Thesis Synopsis

Title : Study of electronic band structure of group III-V semiconductors using optical spectroscopy with linearly and circularly polarized light

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This Thesis describes optical and magneto-optical spectroscopy studies aimed at understanding aspects of the electronic band structure (EBS) of some group III-V semiconductor heterostructure systems. Apart from addressing basic science issues, information regarding the EBS is crucial for the design of semiconductor devices. Optical spectroscopy is an important tool for studying electronic structure. Spectroscopic measurements using polarized light as the probe beam or analyzing the polarization characteristics of emission spectra, gives additional insight about the nature of the electronic bands associated with an optical transition. Our studies have involved both linearly and circularly polarized light. One focus of our studies has been on how the EBS is modified by strain and quantum confinement, and this work has involved analysing response to linearly polarized light. Understanding spin splitting of electronic bands in the presence of a magnetic field is important for the emerging field of spintronics which involves manipulating the spin degree of freedom of electrons and holes for device applications. For such studies we have performed magneto-optical Kerr effect (MOKE) spectroscopy measurements using circularly polarized light. The specific problems we worked on that form a part of this Thesis are listed below.

(i) Effect of anisotropic in-plane strain on the EBS of GaAs/Al$_x$Ga$_{1-x}$As quantum wells and its influence on absorption properties

(ii) Quantum confinement induced modification of the EBS of strained non-polar GaN and Al$_x$Ga$_{1-x}$N quantum wells and its consequences for emission properties

(iii) Experimental test of the prediction of giant light-hole Landé g-factors in GaAs/Al$_x$Ga$_{1-x}$As quantum wells

(iv) Measurement of the exciton Landé g-factors in strained GaN films of non-polar and polar orientations

(v) Building of a novel MOKE spectroscopy measurement setup for the last two of the above studies.

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

Chapter 1: *Introduction*

In this chapter we begin by describing the basic optical absorption, emission and reflection processes in solids. These govern the response of a material to incident light and provide important information about the electronic band structure of the solid. In III-V semiconductors, at the Brillouin zone center, the cell periodic part of the conduction band (CB) wave function has atomic s orbital like character and those for valence bands (VB) have p_x, p_y or p_z character. Transitions between s and p_x states involve *x* polarized light and so on, and this is the basic origin of the linear polarization sensitivity. Therefore optical spectroscopy studies using linearly polarized light provide information regarding the nature of the bands involved in the optical transitions. Such information is important from a practical point of view as it is essential for designing opto-electronic devices like lasers, light emitting diode and also photo-detectors. The above mentioned states in group III-V semiconductors are normally spin degenerate. Probing the materials using circularly polarized light yields additional information if there is spin splitting of these states. Such a situation is relevant for applications in the emerging field of spintronics. We will briefly discuss those conditions under which linear and circular polarization anisotropy arises and which are relevant to the work presented in this Thesis. Phenomenon such as exciton formation which is relevant to all our optical studies, will also be touched upon.

Semiconductors with cubic crystal structure possess high symmetry, consequently their response is generally insensitive to the state of polarization of light. However, in heterostructures such as quantum wells (QW), made by growing a thin layer of low bandgap semiconductor between two thicker layers of a high bandgap semiconductor, the translation symmetry is broken along the direction of growth. In such cases one can detect a difference in the optical response for polarization parallel ($||$) or perpendicular ($\perp$) to the growth direction. Still one does not expect any polarization anisotropy in the plane of the QW, perpendicular to growth direction. This can however change in the presence of anisotropic strain in this plane which can cause a strong mixing of the bands. This modifies the polarization selection rules leading to in-plane polarization anisotropy in such materials. On the other hand in the important class of group III-Nitride semiconductors which have wurtzite crystal structure (see Fig. 6), the lower symmetry already suggests the possibility of optical polarization anisotropy. In wurtzite films grown with *A*-plane ($11\bar{2}0$) and *M*-plane ($1\bar{1}00$) orientations, referred to as non-polar films due to their electrical characteristics, the unique ***c***-axis lies in the film plane and one observes difference in the optical response of such films between light polarization $||\boldsymbol{c}$ and $\perp\boldsymbol{c}$. Such non-polar films often experience large anisotropic in-plane strain which, along with effects of quantum confinement can further modify their response to polarized light. Our studies were on epitaxially grown group III-V semiconductors with both cubic and wurtzite crystal structures. We will briefly discuss the theoretical formalism used to understand how crystal structure, strain and quantum confinement influences the electronic band structure resulting in linear polarization anisotropy in the optical response.

When such semiconductors are subjected to magnetic fields, Zeeman splitting occurs and the spin degeneracy of the CB and VBs is lifted. The Landé g-factor is the measure of the spin splitting. The transitions between these Zeeman split bands are governed by selection rules involving conservation of angular momentum. Hence the semiconductor's optical response becomes sensitive to whether the light is right or left circularly polarized. The g-factor of the carriers (electrons and holes) in the periodic potential of a crystal lattice can be quite different from the g-factor for free electrons (~ 2). Its value is influenced by other CB and VB states lying close by in energy. Again strain or quantum confinement, both of which modify the electronic band structure can further modify the g-factor value. We will briefly discuss how spectroscopic studies using circularly polarized light help in the measurement of the Landé g-factor.

