Temperature-manipulated spin transport through a quantum dot transistor

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We study the spin-polarized transport through a semiconductor quantum dot connected to a normal metal lead and a ferromagnetic lead, applied with different temperatures. Using the master equation approach, it is found that in such a system the spin polarization of thermal current has a rectification effect; that is, in the positive temperature bias range, the current polarization has a nonzero plateau, while in the negative temperature bias range, the current polarization vanishes. In addition, the current polarization exhibits a spin-valve effect, which corresponds to the existence of a finite zero region controlled by the gate voltage, and the size of the zero region is determined by Coulomb interaction and temperature bias.

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I. INTRODUCTION

Up to now, there have been many investigations of the systems based on quantum dots (QDs). A lot of interesting transport properties in these systems have been revealed, such as the Coulomb blockade, spin blockade, tunneling magnetoresistance, Kondo effect, voltage-controlled spin polarization, and so on.[1–7] The rectification effects in these systems, which are important for the field of information, also have attracted many researchers' eyes. Some diodelike behaviors of transport characteristics have been found in the cases of QDs coupled to two ferromagnetic leads (FM-QD-FM) or to a nonmagnetic lead and a ferromagnetic lead (NM-QD-FM).[8–13]

It was found that by changing the electric bias applied to a NM-QD-FM system, the current polarization has a diode effect for a particular bias range due to the interplay between the spin accumulation and Coulomb interaction in the dot.[13] Afterward, tunable spin diodes have been realized experimentally.[14,15] However, these results are all generated by controlling electric bias. Recently, thermal manipulation of spintronic devices has been proposed.[16–21] Uchida *et al.* found the spin-Seebeck effect, in which spin current can be induced by a temperature gradient, similar to the Seebeck effect of charges.[16] In the very latest experiments, the spin-Seebeck effect was measured in thermally driven spin injection from a ferromagnetic metal to a nonmagnetic metal,[17] and people also observed the spin-Seebeck effect in a ferromagnetic semiconductor.[18] Furthermore, it was proposed that a pure spin current can be achieved in a FM-QD-FM system by applying a magnetic field to the system[19] or irradiating the system with circularly polarized light[20] and setting the two leads at different temperatures; in contrast, some spin-dependent thermoelectric effects may be realized in a single-molecule-magnet junction by tuning the gate voltage.[21]

Beginning from the theoretical considerations and experimental results mentioned above, we investigate the current polarization in a transistor, as shown in Fig. 1, composed of a semiconductor QD coupled to a nonmagnetic lead and a ferromagnetic lead. The energy level of the QD is tuned by a gate voltage and the two electrodes are applied by a temperature bias. Owing to the difference between the Fermi distributions of the two leads at different temperatures, also Coulomb interaction and spin accumulation, very obvious rectification effect and spin-valve effect of current polarization can be obtained for a quite large temperature range in this system. The paper is organized as follows. In Sec. II we describe our model and formalism, the numerical results and discussion are presented in Sec. III, and a brief summary is given in Sec. IV.

II. MODEL AND FORMALISM

A NM-QD-FM system, as seen in Fig. 1, can be described by the following Hamiltonian:[13]

$$\mathcal{H} = \sum_{\alpha k\sigma} \varepsilon_{\alpha k} c^{\dagger}_{\alpha k\sigma} c_{\alpha k\sigma} + \sum_{\sigma} \varepsilon_d d^{\dagger}_{\sigma} d_{\sigma} + U n_{\uparrow} n_{\downarrow} + \sum_{\alpha k\sigma} [t_{\alpha k\sigma} c^{\dagger}_{\alpha k\sigma} d_{\sigma} + t^{*}_{\alpha k\sigma} d^{\dagger}_{\sigma} c_{\alpha k\sigma}], \tag{1}$$

where $c^{\dagger}_{\alpha k\sigma}$ ($c_{\alpha k\sigma}$) and $d^{\dagger}_{\sigma}$ (d_{σ}) are the electron creation (annihilation) operators in lead α ($\alpha = L,R$) and the dot with spin σ, respectively. $\varepsilon_{\alpha k}$ is the free-electron energy in lead α with wave vector k, ε_d is the QD energy level, and U is the intradot Coulomb interaction. $n_{\uparrow(\downarrow)} = d^{\dagger}_{\uparrow(\downarrow)} d_{\uparrow(\downarrow)}$ is the number operator, $t_{\alpha k\sigma}$ represents the coupling between the leads and the dot.

