Optical spectroscopic studies on semiconductor nanostructures

Synopsis of Thesis submitted to the
Tata Institute of Fundamental Research
for the degree of
Doctor of Philosophy in Physics

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October 2014
(Final Thesis submitted in February 2015)
Synopsis

Semiconductor nanostructures continue to be of interest both for the fascinating array of novel physical phenomenon observed in them, as well as their potential for application in newer and improved electronic devices. This Thesis describes a set of optical spectroscopic studies carried out on semiconductor nanostructure systems in order to understand aspects of their electronic band structure (EBS) and its possible consequences for practical applications. We have studied group III-V as well as group II-VI semiconductors, where the system has nanometer size in 1-Dimension: such as Quantum Wells (QW), in 2-Dimension: such as nanowires (NW) and also in 3-Dimension: such as Quantum Dots (QD). In general, nano-sized semiconductors can exhibit quantum confinement related changes in the EBS and also other phenomena that affect the electronic energy spectrum such as enhanced exciton effects. That apart nano size form can also result in the formation of new crystal structures which are not found in bulk crystals, leading to a significant modification of the EBS. Understanding the EBS is crucial for the use of these materials for practical device applications. Optical spectroscopy is a powerful tool for investigating the EBS of such systems. In our work we have used a variety of spectroscopic techniques to study such nanostructured systems. Often, multiple spectroscopic techniques were employed to obtain complementary information. The work also involved building spectroscopic measurement setups and novel modifications to existing techniques to address specific problems being studied. The systems studied here exhibit complex optical spectra and analysis of these measured spectra often involved first-principles lineshape simulations. The specific problems that were studied as a part of this Thesis are listed below:

(i) Finding the origins of additional spectral features in the photo-reflectance (PR) spectra of GaAs/AlGaAs semiconductor QWs. This also involved building a novel detection scheme whereby the signal to noise ratio in a PR measurement could be improved by more than an order of magnitude.

(ii) Determining EBS parameters of Wurtzite GaAs through polarized spectroscopic studies on single NWs. This also involved building an optical spectroscopy setup capable of measurements with high spatial resolution at low temperatures.

(iii) Establishing the occurrence of a threshold in pump photon energy $E_{th}$ beyond which photoluminescence (PL) throughput from CdSe-ZnS core-shell QDs do not increase although the absorption coefficient continues to increase and understanding the origin of this phenomenon.
Finding an explanation for the observed large absorption coefficient in CdSe-ZnS core-shell QDs at high photon energies high above their effective bandgap.

The results from these studies are organized in five chapters. A brief description of the contents of these chapters is as follows.

**Chapter 1: Theoretical concepts**

This chapter provides an overview of how optical properties of nanostructured semiconductors are related to the EBS. Basic optical processes like absorption, reflection and emission depend on the accessible electronic energy states in a solid. This subject will be treated under the semiclassical approximation for light-matter interactions. The starting point is a description of the absorption process through the light field induced interband transitions between the valance band (VB) and the conduction band (CB) states in the semiconductor material. From the absorption spectrum one can obtain the imaginary part $k$ of the dielectric function and then using Kramers-Kronig relations the real part $n$. From $n$, $k$ one can determine the reflection spectrum while the emission spectrum can be related to the absorption spectrum after taking into account the occupation probabilities.

To understand reflection from multi-layered nanostructures one has to consider interference effects and the transfer matrix approach used to calculate the optical response of such multi-layered structures will be described.

This will be followed by a discussion on the electronic energy spectrum. Group III-V and II-VI compound semiconductors are found mostly in two crystal forms namely Zinc-Blende (ZB) having a cubic unit cell and Wurtzite (WZ) which has a hexagonal unit cell, as shown in Fig. 1. The crystal structure affects both the relative energy positions of the bands as well as the composition of the cell-periodic parts of the wavefunctions associated with an energy band. In these semiconductors, at the Brillouin zone center (crystal momentum $k=0$), the cell periodic part of the conduction band (CB) wavefunction has atomic $s$ orbital like character and those for valence bands (VB) have a mixture of atomic $p_x$, $p_y$ or $p_z$ orbital character as indicated in Fig. 1. A dipole transition between $s$ and $p_x$ states will involve $x$-polarized light and so on, which gives rise to the possibility of linear polarization sensitivity of the transitions depending on the $p_x$, $p_y$, $p_z$ contribution to the VB [1]. In bulk cubic crystals the high symmetry of the lattice is reflected in their EBS, making their optical properties insensitive to the polarization of light. Semiconductors with WZ crystal structure have an unique c-axis defined normal to hexagonal base of it's unit cell. This lower symmetry suggests the possibility of polarization sensitive optical transitions relative to the
FIG. 1. Unit cell of Zinc-Blende (ZB) and Wurtzite (WZ) crystal structure and the nature of the electronic band structure around the center of the Brillouin zone of unstrained group III-V semiconductors having such crystal structures. The atomic orbitals that contribute to formation of the conduction band (CB) and the three valance bands ZB (heavy-hole HH, light-hole LH and spin-orbit split off hole SO) and WZ (A, B and C hole) are indicated.

