one type of atoms to suppress antiphase domains (APDs) of a compound semiconductors. In typical MBE growth, the group III and V elements fluxes are allowed to deposit on to the substrate at the same time by keeping both the shutters open, while in MEE, the two different types of beam are supplied alternatively by alternating the shutters. For instance, in GaAs growth, the As shutter is first opened to deposit As layer and it is then closed. Ga shutter is opened to supply Ga. This process is repeated until the desired thickness is reached. The shutting off the group- V supply, during the group-III supplying period, the group-III atoms such as Ga, Al can migrate over a much longer distance on the surface due to As free environment. In such circumstances, the atoms have more opportunity to find energy preferable sites such as kinks and steps. This technique is used, when growing at lower temperatures and this results a layer by layer growth mode and smoother interfaces.
3.3 Metal organic vapour phase epitaxy

Metal organic vapour phase epitaxy (MOVPE) is often referred to as metal organic chemical vapour deposition (MOCVD). This technique is used especially for compound semiconductors grown from the surface reaction of organic compounds or metal organics and metal hydrides containing the required chemical elements. This technique is important due to its versatility and increasing interest for the low temperature processes. In the MOVPE, carrier gas plays an important role and it is actually the transport of the group III metal organics and group V source compounds the heating unit of the reactor where it is decomposed to form the required highly pure materials. The growth rate is nearly temperature independent and mainly occurring in the diffusion controlled region which is not that much temperature dependent as in MBE [20], shown in Figure 3.3. The reactor in MOVPE is without ultra high vacuum environment and this technique is suitable for large scale production. The deposition of the layers takes place far away from equilibrium, therefore, the accurate mathematical description of the process is difficult.

The precursors used in MOVPE are organo-metals, such as trimethyl gallium (TMGa), trimethyl indium (TMIn), some pure gases such as phosphine (PH$_3$) and arsine (AsH$_3$) while H$_2$ and N$_2$ are used as carrier gas. The growth of the layers takes place under the group V over pressure and the partial pressure of these group elements is higher as it is necessary for the growth.

3.4 Droplet epitaxy

The droplet epitaxy is the novel technique used for the manufacturing of the self assembled semiconductor nanostructures. This technique allows the growth of nanostructures with good optical quality and low density distribution which can have applications in single photon
devices and quantum applications [21]. This approach have many advantages; for example, the size of the quantum dots (QDs) and its density can be controlled in different ways, the boundaries among the quantum dots and their matrix may be more abrupt and the quantum dots of various shapes (such as spherical) can be synthesised by using droplet epitaxy technique [22].

Droplet epitaxy consists of depositing droplets of nano-dimensions of group-III elements on the substrate following by the supply of group-V elements in the form of vapours. A supersaturated solution is formed which leads to the growth of nano-dimentional crystals of III-V compounds on the substrate. As a result isolated quantum dots can be fabricated without any wetting layer and lattice mismatch. The condition which is mostly necessary here is sufficiently low temperature of the substrate during the initial stage process which provides a melt with high surface tension and thus restricts its spreading over the surface of the substrate [23]. A brief demonstration of the successful growth of GaSb quantum dots on GaAs substrate is given by using droplet epitaxy technique. Ga droplets are first formed and covered with Sb granular crystal which is formed by supplying Sb4 flux and the granular layers are removed by subsequent annealing shown in Figure 3.3., and the temperature range is usually kept in between 200-300°C [22].

![Fabrication process of GaSb QDs through droplet epitaxy technique. (a) formation of Ga droplets, (b) irradiation of Sb flux and (c) annealing.](image)

3.5 Substrate, InAs, GaSb, InSb, GaAs

Substrate in semiconductor industry is a solid substance on which a layer of another substance is usually grown and to which the second substance adheres. It is actually a thin slice of
material Si, Ge, InAs, InSb, GaAs etc and serves as foundation on which electronic devices such as diodes, transistors, integrated circuits etc are deposited.

### 3.5.1 InAs substrate

InAs is one of the commonly used substrates for infrared devi. It has lattice constant 6.0584 Å and direct band gap of 0.36 eV. When other III-V semiconductors, such as GaAs, InP, GaSb and InSb grow on the InAs substrate to form quantum well, quantum wire or quantum dots, their band diagrams and quantized energy levels are different owing to different lattice mismatch and strain as shown in Figure 3.3 shows [24].

![Figure 3.3](image)

*Figure 3.3. The two long lines indicate the conduction and valence band energies for the unstrained substrate materials and the lines of medium length indicate the unstrained valence and conduction energies of the of different well materials. The short colour lines are valence and conduction energies for the QDs, QWRs & QWs of the indicated composition.*

On the InAs substrate, the GaAs forms type-II heterostructure in which holes get confined. On this substrate GaSb and InSb are expected to form type-III material with broken band gaps, where the valence band edge of the GaSb and InSb are above the conduction band minimum of the InAs. This has been reported in [24] which has many promising consequences due to charge transfer in electronic structures.

