Robust strongly modulated transmission of a T-shaped structure with local Rashba interaction

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(Received 19 February 2008; revised manuscript received 8 April 2008; published 7 May 2008)

We propose a scheme of spin transistor that uses a T-shaped structure with a local Rashba interaction. A wide antiresonance energy gap appears due to the interplay of two types of interference: the Fano–Rashba interference and the structure interference. A large current from the gap area can be obtained via changing the Rashba strength and/or the length of the sidearm by using gate voltage. The robustness of the antiresonance gap against strong disorder is demonstrated and shows the feasibility of this structure for a real application.

DOI: 10.1103/PhysRevB.77.193305 PACS number(s): 85.75.−d, 73.23.Ad, 72.25.−b

Spin-polarized electron transport has recently attracted much attention due to the promising application of spintronic devices.[1] One of such devices, namely, the Datta–Das spin field effect transistor,[2] was proposed by utilizing the spin precession due to the Rashba effective magnetic field.[3] After that, the role of the Rashba spin-orbit coupling (SOC) in ballistic transport systems has been extensively studied.[4] Very recently, the effect of local Rashba spin-orbit interaction in quasi-one-dimensional quantum wires was investigated.[5] As reported, there exists at least one bound state localized in the vicinity of the Rashba region due to the equivalent attractive potential from local Rashba interaction. Such a bound state can interfere with direct propagating channels, which leads to the Fano asymmetric line shapes[6–8] of the transmission.[5] Therefore, this effect was called the Fano–Rashba effect. Similar Fano-type inference effect in the quantum wire with an applied magnetic field was also reported, which was based on the interplay of the transmission channel with certain spin and the evanescent mode with opposite spin.[9] The transmission zero dip at Fano antiresonance was very recently proposed to be helpful in realizing a spin transistor by Sánchez *et al.*[9] However, the robustness of this proposal against disorder, which is essential for a real application, remains questionable. In this Brief Report, we will show that the occurrence of such dip is strongly limited by disorder. We further propose a scheme of a device that uses a T-shaped structure[10,11] with a local Rashba interaction. This device can provide a large energy window for antiresonance in contrast to single energy points in ordinary antiresonance devices, with strong a robustness against disorder.

A schematic of the waveguide in our study is shown in Fig. 1, wherein a waveguide of length L with a sidearm protruding from the center is connected to the half-metallic leads through perfect ideal ohmic contacts. We assume that the electron states at the Fermi level are all spin-down ones in the leads, so that only spin-down electrons can propagate in or out of the T-shaped structure. The effective length of the sidearm L_s can be electronically adjusted by a gate voltage V_g.[11] The finite width of the waveguide L_w gives the propagation threshold as the first quantized subband along the transversal direction. A perpendicular magnetic field is uniformly applied on the whole device. This field shifts the energy spectrum by a Zeeman splitting $V_\sigma = \sigma V_0$. We neglect the effect of magnetic field on orbital motion by assuming that the magnetic field is weak and hence the Landau level is negligible. The interference of the different Feynman paths makes it possible to realize a spin transistor by using the T-shaped structure.[10] However, this kind of transistor is also strongly limited by disorder as we will show later. In order to get a robust transistor, we further introduce a local Rashba interaction, which is shown as the gray area in Fig. 1. From a Fano-type interference effect that is due to the local Rashba interaction, the transmission of the propagating channel can also be strongly modulated, especially at the Fano antiresonance.[5,9] We demonstrate that when the individual structure antiresonance and Fano antiresonance are close to each other, there exists a broad energy window in which the conductance is zero, i.e., there exists an antiresonance energy gap. This is in contrast to the single (specific) energy when only the structure or Fano antiresonance is involved. Moreover, this antiresonance energy gap is very robust against the disorder. We also find that a large current can be obtained in this gap area by adjusting the Rashba coupling strength[12] and/or the length of the sidearm by using the gate voltage. Such features are very useful for the spin transistors.

We describe the T-shaped structure by using a tight-binding Hamiltonian with the nearest-neighbor approximation,

$$H = \sum_{l,m,\sigma} \epsilon_{l,m,\sigma} c^{+}_{l,m,\sigma} c_{l,m,\sigma} - t \sum_{l,m,\sigma} (c^{+}_{l+1,m,\sigma} c_{l,m,\sigma} + c^{+}_{l,m+1,\sigma} c_{l,m,\sigma} + \text{H.c.}) + H_R, \quad (1)$$

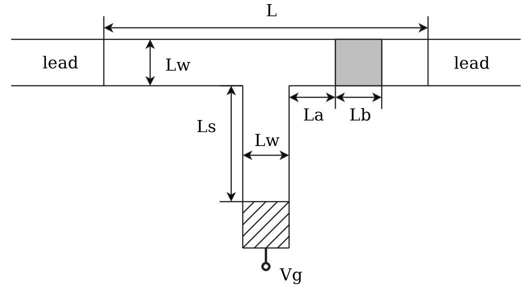

FIG. 1. Schematic of the T-shaped structure with a local Rashba interaction. The Rashba area is shown as the gray area. The shadowed area stands for the gate used to tune the length of the sidearm.