By using the rate equations,[13,19] we can describe the evolution of the occupation probabilities of the different states in the dot by

$$\frac{d}{dt}\begin{pmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{pmatrix} = \begin{pmatrix} -\Gamma^{+}_{\uparrow} - \Gamma^{+}_{\downarrow} & \Gamma^{-}_{\uparrow} & \Gamma^{-}_{\downarrow} & 0 \\ \Gamma^{+}_{\uparrow} & -\bar{\Gamma}^{+}_{\downarrow} - \Gamma^{-}_{\uparrow} & 0 & \bar{\Gamma}^{-}_{\downarrow} \\ \Gamma^{+}_{\downarrow} & 0 & -\bar{\Gamma}^{+}_{\uparrow} - \Gamma^{-}_{\downarrow} & \bar{\Gamma}^{-}_{\uparrow} \\ 0 & \bar{\Gamma}^{+}_{\downarrow} & \bar{\Gamma}^{+}_{\uparrow} & -\bar{\Gamma}^{-}_{\downarrow} - \bar{\Gamma}^{-}_{\uparrow} \end{pmatrix} \begin{pmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{pmatrix}, \tag{2}$$

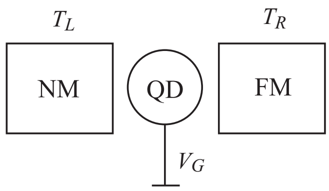

FIG. 1. Schematic diagram for a QD connected by a nonmagnetic left lead and a ferromagnetic right lead. A temperature bias, $\Delta T = T_L - T_R$, and a gate voltage, V_G, are applied to this system.

where P_0, P_1, P_2, and P_3, respectively, are the probabilities of the dot occupied by no electrons, a spin-up electron, a spin-down electron, and two electrons with the opposite spins. $\Gamma_\sigma^+ = \Gamma_{L\sigma}^+ + \Gamma_{R\sigma}^+ = f_L\gamma_{L\sigma} + f_R\gamma_{R\sigma}$ $[\Gamma_\sigma^- = \Gamma_{L\sigma}^- + \Gamma_{R\sigma}^- = (1-f_L)\gamma_{L\sigma} + (1-f_R)\gamma_{R\sigma}]$ is the tunneling rate of an electron with spin σ, which tunnels to (from) the dot, when the dot is not occupied (occupied). Similarly, $\bar{\Gamma}_\sigma^+ = \bar{\Gamma}_{L\sigma}^+ + \bar{\Gamma}_{R\sigma}^+ = \bar{f}_L\bar{\gamma}_{L\sigma} + \bar{f}_R\bar{\gamma}_{R\sigma}$ $[\bar{\Gamma}_\sigma^- = \bar{\Gamma}_{L\sigma}^- + \bar{\Gamma}_{R\sigma}^- = (1-\bar{f}_L)\bar{\gamma}_{L\sigma} + (1-\bar{f}_R)\bar{\gamma}_{R\sigma}]$ represents the tunneling rate of an electron with spin σ, which tunnels to (from) the dot, when the dot is singly occupied by an electron with the opposite spin $\bar{\sigma}$ (doubly occupied by two electrons with the opposite spins). $\gamma_{\alpha\sigma}$ and $\bar{\gamma}_{\alpha\sigma}$ are related to both the dot-lead coupling and the density of states of lead α. Here $f_\alpha = [e^{(\varepsilon_d-\mu_\alpha)/k_BT_\alpha} + 1]^{-1}$ and $\bar{f}_\alpha = [e^{(\varepsilon_d+U-\mu_\alpha)/k_BT_\alpha} + 1]^{-1}$ are the Fermi distributions of lead α with the resonant energy ε_d, chemical potential μ_α, and temperature T_α.