### 3.5.2 GaSb and InSb substrate

GaSb has a lattice constant 6.0594 Å and a direct band gap of 0.72 eV. GaSb is commonly used as a substrate material and its lattice constant is very similar to that of InAs. The Figure 3.4 shows the energies of materials which are strained to the GaSb substrate. It is reported in [24] that the band alignment of quantum structures formed on GaSb substrate as shown in Figure 3.4 is very different that formed on InAs substrates.

The lattice constant of InSb is 6.4788 Å and band gap is 0.18 eV. Very little work has been done so far for growing quantum structures on InSb substrate. This substrate has one very interesting feature that all materials strained to InSb have negative gaps, and for wires and
wells this inversion between the conduction and valence bands edges give a semi metallic structure but for dots discrete confined states will still be there.

Figure 3.4, Band edge diagram of the strained dots, wires and wells on GaSb substrate. (details in Figure 3.3)

3.5.3 GaAs substrate

GaAs is one of the most commonly used substrates. Its lattice constant is 5.6535 Å and band gap is 1.43 eV. InSb structures on the GaAs substrate resemble to that of GaSb on GaAs and they form type-II material in which holes get confined for wells, wires and dots as shown in Figure 3.5 [24]. It is also found that the band edges of InP structures are nearly aligned to the GaAs substrate with some little differences in InP wells, wires and dots. But those materials which have greater mismatch to GaAs than InP, the wires and dots have same profiles of band edge except for the wells which have comparatively small gaps and the reason for this is that wells can get relax easily in the direction of growth and result in a lower strain.

Figure 3.5, Band edge diagram of the strained dots, wires and wells on GaAs substrate (details in Figure 3.3).
Chapter 4

4 Characterization techniques

4.1 Atomic force microscopy

Atomic Force Microscopy (AFM) is a type of Scanning Probe microscopy (SPM) and has a very high resolution. It is one of the foremost tools, which is used for the measuring, imaging and manipulating of the material objects at nanometer scale. The atomic force microscopy basically uses the force between the tip and the surface to generate the image. One should that all this laser beam arrangement is to control the tip-sample distance and the topography image is generated from the piezo voltage. In this set up as shown in Figure. 4.1, a laser beam is reflected from the top of the cantilever carries the tip, which is then focused on the two diodes fixed side by side. At the time of scanning the tip in the cantilever moves up and down and at the same time the laser beam also moves towards one detector or the other and generating the signal. The signal can be monitored and will be adjusted by the piezo in vertical position, thus generating an image. Actually the voltage applied to the piezo is monitored and then generating a topography image [25]. There are three basic modes of AFM, contact, non-contact and tapping mode. In contact mode the tip of the cantilever touches the surface of the sample but in non-contact mode the tip end up while contacting the surface.

![Figure 4.1, Illustration of the measurement setup of the Atomic Force microscope (AFM)](image)

The AFM machine which is used in this project is “Digital Instrument Dimension 3000 AFM”. We used tapping mode most of the times which is a key advance in AFM and it prevent the sample surface from being easily damaged. Moreover, tapping mode also overcome other difficulties associated with friction, electrostatic forces, adhesion by alternately placing the tip of the cantilever in contact with the surface and hence produce a high resolution image. The tip is then lifting off from the surface so as to prevent it from dragging and protect the sample surface. In this mode the oscillating tip slightly touch or tap the surface and the cantilever oscillations are then reduced due to the energy loss caused due
to the tip tap the surface. The reduction in oscillation amplitude is utilized to investigate and measure the surface features.

### 4.2 Transmission electron microscopy

Transmission Electron microscopy (TEM) is a technique in which a beam of electron is transmitted through an extremely thin specimen and interacted with as it passes through it. The image is obtained due to the interaction of the electrons passes through the sample and is magnified and focused onto an imaging device. The TEM is used for the characterization of the materials with extremely high resolution and can give information about the crystal structure, morphology, defects, its different phases and composition.

TEM was developed because of the limitations in the image resolution in light microscopes which is imposed by the wavelength of the visible light. When the electron microscope was developed only then was it realized that there are many other reasons for using the electrons and most of them were used up to some extent in the modern transmission electron microscopy. The TEM generates extremely large range of signals; therefore we can obtain variety of images, several different kinds of spectra from the same small area of the thin sample and diffraction patterns.

In TEM the electrons are accelerated at a several hundred KV, which gives a wavelength much smaller than that of light. The high resolution mode of the TEM images of the crystal lattice of a material is actually due to the interference pattern between the transmitted and the diffracted electron beams, which allows one to observe grain boundaries, planar and line defects, interfaces etc.

The TEM application enables two types of imaging modes, known as bright field and dark field imaging mode. The bright field imaging mode means, the detection of the electrons transmitted from the specimen. The dark field imaging mode consists of the detection of those electrons which are either diffracted or scattered from the specimen. Moreover, the bright and dark field signal in TEM is dependent on the working distance and the selected objective aperture.

