Fiber optic based system for polarization sensitive spectroscopy of semiconductor quantum structures

Ashish Arora,1,a Biswajit Karmakar,1,2 Sayantan Sharma,1 Michael Schardt,3 Stefan Malzer,3 Bhavtosh Bansal,4,b Gottfried Döhler,1,3 and Brij M. Arora1,5
1 Tata Institute of Fundamental Research, Mumbai 400005, India
2 Scuola Normale Superiore, NEST CNR-INFN, S. Silvestro 12-56127 Pisa, Italy
3 Max Planck Institute for the Physics of Light, 91058 Erlangen, Germany
4 IMM, High Field Magnet Laboratory HFML, University of Nijmegen, Toernooiveld 7, 6525 ED Nijmegen, The Netherlands
5 Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

(Received 21 October 2009; accepted 17 June 2010; published online 19 August 2010)

We describe an optical fiber based setup for performing polarization resolved magneto-optical spectroscopy measurements under low temperatures (∼4 K) and high magnetic fields (∼8 T). The measurements are performed in a windowless helium Dewar. Circularly polarized light is produced inside the Dewar by inserting the polarizing elements between the fiber end and the sample. Photoconductivity spectra of a GaAs/AlGaAs multiquantum-well sample have been measured over the photon energy range of 1.5–1.7 eV in left and right circularly polarized light under crossed magnetic and electric fields. It is shown that reversing the direction of magnetic field produces the same spectral changes as caused by changing the direction of circular polarization with the optical components. © 2010 American Institute of Physics. [doi:10.1063/1.3462977]

I. INTRODUCTION

Measurement of fundamental absorption using polarized light is an effective method for investigating the band structure of semiconductor quantum structures as well as the effects of applying electric and magnetic fields. A common measurement apparatus uses an optical cryostat with windows such that the light travels in free space from the light source to the sample with appropriate optics: monochromator, polarizer, retarder, etc. Alternatively, the apparatus may be windowless such as a helium Dewar assembly commonly used in transport experiments. In this setup, light has to be carried to the sample using light guide. Heiman1 described such a system for measuring optical properties of Cd1−xMnxTe using bifurcated fiber optic cable having large diameter of ∼a few milimeters. Using this apparatus, he presented measurements of photoluminescence and reflectivity spectra at 1.5–4 K with magnetic fields up to 15 T. In a subsequent publication, Isaacs and Heiman2 presented a more versatile and compact fiber optic system for Raman scattering and photoluminescence measurements using two 100 μm diameter optical fibers and measurements were made at temperature ∼0.5 K with magnetic fields up to 30 T. In both of these publications, the authors envisioned utilization of polarizing optical elements to carry out polarization dependent measurements; however no such measurement results were actually presented. Apart from these, there are other reports such as one by Rogers et al.,3 who reported magneto-optics of GaAs/AlGaAs quantum wells by measuring photoconductivity spectra in unpolarized light by using fiber optic cable for exciting the sample. We have extended the state of such measurements in the present work, and describe an apparatus for measuring photoconductivity spectra of a GaAs/AlGaAs multiquantum well (MQW) sample in circularly polarized light using optical fiber in a windowless helium Dewar at temperature of ∼4 K and magnetic fields up to 8 T. Effects of applying crossed electric field (in the plane of the sample) and magnetic field (perpendicular to the plane of the sample) have been investigated in the photon energy range of 1.5–1.7 eV. Spectra for both left and right circularly polarized light are measured, and polarization anisotropy is observed. Further, it is shown that reversing the orientation of magnetic field produces the same spectral changes as caused by changing the direction of polarization with the optical elements. This is useful as it greatly simplifies the experimental procedure.