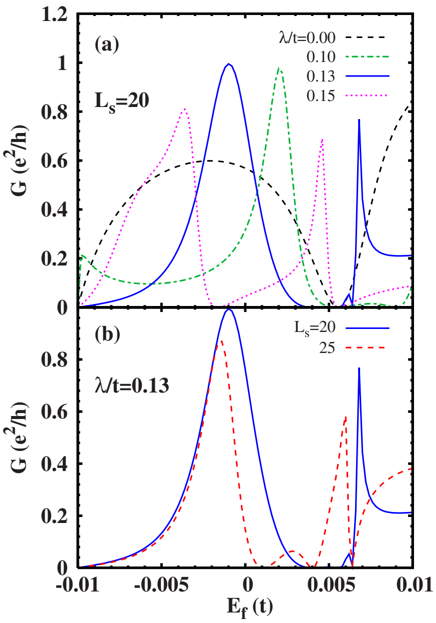

FIG. 2. (Color online) Conductance vs Fermi energy of the leads (a) with different local Rashba SOC strengths when $L_a = L_b = 20a$ and (b) with different sidearm lengths when $L_a = 20a$ and $\lambda/t = 0.13$.

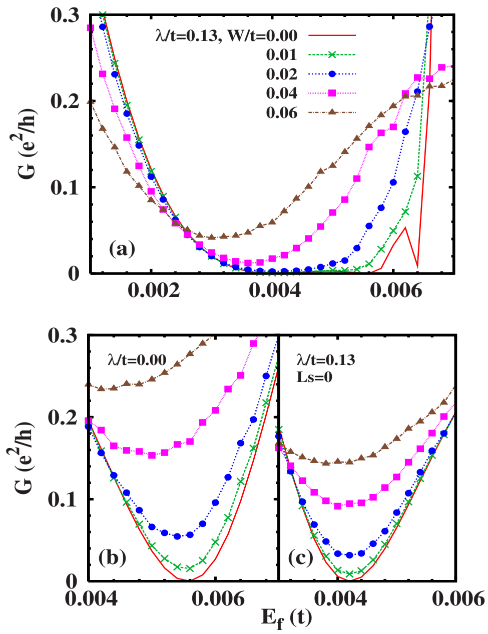

FIG. 3. (Color online) Conductance vs Fermi energy with different disorder strengths W in the vicinity of the antiresonance energy gap, (a) with both the Fano antiresonance and the structure antiresonance, (b) with only the structure antiresonance, and (c) with only the Fano antiresonance.

where the two indices l and m denote the site coordinates along the x and y axes, respectively. The lattice energy $\epsilon_{l,m,\sigma} = 4t + \sigma V_0$, with the hopping energy $t = \hbar^2/(2m^* a^2)$ and the Zeeman splitting V_0. Here, m^* and a stand for the effective mass and lattice constant separately. The last term in Eq. (1) describes the Rashba SOC,[3,13]

$$H_R = \lambda \sum_{l,m,\sigma,\sigma'} [c^{+}_{l+1,m,\sigma} c_{l,m,\sigma'} (i\sigma_y^{\sigma\sigma'}) - c^{+}_{l,m+1,\sigma} c_{l,m,\sigma'} (i\sigma_x^{\sigma\sigma'}) + \text{H.c.}], \quad (2)$$

in which $\lambda = \alpha/2a$, where α represents the Rashba coefficient. The summations (l,m) in H_R are performed only in the gray area in Fig. 1.

The two-terminal conductance is obtained from the Landauer–Büttiker formula[14]

$$G^{\sigma\sigma'}(E) = (e^2/h)\mathrm{tr}[\Gamma_1^{\sigma} G_{1N}^{\sigma\sigma'+}(E) \Gamma_N^{\sigma'} G_{N1}^{\sigma'\sigma-}(E)], \quad (3)$$

where $\Gamma_{1(N)}$ denotes the self-energy of the isolated ideal leads and $G_{1N}^{\sigma\sigma'}$ $(G_{N1}^{\sigma'\sigma})$ is the retarded (advanced) Green's function.[15] For an energy window $[E, E+\Delta]$, the current is given by $I = \int_E^{E+\Delta} G(\epsilon) d\epsilon$. We perform a numerical calculation for a waveguide with a fixed width $L_w = 20a$. The hard wall potential in the transverse direction gives the lowest energy of the nth subband $\epsilon_n = 2t\{1 - \cos[n\pi/(L_w/a+1)]\}$. Throughout this Brief Report, we take the Zeeman splitting energy $V_0 = 0.01t$ and the Fermi energy E_F with regard to $\epsilon_1 = 0.022\,34t$. The conductance G represents the conductance of the only propagating spinor $G^{\downarrow\downarrow}$.

