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Spin–orbit interaction effect on the linear and nonlinear properties of quantum wire in the presence of electric and magnetic fields

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ABSTRACT

Here we have investigated the influence of external electric field and magnetic field on the optical absorption and refractive index changes of a parabolically confinement wire in the presence of Rashba spin orbit interaction. We have used density matrix formulation for obtaining optical properties within the effective mass approximation. The results are presented as a function of quantum wire radius, electric field, magnetic field, Rashba spin orbit interaction strength and photon energy. Our results indicate an increase of electric field redshifts the peak positions of absorption coefficient and refractive index changes. The role of confinement strength and spin orbit interaction strength as control parameters on the linear and nonlinear properties have been demonstrated.

1. Introduction

In the last decades, the physical properties of low dimensional semiconductor structures viz. quantum wires, dots, wells etc., have drawn considerable interest for their appealing potential technological applications [1–4]. The confinement of these structures into low dimension leads to the formation of discrete energy levels (subbands) which results in drastic change in absorption spectra and evolution of many novel properties [5]. The nonlinear properties such as optical absorption and refractive index changes in these low dimensional structures have attracted much attention because of having high potentiality for device applications in photodetectors [6], far-infrared laser amplifiers [7] and high speed electro-optical modulators [8]. Recently, there has been significant research on semiconductor quantum wire (QW), especially the experimental and theoretical investigation of magnetic field on their optical properties [9,10]. Further, the energy spectrum tuneability by the effective radius and external electric and magnetic fields in QW have made it a very strong candidate for study of linear and nonlinear properties for device applications and are extensively investigated [11,12].

An area of high potency is the spin-dependent phenomena in QW for its abundance of physically observable phenomena [13–15]. They have promising potential for future spin electronic devices with low power consumption, high speed, and a high degree of functionality [16–18]. In these devices the observable physical properties like spin degree of freedom is used for information processing in addition to the electron charge. Most of these devices are proposed to manipulate electron spin via spin orbit interaction (SOI). Two basic mechanisms of the SOI are Rashba SOI [19] and Dresselhaus SOI [20]. The former arises due to structural inversion asymmetry, while the latter is caused by bulk inversion asymmetry in non-centro-symmetric materials. The Rashba SOI has the practical advantages of depending on the electronic environment of the hetero-structure. Thus the strength of the Rashba SOI can be tuned by changing the gate voltage [21] and the spin related phenomena can be controlled. Much work has been devoted to investigate the Rashba SOI effects on the energy dispersion of the quantum wires [22]. The optical properties of nanostructures have also been studied by many researchers, both experimental and theoretical [23–26]. External parameters like static magnetic field, electric field, donor impurity, size etc. play important role affecting the optical properties of the nanostructures [25–27]. Karabulut et al. have extensively studied the effects of impurity, electric field, size and optical intensity on the linear and the nonlinear properties of quantum dot [27]. Recently, Rezaei [28] have studied the effects of hydrostatic pressure, external electric and magnetic fields on the linear and nonlinear optical properties of quantum well wires.

Although the linear and the third order absorption coefficients and refractive index change have been investigated, for both quantum dots and quantum wires, [10,27,28–32] in the best of our knowledge the effect of SOI and combined effect of SOI and external electric and magnetic fields on these optical properties of

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a nanostructure have not been studied extensively. In this work, we investigate the effects of Rashba SOI and external electric and magnetic field and the combined effect of all of these three on the linear and nonlinear optical properties of a QW. We obtain the exact wave functions of the charge carriers in a QW with parabolic confinement in one direction and placed in transverse electric and magnetic fields. Using the density matrix formalism we obtain the absorption coefficients and the refractive index changes corresponding to the spin flip transitions and spin allowed transitions. This paper is organized in the following way. In Section 2 we propose a model Hamiltonian with Rasbha SOI and describe the formulation based density matrix theory in presence of THz laser field, In Section 3 we show and discuss the numerical results. Finally, in Section 4 we present our concluding remarks.

