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Nonlocal Andreev reflection and spin current in a three-terminal Aharonov–Bohm interferometer*

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This paper theoretically reports the nonlocal Andreev reflection and spin current in a normal metal-ferromagnetic metal-superconducting Aharonov–Bohm interferometer. It is found that the electronic current and spin current are sensitive to systematic parameters, such as the gate voltage of quantum dots and the external magnetic flux. The electronic current in the normal metal lead results from two competing processes: quasiparticle transmission and nonlocal Andreev reflection. The appearance of zero spin-up electronic current (or spin-down electronic current) signals the existence of nonlocal Andreev reflection, and the presence of zero electronic current results in the appearance of pure spin current.

Keywords: nonlocal Andreev reflection, Aharonov–Bohm interferometer, spin current
PACC: 7430F, 7450, 7335

1. Introduction

In the last decade, mesoscopic normal-metal/superconductor hybrid systems[1−10] have been the main focus of many research activities. In these systems so-called Andreev reflection[11] happens at the interface between the normal metal and the superconductor due to the appearance of a new energy scale: the superconducting energy gap Δ. This phenomenon indicates that an incoming electron from the normal metal side is reflected as a hole into the normal metal side, thereby transferring a Cooper pair into the superconducting condensate. When there are more than two normal metal leads, an electron from a normal metal lead will be reflected as a hole either back into the same normal lead or into another spatially separated lead, so the so-called nonlocal Andreev reflection[12−17] will happen. Since this nonlocal Andreev reflection process is equivalent to injecting two spin-entangled electrons forming the singlet state of a Cooper pair into two different normal leads, the study of electron transport in the multi-terminal mesoscopic hybrid systems may lead to the realization of solid-state entanglers,[13] which is important to quantum information processing.

On the other hand, we know that charge and spin are two elementary degrees of freedom of an electron. Since the proposal of the Datta–Das transistor[18] over ten years ago, much attention[19−22] has been paid to add the spin degree of freedom to conventional semiconductor charge-based electronic devices. This has resulted in the emergence of semiconductor spintronics. Since spin-based electronic devices have many advantages, including a longer coherent lifetime,[23] faster data proceeding speed and less electric power consumption, the generation, manipulation, and measuring of spin currents[24−26] are the central challenges in spintronics and have caused intense interest in recent years. In addition, with the recent developments in micro-fabrication technology, many artificial structures in the mesoscopic scale can be fabricated. Electrons moving in the mesoscopic regime can avoid inelastic scattering and keep the phase coherence. This kind of phase coherent electron transport has been widely investigated with the solid-state Aharonov–Bohm interferometer.[27−32]

2. Model and formula

In this work we will propose a three-terminal Aharonov–Bohm interferometer, i.e., a normal metal (NM) lead, a ferromagnetic metal (FM) lead and a superconducting (SC) lead are coupled to their respective quantum dots to form an Aharonov–Bohm ring (see Fig.1).

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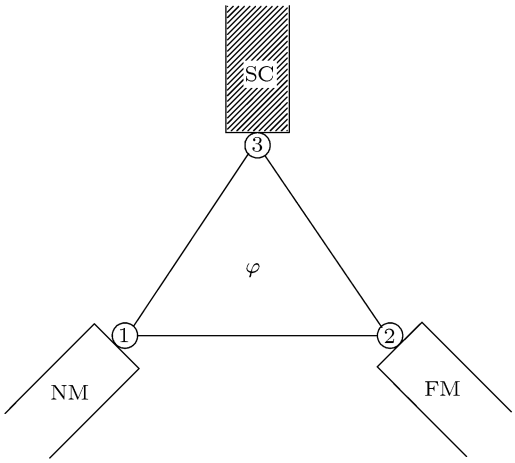


Fig.1. Schematic diagram of our system.