It is easy to check that $n_\uparrow = P_1 + P_3$, $n_\downarrow = P_2 + P_3$, and $n_{\uparrow\downarrow} = P_3$, and therefore from Eq. (2), we have the evolution of n_σ as

$$\frac{d}{dt}n_\sigma = \Gamma_\sigma^+(1 - n_\sigma - n_{\bar{\sigma}} + n_{\uparrow\downarrow}) - \Gamma_\sigma^-(n_\sigma - n_{\uparrow\downarrow}) + \bar{\Gamma}_\sigma^+(n_{\bar{\sigma}} - n_{\uparrow\downarrow}) - \bar{\Gamma}_\sigma^- n_{\uparrow\downarrow}. \tag{3}$$

Taking $I_{\alpha\sigma}$ as the current in lead α, then applying the continuity equation $edn_\sigma/dt = I_{L\sigma} + I_{R\sigma}$, one can write

$$I_{\alpha\sigma} = e[\Gamma_{\alpha\sigma}^+(1 - n_\sigma - n_{\bar{\sigma}} + n_{\uparrow\downarrow}) - \Gamma_{\alpha\sigma}^-(n_\sigma - n_{\uparrow\downarrow})] + e[\bar{\Gamma}_{\alpha\sigma}^+(n_{\bar{\sigma}} - n_{\uparrow\downarrow}) - \bar{\Gamma}_{\alpha\sigma}^- n_{\uparrow\downarrow}]. \tag{4}$$

It is usual to take $\gamma_{\alpha\sigma} = \bar{\gamma}_{\alpha\sigma}$, and then Eqs. (3) and (4) can be simplified into the following forms:

$$\frac{d}{dt}n_\sigma = \Gamma_\sigma^+(1 - n_\sigma - n_{\bar{\sigma}}) - \Gamma_\sigma^- n_\sigma + \bar{\Gamma}_\sigma^+ n_{\bar{\sigma}}, \tag{5}$$

and

$$I_{\alpha\sigma} = e[\Gamma_{\alpha\sigma}^+(1 - n_\sigma - n_{\bar{\sigma}}) - \Gamma_{\alpha\sigma}^- n_\sigma + \bar{\Gamma}_{\alpha\sigma}^+ n_{\bar{\sigma}}]. \tag{6}$$

For the stationary regime, that is, $dn_\sigma/dt = 0$, we have

$$n_\sigma = \frac{\Gamma_{\bar{\sigma}}^-\Gamma_\sigma^+ + \bar{\Gamma}_\sigma^+\Gamma_{\bar{\sigma}}^+}{(\Gamma_\sigma^+ + \Gamma_\sigma^-)(\Gamma_{\bar{\sigma}}^+ + \Gamma_{\bar{\sigma}}^-) - (\bar{\Gamma}_\sigma^+ - \Gamma_\sigma^+)(\bar{\Gamma}_{\bar{\sigma}}^+ - \Gamma_{\bar{\sigma}}^+)}. \tag{7}$$

Substituting Eq. (7) into Eq. (6), $I_{\alpha\sigma}$ is transformed to

$$I_{\alpha\sigma} = e\frac{\Gamma_{\alpha\sigma}^+(\Gamma_\sigma^-\Gamma_{\bar{\sigma}}^- - \bar{\Gamma}_\sigma^+\bar{\Gamma}_{\bar{\sigma}}^+) - \Gamma_{\alpha\sigma}^-(\Gamma_{\bar{\sigma}}^-\Gamma_\sigma^+ + \bar{\Gamma}_\sigma^+\Gamma_{\bar{\sigma}}^+) + \bar{\Gamma}_{\alpha\sigma}^+(\Gamma_\sigma^-\Gamma_{\bar{\sigma}}^+ + \bar{\Gamma}_{\bar{\sigma}}^+\Gamma_\sigma^+)}{(\Gamma_\sigma^+ + \Gamma_\sigma^-)(\Gamma_{\bar{\sigma}}^+ + \Gamma_{\bar{\sigma}}^-) - (\bar{\Gamma}_\sigma^+ - \Gamma_\sigma^+)(\bar{\Gamma}_{\bar{\sigma}}^+ - \Gamma_{\bar{\sigma}}^+)}. \tag{8}$$

