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Rashba spin splitting in quantum nanowires in the presence of hydrogenic donor impurity

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ABSTRACT

The electronic subband states in the presence of hydrogenic donor impurity in quantum nanowires at the interface of semiconductor heterostructures devoid of structural inversion symmetry, are modeled and described in terms of a quasi-one-dimensional hydrogen atom with Rashba spin-orbit coupling. The energy levels and the spin-dependent subband states of the corresponding one-electron Schrodinger equation, are obtained using a two-step analytic solution as a function of the width L of the nanowire and the strength of the Rashba spin-orbit coupling α. The results thus obtained are checked against purely perturbative calculations in the limit of small spin-orbit coupling. In particular, it is found that the level splitting in a suitable range of the control parameters, L and α, results in spin-dependent electronic states of negative energy (bound states) as well as positive energy (scattering states). This novel result is of considerable interest for the generation of spin currents in the presence of hydrogenic donor impurity, as electrons in the scattering states can contribute to a spin current while those in the bound states tend to remain bound to the hydrogenic impurity.

1. Introduction

The electronic structure and transport properties of quasi-one-dimensional (quasi-1D) nanowires [1,2], are presently under much investigation both theoretically and experimentally due to their fundamental importance, and their practical applications in spintronics (spin-based electronics) and nanotechnology [3,4]. If the nanowire is realized in the two-dimensional electron gas formed at the

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interface of a semiconductor heterostructure, there are in practice two main contributions to the spin-orbit coupling: one arising from the structural inversion asymmetry at the interface, which is called the Rashba spin-orbit interaction (SOI) [5,6], and the other due to the bulk inversion asymmetry of the crystal known as the Dresselhaus SOI [7]. The spin-orbit interaction at its basis is a relativistic effect experienced by electrons moving in an external electric field, such as that of the atomic nucleus or the ions in solids [8]. In the electron's rest frame the electric field is Lorentz transformed into a magnetic field that couples to the electronic spin, thus resulting in level splitting, spin precession and relaxation [9]. Of the two spin-orbit effects, i.e. Rashba SOI and Dresselhaus SOI, usually the first is more significant giving rise to a host of phenomena such as spin precession [10], which is the basis for the design of certain spin transistors [11], and anticrossings arising from the mixing of the subband states with opposite spins [9,12]. The strength of Rashba SOI (in effective atomic units), $\alpha = 10^{-3}$–10^{-1}, though small, is a linear function of the electric field normal to the semiconductor heterostructure interface, which not only depends on the materials characteristics, but also can be adjusted and controlled using an external gate voltage [13–15].

In the theoretical work carried out on the quasi-1D Rashba nanowires, it is usually assumed that the confining potential along the transverse direction of the quantum wire is either hard wall or parabolic [16]. The Rashba spin-orbit effect in the presence of the coulomb potential well of a hydrogenic donor impurity, however, has received relatively little attention despite the ubiquity of donor impurities, and their strong influence on the physical properties of semiconductor nanostructures. Nevertheless, the effect of Rashba SOI on the two-dimensional (2D) hydrogen atom has been investigated numerically, thus showing that the Rashba SOI partially removes the degeneracy of the 2D hydrogen atom, but the resulting energy levels remain two-fold degenerate due to the time-reversal invariance of the model system [17]. Also the effect of the pressure induced hydrogenic donor impurity on the level splittings of a corrugated 2D Rashba quantum well, has been investigated theoretically in Ref. [18]. To our knowledge, there has so far been no theoretical report on the effect of the hydrogenic donor impurity on the electronic states in the quasi-1D Rashba nanowires. Therefore, in this paper, we present a two-step analytic solution of the corresponding one-electron Schrodinger equation, using a quasi-1D hydrogen atom with Rashba spin-orbit coupling as our model system. The results thus obtained are further checked against purely perturbative calculations in the limit of small Rashba SOI. The rest of this paper is organized as follows. The model system, i.e. quasi-1D hydrogen atom with Rashba SOI, is described in Section 2. The two-step analytic solution, is presented in Section 3, together with a discussion of the results. The paper is concluded with a summary of the main results in Section 4.

2. Model system

The Hamiltonian of an electron in the presence of the Coulomb attraction of a donor impurity and Rushba SOI at the interface of a semiconductor heterostructure [17], is given by

$$H = \frac{p^2}{2m} - \frac{e^2}{r} + \frac{\alpha}{\hbar}(p_x\sigma_y - p_y\sigma_x), \tag{1}$$

where $p_x = -i\hbar\partial/\partial x$ is the x-component of the electron momentum operator (p_y defined similarly), $p^2 = p_x^2 + p_y^2$, m is the electronic effective mass, and σ's are the Pauli spin matrices. The last term describes the Rashba SOI characterized by a controllable strength parameter α as pointed out in the introduction [13–15], which is often very small compared to the other terms. The associated eigenvalue problem, $H\Psi = E\Psi$, takes the matrix form

$$\begin{bmatrix} \frac{p^2}{2m} - \frac{e^2}{r} & -i\frac{\alpha}{\hbar}p_x - \frac{\alpha}{\hbar}p_y \\ i\frac{\alpha}{\hbar}p_x - \frac{\alpha}{\hbar}p_y & \frac{p^2}{2m} - \frac{e^2}{r} \end{bmatrix} \begin{bmatrix} \varphi(\vec{r}) \\ \upsilon(\vec{r}) \end{bmatrix} = E \begin{bmatrix} \varphi(\vec{r}) \\ \upsilon(\vec{r}) \end{bmatrix}. \tag{2}$$

It must be noted that Eq. (2), describes a two-dimensional situation at the interface of a semiconductor heterostructure.

Our system of interest, however, is an electron in a Rashba nanowire of effectively infinite length along the y-axis, and finite (nanoscale) width along the x-axis, as schematically depicted in Fig. 1. A