Physica B 405 (2010) 3560–3563

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Enhanced strongly modulated spin transmission of Fano–Rashba mesoscopic ring structure

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ARTICLE INFO

Article history:
Received 13 September 2009
Received in revised form
1 April 2010
Accepted 14 May 2010

Keywords:
Ballistic transport
Spin polarized transport
Spintronics: devices exploiting spin polarized transport

ABSTRACT

One-dimensional Rashba quantum ring structure with two leads subjected to a weak external magnetic field is proposed as a possible candidate for spintronic current modulators. By tuning spin–orbit coupling and magnitude of external magnetic field, resonance and antiresonance behavior can be found in our investigation. Comparing with results in other structures like quantum wires with local or periodic Rashba interaction, the T-shaped structure, more broader energy range of vanishing small transmission and larger on/off transmission ratio can be found in the structure and Fano–Rashba interference behaviors of the quantum ring model. Moreover, it is found the enhanced robustness of these interference against random Anderson-type disorder of device, which may conduce to the real application of this device.

1. Introduction

To control the manipulation of electronic spin degree of freedom has been a central issue attracting most interest in spintronics [1–11] since Datta and Das proposed the scheme of spin field effect transistor(SFET) in 1990 [12]. Up to now, most works have focused on the current modulation in semiconductor devices controlled by external electric field via relativistic Rashba spin orbit coupling (SOC). However, the reported works [13–15] reveal ambiguous results in the achievement of device performance rates associated with spin current polarization, filtration, magnification, switching, which in turn are not in favor of the direct application in reality. On the other hand, charge field-effect transistors(CFET) [16–18] have provided the on/off current ratio up to 10^4–10^6. Recently, Wang et al. [19] and Shen et al. [16] investigated the transport properties of mesoscopic structures like quantum wire and T-shaped model with local or periodic Rashba couplings in presence of weak external magnetic field. Their investigation have shown some attractive results with higher performance rate with large on/off current ratio than 10^5, large antiresonance energy gap and its robustness against the on-site disorder. In all these models the Rashba spin–orbit interaction in finite lattice regions plays a similar role of attractive potential [14]. This induces at least one bound state localized in the vicinity of the SOC region, which provides the Fano–Rashba interference possibility for the transmission channel and the bound state. Consequently, dips can be seen in these numerical simulations of conductance curves. Moreover, ordinarily simple devices like 1D quantum wires [14] can only provide some single energy points in their antiresonance transmission curves, which will affect their real application greatly. However, besides Fano–Rashba antiresonance, a larger energy window has been found [16] when considering structure antiresonance in some special device like T-shaped structure. It is well known that conducting Aharonov–Bohm ring is another useful one-dimensional geometric device to manipulate spin current because of its special structure, which can provide AB phase and Aharonov–Casher phase [20]. Citro et al. [21]. has studied the magnification effects in these ring-shaped structures which directly related to the effect of Fano-type antiresonance.

In this work, we study the spin transport properties of a quantum ring structure subject to Rashba SO coupling which is connected to two leads through perfect ideal ohmic contacts. Along the perpendicular direction, an uniform magnetic field B is applied on this structure which leads to the shift of energy spectrum by a Zeeman splitting. We consider the case that only spin-down electrons can propagate through our model, which means the electron states in the leads at the Fermi energies lie inside the spin Zeeman gap. Through regulating the parameters in our model, such as the Rashba SOC strength, magnitude of external magnetic field and Fermi energy et al., we find interesting resonance and antiresonance behaviors appear in the

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doi:10.1016/j.physb.2010.05.040

transmission curves corresponding to different parameters. Especially, in comparing with those works mentioned above more wider antiresonance energy gaps and enhanced robustness of the gaps against Anderson disorders can be found in our simulation results.