In this system, we consider only a bias V in the FM lead and keep zero chemical potential in both the NM and SC leads, so only the quasiparticle transmission and nonlocal Andreev reflection contribute to the electronic current in the NM lead. By tuning the gate voltage of the quantum dots and the external magnetic field, we can get rich electronic current and spin current configurations in the NM lead. The most important thing is that a pure spin current can be obtained in the NM lead. The model Hamiltonian of this system is

$$H = H_{\rm NM} + H_{\rm FM} + H_{\rm SC} + H_{\rm C} + H_{\rm T}, \tag{1}$$

where

$$H_{\rm NM} = \sum_{k,\sigma} \epsilon_k c^{\dagger}_{k\sigma} c_{k\sigma}, \tag{2}$$

$$H_{\rm FM} = \sum_{p,\sigma} \left(\epsilon_p + \sigma M + eV\right) c^{\dagger}_{p\sigma} c_{p\sigma}, \tag{3}$$

$$H_{\rm SC} = \sum_{q,\sigma} \epsilon_q c^{\dagger}_{q\sigma} c_{q\sigma} + \sum_{q} \left(\Delta c^{\dagger}_{q\uparrow} c^{\dagger}_{-q\downarrow} + \Delta c_{-q\downarrow} c_{q\uparrow} \right), \tag{4}$$

$$H_{\rm C} = \sum_{\sigma} \left\{ \sum_{j=1,2,3} \left(\varepsilon_j + V_j\right) d^{\dagger}_{j\sigma} d_{j\sigma} + \left(t_{12} {\rm e}^{{\rm i}\,\varphi/3} d^{\dagger}_{1\sigma} d_{2\sigma} + t_{23} {\rm e}^{{\rm i}\,\varphi/3} d^{\dagger}_{2\sigma} d_{3\sigma} + t_{31} {\rm e}^{{\rm i}\,\varphi/3} d^{\dagger}_{3\sigma} d_{1\sigma} + {\rm c.c.} \right) \right\}, \tag{5}$$

$$H_{\rm T} = \sum_{k,\sigma} T_{kN} c^{\dagger}_{k\sigma} d_{1\sigma} + \sum_{p,\sigma} T_{pF} c^{\dagger}_{p\sigma} d_{2\sigma} + \sum_{q,\sigma} T_{qS} c^{\dagger}_{q\sigma} d_{3\sigma} + {\rm c.c.}, \tag{6}$$

where $H_{\rm NM}$ is the Hamiltonian of the NM lead, in which $c^{\dagger}_{k\sigma}$ ($c_{k\sigma}$) is the electron creation (annihilation) operator, $H_{\rm FM}$ stands for the Hamiltonian of the FM lead in which the spin bands are split by the exchange energy $2M$, $H_{\rm SC}$ describes the Hamiltonian of the SC lead with Δ as the superconductor energy gap. We are only interested in the Andreev reflection process, so we assume the bias voltage V is less than the superconducting energy gap Δ. Note that the bias voltage V is applied in the FM lead and zero chemical potential is kept in the NM and SC leads. The $H_{\rm C}$ is the Hamiltonian for the central scattering region, which consists of three quantum dots with the magnetic flux φ. The quantum dots have discrete bare energy levels ε_j being well controlled by the corresponding gate voltages V_j. The $H_{\rm T}$ is the Hamiltonian describing the couplings between the quantum dots and the leads, in which T_{kN} (T_{pF}, T_{qS}) is the hopping matrix element. For simplicity, we have assumed that all hopping matrix elements are independent of the spin index σ.

We now calculate the spin-up electronic current passing through the NM lead, which is defined as

$$I_{N\uparrow} = e \left\langle \frac{{\rm d}\hat{N}_{N\uparrow}}{{\rm d}t} \right\rangle \tag{7}$$

with $\hat{N}_{N\uparrow} = \sum_k c^{\dagger}_{k\uparrow} c_{k\uparrow}$. From the Heisenberg equation of motion, the spin-up electronic current can be rewritten as ($\hbar = 1$)

$$I_{N\uparrow} = -e \sum_{k} [T_{kN} G^{<}_{d1\uparrow k\uparrow}(t,t') + {\rm c.c.}], \tag{8}$$

where $G^{<}_{d1\uparrow k\uparrow}(t,t') = {\rm i} \left\langle c^{\dagger}_{k\uparrow}(t')\, d_{1\uparrow}(t) \right\rangle$ is the lesser Green's function. Using the Langreth continuation theorem[33] and taking the Fourier transformation, we have

