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Gate-controlled spin polarized current in ferromagnetic single electron transistors

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Gate voltage can be used to tune polarization of current passing through a ferromagnetic single electron transistor when spin accumulate in the central electrode. The shift in spin chemical potential acts as charge offset in the island and alternates the gate dependence of spin current. We demonstrate this phenomenon by applying master equation calculations to ferromagnetic/normal metal/ferromagnetic single electron transistors. Taking advantage of this effect, one can use ferromagnetic single electron transistors as a tunable current polarizer.

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The ferromagnetic single electron transistor (SET) has been an interesting system shown to exhibit novel phenomena with an interplay between spin and charge. Recently, Ono *et al.*[1] and Chen *et al.*[2] succeeded in fabricating small double junctions containing magnetic or superconducting island weakly coupled to ferromagnetic leads. In their experiments, enhanced tunneling magnetoresistance (TMR), magneto-Coulomb oscillations and spin accumulations were observed. On the other hand, theories of ferromagnet/ferromagnet/ferromagnet ($F/F/F$) and ferromagnet/normal-metal/ferromagnet ($F/N/F$) SET's based on transition rate and master equation formalism were developed to derive bias-voltage and gate-voltage dependent TMR in both sequential and strong tunneling regimes.[3–9] The pioneer experiment conducted by Johnson and Silsbee demonstrated the importance of spin accumulation effect on ferromagnet-nonmagnetic metal systems.[10] For $F/N/F$ double junctions, the spin accumulation is predicted to occur when two ferromagnet leads are in antiparallel alignment, which would lead to a new origin of TMR in contrast to that of $F/F/F$ cases.[3,7,8] In this study, we investigate the spin accumulation and related phenomena in $F/N/F$ SET under the influence of gate charge.

The spin dependent transport in a ferromagnet is usually described by the relative difference of the majority and minority spins of conduction electrons, denoted as polarization P.[11] Under the condition that spins do not flip, the transport current in $F/N/F$ double tunnel junctions can be separated into two channels labeled as upspin and downspin which, throughout this article, are assumed to be contributed by majority and minority spins, respectively, in the source ferromagnet. For example, when lead magnetizations are in antiparallel alignment, the upspin channel has a larger tunneling rate for the source junction than for the drain junction. In this case and in the steady condition, the upspin chemical potential in central electrode rises to balance the spin's incoming and outgoing rates, and the chemical potential of the downspin would decrease by the same amount. This shift in spin chemical potential for systems without Coulomb blockade, denoted as $\Delta\mu_{\uparrow(\downarrow)}$, is predicted to be $\pm PeV_b/2$, in which V_b is the applied bias voltage (see inset of Fig. 1) and P is the polarization of the two leads. Therefore, the net spin in normal metal becomes nonzero and this effect is known as the spin accumulation (or spin imbalance).

A gate voltage V_g can be applied to turn on and off the charge transport in the SET by tuning the electrostatic potential of the island. When the SET is symmetrically biased with $V_g = 0$, an energy cost of roughly the charging energy $E_C = e^2/2C_\Sigma$ is required for adding or removing an excess charge in the island, and the charge transport is blockaded. When the gate voltage is tuned so that two adjacent charge states are energetically degenerate, electrons can enter or leave the island without extra energy cost, producing sequential tunneling current. The current is at a minimum and maximum, respectively, for $V_g = 0$ and $e/2C_g$ and can be modulated periodically with a period of $\Delta V_g = e/C_g$; here C_g is the island-to-gate capacitance. These two gate voltages are thus referred to as minimal and maximal gate voltages.

Our study suggests that the shift in spin chemical potentials generated by spin accumulation produces effective charge offsets to the two spin channels. This is best understood by considering the transition rates of the consisting junctions in a SET. For a N/N junction, the transition rate, derived from Fermi's golden rule, depends on the energy difference of the initial and final states. For example, the transition rate from charge state $|Q\rangle$ to $|Q\pm e\rangle$ for source junction is given by $(1/e^2R_S)(-E_S^{\pm})/[1-\exp(E_S^{\pm}/k_BT)]$, where $E_S^{\pm} = \pm(V_i - V_S) + [\pm 2e(Q-Q_0) + e^2]/2C_\Sigma$.[12] V_i and V_S are, respectively, the electrostatic potentials of the central island and source electrode, and Q_0 is the charge

