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Citation: Chin. Phys. B, 2021, 30 (**11**): 117305. DOI: 10.1088/1674-1056/abfbd8
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Pure spin-current diode based on interacting quantum dot tunneling junction*

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(Received 4 February 2021; revised manuscript received 5 April 2021; accepted manuscript online 27 April 2021)

A magnetic field-controlled spin-current diode is theoretically proposed, which consists of a junction with an interacting quantum dot sandwiched between a pair of nonmagnetic electrodes. By applying a spin bias V_S across the junction, a pure spin current can be obtained in a certain gate voltage regime,regardless of whether the Coulomb repulsion energy exists. More interestingly, if we applied an external magnetic field on the quantum dot, we observed a clear asymmetry in the spectrum of spin current I_S as a function of spin bias, while the charge current always decays to zero in the Coulomb blockade regime. Such asymmetry in the current profile suggests a spin diode-like behavior with respect to the spin bias, while the net charge through the device is almost zero. Different from the traditional charge current diode, this design can change the polarity direction and rectifying ability by adjusting the external magnetic field, which is very convenient. This device scheme can be compatible with current technologies and has potential applications in spintronics or quantum processing.

Keywords: pure spin current, semiconductor quantum dot, spin diode

PACS: 73.23.–b, 85.75.–d, 73.21.La, 85.35.–p **DOI:** 10.1088/1674-1056/abfbd8

1. Introduction

Control of the charge and spin in electric devices is an interesting theme, which is experiencing a burst of activity.[1,2] Generally, electronic devices control the charge current, which is the flow of electrons and generates Joule heat. With the development of integrated circuits and the molecularization of electronic devices, the energy consumption of electronic devices will increase. Spintronics may provide a feasible way to reduce heat generation in nanoscale devices.[3,4] In most cases, the charge current can be calculated as the sum of the currents of spin-up and spin-down electrons, while the spin current is the difference between them. If both charge and spin currents coexist, then the current is called a spin-polarized current. When equal amounts of spin-up and spin-down electrons travel in opposite directions, which results in the net charge through the device being zero and the spin current having a finite value, the pure spin current phenomenon appears.[5–10] To date, many studies have been proposed to obtain a pure spin current,[11–13] such as the spin Hall effect,[14,15] and spin-Seebeck effect,[16,17] and spin–photogalvanic effect.[18–20] Some designs have been successfully implemented experimentally, for example, in a quantum wire based on GaAs/AlGaAs heterostructures.[21,22] In these devices, the spin current can be obtained and detected by using a quantum point contact (QPC) electrode or coupled quantum dots (QDs), which does not rely on optical equipment, a magnetic material, or spin–orbit interactions and can be facilely controlled by an electrical method in experiments.

Regarding the charge degree of freedom, an important device in modern electronics is the diode: a charge current can flow through it under a forward bias, but the current is very small under a reverse bias. To date, various diodes have been successfully manufactured, and they have been extensively used in almost all electronic products and instruments.[23] In general, a diode controls the flow of charge in circuits. Very recently, the spin-current diode,[24–27] which is a counterpart to the traditional charge-current diode regarding the spin degree of freedom, has been extensively studied in recent years concerning its potential application in spintronics and quantum information. Many spin-current diodes in low-dimensional systems, such as a stanene nanoribbon,[28] monoaxial chiral magnets[29] or a lead/FM semiconductor/lead heterojunction,[30] have been theoretically proposed. In these systems, the spin current flows only in one spin bias direction, and the net charge through the junction is tiny. Furthermore, it has been mentioned in Ref. [30] that the effect of the spin diode can be extended to a lead-ferromagnetic QD-lead structure. Inspired by these works, it is expected that nanostructures based on QDs can also be de-

*Project supported by the National Natural Science Foundation of China (Grant No. 11404322) and the Natural Science Foundation of Huai'an (Grant No. HAB202150).

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signed as a spin diode devices which is independent of charge current.

