A spin injector

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We theoretically put forward a spin injector, which consists of a three-terminal ferromagnetic-metal (FM) nonmagnetic-semiconductor (NS)-superconductor (SC) mesoscopic hybrid system. This device can inject not only the spin-up current but also the pure spin current into the NS lead. The crossed Andreev reflection plays a key role in this device. Such a spin injector may be realized within the reach of the present-day technology. © *2004 American Institute of Physics*.
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The charge and spin are two elementary degrees of freedom of an electron. Since the proposal of the Datta-Das transistor[1] over ten years ago, much attention[2–5] has been attracted to adding the spin degree of freedom to conventional semiconductor charge-based electronic devices. This results in the emergence of semiconductor spintronics. Because spin-based electronic devices have many advantages including the longer coherent lifetime,[6] faster data proceeding speed and less electric power consumption, the generation, manipulation, and measuring of spin currents[7] are the central challenges in spintronics and have caused an intense interest in recent years.

In this letter we propose that a three-terminal hybrid mesoscopic system, i.e., a two-dimensional (2D) quantum dot coupled to a superconductor (SC) lead, ferromagnetic-metal (FM) lead and nonmagnetic-semiconductor (NS) lead, can be utilized as an ideal spin injector (see Fig. 1). In this device, we consider only a bias V (>0) in the FM lead and keep zero chemical potentials in both NS and SC leads. By tuning the gate voltage of the quantum dot, we can get the rich spin flow configurations in the NS lead. The most important thing is that a pure spin current can be obtained in the NS lead. The physical mechanism is that in the NS lead there is a competition between the normal quasiparticle transmission and the so-called crossed Andreev reflection.[8,9] When a spin-down electron above Fermi energy is injected from the FM lead into the SC lead via the quantum dot, it may be reflected as a hole below Fermi energy with up spin back into the quantum dot, forming a Cooper pair in the SC lead. The reflected hole can go either to FM lead or to NS lead [see Fig. 2(a)]. The former is the normal Andreev reflection[10] and the latter is called the crossed Andreev reflection. In other words, since a hole is just an electron traveling in the opposite direction, the normal Andreev reflection corresponds to the case that a pair of electrons with opposite spins comes from the same lead. On the other hand, if the pair of electrons comes from different leads, e.g., one from FM lead and the other from NS lead, it is the crossed Andreev reflection. The total spin-up current in the NS lead results from two processes: the crossed Andreev reflection [Fig. 2(a)] and direct transmission of up-spin electron from FM to NS lead under small bias voltage between them [Fig. 2(b)]. A similar argument applies to the spin-down current in the NS lead. It is because of these two competing transport processes that one can adjust system parameters to control spin-up (or spin-down) current. For example, when the electron and hole currents in one spin channel cancel each other completely under certain conditions, only can we get the current for the other spin channel. More interestingly, if the spin-up and spin-down currents cancel each other, we can get the pure spin current. Such a physical picture will be clearly shown in the calculations below.

We start from the model Hamiltonian

$$H = H_{NS} + H_{FM} + H_{SC} + H_{dot} + H_c. \quad (1)$$

Here $H_{NS}=\Sigma_{k\sigma}\varepsilon_k C^+_{k\sigma}C_{k\sigma}$ is the Hamiltonian of the NS lead. $H_{FM}=\Sigma_{p\sigma}(\varepsilon_p+\sigma M+eV)C^+_{p\sigma}C_{p\sigma}$ is the Hamiltonian of the FM lead in which the spin bands are split by the exchange energy $2M$. $H_{SC}=\Sigma_q[\Sigma_\sigma\varepsilon_q c^+_{q\sigma}c_{q\sigma}+\Delta c^+_{q\uparrow}c^+_{-q\downarrow}+\Delta c_{-q\downarrow}c_{q\uparrow}]$ is the Hamiltonian of the SC lead with Δ the superconductor energy gap. A bias voltage V (>0) is applied in the FM lead and zero chemical potential is kept in both NS and SC leads.

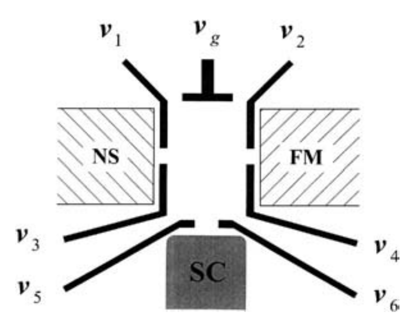

FIG. 1. Schematic diagram of our system.

