Effect of Polarization State of Light on Magnetoabsorption in GaAs/AlGaAs Quantum Well Structures

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ABSTRACT

Rigorous dipole selection rules are derived for an interacting electron-hole (e-h) system in a multiband magnetoactive GaAs/AlGaAs semiconductor quantum well (QW). The valence band structure is modelled using 8x8 Luttinger Hamiltonian in the axial approximation. For three different polarization states of input pulse radiation i.e. linearly polarized ($\sigma^+$), right circularly polarized ($\sigma^+$) and left circularly polarized ($\sigma^-$), we have studied the absorption characteristics of a GaAs/AlGaAs QW under the influence of a magnetic field, applied perpendicular to the growth direction. A strong blue shifting of the absorption peaks is observed with increasing magnetic field. Also, spin splitting of the absorption peaks is seen for the case of linearly polarized input radiation.

1. INTRODUCTION

The field of spintronics involves a whole new area of active manipulation of carrier spin dynamics. This control of spin through application of external magnetic field or by shining polarized light is envisioned to lead to novel magneto-electro-optical technology. Recently, spin effects have begun to attract considerable interest both for physical properties and also in connection with several device applications such as spin transistors, spin-filters, modulators, new memory devices and quantum computers\(^1,2\). The interest in spin effects has been spurred by the observation of long spin-coherence times in semiconductors and their nanostructures, which make solid state implementations of quantum information processing attractive. Example includes, control of spin dynamics in QD and other heterostructures for realization of quantum computing devices. In all these issues the ability to enhance and control spin splitting in semiconductors plays a key role. The carrier spin-based technology derives importance from the fact that spin can store information. Information can be stored in a system of electron spins because these can be polarized. Currently used methods of polarizing electron spins include magnetic field, optical orientation and spin injection. Optical orientation is referred to the direction of propagation and the polarization state of the exciting light in the medium. The current research interests of experimentalists and theoreticians have been to understand the appropriate mechanisms responsible in inducing spin orientation optically and the study of relaxation of spin polarization. The four mechanisms of spin relaxation viz. the Elliot-Yafet, D’yakonov-Perel, Bir-Aronov Pikus, and hyperfine-interaction mechanism can be important in semiconductors depending upon the material doping and geometry.\(^3\) Low-dimensional semiconductor structures provide fertile systems to study the fundamentals of spin relaxation.\(^4,5\) The most widely studied systems are GaAs/AlGaAs QWs and QDs. These nanostructures are gaining importance as potential candidate materials for modern spin based technology.\(^1,6,7\)

The key quantity needed to understand spin effects on the optical properties of nanostructures is the Zeeman splitting in a magnetic field. The splitting is determined by mixing of the spin with the electronic states. Recent advances in the understanding of spin effects on the optical properties of nanostructures includes work on their e-h Landau level splitting.\(^8\) This splitting in quantum wells has strong nonlinear dependence on magnetic field B. In order to understand this effect, reliable theoretical models are needed for realistic systems where the parameters (size, shape, alloy concentration, potential) are known sufficiently well. Many researchers have performed magneto-photoluminescence studies\(^9,10\) and this field has emerged as one of the important branch in the study of basic physical phenomena in nanostructures where investigations are performed making use of high

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magnetic field, which modifies the electronic properties depending upon the strength and the orientation of the applied magnetic field.

In order to investigate the optical properties in semiconductor nanostructures the first step is the evaluation of conduction and valence band energy levels and secondly, we need to evaluate the interband transition dipole matrix elements between these levels.

In the last decade, a lot of attention has been given towards calculating dipole moment on the basis of different approaches such as, tight-binding theory, $\kappa\cdot\p$ approximation etc. It is well known that the transition dipole matrix elements result from a very general expression obtainable within the $\kappa\cdot\p$ theory and the selection rules, that define total allowed transitions in a magneto-active semiconductor QW system. To extend the analysis of simple dipole allowed transitions in a two-band semiconductor model more complicated selection rules have to be considered when additional details of the band structure are taken into account. Typically for III-V semiconductors, such as GaAs, we assume that the optical transitions take place between a P-type valence band (i.e. $l = 1$) with total angular momentum $j = \frac{3}{2}$ and an S-type conduction band (i.e. $l = 0$) with $j = \frac{1}{2}$. To keep our analysis simple, we neglect the split off valence band which corresponds to $l = 1$ and $j = \frac{3}{2}$. Due to spin-orbit interaction this band is energetically well separated from $j = \frac{3}{2}$ band near the zone center.