2. Theoretical framework

We consider a two dimensional electron gas in x–y plane. The electron motion is confined in x-direction by a parabolic confinement making it a thin quantum wire along y-direction. When an external magnetic field, $\vec{B}=(0,0,B)$ whose corresponding vector potential is $\vec{A}=Bxe_y$ in the Landau gauge, is applied to the quantum wire, the single electron Hamiltonian is given as [33,34]

$$H_0=\frac{(\vec{p}+e\vec{A})^2}{2m^*}+\frac{1}{2}m^*\omega_0x^2+\frac{1}{2}g\mu_B\vec{\sigma}\cdot\vec{B}+H_R \tag{1}$$

where ω_0 is the oscillator strength, m^* is the effective mass of charge carrier, g is the Lande's g factor, $\mu_B=e\hbar/2m_0$ the Bohr magnetron and σ is well known Pauli spin matrix vector. H_R in Eq. (1) is the Rashba SOI Hamiltonian term in presence of magnetic field, which is given by

$$H_R=\frac{\alpha}{\hbar}(\vec{\sigma}\times(\vec{p}+e\vec{A}))_z \tag{2}$$

where α is the Rashba SOI factor which can be varied with the gate voltage.

When external electric field, $\vec{F}=(F,0,0)$ is applied to quantum wire then the Hamiltonian of this system transforms into

$$H=\frac{1}{2m^*}(p_x^2+(p_y+eBx)^2)+\frac{1}{2}m^*\omega^2x^2+eFx+\frac{1}{2}g\mu_B\sigma_zB$$
$$+\frac{\alpha}{\hbar}(\sigma_x(p_y+eBx)-\sigma_yp_x) \tag{3}$$

where $\omega=(\omega_0^2+\omega_c^2)^{1/2}$ is the effective cyclotron frequency and $\omega_c=eB/m^*$ is the cyclotron frequency. As the Hamiltonian for the quantum wire is invariant under translation along the length of the wire, the system wavefunction can be written as

$$\Psi(x,y)=\phi(x)\exp(ik_yy), \tag{4}$$

where k_y is wave number of the plane wave along the y-direction. On writing p_y in terms of k_y, H reduces to$H=H_0^i+H_R^i$ where

$$H_0^i=\frac{p_x^2}{2m^*}+\frac{1}{2}m^*\omega^2(x-x_0')^2-\frac{e^2F^2}{2m^*\omega^2}+\frac{{\omega_0}^2\hbar^2{k_y}^2}{\omega^22m^*}-\frac{e^2FB\hbar k_y}{m^{*2}\omega^2}$$
$$+\frac{1}{2}g\mu_B\sigma_zB \tag{5}$$

and

$$H_R^i=\alpha\left(\sigma_x\left(k_y+\frac{eBx}{\hbar}\right)-i\sigma_y\frac{d}{dx}\right) \tag{6}$$

where $x_0'=-(eF/m^*\omega^2)-(eB\hbar k_y/m^2\omega^2)$ is the guiding center coordinate for the harmonic oscillator.

The energy eigenvalues and eigenvectors of H_0^i are given as

$$H_0^i\psi_{n\sigma}(x)=E_{n\sigma}\psi_{n\sigma}(x) \tag{7}$$

where

$$\psi_{n\sigma}(x)=\frac{1}{\sqrt{\sqrt{\pi}c_l2^nn!}}H_n\left(\frac{x-x_0'}{c_l}\right)\exp\left(-\frac{1}{2}\left(\frac{x-x_0'}{c_l}\right)^2\right)\chi_\sigma \tag{8}$$

with $n=0,1,2\ldots$; $\sigma=\pm$, and $c_l=\sqrt{\hbar/m^*\omega}$ are the characteristics length of the harmonic oscillator. $H_n(x)$ are the hermite polynomials, χ_σ are the spinor functions for spin up ($\chi_+=\begin{pmatrix}1\\0\end{pmatrix}$) and spin down ($\chi_-=\begin{pmatrix}0\\1\end{pmatrix}$). The eigenenergies of Eq. (7) are

$$E_{n\sigma}=\hbar\omega\left(n+\frac{1}{2}\right)-\frac{e^2F^2}{2m^*\omega^2}+\frac{{\omega_0}^2\hbar^2{k_y}^2}{\omega^22m^*}-\frac{e^2FB\hbar k_y}{m^{*2}\omega^2}+\frac{1}{2}g\mu_B\sigma B \tag{9}$$