In this work, we propose a novel type of pure spin-current diode based on a single interacting ferromagnetic QD sandwiched between a pair of nonmagnetic electrodes. Similar to the experimental work in reference,[21] a spin bias can be applied via the left QPC electrode, and a spin current will tunnel through and be controlled in the QD-based tunneling junction.[31,32] We focus on the regime where sequential tunneling dominates transport, and the system can be described in terms of a generalized master equation with transition rates obtained via a real-time diagrammatic approach. Our numerical results show that a pure spin current will always emerge in a certain gate voltage regime, regardless of whether the Coulomb repulsion energy exists. More interestingly, the pure spin current exhibits asymmetric I_S–V_S characteristics. Such asymmetry in the spin current suggests diode-like behavior with respect to the spin bias, which can be switched by changing the external magnetic field. Unlike the traditional charge-current diode, the ability to control the polarity direction of the spin current is a great advantage. Note that for the charge-current diode (*e.g.*, p–n junction), its polarity direction is fixed and cannot be changed once the device is fabricated.

2. Model and Hamiltonian

As shown in Fig. 1, the system we consider here consists of a single interacting QD sandwiched between a couple of nonmagnetic electrodes. The Hamiltonian of the system can be written as[33–36]

$$H=\sum_{\sigma}(\varepsilon_{\rm d}+\sigma\Delta H)d_{\sigma}^{\dagger}d_{\sigma}+Un_{\uparrow}n_{\downarrow}+\sum_{\alpha}(H_{\alpha}+H_{t,\alpha}), \quad (1)$$

here, $\varepsilon_{\rm d}$ is the energy level of QD, which can be shifted by the gate voltage. ΔH describes the Zeeman splitting by the external magnetic field applied on QD, where the g factor and Bohr magneton $\mu_{\rm B}$ have been absorbed into ΔH. $n_{\sigma}=d_{\sigma}^{\dagger}d_{\sigma}$ is the number operator and $d_{\sigma}^{\dagger}$ (d_{σ}) denotes the relevant electron creation (annihilation) operator, with σ as the spin index. U is the intradot Coulomb interaction in QD. The label $\alpha=\{{\rm L},{\rm R}\}$ corresponds to the left or right leads and the Hamiltonians for both leads can be written as $H_{\alpha}=\sum_{k\sigma}\varepsilon_{\alpha k\sigma}c_{\alpha k\sigma}^{\dagger}c_{\alpha k\sigma}$. The tunneling Hamiltonian between electrodes and QD are $H_{t,\alpha}=t_{\alpha}c_{\alpha k\sigma}^{\dagger}d_{\sigma}+{\rm h.c}$, where $c_{\alpha k\sigma}^{\dagger}$ ($c_{\alpha k\sigma}$) is the creation (annihilation) operator for the electron of momentum $\boldsymbol{k}$, spin σ, and energy $\varepsilon_{\boldsymbol{k}\sigma}$ in lead α. The coupling between QD and two leads is described by t_{α}, which is assumed to be independent of momentum $\boldsymbol{k}$ and spin σ.

By using the rate equation,[25,37] we obtain the evolution of the occupation probabilities of the different states in the QD as

$$\mathrm{d}P_i/\mathrm{d}t=\Sigma_j(P_jW_{ji}-P_iW_{ij}). \quad (2)$$

Here, P_i is the probability of finding electrons of the dot in state $|i\rangle$, with $i=0$, $\uparrow$, $\downarrow$, and $\uparrow\downarrow$ representing empty, spin-up, spin-down, and doubly occupied states, respectively. $W_{ij}=\Sigma_{\alpha\sigma}(W_{ij}^{\alpha\sigma+}+W_{ij}^{\alpha\sigma-})$ describes the transition rate between state $|i\rangle$ and state $|j\rangle$, which, with the aid of the Fermi golden rule, can be written as