c-axis. The crystal structure of our nanostructured semiconductors will play an important role in determining their EBS. We will briefly discuss the theoretical formalism used to understand how crystal structure influences the EBS resulting in linear polarization anisotropy in the optical response.

When the size of a semiconductor is reduced to nanometer length scale so that it is comparable to the de-Broglie wavelength of charge carriers having kinetic energy \( \sim k_B T \), effects of quantum confinement become prominent. Such systems include quantum wells, quantum wires and quantum dots. We will describe how quantum confinement affects the EBS which results in an increase of the effective bandgap and modification of the joint density of states. For instance quantum confinement in 3-dimensions give rise to the possibility of discreet atomic spectra like transitions. Nanostructuring also affects carrier-carrier interactions. In particular we would be interested in excitons which can be thought of as “hydrogen atom like” bound state of an electron and hole pair due to Coulomb interaction. Excitonic effects give rise to spectral features below the bandgap in an absorption spectrum and also modify the absorption spectra above the bandgap [2]. The exciton energy spectra can be modified in nanostructured semiconductors, for instance
the exciton binding energy increases significantly in a QW. Changes in the EBS due to quantum confinement and due to modification of exciton properties in semiconductor nanostructures will be described in this chapter.

Chapter 2: Experimental techniques

This chapter describes the experimental setups built and the various spectroscopic techniques used in our studies. These include reflectance, transmittance, conventional photoluminescence (PL) as well as spatially resolved micro-photoluminescence ($\mu$-PL) and micro-Raman, photoluminescence excitation (PLE), and photoreflectance (PR) spectroscopy. For the measurements that required a monochromatic probe beam, reflection grating based Monochromators (MC) were used to disperse white light from Xenon discharge lamps or conventional Tungsten filament lamps. Lasers with photon energy higher than the bandgap of the sample under study were used for excitation in PL and PR measurements. While silicon photo-diodes were used to detect signal of normal intensity, thermo-electrically cooled silicon charge coupled device (CCD) was used to detect low intensity emission signals during PL and PLE measurements. PR measurements requiring phase sensitive detection were carried out using Lock-in amplifiers. A Glan-Taylor, Glan-Thomson or polymer-film polariser was used for polarization selective measurements. Low temperature measurements were accomplished using either a continuous-flow liquid He cryostat (4.5 K) or a closed-cycle He cryostat (10 K). Programs were written in LabVIEW software for data acquisition and instrument control for all the measurement setups. The semiconductor crystals used in our studies were obtained from our collaborators. We briefly described below the main spectroscopy setups used.

PL spectroscopy provides useful information about the EBS around the fundamental bandgap which includes the bandgap energy, defect states as well as nature of electronic wavefunctions associated with the states involved in the transition. $\mu$-PL spectroscopy combines microscopy with PL spectroscopy to achieve high spatial resolution. In a conventional PL measurement a relatively large area is probed which might contain a large number of nanostructures, for example NWs, under study. This results in an ensemble averaging of the spectra which can smear out distinct spectral features associated with individual NWs. $\mu$-PL spectroscopy with its high spatial resolution is therefore useful for studying individual NWs so that the spectrum is free from ensemble averaging effects. The microscope part of the setup was built around a high magnification (100x, NA=0.5) long-working-distance (12 mm) objective. It was coupled to a 0.55 m focal length MC and the signal was detected using a thermo-electrically cooled Si-CCD with 512(rows)