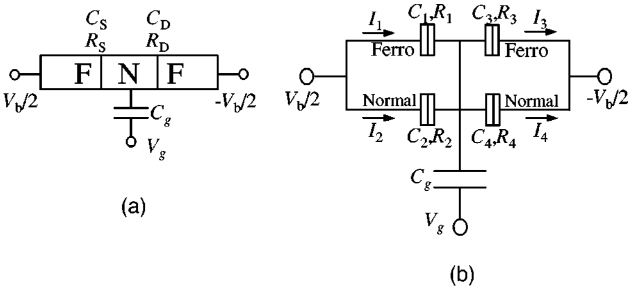

FIG. 1. (a) The scheme of the $F/N/F$ SET considered. (b) The proposed 4-lead current polarizer device. Ferromagnet leads 1 and 3 are set in antiparallel configuration to produce spin accumulation. I_4 is the current output.

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offset usually controlled by the gate voltage $Q_0=C_gV_g$. When spin accumulates, the potential of the island becomes $V_i+\Delta\mu_{\uparrow(\downarrow)}$, and $E_S^{\pm}$ changes accordingly. This potential shift can be taken into consideration by defining new charge offsets $Q_0=C_gV_g-C_{\Sigma}\Delta\mu_{\uparrow(\downarrow)}/e$ for upspin and downspin channels, respectively. With this new variable, the effect of spin accumulation on gate dependence of spin-polarized current can be clearly understood. Spin accumulation would result in a positive chemical potential shift for upspin, which will, in turn, bring in a positive-direction tilt in the upspin current-gate voltage ($I_{\uparrow}V_g$) characteristics, and a negative direction tilt in the $I_{\downarrow}V_g$ characteristics.

To demonstrate this charge offset effect, we apply a modified master equation calculation which takes into account the spin dependent charge states of the island. In this framework, which is developed by Barnaś and co-workers,[5] the states are described by two parameters $Q_{\uparrow}$ and $Q_{\downarrow}$, denoting excess upspin charge and excess downspin charge, respectively. Generally speaking, these spin dependent charge states are in nonequilibrium with the presence of spin accumulation. However, under limit of short energy relaxation time, the occupation distribution of a particular spin would form an equilibrium Gibbs distribution. In our study, we focus on the limit that k_BT is much larger than the level spacing δ, and the occupation distribution can be approximated by the Fermi distribution, i.e., $f(\varepsilon_{\alpha}-\mu_{\uparrow(\downarrow)})$ for an energy level ε_{α}. The numbers of net spin $N=(Q_{\uparrow}-Q_{\downarrow})/e$ is related to the spin chemical potentials and the density of states of the island $\rho(\varepsilon_{\alpha})$ as $N=\Sigma_{\alpha}[f(\varepsilon_{\alpha}-\mu_{\uparrow})-f(\varepsilon_{\alpha}-\mu_{\downarrow})]\simeq\int d\varepsilon\rho(\varepsilon)\times[f(\varepsilon-\mu_{\uparrow})-f(\varepsilon-\mu_{\downarrow})]$.

Although the electrostatic energy of each charge state is spin independent, the tunneling rate is spin dependent in two ways: first, the effective tunneling resistances for the majority and minority spin tunneling processes are multiplied, respectively, by $2/(1-P)$ and $2/(1+P)$. Second, the spin chemical potential shift's presence also modifies transition rates by changing the numbers of possible tunneling processes. Consequently, the master equation for each spin charge state, together with certain spin flipping transitions, reads

$$\frac{dp_{ij}}{dt}=\sum_{l=S,D}\{\Gamma_{\uparrow}^{l}(i,j|i\pm 1,j)p_{i\pm 1,j}+\Gamma_{\downarrow}^{l}(i,j|i,j\pm 1)p_{i,j\pm 1}\}-\sum_{l=S,D}\{\Gamma_{\uparrow}^{l}(i\pm 1,j|i,j)+\Gamma_{\downarrow}^{l}(i,j\pm 1|i,j)\}p_{ij}+\left(\frac{dp_{ij}}{dt}\right)_{\mathrm{sf}},\tag{1}$$