In Fig. 2(a), the conductance G is plotted as a function of the Fermi energy at different Rashba coefficients λ. In the calculation, $L_s = L_a = L_b = 20a$. The result without the local Rashba SOC is plotted as the black dashed curve, which shows a transmission zero dip, i.e., the structure antiresonance[11,16] dip, at $E_F \simeq 0.005t$. The presence of the local Rashba interaction also strongly influences the conductance and provides another transmission zero dip, i.e., the Fano-antiresonance dip, as shown by the remaining curves with $\lambda \neq 0$. One finds that the Fano dip moves to small E_F region with the increase in the SOC coefficient.[9] The most interesting feature is that when the Fano dip is close to the structure dip $(\lambda = 0.13t)$, a wide energy gap $[0.0034t, 0.0058t]$ for antiresonance appears (see the blue solid curve). Moreover, this gap can be turned off via changing the SOC coefficient. Specifically, there exists a peak at $\lambda = 0.15t$, which gives a current $I \simeq 3 \times 10^{-4} e^2 t/h$ for the energy window $[0.0040t, 0.0045t]$, which is originally in the gap area. Therefore, it can work as a spin transistor with the on and off features by tuning the Rashba strength with a gate voltage. From Fig. 2(b), one can also see that the on and off features of the transistor can also be remotely controlled by changing the length of the sidearm L_s by another gate voltage.[11]

We now show the feasibility of the above proposed device for a real application by analyzing the robustness of the antiresonance gap [i.e., the solid blue curve in Fig. 2(a)] against the Anderson disorder. The converged conductance that is averaged over 3000 random configurations is plotted in Fig. 3(a) against the Fermi energy in the vicinity of the gap for different Anderson disorder strengths W. From Fig. 3(a), one can see that the leakage conductance near the gap is extremely small $(G < 0.02e^2/h)$ until the strength of the disorder exceeds $0.04t$, which is three times larger than the Zeeman splitting. For the large disorder strength $W = 0.04t$, the corresponding leakage current for the energy window $[0.0040t,\ 0.0045t]$ is smaller than $1.5\times10^{-5}e^2t/h$, which is more than 1 order of magnitude smaller than the "on" current in the same energy interval. The leakage current is even much smaller for $W=0.01t$ ($0.02t$), i.e., $I\simeq7\times10^{-7}e^2t/h$ ($2\times10^{-6}e^2t/h$). For comparison, we also check the robustness of the previous proposed transistors.[9,11] In Fig. 3(b), the results of the T-shaped structure without the local Rashba SOC are plotted. The conductance rapidly increases with the strength of the disorder, specifically, it already reaches $0.05e^2/h$ at $W\sim0.02t$. A similar feature is also obtained for the device with only the Fano antiresonance where the length of the sidearm $L_s=0$ and $\lambda=0.13t$, as shown in Fig. 3(c). Therefore, the transistors based on the structure antiresonance or the Fano antiresonance alone are very weak against the disorder and do not provide an energy window, both in contrast to our scheme that combines both the Fano and the structure antiresonance. We also checked the robustness of the antiresonance gap against the disorder of the Rashba SOC and obtained results that are very similar to those of the case with the on-site disorder. The average leakage conductance in the gap is about $0.01e^2/h$ with a disorder strength $W'=0.5\lambda$, which is much smaller than the conductance with the same disorder strength at the Fano-antiresonance point in the structure without a sidearm ($\sim0.08e^2/h$).

In summary, we have proposed a scheme for a spin transistor by studying a T-shaped structure with local Rashba SOC. Both leads are assumed to be half-metallic. The relevant conductance can be strongly modulated by the Fermi energy of the leads, the strength of the Rashba SOC, and the length of the sidearm. We have also demonstrated that a wide antiresonance energy gap can be obtained by adjusting the Fano antiresonance and the structure antiresonance close to each other. We propose that our structure can be used as a spin transistor since a large current can be obtained in the same antiresonance energy gap region when the two types of the antiresonance are tuned away from each other by either changing the Rashba coefficient or electronically changing the length of the sidearm. We also show the robustness of the antiresonance energy gap against the on-site disorder. The wide working energy window (in contrast to a single energy) and the much improved robustness against disorder suggest that the proposed structure has great potential for real applications.

This work was supported by the Natural Science Foundation of China under Grant Nos. 10574120 and 10725417, the National Basic Research Program of China under Grant No. 2006CB922005, and the Knowledge Innovation Project of Chinese Academy of Sciences. One of the authors (M.W.W.) was also partially supported by the Robert-Bosch Stiftung and GRK 638. He would like to thank J. Fabian and C. Schüller at Universität Regensburg for hospitality where this work was finalized and J. Fabian for valuable discussions. S.K. acknowledges J. Zhou for valuable discussions.

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