In this paper, we investigate interband transitions in a single magneto-active GaAs/AlGaAs QWS by using different polarizations of input radiation. For detailed understanding of the polarization dependent and interband transitions, an eight band $\kappa\cdot\p$ Luttinger Hamiltonian for the valence band in III-V semiconductor is used which includes the coupling of light-hole (lh) and heavy-hole (hh) valence subbands. This Luttinger Hamiltonian is diagonalized and dipole matrix elements for different transitions are obtained. The inclusion of polarization dependent dipole matrix elements and e-h transition strengths allows for accurate predictions of excitation spectra of quantum wells.

In section II, we present the theoretical analysis of absorption characteristics in a magneto-active GaAs/AlGaAs QW structure. Detailed calculations of the dipole matrix elements for total allowed transitions are also given, leading to the calculation of induced polarization and differential transmission spectra. Section III deals with the results and discussions of numerical estimation of Differential Transmission Spectra (DTS) in GaAs/AlGaAs semiconductor QW.

2. THEORETICAL FORMULATIONS

In this paper we study the interband absorption characteristics in GaAs/AlGaAs QW for the Faraday configuration using circular and plane polarized light. Selection rules are used to evaluate both allowed and forbidden transitions at $k=0$. We shall first treat an idealized semiconductor with eight valence and four conduction subbands having a parabolic energy-momentum relation. We shall use this model to derive simple selection rules and the expected shape of absorption as a function of photon energy for direct transitions.

2.1. Hamiltonian Formulation

We begin with the well known Luttinger-Kohn Hamiltonian to incorporate the multiple valence subband structure in our formalism along with the modification in the energy of the states due to magnetic field effects. The system being considered is GaAs/Al$_x$Ga$_{1-x}$As QW. The well width $l_Z(=70\text{Å})$ and the Aluminium concentration in Al$_x$Ga$_{1-x}$As $x(=0.05)$ is chosen such that we have two hh and two lh states in the valence band and two electron states in the conduction band. These states being spin degenerate, split on application of magnetic field, yielding 8 hole subbands and 4 electron states in the conduction band. Thus, we have considered photoinduced transitions from 8 holes subbands to 4 conduction subbands. For valence band we obtain the Luttinger Hamiltonian as a 8X8 matrix in our case of a GaAs/AlGaAs QW structure under the influence of a moderately strong magnetic field.

The electron and hole motion are affected by magnetic field in the z-direction. The wavefunction for the valence band can be written as,

$$\psi^n(\vec{r}) = \sum_{m_j} f_{m_j}^{n}(\vec{r}) u_{m_j}^{n}(\vec{r}) \exp(i ky),$$

(1)
with the sum extending over the allowed values of \(m_j\), viz. \(\pm \frac{3}{2}\) for \(hh\) and \(\pm \frac{1}{2}\) for \(lh\). \(u_m^v(\mathbf{r})\) are the degenerate Bloch functions. In our case \(f_m^v\) is comprised of two components \(\chi_v(z)\) and \(\phi_v(x)\) to account for the quantum confinement and magnetic field effects. Since the magnetic field in Landau gauge leads to the potential similar to that of harmonic oscillator, we choose \(\phi's\) to be the Hermite-Gaussian functions.

Thus, the basis functions for the valence bands in our case can be written as,

\[
\begin{align*}
\chi_{hh1}^1(z) & \phi_{n-2}(x) \quad u_{\frac{3}{2}}(x, y, z) \\
\chi_{hh1}^2(z) & \phi_n(x) \quad u_{-rac{1}{2}}(x, y, z) \\
\chi_{hh2}^1(z) & \phi_{n-1}(x) \quad u_{\frac{3}{2}}(x, y, z) \\
\chi_{hh2}^2(z) & \phi_{n+1}(x) \quad u_{-rac{1}{2}}(x, y, z)
\end{align*}
\]

(2)

where the superscripts 1 and 2 denote the two quantum well levels considered. Similarly in the conduction band the wave functions can be written as,

\[
\begin{align*}
\chi_c^1(z) & \phi_{n-1}(x) \quad u_{\frac{1}{2}}(x, y, z) \\
\chi_c^2(z) & \phi_n(x) \quad u_{-rac{1}{2}}(x, y, z) \\
\chi_c^3(z) & \phi_{n-1}(x) \quad u_{\frac{1}{2}}(x, y, z) \\
\chi_c^4(z) & \phi_{n+1}(x) \quad u_{-rac{1}{2}}(x, y, z)
\end{align*}
\]

(3)