In the present system, it is reasonable for us to assume $\gamma_{L\uparrow} = \gamma_{L\downarrow} = \gamma_0$ and $\gamma_{R\uparrow} = \gamma_0(1+p)$, $\gamma_{R\downarrow} = \gamma_0(1-p)$, where γ_0 is the lead-dot coupling and p is the spin polarization degree of the ferromagnetic lead.[22] It should be pointed out that, as easily to be checked, the value of p changes very little with T in the range of temperature bias considered, so p is almost a constant. Meanwhile, we set $\mu_L = \mu_R = 0$, namely, no electric bias. Then we can derive the current polarization:

$$\chi = \frac{I_\uparrow - I_\downarrow}{I_\uparrow + I_\downarrow} = \frac{(f_L - \bar{f}_L - 1)p}{f_L - \bar{f}_L + f_R - \bar{f}_R - (f_R - \bar{f}_R - 1)p^2 - 2}. \tag{9}$$

This is the central result in this paper. From it, we can perform our numerical calculations and give some simplified analytic treatments.

III. RESULTS AND DISCUSSION

A. Thermal rectification effect

First of all, we are ready to give a simple analysis about Eq. (9) in some approximations. When the temperature bias ($\Delta T = T_L - T_R$) is large, and the reference temperature T_0, which is T_R for the positive temperature bias ($\Delta T > 0$) or T_L for the negative temperature bias ($\Delta T < 0$), is very low, we can approximate the Fermi distributions $f_L = \bar{f}_L = 1/2$, $f_R = 1$, $\bar{f}_R = 0$ for $\Delta T > 0$ and $f_R = \bar{f}_R = 1/2$, $f_L = 1$, $\bar{f}_L = 0$ for $\Delta T < 0$. Using these results in Eq. (9), one finds

$$\chi = \begin{cases} p, & \Delta T > 0, \\ 0, & \Delta T < 0, \end{cases} \tag{10}$$

in accordance with the numerical results in Fig. 2, which shows χ versus $k_B\Delta T$ with the QD energy level $\varepsilon_d = -3.0$ meV, the Coulomb interaction $U = 7.0$ meV, $k_BT_0 = 0.2$ meV, and $\gamma_0 = 0.01$ meV. From this figure, we can see that the current polarization has an obvious rectification effect. For the positive temperature bias, $T_L > T_R$, χ keeps on a nonzero plateau in a large range and the plateau rises with p. Oppositely, it is found that for the negative temperature bias, $T_L < T_R$, χ vanishes no matter what the p value is, except $p = 1$, because for $p = 1$, $I_\downarrow = 0$ and $I_\uparrow \neq 0$, $\chi = (I_\uparrow - I_\downarrow)/(I_\uparrow + I_\downarrow) = 1$ all along.

To find the reason for this remarkable rectification effect, we need to analyze the spin-dependent currents (see the inset of Fig. 2) and the spin accumulation (see Fig. 3). When a temperature bias is applied to the device, the Fermi distributions of the two leads are different. If the temperature bias is positive, electrons above the Fermi surface of lead L are more than the electrons in the right lead. Electrons below the

