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Influence of hydrostatic pressure and spin orbit interaction on optical properties in quantum wire

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ABSTRACT

The role of hydrostatic pressure and temperature on the optical properties of a two dimensional electron gas confined in a quantum wire having Rashba spin orbit interaction is studied in this work. The energy band gap and thus the effective mass of the charge carriers are found to have strong dependence of the hydrostatic pressure on the quantum wire and its absolute temperature. This in turn affects the linear as well as the nonlinear optical properties of the quantum wire. The external magnetic field, temperature, hydrostatic pressure and the Rashba spin orbit interaction are found to interplay in determining the linear and nonlinear absorption coefficient and refractive change in the quantum wire as a response to incident electromagnetic radiation.

1. Introduction

Recently, much attention have been paid to the low dimensional semiconductor structures e.g. quantum well, wire, dot etc., for their promising applications in the field of optoelectronics [1–5]. The strong confinement effects induce profound optical response in the quantum nanostructures in comparison to the bulk materials. Therefore these structures have gained high potentiality for device applications in laser and optical modulation technology such as photodetectors, far-infrared laser amplifiers, and high-speed electro-optical modulators [6–10]. The energy spectrum tunabilty of quantum wire (QW) by the confinement potential and other parameters make it suitable system for studying the optical properties in the THz regime. Among the optical properties, there has been significant research on linear and nonlinear optical absorption coefficients and refractive index changes in semiconductor QW, especially in the theoretical and experimental investigation [11–15].

There has been growing interest in the studies of spin-related phenomena in quantum confined structures for their fundamental role in future spin based electronic devices with high speed, low power consumption and a high degree of functionality [16–20]. These devices use the observable physical properties of electron spin for information processing along with the electron charge. The mechanism of most of the proposed devices work for manipulation of electron spin is the Rashba Spin Orbit Interaction (SOI) [21]. An important characteristic of Rashba SOI is that its strength can be influenced by applying gate voltage [22]. Rashba SOI, therefore, is one of the choicest physical processes for studies associated with device applications dependent on spin manipulations in quantum nanostructures. One of the revolutionary device proposals in this direction is the Datta-Das spin field effect transistor [19]. Alternatively, optical properties of nanostructures exhibiting Rashba SOI hold promising potential in the areas of spin dependent device applications. There are number of theoretical and experimental investigations on effects of Rashba SOI on the optical properties of nanostructures [23–31], such as, Khordad has investigated the influence of Rashba SOI and external magnetic field on the optical properties for QW [28]. Lahon et al. have studied the effects of Rashba SOI on the optical properties for quantum wire with external electric field and magnetic field [23]. Gisi et al. reported the simultaneous effects of in-plane magnetic field and spin-orbit interaction on the optical response for the QW [29]. Y. Karaaslan et al. have studied the effects of Rashba SOI and magnetic field on nonlinear optical properties for double QW [31].

Another externally controlled parameter which is able to manipulate the optical properties of quantum nanostructures is hydrostatic pressure. The hydrostatic pressure results in modification of the

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electronic band structure thereby leading to a change in effective masses of electron and holes, and resulting in a number of novel optical and physical responses of the confined systems [32–37]. In the recent times, these effects of hydrostatic pressure on the optical and electronic properties have been theoretically investigated by many researchers with different confinement potential for the low-dimensional structures [38–43]. Duque et al. have demonstrated on exciton related optical properties with hydrostatic pressure [34]. Ungan et al. reported the hydrostatic pressure effects on intersubband transitions in graded quantum well [36]. Rezaei et al. have extensively investigated the influences of hydrostatic pressure, on the linear and the nonlinear properties of quantum dot with external electric and magnetic fields [41]. Effects of hydrostatic pressure and temperature in disc shaped quantum dot have been studied by Liang and Xie [42]. Combined effects of hydrostatic pressure and SOI in quantum ring have been reported by Mughnetsyan et al. [25]. Lots of researchers have studied the effects of different parameters on the optical properties of low-dimensional structures; however, to the best of our knowledge, the influences of pressure, temperature and external magnetic field on optical properties with spin orbit interaction, have not been discussed in the parabolic confinement quantum wire so far. The understanding of Rashba SOI on the optical response for the quantum confined structures is fascinating and would be beneficial in many possible applications such as optospintronics devices and quantum information systems [43,44]. Thus, it will be very interesting to study on the optical properties in a quantum wire under the influence of pressure and temperature with spin orbit interaction.

This work explores the interplay of hydrostatic pressure, temperature and external magnetic field in a QW exhibiting Rashba SOI. The study uses the exact spin inclusive wavefunction of charge carrier in the parabolic confinement potential QW, placed in an external magnetic field. We have computed the eigenenergies and eigenfunctions using perturbation theory and diagonalisation technique. This work is structured as follows: Sec. 2 is related to computation of eigenenergies and eigenfunctions of QW with magnetic field, hydrostatic pressure, temperature and Rashba SOI. These quantities are further employed to determine the ACs and RICs using density matrix theory in presence of THz laser field, whereas Sec. 3 is related to discussion of the numerical results obtained for QW. Finally, the conclusions are presented in sec. 4.