### 4.3 Photoluminescence

Photoluminescence (PL) is the re-emission of the light after absorption of higher energy photons. Photoluminescence is a powerful optical spectroscopy which is a non-destructive and has been widely employed in the studies of the optical properties of semiconductors and brought drastic advancement in the understanding of the optoelectronic characteristics of the related materials. Photoluminescence has emerged an important tool for studying the optical and electronic properties of solid state materials and most suitably used for optoelectronic applications. Photoluminescence measurements are used to provide direct information about the recombination of electrons and holes and their relaxation processes. An external light source, usually laser is used to excite the sample with the energies of photon larger than the bandgap of the sample material. At the absorption of the photons, the electrons jump from the valence band to the conduction band. Majority of the carriers are relaxed to their lowest energy levels before their recombination and emit radiations of energies corresponding to
their bandgap energies. It can not only reveal the materials, its electronic band structures such as bandgap and band–tail states but also provide perspective to impurities and deep-level defects. In general, PL experiments give useful information in the investigation of the electronic properties of the excited states. In addition, the time-resolved modes are very important for the studies of the excitation dynamics.

The spectrum of the photoluminescence can be obtained with an experimental set up which is shown in the Figure 4.2. The sample is mounted in the 77K temperature cryostat and is illuminated with a laser having photon energy greater than the bandgap of the material (Cobalt laser of 532 nm wavelength in this work). The luminescence is emitted at lower frequencies and is collected on to the detector with the help of lens and then the spectrum is recorded.

![Figure 4.2, Experimental arrangement used for the observation of the photoluminescence (PL) spectra](image)

In conventional PL spectroscopy, the sample is excited with the tunable power laser and the intensity of the luminescence is measured at the peak of the emission as the wavelength of the laser is tuned. The signal strength is proportional to the density of the excited carriers and the shape of the emission spectrum is not dependent on the way the carriers are excited [26]. However we could only have one fixed excitation wavelength due to the laser used in this work.
4.4 Absorption

The semiconductors and insulators have a fundamental absorption edge in the rage of near infrared, visible or ultraviolet spectral regions. This absorption edge is due to the onset of optical transition across the fundamental band gap of the material in which the electrons are excited between the bands of a solid by making optical transitions. This phenomenon is called interband absorption that is the opposite process of the interband luminescence, in which the electrons drop down from the excited state bands to the de-excited states by emitting photons. The optical interband transitions between different discrete energy levels give rise to sharp lines in the absorption and emission spectra. Figure 4.3 shows simplified energy diagram with two separated energy bands and the interband optical transition between the bands is possible, if the selection rules allow them. An incident photon when strike the surface of a material, it excites an electron from the lower band to the upper band (shown in Fig. 4.3) according to the law of conservation of energy;

\[ E_f = E_i + \hbar \omega \]

where \( E_i \) is the energy of the electron in the ground state, \( E_f \) is the energy of the (final) excited state and \( \hbar \omega \) is the energy of the photon. Interband transition will not be possible unless, \( \hbar \omega > E_g \). Since the range of energy states are continuous within the lower and upper bands, therefore, the interband transition will be possible over a continuous range of frequencies. The difference in frequencies range is determined by the upper and lower limits of the bands.

The excitation of the electron creates a hole in the initial state of the lower band and electron in the final state and may be considered as the creation of an electron-hole pair. The interband absorption rate depends on the band structure of the material and here we will consider just a one general distinction that whether the bandgap is direct or indirect. Figure. 4.4 (a) shows the direct band gap, and Figure 4.4 (b) shows the indirect bandgap material. The distinction between the direct and indirect bandgap material in the \( E-K \) diagram concerns mainly with the position of the conduction band minima and valence band maxima in the Brillion zone. In the direct bandgap material, both occur at the centre of the zone where the value of \( k = 0 \) and in the indirect bandgap material the minimum of the conduction band does not occur at \( k = 0 \) but
rather at some other value of $k$. It is obvious from the Figure 4.4 (a) that during the absorption of photon the momentum conservation of the electron wave vector takes place, therefore the photon absorption process is represented by vertical lines on $E$-$K$ diagram. On the other hand Figure 4.4 (b) shows the in the indirect bandgap materials must involve phonon in order to conserve momentum.

![Figure 4.4, Absorption mechanism in the direct and indirect bandgap materials](image)

The distinction of the bandgap nature has very importance for the optical properties. Indirect absorption also plays a very important role in the semiconductor technology.

### 4.5 Dark current

The current that originates from the sources other than the photo excitation caused is called dark current, namely a current flows without incident light. Dark current is relatively small electric current that flows through the device even when no photons are entering the device. In imaging applications a very low dark current is desired. The reason is that the magnitude of current that can be read at one time is limited, and the total amount of current should be dominated by the photocurrent and not the dark current. There are three main mechanisms for causing dark current in the intersubband quantum wells or dots detectors, shown in Figure 4.2.