in which $i=Q_{\uparrow}/e$ and $j=Q_{\downarrow}/e$ denote the numbers of up and down spins, respectively, and $\Gamma_s^l(i',j'|i,j)$ is the tunneling rate for spin direction $s(=\uparrow,\downarrow)$ in junction l (S for source and D for drain) from states $|i,j\rangle$ to $|i',j'\rangle$, and p_{ij} is the probability that the island is in state $|i,j\rangle$. In this equation, only sequential tunneling process is considered. By introducing an energy-independent spin relaxation time τ_s, the spin flipping transitions can be explicitly written as

$$\left(\frac{dp_{ij}}{dt}\right)_{\mathrm{sf}}=\frac{1}{\tau_s}\left\{\frac{U/\delta}{1-\exp(-\beta U)}p_{i+1,j-1}+\frac{-U/\delta}{1-\exp(\beta U)}p_{i-1,j+1}\right\}-\frac{1}{\tau_s}\frac{U}{\delta}\frac{1+\exp(-\beta U)}{1-\exp(-\beta U)}p_{ij}.\tag{2}$$

The first and second terms describe respectively the increase of probability due to up-to-down and down-to-up flip processes, and the third term is the decrease arising from the opposite processes. Here we assume that the up-to-down spin flipping rate is proportional to $f(\varepsilon_{\alpha}-\mu_{\uparrow})[1-f(\varepsilon_{\alpha}-\mu_{\downarrow})]$ for electron with energy ε_{α}, and a small energy level spacing δ allows the summation of discrete energy levels approximated by a integration of continuous spectrum $\rho\sim 1/\delta$. $U=\mu_{\uparrow}-\mu_{\downarrow}\simeq(i-j)\delta$ is the chemical potential difference of up and down spins. For positive U, up-to-down spin flip is favorable, while for negative U, down-to-up spin flip dominates. Under these conditions the probabilities of major spin states with large $|U|$ are greatly reduced while suppressing the spin accumulation.

Equation (1) can be solved under the stationary condition given by $dp_{ij}/dt=0$ as described in the spin independent case.[12] Through a particular distribution of p_{ij}, one can obtain the amount of spin accumulation, quantified as average chemical potential difference $\bar{U}=\Sigma_{i,j}(i-j)\delta p_{ij}$ and the spin current for spin s tunneling through junction l,

$$I_s^l=e\sum_{ij}[\Gamma_s^l(i+1,j|i,j)-\Gamma_s^l(i-1,j|i,j)]p_{ij}.\tag{3}$$

If there is no spin flipping processes, the spin is conserved and the spin current passing through the source and drain junctions is the same. If the spin flips too quickly so as to completely destroy the spin accumulation, then the ratios between the two spin currents $I_{\uparrow}/I_{\downarrow}$ for source and drain junctions, will be the same as polarization of source and drain electrodes, respectively.

To gain an understanding about this phenomena, here, we perform a simulation using device parameters similar to those in experiments *et al.*:[2] $R_S=R_D=400$ kΩ, $C_S=C_D=300$ aF, $C_g=0.8$ aF, $P_S=P_D=0.4$. Because the resistances are much higher than quantum resistance R_Q, the contribution due to higher order tunneling processes is negligible and only sequential tunneling process is included. We consider IV_b characteristics and current-gate voltage dependences (IV_g) with both parallel and antiparallel alignment of leads under the no spin-flipping condition at a temperature of $k_BT/E_C=0.1$. In the parallel configuration, no particular feature is found because the ratio between two spin currents is simply the polarization 0.4, and total current is the same as that of the spin independent case. When the leads are in antiparallel alignment, the calculation provides much more interesting results. The total current is smaller than that of the parallel case, and the high bias differential resistance is increased by a factor of $1/(1-P^2)$ and shows a generic