x 1024(columns) pixels. The setup also had a separate camera to see and align the sample precisely. A schematic of the setup is shown in Fig. 2. During measurements, a NW was imaged on the entrance slit of the MC. The gold coated Si substrate on which the NWs were dispersed was carefully oriented so that image of the NW on the MC slit was aligned with its axis parallel to the entrance slit and an entire NW could be imaged on the CCD. To see such images of the NW we set the MC grating to zero-order position which results in a image of the entrance slit forming on the CCD with the grating acting like a simple plane mirror. By using an extra lens in the path of the laser (He-Ne 633 nm), the excitation laser spot on the sample was defocused so that the entire NW was uniformly excited. With this arrangement, the readings from a row of pixels on the CCD corresponds to emission spectrum of a specific section along the length of the NW. Thus reading out and storing signals from each row of pixels separately, enabled recording the emission spectrum of different sections along the length of the NW at one go, with a spatial resolution of \( \approx 1.5 \mu \text{m} \). The polarization of the emitted PL signal was resolved into components parallel (\( \parallel \)) and perpendicular (\( \perp \)) to the NW axis using a Glan-Thomson polariser placed in front of the MC. Using a sharp cut-off long pass interference filter for the laser, we could also perform \( \mu \)-Raman spectroscopy with this setup. We also designed a PLE measurement setup for studying QDs where
we made use of polarized excitation and detection in order to efficiently suppress the scattered pump beam from reaching the detector and thereby eliminated spurious signals. This enabled us to estimate the absorption spectrum of QDs very close to the PLE detection wavelength.

PR spectroscopy is an important tool for probing the EBS, especially at energies above the bandgap, and has been extensively used for studying semiconductor QWs. In PR one perturbs the sample using a pump beam which is typically a laser that gets absorbed and generates electron-hole pairs which in turn modify the built-in electric fields at the surface or interfaces. The consequent dielectric function change results in a relative reflectivity change $\Delta R/R$, which is measured using a second probe beam of variable photon energy [3]. Typically $\Delta R/R \sim 10^{-2} - 10^{-4}$ and peaks around energies where critical points occur in the joint density of states, helping determine their energy. In a PR measurement the weak signal usually rides on a large background signal arising from PL, especially at low temperatures. Drift and fluctuations in the laser intensity causes variations in this background which can be large compared to the PR signal and can overwhelm it if the PR signal is weak. We devised a novel method for nullifying the PL background signal in real time [4]. This involved a detection scheme with two detectors, one measured the PL + PR signal while the other measured just the PL signal. The signal from the two detectors were subtracted in real time after providing electronic compensation to account for the difference in the amplitude and phase response of the two detection channels. In the resultant PR measurement the Signal/Noise ratio improved by more than an order of magnitude. The above techniques and others [5] used in our work will be described in this chapter.

Chapter 3 : Systems with nanostructure along 1-Dimension : GaAs/Al$_x$Ga$_{1-x}$As Quantum Wells

This chapter describes a study on single QWs which have nanometer size in 1-Dimension in terms of the QW width. The EBS changes significantly when carrier motion is constrained along 1-Dimension in a QW, giving rise to confined electron and hole states. In a GaAs/Al$_{0.3}$Ga$_{0.7}$As QW, PR spectral features are expected at the onset of transitions involving confined electron and heavy-hole ($e_mhh_{m'}$) or light-hole ($e_mlh_{m'}$) states, where m, m’ are the confinement indices. In a QW carriers are free to move only in the 2-Dimensional QW plane which also affects the exciton energy spectrum. Due to increased exciton binding energy $E_b$, transitions in a QW typically involve excitons. The increase $E_b$ gives rise to the possibility of observing features not just due to the ground state exciton (n=1, n being the exciton level index) associated with each $e_mhh_{m'}$ or $e_mlh_{m'}$ transition, but also due to higher excitonic states (n=2 and so on) [6]. In addition there have been
suggestions about the possibility of a spectral feature at the exciton continuum edge [7], where the \( n=\infty \) excitonic transition occurs and which coincides in energy with the onset of interband transitions. That apart, there can be transitions that are normally forbidden by symmetry considerations but arise if the QW symmetry is disturbed by perturbations such as built-in electric fields [8]. This study [9] deals with the observation of additional weak PR features at energies slightly higher than the \( e_1hh_1 \) and \( e_1lh_1 \) ground state \((n=1)\) exciton energies in a GaAs/Al\(_{0.35}\)Ga\(_{0.65}\)As QW and finding their origins. Such a spectrum is shown in Fig. 3. Finding the origins of such features has become important in the context of understanding the optical response of the new class of 2-Dimensional semiconductors such as MoS\(_2\).