$$I_{N\uparrow} = -\,\mathrm{i}\,e\int\frac{\mathrm{d}E}{2\pi}\Gamma_N\left\{\left[G^{\mathrm{r}}(E)-G^{\mathrm{a}}(E)\right]f_N(E)+G^{<}(E)\right\}_{11}, \tag{9}$$

and similarly

$$I_{N\downarrow} = \mathrm{i}\,e\int\frac{\mathrm{d}E}{2\pi}\Gamma_N\left\{\left[G^{\mathrm{r}}(E)-G^{\mathrm{a}}(E)\right]f_N(E)+G^{<}(E)\right\}_{22}, \tag{10}$$

where $f(E)=1/(\mathrm{e}^{\beta E}+1)$ is the Fermi distribution functions, $\Gamma_N = 2\pi\sum_k |T_{kN}|^2\,\delta(E-\varepsilon_k)$ is the linewidth function which describes the coupling strength between the NM lead and the corresponding quantum dot. The G^{r} is the Fourier transformation of the retarded Green's function for the quantum dots in a 6×6 Nambu representation[4,31]

$$G^{\mathrm{r}}(t,t') = -\,\mathrm{i}\,\theta(t-t')\langle\{\Psi(t),\Psi^{\dagger}(t')\}\rangle \tag{11}$$

with row vector $\boldsymbol{\Psi}^{\dagger} = (\,d^{\dagger}_{1\uparrow},\, d_{1\downarrow},\, d^{\dagger}_{2\uparrow},\, d_{2\downarrow},\, d^{\dagger}_{3\uparrow},\, d_{3\downarrow}\,)$.

In order to obtain the spin-up and spin-down electronic current, one must know the expressions of the retarded and lesser Green's functions for the central scattering region. The most convenient way to calculate the retarded Green's function is the Dyson equation, which is given by

$$\boldsymbol{G}^{\mathrm{r}}(E) = \frac{1}{\boldsymbol{G}_0^{r}(E)^{-1}-\boldsymbol{\Sigma}^{r}(E)} \tag{12}$$

with

$$G_0^{r}(E)^{-1} = \begin{pmatrix} E-\varepsilon_1 & 0 & -t_{12}\mathrm{e}^{\mathrm{i}\,\varphi/3} & 0 & -t_{13}\mathrm{e}^{-\mathrm{i}\,\varphi/3} & 0 \\ 0 & E+\varepsilon_1 & 0 & t_{12}\mathrm{e}^{-\mathrm{i}\,\varphi/3} & 0 & t_{13}\mathrm{e}^{\mathrm{i}\,\varphi/3} \\ -t_{12}\mathrm{e}^{-\mathrm{i}\,\varphi/3} & 0 & E-\varepsilon_2 & 0 & -t_{23}\mathrm{e}^{\mathrm{i}\,\varphi/3} & 0 \\ 0 & t_{12}\mathrm{e}^{\mathrm{i}\,\varphi/3} & 0 & E+\varepsilon_2 & 0 & t_{23}\mathrm{e}^{-\mathrm{i}\,\varphi/3} \\ -t_{13}\mathrm{e}^{\mathrm{i}\,\varphi/3} & 0 & -t_{23}\mathrm{e}^{-\mathrm{i}\,\varphi/3} & 0 & E-\varepsilon_3 & 0 \\ 0 & t_{13}\mathrm{e}^{-\mathrm{i}\,\varphi/3} & 0 & t_{23}\mathrm{e}^{\mathrm{i}\,\varphi/3} & 0 & E+\varepsilon_3 \end{pmatrix} \tag{13}$$

and

$$\boldsymbol{\Sigma}^{r}(E) = -\frac{\mathrm{i}}{2}\begin{pmatrix} \Gamma_N & 0 & 0 & 0 & 0 & 0 \\ 0 & \Gamma_N & 0 & 0 & 0 & 0 \\ 0 & 0 & \Gamma_{F\uparrow} & 0 & 0 & 0 \\ 0 & 0 & 0 & \Gamma_{F\downarrow} & 0 & 0 \\ 0 & 0 & 0 & 0 & \Gamma_S\beta_1 & \Gamma_S\beta_2 \\ 0 & 0 & 0 & 0 & \Gamma_S\beta_2 & \Gamma_S\beta_1 \end{pmatrix}, \tag{14}$$

