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Voltage-controllable spin polarization of current: Model of three-terminal spin device

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In order to enhance spin injection from ferromagnetic metals into nonmagnetic semiconductors, we propose a three-terminal spin device composed of a ferromagnetic metal lead coupling with two semiconductor leads via a quantum dot. By modulating the voltage at one of the leads, a pure spin current, or a fully spin-polarized current, can be obtained in one of the semiconductor leads. The intrinsic physics is that the quasi-Fermi energy in the quantum dot is spin splitted when a current flows from the ferromagnetic lead into the quantum dot. The proposed device should be realizable using present technology for efficient spin injection into the so-called spin field effect transistor or a nanowire device.

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Spin-polarized transport in microstructures and nanostructures has drawn considerable attention in the last decade. With the development of emerging technology, the spin degree of freedom of electrons could entirely replace the charge degree of freedom as the carrier of information. Spin-based devices are believed to be a recent generation of electronic devices. Presently some spin-based devices have already been developed and appeared in the market, such as the giant magnetoresistance (GMR) spin-valve read heads, which have many advantages such as a longer coherent lifetime, faster data processing speed, and lower electric power consumption. The generation, manipulation, and measurement of spin currents are the central challenges in the spintronics field and cause an intense interest in recent years.[1–3]

The spin field effect transistor (SFET) proposed by Datta and Das[4] is one of the most attractive spin devices. It can modulate the spin state of an electron by using an external electric field instead of a magnetic field. The principle of a SFET is the rotation of electron spins by the Rashba spin-orbit (RSO) interaction[5] in a two-dimensional electron gas (2DEG). When a spin-up or spin-down electron is incident on a SFET, the electron wave function is splitted into two propagating waves (corresponding to the two spin eigenfunctions in the SFET) with different wave vectors due to the RSO interaction. At the collector, the accumulated phase difference of these two waves, which is proportional to the RSO strength and the length of the SFET, determines the final spin state of the electron. Therefore the SFET is actually a spin-modulation device which works like an optical polarimeter. To obtain the maximum efficiency, all the incident electrons must be fully spin polarized. If the incident electrons have mixed spin states, their spin states at the collector are still mixed as one cannot arbitrarily control the spin states of electrons by a SFET. Thus high spin-injection efficiency from ferromagnetic (FM) metals into nonmagnetic semiconductors (SC) is one of the prerequisites of a properly working SFET.[6]

Much effort has been devoted to enhancing spin injection from ferromagnetic materials into SC. Although, in some experiments, a spin injection efficiency as high as 90% has been achieved with a dilute magnetic semiconductor or ferromagnetic semiconductor source, its low Curie temperature limits its room temperature applications in spintronics.[7] Other suitable candidates for spin sources are ferromagnetic metals, such as Co and Fe; however, their conductivities are so much larger than that of SC that one cannot obtain effective spin injection in a FM/SC heterostructure.[8,9] Other efficient spin injection methods are therefore highly desirable. Recently, pure spin current as a possible solution to spin injection has generated widespread interest in the research community since its experimental realization using the quantum interference of two-color laser fields with crossed linear polarizations in ZnSe and GaAs semiconductors.[10] Other approaches were also theoretically proposed for obtaining pure spin current.[11–16] A notable example is the hotly discussed spin Hall current, which was recently found in 2DEG with the RSO interaction by Sinova *et al.*[17] and in *p*-doped semiconductors by Murkami *et al.*[18] as a transverse response to a longitudinal external electric field E_x applied to the sample.