II. EXPERIMENTAL SETUP

The experimental setup is shown schematically in Fig. 1. It consists of a top loading Al-fiberglass He Dewar manufactured by Precision Cryogenics (Indianapolis, IN). An 8 T NbTi solenoidal superconducting magnet (American Magnetics, Inc., Oak Ridge, TN) is suspended from the top opening of the Dewar to a position close to the bottom of the Dewar. Magnet leads are brought out at the top of the Dewar using the normal cryogenic practice. The main cryogenic system consists of three concentric stainless steel tubes positioned in the solenoid core as shown. All the three tubes can be evacuated or backfilled with helium gas. The innermost chamber (number 1) carries the sample insert with mea-
measurement and monitoring accessories. The middle chamber (number 2) has a capillary tube at the bottom which opens into the helium bath. Liquid helium can be pumped through the capillary into this chamber (number 2) from the bath by a vacuum pump so as to lower the temperature down to ~2 K in chamber number 2 as well as in chamber number 1. Under this mode of operation, chamber number 3 is kept under vacuum to provide thermal isolation between the helium bath and the chamber numbers 1 and 2. For operation at 4 K, all the three chambers are back filled with helium exchange gas. The sample insert is loaded into chamber number 1 from the top such that the sample is positioned at the center of the solenoid. The insert carries wires for electrical measurements and one 3 m long 1 mm diameter flexible silica optical fiber\(^4\) which takes 20 Hz chopped unpolarized light from 1/8 m monochromator/quartz halogen lamp to the sample. For polarization sensitive measurements, an optical assembly (shown in Fig. 1) is attached to the insert to produce circularly polarized light. The assembly consists of a pair of 5 mm diameter, 10 mm focal length convex lenses,\(^5\) a high contrast (1000:1) dichroic glass linear polarizer of 12.5 mm diameter,\(^6\) and a mica quarter wave retarder plate of 10 mm diameter\(^7\) for producing circularly polarized light. Room temperature operation of the polarizing optics was tested by using Babinet compensator and a cross polarizer. For checking the low temperature operation, we have relied on (a) comparison of our polarized spectra with similar spectra (Fig. 4) measured on a device from a part of the same wafer, by using a window cryostat and polarizing optics kept in free space outside the cryostat,\(^8\) as well as (b) comparison with the reported polarization resolved spectral measurements of Schmitt-Rink et al.\(^9\)

The assembly housing the optical elements is machined from copper and has a stage for mounting the sample or sample carrier as shown in Fig. 1. The sample mount is adjustable with three side screws to optimize the sample position with respect to the light beam exiting the optical assembly (as is required for photoconductivity measurements, the light spot should fall on the semiconductor between the electrodes). Photoconductivity was initially measured at room temperature for optimizing the sample position before loading the insert into the Dewar. The samples used in this study consist of 20 periods of 10 nm GaAs/12 nm Al\(_{0.2}\)Ga\(_{0.8}\)As MQWs. For applying a uniform in-plane electric field, the MQWs were sandwiched between 200 nm thick low conducting low temperature grown GaAs top and bottom layers. The structures were synthesized by molecular beam epitaxy. For photomeasurements, 10 \(\mu\)m wide mesa structures were etched and provided with lateral Au contacts using photolithography. The structure has been described earlier in references.\(^{10,11}\)

In order to produce circularly polarized light, the fast axis of the quarter-wave plate was kept at 45° with respect to the pass axis of the linear polarizer. The photoconductivity measurements were performed at \(T = 4\ \text{K}\) at various settings of the applied voltage of 0.5 to 8 V (providing lateral electric field \(5 \times 10^2\) to \(8 \times 10^3\) V/cm) and perpendicular magnetic field (0–8 T). Experiments for the two circular polarizations are performed by rotating the direction of the fast axis of the quarter wave plate by 90°. Measurements were also made by reversing the direction of current through the superconducting magnet which is shown to produce the same spectral changes as by the rotation of the retarder plate (see Appendix for discussion on this aspect). For measurements under \(B_+\) and \(B_-\) fields, the current was initially ramped up in one direction with a ramp rate of 0.1 A/s. During this process, the current was held steady at specific \(B\) values for measuring the spectra. In order to reverse the magnetic field polarity, the current was ramped down to zero and the magnet leads to the power supply were reversed. The spectral measurements were repeated by ramping up the current again, holding at specific values for recording the spectra as in the previous case, but under magnetic field of opposite polarity. The total time taken for reversing the polarity of the magnetic field from one direction to the opposite was 30 min for 8 T or less depending on the magnitude of the field. An added advantage of the above procedure is that the optics and therefore the optical path are left undisturbed during the above process such that one is sure of probing the same area of the sample during all the measurements.