2. Model and formulism

The simplified structure of the mesoscopic ring-shaped conductor used to study the spin carrier properties in the presence of a weak external magnetic field and local Rashba SO coupling is shown in Fig. 1. In the tight-binding representation the total amount of sites in the ring is $2M$ with M chosen to be 30 throughout our simulations. Two leads connect to the ring at points 1, $M+1$, respectively. The Rashba SOC interaction only exist in the ring region, and the weak uniform perpendicular magnetic field makes Landau levels neglected in the whole device. The Hamiltonian of the whole system can be written as follows:

$$\hat{H}=\hat{H}_{lead}+\hat{H}_{ring}+\hat{H}_{lead,ring}. \tag{1}$$

The first term given by expression

$$\hat{H}_{lead}=-t_0\sum_{n,\sigma}c^{\dagger}_{n,\sigma}c_{n+1,\sigma}+H.c.+\sum_{n,\sigma}(\varepsilon_0+\sigma\Delta_Z)c^{\dagger}_{n,\sigma}c_{n,\sigma},$$

represents the motion of electrons along linear leads subject to a perpendicular magnetic field, where all the summations are carried out over the semi-infinite $1D$ sites $n\le 0$ and $n\ge 2M+1$. $\hat{H}_{ring}$ given by

$$\hat{H}_{ring}=-t_0e^{-i\Phi/2M}\sum_{n,\sigma}c^{\dagger}_{n,\sigma}c_{n+1,\sigma}+H.c.+\sum_{n,\sigma}(\varepsilon_1+\sigma\Delta_Z)c^{\dagger}_{n,\sigma}c_{n,\sigma}$$
$$+it_{so}e^{-i\Phi/2M}\sum_{n,\sigma,\sigma'}(\cos\phi_{n,n+1}\hat{\sigma}_x+\sin\phi_{n,n+1}\hat{\sigma}_y)c^{\dagger}_{n,\sigma}c_{n+1,\sigma'}+H.c.$$

describes the motion of electrons in the ring subjected to both Rashba SOC interaction and perpendicular magnetic field B. In these equations, the summations are carried out within $[1,2M]$. t_{so} is the Rashba SOC strength, $\Phi=B\pi r^2$ is the magnetic fluxes with r being the radius of quantum ring, and $\phi_{n,n+1}=(\phi_n+\phi_{n+1})/2$ with the angular coordinate $\phi_n=2\pi(n-1)/2M$. The Zeeman effect induced by the weak uniform perpendicular magnetic field splits the on-site energy into $\sigma\Delta_z$ both along the ring and two linear leads with $\sigma=\pm$ for spin-up and down electrons. The sub-Hamiltonian of the coupling between the ring and the lead is

$$\hat{H}_{lead,ring}=-t_0\sum_{\sigma}(c^{\dagger}_{0,\sigma}c_{1,\sigma}+c^{\dagger}_{M+1,\sigma}c_{2M+1,\sigma})+H.c., \tag{2}$$

where 1 and $M+1$ define the connection positions in the ring of the corresponding leads. For simplicity the hopping strength $t_0=\hbar^2/(2m^*a^2)$ between the leads and the ring is supposed to be same as that in the leads and the ring.

With this Hamiltonian we assume the propagating electron states are all spin down ones in the leads, which means the energy range we now focus on is $[\varepsilon_0-2t_0-\Delta_Z,\varepsilon_0-2t_0+\Delta_Z]$, where $E=\varepsilon_0-2t_0\cos ka$ is the well known expression for the energy band spectrum for $t_{so}=0$ and $\Delta_Z=0$. To solve the transmission problem of an electron with spin-down propagating through our Rashba quantum ring region, the wave function of the system, denoted as $|\psi\rangle$, can be written as

$$|\psi\rangle=\sum_{P,n,\sigma}b_{P,n,\sigma}c^{\dagger}_{P,n,\sigma}|0\rangle,$$

where the sum for P is over the leads (L, R) and the ring, $|0\rangle$ denotes the vacuum, and $b_{P,n,\sigma}$ is the corresponding coefficient in the linear combination, which represents the wave amplitude in different propagating region. For left lead