The total 8x8 Hamiltonian that determines the solutions for the hole wavefunctions is given by,

\[
\begin{bmatrix}
A_{hh1} - 3C_1 & B_1a^2 & 0 & 0 & 0 & 0 & \Delta_{12a}^\dagger & 0 \\
B_1a^2 & A_{hh1} + C_1 & 0 & 0 & 0 & 0 & \Delta_{12a} & 0 \\
0 & 0 & A_{hh1} - C_1 & B_1a^2 & \Delta_{21a} & 0 & 0 & 0 \\
0 & 0 & B_1a^2 & A_{hh1} + 3C_1 & 0 & \Delta_{12a}^\dagger & 0 & 0 \\
0 & 0 & \Delta_{21a} & 0 & A_{hh2} - 3C_1 & B_2a^2 & 0 & 0 \\
0 & 0 & 0 & \Delta_{12a} & B_2a^2 & 0 & A_{hh2} + C_1 & 0 \\
\Delta_{12a}^\dagger & 0 & 0 & 0 & 0 & 0 & A_{hh2} - C_1 & B_2a^2 \\
0 & \Delta_{21a}^\dagger & 0 & 0 & 0 & 0 & B_2a^2 & A_{hh2} + 3C_1
\end{bmatrix}
\]

(4)

Here, \(A_{\lambda j} = E_{\lambda j} + \hbar \omega_1(a^j a + 1/2), B_j = C_2 < \chi_{hh1}|\chi_{hh1}>, \Delta_{ij} = 2\gamma_3C_3 < \chi_{lh1}|\partial_z|\chi_{lh1}>, C_1 = \kappa \mu_B B\)

and \(C_2 = \hbar^2(\gamma_2 + \gamma_3)/(2\ell_c^2m_0), C_3 = \hbar^2\sqrt{\gamma_3}/(2m_0\lambda')\); \(i, j\) take the values 1, 2. Also \(a^j\) and \(a^\dagger\) are the Landau level lowering and raising operators, \(\lambda = lh, hh\) and \(\lambda'\) is the magnetic length. The 8x8 matrix in equation 4 is diagonalized to obtain the energy eigenvalues and the corresponding eigenvectors \(W_j\), \(j\) ranging from 1 to 8.

### 2.2. Transition dipole moment matrix elements and selection rules

We now calculate the transition dipole moment matrix elements according to the selection rules to find the allowed and forbidden transitions. The dipole matrix element of a transition between valence subband states and conduction band states can be written as,

\[
\mu_j = \psi_{m_j}^c|\bar{\epsilon} p \psi_{m_j}^v| = \sum_{m_j} J_{m_j} < u_{m_j}^c|\bar{\epsilon} p V_{m_j}^v >,
\]

(5)

\[
J_{m_j} = < \bar{f}^c(\mathbf{r})|f_{m_j}^v(\mathbf{r}) >.
\]

(6)

In our case

\[
J_{m_j} = < \chi^v(z) \phi_v(x)|\chi^v(z) \phi_v(x) >
\]

(7)

and the matrix element

\[
< u^v|p_v|V^v > = \delta_{v',v} \imath \eta P/\hbar, \quad v, V' \epsilon \{x, y, z\},
\]

(8)
The dipole matrix elements for optical transitions according to selection rules \((p_x = p_y = p_z)\)

<table>
<thead>
<tr>
<th>(m_j)</th>
<th>(m_s)</th>
<th>RCP ((\sigma^+ ))</th>
<th>LCP ((\sigma^-))</th>
<th>Linearly Polarized ((\sigma^0))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+\frac{1}{2})</td>
<td>(+\frac{1}{2})</td>
<td>0</td>
<td>(-\frac{i E \sqrt{2}}{\hbar}[(u^c \uparrow</td>
<td>p_{x,y}</td>
</tr>
<tr>
<td>(+\frac{1}{2})</td>
<td>(-\frac{1}{2})</td>
<td>(-\frac{i E \sqrt{2}}{\hbar}[(u^c \uparrow</td>
<td>p_{x,y}</td>
<td>x, y \downarrow)])</td>
</tr>
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<td>(+\frac{1}{2})</td>
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<td>p_{x,y}</td>
<td>x, y \downarrow)])</td>
</tr>
<tr>
<td>(-\frac{1}{2})</td>
<td>(+\frac{1}{2})</td>
<td>(\frac{i E \sqrt{2}}{\hbar}[(u^c \uparrow</td>
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<td>(\frac{i E \sqrt{2}}{\hbar}[(u^c \uparrow</td>
<td>p_{x,y}</td>
<td>x, y \downarrow)])</td>
</tr>
</tbody>
</table>

Table 1. The Dipole Matrix elements for optical transitions according to selection rules \((p_x = p_y = p_z)\)

where \(\vec{e}\) is the electric field and \(\vec{p}\) is the momentum vector. For GaAs the value of the Kane matrix element \(P\) is calculated as \(2m_e P^2 = 22.71\ eV\).