where $\Gamma_{F\uparrow}$ ($\Gamma_{F\downarrow}$) is the linewidth function of the spin-up (spin-down) electrons in the FM lead, Γ_S is the linewidth function of electrons in the SC lead; they have similar expressions of Γ_N. Other symbols $\beta_1 \equiv \zeta(E)E/\sqrt{E^2-\Delta^2}$, $\beta_2 \equiv \zeta(E)\Delta/\sqrt{E^2-\Delta^2}$ with $\zeta(E)=1$ for $E>-\Delta$, otherwise $\zeta(E)=-1$.

The lesser Green's function can be obtained from the Keldysh equation $G^{<} = G^{\mathrm{r}}\Sigma^{<}G^{\mathrm{a}}$, where the lesser self-energy is given by

$$\boldsymbol{\Sigma}^{<}(E) = \mathrm{i}\begin{pmatrix} \Gamma_N f(E) & 0 & 0 & 0 & 0 & 0 \\ 0 & \Gamma_N f(E) & 0 & 0 & 0 & 0 \\ 0 & 0 & \Gamma_{F\uparrow} f^{+}(E) & 0 & 0 & 0 \\ 0 & 0 & 0 & \Gamma_{F\downarrow} f^{-}(E) & 0 & 0 \\ 0 & 0 & 0 & 0 & f(E)\,\theta(|E|-\Delta)\,\Gamma_S\beta_1 & f(E)\,\theta(|E|-\Delta)\,\Gamma_S\beta_2 \\ 0 & 0 & 0 & 0 & f(E)\,\theta(|E|-\Delta)\,\Gamma_S\beta_2 & f(E)\,\theta(|E|-\Delta)\,\Gamma_S\beta_1 \end{pmatrix}. \tag{15}$$

Using the above relations, we can obtain general expressions for the spin-up and spin-down electronic currents

$$I_{N\uparrow} = e\Gamma_N\int\frac{\mathrm{d}E}{2\pi}\left\{\Gamma_{F\uparrow}\left|G^{\mathrm{r}}_{13}\right|^2\left[f^{-}(E)-f(E)\right]+\Gamma_{F\downarrow}\left|G^{\mathrm{r}}_{14}\right|^2\left[f^{+}(E)-f(E)\right]\right\}, \tag{16}$$

$$I_{N\downarrow} = -e\Gamma_N \int \frac{\mathrm{d}E}{2\pi} \left\{ \Gamma_{F\downarrow} \left|G^{\mathrm{r}}_{24}\right|^2 \left[f^+(E) - f(E)\right] + \Gamma_{F\uparrow} \left|G^{\mathrm{r}}_{23}\right|^2 \left[f^-(E) - f(E)\right] \right\}, \tag{17}$$

where $f^{\pm}(E) = f(E \pm eV) = 1/(\mathrm{e}^{\beta(E\pm eV)} + 1)$.

Using the spin-up and spin-down electronic current, we get the total electronic current and spin current as

$$I_N = I_{N\uparrow} + I_{N\downarrow}, \tag{18}$$

$$I_{Ns} = \left(I_{N\uparrow} - I_{N\downarrow}\right)/2e. \tag{19}$$

Equations (16), (17), (18), and (19) are the central results of this paper, and are valid for any temperatures. Here we focus on the case of $eV < \Delta$ at the zero temperature limit. The physical meanings of Eq.(16) are as follows: the first term corresponds to the spin-up quasiparticle current due to the applied bias V between the NM lead and the FM lead; the second term is the most interesting nonlocal Andreev process: a spin-down electron in the FM lead is reflected as a spin-up hole into the NM lead. Equation (17) has similar physical meanings.

