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Spin–orbit interaction and magnetic field effects on the energy dispersion of double quantum wire

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ABSTRACT

We investigate the effects of Rashba spin–orbit interaction on the electronic energy dispersion and zero-temperature ballistic conductance of double quantum wire under the influence of perpendicular magnetic field. The wire system is represented by a symmetric, double quartic-well confinement potential. Numerical results reveal that competing effects between spin–orbit interaction and magnetic field modify strongly the energy subband structure and introduce anticrossings between subbands. Moreover, it is found that the conductance character of a quasi-one-dimensional ballistic conductor, which is closely related to the energy-dispersion spectrum, is very sensitive to the shape of potential profile, magnetic field and Rashba spin–orbit coupling.

1. Introduction

The examination of electronic and optical properties of low-dimensional semiconductor structures formed by restricting the motion of charge carriers in the bulk structures, offers significant contributions to the evolving product technology of today. In the last two decades, with the advances in fabrication technology low-dimensional double semiconductor structures as well as single ones (such as quantum wells, quantum wires and quantum dots) are produced [1].

The one-dimensional double well potential (called as quadratic anharmonic double well oscillator, double minimum problem) in physics and chemistry is a well-known problem that have been studied for many years. This potential has been used to explain the many physical phenomena such as tunneling and doublet splitting by using quantum mechanical or semi-classical methods [2–7]. In these studies, usually WKB approximation, variational perturbation method etc. have been used for calculation of energy eigenvalues. In addition to these, vibrational-energy eigenvalues, eigenfunctions, transition moments, and absorption intensities have been investigated in detail with model of H bonds for symmetric and asymmetric double well potentials in the study given with Ref. [3]. Furthermore, there are also many studies about the inverse structure of ammonia molecule (NH_3) with this potential function in the literature [2,8].

Many interesting characteristics has been reported in double well and double-wire system. In the double-well potential system studies exhibit that if the two wells are sufficiently separated from each other, the lower energy eigenvalues are closely bunched as a couple [9–11]. Similar to this occurrence was obtained also in the study of double quantum wire structure (if the potential barrier is height enough) in Ref. [12]. Several theoretical [12–14] and experimental [15,16] studies investigated the effects of external fields on the electronic and transport properties of coupled double quantum wire structure

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which is created with the separation of two identical narrow quantum wires by a potential barrier. In particular, Lyo and his colleagues have investigated mobility, conductivity and magnetoresistance of the coupled double quantum wires subjected to magnetic field [17,18]. Morever, Korepov and Liberman have searched theoretically different physical properties (such as transport, spectrum of impurity states etc.) of two parallel quantum wires coupled by tunneling in an external perpendicular magnetic field [19,20]. Recently, magnetotransport properties of window-coupled double quantum wire have been investigated by Tang et al. [21,22].

On the other hand, the electron spin as well as the electron charge started to taken into account for information processing in the examinations of low-dimensional semiconductor structures. New devices based on manipulation and control of electron spin have the characteristics of more powerful, smaller and faster than those of existing [23–27]. The spin orientation in a semiconductor structure can generally be adjusted by the Rashba spin–orbit coupling (SOC) effect which arises due to the asymmetry associated with the confinement potential [28]. The effect of Rashba spin–orbit coupling can be varied by gate electric field and magnitude of coupling parameter can be determined from the characteristic beating pattern of the Shubnikov-de Haas oscillations in the magnetoresistence of two-dimensional electron gas [29,30].

Several theoretical and experimental works investigated the effects of external fields and spin–orbit coupling on the electronic and transport properties in low-dimensional systems [31–42]. Mireles and Kirczenow [43] researched the ballistic spin-transport properties of quasi-one-dimensional wires in the presence of the Rashba spin–orbit interaction, Governale and Zülicke [44] presented the effect of Rashba spin–orbit coupling on the band structure, spin accumulation and transport properties of quantum wires. Influence of a perpendicular magnetic fields on the spectral, spin and transport properties of semiconductor quantum wires with Rashba SOC has been investigated in Ref. [31,45,46]. Serra and coworkers reported the effects of in-plane magnetic field [47] whereas Su et al. focused on an inhomogeneous magnetic field [48] effects in quantum wires considering SOC.

Despite there are several works reporting the effects of magnetic field on electronic energy spectrum and conductance in tunnel-coupled (double) quantum wires [17], to our knowledge, less attention has been paid on the influence of spin–orbit coupling in double quantum wires. In the present work we will focus energy spectra and ballistic conductance quantum wire defined by a non-parabolic confinement potential, subjected to an external perpendicular magnetic field and taking into account the Rashba spin–orbit interaction. The organization of this work is as follows. Firstly in Section 2, we briefly describe the system and present the methodology used throughout our study. Section 3 is devoted to a summary of numerical results which is followed by a short concluding section.

2. Theoretical model and formalism

We consider a quasi-one-dimensional double quantum wire subjected to a perpendicular magnetic field as shown in Fig. 1. The system is imagined to be confined by a double-well potential given as

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

where μ and λ are positive, adjustable structural parameters controlling the height of the barrier between wells and the width of wells. The double-quantum wire system is chosen on the xy-plane therefore the electrons can move freely along the y-direction. The orientation of applied magnetic field is assumed to be in the z-direction, $\vec{B} = (0,\ 0,\ B)$. Thus, the vector potential corresponding to this field can be chosen as $\vec{A} = (0,\ Bx,\ 0)$ in Landau gauge. Under these conditions, the single-particle Hamiltonian for a quasi-one-dimensional double-quantum wire taking into account the Rashba spin–orbit interaction is

$$H = \frac{1}{2m^*}\left[p_x^2 + (p_y + eBx)^2\right]\sigma_0 + V(x)\sigma_0 + \frac{1}{2}g^*\mu_B B\sigma_z + H_R. \tag{2}$$

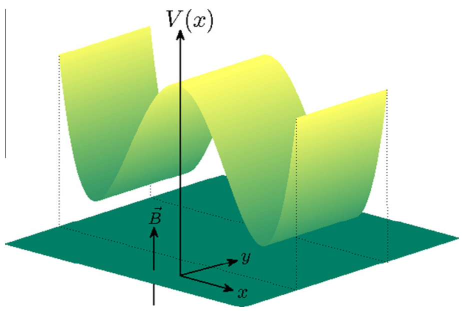

Fig. 1. (color online) Schematic representation of double quantum wire system.