$$\begin{aligned}W_{ij}^{\alpha\sigma+}&=\Gamma_{\alpha\sigma}f_{\alpha}(\varepsilon_j-\varepsilon_i-\mu_{\alpha})|\langle j|d_{\sigma}^{\dagger}|i\rangle|^2,\\ W_{ij}^{\alpha\sigma-}&=\Gamma_{\alpha\sigma}f_{\alpha}(\varepsilon_i-\varepsilon_j+\mu_{\alpha})|\langle i|d_{\sigma}|j\rangle|^2,\end{aligned} \quad (3)$$

where $\Gamma_{\alpha\sigma}=2\pi\rho_{\alpha\sigma}|t_{\alpha}|^2$ is the linewidth function for lead α, with $\rho_{\alpha\sigma}$ being the density of states at the Fermi energy. $f_{\alpha}=[{\rm e}^{(\varepsilon_{\rm d}-\mu_{\alpha})/k_{\rm B}T_{\alpha}}+1]^{-1}$ is the Fermi distribution of lead α with chemical potential μ_{α} and lead temperature T_{α}. If both of the electrodes are made of nonmagnetic metals, we can simplify the linewidth functions as $\Gamma_{\alpha\sigma}=\Gamma_0$. In the stationary state, the probabilities of the system can be obtained by $\sum_i P_i=1$ and $\mathrm{d}P_i/\mathrm{d}t=0$. The spin-resolved electron current in electrode α is

$$I_{\alpha,\sigma}=-(e/h)\sum_{i,j}(n_i-n_j)W_{ji}^{\alpha\sigma}P_j. \quad (4)$$

The spin-σ current flowing through the QD can be written as $I_{\sigma}=(I_{{\rm L}\sigma}-I_{{\rm R}\sigma})/2$ and scaled by $e\Gamma_0/\hbar$. Then, the total spin current and charge current flowing through the system can be calculated by the formulas $I_{\rm S}=I_{\uparrow}-I_{\downarrow}$ and $I_{\rm C}=I_{\uparrow}+I_{\downarrow}$.

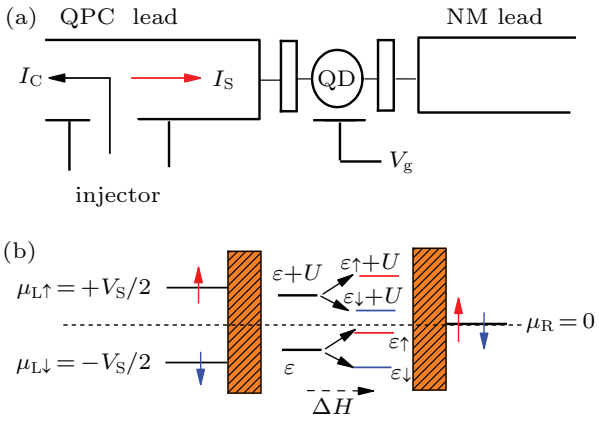


Fig. 1. Model setup: (a) illustration showing a possible realization of a QD-based spin diode device employing one QPC lead and one nonmagnetic lead with a spin bias applied across the junction. (b) Schematic energy diagram of the device with an external magnetic field applied on the dot.

In the following calculation, we set $\hbar=e=k_{\rm B}=1$ (unless noted otherwise). A spin bias voltage is applied in the left (QPC) electrode, so the chemical potentials μ_{α} in the electrodes are given as $\mu_{\rm L\uparrow}=-\mu_{\rm L\downarrow}=V_{\rm S}/2$ and $\mu_{\rm R\uparrow}=\mu_{\rm R\downarrow}=0$. To discuss the spin current rectification ability, we define the rectification coefficient as $R_{\rm S}=1-|I_{\rm S}^{-}|/|I_{\rm S}^{+}|$. $I_{\rm S}^{+}$ and $I_{\rm S}^{-}$ are the spin currents for the forward spin bias $V_{\rm s}>0$ and the reverse spin bias $V_{\rm S}<0$. Note that $R_{\rm S}=0$ when no rectification occurs and $R_{\rm S}=1$ (or $-\infty$) for a perfect spin-current diode.