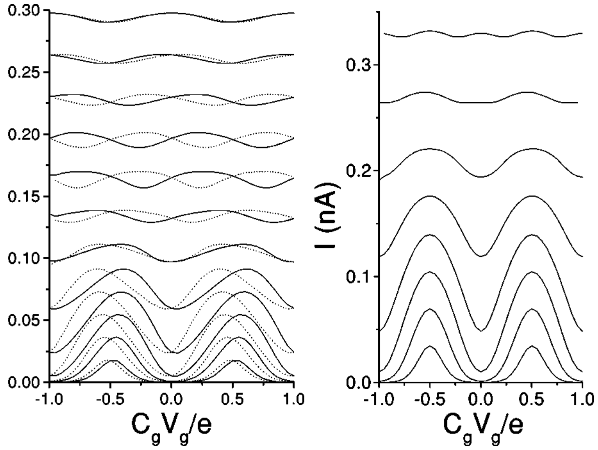

FIG. 2. Current-gate voltage dependences for (a) the spin currents from $eV_b = 0.5E_C$ (bottom) to $6.0E_C$ (top) and (b) total current from $eV_b = 0.5E_C$ (bottom) to $4.0E_C$ (top) with a step $0.5E_C$ for an $F/N/F$ SET in the antiparallel configuration, whose parameters are described in the text. In (a) the dotted and solid curves represent, respectively, up-spin and down-spin currents. Notice that the peaks and valleys for the two spin currents appear at different gate voltages. At $eV_b = 4.5E_C$ the two currents shift half period while near $eV_b = 6.0E_C$, they are the same. In (b) IV_g curves shift with bias voltages: at $eV_b = 6.0E_C$, it shifts by $0.5e$.

$F/N/F$ TMR effect. The differential TMR as a function of bias voltage also exemplifies expected oscillatory behaviors.[8]

The IV_g characteristics shown in Fig. 2(a) exhibit particularly different behaviors than from the parallel case. The upspin and downspin currents are only the same at $V_g = 0$ and $V_g = e/2C_g$. A closer inspection reveals that the peaks of two IV_g curves with opposite spins shift with increasing bias voltage. This effect can be explained when we consider two separated spin transport channels. When the leads are in antiparallel alignment, the source and drain resistances for a particular spin channel may differ by several times. This results in a steplike structure, called Coulomb staircase, in the IV_b characteristics, and a distorted saw-tooth-like IV_g modulation. The Coulomb staircase effect can explain the TMR oscillation and the asymmetric gate dependence of spin currents.[5,6] However, for a more rigorous study, it is necessary to include the spin entanglement term in the Hamiltonian $2E_CQ_\uparrow Q_\downarrow/e^2$. In fact, our calculations suggest that the results of the two methods differ especially at high bias voltages where both $Q_\uparrow$ and $Q_\downarrow$ are large.

From the view point of spin accumulation, the raised upspin (lowered downspin) chemical potential effectively gives rise to a positive (negative) charge offset. At low bias voltage regime ($V_b < 2E_C/e$), when V_g is gradually raised from zero to maximal value ($= e/2C_g$), the electrical current increases due to suppression of Coulomb blockade. The spin accumulation is, in turn, enhanced by the increased current, and consequently there is a rise in both up spin chemical potential and the effective charge offset for up spin. Since within $0 < V_g < e/2C_g$ region, the charge offset is an ascending function of V_g, and the up spin current increases more rapidly than that of the zero spin accumulation. On the other hand, the increment of down spin current is less effective, because the downspin chemical potential decreases as V_g increases. Therefore, at low bias regime, the IV_g for up and down spin are tilted, respectively, toward lower and higher V_g directions, and form saw-tooth-like IV_g patterns. At bias voltages far beyond threshold ($V_b \gg 2E_C/e$), the current is not much affected by V_g and the spin chemical potential is less sensitive to V_g. The shift in spin chemical potential (relative to the no spin accumulation case) $\Delta\mu_{\uparrow(\downarrow)}$ increases (decreases) with V_b. At $V_b = 6E_C/e, \Delta\mu_{\uparrow(\downarrow)}$ is about $\pm E_C$, corresponding to a charge offset of about $\pm e$. Consequently, as shown in Fig. 2(a), the up and down spin IV_g characteristics shift by one period in respect with each other and differ from IV_g characteristics at low bias voltages by half period. The total current is shown in Fig. 2(b), allowing a comparison with the experiments.