In this work we propose a three-terminal spin device to obtain a pure spin current or even a fully spin-polarized current in a SC lead by adjusting the voltage of one of terminals. The device is composed of a FM metal and two SC leads coupling with a quantum dot (QD) as shown in Fig. 1. If a current flows from the FM lead to the quantum dot, the spin asymmetry of the coupling between the FM lead and the quantum dot, which results from the spin-polarized density of states of the FM lead, will lead to spin splitting of the quasi-Fermi energy in the QD as found in nonequilibrium spin accumulation in bulk materials. Thus it is possible to change the voltage at one of the SC leads to modulate the splitted spin-up or spin-down chemical potential in the QD so that a fully spin-polarized current (either the spin-up or spin-down charge current is completely suppressed) can be realized in one of the SC leads. In fact, the fully spin-polarized current realized in the proposed three-terminal spin

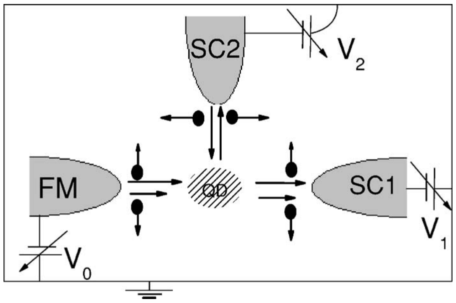

FIG. 1. Schematic of a three-terminal device, a FM and two SC leads coupled with a quantum dot. V_0, V_1, and V_2 denote the adjustable voltages of lead FM, SC1, and SC2, respectively. In lead SC2 two equal but opposite spin-resolved currents flowing between the QD and the lead are schematically shown.

device can be obtained by changing the voltage of any one of the leads, but the currents of both SC leads cannot be fully spin polarized at the same time. With the voltage of one of the SC leads lying between the two spin-splitted chemical potentials in the QD, a pure spin current without any charge current can also be obtained in this three-terminal device, i.e., equal spin-up and spin-down charge currents flowing along opposite directions in a single SC lead, $I^{\uparrow}=-I^{\downarrow}$.

The three-terminal spin device can be described by the following model Hamiltonian:

$$\mathcal{H}=\mathcal{H}_{\rm lead}+\mathcal{H}_{\rm dot}+\mathcal{H}_T \tag{1a}$$

$$\mathcal{H}_{\rm lead}=\sum_{k\sigma\alpha}\varepsilon_{k\sigma\alpha}a^{\dagger}_{k\sigma\alpha}a_{k\sigma\alpha} \tag{1b}$$

$$\mathcal{H}_{\rm dot}=\sum_{\sigma}\varepsilon_0 d^{\dagger}_{\sigma}d_{\sigma}+Ud^{\dagger}_{\uparrow}d_{\uparrow}d^{\dagger}_{\downarrow}d_{\downarrow} \tag{1c}$$

$$\mathcal{H}_T=\sum_{k\sigma\alpha}(t_{k\alpha}a^{\dagger}_{k\sigma\alpha}d_{\sigma}+\text{h.c.}), \tag{1d}$$

where $a^{\dagger}_{k\sigma\alpha}(a_{k\sigma\alpha})$ and $d^{\dagger}_{\sigma}(d_{\sigma})$ are the creation (annihilation) operators of lead α (α=FM, SC1, and SC2 in Fig. 1) and QD, respectively. $\sigma=\pm=\uparrow\downarrow$ is the spin index. All three leads are described by the noninteracting free electron model. The spin polarization in the FM lead $\varepsilon_{k\sigma,\rm FM}=\varepsilon_{k,\rm FM}+\sigma h$ is produced by the intrinsic molecular field h, and in the nonmagnetic SC1 and SC2 lead $\varepsilon_{k\uparrow,\rm SC1(2)}=\varepsilon_{k\downarrow,\rm SC1(2)}$. The QD has a single particle energy level ε_0 with U being the intradot Coulomb interaction constant. The Hamiltonian $\mathcal{H}_T$ is the coupling between the QD and the three leads and $t_{k\alpha}$ is the spin-independent hopping matrix element. For simplicity, we assume both SC leads are identical ($t_{k\rm SC1}=t_{k\rm SC2}$) but with different externally applied voltages as shown in Fig. 1.