The GaAs/Al\(_{0.3}\)Ga\(_{0.7}\)As QWs used in the study had well width of 4 nm and were grown using metal-organic vapor-phase epitaxy in the laboratory of Prof. S. K. Shastry. The PR experiments involved a special dual detection technique [4] described previously which enabled measurement of lineshapes of these weak additional features precisely. PLE spectroscopy measurement was also done on the sample, which showed broadened step-like features around these energies. A detailed lineshape analysis, including first principles simulations, was performed to understand the origins of these additional PR spectral features. It included determining the absorption spectrum of inhomogenously broadened exciton transitions in 2-Dimensions and then using Kramers-Kronig transformations to ultimately obtain the real and imaginary parts of the refractive indices. There-
after the quantum-confined Stark effect was invoked to simulate the PR spectrum [10]. The analysis showed that these additional features arise primarily from inhomogeneously broadened first excited state transition of the excitons, rather than from a change in the joint density of states at the exciton continuum edge. The analysis also suggests that such features are more likely in the case of 2-Dimensional excitons as compared to 3-Dimensional excitons in bulk material. Apart from its significance for post-growth characterization of QWs, with the identification of these two additional PR features with excited state exciton transitions with n=2, one can directly estimate the effective Rydberg constants and $E_b$ which was found to be in good agreement with the ones estimated from fitting the PLE spectrum. On the issue of whether these features have any direct connection with the exciton continuum edge, our analysis negates such a possibility. This is because the joint density of states in 2D is continuous at the exciton continuum edge, as it is in 3D, and therefore a feature in the modulated reflectance spectrum related to the exciton continuum edge cannot arise.

**Chapter 4 : Systems with nanostructure along 2-Dimensions : GaAs Nanowires**

This chapter describes a study on single GaAs NWs which have nanometer size in 2-Dimensions in terms of the NW diameter. As such semiconductor NWs are of interest due to their potential for application in high-density electronics and opto-electronics. In nano-size form materials can exhibit polytypes which are not present in the bulk [11]. For example in the case of GaAs, NWs can from with Wurtzite (WZ) crystal structure which is not found in bulk, since bulk GaAs always crystallizes in the Zinc-Blende (ZB) structure. The band structure of WZ GaAs is currently under debate [12–14]. The band alignment of the WZ and ZB sections in a mixed phase GaAs NW is predicted to be of type II [15]. Such a band alignment in mixed phase GaAs NWs offers interesting possibilities for the quantum confinement along the NW axis, for which one normally would have to grow a different material with a lower band gap in the middle of the NW. We investigated the EBS of single GaAs NWs which have both WZ and ZB sections, using polarization resolved $\mu$-PL spectroscopy [16].

The GaAs NWs used in the study were grown using molecular beam epitaxy [13] at the Paul Drude Institute (Berlin). They typically have a diameter of 150 nm with length of 8-10 $\mu$m and are covered by a thin shell of $\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$ to passivate surface states and thereby increase PL output. These NWs were broken off and dispersed on a Au coated Si substrate for spectroscopic measurements. Results of $\mu$-PL spectroscopy study on such a NW is shown in Fig. 4. The
FIG. 4. (a) Diffraction limited image of a GaAs NW under white light illumination seen through the monochromator (MC) input slit. The image was taken with the CCD attached to the MC with its grating set to zero-order position. Spectrally dispersed PL image of the NW for emission polarization (b) $E \perp z$ and (c) $E \parallel z$, where $z$ is along the NW length. The pixels along the vertical direction represent position along the NW length. In plots (b) and (c) pixels along horizontal direction represent emitted photon energy and have been transformed accordingly. The sample temperature and excitation intensity were 4.5 K and 1.8 kW/cm$^2$, respectively. In (b) and (c), Log$_{10}$ of the PL signal count (scale indicated by bar on top) has been plotted to simultaneously show up weakly and strongly emitting regions. The dashed horizontal lines mark highly luminescent sections along the NW length from which the emission is (i) strongly (ii) weakly polarized.