(A). Thermionic emission - in which the electrons are excited thermally from the ground state to the continuum.

(B). Thermally assisted tunneling – in which the electrons are thermally excited to the excited states which is then tunnel out from those states into the continuum.

(C). Sequential tunneling – here the electrons tunnel directly between dot or well ground states and then to the contact [27].

The (A) and (B) mechanisms are most dominant in the detectors and are mostly affected by the energy level structure of the dot or well, the operating temperature of the devices and the applied bias.
Figure 4.2, Dark current mechanism in QDIPs and QWIPs. (A). Thermionic emission. (B). Thermally assisted tunneling. (C). Sequential tunneling

Dark current is the main source of noise which limits the performance of the QDIPs. However, surface leakage current also might contributed in the dark current, if the surface is not passivated properly. The thermionic emission, i.e., when the electrons are excited thermally to the continuum states above the barrier where they then become a part of the overall current is exponentially dependent on the temperature.

As the structure of the quantum wells and quantum dots are different, therefore, the effect of the dark current is also different for them. In a QW, a continuous energy band is there above each quantized energy level due to the plane wave character of the electrons in the plane of the quantum well. When the temperature increases, the electrons move towards the higher energy levels in the bands and consequently the dark current is rapidly increasing. In the QWIPs the dark current can be reduced by cooling the detector, so that the electrons can just occupy the lowest energy levels in the mechanism.

In QDs, the charge carriers are confined in all the three dimensions, therefore, the energy levels are quantized in all directions. The electrons in the ground state of the QDs need energy from the external source to jump to the higher energy states and get escape from the dot as compare to that of QWs. This is the reason, that the dark current decreases by using QDs in the infrared photodetectors as the electrons trapped in the ground states of the quantum dots.

### 4.6 Photoresponse

It is the ratio of a photodetector’s electrical output to its optical input and is most often expressed in amperes/watt (A/W) or V/W.

\[
R = \frac{S}{P_A} \quad [V/W]
\]

Where "S" stands for signal output of the detector in [V], "P" for energy \( [W/cm^2] \) and "A" is the detector active area [cm²]. In other words, photorespose can also be defined as,
“It is the ratio of the photodetector output electrical signals, either a current output $I_{\text{out}}$ or a voltage $V_{\text{out}}$ to the input optical signals expressed in terms of the incident optical power $P_{\text{in}}$”. The current and voltage responsivity is expressed mathematically as,

$$R_i = \frac{I_{\text{out}}}{P_{\text{in}}} \text{ and } R_v = \frac{V_{\text{out}}}{P_{\text{in}}}$$

The current responsivity $R_i$ is expressed in terms of A/W, while the voltage responsivity $R_v$ is expressed as V/W. The output current and output voltage are often called photocurrent ($I_{\text{ph}}$) and photovoltage ($V_{\text{ph}}$) respectively as they arise in the presence of light.

### 4.6.1 Quantum efficiency

Quantum efficiency and internal gain of the detector are two important parameters of the detectors. Quantum efficiency of infrared photodetector is intended as the average fraction of the input quanta which is used in the production of the output signal and it doesn’t matter if the signal input quantum generates a distinct output signal or not. In quantum structures the absorption quantum efficiency is related to the quantum efficiency and the ratio between the light absorbed and that of incident light is given by,

$$\eta_a = \frac{b-I_b}{I_b} = 1 - e^{-\alpha l}$$

Where, $I_0$ is the initial intensity of the light, $l$ is the thickness of the material and $\alpha$ is the absorption coefficient. The relation between the absorption coefficient and the quantum efficiency is given as,

$$\eta = \gamma \eta_a$$

where, $\gamma$ is the transmission factor.

### 4.6.2 Internal gain

In an intersubband detectors, electrons are injected from the emitter contact in order to maintain the is actually the number of charge carriers moving in external circuit for each absorbed photon. The gain “g” is the ratio of the free carriers life time to that of the transit time between the electrodes.

$$g = \frac{\tau_{\text{free}}}{\tau_{\text{transit}}} = \frac{\text{carrier life time}}{\text{carrier transit time}}$$
If the gain of the device is greater than unity, it means that the photogenerated electron can travel through the device more than once and create a greater signal per photoexcitation. This can increase the responsivity of the QDs based detectors as the responsivity is proportional to the gain.
5  IR detector fabrication

Infrared photodetector (IRPDs) structure and device processing are mainly described in this chapter.

5.1  InSb QD structures

Three types of QDs structures were used and investigated in this thesis work. The structure (a) and (b) grown by molecular beam epitaxy (MBE) are used for the QD’s structural and optical characterization while the structure-(c) grown by MOVPE is used for fabricating IR detectors.