We calculate the electronic current using the standard Keldysh nonequilibrium Green's function method[19] as ($e=\hbar=1$)

$$I^{\sigma}_{\alpha}=-i\int\frac{d\varepsilon}{2\pi}\Gamma^{\sigma}_{\alpha}\{[G^{r}_{\sigma}(\varepsilon)-G^{a}_{\sigma}(\varepsilon)]f_{\alpha}(\varepsilon)+G^{<}_{\sigma}(\varepsilon)\}, \tag{2}$$

where $\Gamma^{\sigma}_{\alpha}=2\pi\Sigma_k|t_{k\alpha}|^2\delta(\varepsilon-\varepsilon_{k\sigma\alpha})$ is the linewidth function in the wide band approximation (WBA) which describes the coupling strength of lead α to the QD. Here, we consider $\Gamma^{\uparrow}_{\rm FM}\neq\Gamma^{\downarrow}_{\rm FM}$ as a result of the spin-polarized density of states in the FM lead, and $\Gamma^{\sigma}_{\rm SC1}=\Gamma^{\sigma}_{\rm SC2}=\Gamma_{\rm SC}$. $f_{\alpha}(\varepsilon)$ is the Fermi-Dirac distribution function at lead α, which is assumed to be in local equilibrium. $G^{r,a,<}_{\sigma}(\varepsilon)$ are the retard, advanced, and lesser Green's functions of the QD.

Before calculating the current given by Eq. (2), one must know the expressions of the Green's functions of the QD. We employ the standard equation of motion of Green's function to solve G^{r}_{σ} and the equations thus obtained do not automatically close by themselves. So, using some decoupling procedure,[20] one can easily obtain

$$G^{r}_{\sigma}=\left\{\frac{1}{[1-G^{r}_{0\sigma}U(1-n_{\bar{\sigma}})]\bar{G}^{r}_{0\sigma}}+i\Gamma^{\sigma}/2\right\}^{-1}, \tag{3}$$

where $\Gamma^{\sigma}=\Gamma^{\sigma}_{\rm FM}+2\Gamma_{\rm SC}$, $G^{r}_{0\sigma}=(\varepsilon-\varepsilon_0)^{-1}$, and $\bar{G}^{r}_{0\sigma}=(\varepsilon-\varepsilon_0-U)^{-1}$. $n_{\bar{\sigma}}$ is the intradot occupation number of state $\bar{\sigma}$ of the QD, which has to be calculated self-consistently. Spin $\bar{\sigma}$ is opposite to spin σ. Thus the Green's function G^{r}_{σ} has two resonances at $\varepsilon=\varepsilon_0$ and $\varepsilon=\varepsilon_0+U$ and its spectral function has two Lorentzian peaks, as a result of the Coulomb blockade effect.

We assume the electron distribution in the QD is described by the quasi-Fermi distribution functions f^{σ}_{ϕ} and, as long as the quasiparticle scenario holds, they can be derived by the conservation of electronic current of the whole system as $f^{\sigma}_{\phi}(\varepsilon)=\Sigma_{\alpha}[\Gamma^{\sigma}_{\alpha}f_{\alpha}(\varepsilon)]/\Gamma^{\sigma}$.[21] They are spin dependent since the quasi-Fermi energy in the QD is spin splitted. Consequently the spin-dependent occupation number can be expressed as

$$n_{\sigma}=-i\int\frac{d\varepsilon}{2\pi}G^{<}_{\sigma}(\varepsilon)=i\int\frac{d\varepsilon}{2\pi}[G^{r}_{\sigma}(\varepsilon)-G^{a}_{\sigma}(\varepsilon)]f^{\sigma}_{\phi}(\varepsilon). \tag{4}$$

The last equality can also be derived from the equation of motion of the Green's function.[22]

It is assumed in the calculation that the energy bandwidths of the leads are quite large ($W\gg k_BT,eV,\Gamma$) so that the linewidth functions Γ are energy independent in the integration expression of the current in Eq. (2). Voltages V_0, V_1, and V_2 are applied to the lead FM, SC1, and SC2, respectively, and here voltages V_0 and V_1 are fixed as follows, $V_0=0.5$ and $V_1=0$. In Fig. 2 the spin-polarized currents of lead SC1 [Fig. 2(a)] and lead SC2 [Fig. 2(b)] are plotted as a function of the voltage V_2 of lead SC2. In Fig. 2(b), two spin-resolved currents in lead SC2 decrease with increase in V_2 and, at point A, the spin-down current is completely suppressed and the total electronic current is fully spin polarized (i.e., $I^{\downarrow}_{\rm SC2}=0$ and $I^{\uparrow}_{\rm SC2}\neq 0$). With further increase of V_2, the spin-down current begins to increase along a direction opposite to the spin-up current. At point B the spin-up current is completely suppressed and the current in lead SC2 is fully spin polarized