PL is from localized regions along the NW. At low excitation intensity ($5.6$ W/cm$^2$) the PL is strongly polarized perpendicular ($E \perp z$) to the nanowire axis along $z$. At high excitation intensity ($1.8$ kW/cm$^2$) one observes regions along the nanowire length from which the PL continues to be strongly polarized with $E \perp z$ (dashed white line indicating region (i) in Fig. 4), and also regions from which the PL is not strongly polarized (dashed white line indicating region (ii) in Fig. 4). The strongly polarized PL from region (i) at high excitation has higher average photon energy, with the $E \parallel z$ emission occurring at a higher energy than the emission with $E \perp z$. This can be seen in Fig. 5. We considered various factors that can cause such polarization anisotropy in the measured emission from such NWs. The measured transition energies and polarization characteristics were analysed by comparison with EBS calculations. The strongly polarized emission at high energies is identified as arising from predominantly WZ regions of the NW, while the mostly un-polarized emission comes from the predominantly ZB regions. In WZ GaAs the top two valance bands
FIG. 5. µ-PL spectra from region (i) of the GaAs NW shown in Fig. 4, for polarization $E \perp z$ and $E \parallel z$, where $z$ is along the NW length. The sample temperature and excitation intensity were 4.5 K and 1.8 kW/cm$^2$, respectively. The dashed lines represent fits to the dominant features in the spectrum using Gaussian functions. The inset shows a plot of difference in the energy position of $E \parallel z$ and $E \perp z$ PL emission peaks versus the energy of $E \perp z$ peak from type (i) regions of several nanowires.

(VB), which are degenerate in ZB GaAs, are split due to crystal field effects. The $E \perp z$ polarized emission has contribution from transitions involving both these split VB in WZ GaAs while the $E \parallel z$ polarized transition has contribution only from the split VB at higher energy. We calculated how the relative oscillator strength of the transitions in WZ GaAs and their energy splitting would depend on the crystal field energy parameter $\Delta_{cr}$. The analysis suggests that the low temperature bandgap in the WZ dominated regions is at least 1.535 eV and $\Delta_{cr} \approx 20$ meV. These values are much smaller than theoretical predictions. One possible reason for this could be that in the mixed phase NWs the carriers recombine from regions which have lower hexagonality due to twinning. Such regions are expected to have lower bandgap and $\Delta_{cr}$.

Chapter 5 : Systems with nanostructure along 3-Dimensions : CdSe-ZnS core-shell Quantum Dots

In this chapter we describe two studies on semiconductor QDs which have nanometer size in all 3-Dimensions. These studies involved CdSe-ZnS core-shell QD ensembles, with mean core diameters ranging from 2.6 nm to 7.2 nm. These commercially obtained highly luminescent group II-VI semiconductor QDs [17] are used in different kinds of biological assays based on luminescence imaging of tissues [18, 19]. An important advantage of such QDs over molecular dyes for imaging applications is that the QD ensembles have a continuous absorption (Abs) spectrum and
FIG. 6. Room temperature PL, PLE and Abs spectra of CdSe-ZnS core-shell QD ensembles with average core diameters (a) 7.2 nm (b) 5.1 nm (c) 3.0 nm and (d) 2.6 nm. The PL peak and the first Abs peak are scaled to identical heights. (e) Schematic band diagram of a CdSe-ZnS core-shell quantum dot identifying the possible origin of the threshold energy $E_{th}$

therefore a single laser can be used to excite QDs emitting at different wavelengths allowing for easy multi-color imaging [20]. In the first study [21] we tried to understand what is the optimal pump photon energy for exciting these QDs.