The structure-(a) (Figure. 5.1a) consisted of 20- period stacked InSb QDs layers with InAs capping layers and a surface dot layer. The intrinsic QDs layers were sandwiched in the InAs layers grown on undoped (100) InAs wafers in Riber Compact 21 cluster MBE  (3 MBE + 1 E-beam evaporator + 1 Sputter). A InAs buffer layer was first grown on the substrate. The QDs absorption regions were then grown which were separated by 40 nm spacer layers.

The device structure-(b) (Figure 5.1, b) twenty-period stacked InSb Q-dashes with InAsSb capping layers were grown. The InSb Q-dashes are separated by 50 nm spacer of InAsSb from the surface InSb Q-dashes. The structure is terminated by a InSb surface dash layer.

The device structure-(c) (Figure 5.1c) consisted of 10- period stacked InSb QDs layers with InAs capping layers. The intrinsic QDs layers were sandwiched between the bottom and top of the InAs contact layers grown on undoped (100) InAs wafers. A 300 nm InAs bottom p-contact layer (1x10$^{18}$ cm$^{-3}$) was first grown on the substrate, followed by the growth of 200 nm undoped InAs buffer layer. The QDs absorption regions were then grown which were separated by 40 nm spacer layers. A 100 nm InAs (1x10$^{16}$ cm$^{-3}$) layer is grown over the 10-period stacked InSb QDs with InAs capping layers and finally n-contact InAs (5x10$^{17}$ cm$^{-3}$) with 100 nm is grown (as shown in Figure 5.1c)
5.2 Types of the devices

In this section some important details about the device processing are described briefly.

The designed InSb QD device structure as shown in Figure 5.1 (C) was grown on InAs wafers, which were cleaved into quarters as shown in Figure 5.2 before processing to fabricate the devices with different techniques. Quarter A and B from the device structure-III (Figure 5.1C) were used to fabricate the devices by dry etching to form device’s mesas, while another quarter C was used to process the detectors by wet etching.

The quarter D was left unprocessed and did not have any device which was used to perform absorption, AFM and TEM measurements.

Figure 5.3 shows the microscopic images of a fabricated chip. The size for one chip is approximately 7.5 cm by 5 cm, which is mainly partitioned into three regions A, B & C. In region B, most of the detectors have optical windows could be used both for the optical measurement as well as dark current measurement. In region C, the optical windows of detectors are shielded by metals and are designed for dark current measurement. Keeping in view the geometry of the single pixel detectors, they are in four different shapes as shown in Figure 5.3. These single pixel detectors are in square shape with and without metal pad and round in shape with and without metal pad. Each quarter contains six complete chips.
5.3 Device mesa formation by dry or wet etching

In the case of mesas formation through dry etching, the parameters listed in table 5.1, the following steps were carried out.

- Silicon nitride deposition
- Photolithography (resist mask)
- Formation of SiN mask
- Fabio (ICP dry etching)
- Removal of remaining SiN mask
- Formation of bottom and top metal contacts

While in the case of mesas formation through wet etching, with etchant listed in table 5.2, the following steps were followed.

- Spin photoresist
- Lithography
- Baking and exposure
- Removal of photoresist

Table 5.1

<table>
<thead>
<tr>
<th>Dry etching and its recipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine: ICP plasalab system 100, Oxford Inst. (Fabio)</td>
</tr>
<tr>
<td>Programme: InP Cl₂/H₂/CH₄ etch</td>
</tr>
<tr>
<td>Gas: Cl₂=7 sccm, H₂= 5.5 sccm, CH₄=8 sccm</td>
</tr>
<tr>
<td>Pressure: 4 m Torr</td>
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<tr>
<td>RF generator forward power: 80 W</td>
</tr>
<tr>
<td>ICP forward power: 1000W</td>
</tr>
<tr>
<td>Temperature: 60°C</td>
</tr>
<tr>
<td>Table 5.2</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>Wet etching and its recipe</td>
</tr>
<tr>
<td>H₃PO₄: H₂O₂:H₂O = 1:1:22</td>
</tr>
</tbody>
</table>

5.4 Passivation

Although the devices fabricated in this work without any passivations, some general passivation techniques are still described as follows to complete device fabrication technique in a general sense. There are so many techniques used for the passivation of InAs based devices. Only few are described here very briefly.

5.4.1 SU8 photoresist passivation

It is an epoxy based negative photoresist which is sensitive to UV light up to 350-400 nm. On exposure to UV light, it generates a strong acid which could induce the photoresist to form solid structures with high aspect ratio. The use of SU8 for passivation in single pixel infrared photodetectors, it has been observed that considerable reduction in the dark current takes place as compared to unpassivated one.

5.4.2 Thermal annealing

Clean surface is very important in the growth and fabrication of semiconductor devices and for this purpose thermal annealing is one of the efficient technique to obtain the clean surface. According to reference [28], the thermal annealing could remove the oxides and carbon contamination from the InAs (100) surface. The reduction of the surface states in opto-electronic devices by annealing approach to passivate the surface of opto-electronic devices is a new area.