3. Result and discussion

First, we demonstrate the pure spin-current diode effect in this junction without the intradot Coulomb interaction ($U = 0$ meV). As shown in Fig. 2(a), we studied the spin current I_S as a function of spin bias and gate voltage with field-induced Zeeman splitting $\Delta H = 0.2$ meV and equilibrium temperature $T = 1$ K. The spin current spectrum can be divided into two parts. In the gate voltage windows far from the $\varepsilon_d = 0$ point, for example, $\varepsilon_d \gg 0.1$ meV or $\varepsilon_d \ll -0.1$ meV, symmetry of the I_S change can be seen with respect to the spin bias direction. In these regions, the device does not have spin diode features. However, if the QD level lies in the regime close to the $\varepsilon_d = 0$ point, for example, -0.1 meV $< \varepsilon_d < +0.1$ meV, then an asymmetry in spin current I_S with respect to the spin bias is typically observed. On the other hand, the charge current I_C in Fig. 2(b) can also be divided into two parts: In the gate voltage windows far from the $\varepsilon_d = 0$ point, symmetry and a nonzero distribution of I_C can be seen with respect to the spin bias. However, if the QD level lies in the regime close to the $\varepsilon_d = 0$ point, for example, -0.1 meV $< \varepsilon_d < +0.1$ meV, then the charge current completely vanishes, which indicates that equal amounts of spin-up and spin-down electrons tunnel through the junction in opposite directions, *i.e.*, pure spin-current diode behavior occurs. To further examine this anomalous suppression for the pure spin current, we display the I_S–V_S characteristics at gate resonance voltage $\varepsilon_d = 0$ meV. As shown in Fig. 2(c), it is obvious that the spin currents can flow easily from the QPC (left) lead to the NM (right) lead with a positive spin bias $V_S > 0$, while these flows are suppressed for the opposite direction $V_S < 0$. With a decrease in equilibrium temperature T, the spin current for a forward spin bias increases, whereas the reverse one decreases, and the diode feature is gradually enhanced, as shown in Fig. 2(c). However, regardless of how the equilibrium temperature changes, the tunneling charge current I_C is always suppressed to zero, which means that this QD structure can always function as a pure spin-current diode in the gate resonance voltage $\varepsilon_d = 0$ regime.