We first obtained the Abs spectrum of these QDs through transmission measurements and then the PLE spectrum which is expected to be similar to the Abs spectrum. We found that the larger dots show a threshold phenomenon wherein for excitation photon energy greater than a value $E_{th}$, the PLE and Abs spectra diverge abruptly. Beyond $E_{th}$ the PLE signal tends to decrease while absorption continues to increase. This is shown in Fig. 6(a)-(d). For the PLE measurements we devised a special polarization resolved arrangement to eliminate spurious signals close to the PLE detection wavelength. To understand these results we performed an electronic band structure cal-
culation under the effective-mass envelope-wavefunction approximation. For the calculation we
considered a spherically symmetric core-shell potential with infinite barriers beyond the shell. We
numerically solved the Schrodinger equation and obtained the confinement energies in the CB and
the VB and the associated wavefunctions in terms modified and unmodified spherical Bessel func-
tions of the first and the second kind [22, 23]. In these calculations we took into account the CB
and the three top most VB in wurtzite CdSe at the Brillouin zone center. We next calculated the
Abs spectrum for which we considered the dominant symmetry allowed transitions with appro-
priate level degeneracy and linebroadening. We then sum over the ensemble assuming Gaussian
distribution of the QD core sizes to finally estimate the Abs spectrum. We fine tuned the results by
matching the first peak of the measured Abs spectrum obtained from transmission and PLE mea-
surements. From the calculated energy spectrum of the larger QDs one finds that $E_{th}$ matches with
the minimum photon energy required to create holes with energy equal to the core-shell potential
energy barrier for holes, as shown in Fig. 6(e). The radial probability density distribution for the
holes at these and higher energy states, as obtained from the envelope wavefunctions, indicate that
there is considerable probability of finding them in the shell region. These holes are therefore
more exposed to shell surface defects [24] and are likely to be lost through non-radiative pathways
thereby reducing luminescence. Thus for luminescence imaging with larger CdSe-ZnS core-shell
QDs, the optimum excitation photon energy is one which is just below $E_{th}$ whose origins we
determined.

The second study [25] involved understanding an aspect of the Abs spectra of these CdSe-ZnS
core-shell QDs. The measured Abs coefficient of the ensembles of these QDs at energies ≃ 1 eV
above the effective bandgap increases monotonically as in bulk solids [26, 27]. This is understood
in terms of ensemble averaging of inhomogeneously broadened interband transitions in individual
QDs. As explained earlier, one can calculate the Abs spectrum of such ensembles by starting with
solving the quantum mechanical core-shell potential problem. The magnitude of such a calculated
Abs coefficient however turns out to be relatively smaller than the measured value at high photon
energies. To verify the correctness of our measured Abs spectra we adopted two independent
methods : Transmission and PLE. Both measurements give similar Abs spectra in the smaller
QDs where carrier loss related PLE signal reduction is not significant. To further investigate this
discrepancy between measured and calculated Abs at high energies we again studied the elec-
tron and hole envelope wavefunctions in the core-shell potential. We find that the wavefunctions
acquire considerable asymmetry due to the core-shell structure. This in turn leads to normally
FIG. 7. Measured and simulated room temperature Abs spectra of CdSe-ZnS core-shell QD ensembles with four different average core diameters $d_o$ (a) 7.2 nm, (b) 5.1 nm, (c) 3.0 nm and (d) 2.6 nm. The simulated total Abs considered both strongly allowed (SA) and normally disallowed (ND) transitions in the QDs. The contribution of only the SA transitions, which does not match the measured spectrum at high energies, is also shown separately by dashed lines. The vertical lines indicate the position and strength of the strongly allowed transitions involving confined electron levels and confined hole level corresponding to the three A, B and C valance bands in CdSe, for core diameter equal to $d_o$. In the inset Figure, the circles show how a quantity $\beta E_o$ which gives a measure of the average oscillator strength of the normally disallowed transitions, varies with $d_o$. The line in the inset Figure is an empirical fit.

symmetry-disallowed transitions acquiring a weak oscillator strength, with their numbers and strength increasing with energy. We developed a phenomenological model that invokes normally disallowed transitions in general and show that it reproduces the measured absorption spectrum at higher energies quite well. This is indicated in the results shown in Fig. 7. The oscillator strength
scaling factor for such transitions, defined in terms of a quantity $\beta E_o$, was found to increase with decrease in QD size, consistent with expectations.