Chapter 2: *Experimental techniques*

This chapter describes the details of the various spectroscopic techniques used and experimental setups built for our studies. These include reflectance, transmittance, photoluminescence (PL), photoconductivity (PC), photoreflectance (PR), ellipsometry and magneto-optical Kerr effect (MOKE) spectroscopy. The monochromatic probe beam required in these measurements was obtained by dispersing light from a Xenon or a Tungsten lamp using grating based monochromators and detected using Si-photodiode or photomultiplier tube detectors. For linearly polarizing the light Glan-Taylor or Glan-Thomson polarizers were used. Lock-in amplifiers were used for phase sensitive signal detection. For PL and PR measurements a laser with photon energy larger than the bandgap of the sample under study was used as the pump beam. For performing ellipsometry and MOKE spectroscopy measurements with circularly polarized light, a polarization modulation technique was adopted through the use of a photoelastic modulator (PEM). The experiments were performed in the temperature range from 4.5 K to 300 K using either a continuous-flow He cryostat or a closed-cycle He cryostat both having optical access. Magneto-optical measurements were performed under magnetic fields up to 1.8 T generated using a conventional H-frame electromagnet, for higher fields up to 7.0 T we used an open bore superconductor coil. All measurements were controlled using computers and the control/data acquisition programs were written using the LabVIEW software. Amongst the setups we built there were some novel ones which are briefly described below.

An important requirement in magneto-optical measurements is to be able transport an elliptically (in general) polarized light from the generation stage to the sample and then from the sample to the detection stage without altering its polarization state. If light is transported to the sample (which may be in a cryostat)

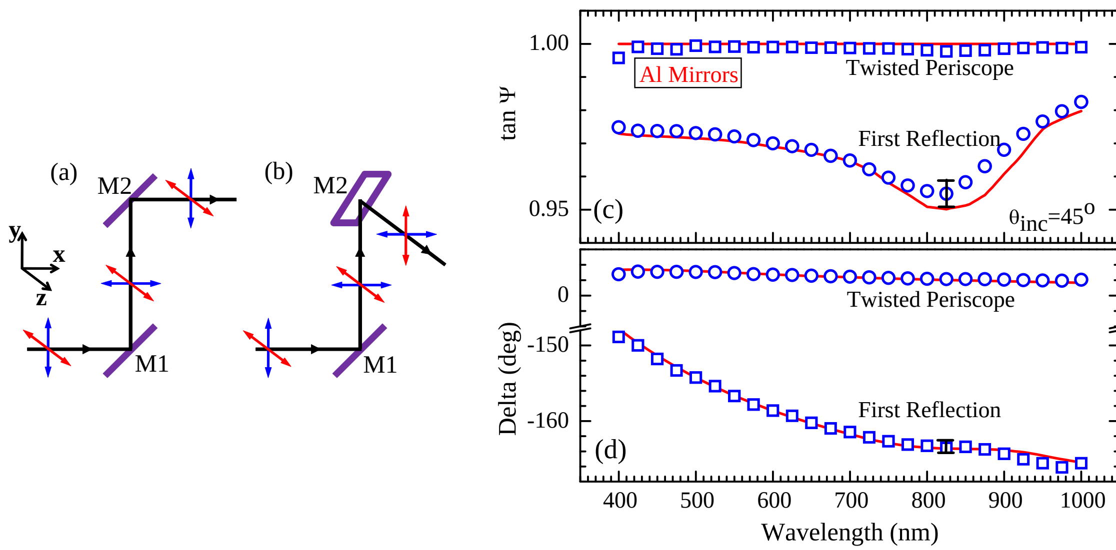

FIG. 1. (a) Light trajectory in a normal periscope arrangement and (b) in the 90° twisted periscope arrangement. Blue and red arrows indicate the two independent linear polarizations that need to be considered. M1 and M2 are identical metal or dielectric mirrors. The effective ellipsometric parameters (c) $\tan\psi$ and (d) Δ measured after reflection from the first Al mirror (squares) and the second Al mirror (circles) in a twisted periscope arrangement. The lines represent theoretically expected values.

by using an optical fiber, the state of polarization after passing through the fiber will change. We showed that this problem can be overcome by generating the required state of polarization in-situ just above the sample inside the cryostat.[1] If mirrors are used to transport light then the state of polarization will again change upon reflection. We came up with an idea for a dual-mirror 90° twisted periscope (TP) arrangement for transporting polarized light in air, wherein a general polarization state of the light is preserved. We demonstrated this in the wavelength range 400 nm to 1000 nm.[3] Figure 1(a) and (b) show the trajectory of the two orthogonal components of polarized light after it undergoes dual reflections in a normal periscope (NP) and a TP arrangement. Figure 1(c) and (d) represent the measured effective ellipsometric parameters $\tan\Psi$ and Δ that the polarized light experiences after it suffers the first and second reflections from an Al mirror in a TP arrangement. A value of $\tan\Psi \sim 1$ and $\Delta \sim 0$ after light undergoes second reflection depicts that the polarization state of light is preserved. This effect was also demonstrated using dielectric (polished Si) mirrors. The same does not hold true for NP arrangement where final state of polarization can be very different from that of the incident light.