3. Results and discussions

Before our numerical calculations, we first analyse the physics of the electronic current in the NM lead. The physical mechanism is that in the NM lead there is competition between normal quasiparticle transmission and nonlocal Andreev reflection. When a spin-down electron above the Fermi energy is injected from the FM lead into the SC lead, it may be reflected as a hole below the Fermi energy with up spin either back into the FM lead or into the NM lead, forming a Cooper pair in the SC lead. The former is normal Andreev reflection and the latter is nonlocal Andreev reflection. In other words, since a hole is equivalent to an electron travelling in the opposite direction, the normal Andreev reflection corresponds to the case that a pair of electrons with opposite spins comes from the same FM lead. On the other hand, if the pair of electrons comes from different leads, e.g., one from the FM lead and the other from the NM lead, it is nonlocal Andreev reflection. The total spin-up current in the NM lead results from two processes: the nonlocal Andreev reflection process due to the presence of the SC lead, and direct normal quasiparticle transmission of the spin-up electron from the FM to the NM lead under the small bias voltage between them. A similar argument applies to the spin-down current in the NM lead. Because of these two competing transport processes, we can adjust the systematic parameters to control spin-up (or spin-down) current. When the electron and hole currents with one spin cancel each other completely under certain conditions, the current for this spin disappears and we can only get the current for the other spin channel. More interestingly, if the spin-up and spin-down currents cancel each other, we can get a pure spin current.

Next, we numerically study the spin-up and spin-down electronic current varation with systematic parameters, from which we can demonstrate the appearance of the nonlocal Andreev reflection. The electronic current in the NM lead comes from the normal quasiparticle current and nonlocal Andreev reflection current. These two processes contribute to the opposite sign and therefore the total electronic current depends on the competition between the normal transmission and the nonlocal Andreev reflection. In Fig.2, we plot the spin-up (spin-down) electronic current in the NM lead which changes with gate voltage V_{g} of quantum dot 1. We set the systematic parameters as follows: the magnetic flux $\varphi = 1.6$, $\Gamma_N = \Gamma_{F\uparrow} = 1$, $\Gamma_{F\downarrow} = 0.6$, $\Gamma_S = 2$, $t_{12} = t_{23} = t_{13} = 10$, the bare energy level $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0$. Note that the common factor $e^2V/2\pi$ has been used as the unit of the electronic current. It is found that there are two zero-points in the total spin-up (spin-down) electronic current, which implies that the normal quasiparticle current and nonlocal Andreev reflection current cancel each other. These zero-points signal the existence of nonlocal Andreev reflection, which dominates the electronic transport in the NM lead when the electronic current is negative. At the same time, we can know that due to the presence of the FM lead, the positions for zero-points of the spin-up (spin-down) electronic current are different, and the spin-up current is bigger than the spin-down current.

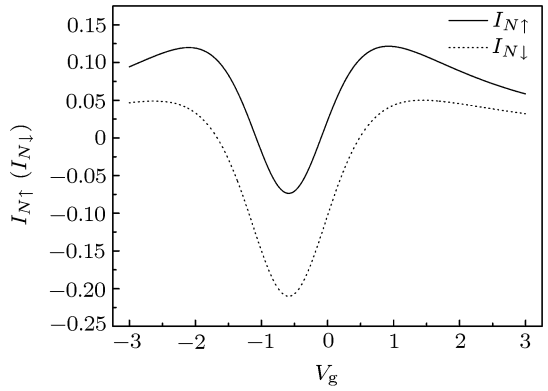


Fig.2. Spin-up current $I_{N\uparrow}$ (solid line) and spin-down current $I_{N\downarrow}$ (dotted line) versus the gate voltage of quantum dot 1 with the external magnetic flux $\varphi = 1.6$. The symmetric parameters are set: $\Gamma_N = \Gamma_{F\uparrow} = 1$, $\Gamma_{F\downarrow} = 0.6$, $\Gamma_s = 2$, $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0$, and $t_{12} = t_{13} = t_{23} = 10$.

Similarly, we also find that there are two zero-points in Fig.3 in which we give the relationship between the spin-up and spin-down electronic current in the NM lead and the external magnetic flux φ. We set the gate voltage of quantum dot 1 $V_g = 0$ and other parameters are the same as those in Fig.2. The two zero-points also characterize the appearance of nonlocal Andreev reflection. On the other hand, from our calculation, we can see that in our Aharonov–Bohm interferometer there are two oscillation periods h/e and $h/2e$ in the spin-up and spin-down electronic current oscillation because of the appearance of the SC lead, which is consistent with the results in the relevant literature.[31,34]

