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Effect of Rashba spin–orbit coupling on electron transport in asymmetrically coupled regular polygonal quantum ring

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ABSTRACT

The effect of Rashba spin–orbit coupling (SOC) on electron transport in asymmetrically coupled regular polygonal quantum ring is investigated. In absence of SOC, two kinds of conductance zeros appear periodically. In presence of SOC, one kind of conductance zero can be lifted by the Rashba SOC, the others persist.

1. Introduction

In recent years, much attention has been paid to the manipulation of the spin degrees of freedom of electrons in low-dimensional semiconductor structures, usually referred to as spintronics [1]. The major goal in this field is the generation of spin-polarized currents and their appropriate manipulation in a controllable environment, preferably in semiconductor system. Rashba spin–orbit (SO) effect [2], which arises in a two-dimensional electron gas confined to an asymmetric potential well, appear to be of particular interest. As a relativistic effect, it has been proven to be a convenient means of all-electrical control of spin-polarized currents [3]. In addition, suitable means for controlling spin at mesoscopic scales are provided by quantum interference effects in coherent ring conductors under the influence of electromagnetic potentials, known as the Aharonov–Bohm [4] and Aharonov–Casher [5] effects. Spin interferometers (SI) are interesting not only in view of possible spintronics applications but also from a fundamental perspective regarding the study of spin dynamics and related quantum phases. The transmission properties of mesoscopic Aharonov–Bohm and Aharonov–Casher rings symmetrically and asymmetrically coupled to current leads have been extensively studied under various aspects [6–14]. These studies referred to Aharonov–Bohm flux, geometric phases, spin flip, precession, and interference effects. Besides the model of circular quantum ring, more interest has been put on other relevant geometrical aspects [15–22]. Dario Bercioux et al. [15] have studied a quantum network extending in one dimension, which is a chain of square loops connected at one vertex. The Rashba spin–orbit coupling (SOC) in the quantum wires may give rise to an electron localization phenomenon. Koga et al. [19,20] propose a ballistic spin interferometer using a square loop geometry, and investigate the SO induced SI pattern of ballistic electrons travelling along any regular polygon. Bercioux et al. [18] have also discussed the two-contact transport properties of regular polygons subject to Rashba SOC.

In this Letter we investigate the transport properties of a regular polygonal quantum ring subject to the Rashba SOC, which is asymmetrically coupled to two leads. The one-electron scattering problem is solved by using the typical method of quantum network. By means of the Landauer–Büttiker formula, we get the conductance with quantum transmission. We calculate the conductance of several polygons made of one-dimensional (1D) ballistic wires as a function of the SO strength. It is found that, in absence of SOC, two kinds of conductance zeros appear periodically. In presence of SOC, one kind of conductance zero can be lifted by the Rashba SOC, the others persist. Moreover, we compare our results to those of the circular model as the polygon converges to a circle.

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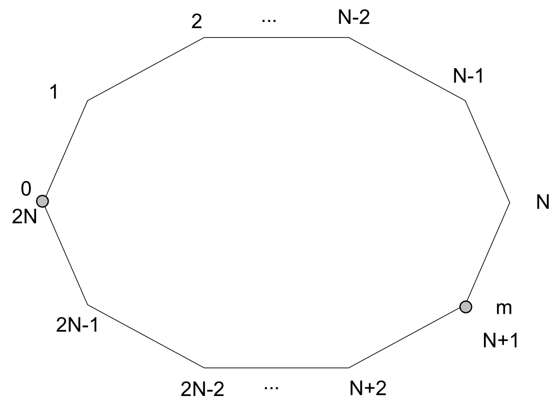

Fig. 1. The one-dimensional polygon quantum ring asymmetrically coupled to two conducting leads. Vertices are connected by single-channel ballistic quantum wires with the Rashba SOC. In the limit of large number of vertices ($N \to \infty$) the regular polygon converges to a single-channel circular conductor. The full dots represent the point where input and output leads are attached.

The remainder of the Letter is as follows. The physical model is showed in Section 2. The numerical results and discussions are presented in Section 3. The conclusions is made in Section 4.