We also built a novel setup for performing MOKE spectroscopy in polar geometry using a conventional H-frame type electromagnet.[4] The arrangement is shown in Fig. 2. It uses an additional mirror which eliminates the need for a hole in one of the magnet pole pieces in a conventional MOKE setups. It also al-

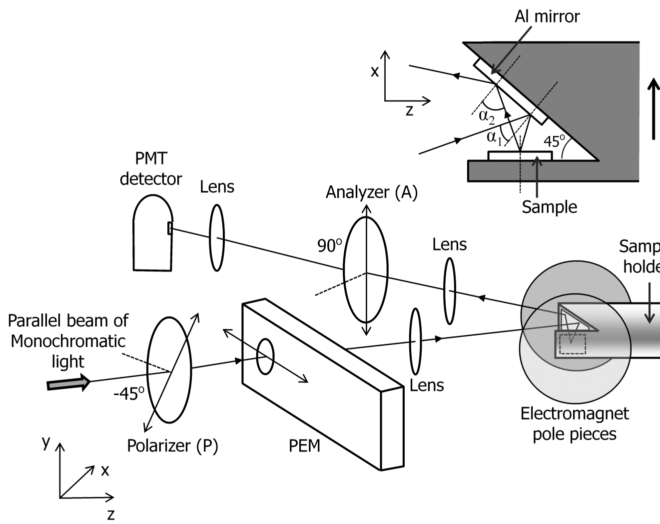

FIG. 2. Schematic of the polar MOKE arrangement which uses a conventional electromagnet and a cylindrical sample holder finger with a 45° cut. The sample is mounted on the straight face and an Al mirror is mounted on the inclined face. The top right inset has a magnified $x - z$ plane cross-section of the sample holder finger showing the light trajectory.

lows for easy switching between polar MOKE geometry and longitudinal or transverse MOKE geometries. The mirror however can modify the state of polarization. We performed a theoretical analysis of the PEM based measurement scheme using the Jones matrix approach and showed how the mirror caused a strong mixing of signals corresponding to Kerr rotation and ellipticity. The influence of the mirror was experimentally demonstrated and a procedure to correct for its effect by using appropriate ellipsometry parameters of the mirror, was also described. As a test, Kerr rotation and ellipticity spectra of Nickel films measured using this arrangement are shown in Fig. 3. The dashed spectra do not take into account the influence of the extra mirror. The dotted spectra were obtained after applying a correction for the extra mirror. A comparison of the dotted spectra with those reported in literature (solid lines in the figure) shows that this novel MOKE arrangement works satisfactorily. Built-in strain in our thin film samples played an important role in many of our studies. The strain was estimated independently using high resolution X-ray diffraction (HRXRD) measurements. The samples used in our studies were grown by molecular beam epitaxy (MBE) or metal organic vapor phase epitaxy (MOVPE). Growth of these samples does not form a part of this Thesis, these samples were obtained from our collaborators.

Chapter 3: *Effect of anisotropic in-plane strain on cubic GaAs quantum wells*

This chapter describes a study of the effect of anisotropic in-plane strain on the electronic band structure of QWs of group III-V semiconductors with cubic symmetry. This study has practical implications

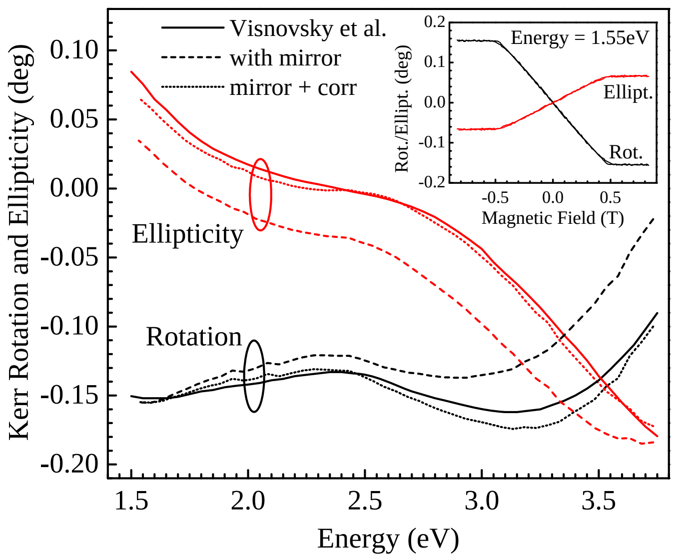

FIG. 3. Polar Kerr rotation and ellipticity spectra of a 500 nm thick Ni film under 1 T magnetic field. The dashed lines were obtained using an analysis that did not account for the extra Al mirror while the dotted lines take into account the influence of the Al mirror. For comparison, the continuous lines show the results obtained by Visnovsky *et al.*, J. Magn. Magn. Mater. **127**, 135 (1993). The inset shows the Kerr hysteresis loops obtained at a photon energy of 1.55 eV ($\lambda = 800$ nm).

in the context of linear polarization sensitive photo-detection which finds application in optical logic circuits, including optical computation where the state of polarization defines the high/low bit value. A high-density cost-effective solution requires a semiconductor structure whose absorption coefficient can be high or low depending on the polarization of the incident light. Detectors working at optical communication wavelengths are made from conventional cubic semiconductors where the high crystal symmetry precludes polarization sensitivity of absorption. A way to overcome this is by directly etching gratings on device structures for polarization sensitive light coupling and thereby achieve polarization sensitive detection, but such devices work at very long wavelengths ($\simeq 9$ μm). One can get large polarization anisotropy in the absorption coefficient of cubic III-V semiconductor based QWs but only for light propagating along the plane of the well in a waveguide geometry, which offers a relatively small active area for light detection. As such in-plane polarization anisotropy of absorption is desirable and we studied a device structure where this was achieved.