2. Model and theory

We consider a system where the electrons are confined by split gates

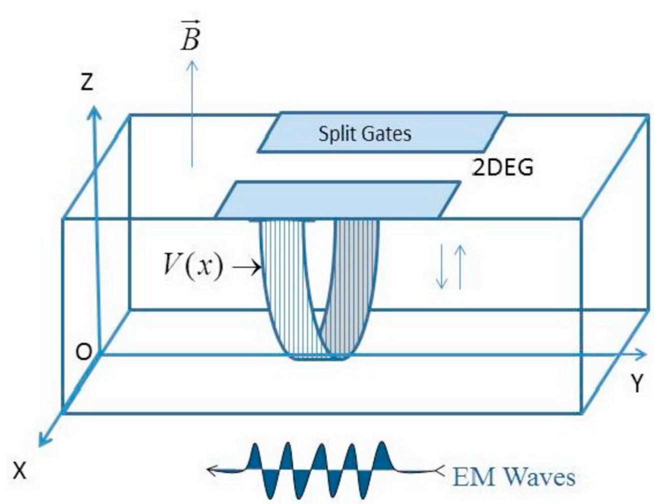

Fig. 1. Schematic view of the quantum wire model (non-layered) within the two dimensional electron gas with the parabolic potential showing the directions of an applied static magnetic field and laser field.

of the two dimensional electron gas in a x-y plane. This makes the semiconductor quantum well with its growth direction along the z direction. The lateral confinement along the x direction makes the quantum wire in the y direction. A relatively narrow quantum wire is chosen, so the form of confinement is approximated as a parabolic potential, $V(x) = m^*\omega_0 x^2/2$. Such narrow confinement can be realized by surface ploughing followed by a wet-chemical etching [45,46]. Here, the lowest subband in the z direction is considered because of very thin quantum well. An external magnetic field, $\vec{B} = (0, 0, B)$, is taken along the z direction, this makes the corresponding vector potential as $\vec{A} = Bxe_y$, in the Landau gauge. The single electron Hamiltonian of this system with spin orbit interaction under the action of hydrostatic pressure and temperature in the effective mass approximation may be complied as [16,47–49]

$$H = H_0 + H_Z + H_{SO}, \tag{1}$$

where H_0, contains the kinetic energy contribution with parabolic potential, H_z is the Zeeman energy splitting and H_{S0} is the Rashba spin orbit interaction term as

$$H_0 = \frac{(\vec{p} + e\vec{A})^2}{2m^*(P, T)} + V_i(P) \tag{2}$$

$$H_Z = \frac{1}{2} g\mu_B \vec{\sigma}\cdot\vec{B} \tag{3}$$

$$H_{SO} = \frac{\alpha}{\hbar}(\vec{\sigma} \times (\vec{p} + e\vec{A}))_z \tag{4}$$

Where σ is the Pauli spin matrix vector, g is the Lande's g factor, $\mu_B = \frac{e\hbar}{2m_0}$ the Bohr magnetron, α is the top gate [22,51,52] controlled Rashba SOI factor. $V_i(P) = \frac{1}{2}m^*(P)\omega_0^2(P)x^2$ is the pressure dependent potential and $m^*(P, T)$ is the effective mass of charge carrier which is dependent on pressure and temperature. For GaAs material, we have

$$m^*(P, T) = m_0[1 + \frac{15020\text{meV}}{E_g(P, T)} + \frac{7510\text{meV}}{E_g(P, T) + 341\text{meV}}]^{-1}, \tag{5}$$

where $E_g(P, T)$ is the bulk GaAs bandgap [36]

$$E_g(P, T) = (1519 + 10.7\text{kbar}^{-1}P - \frac{0.5405\text{K}^{-1}T^2}{T + 204})\text{meV}, \tag{6}$$

The static dielectric constant, which is dependent on temperature and pressure, for GaAs is given by Ref. [36]

$$\varepsilon_r(P, T) = \varepsilon_r(0, T_0)\exp(d_1(T - T_0))\exp(-d_2 P), \text{ for } \text{T} \geq 200 \text{ K}, \tag{7}$$

Where
$\varepsilon_r(0, T_0) = 13.18$, $d_1 = 20.4 \times 10^{-5}K^{-1}$, $d_2 = -1.73 \times 10^{-3}K^{-1}$ and $T_0 = 300$ K.

$$\varepsilon_r(P, T) = 12.74\exp(d_3(T - 75.6))\exp(-d_2 P), \text{ for } \text{T} < 200 \text{ K}, \tag{8}$$

Where $d_3 = 9.4 \times 10^{-5}K^{-1}$. The effective radius of QW is dependent on HP as relation given as

$$R(P) = R(0)[1 - 2P(S_{11} + S_{12})]^{1/2}, \tag{9}$$

where $S_{11} = 1.16 \times 10^{-3}\,\text{kbar}^{-1}$ and $S_{12} = -3.7 \times 10^{-4}\,\text{kbar}^{-1}$ are the component of the compliance tensor of GaAs [34]. $R(0)$ is the effective radius at zero HP. The effective radius is related to the confinement potential as

$$R(P) = \sqrt{\frac{\hbar}{m^*(P, T)\omega_0(P)}}, \tag{10}$$

Thus, the operable form of the harmonic potential strength is given as

$$\omega_0(P) = \omega_0(0)/[1 - 2P(1.16 \times 10^{-3}\text{kbar}^{-1} - 7.4 \times 10^{-4}\text{kbar}^{-1})]. \tag{11}$$

After keeping the vector potential, H_0 can be explicitly written as