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Spin–orbit interaction effect on nonlinear optical rectification 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 nonlinear optical rectification of a parabolic 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 gives the red-shift of the peak positions of nonlinear optical rectification. The role of confinement strength and spin–orbit interaction strength as control parameters on this nonlinear property 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 [1–3]. The confinement of these structures into the low dimension leads to the formation of discrete energy levels (subbands) which results in drastic change for absorption spectra and evolution of many novel properties [4]. The nonlinear properties in these low dimensional structures have attracted much attention because of having high potentiality for several applications [5,6]. Among the nonlinear optical properties, significant attention has been paid to second order optical properties such as nonlinear optical rectification (OR) [7–9]. Recently, there has been significant research on semiconductor quantum wire (QW), especially the experimental and theoretical investigation of magnetic field on their optical properties [10,11]. Further, the energy spectrum tune-ability by the effective radius and external electric and magnetic fields in QW have made it a very strong candidate for study of nonlinear properties for device applications and are extensively investigated [12,13].

An area of high potency is the spin-dependent phenomena in QW for its abundance of physically observable phenomena [14,15]. They have promising potentiality for future spin electronic devices with low power consumption, high speed, and a high degree of functionality [16,17]. 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 [18] and Dresselhaus SOI [19]. 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 [20] 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 [21,22]. 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 [9,25]. Baskoutas 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 et al. [28] have studied effects hydrostatic pressure, external electric and magnetic fields on the linear and nonlinear optical properties of quantum well wires.

Although the second order optical rectification has been investigated, for both quantum dots, quantum wells and quantum wires [7–9,24,29–31], 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 a nanostructure has not been studied extensively. In this work, we investigate the effects of

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Rashba SOI and external electric and magnetic field and the combined effect of all of these three on the nonlinear optical rectification 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. Then using the density matrix formalism we obtain the optical rectification corresponding to the spin flip transition. The red-shifting effect on this property due to the external electric field is also demonstrated.

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 $\vec{A}=Bx\hat{e}_y$ in the Landau gauge, is applied to the quantum wire, the single electron Hamiltonian is given as [32,33]

$$H_0=\frac{(\vec{p}+e\vec{A})^2}{2m^*}+\frac{1}{2}m^*\omega_0^2x^2+\frac{1}{2}g\mu_B\vec{\sigma}\times\vec{B}+H_R \tag{1}$$

where ω_0 is the oscillator strength, m^* is the effective mass if charge carrier, g is the Lande′s g factor, $\mu_B=e\hbar/2m_0$ is 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

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

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

$$x_0'=-\frac{eF}{m^*\omega^2}-\frac{eB\hbar k_y}{m^{*2}\omega^2}$$

is the guiding center coordinate for the harmonic oscillator.

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

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

where

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

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

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

we have introduced length scale characterizing the strength of lateral confining potential $l_0=\sqrt{\hbar/m^*\omega_0}$. Energy scales corresponding to confining potential and Rashba SOI are $\mathrm{E}_p=\hbar\omega_0$ and $\Delta_{so}=m^*\alpha^2/2\hbar^2$ respectively. Expanding $\phi(x)$ of Eq. (4), 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,

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

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

$$(\mathrm{E}_{n\sigma}-E)a_{n\sigma}+\sum_{n'\sigma'}a_{n'\sigma'}\left\langle\psi_{n\sigma}right.|H_R^i\middle|left.\psi_{n'\sigma'}\right\rangle=0 \tag{11}$$

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

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

For studying the nonlinear OR coefficient of the QW, we use the density matrix approach and perturbation expansion method. The analytical forms of the nonlinear OR for the lowest two spin split sub bands are obtained as [7–9]

$$\chi_0^{(2)}(\omega)=\frac{4e^3N_c\delta_{01}M_{if}{}^2}{\varepsilon_0\hbar^2}\times\frac{\omega_{fi}^2\left(1+\frac{T_1}{T_2}\right)+\left(\omega^2+\frac{1}{T_2^2}\right)\left(\frac{T_1}{T_2}-1\right)}{\left((\omega_{fi}-\omega)^2+\frac{1}{T_2^2}\right)\left((\omega_{fi}+\omega)^2+\frac{1}{T_2^2}\right)} \tag{13}$$

where $\hbar\omega$ is the incident photon energy, N_c is the electron density, ε_0 is the permittivity of vacuum, T_1 is the longitudinal relaxation time, T_2 is the transverse 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 diagonalisation of Eq. (11). M_{if} is the transition matrix element between the initial and final states, and it is defined as $M_{if}=|\langle\phi_i|ex|\phi_f\rangle|$ and $\delta_{01}=|M_{11}-M_{00}|$. Here the polarization of the electromagnetic radiation is chosen as the x direction.

In the next section we present the results obtained and their relevant discussions.

3. Results and discussions

In this work, we study the nonlinear optical rectification for different external electric and magnetic field strength in presence of Rashba spin–orbit coupling. Taking cognizance of the fact that the inter-level energy spacing is of the order of a few meV s, we have used the effective atomic units where in $e=\hbar=m^*=\varepsilon=1$, where m^* and ε are the relative effective mass and the relative dielectric constant respectively. For the evaluation of the optical rectification, we have considered the following parameters [34] for InAs quantum wire: $m^*=0.030m_0$, $\varepsilon=13.11$, $g=-15$, $\hbar\omega_0=10$ meV to 40 meV that is confinement potential which corresponds to a quantum wire with diameter of about 11.2–8 nm and Rashba coupling factor, $\alpha=10$–50 meV nm.