The devices were based on MBE grown GaAs/$Al_{0.3}Ga_{0.7}As$ QWs with well-width $L_w \sim 11$ nm (see inset of Fig. 4) and were formed by etching an elongated mesa having long length (3 mm $\|y$) and narrow width (10 μm or 20 μm $\|x$) in the (001) plane. Polarization resolved lateral photoconductivity spectroscopy measurements were performed on the devices with light incident along $z \parallel$ [001] direction. Figure 4 shows

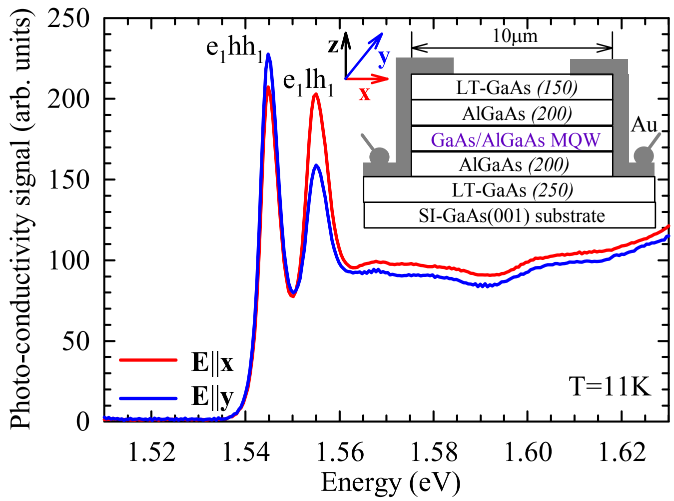

FIG. 4. Lateral photo-conductivity signal in the QW based structure for probe beam incident along z and polarized with $\boldsymbol{E}\|\boldsymbol{x}$ and $\boldsymbol{E}\|\boldsymbol{y}$. The inset shows a schematic of the x-z cross section of the device, with the main layers identified along with their thickness in nm (in italics).

the photoconductivity spectra of a 10 μm wide device for two orthogonal in-plane polarizations of the probe beam with electric field $\boldsymbol{E}\|\boldsymbol{x}$ and $\boldsymbol{E}\|\boldsymbol{y}$. We notice that the ground state light-hole exciton (e_1lh_1) transition is stronger by 19% for linear polarization with $\boldsymbol{E}\|\boldsymbol{x}$, compared to $\boldsymbol{E}\|\boldsymbol{y}$ whereas the heavy-hole exciton (e_1hh_1) transition shows a weaker polarization anisotropy of opposite sign, being stronger for $\boldsymbol{E}\|\boldsymbol{y}$ by 5%. In the 20 μm wide devices (not shown here), the maximum measured anisotropy was lower, being $\simeq 10$ % for the e_1lh_1 transition.

We explained the origin of this polarization anisotropy in the photo-conductivity signal as arising from a modification of the electronic band structure (EBS) due to anisotropic in-plane strain in the QWs. The strain arose since the QW structure was pseudomorphically grown on a low temperature grown GaAs layer (LT-GaAs) whose lattice constant is known to be $\simeq 0.12$ % larger than that of GaAs. In addition the highly skewed mesa geometry and the gold contacts were responsible for the in-plane strain anisotropy. To study the effect of such strain on the EBS we performed calculations based on the $\mathbf{k}\cdot\mathbf{p}$ perturbation theory which included strain. A value of $\pi/13.3$ nm^{-1} was considered for crystal momentum component k_z ($k_x = 0$, $k_y = 0$) of both electrons and holes, in order to include the effects of quantum confinement and match with the experimentally obtained transition energies. From the calculations f_x, f_y and f_z, which are the components of the relative oscillator strength for x, y and z polarization respectively, for the e_1hh_1 and e_1lh_1 exciton transitions were determined. These are plotted in Fig. 5 as a function of in-plane strain components ϵ_{xx} and ϵ_{yy}. The observed polarization anisotropy of the oscillator strengths in the x-y plane arises essentially from valence band mixing induced by the combined effect of quantum confinement and

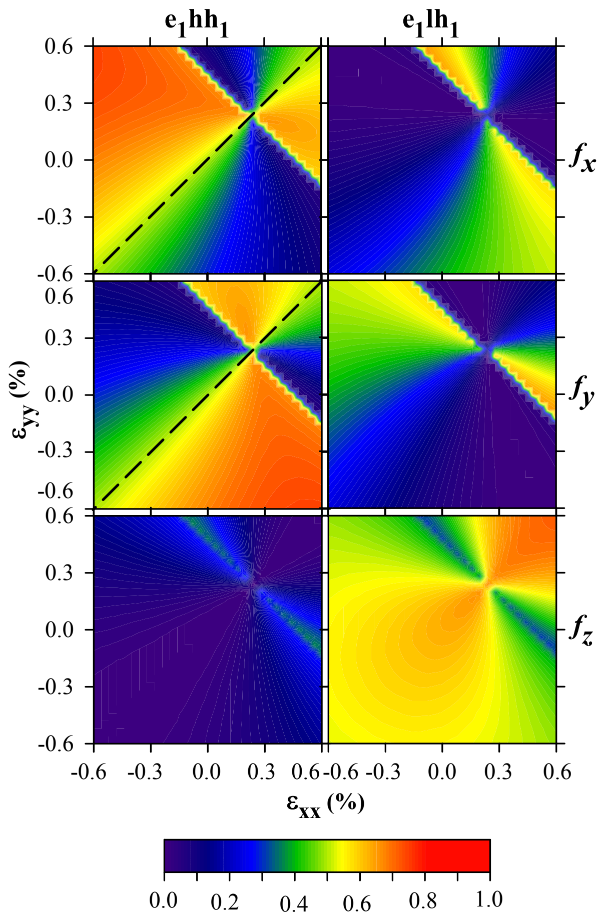

FIG. 5. Variation of the relative oscillator strength components (f_x, f_y and f_z) of e_1hh_1 and e_1lh_1 transitions in a [001] oriented GaAs/$Al_{0.3}Ga_{0.7}$As QW (L_w=11 nm) as a function of strain ϵ_{xx} and ϵ_{yy} in the plane of the QW. The dashed lines identify the isotropic in-plane strain case when $\epsilon_{xx} = \epsilon_{yy}$.

anisotropic in-plane strain. We explained our measured polarization anisotropy in the photo-conductivity on the basis of these theoretical results. By comparison with the measured transition energies and relative oscillator strengths we also estimated the in-plane strain in the QW layers, which for the 10 μm wide device was found to be $\epsilon_{xx} \simeq 0.13$ % and $\epsilon_{yy} \simeq 0.10$ %.