2. Model and formulas

We consider electron transport through regular polygons with an even number of vertices 2N like that shown in Fig. 1. The vertices are connected by single-channel ballistic quantum wires subjected to Rashba SOC. The polygons are asymmetrically coupled to two 1D leads which are free of SOC. Neglecting subband hybridization due to the Rashba effect [23,24], the Hamiltonian for a single-channel wire along a generic direction $\hat{\gamma}$ in the x–y plane can be written as [2]

$$\hat{H} = \frac{p_\gamma^2}{2m^*} - \frac{\hbar k_{so}}{m^*} p_\gamma (\hat{z} \times \hat{\gamma}) \cdot \vec{\sigma}, \tag{1}$$

where k_{so} is the SOC strength, and $\vec{\sigma}$ is the vector of the Pauli matrices. $p_\gamma = -i\hbar \frac{\partial}{\partial l}$ is momentum operator in γ direction, m^* is the effective mass. The SOC strength k_{so} is related to the spin precession length L_{so} by $L_{so} = \pi / k_{so}$. In InAs quantum wells the spin-precession length ranges from 0.2 to 1 μm [25–27]. In order to calculate transport properties of the network, we need to write the wave function on a bond (quantum wire) connecting the nodes α and β along the direction $\hat{\gamma}_{\alpha\beta}$ [15],

$$\Psi_{\alpha\beta}(r) = \frac{e^{ik_{so} r (\hat{\sigma} \times \hat{z}) \cdot \hat{\gamma}_{\alpha\beta}}}{\sin(k l_{\alpha\beta})} \left\{ \sin\left[k(l_{\alpha\beta} - r)\right] \Psi_\alpha + \sin(kr) e^{-ik_{so} l_{\alpha\beta} (\hat{\sigma} \times \hat{z}) \cdot \hat{\gamma}_{\alpha\beta}} \Psi_\beta \right\}, \tag{2}$$

where $k = \sqrt{k_0^2 + k_{so}^2}$, and r is the coordinate along the bond which length is $l_{\alpha\beta}$. The spinor Ψ_α and Ψ_β are the values of the wave function at the nodes α and β, respectively. γ describes the electron's position on the quantum wire. At the vertices α and β, $\gamma_\alpha = 0$ and $\gamma_\beta = l_{\alpha\beta}$, respectively. The spin precession due to the Rashba effect is described by the exponentials containing Pauli matrices in Eq. (2), which is the key step to generalize the existing methods to study quantum networks [28,29] in the presence of Rashba SOC. The wave function of the whole network is obtained by using the Griffith's boundary conditions [10,30],

$$\sum_{\langle \alpha, \beta \rangle} \frac{\partial}{\partial l} \left[e^{-ik_{so} r (\hat{\sigma} \times \hat{z}) \cdot \hat{\gamma}_{\alpha\beta}} \right] \Psi_{\alpha\beta} = 0. \tag{3}$$

The sum $\sum_{\langle \alpha, \beta \rangle}$ runs over all nodes β which are connected by a bond to the node α. For a generic node α it reads

$$M_{\alpha\alpha} \psi_\alpha + M_{\alpha\beta} \psi_\beta = 0, \tag{4}$$

where

$$M_{\alpha\alpha} = \sum_{\langle \alpha, \beta \rangle} \cot(k l_{\alpha\beta}), \qquad M_{\alpha\beta} = -\frac{e^{[-ik_{so} l_{\alpha\beta} (\hat{z} \times \hat{\gamma}_{\alpha\beta}) \cdot \vec{\sigma}]}}{\sin k l_{\alpha\beta}}. \tag{5}$$

We consider an electron injected from the left wire with energy E along a generic direction, the wave functions on the external leads are simply

$$\Psi_L = A e^{ik_0 l} + B e^{-ik_0 l}, \tag{6}$$

$$\Psi_R = F e^{ik_0 l}, \tag{7}$$

where l is the coordinate on the semi-infinite input/output lead, with the origin fixed at the position of the input/output node. The conditions for the continuity of the probability current at internal nodes are given in Eq. (4). For the external nodes they read