The dipole matrix elements must satisfy certain selection rules for a transition to be allowed. These include the usual dipole selection rules which depend on the polarization of the incident light and that for envelope functions. Transitions are allowed only between the states with identical parity due to envelope function selection rules. Also the dominant allowed transitions obey the selection rules include the usual dipole selection rules which depend on the polarization of the incident light and that for envelope functions. Transitions are allowed only between the states with identical parity due to envelope function selection rules.

We present here the detailed numerical analyses of absorption characteristics of a GaAs/Al\(_x\)Ga\(_{1-x}\)As QW under the influence of moderately strong magnetic field applied normal to the QW surface. The QW is assumed to be shined by a femto-second pulsed Ti:sapphire laser.

The material parameters used are: \(m_e = 0.067m_0\) (\(m_0\) being the free electron mass), Luttinger parameters \(\gamma_1 = 6.85, \gamma_2 = 2.1\) and \(\gamma_3 = 2.9\),\(^{16}\) dephasing time \(T_2 = 1^{-1} = 10^{-12}\) s, bulk crystal band gap energy, \(E_g = 1.5117\ eV\), QW width \(L=70\) Å.

### 3. RESULTS AND DISCUSSIONS

We present here the detailed numerical analyses of absorption characteristics of a GaAs/Al\(_x\)Ga\(_{1-x}\)As QW under the influence of a moderately strong magnetic field applied normal to the QW surface. The QW is assumed to be shined by a femto-second pulsed Ti:sapphire laser.

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We have studied the absorption characteristics in magnetoactive GaAs/AlGaAs QWs for different polarization states of the input radiation. A perturbative approach is developed for spin splitting in nanostructures which shows in a simple and intuitive way that confinement due to magnetic field and the polarization states of incident electromagnetic radiation are intimately connected with the blue shifting and spin splitting as shown in Figure 1. These results provide an explanation of the dependence of optical transitions on polarization of incident radiation in quantum well structures. In Figure 1(a), we plot the Differential Transmission Spectra for linear polarization of light. According to the selection rules [see table 1], the linear polarized light excites spin-up and spin-down light-holes only. Application of magnetic field results in the spin splitting of the absorption peak and splitting increases with increasing magnetic field. Similar results are reported by Barticevic et al, Fromer et al and Munteanu et al. The most prominent peak appearing in the Fig. 1(a), splits in two parts corresponding to light-hole spin up and down states and the splitting increases with increase in the applied magnetic field. This enhancement in splitting can be attributed to the factor $C_1$ defined in equation (5) in our theoretical model. This is manifestation of the energy shifting of spin-up and -down states with increasing
magnetic field. This feature is absent in absorption spectra plotted for the circularly polarized ($\sigma^+$ and $\sigma^-$) input radiation (Figures 1(b) and 1(c)). The $\sigma^+$ and $\sigma^-$ polarized light excites only one lh and hh as shown in table 1. Thus, the spin splitting due to magnetic field is not observed, as the allowed transition is either for spin down or spin up states. In addition to this, the blue shift of the absorption peaks with increase in magnetic field is seen for $\sigma^+$, $\sigma^-$ and linear polarized light excitation as found in the present work agrees well with the results reported by Barticevic et al.\textsuperscript{17} at high magnetic field.

We observe a number of small peaks in the spectrum arising due to the valence band mixing effect.\textsuperscript{10} In absence of band mixing, the parabolic confinement lead to only two dipole-transitions for every polarization state, with the well known resonance frequencies for quantum wells. The strong coupling of light-hole and heavy-hole states with conduction band electron energy states leads to substantial shift of the resonance frequencies and introduces additional peaks in the spectra. This feature can be attributed to the fact that number of allowed transitions for higher magnetic field are more than that calculated using the selection rules. These multiple peaks at higher magnetic field have been reported in the past.\textsuperscript{19–23}

As is evident from Figs. 1(b) and 1(c), under both $\sigma^+$ and $\sigma^-$ polarized excitation, the DTS remains almost unaffected. This has been observed experimentally by Gerlovin et al.\textsuperscript{24}

4. CONCLUSIONS

The effect of polarization state of light on magnetoabsorption in GaAs/AlGaAs QW has been analyzed theoretically under Faraday configuration. We have applied the appropriate selection rules to calculate the transition dipole matrix elements for different states of polarization of the input light. Luttinger Hamiltonian formalism has been used to include valence subband mixing in the presence of magnetic field. We find Zeeman splitting of the spin-up and spin-down lines in case of light linearly polarized along the magnetic field direction. This Zeeman splitting is not observed for the circularly polarized light due to the contribution of only a single spin state following the selection rules. The spectra show the expected blue shift with the increase in magnetic field. Appearance of additional lines with magnetic field has been explained in terms of bandmixing. The results are found to be in good agreement with reported experimental observations.

5. ACKNOWLEDGEMENT

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REFERENCES