5.4.3 Dielectric thin film passivation

SiO₂ and SiN are both insulating materials which could be used to coat the exposed surface of the device to terminate the dangling bonds. It is reported in [29, 30], that a thin layer of SiO₂ deposited to type-II InAs/GaSb superlattice infrared photodiodes could significantly reduce the dark current and increase the device resistivity. SiN is demonstrated to be another good candidate for the surface passivation.
5.5 Metal contact

After the formation of mesas by the processing steps described above, top and bottom contact were formed by lithography, metal deposition and lift-off process steps, which can be seen clearly in Figure 5.3.
Chapter 6

6 Experiment results and discussions
This chapter focuses on the description of characterization techniques including atomic force microscopy (AFM), transmission electron microscopy (TEM) and photoluminescence (PL) for evaluating the grown InSb QD materials which will then be processed further to devices.

6.1 AFM images analysis
Atomic force microscopy (AFM) is a method used for the measurement of the topography of a surface by scanning the surface with the sharp tip. The tip is mounted on a cantilever and it interacts with the sample through van der Waals forces and a regulation system is used to keep a constant force between the tip of the cantilever and the surface of the sample. The changes in the topography of the sample and hence the force between them is detected by the deflection of the cantilever. The change in deflection is detected by the laser spot position reflected from the cantilever on a position sensitive photodetector. A feedback signal is sent to a piezoelectric sample stage in order to compensate for the deflection, which moves to compensate for the change in force.

In this work we measured five samples QD samples with different thicknesses grown on InAs substrate by MBE. The descriptions of the samples are given in table 6.1.

Table 6.1

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Growth time (s)</th>
<th>Thickness (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E11167</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>E11181</td>
<td>4.5</td>
<td>3</td>
</tr>
<tr>
<td>E11182</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>E11190</td>
<td>2.7</td>
<td>1.8</td>
</tr>
<tr>
<td>E11191</td>
<td>2.4</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Figure 6.1 to Figure 6.3 are the AFM images of the samples described in table 6.1. Figure 6.1 (a) shows the AFM image of E11167 InSb QDs sample with 2 ML thickness. The density of the surface QDs is the highest which is about $3 \times 10^{10}$ cm$^{-2}$. Figure 6.1 (b) shows the 3D AFM image of the same sample. The base diameter of the InSb surface QDs is about 30-40 nm while its height is 3 nm.

![E11167](image)

(a)

![3D AFM image of E11167 InSb QDs sample with 2 ML thickness](image)

(b)

Figure 6.1, (a) and (b) top view and 3D AFM images of E11167 InSb QDs sample with 2 ML thickness, respectively.
Figure 6.2 (a) shows the AFM image of E11190 InSb QDs sample and Fig. 6.2 (b) is its 3D AFM image. The InSb QDs thickness is 1.8 ML. The surface QDs density is $2 \times 10^{10}$ cm$^{-2}$. The base diameter of the surface QDs is 30-40 nm and its height is about 3 nm. Although the base diameter and height of the QDs are the same to that of E11167 but the density of the QDs is less in comparison with that in the previous InSb sample.

Figure 6.2, (a) and (b) top view and 3D AFM images of E11190 InSb QDs sample with 1.8 ML thickness, respectively.
Figure 6.3, (a) shows the AFM image of E11191 InSb QDs sample with 1.6 ML thickness. The base diameter of these surface QDs is about 40-50 nm and the height is 5 nm. The density of the QDs is $7 \times 10^9$ cm$^{-2}$ which is one order less than the previous two samples. Figure 6.3 (b) shows the cross section of the same sample.

(a)

(b)

Figure 6.3, (a) AFM image of E11191 InSb QDs sample with 1.6 ML thickness. (b) the cross section of the same sample.
Figure 6.4 (a) and (b) depicted the AFM image of the E11181 InSb QDs and E11182 InSb QDs samples, respectively. The InSb QDs thickness is 3 ML for E11181 and 4 ML for E11182. One can easily observe in these two images that the InSb surface QDs have relaxed and formed some structural defects.

**E11181**

![AFM image of E11181 InSb QDs](image1)

**E11182**

![AFM image of E11182 InSb QDs](image2)

Figure 6.4, (a) and (b) the AFM images of the E11181 InSb QDs and E11182 InSb QDs samples, respectively.
Figure 6.5 (a) and (b), shows the AFM image of 1µm x 1µm E11062 sample of InSb Q-dashes (dots) on GaAs substrate. The thickness of the InSb Q-dashes (dots) is 6 ML and have been grown with migration enhanced epitaxy (MEE) at 380°C. The height of the surface Q-dashes (dots) is about 20 nm, width is 100 nm and length is about 260 nm. Figure 6.5 (b) shows the 3D AFM image of the same sample.