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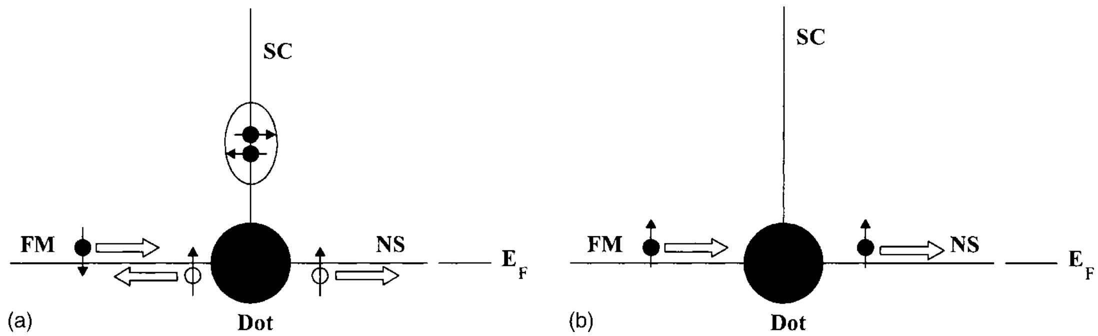

FIG. 2. Two competing processes for the spin-up current in NS lead: normal Andreev reflection and crossed Audreev reflection (a), and normal quasiparticle transmission (b).

$H_{dot}=\Sigma_\sigma(\varepsilon_0+ev_g)d_\sigma^+ d_\sigma$ is the Hamiltonian for the quantum dot, which is used as a tunable beam splitter. The discrete bare energy level ε_0 is well controlled by a gate voltage v_g. H_c is the Hamiltonian describing the couplings between the quantum dot and three leads, which is given by $H_c=\Sigma_{p\sigma}[T_p^F c_{p\sigma}^+ d_\sigma+\text{c.c.}]+\Sigma_{k\sigma}[T_k^N c_{k\sigma}^+ d_\sigma+\text{c.c.}]+\Sigma_{q\sigma}[T_q^S c_{q\sigma}^+ d_\sigma+\text{c.c.}]$. For simplicity, we have assumed that the hopping matrix elements are independent of the spin index.

We now calculate the spin-tip electronic current passing through the NS lead, which is defined as $I_{N\uparrow}=e\langle d\hat{N}_{N\uparrow}/dt\rangle$, with $\hat{N}_{N\uparrow}=\Sigma_k c_{k\uparrow}^+ c_{k\uparrow}$. From Heisenberg equation of motion, the spin-up electronic current can be rewritten as ($\hbar=1, e=1$) $I_{N\uparrow}=-\Sigma_k[T_k^N G_{d\uparrow k\uparrow}^<(t,t)+\text{c.c.}]$, where $G_{d\uparrow k\uparrow}^<(t,t')=i\langle C_{k\uparrow}^+(t')d_\uparrow(t)\rangle$ is the lesser Green's function. Using the Langreth continuation theorem[11] and taking the Fourier transformation, we have

$$I_{N\uparrow}=-i\int\frac{dE}{2\pi}\Gamma_N\{[G^r(E)-G^a(E)]f(E)+G^<(E)\}_{11} \quad (2)$$

and similarly

$$I_{N\uparrow}=i\int\frac{dE}{2\pi}\Gamma_N\{[G^r(E)-G^a(E)]f(E)+G^<(E)\}_{22}, \quad (3)$$

where $f(E)=1/(e^{\beta E}+1)$ being the Fermi distribution function, $\Gamma_N=2\pi\Sigma_k|T_k^N|^2\ \delta(E-\varepsilon_k)$ is the linewidth function of the NS lead which describes the coupling strength of the NS lead to the quantum dot, and $G^{r,a,<}$ are the retarded, advanced, and lesser Green's functions of the quantum dot in 2×2 Nambu representation.[12]

In order to calculate the spin-up and spin-down currents, one must know expressions of the Green's functions for the quantum dot. By use of the Dyson equation, the retarded Green's function[12–14] is given by $G^r(E)=1/[G_0^r(E)^{-1}-\Sigma^r(E)]$, with $G_0^r(E)^{-1}=\begin{pmatrix} E-\varepsilon_0-v_g & 0 \\ 0 & E+\varepsilon_0+v_g \end{pmatrix}$ and $\Sigma^r(E)=-(i/2)\begin{pmatrix} \Gamma_{F\uparrow}+\Gamma_N+\Gamma_S\beta_1 & \Gamma_S\beta_2 \\ \Gamma_S\beta_2 & \Gamma_{F\downarrow}+\Gamma_N+\Gamma_S\beta_1 \end{pmatrix}$, where $\Gamma_{F\uparrow}(\Gamma_{F\downarrow})$ is the linewidth function of the spin-up (spin-down) electrons for the FM lead, Γ_S is the linewidth function of electrons in the SC lead. They have the expressions similar to Γ_N. Here $\beta_1=\zeta(E)E/\sqrt{E^2-\Delta^2}, \beta_2=\zeta(E)\Delta/\sqrt{E^2-\Delta^2}$, and $\zeta(E)=1$ for $E>-\Delta$, otherwise $\zeta(E)=-1$. The lesser Green's function can be obtained from the Keldysh equation $G^<=G^r\Sigma^<G^a$, where the lesser self-energy is given by $\Sigma^<(E)=if(E)\theta(|E|-\Delta)\Gamma_S\begin{pmatrix} \beta_1 & \beta_2 \\ \beta_2 & \beta_1 \end{pmatrix}+\begin{pmatrix} \Gamma_{F\uparrow}f(E-V) & 0 \\ 0 & \Gamma_{F\downarrow}f(E+V) \end{pmatrix}+i\Gamma_N f(E)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$. Using the above relations, we can obtain general expressions for the spin-dependent currents