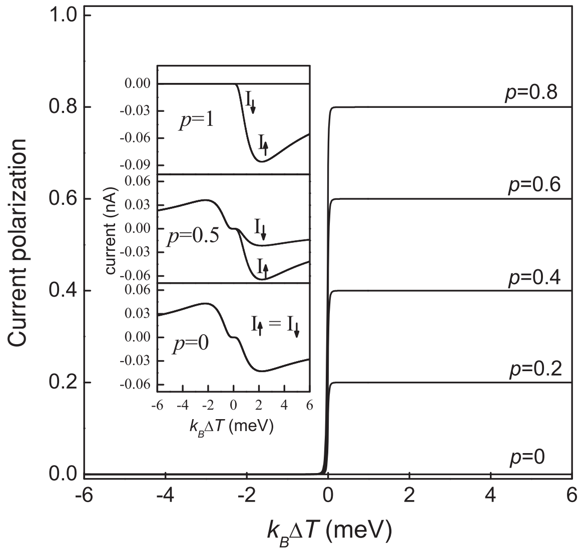

FIG. 2. Current polarization χ vs $k_B\Delta T$ for different p values. (Inset) Spin-resolved currents vs $k_B\Delta T$. The other parameters are $U = 7.0$ meV, $\varepsilon_d = -3.0$ meV, $k_B T_0 = 0.2$ meV, and $\gamma_0 = 0.01$ meV.

Fermi surface of lead L are less than the electrons in the right lead. Because we set $\varepsilon_d = -3.0$ meV (less than $\mu_L = \mu_R = 0$), electrons move from the right lead to the left lead through this channel below the Fermi surface, which generates negative currents as the inset shows (we assume current flowing from the right lead to the left lead is positive). Because $\gamma_{R\uparrow} > \gamma_{R\downarrow}$ and $\gamma_{L\uparrow} = \gamma_{L\downarrow}$, the spin-up electrons are injected into the dot more easily than the spin-down electrons, but with equal ease while the spin-up and spin-down electrons leave the dot. So the spin-up electrons relatively accumulate in the dot, as we can find in Fig. 3. The spin accumulation $m = n_\uparrow - n_\downarrow$ is positive for the positive temperature bias. At the same time, due to the Coulomb interaction, there is a resonant channel $\varepsilon_d + U$ (=4.0 meV here) above the Fermi surface. Because the electrons above the Fermi surface in the left lead are more than the electrons in the right lead, they go from the left lead to the right lead through this channel, just like electrons in the opposite direction through the channel $\varepsilon_d = -3.0$ meV. That results in a decrease of $I_\downarrow$ and a widening of the gap between

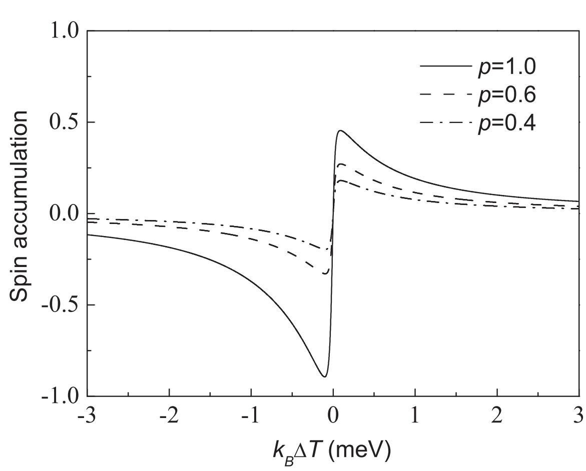

FIG. 3. Spin accumulation $m = n_\uparrow - n_\downarrow$ vs $k_B\Delta T$ for several p. Other parameters are the same as those in Fig. 2.

the two currents and then enhances χ. As the temperature bias goes larger, we can see in the inset of Fig. 2 that both $I_\uparrow$ and $I_\downarrow$ decrease. That is because the gap between the contributions to the electron transport of the two channels gets narrow. Interestingly, although the currents have such variation, χ stays almost invariant all along. That is primarily because the changes of the two currents can be consistent with each other.