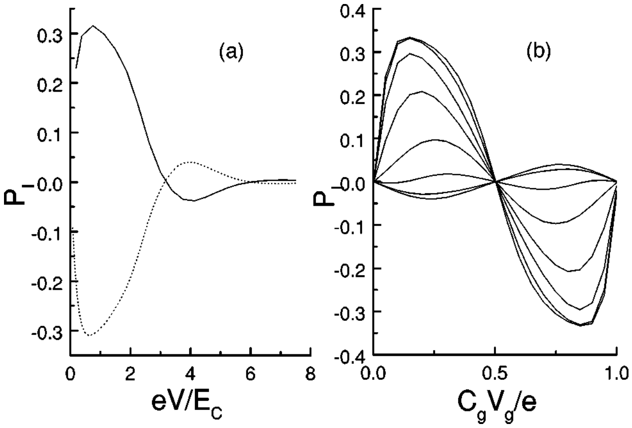

FIG. 3. (a) Polarization of current dependences on bias voltage at $eV_g/C_g = 0.15$ (solid curve) and -0.25 (dotted curve) in the antiparallel configuration. At $eV_b/E_C = 0.7$ and $eV_g/C_g = \pm 0.15$, P_I reaches a maximum value of ± 0.33 while at $eV_b/E_C = 4.0$ and $eV_g/C_g = \pm 0.25$, P_I has another maximum, which is approximately 0.04 with an opposite direction. (b) Polarization as a function of gate voltage at $eV_b/E_C = 0.5$ to 4.0 with a step 0.5.

For further investigation of the effect of applied gate voltage on two spin currents, we define a quantity describing the polarization of the tunneling current $P_I = (I_\uparrow - I_\downarrow)/(I_\uparrow + I_\downarrow)$. Figure 3 shows bias and gate voltage dependence of P_I. Such dependence suggests the possibility of using a ferromagnetic SET as a gate-controlled current polarizer. Because of large P_I values, the optimum operating regime is at low bias voltage. At $eV_g/C_g = \pm 0.15$ and $eV_b/E_C = 0.7$, the current polarizations reach a maximum value of ± 0.33. One can also explore the temperature dependence of the polarization current. There are two ways that the effects of temperature can enter, both leading to the destruction of current polarization. One is thermal activated charge fluctuation and the other is decrease of spin flip time. The former is automatically included in the master equation calculation and its effect is shown in Fig. 4(a). At $T = 0$, the value of P_I can be as large as the polarization of the lead itself, while at $k_BT \gtrsim 0.5E_C$, the gate charge effect becomes negligible. To evaluate the effect of the spin flip process, we assume an

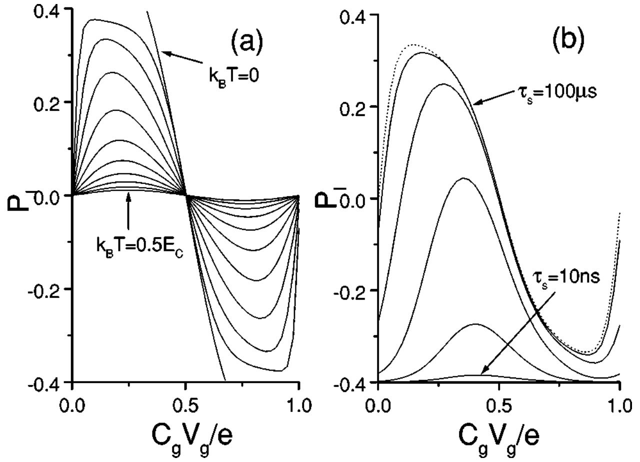

FIG. 4. (a) Gate voltage dependences of polarization at $eV_b/E_C=0.7$ for temperatures ranging between 0 and $0.5E_C/k_B$ with a step 0.05 under no spin flip assumption. At $T=0$, P_I cannot be defined for $C_gV_g/e<0.33$ and $C_gV_g/e>0.67$ since the current is zero within that range. The effect is more pronounced at lower temperatures. (b) The same dependence for the drain junction at $eV_b/E_C=0.7$ and $k_BT/E_C=0.1$ with several spin flipping times τ_s, from bottom to top: 10 ns, 100 ns, 1 μs, 10 μs, 100 μs (solid curves), and ∞ (dotted curve). For $\tau_s=10$ ns, P_I is fairly close to the P value of the drain electrode, i.e., no spin accumulation. For $\tau_s=100$ μs, spin accumulation is almost the same as the nonflipping case and P_I increases dramatically.