$$I_{N\uparrow}=\int\frac{dE}{2\pi}\frac{\Gamma_N}{|ac-b^2|^2}(\Gamma_{F\uparrow}|a|^2 f_+ + \Gamma_{F\downarrow}|b|^2 f_-), \quad (4)$$

$$I_{N\downarrow}=-\int\frac{dE}{2\pi}\frac{\Gamma_N}{|ac-b^2|^2}(\Gamma_{F\uparrow}|b|^2 f_+ + \Gamma_{F\downarrow}|c|^2 f_-). \quad (5)$$

Here $f_\pm\equiv f(E\mp V)-f(E)$, and $a\equiv E+\varepsilon_0+v_g+i(\Gamma_{F\downarrow}+\Gamma_N+\Gamma_S\beta_1)/2$, $b\equiv -i\Gamma_S\beta_2/2$, $c\equiv E-\varepsilon_0-v_g+i(\Gamma_{F\uparrow}+\Gamma_N+\Gamma_S\beta_1)/2$. Equations (4) and (5) are the central results of this paper, which are valid for finite temperattires and any bias voltage. In order to get more physical insight, we consider the case of zero temperature and small bias voltage. A little algebra yields

$$I_{N\uparrow}=\frac{V\Gamma_N}{2\pi D}\{[4(\varepsilon_0+v_g)^2+(\Gamma_{F\downarrow}+\Gamma_N)^2]\Gamma_{F\uparrow}-\Gamma_S{}^2\Gamma_{F\downarrow}\}, \quad (6)$$

$$I_{N\downarrow}=\frac{V\Gamma_N}{2\pi D}\{[4(\varepsilon_0+v_g)^2+(\Gamma_{F\uparrow}+\Gamma_N)^2]\Gamma_{F\downarrow}-\Gamma_S{}^2\Gamma_{F\uparrow}\}. \quad (7)$$

Here $D=[4(\varepsilon_0+v_g)^2+\Gamma_S^2+(\Gamma_{F\downarrow}+\Gamma_N)(\Gamma_{F\uparrow}+\Gamma_N)]^2/4+[(\varepsilon_0+v_g)^2(\Gamma_{F\uparrow}-\Gamma_{F\downarrow})^2$. These expressions have clear physical meanings. As an example, for the spin-tip current, the first term in the latter bracket of Eq. (6) indicates that the spin-up electrons are injected from the FM lead into the NS lead due to the normal quasiparticle transmission, and the second term comes from the crossed Andreev reflection process due to the presence of the SC lead. A spin-down electron from the FM lead may give rise to a spin-up hole into the NS lead with the formation of a Cooper pair in SC lead. The sign and magnitude of the spin-up current depend on a competition between the normal transmission and the crossed Andreev reflection. The similar discussion applies to the spin-down current.

Theoretically, by changing the system parameters, such as $v_g, \Gamma_N, \Gamma_{F\uparrow}$, and $\Gamma_{F\downarrow}$ and $\Gamma_{F\downarrow}$ one can get all kinds of spin flow configurations. When the parameters satisfy the relation, $[4(\varepsilon_0+v_g)^2+(\Gamma_{F\uparrow}+\Gamma_N)^2]\Gamma_{F\downarrow}-\Gamma_S^2\Gamma_{F\uparrow}=0$, the spin-down electrons are totally frozen, and there is only the spin-up electronic current in the NS lead. Similarly, if $[4(\varepsilon_0+v_g)^2+(\Gamma_{F\downarrow}+\Gamma_N)^2]\Gamma_{F\uparrow}-\Gamma_S^2\Gamma_{F\downarrow}=0$ is satisfied, only the spin-down electronic current exists in the NS lead. More interestingly, when $I_{N\uparrow}+I_{N\downarrow}=0$, the corresponding quantum dot energy levels at $\varepsilon_0+v_g=\pm\frac{1}{2}\{\Gamma_S^2-[\Gamma_{F\uparrow}(\Gamma_{F\downarrow}+\Gamma_N)^2+\Gamma_{F\downarrow}(\Gamma_{F\uparrow}+\Gamma_N)^2]/(\Gamma_{F\uparrow}+\Gamma_{F\downarrow})\}^{1/2}$, only is there the pure spin current in the NS lead.