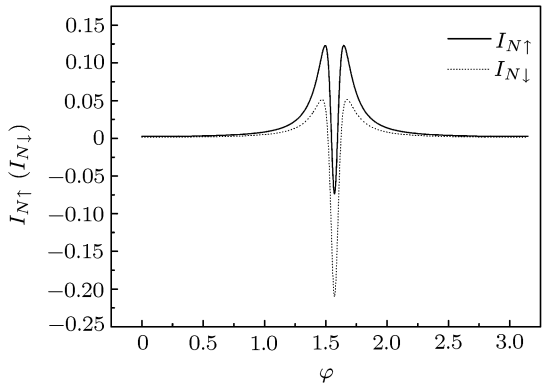


Fig.3. Spin-up current $I_{N\uparrow}$ (solid line) and spin-down current $I_{N\downarrow}$ (dotted line) versus the external magnetic flux φ. The gate voltage of quantum dot 1 $V_g = 0$ and other parameters are the same as those in Fig.2.

Finally, we numerically study the spin current modulated by the systematic parameters. Note that we have set the factor $eV/2\pi$ as the unit of the spin current. In Fig.4, we depict the spin current as a function of the gate voltage V_g of quantum dot 1. All parameters are the same as those in Fig.2. The spin current exhibits oscillation behaviour. To get more meanings, we plot the electronic current in the inset of Fig.4. We find that the electronic current becomes zero at some gate voltage positions, but at the same position the spin current is not zero. This implies that electrons with different spins in the NM flow in opposite directions, and the spin-up current and spin-down current cancel each other, thereby giving rise to a pure spin current without an electronic current. The pure spin current means that the spin-up electrons are most easily injected into the NM lead while the spin-down electrons are extracted from the NM lead. Figure 5 shows how the spin current varies with the external magnetic flux φ. All parameters are the same as those in Fig.3. The spin current also oscillates with the magnetic flux. There are also zero-points of the electronic current in the inset of Fig.5 at which the pure spin current appears. So we can conveniently control the spin current and spin injection by the gate voltage and the external magnetic flux from an experimental point of view.

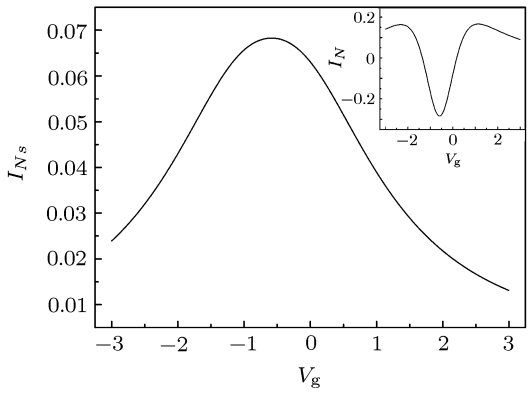


Fig.4. The spin current versus gate voltage of quantum dot 1. All parameters are the same as those in Fig.2. Inset: the electronic current versus the gate voltage of quantum dot 1.

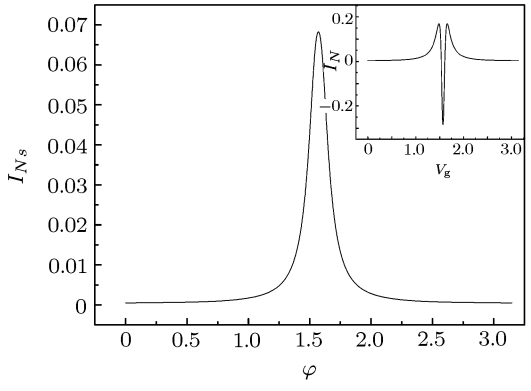


Fig.5. The spin current versus the external magnetic flux φ. All parameters are the same as those in Fig.3. Inset: the electronic current versus the external magnetic flux.

4. Summary

We have theoretically studied the nonlocal Andreev reflection and spin current in a normal metal-ferromagnetic metal-superconducting Aharonov–Bohm interferometer, and found that the electronic current and spin current can be modulated by systematic parameters, such as gate voltages and external magnetic fluxes. For the spin-up current (or spin-down current) and electronic current in the NM lead, zero-points with varying gate voltage and external magnetic field appear, which demonstrates unambiguously that nonlocal Andreev reflection happens. Under certain conditions, we can obtain pure spin current. These conclusions can be used to detect nonlocal Andreev reflection and inject spin into the NM lead experimentally, since our proposed system is within the reach of current nanotechnology.

