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Spin conductance in three-terminal rings subject to Rashba and Dresselhaus spin-orbit coupling

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ABSTRACT

Based on the Green's function formalism, we investigated spin transport properties in one-dimensional three-terminal rings in the presence of the Rashba spin-orbit coupling (RSOC) and Dresselhaus spin-orbit coupling (DSOC). The conductance as a function of the Fermi energy shows typical resonance and antiresonance (conductance zero) characteristics in the absence of spin-orbit coupling (SOC). When one type of SOC (RSOC or DSOC) is introduced, the original conductance zeros are lifted, but new conductance zeros emerge. It is found that all the conductance zeros depend sensitively on the disorder, and the fluctuate weakens and smoothens the oscillations of the conductance. In the presence of both types of SOCs, the interplay between the RSOC and the DSOC opens a gap in the energy spectrum and breaks the cylindrical symmetry of the ring. Consequently, symmetrically coupled three-terminal rings show anisotropic conductances, which are robust against weak disorders.

1. Introduction

In recent years, much attention has been paid to spin accumulation and spin current by passing electric current through coherent ring conductors with spin-orbit coupling (SOC) [1]. In conventional semiconductors, two types of SOCs have attracted considerable interest: Dresselhaus spin-orbit coupling (DSOC) induced by bulk inversion asymmetry [2] and Rashba spin-orbit coupling (RSOC) induced by structure inversion asymmetry [3,4]. In coherent ring conductors, the interplay between SOC and quantum interference of the system have been used to control the spin degrees of freedom [5–7].

Recently, three-terminal rings with SOC have been proposed since this structure can generate spin polarized current in the absence of a magnetic field [8–12]. Földi et al. [12] have investigated the spin-dependent transport properties of a three-terminal ring in the presence of RSOC. They have shown that a three-terminal ring can act as a spintronic quantum gate. Zero-conductance resonances in three-terminal Rashba rings have also been investigated [13], and the conductance zeros appearing in such systems have been categorized into three types. The transmission phase [14] and conductances [15] in multi-terminal rings have been studied experimentally. Three-terminal ring devices have been fabricated at a temperature of 4 K, and clear Aharonov-Bohm oscillations have been observed by Strambini et al. [15]. In addition, an obvious anisotropic conductance in a symmetric three-terminal ring has also been observed at zero magnetic field, i.e., the measured conductance of one of the output leads significantly exceeds that of the other near $B = 0$. This feature suggests that the potential landscape within the ring is asymmetric [16]. Szafran et al. [16] studied electron transport in a total symmetric three-terminal ring where an elastic scatterer was present within one of the arms of the ring. They found that the scatterer can introduce an anisotropic conductance. In their studies, the SOC was not considered. Wang et al. [17] have investigated a two-terminal ring with both RSOC and DSOC, and they found that the interplay between RSOC and DSOC can induce an anisotropic conductance.

In this study, we theoretically investigated the spin conductances in three-terminal rings in the presence of both RSOC and DSOC. We focused on the conductance zeros and the anisotropic

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conductances, as well as their robust behaviors in the presence of disorder. The remainder of the paper is organized as follows: in Sec. 2, the model and details of the calculation are introduced; in Sec. 3, we present our main results and analyses; and finally, the summary is presented in Sec. 4.

2. Model and formulas

The system under study is a quantum ring with one incoming lead and two outgoing leads, which is depicted in Fig. 1. We define R_1, R_2, and R_3 as the ratios of the upper, middle, and lower ring arm lengths to the circumference of the ring, respectively. The Hamiltonian corresponding to the setup depicted in Fig. 1 contains three terms:

$$\mathbf{H} = \mathbf{H}_{ring} + \mathbf{H}_{lead} + \mathbf{H}_T. \tag{1}$$

The first term describes the electrons in an isolated ring with RSOC and DSOC. Within the discrete lattice approximation, we model the three-terminal ring in the presence of RSOC and DSOC by the Hamiltonian [18]

$$\mathbf{H}_{ring} = \sum_{n=1}^{N}\sum_{s=\uparrow,\downarrow}(\varepsilon_n + w_n)c_{n,s}^{\dagger}c_{n,s} - \sum_{n=1}^{N-1}\sum_{s,s'=\uparrow,\downarrow}\Big[t^{n,n+1;s,s'}c_{n,s}^{\dagger}c_{n+1,s'} + h.c.\Big], \tag{2}$$

in which the hopping potential is

$$t^{n,n+1} = tI_{2\times2} - i\frac{\alpha}{2a}(\cos\theta_{n,n+1}\sigma_x + \sin\theta_{n,n+1}\sigma_y) - i\frac{\beta}{2a}(\cos\theta_{n,n+1}\sigma_y - \sin\theta_{n,n+1}\sigma_x). \tag{3}$$

Here, $c_{n,s}^{\dagger}(c_{n,s})$ creates (annihilates) an electron with spin s at the nth site of the ring. N is the number of sites of the ring. We introduced a random on-site disorder energy uniformly distributed within $-w/2 < w_n < w/2$. The on-site energy w_n in Eq. (2) is randomly distributed around zero according to a box distribution in the range $-w/2 < w_n < w/2$. The disorder strength w represents the degree of the disorder. In our calculation, 1000 random values of w are used to calculate the conductance. Then, the sum of the 1000 results is averaged. a and $t = \hbar^2/(2m^*a^2)$ denote the lattice constant and the nearest neighbor hopping potential of the ring. $\theta_{n,n+1}$ is the angle between the nth site and the $n+1$th site. σ_x and σ_y are the elements of the Pauli matrices. α and β are the strengths of the RSOC and DSOC, respectively.