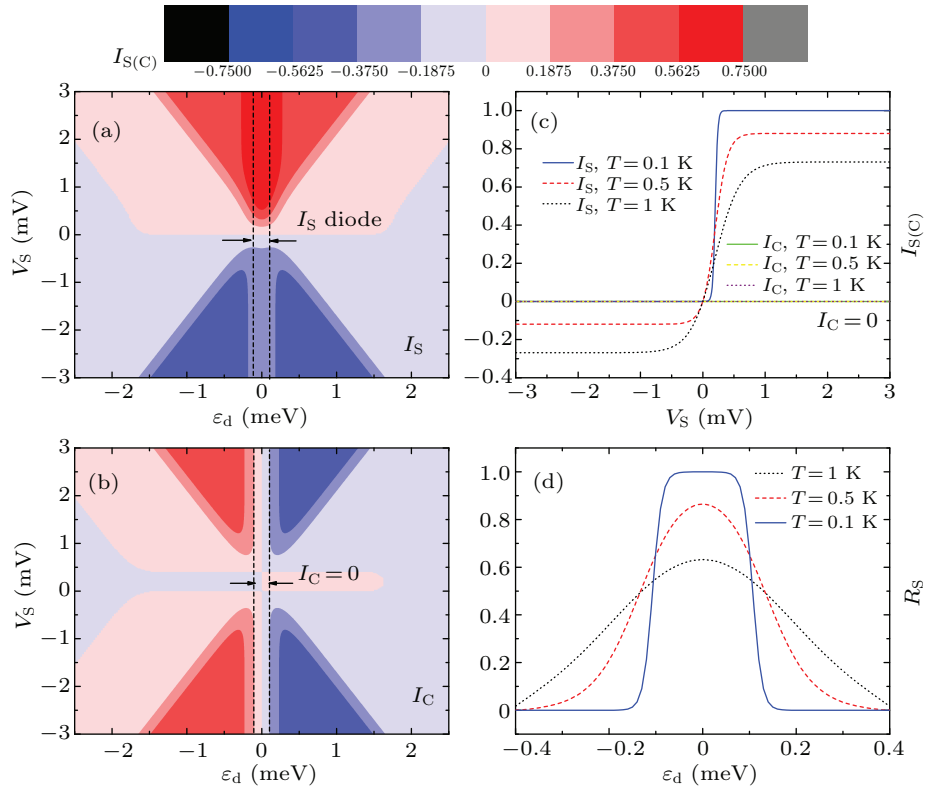


Fig. 2. (a) Spin current and (b) charge current as a function of spin bias and gate voltage in the absence of the Coulomb interaction with equilibrium temperature $T = 1$ K. (c) Spin current and charge current variations with spin bias with a fixed gate voltage $\varepsilon_d = 0$, and (d) rectification ability variation with gate voltage under different equilibrium temperatures with spin bias $V_S = \pm 1.5$ mV.

To understand the underlying physics, we give a simple analysis of the spin current and charge current under some approximations. For the intradot Coulomb interaction $U = 0$, the energy level of the spin-up (down) state is $\varepsilon_{\uparrow(\downarrow)} = \varepsilon_d \pm \Delta H/2$. By using the rate equation we mentioned in Section 2, if we define

$$E_H = \exp\left[-\frac{\Delta H}{2k_B T}\right], \quad E_V = \exp\left[\frac{V_S}{2k_B T}\right],$$

$$E_\varepsilon = \exp\left[\frac{\varepsilon_d}{k_B T}\right],$$

then the charge current can be obtained as

$$I_C = \Lambda \Gamma_0 (E_\varepsilon^2 - 1). \tag{5}$$

Here,

$$\Lambda = \frac{E_\varepsilon E_H (1 + E_V^2 E_H^2 - 2E_V E_H^2)}{(E_\varepsilon + E_V E_H)(1 + E_\varepsilon E_V E_H)(E_\varepsilon + 2E_H + 2E_\varepsilon^2 E_H + 3E_\varepsilon E_H^2)}. \tag{6}$$

Obviously, from Eq. (5), we can see that regardless of how other parameters change, the charge current is always fixed at zero when the gate voltage is given at the $\varepsilon_d = 0$ point. However, at this gate voltage point, the spin current yields

$$I_S = \frac{E_H (E_V - 1)}{(1 + E_H)(1 + E_H E_V)} \Gamma_0. \tag{7}$$

If the temperature is extremely low ($T \to 0$), then equation (7) can be approximated as

$$I_S \approx \begin{cases} 0, & (V_S \ll 0), \\ \Gamma_0, & (V_S \gg 0), \end{cases} \tag{8}$$

which indicates that a perfect spin-current diode without any electron charge tunneling through it can be present under low equilibrium temperature conditions.

To investigate the spin current rectification ability in this device, we plot the rectification coefficient R_S as a function of gate voltage with a spin bias $V_S = \pm 1.5$ mV in Fig. 2(d). If the gate voltage is set far from the regime of $[-\Delta H/2 < \varepsilon_d < \Delta H/2]$, then the coefficient R_S is equal to 0, which means that no rectification occurs in these regimes. In contrast, if the gate voltage lies within this window, then R_S quickly rises to a finite value depending on the equilibrium temperature T. According to Eq. (7) and Eq. (8), if given an extremely low equilibrium temperature and a positive Zeeman splitting energy, then R_S can reach up to 1, which represents a perfect spin-current diode device.