we have introduced the length scale characterizing the strength of lateral confining potential $R=\sqrt{\hbar/m^*\omega_0}$, i.e. effective radius of quantum wire. Expanding $\phi(x)$ in terms of $\psi_{n\sigma}(x)$ as $\phi(x)=\sum_{n\sigma}a_{n\sigma}\psi_{n\sigma}(x)$, the eigenvalue equation for the Hamiltonian 'H' can be written as

$$\sum_{n\sigma}a_{n\sigma}(E_{n\sigma}-E)\psi_{n\sigma}(x)+\sum_{n\sigma}a_{n\sigma}H_R^i\psi_{n\sigma}(x)=0 \tag{10}$$

and using the orthogonality conditions of $\psi_{n\sigma}(x)$, we have

$$(E_{n\sigma}-E)a_{n\sigma}+\sum_{n'\sigma'}a_{n'\sigma'}\langle\psi_{n\sigma}|H_R^i|\psi_{n'\sigma'}\rangle=0 \tag{11}$$

where the matrix elements of 2nd term of this equation are evaluated as

$$\langle n\sigma|H_R^i|n'\sigma'\rangle=\alpha\left[\left(1-\frac{{\omega_c}^2}{\omega^2}\right)k_y-\frac{\omega_ceF}{\hbar\omega^2}\right]\delta_{n,n'}\delta_{\sigma,-\sigma'}$$
$$+\frac{\alpha}{c_l}\left[\left(\frac{\omega_c}{\omega}+\sigma\right)\sqrt{\frac{n+1}{2}}\delta_{n,n'-1}+\left(\frac{\omega_c}{\omega}-\sigma\right)\sqrt{\frac{n}{2}}\delta_{n,n'+1}\right]\delta_{\sigma,-\sigma'} \tag{12}$$

For studying the linear and the nonlinear optical properties of the QW, we use the density matrix approach and perturbation expansion method. The analytical forms of the linear and third order absorption coefficients for the lowest two spin split sub bands are obtained as [26–32]

$$\alpha^{(1)}(\omega)=\omega\sqrt{\frac{\mu}{\varepsilon_r}}\frac{N_c\Gamma_{if}|M_{if}|^2}{\hbar\{(\omega_{fi}-\omega)^2+\Gamma_{if}^2\}} \tag{13}$$

and

$$\alpha^{(3)}(\omega,I)=-\omega\sqrt{\frac{\mu}{\varepsilon_r}}\frac{I}{2\varepsilon_0n_rc}\frac{4N_c\Gamma_{if}}{\hbar^3}\frac{|M_{if}|^2}{(\omega_{fi}-\omega)^2+\Gamma_{if}^2}$$
$$\times\left[\frac{|M_{if}|^2}{(\omega_{fi}-\omega)^2+\Gamma_{if}^2}+\frac{(M_{ff}-M_{ii})^2(3{\omega_{fi}}^2-4\omega_{fi}\omega)({\omega_{fi}}^2-\Gamma_{if}^2)}{4({\omega_{fi}}^2+\Gamma_{if}^2)\{(\omega_{fi}-\omega)^2+\Gamma_{if}^2\}}\right] \tag{14}$$

where $\hbar\omega$ is the incident photon energy, I is the intensity of incident light, μ is the magnetic susceptibility, ε_r is the relative permittivity of the quantum wire, N_c is the electron density, ε_0 is the permittivity of vacuum, n_r is the refractive index of quantum wire material, $1/\Gamma_{if}$ is the relaxation time and subscript i and f denote the initial and final states. $\omega_{fi}=(E_f-E_i)/\hbar$ with E_i and E_f are the initial and final sublevel. These eigenvalues are obtained by diagonalization of Eq. (11). M_{if} is the transition matrix element between the initial and final states, and it is defined as $M_{if}=|\langle\phi_i|ex|\phi_f\rangle|$. Here the polarization of the electromagnetic radiation is chosen as the x-direction.

The total absorption coefficient is written as

$$\alpha_T(\omega,I)=\alpha^{(1)}(\omega)+\alpha^{(3)}(\omega,I) \tag{15}$$

The linear and third order nonlinear relative changes in refractive index associated with the optical transition are