Spin-bias-induced transport through a quantum dot coupled to a ferromagnetic lead

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Abstract. We investigate the spin-bias-induced transport through a quantum dot coupled to a ferromagnetic lead and a nonmagnetic semiconductor lead. Electron transport through this quantum dot is analyzed theoretically by means of the master equation method. It is shown that the polarization direction and the magnitude of the spin bias can be detected through adjusting the energy level of the quantum dot. The effects of the temperature and the tunneling rates on the charge current are also investigated numerically. The spin-bias-induced current can be easily measured in systems with low temperature and high tunneling rates. Even though the tunneling rate is small due to the conductance mismatch between the quantum dot and the ferromagnetic lead, the spin bias can still be detected through measuring the charge current.

1. Introduction
Spin based electronics or spintronics [1, 2] aims at exploiting electron spin to develop a new generation of electronic devices. The spin current is one of the essential concepts in spintronics. Thus it becomes an important task to generate, manipulate, and detect the spin current for further advancement of spintronic devices. The manipulation of the spin current, the flow of electron spins in a solid, is the key spintronics technology that will allow the achievement of efficient magnetic memories and computing devices. Many recent works have proposed some methods to generate the spin current, such as pumping excitation [3], optical injection [4, 5], magnetic tunneling injection [6] and spin-Hall effect [7]. Kato et al. reported the first experimental observation of the spin-current induced spin accumulation via the magneto-optical Kerr effect in GaAs semiconductor systems [8]. The spin current can also be observed through conversing it into an electric current via the inverse process of the spin-Hall effect [9]. In addition, some works proposed to indirectly measure the spin current through measuring the spin torque [10] or the spin-induced electric field [11].

A spin accumulation induced by the spin current can generate a spin-dependent splitting of chemical potentials or spin bias in nonmagnetic materials. The spin bias is regarded to be the driving force of the spin current. Since many of the intensively investigated spin-injected nonmagnetic materials were widely used to fabricate electrodes probing semiconductor [12], and single-molecular quantum dots [13]. The spin transport induced by spin bias in quantum dots were theoretically investigated [14, 15]. On the other hand, the materials and geometries including ferromagnets can not only serve as effective injectors, and also act as a part of the detector of spin bias. A small ferromagnet attached to the outlet of a spin filter may be used...
as a detector of spin bias owing to its spin-dependent transparent coefficients if one can reduce the effect of conductance mismatch and disorder-induced scattering.

As discussed above, both the spin-bias-induced transport in nonmagnetic materials and the spin transport in the geometries including ferromagnets were already extensively studied. However the interplay of lead’s ferromagnetism and spin bias in the nonmagnetic lead remains to a large extent unexplored. Therefore, in this paper we consider the spin-bias-induced transport through a quantum dot coupled to a ferromagnetic lead and a nonmagnetic lead. We use the master equation method to calculate the charge current flowing through the quantum dot. Thus the polarization direction and the amplitude of the spin bias can be detected through tuning the energy level of the quantum dot. And the effects of the temperature and the tunneling rates are also analyzed numerically in detail. It is shown that the spin-bias-induced current can be easily measured in systems with high tunneling rates in low temperature. Even though the tunneling rate is small due to the conductance mismatch between the quantum dot and the ferromagnetic lead, the spin bias can still be detected through measuring the charge current.

The paper is organized as follows. In Sec. 2, the model for the quantum dot coupled to a ferromagnetic and a nonmagnetic lead and the general formalism for the master equation method are presented. According to this method, we calculate the spin-bias-induced charge current and the electron occupation numbers of the quantum dot. In Sec. 3, We numerically analyze the occupation numbers and the charge current as a function of the spin bias, and discuss the effect of the temperature and the tunneling rates on the charge current. Final conclusions and summary appear in Sec. 4.

2. Theoretical description

The considered system consists of a single-level quantum dot coupled to left nonmagnetic semiconductor lead and right ferromagnetic lead. A spin bias in the nonmagnetic semiconductor lead can be applied by spin injection from a spin-polarized quantum point contact in combination with magnetic focusing. The general device structure we consider is schematically shown in Figure 1. The Hamiltonian can be written as $H = H_L + H_R + H_d + H_t$, with $H_L$ and $H_R$ describing the left nonmagnetic semiconductor lead and the right ferromagnetic lead,

$$H_{L,R} = \sum_{k\sigma} \varepsilon_{k\sigma} a_{\nu k\sigma}^\dagger a_{\nu k\sigma},$$