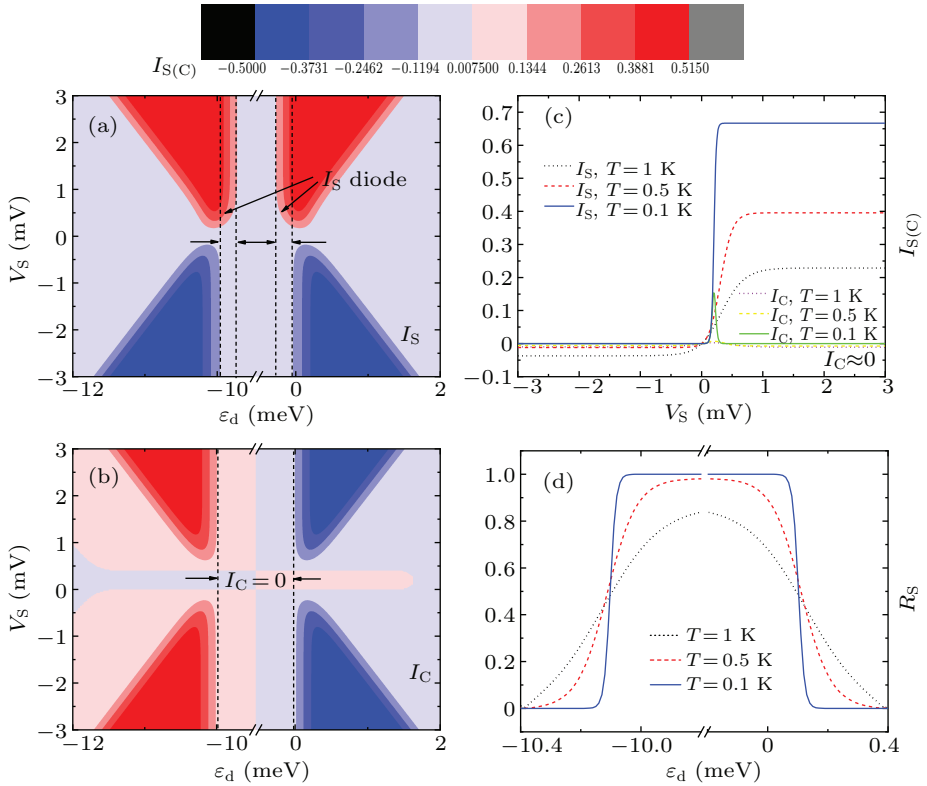


Fig. 3. (a) Spin current and (b) charge current as a function of spin bias and gate voltages with Coulomb interaction $U = 10$ meV and equilibrium temperature $T = 1$ K. (c) Spin current and charge current variations with spin bias and (d) rectification ability variation with gate voltage under different equilibrium temperatures with spin bias $V_S = \pm 1.5$ mV and $\varepsilon_d \approx -9.9$ meV.

Thus far, we have considered cases in which the Coulomb repulsion energy in the QD is extremely small. Next, we generalize this pure spin-current diode effect to a regime of a finite Coulomb repulsion energy in this device. As shown in Figs. 3(a) and 3(b), we studied the spin current I_S and charge current I_C as a function of spin bias and gate voltage, with temperature $T = 1$ K and intradot Coulomb interaction $U = 10$ meV, corresponding to the real experimental conditions.[38] Similar to the diode effect we discussed in relation to Fig. 2, the charge current can also be divided into two parts. In the gate voltage windows of $\varepsilon_d \gg 0$ or $\varepsilon_d \ll -U$, symmetry of the charge current changes can be seen with respect to the direction of the spin bias V_S. In these regions, a pure spin current phenomenon does not exist because of the $I_C \neq 0$. However, if the QD level lies in the Coulomb blockade regime, *i.e.*, -10 meV $< \varepsilon_d < 0$ meV, then the net charge through the junction rapidly decreases to zero. More interestingly, compared to the spin diode effect studied in Fig. 2, the spin current tunneling through the junction with a finite Coulomb repulsion energy is quite different. In Fig. 3(a), we can see that in