energy independent spin flipping time and an energy level spacing δ of $1\mu e$V in the island, and perform the calculations using the same device parameters as above. Figure 4(b) shows the current polarization for drain junction operating at $V_b=0.7E_C/e$ as a function of gate voltage at $k_BT/E_C=0.1$ under several spin flipping times. Clearly, when the spin flip time is short as compared with the tunneling time $\tau_t=e/I$ of approximately 10 ns, the spin accumulation diminishes and $P_I=-0.4$, which is simply the polarization of the drain electrode. However, since the chemical potential is proportional to the island's density of states, the required spin flip time would be shorter for nanometer-sized normal-metal islands in which the level spacing is of the order of 10^{-8}–10^{-9} eV, which is much smaller than the assumed value. It has been proposed that the criteria for spin accumulation is related to the tunneling resistance R_t as $\tau_s\delta/\hbar>R_t/R_Q$.[8] Our calculation results agree with this prediction.

The cotunneling processes, which are thus far not included in our calculations, can also give induce effective spin flipping. In the spin independent case, cotunneling is a second order process that preserves the charge state but also produces current. In the Coulomb blockade regime, where sequential tunneling is suppressed, the current is mainly due to cotunneling. For spin cotunneling, there are spin-conserved and spin-nonconserved processes. The latter, which is a spin enters the island and an opposite spin leaves, would give extra spin-flipping transition terms in the master equations described by Eq. (1). The forward and backward cotunneling rates $\overrightarrow{\Gamma}_{\rm co}$, $\overleftarrow{\Gamma}_{\rm co}$ for $F/N/F$ SET can be written as[13]

$$\overset{\rightleftarrows}{\Gamma}_{\rm co}=\frac{R_Q}{4\pi^2e^2R_{S,\rm eff}R_{D,\rm eff}}\times\int d\varepsilon\frac{\varepsilon}{1-\exp(-\beta\varepsilon)}\,\frac{\Delta E-\varepsilon}{1-\exp[-\beta(\Delta E-\varepsilon)]}|\overset{\rightleftarrows}{M}|^2, \tag{4}$$

where

$$\overset{\rightleftarrows}{M}=\frac{1}{E_S^{\pm}+\varepsilon+i\gamma^{\pm}}+\frac{1}{E_D^{\mp}+\Delta E-\varepsilon+i\gamma^{\mp}}. \tag{5}$$

The ΔE is the energy difference between initial and final states. For spin conserved co-tunneling, $\Delta E=\pm eV$, whereas for up-to-down and down-to-up cotunneling $\Delta E=\pm eV-U$ and $\Delta E=\pm eV+U$, respectively ("+" for forward and "−" for backward). $E_S^{\pm}$ and $E_D^{\pm}$ are, again, energy changes of the tunneling processes $Q\rightarrow Q\pm e$ for source and drain junctions. $R_{S,\rm eff}$ and $R_{D,\rm eff}$ are the effective tunneling resistances for the source and drain junctions. Note that for antiparallel configuration, $R_{S,\rm eff}R_{D,\rm eff}$ product in Eq. 4 is R_SR_D product multiplied by $4/(1-P_S)(1+P_D)$,$4/(1+P_S)(1-P_D)$,$4/(1+P_S)(1+P_D)$, and $4/(1-P)(1-P_D)$ for up-to-up, down-to-down, up-to-down, and down-to-up forward cotunneling events, respectively. $\gamma^{\pm}$ are decay rates for the final charge states $Q\pm e$ of the two processes and are given by

$$\gamma^{\pm}=\frac{R_Q}{4\pi}\left(\frac{E_S^{\pm}}{R_{S,\rm eff}}\coth\frac{\beta E_S^{\pm}}{2}+\frac{E_D^{\pm}}{R_{D,\rm eff}}\coth\frac{\beta E_D^{\pm}}{2}\right). \tag{6}$$

To investigate the cotunneling spin flipping, we use tunneling resistances of 40 kΩ, which is closer to R_Q, and leave other parameters unchanged. In the Coulomb blockade regime, the cotunneling spin flipping rate can be as large as 10^8 Hz, which is comparable to the tunneling rate of I/e $\sim10^9$ Hz. However, different from the spin relaxation as discussed above, the spin flipping induced by cotunneling for $|U|\ll eV_b$ does not have preferred direction. That is, it does not smear out the spin accumulation but rather only enhances spin fluctuation. Figure 5 shows the spin fluctuation δN $=\sqrt{\overline{U^2}-\overline{U}^2}/\delta$ as a function of gate voltage at V_b $=0.75E_C/e$ with and without consideration of cotunneling processes.