for $\nu = L$ and $R$, where $\varepsilon_{k\sigma}^\nu$ is the single-electron energy in lead $\nu$ with the wave vector $k$ and spin $\sigma$ ($\sigma = \uparrow, \downarrow$), and $a_{\nu k\sigma}^\dagger$ and $a_{\nu k\sigma}$ are the corresponding creation and annihilation operators, respectively. $H_d$ is the Hamiltonian for the interacting quantum dot, and is of the form

$$H_d = \sum_{\sigma} \varepsilon_{\sigma} d_{\sigma}^\dagger d_{\sigma} + U d_{\uparrow}^\dagger d_{\uparrow}^\dagger d_{\downarrow}^\dagger d_{\downarrow},$$
where $\varepsilon_d$ is the single energy of the quantum dot, $d^\dagger_\sigma$ ($d_\sigma$) creates (annihilates) an electron in the quantum dot, and $U$ denotes the on-site Coulombic repulsion. The tunneling processes are described by the Hamiltonian

$$H_t = \sum_{k\sigma \in L,R} (t_{\nu\sigma} d^\dagger_{\nu\sigma} a_{\nu k\sigma} + \text{H.c.}),$$

(3)

where $t_{\nu\sigma}$ is the tunneling parameter, and it was assumed that electron spin is conserved in the tunneling processes.

In the sequential tunneling regime, the tunneling of an electron from source to drain electrodes is a sequence of two incoherent processes. Therefore we can use the master equation method to describe spin-bias-induced transport through the interacting quantum dot. Firstly we define four physical quantities $P_0$, $P_1$, $P_\uparrow$ and $P_\downarrow$, which describe the probabilities of the four states in the quantum dot, namely the empty state, the spin-up and spin-down occupied states, and the doubly occupied state. The occupation probabilities can be related by the normalization condition $P_0 + P_\uparrow + P_\downarrow + P_d = 1$. According to the master equation method developed by Glazman and Matweev\cite{16}, we can obtain that

$$\frac{dP_i}{dt} = -P_0(\Gamma^\uparrow_\sigma + \Gamma^\downarrow_\sigma) + P_1\Gamma^\uparrow_\sigma + P_\downarrow\Gamma^\downarrow_\sigma,$$

$$\frac{dP_\uparrow}{dt} = P_0\Gamma^\uparrow_\sigma - P_1(\Gamma^\uparrow_\sigma + \Gamma^\downarrow_\sigma) + P_d\Gamma^\downarrow_\sigma,$$

$$\frac{dP_\downarrow}{dt} = P_0\Gamma^\downarrow_\sigma - P_\downarrow(\Gamma^\uparrow_\sigma + \Gamma^\downarrow_\sigma) + P_d\Gamma^\uparrow_\sigma,$$

$$\frac{dP_d}{dt} = P_1\Gamma^\uparrow_\sigma + P_\downarrow\Gamma^\downarrow_\sigma - P_d(\Gamma^\uparrow_\sigma + \Gamma^\downarrow_\sigma),$$

(4)

where $\Gamma^\uparrow_\sigma$ ($\Gamma^\downarrow_\sigma$) denotes the tunneling rate of electrons with spin $\sigma$, which tunnel to (from) the single level of the quantum dot when the level is not occupied. Similarly $\Gamma^\uparrow_\sigma$ ($\Gamma^\downarrow_\sigma$) also refers to the tunneling rate of electrons associating with the tunneling processes when the single level is already occupied by an electron with spin $-\sigma$ in the quantum dot. These tunneling rates can be written as

$$\Gamma^\pm_\sigma = f^\pm_{\nu\sigma} \zeta_{\nu\sigma} + f^\pm_{\nu\sigma} \tilde{\zeta}_{\nu\sigma},$$

$$\tilde{\Gamma}^\pm_\sigma = \tilde{f}^\pm_{\nu\sigma} \zeta_{\nu\sigma} + \tilde{f}^\pm_{\nu\sigma} \tilde{\zeta}_{\nu\sigma},$$

(5)

where $f^\pm_{\nu\sigma}$ and $\tilde{f}^\pm_{\nu\sigma}$ are the Fermi distribution functions

$$f^\pm_{\nu\sigma} = \frac{1}{\exp[(\varepsilon_d - \mu_{\nu\sigma})/k_BT] + 1},$$

$$\tilde{f}^\pm_{\nu\sigma} = \frac{1}{\exp[(\varepsilon_d + U - \mu_{\nu\sigma})/k_BT] + 1},$$

(6)

where $\mu_{\nu\sigma}$ denotes the electrochemical potential of the lead $\nu$, and $f^\pm_{\nu\sigma} = 1 - f^\pm_{\nu\sigma}$ and $\tilde{f}^\pm_{\nu\sigma} = 1 - \tilde{f}^\pm_{\nu\sigma}$.