In conclusion, we showed that the combination of an appropriate underlying stressor layer and a highly skewed metal coated mesa geometry, can be used to generate anisotropic in-plane tensile strain and thereby obtain optical polarization anisotropy in the in-plane photoconductivity of cubic III-V semiconductor QWs. Such structures can be used for polarization sensitive detection/switching applications. Multiple stripes can provide larger active area for broader light beams, while a desired operating wavelength can be achieved by appropriate QW/stressor layer material combination, with the possibility of fine tuning it by adjusting L_w.

Chapter 4: *Effect of quantum confinement on anisotropically strained non-polar wurtzite group III-Nitrides*

We extended our linear polarization resolved studies to group III-Nitride semiconductors which have wurtzite lattice structure. In particular we were interested in non-polar $(1\bar{1}00)$ *M*-plane and $(11\bar{2}0)$ *A*-plane QWs made with these materials [see Fig.6(a)]. Interest in non-polar oriented group III-Nitride QWs is driven by the fact that large piezo-/pyro-electric fields are absent in them, quite unlike the case with commonly used (0001) *C*-plane oriented QWs. This leads to improved radiative recombination rates and therefore more efficient light emitters can be made using such materials. Polarization of emission is an inherent property of non-polar wurtzite group III-Nitride films and it has important consequences for the design and functioning of opto-electronic devices. For instance if the emission is polarized out-of-plane, that is along the normal to the film surface, then such light can only propagate within the film plane and will eventually get reabsorbed. If light emitting diodes (LED) are made with such a material it would be difficult to extract light. Similarly it would be impossible to use them in vertical cavity surface emitting lasers (VCSEL) or get efficient transverse-electric mode emission if used in edge emitting lasers (EEL). In contrast a strong in-plane polarization of emission will favor both LEDs and lasers. Since the ***c***-axis of a wurtzite crystal lies in the plane of an *M*-plane or *A*-plane film, such films typically experience anisotropic in-plane strains which differ along directions parallel and perpendicular to the ***c***-axis. This strain further influences the electronic band structure and can strongly modify the linear optical polarization properties of inter-band transitions.[5] Quantum confinement of carriers also modifies the EBS. In the case of a QW, carriers in the ground state acquire a finite out-of-plane crystal momentum along the confinement direction resulting in polarization anisotropy of emission relative to it.

In this chapter, we present results of a perturbation theory based study to bring out the combined influence of quantum confinement and anisotropic strain on the EBS of non-polar group III-Nitride QWs and its consequences for the linear optical polarization selection rules for emission. The study is based on the Bir-Pikus Hamiltonian. We take *M*-plane oriented GaN QWs as an example and show that the finite out-of-plane crystal momentum magnitude arising due to quantum confinement can significantly alter valence band mixing and modify the polarization selection rules for inter-band optical transitions in such QWs.

As a practical implication of the modified emission polarization characteristics, we show that *M*-plane oriented $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ QWs with $y > x$ which might experience anisotropic in-plane tensile strain when grown pseudomorphically on *M*-plane GaN substrates, are capable of working as efficient ultra-violet light-emitters unlike bulk AlGaN films with identical composition and strain. An example of the results from our calculations are as shown in Fig. 6 where we plot various properties of an anisotropically strained *M*-plane AlGaN bulk film and a QW with $L_w = 4.5$ nm as a function of Al concentration. With *y* direction as the direction of growth, the strain tensor components ϵ_{xx}, ϵ_{zz} and ϵ_{yy} of $Al_xGa_{1-x}N$

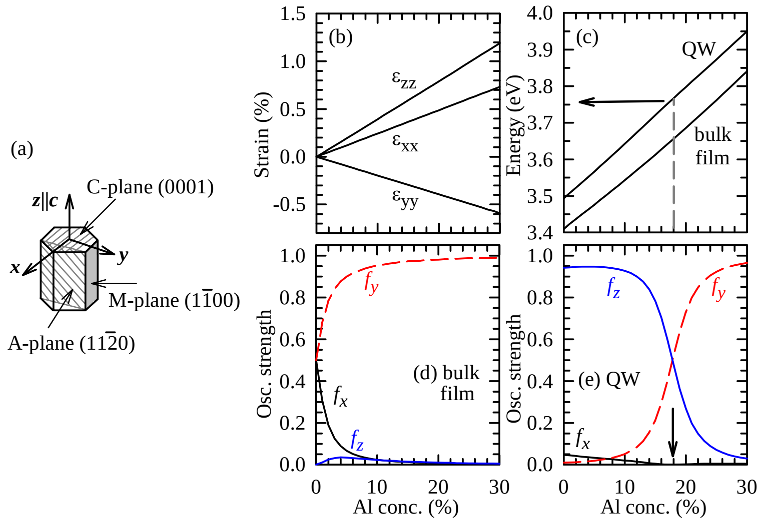

FIG. 6. (a) Schematic of a wurtzite unit cell showing the relevant planes and the choice of coordinates. The adjacent plots show variation of several properties of *M*-plane $Al_xGa_{1-x}N$ pseudomorphically grown on *M*-plane GaN substrate, as a function of Al concentration : (b) in-plane (ϵ_{xx}, ϵ_{zz}) and out-of-plane (ϵ_{yy}) strain components, (c) energy of the ground state transition in bulk films and in 4.5 nm thick QWs. Relative oscillator strength components f_x, f_y and f_z for these transitions in (d) bulk films and in (e) QWs.

