Physica E 81 (2016) 59–65

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Optical properties of double quantum wires under the combined effect of spin-orbit interaction and in-plane magnetic field

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HIGHLIGHTS

- Quantum wire formed by a symmetric, double quartic-well potential is considered.
- In-plane magnetic field and spin-orbit interactions are taken into account.
- Optical absorption coefficients and refractive index changes are surveyed.
- Remarkable modifications in the optical characteristics have been observed.

ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form
10 February 2016
Accepted 18 February 2016
Available online 20 February 2016

Keywords:
Double quantum wire
In-plane magnetic field
Spin-orbit coupling
Optical properties

ABSTRACT

In this work, we investigate the intersubband optical absorption coefficients and refractive index changes for transitions between the lower-lying electronic levels of double quantum wires formed by a symmetric, double quartic-well potential. The system is subjected to an external in-plane magnetic field and Rashba and Dresselhaus spin-orbit couplings are taken into account. The analytical expressions of the linear and nonlinear absorption coefficients and refractive index changes are obtained by using the compact density-matrix approach and iterative method. The dependence of the optical characteristics on the magnetic field, spin-orbit interactions, quantum wire radius, structural parameter and photon energies has been examined. Numerical results exhibit that the optical properties are considerably sensitive to the strength and orientation of magnetic field as well as to the spin-orbit couplings and thus can be controlled by these parameters.

1. Introduction

Recently, remarkable amount of work has been devoted to study nonlinear optical properties of the low-dimensional semiconductor structures such as quantum wells, quantum wires and quantum dots due to their novel physical and optical properties [1–6]. Strong quantum confinement of the charge carriers leads to the formation of discrete energy levels which causes drastic changes in the optical properties [7–9]. The nonlinear effects in these systems are enhanced significantly over those in their bulk counterparts. Therefore, these structures become attractive for theoretical and experimental studies owing to their potential for device applications in laser and optical modulation technology such as laser amplifiers, photodetectors, and high-speed electro-optical modulators [10–12].

Furthermore, a great deal of effort has been dedicated to understand the basic properties of double semiconductor structures (double quantum wells, double quantum wires, and double quantum dots) which play an essential role for the explanation of many physical phenomena such as tunneling and doublet splitting. Effects of external fields on the electronic and transport properties of double quantum wires (QWs), consisting of two parallel long wires coupled through a potential barrier which allows the tunneling of the electrons between them, have been investigated both theoretically [13,14] and experimentally [15,16]. The influence of magnetic field on the energy dispersion and magnetotransport properties of dual QWs has been reported by Shi and Gu [17]. The energy spectrum, magnetization and conductivity of tunnel-coupled double QWs subjected to an external magnetic field have been searched theoretically by Lyo and his collaborators [18,19]. Korepov and Liberman [20,21] studied the electronic transport properties of double QWs by considering impurity, perpendicular magnetic field and correlated disorder.

On the other hand in recent years, considerable interest has been

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http://dx.doi.org/10.1016/j.physe.2016.02.048
1386-9477/

focused on the spin-dependent phenomena in low-dimensional semiconductors because they offer advantages for spintronic devices with higher speed, lower power consumption and higher degree of functionality [22,23]. The key process in the device functionality relies on the generation or manipulation of spin-polarized electronic population which designate an excess of spin up or spin down electrons. Efficient spin control can be achieved by means of spin-orbit (SO) interactions which arise from inversion asymmetry properties of semiconductor structures. Bulk inversion asymmetry gives rise to Dresselhaus SO interaction [24], whereas structural inversion asymmetry induces Rashba SO interaction [25]. Increasing number of works have surveyed the effects of external fields and SO couplings on the band structure behavior and transport properties of low-dimensional systems [26–33].

Theoretical and experimental examination of the optical properties of nanostructures have become an extensively studied pursued area of research over the last decades [34–42]. According to the results obtained from these studies, the external agents such as electric/magnetic fields, impurity, temperature, and size as well as the internal mechanisms, play an important role on the optical response of a system. Khordad [43] studied the optical properties of QW considering an external perpendicular magnetic field and Rashba SO interaction. The influence of an external electric and magnetic fields on the optical absorption and refractive index changes in QW with Rashba SO coupling has been investigated by Lahon et al. [44]. Lastly, in our previous study we reported the optical properties of parabolically confined QW by taking into account an in-plane magnetic field and Rashba SO interaction [45]. Even though considerable attention has been paid to explore the effects of Rashba SO interaction and magnetic/electric fields on optical properties of single QWs, optical characteristics of double QWs under an in-plane magnetic field considering the simultaneous presence of both Rashba and Dresselhaus SO interactions have not been investigated so far. In the present work, we focus on exploring the influence of both SO interactions and its competition with an external in-plane magnetic field on the linear and third-order nonlinear optical absorption coefficients and refractive index changes in QW described by an anharmonic potential.

The paper is organized as follows. In Section 2 the theoretical framework is briefly presented. We discuss the numerical results in Section 3 and finally, the conclusions are given in Section 4.