In Eq. (5), $\zeta_{\nu\sigma}$ and $\tilde{\zeta}_{\nu\sigma}$ are defined as follows

$$\zeta_{\nu\sigma} = 2\pi \sum_{k} |t_{\nu\sigma}|^2 \delta(\varepsilon_d - \varepsilon'_{k\sigma}),$$

$$\tilde{\zeta}_{\nu\sigma} = 2\pi \sum_{k} |t_{\nu\sigma}|^2 \delta(\varepsilon_d + U - \varepsilon'_{k\sigma}).$$

(7)

Since in this paper we are only interested in a stationary solution, the equations satisfied by $P_\nu (i = 0, \uparrow, \downarrow, d)$ can be reduced to a simple form due to the stationary conditions $dP_i/dt = 0$. 

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After obtaining the explicit forms of the probabilities $P_i$ through solving the stationary equations, we can calculate all the electron occupation numbers by $n_\sigma = P_\sigma + P_d$ and the charge current flowing from the quantum dot to the right ferromagnetic lead, namely,

$$I(t)/e = \sum_\sigma [P_\sigma \tilde{f}_{\sigma r} \tilde{\gamma}_{\sigma r} - P_0 \tilde{f}_{\sigma r} \tilde{\gamma}_{\sigma r} + P_d \tilde{f}_{\sigma r} \tilde{\gamma}_{\sigma r} - P_{-\sigma} \tilde{f}_{\sigma r} \tilde{\gamma}_{\sigma r}],$$

with $e$ denoting the absolute value of the electron charge.

3. Numerical results

In this section we numerically analyze the spin-bias-induced transport through the quantum dot coupled to a ferromagnetic lead and a nonmagnetic semiconductor lead. The transport problems considered in this paper follow from the spin dependence of tunneling processes described by the parameters $\Gamma_{+}^{\pm}$ and $\Gamma_{-}^{\pm}$. For simplicity, we will neglect all effects following from the band structure, and assume $\zeta_{\sigma r} = \tilde{\zeta}_{\sigma r}$ in the following numerical calculation. According to the above derivation, we can analyze the transport behavior of this system in the two cases $\mu_{L\uparrow} > \mu_{L\downarrow}$ and $\mu_{L\uparrow} > \mu_{L\downarrow}$. And the right lead is ferromagnetic and the chemical potential $\mu_R$ is set to be zero. One can tune the energy level of the quantum dot $\epsilon_d$ thus to change spin current of this system. We start with calculating the occupation number of the quantum dot. In the following numerical calculations, we set the on-site Coulombic repulsion $U = 1$ as the energy unit. We also set $\hbar = e = k_B = 1$, and then the temperature $T$ is in unit of energy. We choose $\zeta_{L\uparrow} = \zeta_{L\downarrow} = \zeta_L = 0.05$, and adopt the spin asymmetry factor $p_r$ for the right barrier $\zeta_{R\uparrow/\downarrow} = \gamma \zeta_L (1 \pm p_r)$ to describe the spin dependence more quantitatively, where the upper (lower) sign is for the spin-majority ($\sigma = \uparrow$) and spin-minority ($\sigma = \downarrow$) electrons, and $\gamma$ denotes the asymmetry between the left and right barriers. The system’s parameters are chosen as $p_r = 0.9$, $\gamma = 0.5$, $\mu_R = 0$, and $T = 0.01$. According to experimental measurement [17], the on-site Coulombic repulsion is about 10mev, then $T = 0.01$ in unit of $U$ corresponds to $T = 1K$ for $k_B T \approx 0.1 \text{meV}$.