III. RESULTS

Figure 2 shows photoconductivity spectra of GaAs MQW structure in unpolarized light and right circularly polarized light for various magnetic fields from 0 to 8 T. The two peaks (1.544 and 1.554 eV) observed at \(B = 0\) correspond to hh1—e1 and lh1—e1 excitonic transitions. At \(B \neq 0\), we see several new peaks corresponding to the transitions between Landau levels (LLs). These peaks show significant shift to higher energy with increasing \(B\) field, whereas the positions of the excitonic peaks remain relatively unaffected. The unpolarized spectra for the same sample were reported earlier\(^{11}\) for various magnetic and lateral electric fields. Apart from the redshift characteristic of the Stark effect, additional changes such as those in line shapes and relative strengths of
the peaks were also observed. However, analysis of the spectra proved to be very difficult. In order to facilitate the understanding of the transitions related to the spectral features, it was decided to measure the spectra by using polarized light. Figure 2 shows the spectra measured by using right circularly polarized light as a function of magnetic field. Comparison between Figs. 2 and 2 shows that emergence of the Landau fan with increasing magnetic field is seen much more clearly in the polarized light as compared to the spectra measured with the unpolarized light. The reason for this can be appreciated from Fig. 3, where we have plotted the spectra for left and right circular polarizations at 8 T magnetic field and applied bias of 1 V. The nature of spectral shifts between the left and right circular polarizations observed in Fig. 3 is very similar to that reported earlier by Schmitt-Rink et al. Peaks 3 and 4 exhibit a pronounced redshift and peaks 2 and 6 a pronounced blueshift between $\sigma_e$ and $\sigma_\perp$ configuration, while peaks 1 and 5 are hardly shifting at all. Peak 7 is turning into a shoulder to peak 8. The nonmonotonic nature of the relative shifts between the peaks in the spectra of the two polarizations can cause the features appearing in the unpolarized spectra to be mixed and difficult to analyze. As such, changing the polarization of light from left circularly polarized light to right circularly polarized light as in Fig. 3 requires rotating the fast axis of the quarter wave plate by 90° with respect to the pass axis of the linear polarizer. In an apparatus such as ours, in which the optical parts are at low temperature, this operation can be automated by either using a cryogenic motor inside the Dewar or by a suitable mechanical arrangement to rotate the retarder plate from outside the Dewar. However in our present setup, these facilities do not exist as yet. As a result, the apparatus has to be warmed up to room temperature and the insert has to be taken out of the Dewar carefully without giving a thermal shock to the parts to perform this operation, which is a fairly time consuming task. We next show that reversing the magnetic field, while keeping the relative orientations of the optic axis of the polarizer and the retarder fixed, produces the same spectral changes as caused by rotating the direction of polarization with optical elements. Figure 4 shows four spectra (plots a–d) obtained at 8 T magnetic field where the correspondence between the rotation of the retarder plate and changing the direction of magnetic field is established. Spectrum a is obtained with the $B$ field in the $+z$ direction and optical elements arranged for $\sigma_e$ polarization configuration. Spectrum b is obtained with the $B$ field in the $-z$ direction and optical elements in $\sigma_\perp$ configuration. Spectrum c is obtained by keeping the $B$ field in the $+z$ direction and optical elements arranged for $\sigma_\perp$ polarization configuration. Spectrum d is obtained with the $B$ field in the $-z$ direction and optical elements arranged for $\sigma_e$ configuration. Spectrum c is obtained by keeping the $B$ field in the

FIG. 2. (Color online) The magnetoabsorption spectra of GaAs MQWs in (a) unpolarized light, (b) right circularly polarized light with constant in-plane bias=1 V for various magnetic fields from 0 to 8 T. The gradual emergence of hh and lh LL transition peaks is seen.

FIG. 3. (Color online) The absorption spectra for left and right circularly polarized light at $B=8$ T and bias $V=1$ V. The nomenclature (for dashed spectrum): first digit is subband in CB and VB, the second digit is LL index $(n, n)$ in CB and VB (only one digit is used since the strongest transitions correspond to $\Delta n=0$).