References

[1] Samuelsson P and Büttiker M 2002 *Phys. Rev. Lett.* **89** 046601
[2] Yamashita T, Takahashi S and Maekawa S 2006 *Phys. Rev.* B **73** 144517
[3] Wang J, Wei Y D, Wang B G and Guo H 2001 *Appl. Phys. Lett.* **79** 3977.
[4] Sun Q F, Wang J and Lin T H 1999 *Phys. Rev.* B **59** 3831
[5] Lin T H 2001 *Chin. Phys.* **10** 4
[6] Wei Y D, Wang J, Guo H, Mehrez H and Roland C 2001 *Phys. Rev.* B **63** 195412
[7] Zhu Y, Lin T H and Sun Q F 2004 *Phys. Rev.* B **69** 121302(R)
[8] Li X W 2007 *Chin. Phys.* **16** 3514
[9] Chen G B, Dong J M, Dong Z C and Xing D Y 2000 *Acta Phys. Sin.* **49** 2276 (in Chinese)
[10] Yu H L 2007 *Acta Phys. Sin.* **56** 6038 (in Chinese)
[11] Beenakker C W J 1997 *Rev. Mod. Phys.* **69** 731
[12] Russo S, Kroug M, Klapwijk T M and Morpurgo A F 2005 *Phys. Rev. Lett.* **95** 027002
[13] Cadden-Zimansky P and Chandrasekhar V 2006 *Phys. Rev. Lett.* **97** 237003
[14] Yeyati A L, Bergeret F S, Martín-Rodero A and Klapwijk T M 2007 *Nature Phys.* **3** 455
[15] Duhot S and Mélin R 2007 *Phys. Rev.* B **75** 184531
[16] Brinkman A and Golubov A A 2006 *Phys. Rev.* B **74** 214512
[17] Benjamin C 2006 *Phys. Rev.* B **74** 180503(R)
[18] Datta S and Das B 1990 *Appl. Phys. Lett.* **56** 665
[19] Wolf S A, Awschalom D D, Buhrman R A, Daughton J M, Molnar S von, Roukes M L, Chtchelkanova A Y and Treger D M 2001 *Science* **294** 1488
[20] Tsukagoshi K, Alphenaar B W and Ago H 1999 *Nature* (London) **401** 572
[21] Koga T, Nitta J and Takayanagi H 2002 *Phys. Rev. Lett.* **88** 126601
[22] Schliemann J, Carlos Egues J and Loss D 2003 *Phys. Rev. Lett.* **90** 146801
[23] Kikkawa J M, Smorchkova I P, Samarth N and Awschalom D D 1997 *Science* **277** 1284
[24] Tserkovnyak Y and Brataas A 2002 *Phys. Rev. Lett.* **88** 117601
[25] Wang B G, Wang J and Guo H 2003 *Phys. Rev.* B **67** 092408
[26] Sun Q F, Guo H and Wang J 2003 *Phys. Rev. Lett.* **90** 258301
[27] Yacoby A, Heiblum M, Mahalu D and Shtrikman H 1995 *Phys. Rev. Lett.* **74** 4047
[28] Ji Y, Heiblum M, Sprinzak D, Mahalu D and Shtrikman H 2000 *Science* **290** 779
[29] Aikawa H, Kobayashi K, Sano A, Katsumoto S and Iye Y 2004 *Phys. Rev. Lett.* **92** 176802
[30] Levy Yeyati A and Büttiker M 1995 *Phys. Rev.* B **52** R14360
[31] Peng J, Wang B G and Xing D Y 2005 *Phys. Rev.* B **71** 214523
[32] Li H M, Li Y J and Liang F Y 2006 *Acta Phys. Sin.* **55** 830 (in Chinese)
[33] Langreth D C 1976 *Linear and Nonlinear Electron Transport in Solids* (New York: Plenum)
[34] Courtois H, Gandit P, Mailly D and Pannetier B 1996 *Phys. Rev. Lett.* **76** 130