While $\epsilon_d < 0.1$, as shown in Figure 2(a), there is no electron in the quantum dot associating with $n_{\uparrow} = n_{\downarrow} = 0$. When the spin bias approaches to 0.1, the occupation number of the spin-up electron $n_{\uparrow}$ abruptly increases from 0 to about 0.5. While $n_{\downarrow}$ still remains to be zero due to $\mu_{L\downarrow} < \mu_R < \epsilon_d$. Supposed the level $\epsilon_d$ tuned to be $-0.9$, there exist spin-up and spin-down electrons in the quantum dot while $V_s = 0$ seen from Figure 2(b). With increment of the spin bias, $n_{\uparrow}$ abruptly increases to 1, while $n_{\downarrow}$ decreases to zero. That is to say, in this stage, the
energy level the spin-bias-induced current in the low temperature, for example to zero in the regime smaller than the case of low temperature. It is expected that the charge current can approach while for higher temperatures charge current induced by the effect of the temperature though the level \( \epsilon \) can tunnel to the quantum dot from the left lead and flow to the right ferromagnetic lead which contribute to the large current. After the level \( \epsilon_d \) is tuned to be \(-0.9\), the spin-up electron can occupy the lower energy \( \epsilon_d \) because \( \epsilon_d, \epsilon_d + U < \mu_{L\uparrow} \), then the spin-down level is pushed up to be \( \epsilon_d + U > \mu_{L\uparrow} \), and so it is empty. According to numerical analysis, the variable trends of \( n_\sigma \) are different in the case \( \mu_{L\downarrow} = -\mu_{L\uparrow} = V_s \). The variation trend of \( n_\uparrow \) is similar with \( n_\downarrow \)'s as shown in Fiure 2, namely the spin-down electron will occupy the energy level \( \epsilon_d \) and the spin-up level is empty.

Next we start with analyzing the spin-bias-induced current in the two case \( \mu_{L\uparrow} = -\mu_{L\downarrow} = \pm V_s \). According to the stationary solutions of \( P_s \), we can calculate the charge current \( I \) in terms of Eq. (8). As shown in Figure 3(a), there is no current flowing through the quantum dot while \( \epsilon_d < 0.1 \) for \( \mu_{L\downarrow} < \mu_{L\uparrow} < \epsilon_d \). However, the current will abruptly increase to about 0.025 when the spin bias \( V_s > 0.1 \). The variation of the charge current can be explained in terms of the analysis of the occupation number of the quantum dot. While \( V_s > 0.1 \), the spin-up electron can tunnel to the quantum dot from the left lead and flow to the right ferromagnetic lead which contribute to the large current. After the level \( \epsilon_d \) is tuned to be \(-0.9\), the spin-up electron will occupy the level \( \epsilon_d \) and \( n_\uparrow = 1 \) which can block the spin-up current. While the spin-down level is pushed up to be \( \epsilon_d + U > \mu_{L\downarrow} \), hence the spin-down electron can not tunnel into the quantum dot. For the case \( \mu_{L\downarrow} = -\mu_{L\uparrow} = V_s \), the charge current can only increase to about 0.0025 for \( V_s > 0.1 \) and \( \epsilon_d = 0.1 \), see Figure 3(b). In comparison to the previous case, the maximum value of the current is a lower-order quantity. Hence one can detect the polarization direction of the spin bias in terms of the amplitude of the charge current through tuning the level \( \epsilon_d \). Accordingly, the amplitude of the spin bias can also be determined in terms of the abrupt change of the charge current.

In order to investigate the transport property of this model in detail, we consider the effects of the temperature and the tunneling rates on the charge current. Figure 4 shows variation trends of the charge current as the function of the energy level \( \epsilon_d \) in the two cases \( \mu_{L\downarrow} = -\mu_{L\uparrow} = \pm 0.5 \) for different temperatures. Let us, first, analyze the case \( \mu_{L\downarrow} = -\mu_{L\uparrow} = 0.5 \), see from Figure 4(a). While \( \epsilon_d < 0 \), the charge current approaches to zero for \( T = 0.002 \) and \( T = 0.02 \) describing by the black square and red dot curves because the level \( \epsilon_d < \mu_R \).

With increment of the temperature, for example \( T = 0.2 \) and \( T = 0.6 \), there exists a small charge current induced by the effect of the temperature though the level \( \epsilon_d < \mu_R \). Once the energy level \( \epsilon_d > 0 \), the charge current abruptly increases to about 0.025 due to \( \mu_R < \epsilon_d < \mu_{L\downarrow} \). While for higher temperatures \( T = 0.2 \) and \( T = 0.6 \), the charge current \( I \) is suppressed and smaller than the case of low temperature. It is expected that the charge current can approach to zero in the regime \( \epsilon_d > 0 \) with enough high temperature. Hence it is suggested to measure the spin-bias-induced current in the low temperature, for example \( T < 0.02 \).
and the ferromagnetic lead. Similarly, the charge current is also temperature-dependent in this case.

\[ I = \sum_{\mu=\uparrow,\downarrow} \sum_{r,L} \langle \gamma_{\mu rL} \rangle \]

Figure 4. The current \( I \) as a function of the energy level \( \epsilon_d \) for (a) \( \mu_{L\uparrow} = -\mu_{L\downarrow} = 0.5 \) and (b) \( \mu_{L\uparrow} = -\mu_{L\downarrow} = 0.5 \). The black square, red dot, blue triangle and green triangle curves are for \( T = 0.002 \), \( T = 0.02 \), \( T = 0.2 \) and \( T = 0.6 \), respectively. Other parameters are \( \zeta_L = 0.05 \), \( p_r = 0.9 \), \( \mu_R = 0 \), \( U = 1 \).