Figure 6.5, (a) and (b), are the AFM images of InSb Q-dashes (dots) on GaAs substrate.
6.2 TEM images analysis of InSb QDs samples

The TEM analysis was done on [011] cross-section mode on a JEOL JEM-2100F system which also have the capability of performing scanning- TEM also called STEM. It is also equipped with an EDX detector for chemical analysis. In order to obtain the compositional information of the samples EDX line scan can be used to obtain across the mesa side wall using an electron beam size of < 1 nm. The TEM specimens were prepared using the focused ion beam (FIB) technique. In the focused ion beam a 30 KeV beam of Ga ions is used to sputter away the material to obtain the required patterns on a sub-micrometer scale. An FEI Quanta 3D FEG tool was used to prepare site selective TEM specimen from mesa side walls.

Figure 6.5 depicted a TEM image from a test sample of InSb QDs grown on an InAs substrate to get growth initiation conditions. Therefore, the test InSb QDs were designed and grown on a wide range, that is from 0.7 ML upto 4 ML thickness. The growth time is also mentioned along with the InSb QDs thickness. The growth rate of InSb QDs was 0.68 ML/sec. It can be easily observed from the test sample that the structure and density of the InSb QDs are fine in the range of 1.7 ML to 2.0 ML. Below this limit the density of the QDs are very low and the size of the QDs is also very small. Above 2.0 ML thickness range the QDs seems to be relaxed due to the high magnitude of strain between the InSb and InAs materials.

![Figure 6.5, TEM image of a InSb QD test sample grown on an InAs substrate.](image)
Figure 6.6 (a) and (b) shows a TEM image of E11190. This sample contains InSb QDs of thickness 1.8 ML. We used Fig. 6.6 (a) the magnified part of the TEM image to calculate the size and height of the buried QDs. The base diameter of the buried InSb QDs is 10-15 nm and the height of the QDs is about 3 nm. This image shows that the density and the size of the InSb QDs is uniform and according to the requirement.

(a)

(b)

Figure 6.6, (a) and (b) shows a TEM images of E11190
Figure 6.7, (a) and (b) depicted a TEM image of E11181 of InSb QDs of thickness 3 ML. It is calculated from Figure 6.7 (a), the higher magnification part that the base diameter of the buried InSb QDs is 45 nm and the height is about 15 nm. As discussed in Fig. 6.5, a test sample, the 3 ML thickness of InSb QDs is out of the range having good quality QDs. It can be easily analyzed from this image that the InSb QDs are relaxed due to larger amount of strain between InSb and InAs which constituted some structural defects.

Figure 6.7, (a) and (b) depicted a TEM images of E11181 of InSb QDs of thickness 3 ML.
Figure 6.8, shows the TEM image of E11062, an InSb Q-dashes (dots) sample with 6 ML thickness on GaAs substrate. It is clearly visible that the InSb Q-dashes (dots) are formed with some structural defects. No PL intensity signal was observed during the photoluminescence measurement and it might be due to a lot of dislocations and defects.

Figure 6.8, shows the TEM image of E11062, an InSb Q-dashes (dots) sample
6.3 Absorption measurement

The absorption measurements were performed using Thermo Nicolet Avatar 360 Fourier transform infrared spectroscopy (FTIR) at IMAGIC Lab. Acreo. In order to obtain the absorption spectra a wave guide type sample with 45° facet was used in the measurement. The size of the waveguide type sample was 4.95 mm x 7.5 mm.

Figure 6.8, shows the absorption spectra of five samples of InSb QDs with different thickness. The details of the samples are given in the figure. The absorption measurements were taken at room temperature. Absorption measurement results show high absorbance at 4 µm, which is in agreement with PL measurements results that will be discussed in following section. One should note that the spectra at short wavelength were limited by the experimental set-up.

![Figure 6.8](#)  
*Figure 6.8, shows the absorption spectra of five InSb samples with different thickness.*
6.4 Photoluminescence measurement

The PL measurements were performed using a Broker Vertex 70V Fourier transform infrared (FTIR) spectrometer in step-scan mode at 77K. In the time-resolved step-scan FTIR measurements, the movable mirror of the Michelson interferometer stops at every sampling position of the interferogram. On the sample at each position the reaction is started by a laser flash and the time course is recorded. In addition, to improve the signal to noise ratio, it is necessary to average the time courses at every sampling position [31].

Figure 6.9, depicts the comparison of PL spectra of three InSb QDs structures with different thickness. The 2 ML thickness InSb QDs sample E11167 contains the highest density of the QDs shown in Fig. 6.1 (a) and it exhibits the strongest PL intensity peak. The 1.8 ML thickness InSb QDs sample E11190 contains lower density of QDs comparatively, therefore, it exhibits lower PL intensity. The width of the 2 ML InSb QDs sample is slightly narrower as compare to the 1.8 ML InSb QDs sample. This reveals that the uniformity of the QDs is better in the 2 ML InSb QDs sample.