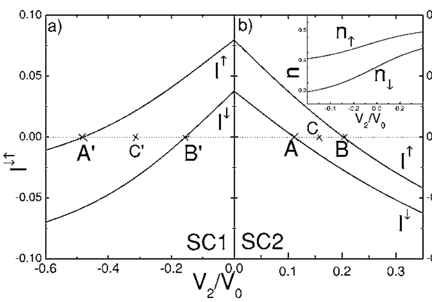

FIG. 2. The spin-polarized currents in leads SC1 (a) and SC2 (b) plotted against the voltage V_2. A, B, A′, and B′ represent the crossed points between the horizontal dot line and the current curves. C and C′ denote the positions for pure spin current. In the inset the occupation number of QD $n_{\uparrow(\downarrow)}$ are plotted against V_2. Other parameters used in the calculation are $\Gamma_{FM}^{\uparrow}=\Gamma_{SC}=0.1$, $\Gamma_{FM}^{\downarrow}=0.05$, $\varepsilon_0=0$, $U=1$, and $k_BT=0.1$. The ratio of $\Gamma_{FM}^{\uparrow}/\Gamma_{FM}^{\downarrow}$ depends mainly on that of spin-resolved density of states of electron at the Fermi energy of the FM lead, which is about 2.4 for metal iron (Ref. 23) (spin up is assumed to be the majority spin).

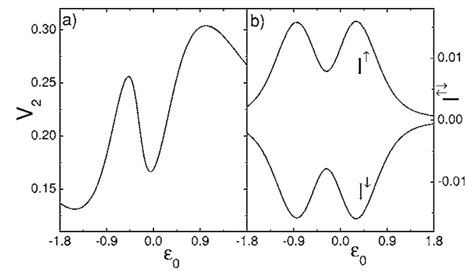

FIG. 3. (a) The voltage V_2 versus the site energy of the QD ε_0 for maintaining a pure spin current in the lead SC2; (b) the corresponding spin-up and spin-down currents $I_{SC2}^{\uparrow(\downarrow)}$ plotted as a function of ε_0.

again. Due to the spin-polarized density of states in the FM lead and $\Gamma_{FM}^{\uparrow}\neq\Gamma_{FM}^{\downarrow}$, the quasi-Fermi energy in the QD is spin splitted. As can be seen in the inset of Fig. 2(b), the spin-up occupation number is always different from the spin-down one ($n_\uparrow > n_\downarrow$) when V_2 is changed. Therefore, when the voltage V_2 matches one of the spin-splitted quasi-Fermi energies in the QD, the corresponding spin-up or spin-down current vanishes in lead SC2. At point C where $V_2/V_0 \simeq 0.16$ in Fig. 2(b), a pure spin current is obtained; the two charge currents for both spin types have identical values but opposite directions. In this case, a zero charge current $I_e=I^\uparrow+I^\downarrow=0$ and a nonzero pure spin current $I_s=I^\uparrow-I^\downarrow=2I^\uparrow(I^\downarrow)$ are obtained as schematically illustrated in Fig. 1. Hence at this fixed external voltage V_2, the QD with spin-splitted Fermi energies acts like a single-pole spin battery[16] driven by the electric circuit FM-QD-SC1. The exact ratio of V_2/V_0 for pure spin current or fully polarized charge current in the experimental realization depends on several parameters such as the spin injection rates $\Gamma_\alpha/\hbar$ between leads and QD, the temperature, and the energy level ε_0 in QD which can be controlled by a gate voltage. From the definition of Γ_α^σ it is determined by the density of states of the material as well as the hopping energy $t_{k\alpha}$.