$$b_{L,n,\sigma}=\begin{cases} ce^{k_\uparrow na}, & \sigma=+,\\ e^{ik_\downarrow na}+re^{-ik_\downarrow na}, & \sigma=-,\end{cases} \tag{3}$$

where $n\le 0$, and r is the reflection probability amplitude for spin-down electron. For right lead region

$$b_{R,n,\sigma}=\begin{cases} de^{-k_\uparrow na}, & \sigma=+,\\ \tau e^{ik_\downarrow na}, & \sigma=-,\end{cases} \tag{4}$$

where $n\ge 2M+1$, and τ is the transmission probability amplitude. In both expressions related to the total energy E, the wave number $k_\uparrow$ for evanescent waves is given by $k_\uparrow=\cosh^{-1}[(E-\Delta_Z)/(-2)]$ and $k_\downarrow$ for propagating state is $k_\downarrow=\cos^{-1}[(E+\Delta_Z)/(-2)]$. The reflection and transmission probability amplitudes, together with other amplitudes within the ring region, can be solved by a set of linear equations obtained from the Schrödinger equation $H|\psi\rangle=E|\psi\rangle$. Consequently, the two-terminal conductance can be obtained from Landauer–Büttiker formula [22]

$$G=\frac{e^2}{h}T, \tag{5}$$

where $T=|\tau|^2$ is the quantum probability of transmission.

3. Results

Fig. 2 displays the conductance G as a function of Fermi energy for different large Rashba SOC strength with a given value of Zeeman splitting energy $\Delta_Z=0.01t_0$. For specific values of local spin–orbit coupling strength, we notice the conductance can modulated largely as a function of Fermi energy. Especially when t_{so}=0.1t_0 and 0.9t_0, multi-discrete resonances peaks plotted as

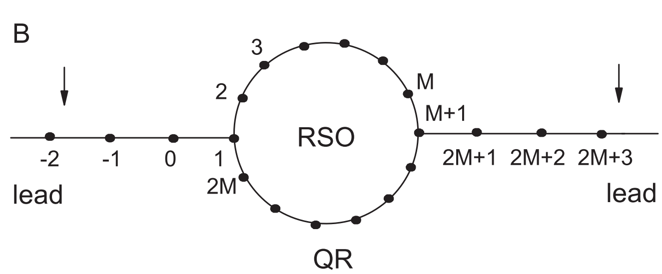

Fig. 1. Schematic view of 1D mesoscopic ring-shaped lattice connected to two leads. A vertical external magnetic field B is applied to the whole structure, while the ring part is subjected to local Rashba SOC interaction.

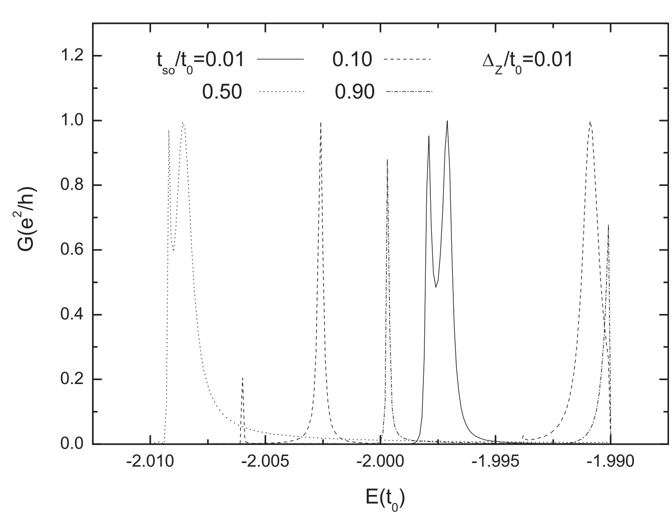

Fig. 2. Conductance versus the Fermi energy of the leads for Zeeman splitting energy $\Delta_Z=0.01t_0$ with different values of local Rashba SOC strength: t_{so}=0.01t_0, 0.10t_0, 0.50t_0, 0.90t_0.