**Summary :**

This Thesis gives an account of optical spectroscopic studies on semiconductors with nanometer size along one (quantum well QW), two (nanowire NW) and three dimensions (quantum dot QD), aimed at understanding aspects of their electronic band structure and related physical properties. The work included designing and building setups for spectroscopy measurements [4, 5], detailed spectral lineshape analysis including simulations and comparisons with electronic band structure calculation to understand the experimental results. The study on GaAs/Al$_{0.35}$Ga$_{0.65}$As QWs reported the observation of distinct additional spectral features in their photoreflectance spectrum and determined their origins as being due to transitions associated with the first excited state of heavy and light hole excitons in the QW. The spectral lineshape studies indicated that such features are more likely to show up in two dimensional systems. Apart from its importance for post growth characterization of QW based device structures, the identification of such features also helps in direct estimation of the exciton binding energy [9]. The next study was on single GaAs NWs with mixed wurtzite and zinc-blende phases which used polarization resolved low temperature micro-photoluminescence spectroscopy. The spatially resolved luminescence spectra of these NWs reveal localized emission from regions along their axis, with some showing strong polarization anisotropy. The polarized emission occur at photon energies higher than the bandgap of GaAs having zinc-blende crystal structure. Analysis of the emission energy and polarization properties led us to identify these regions with GaAs having predominantly wurtzite crystal structure. Further comparison with electronic band structure calculations helped determine the bandgap and crystal field energy parameter, which were lower than theoretically expected values for wurtzite GaAs [16]. A possible reason could be that carriers in such mixed phase NWs accumulate in regions having lower hexagonality than wurtzite structure due to twinning. The final two studies were on CdSe-ZnS core-shell QD ensembles. The first study reported the observation of a threshold pump photon energy $E_{th}$ beyond which the luminescence intensity does not follow the increase in the absorption coefficient. This happens in the larger QDs and $E_{th}$ was shown to be the minimum energy that is required to create a hole with enough energy to cross the core-shell hole potential barrier. The loss of such holes to shell surface defects results in reduced luminescence efficiency [21]. The second study on the CdSe-ZnS core-shell QDs tried to understand the origin of the
bulk-like absorption spectra and relatively high absorption coefficient in such QDs, at high photon energies. The core-shell confinement potential form and distortions, give rise to the possibility of having normally disallowed interband transitions. A phenomenological model that took into account such transitions in addition to the symmetry allowed ones, was able to reproduce the measured absorption spectra at higher energies [25]. In conclusion we have successfully used optical spectroscopy to study some specific problems related to semiconductor nanostructures that are of relevance to both basic physics as well as practical application of such materials.


Publications in Journals

1. “Improved sensitivity of photoreflectance measurements with a combination of dual detection and electronic compensation”, Amlan Mukherjee, Sandip Ghosh and Vasam Sugunakar


3. “Origin of additional spectral features in modulated reflectance spectra of 2-dimensional semiconductor systems”, Amlan Mukherjee and Sandip Ghosh

4. “Angle of incidence averaging in reflectance measurements with optical microscopes for studying layered two-dimensional materials”, Nihit Saigal, Amlan Mukherjee, Vasam Sugunakar and Sandip Ghosh

5. “Absorption spectra of CdSe-ZnS core-shell quantum dots at high photon energies: experiment and modelling”, Amlan Mukherjee and Sandip Ghosh
   Physica E: Low-dim. Syst. & Nanostruc. 64, 234 (2014)

6. “Spatially resolved study of polarized micro-photoluminescence spectroscopy on single GaAs nanowires with mixed zincblende and wurtzite phases”, Amlan Mukherjee, Sandip Ghosh, Steffen Breuer, Lutz Geelhaar, Uwe Jahn and Holger T. Grahn

Conference/Meetings

(i) “Emission and excitation studies on CdSe-ZnS core-shell quantum dots used as luminescent tags for imaging biological samples” (Poster), Amlan Mukherjee and Sandip Ghosh, 28th Photonics Conference, Indian Institute of Technology, Guwahati, India, December 2010

(ii) “Photoreflectance lineshape due to Exciton continuum edge in Quantum Wells” (Poster), Amlan Mukherjee and Sandip Ghosh, 29th Internat. Conf. on Superlattices, Nanostructures and Nanodevices, ICSNN-12, Dresden, Germany, July 2012
(iii) “Origin of bulk like absorption in quantum dots” (Poster), Amlan Mukherjee and Sandip Ghosh, DCMP&MS Annual Meeting, Tata Institute of Fundamental Research, Mumbai, India, April 2012

(iv) “Optical spectroscopic studies on semiconductor nanostructures” (Oral), Amlan Mukherjee, 32nd Young Physicists Colloquium, Saha Institute of Nuclear Physics, Kolkata, India, August 2014