Varying the voltage V_2, we can also obtain fully spin-polarized currents at lead SC1 at the points A' and B' shown in Fig. 2(a), where V_2 is less than the voltage of lead SC1 ($V_1=0$). In this case, the electric circuit FM-QD-SC2 makes the quasi-Fermi energy of QD spin splitted and alters their magnitudes so that one of the two spin-resolved quasi-Fermi energies can match the voltage of lead SC1 and a fully spin-polarized current can flow in lead SC1. However, it is impossible to obtain fully spin-polarized currents in both SC leads at the same time in this device configuration. The spin asymmetry in either the FM-QD-SC1 or FM-QD-SC2 circuit is the prerequisite of the spin-splitted Fermi energy in QD and thus the voltage difference between the two terminals in a circuit (for example FM and SC1 in FM-QD-SC1 circuit) must make both the spin-up and spin-down currents nonzero in one of the SC leads (in the present example SC1 in the FM-QD-SC1 circuit). This point is also shown in Fig. 2, where points A' and B' (for spin polarized currents in SC1) are at $V_2<0$ while points A and B (for spin polarized currents in SC2) are at $V_2>0$. Actually, by fixing the voltages V_2 and V_1 ($V_1\neq V_2$) and changing V_0 in the FM lead, fully spin-polarized current is also formed in either lead SC1 or lead SC2. Therefore if one of the SC leads is replaced by a SFET or a nanowire in the proposed device, we can modulate the spin-splitted quasi-Fermi energy in the QD of the FM-QD-SC circuit to inject one kind of spin (up spin or down spin) into the SFET or the nanowire. This electrical approach to achieve a spin source circumvents the stray magnetic field found in the magnetic approach to spin injection, which would affect the functionality of the SFET.[24]

It is worth studying the effect of the site energy ε_0 of the QD, which can be controlled by an external gate voltage applied to the QD, on the operation of this spin-injection device. This is important since in real experimental situations some background charges or environment noise near the device may alter the overall potential of the QD. In Fig. 3 we show the voltage V_2 of lead SC2 as a function of the site energy ε_0 for maintaining a pure spin current flowing between the QD and SC2 [maintaining the situation at point C in Fig. 2(b)]. Since the site energy ε_0 determines the quasi-Fermi energy of QD, the voltage V_2 must vary in order to maintain a pure spin current in lead SC2 when ε_0 is varied. Similar curves for V_2 versus ε_0 can also be obtained for maintaining fully spin-polarized currents in lead SC2 [maintaining the situations at points A and B in Fig. 2(b)], but they are not shown here. The nonmonotonic curve of Fig. 3(a) is the reminiscence of Coulomb blockade and this point is more clearly illustrated in Fig. 3(b), in which two equal but opposite spin-resolved currents are plotted as a function of ε_0. The two peaks in the I^σ-ε_0 curves come from the broadening of the QD energy levels ε_0 and ε_0+U due to the coupling to the leads. This broadening effect by the lead cannot be obtained in the master equation approach. The distance between the two peaks deviates slightly from U, which is a result of the variation of the voltage V_2 at the SC2 lead when ε_0 is varied. The proposed device not only works as described here in the coherent transport regime but can also work in the noncoherent transport regime since the nonequilibrium spin accumulation can still be used as a spin-injection source. Similar nonequilibrium spin accumulation was recently observed experimentally in the SC layer of a bulk FM/SC/FM tunneling junction when the two FM layers have antiparallel magnetizations.[25] In real experiments, several energy levels of the QD may be involved in the transport and the single electron effect may disappear, but the quasi-Fermi energy in the QD is still spin splitted as a result of the spin asymmetry of the FM lead, and thus it is still possible to change the voltage in one of leads to modulate the spin polarization of the current in the SC1 or SC2 lead.

In summary, we have shown it is possible to obtain a fully spin-polarized current in a SC lead in the proposed three-terminal device by modulating the voltage of one of the leads. If one of the SC leads is replaced by a SFET, it is rather convenient to adjust other leads' voltage to control the spin polarization of the current injected into the SFET. We believe by using the present technology the proposed device can be realized in experiments and used to control the spin state of the input electron into a SFET or other nanostructures. For instance, if nanowires are used as the SC leads, the proposed device can be used as a spin-injection source in nanowire spintronics.

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