For the negative temperature bias ($T_L < T_R$), the electrons below the Fermi surface in the left lead are more than the electrons in the right lead. That creates positive currents (see the negative temperature bias range in the inset of Fig. 2). Likewise, because of $\gamma_{R\uparrow} > \gamma_{R\downarrow}$ and $\gamma_{L\uparrow} = \gamma_{L\downarrow}$, the channel $\varepsilon_d = -3.0$ meV is occupied by the spin-down electrons (we can see that the spin accumulation is negative in the negative temperature bias range from Fig. 3). Above the Fermi surface, electrons transport from the right to the left through the resonant channel $\varepsilon_d + U$. That similarly results in the decrease of currents in the negative temperature bias range. Moreover, due to the accumulation of the spin-down electrons, the spin-up current is suppressed a lot. It is found that $I_\uparrow$ can be kept equal to $I_\downarrow$ throughout the negative temperature bias range, resulting in the zero current polarization seen in Fig. 2. It is noteworthy that in Ref. 13, the suppression of currents is mainly caused by the fact that the resonant channel $\varepsilon_d + U$ is without the conduction window; that is, it is fully blocked. However, in our system it is not blocked, but it provides reverse currents all along, so that χ retains zero for a large range.

In Fig. 4(a), we consider the influence of the reference temperature T_0 to the rectification effect of polarized current.

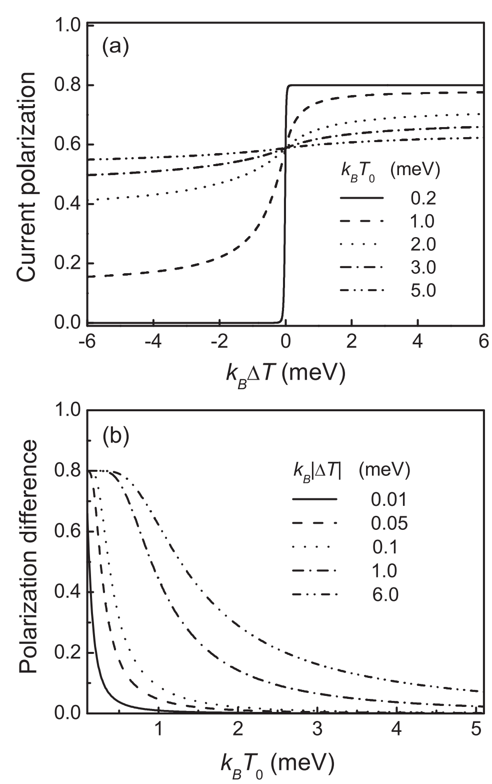

FIG. 4. (a) Current polarization χ vs $k_B\Delta T$ with different reference temperatures. (b) Polarization difference $\Delta\chi$ vs $k_B T_0$ with several fixed temperature biases. In both (a) and (b), the value of p equals 0.8 and the other parameters are the same as those in Fig. 2.

Actually, T_0 is important for device applications, because it represents the working temperature or environment temperature. It is obvious to see that the rectification effect gradually wears off with increasing T_0. So a high reference temperature can reduce the asymmetry caused by temperature bias. To further investigate the influence of T_0, we show the calculated curves of polarization difference against $k_B T_0$ with several fixed temperature biases in Fig. 4(b). Here we define the polarization difference $\Delta\chi = \chi_+ - \chi_-$ to characterize the asymmetry, where $\chi_{+(-)}$ is the polarization in the positive (negative) temperature bias range. In Fig. 4(b), we can see that when the reference temperature T_0 is small, the value of $\Delta\chi$ is high; that is, the rectification effect shown by χ is evident. The maximal value of $\Delta\chi$ can reach about 0.8, namely, the value of p. That is consistent with our previous analysis. With T_0 increasing higher and higher, $\Delta\chi$ becomes smaller and smaller and finally zero; that is, the rectification effect disappears. It is also seen from Fig. 4(b) that when T_0 is fixed, the larger the temperature bias is, the larger $\Delta\chi$ is.

B. Spin-valve effect

We plot in Fig. 5(a) the current polarization χ versus the gate voltage V_G applied on the QD for different Coulomb interactions U. The variation in the gate voltage V_G is equivalent to the variation of the QD energy level ε_d. It is appropriate to write $\varepsilon_d = e^* V_G$, where e^* is the effective charge and is assumed to be the free charge e for convenience. Here we set $k_B \Delta T = -4.0$ meV and $k_B T_0 = 0.2$ meV. For $V_G < 0$, there is a finite region where χ approaches zero and the region gets larger with U increasing. This shows an obvious spin-valve effect modulated by the gate voltage. It is possible only for the fact that there exist currents through the two channels ε_d and $\varepsilon_d + U$ with opposite directions; then the currents are suppressed and χ equals zero. Furthermore, increasing U makes the possibility greater, which leads to the larger region.