FIG. 4. (Color online) Plots a–d are measured with the optical fiber based setup to demonstrate equivalence of the spectra measured with the $B$ field reversal and the spectra measured with the rotation of the retarder plate as described in the text. Plots a’ and b’ are obtained from another part of the sample by using window based cryostat measurement setup (Ref. 8).
cryostat at room temperature. The spectra a
mation by Maan
general nature of the fan diagram is also very similar to that
polarized light are summarized in Landau-fan diagram drawn
in the nonmonotonic shifts for different peaks in both the
spectra obtained using our apparatus, the close agreement
with those obtained using our technique were made. Comparison of these spectra
layers of the different devices, on which measurements by
slight nonuniformity in the thickness of the quantum well
be globally shifted towards right on energy axis, by

+zf direction, while the optical elements are in \( \sigma_\perp \) configuration. We see that spectrum b is identical to the spectrum c in
every detail. To complete the equivalence, spectrum d is ob-
tained with \( B \) field in \(-zf\) direction and optical elements in the
\( \sigma_\perp \) configuration; spectrum d is seen to be identical to spec-
trum a, thus establishing the equivalence of spectra measured
in two different ways. Using a simple picture of Zeeman
splitting and the selection rules for the transitions, we show
in the Appendix that the equivalence described above can be
understood easily.

Figure 4 shows two more spectra (plots a’ and b’) ob-
tained by performing measurements on a device made from a
part of the same wafer, using the optical window based cry-
ostat, where the optical elements were placed outside the
cryostat at room temperature.\(^8\) The spectra a’ and b’ have
been globally shifted towards right on energy axis, by
\(-4\) meV to match the corresponding peak positions with the
spectra obtained using our setup. This shift may be due to a
slight nonuniformity in the thickness of the quantum well
layers of the different devices, on which measurements by
both the techniques were made. Comparison of these spectra
with those obtained using our apparatus, the close agreement
in the nonmonotonic shifts for different peaks in both the
spectra, confirms the proper functionality of optical elements
at low temperature.

The spectra observed for the two directions of circularly
polarized light are summarized in Landau-fan diagram drawn
from the peak positions, shown in Fig. 5. We note that the
general nature of the fan diagram is also very similar to that
observed by Maan et al.\(^5\) A tentative labeling of the various
branches of the fan diagram is also given. A more complete
analysis of the polarization resolved spectra and the changes
observed at different electric fields are currently under
progress and will be reported elsewhere.

IV. SUMMARY

We have constructed an apparatus for spectral measure-
ments with polarized light in a windowless helium Dewar by
using optical fiber and polarizing components kept close to
the sample. Using this apparatus, measurements of photocon-
ductivity spectra of a MQW sample have been performed with circularly polarized light under crossed electric and
magnetic fields. It is shown that reversing the direction of magnetic field is equivalent to changing the direction of cir-
cular polarization. The apparatus should be of use to experi-
mentalists who would like to combine transport and optical
spectroscopy measurements at high magnetic fields and cryo-
genic temperatures in windowless apparatus.

ACKNOWLEDGMENTS

We thank TIFR central workshop facility for help in
various stages. Experiments at HFML were supported by Eu-
romagNET under the EU Contract No. RII3-CT-2004-
506239.

APPENDIX: EFFECT OF B FIELD REVERSAL IN
CIRCULARLY POLARIZED SPECTRUM

The effect of reversing the direction of magnetic field on
the polarization resolved spectrum can be understood as a
result of Zeeman interaction as follows. Electron states in the
GaAs/AlGaAs QW conduction band (CB) are s-like with
\( m_i^e = \pm \frac{1}{2} \) and valence band (VB) states are p-like with \( m_i^{hh} = \pm \frac{1}{2} \)
for heavy holes (HH) and \( m_i^{hh} = \pm \frac{3}{2} \) for light holes (LHs). Localization in the QW removes the degeneracy be-
between HH and LH states as shown in Fig. 6(a) at \( B=0 \).
Fundamental optical transitions for circularly polarized light
incident normal to the QW are also shown. Application of
magnetic field perpendicular to the plane of the QW pro-
duces two effects: (i) The 2D density of states of the QW in
the CB as well as VB split into LLs, and (ii) Zeeman inter-
action with magnetic moment further splits the Landau states

![Diagram of Landau-fan diagram](https://example.com/landau-fan-diagram.png)

FIG. 5. The Landau-fan diagram representing LL transitions between
electron-hole states at 1 kV/cm in-plane electric field. The inset shows the
possible interband transitions between the first subbands (i.e., \( n=1 \)) at \( B=0 \).