two small gate voltage windows, *i.e.*, $[-10.1,-9.9]$ meV and $[-0.1,0.1]$ meV, obvious asymmetry of the I_S change can be observed with respect to the spin bias direction. Because the charge current only decays to zero in the Coulomb blockade regime, the pure spin-current diode effect can be detected in the parts overlapping with these gate voltage windows, *i.e.*, $[-10,-9.9]$ meV and $[-0.1,0]$ meV. In Fig. 2(c), we plot the I_S–V_S characteristics in these gate voltage regimes. It is obvious that the spin currents can flow easily from the left lead to the right lead with a positive spin bias $V_S > 0$, while these flows are suppressed for the opposite direction $V_S < 0$. With a decrease in equilibrium temperature T, the spin current for a forward spin bias increases, whereas the reverse one decreases, and the diode feature is gradually enhanced, as shown in Fig. 3(c). Furthermore, compared with Fig. 2(c), the suppression effect of spin current under a negative spin bias regime with a finite temperature seems to be stronger due to the existence of Coulomb repulsion energy. This means that the Coulomb repulsion energy in QD structure under real experimental conditions will be beneficial to the discovery of this phenomenon.

To investigate the spin current rectification ability, we also investigated the rectification coefficient R_S as a function of gate voltage with a spin bias $V_S = \pm 1.5$ mV in Fig. 3(d). If the gate voltage is set far from the Coulomb repulsion regime, *i.e.*, $\varepsilon_d \gg 0$ or $\varepsilon_d \ll -U$, then the coefficient R_S is equal to 0, which means that no rectification occurs in these regimes. In contrast, if the gate voltage lies within the window of $\varepsilon_d \in [-U,0]$, then R_S quickly rises to a finite value depending on the equilibrium temperature T. If an extremely low equilibrium temperature and a positive Zeeman splitting energy are given, then R_S can reach 1, which means that a perfect spin-current diode effect is robustly maintained and does not depend on whether the Coulomb repulsion energy exists.

To understand the physical mechanism behind Fig. 3, we plot a schematic diagram of the electron tunneling process in this QD-based junction. In the presence of a Coulomb repulsion energy on the QD, there are a total of four electron transmission channels in the system, with two for spin-up states and the other two for spin-down states (see Figs. 1 and 4). For ease of discussion, we assume that the equilibrium temperature is very low ($T \to 0$ K). If we apply a positive spin bias $V_S > 0$, then equal amounts of spin-up and spin-down electrons will tunnel through this junction in opposite directions in two resonance voltage regimes, $[-\Delta H/2-U,\ \Delta H/2-U]$, and $[-\Delta H/2,\ \Delta H/2]$, as shown in Figs. 4(a) and 4(b). In these two regimes, the spin current can flow easily from the left lead to the right lead, and the device switches "on". In contrast, if the device works in the negative V_S direction, then a down-spin electron will be trapped in the QD due to the positive Zeeman splitting energy and negative spin bias voltage in the Coulomb blockade regime. Neither a spin current nor a charge current can tunnel through the device easily in this gate voltage regime, and the device switches "off". Therefore, a perfect pure spin current diode can only be found in the gate voltage region where the two phenomena coexist, *i.e.*, the gate voltage windows $[-U,\ \Delta H/2-U]$ and $[-\Delta H/2,\ 0]$.