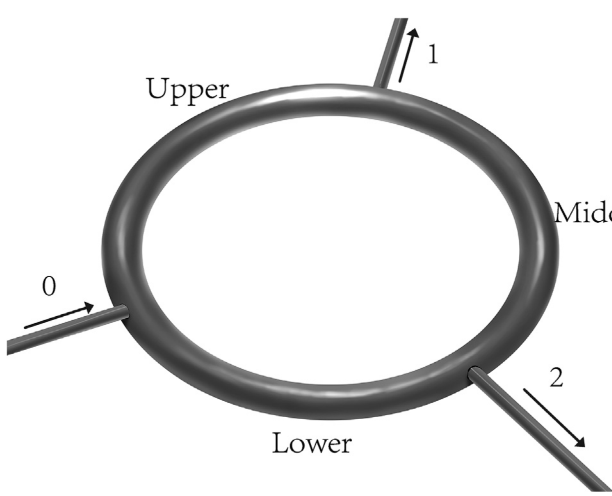

Fig. 1. Schematic of a three-terminal ring coupled to three leads. RSOC and DSOC exist only in the ring.

In Eq. (1), the second term is the Hamiltonian for one incoming lead and two outgoing leads.

$$\mathbf{H}_{lead} = \sum_{\alpha,s}\varepsilon_{\alpha,s}b_{\alpha,s}^{\dagger}b_{\alpha,s}, \tag{4}$$

where $b_{\alpha,s}^{\dagger}(b_{\alpha,s})$ annihilate (create) spin s electron in the lead. The subscript α stands for the one incoming lead (0) and two outgoing leads (1 and 2) in Fig. 1.

The last term in Eq. (1), $\mathbf{H}_T$, describes electron tunneling between the ring and leads

$$\mathbf{H}_T = t_{0,s}b_{0,s}^{\dagger}c_{1,s} + t_{1,s}b_{1,s}^{\dagger}c_{m1,s} + t_{2,s}b_{2,s}^{\dagger}c_{m2,s} + h.c., \tag{5}$$

in which $t_{0,s}$, $t_{1,s}$and $t_{2,s}$ represent the ring-lead couplings. $m1$ and $m2$ are the outgoing nodes of ring, respectively. It is assumed that the couplings between three leads and the ring are same.

Within the framework of the Green's function approach, the spin transmission probability from incoming lead 0 to outgoing lead j ($j = 1, 2$) is obtained from the Landauer-Büttiker formula [19]:

$$\mathbf{T}_{j,ss'} = \mathrm{Tr}\big[\Gamma_{0,s}G^r\Gamma_{j,s'}G^a\big]. \tag{6}$$

The retarded Green's function is $G^r(E) = [(E + i\eta)\mathbf{I} - \mathbf{H}_{ring} - \Sigma^r]^{-1}$, where E is the Fermi energy. $\Sigma^r = \sum_{\alpha=0,1,2}\Sigma_\alpha^r$ is the retarded self-energy and $\Sigma_\alpha^r = -\frac{i}{2}\Gamma_\alpha$. Γ_α is the bandwidth function, which is assumed to be independent of the energy E in the wide-band limit.

Therefore, we obtain the spin conductance through a three-terminal ring

$$\mathbf{G}_j = \begin{pmatrix} \mathbf{G}_{j,\uparrow\uparrow} & \mathbf{G}_{j,\uparrow\downarrow} \\ \mathbf{G}_{j,\downarrow\uparrow} & \mathbf{G}_{j,\downarrow\downarrow} \end{pmatrix} = \frac{e^2}{h}\begin{pmatrix} |\mathbf{T}_{j,\uparrow\uparrow}|^2 & |\mathbf{T}_{j,\uparrow\downarrow}|^2 \\ |\mathbf{T}_{j,\downarrow\uparrow}|^2 & |\mathbf{T}_{j,\downarrow\downarrow}|^2 \end{pmatrix}. \tag{7}$$

3. Results and discussion

In this section, we will first study the spin transport through a three-terminal ring subject to one type of SOC, and then, we will study the case with both types SOCs. In the following discussion, we focus on three typical ring configurations: case 1 (the asymmetric configuration) where $R_1 = 1/8$, $R_3 = 3/8$; case 2 (the partial symmetric configuration) where $R_1 = R_3 = 3/8$; and case 3 (the total symmetric configuration) where $R_1 = R_3 = 1/3$. We set $a = 1$ and $t = 1$, which are taken as the units of length and energy, respectively. The number of the sites of the ring is $N = 120$. We define the strength of dimensionless RSOC and DSOC as $Q_R = \alpha N/2\pi ta$ and $Q_D = \beta N/2\pi ta$, respectively. The eigenstates for the RSOC case alone and the DSOC case alone are connected by a unitary transformation [20]. The spin transport properties for the RSOC case are the same as that of the DSOC case.

Fig. 2 shows the dependence of the conductances on the Fermi energy E in the absence of SOC. From Fig. 2, we find that the conductances oscillate periodically with E and exhibit typical resonance and antiresonance (conductance zero) characteristics. There are distinct conductance zeros in the conductance curves. The