![Diagram of magnetic field reversals](https://example.com/magnetic-field-reversal-diagram.png)

FIG. 6. (Color online) Schematic energy level diagram and arrows showing
allowed electronic transitions at left (\( \sigma_\perp \)) and right (\( \sigma_\parallel \)) circular polarization
of light. (a) Zero magnetic field (b) \( B \) forward and (c) \( B \) reverse. The indi-
cated Zeeman splitting at finite magnetic fields reflects the positive \( g \)-factor
of lh- and hh-states and the negative \( g \)-factor of the electronic energy levels.
A comparison of the figures (b) and (c) shows that keeping the circular
polarization of the light the same allows to access the transitions corre-
sponding to the opposite circular polarization by simply reversing the direc-
tion of the magnetic field.

- \( \sigma_\perp \) refers to circular polarization where the direction of circular
polarization is perpendicular to the plane of the QW.
- \( \sigma_\parallel \) refers to linear polarization.
- The magnetic field \( B \) can be reversed in the positive and negative direc-
tions.
- Zeeman splitting \( g \) factor is positive for light holes (lh) and negative for heavy holes (hh).
- The Landau levels (LLs) are the quantum states in a magnetic field.
- The Landau fan diagram is used to understand the transitions between these states.
into sublevels. The CB Landau states with $m_l^c = \pm \frac{1}{2}$ split into spin-up $|\frac{1}{2}\rangle$ and spin-down $|\frac{-1}{2}\rangle$ sublevels given by

$$E_{M}^{c} = g_{c}^{*} \mu_{B} B m_{j}^{c},$$

where $g_{c}^{*}$ is the effective Landé factor, $\mu_{B}$ is Bohr magneton, and $B$ is the applied magnetic field. Similarly the VB LLs (HH and LH) split into sublevels

$$E_{M}^{hh} = g_{hh} \mu_{B} B m_{j}^{hh}$$

and

$$E_{M}^{lh} = g_{lh} \mu_{B} B m_{j}^{lh}.$$

It is known\(^{13}\) that $g_{c}^{*}$ is negative $(-0.44)$ for bulk GaAs. In QWs, $g_{c}^{*}$ increases with decreasing well width. For the sample used in this work, we expect $g_{c}^{*} \approx -0.14$. Accordingly in $+B$ field, the states with $m_{j}^{c} = -\frac{1}{2}$ lie at higher energy than the states with $m_{j}^{c} = \frac{1}{2}$ as shown in Fig. 6(b). Also shown in Fig. 6(b) are spin split HH and LH levels following the Landé factor values in the literature.\(^{14}\) Figure 6(c) shows the CB and VB spin split levels when the direction of the magnetic field is reversed. Comparison of the Figs. 6(b) and 6(c) shows mirror symmetry in the energy levels with respect to the reversal of $B$-field. We can see that the transitions between the states $|\frac{-1}{2}\rangle_{VB} \rightarrow |\frac{-1}{2}\rangle_{CB}$ and $|\frac{1}{2}\rangle_{VB} \rightarrow |\frac{1}{2}\rangle_{CB}$, under right circularly polarized light ($\sigma_+$) excitation with $-B$ field, mimic the transitions between the states $|\frac{1}{2}\rangle_{VB} \rightarrow |\frac{1}{2}\rangle_{CB}$ and $|\frac{-1}{2}\rangle_{VB} \rightarrow |\frac{-1}{2}\rangle_{CB}$, under left circularly polarized ($\sigma_-$) excitation with $+B$ field. Same holds true for the transitions between the other set of states, thereby showing that spectrum measured by changing the orientation of the $B$-field ($+/ -$) is equivalent to the spectrum measured by exchanging $\sigma_+$ and $\sigma_-$ polarizations.

---