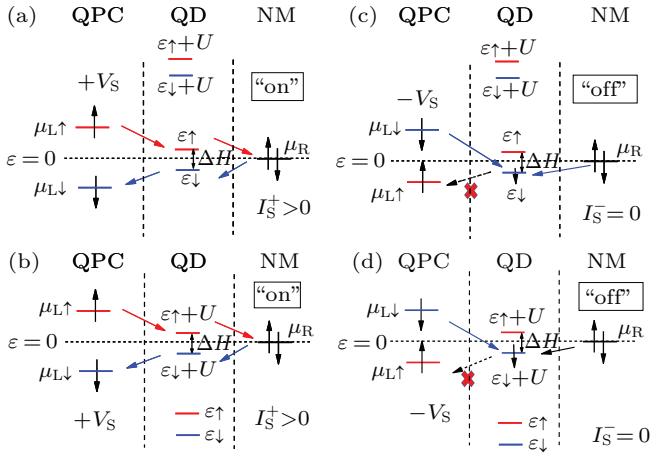


Fig. 4. Schematic diagram of the electron tunneling process for (a) [(b)] the forward spin bias and (c) [(d)] backward spin bias directions, with a positive Zeeman splitting $\Delta H > 0$ and the gate voltage tuned in the windows of $[-\Delta H/2-U,\ \Delta H/2-U]$ and $[-\Delta H/2,\ \Delta H/2]$.

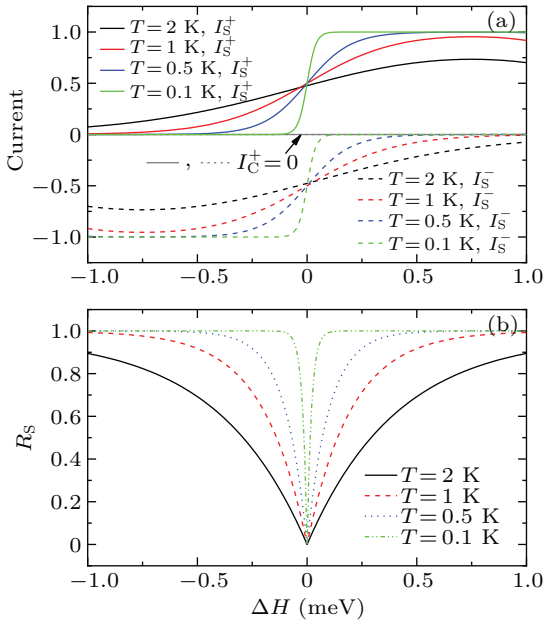


Fig. 5. (a) Forward (or reverse) spin current or charge current and (b) rectification coefficient R_S as a function of the external magnetic field, with gate voltage $\varepsilon_d = 0$ meV and $U = 0$ meV.

Finally, we demonstrate how to use external magnetic fields to control the polarity direction of the pure spin-current diode. In Fig. 5(a), we plot the tunneling currents $I^+_{S(C)}$ and $I^-_{S(C)}$ as a function of Zeeman splitting energy with spin bias $V_S = \pm 1.5$ mV. Apparently, the forward spin current I^+_S will be amplified and the reverse current I^-_S will be weakened in a positive external magnetic field regime, and vice versa. The ability of an external magnetic field to enhance/suppress the

spin current is weakened with increasing equilibrium temperature. However, regardless of how the temperature changes, the charge current is always fixed at zero and a magnetic field can only obviously change the polarity direction of the spin-current . In Fig. 5(b), we plot the rectification coefficient R_S as a function of ΔH, and it is shown that as the magnetic field becomes stronger, for example, ΔH changes from $0 \rightarrow \pm 1$ meV, almost all the current R_S values tend to 1. This means that we can improve the efficiency of this spin diode by increasing the magnetic field.

4. Conclusion

In conclusion, we have proposed a pure spin-current diode device based on a single quantum dot weakly coupled to one QPC lead and one NM lead. By tuning the gate voltage to certain windows, we observed a clear asymmetry in the spectrum of spin current I_S as a function of spin bias, regardless of whether the Coulomb repulsion energy was present. Our analysis shows that the performance of the spin-current diode depends on the competition between the external magnetic field and the equilibrium temperature. More interestingly, by adjusting the magnetic field, we can change the polarity of the spin-current diode or enhance its rectification ability performance. The numerical results in this device scheme are based on the real experimental environment, which can be easily fabricated and realized with current technology.

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