films pseudomorphically grown on *M*-plane GaN would vary with Al concentration as given in Fig. 6(b). The corresponding change in the ground state emission energy for the bulk film and the QWs are shown in Fig. 6(c). For bulk films, the oscillator strength components of the ground state transition T1 vary with Al concentration as shown in Fig. 6(d). One finds that in bulk films even for small Al concentrations the oscillator strength component f_y rapidly reached ~ 1, which means that the emission polarization becomes predominantly out-of-plane. Such films will not be good light emitters. However for the QW the oscillator strength variation with Al concentration, shown in Fig. 6(e) is quite different. Here for Al concentration up to 18% the emission polarization has a strong in-plane character with $f_z > 0.5$ and therefore a 4.5 nm thick *M*-plane $Al_xGa_{1-x}N$ QW with 18% Al is well suited for UV light emitter applications at ~ 3.75 eV (330 nm). Thus although increase in Al content increases in-plane tensile strain which results in the deterioration of desirable emission polarization characteristics in bulk films, in the case of a QW the finite out-of-plane crystal momentum negates the adverse influence of this in-plane tensile strain. After interchanging *x* with *y*, these results are also applicable to *A*-plane oriented QWs.

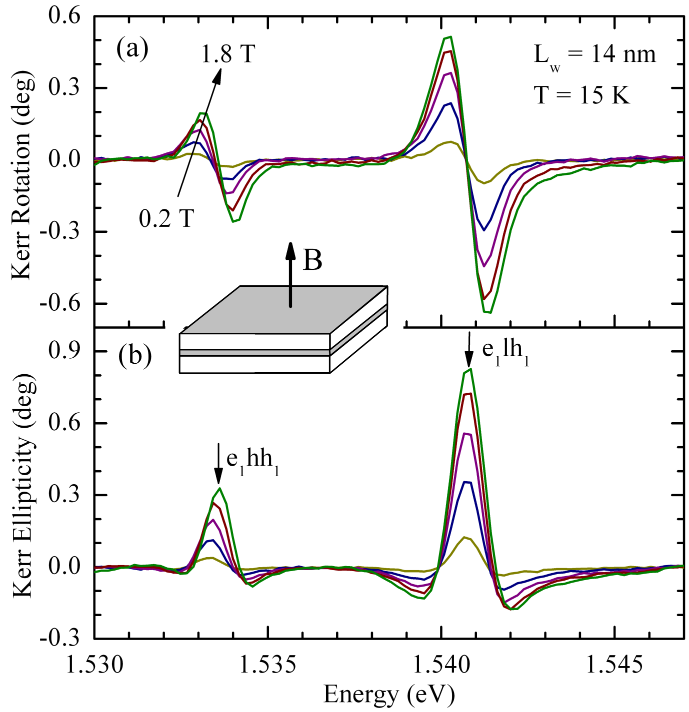

FIG. 7. (a) Kerr rotation and (b) Kerr ellipticity spectra of a GaAs/$Al_{0.3}Ga_{0.7}$As QW of width $L_w = 14$ nm, for magnetic fields ranging from 0.2 T to 1.8 T. The sample temperature was 15 K and the measurements were done in the polar geometry with the magnetic field **B** perpendicular to the plane of the thin GaAs quantum well layer sandwitched between two $Al_{0.3}Ga_{0.7}$As barrier layers as shown in the inset. The sharp features arise at energies corresponding to e_1hh_1 and e_1lh_1 exciton transitions.

Chapter 5: *Effect of magnetic fields on cubic GaAs quantum wells*

The earlier chapters dealt with studies of the electronic band structure using linearly polarized light. The next two chapters deal with studies involving circularly polarized light where we explore the spin-split electronic band structure of the semiconductors under a magnetic field. In this chapter we will deal with semiconductors possessing cubic symmetry. There is a renewed interest in understanding details of spin related phenomena of these GaAs/Al_xGa_{1-x}As QW systems due to their potential for application in the emerging area of spintronics which involves controlling and manipulating the spin degree of freedom of electrons and holes for device applications. An important property in this context is the effective Landé g-factor which determines the Zeeman splitting of spin degenerate electronic levels in such systems under an applied magnetic field. A large value of the g-factor implies spin polarized bands well separated in energy at relatively low magnetic fields. Such a situation is desirable for the generation of spin polarized carriers with high fidelity.

In general the Zeeman splitting at low magnetic fields is small compared to the inhomogeneous broadening of the exciton linewidth. It is therefore difficult to directly measure the splitting from energy shift of the spectral features using simple magneto-photoluminescence or magneto-absorption spectroscopy, even at low temperatures.[1] Also, in luminescence based measurements only the lowest energy states are occupied by the photo-excited excess carriers, hence they mostly yield g-factors for n = 1 confined electron (e_1) and heavy-hole (hh_1) subbands and not for states at higher energy such as the light-hole (lh_1) subbands of the QWs. A recent theoretical study by Durnev et al. [Physica E **44**, 797 (2012)] has suggested the possibility of giant g-factors of $\sim$40 for light-holes in these QWs for $L_w > 10$ nm. MOKE spectroscopy readily gives information about the spin polarized structure of electronic states at higher energies and is currently also a popular diagnostic tool in spintronics for estimating the degree of spin polarization of carriers in practical device structures. We have used MOKE spectroscopy to measure g-factors in low magnetic fields (< 1T) suitable for practical device applications. Optical transitions involving spin split initial and final states are sensitive to right and left circularly polarized (RCP and LCP) light arising from angular momentum conservation based selection rules. When light with a state of polarization that is a composite of RCP and LCP is made incident normally on a magnetized sample, the reflected light's state of polarization is altered in general. The MOKE signal is a measure of this change and is quantified in terms of Kerr rotation ϕ_k and Kerr ellipticity η_k parameters. An analysis of the MOKE spectral lineshape yields the Zeeman splitting and thereby the g-factor.