2. Theory and formalism

We consider a quasi-one-dimensional quantum wire with double-well confinement potential in y direction given as

$$V(y) = \frac{1}{4}\lambda\left(y^2 - \frac{\mu^2}{\lambda}\right)^2. \tag{1}$$

Height of the barrier between the wells and their width are controlled by positive, adjustable structural parameters μ and λ. In-plane magnetic field applied with an arbitrary orientation is chosen as $\mathbf{B} = B(\cos\phi\,\mathbf{e}_x + \sin\phi\,\mathbf{e}_y)$, where ϕ represents the azimuthal angle. The single-particle Hamiltonian of the quasi-one-dimensional double QW with Rashba and Dresselhaus SO interactions is given by

$$\mathcal{H} = \left[\frac{p_x^2 + p_y^2}{2m^*} + V(y)\right]\sigma_0 + \frac{1}{2}g^*\mu_B B(\cos\phi\sigma_x + \sin\phi\sigma_y) + \mathcal{H}_R + \mathcal{H}_D. \tag{2}$$

Here the first term consists of the kinetic energy and confinement potential whereas second term stands for the Zeeman contribution. p_x and p_y are actual components of linear momentum, m^* is effective mass, g^* and μ_B are the effective Lande g-factor and Bohr magneton, respectively. σ_x and σ_y represent the Pauli spin matrix components. $\mathcal{H}_R$ and $\mathcal{H}_D$ are the contributions due to Rashba and Dresselhaus SO interactions that are given as

$$\mathcal{H}_R = \frac{\alpha_R}{\hbar}(p_y\sigma_x - p_x\sigma_y), \tag{3}$$

$$\mathcal{H}_D = \frac{\alpha_D}{\hbar}(p_x\sigma_x - p_y\sigma_y). \tag{4}$$

α_R is Rashba SO coupling parameter that can be tuned by changing gate voltages and α_D corresponds to Dresselhaus SO coupling factor which can be varied by sample thickness or electron density [46,47].

Due to the translational invariance in the x direction, the eigenfunctions of Hamiltonian can be decomposed into a plane wave in the longitudinal direction and a y-dependent spinor part as follows:

$$\psi_{nk_x}(\mathbf{r}) = \frac{e^{ik_x x}}{\sqrt{L}}\begin{pmatrix}\varphi_{nk_x}(y,\uparrow)\\ \varphi_{nk_x}(y,\downarrow)\end{pmatrix} \tag{5}$$

where φ_{nk_x} defines spinor function. The energy eigenvalues and eigenfunctions of double QW are obtained by using the finite element method in one-dimension which is based on expressing the wave functions as a linear combination of interpolation polynomials multiplied by as-yet-unknown coefficients in these elements [48,49].

Subsequent to the calculation of the energy eigenvalues and eigenfunctions, by using the framework of compact-density matrix formalism and iterative scheme, absorption coefficients and relative changes in the refractive index corresponding to the optical transitions between two subbands can be determined. The system under debate is subjected to an electromagnetic field of frequency ω such that

$$\mathbf{E}(t) = \tilde{E}e^{i\omega t} + \tilde{E}^* e^{-i\omega t}. \tag{6}$$

The electronic polarization response $P(t)$ and the susceptibility $\chi(\omega)$ caused by the optical field $E(t)$ are expressed by dipole operator M and density matrix as [50]

$$P(t) = \varepsilon_0\chi(\omega)\tilde{E}e^{-\omega t} + \varepsilon_0\chi(-\omega)\tilde{E}^* e^{\omega t} = \frac{1}{V}\mathrm{Tr}(\rho M), \tag{7}$$

where ε_0 is the permittivity of the free space, ρ and V are the one-electron density matrix and the volume of the system and Tr stands for the trace. The susceptibility $\chi(\omega)$ is related to the absorption coefficient $\alpha(\omega)$ as

$$\alpha(\omega) = \omega\sqrt{\frac{\mu}{\varepsilon_r}}\,\mathrm{Im}[\varepsilon_0\chi(\omega)]. \tag{8}$$

μbeing the permeability of the system, $\varepsilon_r = n_r^2\varepsilon_0$ is the relative permittivity of the QW material where n_r states the medium refractive index. The analytical forms of the linear and third-order nonlinear optical absorption coefficients are given as follows [40,43]:

$$\alpha^{(1)}(\omega) = \omega\sqrt{\frac{\mu}{\varepsilon_r}}\left[\frac{\sigma_v\hbar\Gamma_{ij}|M_{ij}|^2}{(E_{ij} - \hbar\omega)^2 + (\hbar\Gamma_{ij})^2}\right] \tag{9}$$

$$\alpha^{(3)}(\omega) = -\omega\sqrt{\frac{\mu}{\varepsilon_r}}\left(\frac{I}{2\varepsilon_0 n_r c}\right)\frac{\sigma_v\hbar\Gamma_{ij}|M_{ij}|^2}{[(E_{ij} - \hbar\omega)^2 + (\hbar\Gamma_{ij})^2]^2} \times\left\{4|M_{ij}|^2 - \frac{|M_{ii} - M_{jj}|^2[3E_{ij}^2 - 4E_{ij}\hbar\omega + \hbar^2(\omega^2 - \Gamma_{ij}^2)]}{E_{ij}^2 + (\hbar\Gamma_{ij})^2}\right\}. \tag{10}$$

Here I is the intensity of the incident field, σ_v is the density of