A $F/N/F$ SET cannot be used as a current polarizer because the drain ferromagnetic lead will destroy controlled polarization of injected currents. To overcome the problem, we propose a four-lead type device which can be used in reality. The proposed device, shown in Fig. 1(b), consists of two parallel $F/N/F$ and $N/N/N$ SET's sharing a common nonmagnetic island. The pair of ferromagnet leads can produce spin accumulation in the central electrode while the gate charge effect can change the polarization of current passing through the nonmagnetic leads. This system behaves effectively as a $F/N/F$ SET with $P_S=R_2P/(R_1+R_2)$, P_D $=R_4P/(R_3+R_4)$, $R_S=R_1R_2/(R_1+R_2)$, $R_D=R_3R_4/(R_3$ $+R_4)$, $C_S=C_1+C_2$, and $C_D=C_3+C_4$. Therefore, our previous calculation can also be applied to this system and give

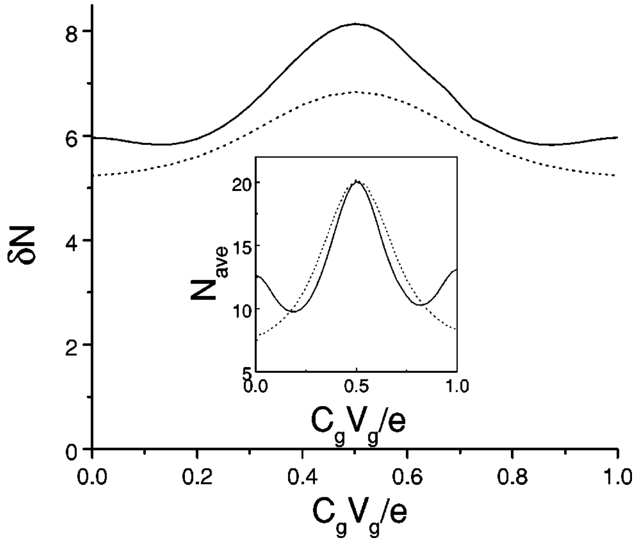

FIG. 5. Spin fluctuation δN vs gate voltage V_g in the Coulomb blockade regime, $V_b=0.1$ mV. The solid and dotted curves represent respectively the result for sequential tunneling with and without cotunneling processes. The fluctuation is increased by about 20%. The inset shows the average spin number $N_{\rm ave}=\overline{U}/\delta$ for the two cases.

result on P_I value of current passing through the normal drain (lead 4), which is assigned as the output of the polarizer. Because the two drain junctions are connected in parallel, the ratio of spin current through the two junctions only depends on resistance ratio and P, and is given by $I_{3,\uparrow}/I_{4,\uparrow}=(1-P)R_4/R_3$ and $I_{3,\downarrow}/I_{4,\downarrow}=(1+P)R_4/R_3$. Therefore, for a symmetric condition that $R_2=R_4=rR_1=rR_3$ and $P_S=P_D=rP/(1+r)$, a simple algebra gives the polarization of I_4 as $P_{I_4}=[P_I(1+r)+rP]/[(1+r)+rP_IP]$, where P_I is the polarization of total drain current I_3+I_4. Our study suggests that $r\simeq 1$ is a good condition for which P_{I_4} spans a large range and I_4 is considerable large. At zero temperature, where P_I can be varied between $\pm P/2$,P_{I_4} is approximately in the range $0<P_{I_4}<P/(1+P^2/4)$.

In summary, we proposed theoretically a gate-controlled polarized current in ferromagnetic single electron transistors under the limit of $E_C \gg k_BT \gg \delta$. Using a modified master equation formalism, we calculate spin sequential tunneling rates and spin current when spin accumulation is present. The spin accumulation-induced chemical potential shift behaves as charge offsets, producing interesting effects to the IV_g characteristics. When the gate voltage is tuned away from the maximal and minimal gate voltages, the current passing through the junctions is polarized. The thermal fluctuation and spin flipping processes are both shown to suppress the effects from charge offset. The cotunneling event provides effective spin flipping processes, but it only enhances spin fluctuation. Taking advantage of the gate dependence of polarized current in a ferromagnetic SET, a four-lead device can be used as a tunable current polarizer.

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