We studied GaAs/$Al_{0.3}Ga_{0.7}As$ single QWs with widths ranging from 4.3 nm to 14 nm. The measurements were performed in polar MOKE geometry where a magnetic field up to 1.8 T could be applied with sample kept at 15 K. The setup used in the study is shown in Fig. 2. Features in the reflectance, Kerr rotation and Kerr ellipticity spectra were observed at energies corresponding to the e_1hh_1 and e_1lh_1 exciton transitions. The authenticity of the Kerr spectra was verified using a Kramers-Kronig transformation based analysis. A first principles simulations based procedure was used for simultaneously analyzing both the measured spectral lineshapes. A Lorentz oscillator model was used to represent the excitonic contribution to the dielectric function. This procedure is described in detail. A second approach based on the comparison of Kerr ellipticity spectrum with the derivative of logarithm of reflectivity was also used an an independent check. Both these methods used to determine the e_1hh_1 and e_1lh_1 exciton Zeeman splittings yielded similar values. The Zeeman splitting was found to vary linearly with magnetic field up to the maximum applied field of 1.8 T and yielded the longitudinal Landé g-factors of the excitons with a $\pm 5\%$ error margin. Thereafter, hh_1 and lh_1 g-factors were determined by making use of the widely studied e_1 g-factor values from the literature.

The hole g-factors were found to vary with well width[6], ranging from -0.6 to 1.1 for heavy-holes and 6.5 to 8.6 for light-holes. While the heavy-hole g-factors values agree well with earlier theoretical

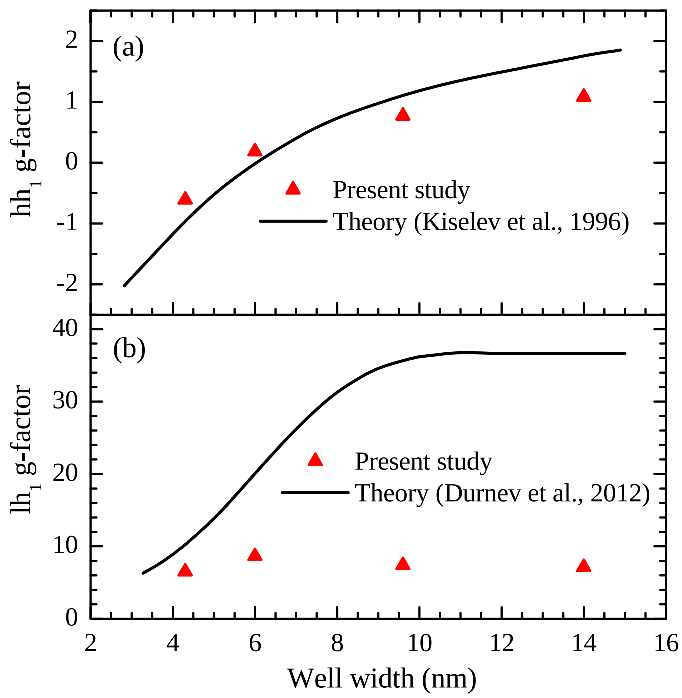

FIG. 8. Variation of (a) g_{hh_1} and (b) g_{lh_1} as a function of well width obtained through the present study (triangles) compared with theoretical results (line) from Kiselev et al., Phys. Sol. Stat. **38(5)**, 866 (1996) and Durnev et al., Physica E **44**, 797 (2012), respectively.

predictions, the light-hole g-factor is much smaller in value than the latest theoretical prediction. In conclusion we showed that there is no evidence for giant light-hole g-factors in GaAs/Al$_x$Ga$_{1-x}$As QWs. Our results suggest the need for an improved theoretical model for understanding the light-hole g-factor values in GaAs/Al$_x$Ga$_{1-x}$As QWs. Ideally it should be a model which can simultaneously explain the well width dependent g-factor values of confined electrons, heavy-holes and light-holes in this system.

Chapter 6: *Effect of magnetic fields on polar and non-polar oriented wurtzite GaN films*

In this chapter we report on our spectroscopic studies with circularly polarized light but this time we deal with bulk GaN which has wurtzite crystal structure. Mn doped GaN is expected to achieve high Curie temperature making it a potentially important material candidate for room temperature spintronic device applications. It is therefore important to understand its spin split electronic band structure under a magnetic field. So far all magneto-optical studies on GaN have involved polar (0001) *C*-plane films. These studies helped determine the carrier effective masses as well as g-factors of the conduction and valence bands. However, most of these studies have been performed under relatively high magnetic fields ($>$5 T) which are not practical for device applications. Also g-factors can vary non-linearly with applied magnetic field and