The sample E11191 consists of InSb QDs with 1.6 ML thickness, which contains the least density of QDs compare to the samples E11167 and E11190. Moreover, this sample has too low QDs density; therefore, we can’t see any InSb QDs PL peak and only InAs substrate peak is visible in range around 3.25 µm.

Figure 6.9 (a), strong QDs related PL signals in MWIR range can be observed, which can be attributed to interband transition between InSb QDs (holes) and their InAs matrix (electrons), shown in Figure 6.9 (b).
Figure 6.10 shows the PL spectra of E11167 with 2 ML thickness InSb QDs measured at different excitation powers. We can see that with increase in excitation power (as seen in inserted smaller Figure 6.10), the PL intensity is also increasing. We used three different excitation powers in this measurement and observed that the integrated PL intensity enhances and peak wavelength blue shifts with increasing the excitation power. One could note that the PL intensity dependence on the excitation power is linear, which means that the prevailing recombination in the QDs is radiative. (In case if the nonradiative recombination is stronger, a quadratic dependence, $I(PL) \sim I(ex)^2$ would be observed).
Figure 6.11, shows PL peaks of E11190 sample of InSb QDs with 1.8 ML thickness. We used five different excitation powers from 71 mW to 188 mW, the intensity of the PL peak is also increased and reached at a saturation point at contain high excitation values (as seen in inserted smaller Figure 6.11). As the integrated PL intensity increases with the increasing of excitation power, the wavelength blue shifts.

We also observed that the InSb QDs samples with 3 MLs or more contain relaxed quantum dots with some structural defects due to a large amount of strain between the InSb and InAs, which results in the quench of their photoluminescence intensity.
Figure 6.12, shows the PL spectra of the InSb QDs sample with 1.6 ML thickness. We can only see the substrate peak at about 3.25 µm. Although the excitation power has been increased from 123 mW to 188 mW but we couldn’t observe any InSb QDs related PL signal. The density of the InSb surface QDs (calculated from the AFM image) is $7 \times 10^9$ cm$^{-2}$, which is about one order less in magnitude in comparison with other two InSb QD samples. Therefore, we don’t observe any PL signal due to its low QD density.

![Figure 6.12, PL spectra of the InSb QDs sample with 1.6 ML thickness.](image)

**Figure 6.12, PL spectra of the InSb QDs sample with 1.6 ML thickness.**

### 6.5 Photoresponse of fabricated IR detectors based on InSb QDs

The fabrication of the InSb QDs IR detectors as described in chapter 5 was a part of this work but unfortunately due to the limited time frame work we couldn’t include that in this report. In fact the InSb QD quantum structures grown by MOVPE were processed into the single pixel IR detectors, however, which is out of scope of this work, and was submitted for publication separately [32]. Therefore the photoresponse results from fabricated devices couldn’t include in this thesis. Encouragingly, the photoresponse obtained from a similar structure as E11167 and E11190 (2.0 ML and 1.8 ML InSb) has a cut-off wavelength at about 4.5 µm, which is in agreement with both the PL and absorption measurement results achieved in this work.
Chapter 7

7 Summary and future work

7.1 Summary

- Optical and structural characterization of various size InSb quantum dots (QDs) in InAs matrix grown on InAs (100) substrate by molecular beam epitaxy (MBE) have been carried out.

- Absorption measurement results show high absorbance at about 4 µm, which is in agreement with the photoluminescence measurement result.

- Strong quantum dots related photoluminescence signals in mid wavelength infrared range (MWIR) were observed, which can be attributed to the inter-band transition between InSb quantum dots (holes) and their InAs matrix (electrons).

- Experimental results reveal promising potential for enabling high temperature operating MWIR and LWIR photodetectors.

7.2 Future work

- Temperature dependence photoluminescence for current InSb QD samples will be characterized.

- The density and the morphology of the buried InSb QDs should be studied by etching away the surface layers.

- Based on obtained results through this work design new D2B structures to fabricate long wavelength IR photodetectors and FPA.

- Device characterization
8 References


9 Acronyms

NIR : Near Infrared Radiation
SWIR : Short Wavelength Infrared Radiation
MWIR : Medium Wavelength Infrared Radiation
LWIR : Long Wavelength Infrared Radiation
FPAs : Focal Plane Arrays
QDs : Quantum Dots
QWs : Quantum Wells
QWRs : Quantum Wires
D2B : Dot to Bulk
MBE : Molecular Beam Epitaxy
MOVPE: Metal Oxide Vapour Phase Epitaxy
MEE : Migration Enhanced Epitaxy
AFM : Atomic Force Microscopy
TEM : Transmission Electron Microscopy
DOS : Density of States
QDIPs : Quantum Dots Infrared Photodetectors
UHV : Ultra High Vacuum
ML : Mono Layer
PL : Photoluminescence
FTIR : Fourier Transform Infrared