We can also analyze the spin-valve effect in the proper limits. When the reference temperature $T_0 = T_L$ is very low and the temperature bias is large, that is, T_R is high, for $\varepsilon_d < 0$, $\varepsilon_d + U > 0$, we approximate $f_L = 1$, $\bar{f}_L = 0$ and $f_R = \bar{f}_R = 1/2$. For $\varepsilon_d < 0$, $\varepsilon_d + U < 0$, we have $f_L = \bar{f}_L = 1$ and $f_R = \bar{f}_R = 1/2$. For $\varepsilon_d > 0$, $\varepsilon_d + U > 0$, we approximate $f_L = \bar{f}_L = 0$ and $f_R = \bar{f}_R = 1/2$. Putting all these results into Eq. (9), we have

$$\chi = \begin{cases} 0, & -U < \varepsilon_d < 0, \\ \frac{p}{2-p^2}, & \varepsilon_d < -U \text{ or } \varepsilon_d > 0, \end{cases} \tag{11}$$

in accordance with numerical curves in Fig. 5(a). In fact, from Eq. (11), for $p = 0.8$, we find $\chi \approx 0.6$ for its nonzero region. Also from this expression, we can see that the zero region gets larger with increasing U, as its range is approximatively located in $-U < \varepsilon_d < 0$.

The calculated results for χ as a function of V_G for different temperature biases with fixed U is shown in Fig. 5(b). One can see the zero region gets larger when the temperature bias gets higher. However, the variation is not very remarkable as tuned by the Coulomb interaction.

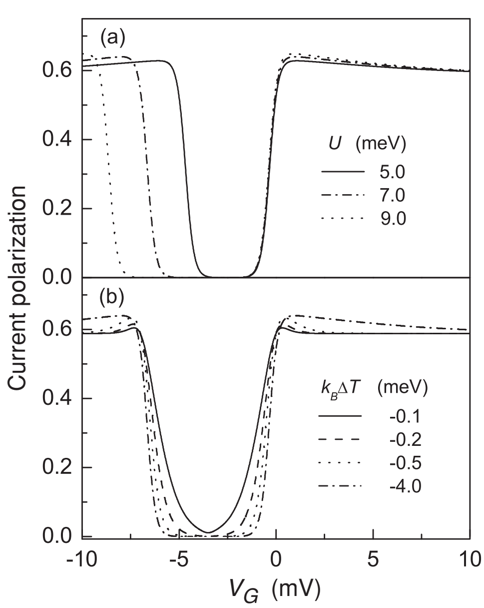

FIG. 5. Current polarization χ vs gate voltage (a) for different Coulomb interaction U and $k_B \Delta T = -4.0$ meV and (b) for different temperature bias $k_B \Delta T$ and $U = 7.0$ meV. Here we set $p = 0.8$, $k_B T_0 = 0.2$ meV, and other parameters are the same as those in Fig. 2.

IV. SUMMARY

We have investigated the spin polarization of current in a NM-QD-FM transistor modulated by a temperature bias as well as a gate voltage. We find that the spin polarization of current has an obvious rectification effect. In a large negative temperature bias range, the current polarization χ is zero, while in a large positive temperature bias range, χ keeps almost a nonzero constant. The different Fermi distributions of the left and right electrodes caused by temperature bias and the interplay of spin accumulation and the Coulomb interaction result in the effect. At the same time, the behavior of polarized current can be tuned by the applied gate voltage. It is found that there is a transition for χ between a zero and nonzero regions, corresponding to a spin-valve effect, or a polarization switch, with the zero region being determined by the temperature bias and Coulomb interaction.

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