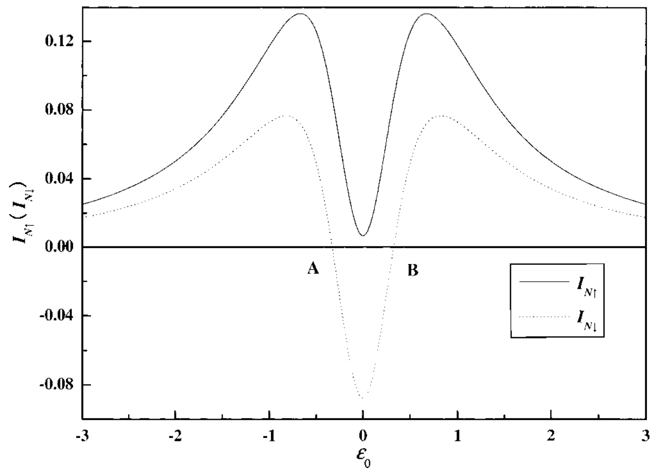

FIG. 3. Spin-up current $I_{N\uparrow}$ (solid line) and spin-down current $I_{N\downarrow}$ (dotted line) versus the gate voltage v_g of the quantum dot. All of the parameters are: $\Gamma_S=1, \Gamma_N=\Gamma_{F\uparrow}=0.5$, and $\Gamma_{F\downarrow}=0.35$.

Experimentally, we consider a two-dimensional quantum dot coupled to the FM, NS, and SC leads through the narrow constrictions, which can be controlled by the gate voltages. The schematic diagram of the device is depicted in Fig. 1 where the quantum dot is formed using seven electrostatic gates on InGaAs/InP heterostructure.[15] The quantum dots are linked to an NS lead, a niobium SC lead, and an FM permalloy ($Ni_{40}Fe_{60}$) lead.[16,17] Gates $v_1/v_3, v_2/v_4$, and v_5/v_6 control, respectively, the coupling to the NS, FM, and SC leads, i.e., $\Gamma_N, \Gamma_{F\sigma}$, and Γ_S. Gaps between $v_1/v_g, v_2/v_g$, v_3/v_5, and v_4/v_6 are fully depleted. The gate voltage v_g can change the discrete energy level ε_0 in the quantum dot so that the different spin flow configurations can be obtained. For the practical application of this device, we need to stress two points: First, the size of the window facing the supercondticting electrode must be smaller than the coherence length ζ of the superconductor, which has been discussed in Ref. 9. Second, in order for electrons and holes to pass through the central scattering regime in a coherent way, the size of quantum dot should be also smaller than the inelastic mean free path L_ϕ. In Fig. 3 we plot the spin-up current $I_{N\uparrow}$ (solid line) and spin-down current $I_{N\downarrow}$ (dotted line) versus v_g, where all the system parameters are chosen as $\Gamma_S=1$, $\Gamma_N=\Gamma_{F\uparrow}=0.5, \Gamma_{F\downarrow}=0.35$. The corresponding spin polarization in FM is 17.6%, which is close to the experimental value.[18] The bare energy level ε_0 is set to zero. Note that the common [actor $V/2\pi$ in Eqs. (6) and (7) has been used as unit of the current. It is found that the spin-up current is always positive while the spin-down current may either be positive or negative. The spin-down current vanishes at points A and B in Fig. 3, and only spin-tip current is injected into NS. Between A and B, the spin-up and spin-down electrons traverse in the opposite directions, which means that the spin-up electrons are injected into the NS lead while the spin-down electrons are extracted from the NS lead. Especially, when $I_{N\uparrow}+I_{N\downarrow}=0$, the corresponding quantum dot energy levels at $v_g=\pm\frac{1}{2}\{\Gamma_S^2-[\Gamma_{F\uparrow}(\Gamma_{F\downarrow}+\Gamma_N)^2+\Gamma_{F\downarrow}(\Gamma_{F\uparrow}+\Gamma_N)^2]/(\Gamma_{F\uparrow}+\Gamma_{F\downarrow})\}^{1/2}\approx 0.20$, the pure spin current is injected into the NS lead. Finally, we wish to emphasize that the rich spin flow configurations can be obtained for a wide range of system parameters and are the generic features of our spin injector.

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