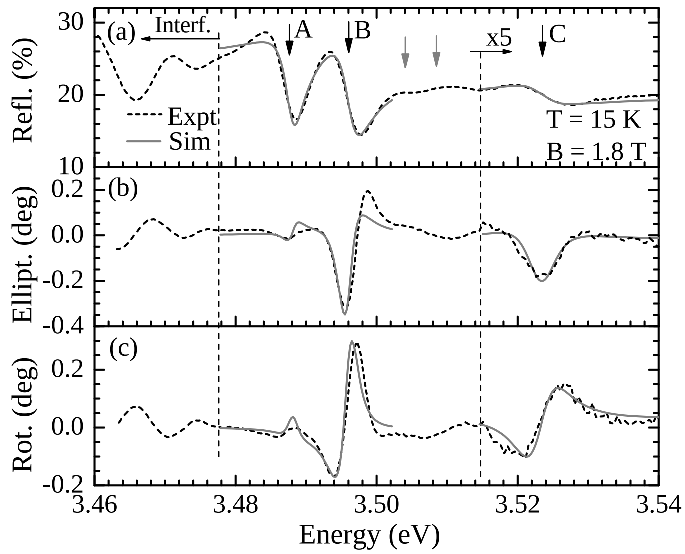

FIG. 9. An example of lineshape fitting of (a) Reflectance (b) Kerr ellipticity and (c) Kerr rotation spectra of the *C*-plane GaN film from first principles. The two gray arrows in (a) identify the transition energies corresponding to the first excited states of A and B excitons.

therefore it is important to explore these properties under low magnetic fields (<1 T). That apart non-polar $(11\bar{2}0)$ *A*-plane GaN films have become important for device applications in recent times because of the absence of piezo-/pyro-electric fields in them. We have performed polar MOKE spectroscopy studies to measure the exciton g-factors in epitaxial GaN films with both *C*-plane and *A*-plane orientations.

The measurements were performed under magnetic fields upto 1.8 T with samples cooled to 15 K. The setup used for the measurements was the same as shown in Fig. 2. In the MOKE spectra of *C*-plane GaN we observed features at energies corresponding to the A, B and C exciton of GaN (see Fig. 9). Since the A and B exciton transition lineshapes overlap significantly, the method that compares the Kerr ellipticity spectrum with logarithm of the derivative of reflectance spectrum is not suitable for analysis and we performed a first principles MOKE spectral lineshape analysis using the approach described in Chapter 5 for GaAs/$Al_{0.3}Ga_{0.7}As$ QWs. This is possible because in the case of a *C*-plane film there is no in-plane linear optical polarization anisotropy. An example of the lineshape fitting using first principles approach is shown in Fig. 9. The g-factors obtained[7] for the A, B and C excitons were 0.09 ± 0.02, 0.74 ± 0.05 and 3.9 ± 0.2 respectively in fair agreement with an earlier report.

In the case of *A*-plane GaN the ***c***-axis lies in the film plane and there is an inherent in-plane linear polarization anisotropy. We did a Jones matrix analysis to understand how to perform the experiment in this case and it suggested that two measurements were required, one where the ***c***-axis is parallel to the analyzer axis and another where it is perpendicular. We found that the MOKE spectra of the *A*-plane GaN film had one dominant feature each for $\boldsymbol{c} \perp$ and $\boldsymbol{c} \parallel$ to the analyser axis, and they occur at different energies. Low temperature polarized photoreflectance measurements were also performed for verifying that there was only one dominant exciton transition for polarization $\perp \boldsymbol{c}$ and $\parallel \boldsymbol{c}$, respectively. The measured g-factors[7] for these features were $g_{\perp c} = 4.7 \pm 1$ and $g_{||c} = 7.1 \pm 1.2$. Comparison with a **k·p** perturbation theory based calculation, which included strain, indicated that these features were associated with exciton transitions involving valance bands that were strongly mixed by anisotropic in-plane strain.

In conclusion, we used MOKE spectroscopy to determine the exciton g-factors in *C*-plane and *A*-plane oriented GaN films under low magnetic fields. While the g-factors obtained for *C*-plane GaN agreed with those reported in the literature, we found relatively large g-factors in the *A*-plane films where there is evidence of significant band structure modification due to anisotropic in-plane strain.

Summary: In summary, this Thesis describes results of several optical spectroscopy studies on group III-V semiconductor heterostructures using linearly and circularly polarized light. The work also involved novel spectroscopic instrumentation, detailed spectral lineshape simulations for analysis and electronic band structure calculations and provided important information about the electronic band structure of these materials. Studies involving linearly polarized light dealt with understanding the origins of in-plane polarization anisotropy in the photoconductivity response of structures based on GaAs/$Al_{0.3}Ga_{0.7}As$ QWs. This was shown to arise from anisotropic in-plane strain induced valence band mixing. The next study involving *M*-plane oriented GaN QWs demonstrated how the combined influence of both strain and quantum confinement were important in determining the linear polarization properties of emission in such materials. As a practical example of its significance we showed that the modified emission polarization characteristics of *M*-plane $Al_xGa_{1-x}N$ QWs under in-plane tensile strain are such that they can work as efficient light emitters, unlike identically strained bulk $Al_xGa_{1-x}N$ films. Results of electronic band structure calculations based on the **k·p** formalism were used to support both these studies. These two studies have implications for both light detector and light emitter designs. The latter part of the Thesis deals with circular polarization resolved measurements for studying spin-split electronic band structures using MOKE spectroscopy. We measured the well width dependent Landé g-factors of the ground state heavy-hole and light-hole subbands in GaAs/$Al_{0.3}Ga_{0.7}As$ QWs under low magnetic fields and showed that the results do not support a recent theoretical prediction of giant light-hole g-factor values. We also performed MOKE spectroscopy studies on *C*-plane and *A*-plane oriented GaN epitaxial films. The exciton g-factors which we obtained for *C*-plane-GaN were in agreement with those reported in the literature. However the g-factor values were much larger for the single exciton transitions observed in the anisotropically strained *A*-plane film. These results suggest the need for improved theoretical models for understanding the well width dependence of g-factor values in cubic QWs, as well as strain dependence of g-factors in wurtzite group III-Nitrides.

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