Figure 5. The current \( I \) as a function of the energy level \( \epsilon_d \) for (a) \( \mu_{L\uparrow} = -\mu_{L\downarrow} = 0.5 \) and (b) \( \mu_{L\uparrow} = -\mu_{L\downarrow} = 0.5 \). The black square, red dot, blue triangle, green triangle and purple triangle curves are for \( \gamma = 0.1 \), \( \gamma = 0.2 \), \( \gamma = 0.3 \), \( \gamma = 0.4 \) and \( \gamma = 0.5 \), respectively. Other parameters are \( \zeta_L = 0.05 \), \( p_r = 0.9 \), \( \mu_R = 0 \), \( U = 1 \) and \( T = 0.08 \).

Next we turn to analyze the second case \( \mu_{L\uparrow} = -\mu_{L\downarrow} = 0.5 \) shown in Figure 4(b). Firstly let us discuss the energy-dependent relation of the charge current for the low temperature \( T = 0.002 \) and \( T = 0.02 \). It is obvious that there exists a large current associating with the special energy level \( \epsilon_d = -1 \). This phenomenon can be explained in terms of the previous analysis of the occupation number in the quantum dot. While \( \epsilon_d = -1 \), the spin-down electron can occupy this level because \( \epsilon_d, \epsilon_d + U < \mu_{L\downarrow} \), then the spin-up level is pushed up to be \( \mu_R = \epsilon_d + U > \mu_{L\uparrow} \). Therefore the spin-up electron can flow from the right ferromagnetic lead to the quantum dot which contributes to the large current. If the energy level is tuned to the regime \(-1 < \epsilon_d < 0\), the charge current equals to zero. When \( \epsilon_d > 0 \), there occurs a small charge current associating with the spin-down electron flowing through the quantum dot to the right ferromagnetic lead. The amplitude of the charge current is a lower-order quantity compared to the case \( \mu_{L\uparrow} = -\mu_{L\downarrow} = 0.5 \) because the spin-down electron is reflected strongly in the interface between the quantum dot and the ferromagnetic lead. Similarly the charge current is also temperature-dependent in this case.

For the device considered in this paper, the spin-bias-induced current can be affected by the
tunneling rates between the quantum dot and two leads. It is necessary to investigate the effect of the tunneling rate describing by $\zeta_{\sigma\tau}$. Figure 5 shows the charge current $I$ as a function of the energy level $\epsilon_d$ for $\gamma = 0.1 \sim 0.5$, where the coefficient $\gamma$ describing the difference of the tunneling rates between $\zeta_{L\sigma}$ and $\zeta_{R\sigma}$ with $\zeta_{R/L\sigma} = \gamma \zeta_{L}(1 \pm p_\tau)$ for two leads. We define the tunneling rate of the right lead as $\zeta_{R} = (\zeta_{R\uparrow} + \zeta_{R\downarrow})/2$, then the ratio between tunneling rates of the right and left leads can be calculated, i.e., $C = \zeta_{R}/\zeta_{L} = \gamma$. As illustrated in Figure 5(a), the charge current begins to increase from zero while the energy level $\epsilon_d > -0.3$ arising from the effect of the temperature with $T = 0.08$. Obviously, the charge currents are different for different tunneling rates. The maximum amplitude of the charge current is about 0.0075 for $\gamma = 0.1$. With increment of the tunneling rate, the charge current can increase to about 0.025 associating with $\gamma = 0.5$. That is to say, the spin-bias-induced current can be enhanced through increasing the tunneling rate between the quantum dot and the ferromagnetic lead. The similar result can be obtained through analyzing the variation trends of the charge current in the case $\mu_{L\downarrow} = -\mu_{L\uparrow} = 0.5$ shown in Figure 5(b). Finally we can conclude that it is easier for the spin-bias-induced current to be measured in the systems with low temperature and high tunneling rates. For those systems with low tunneling rates, however, the spin polarization direction of the spin bias can also be detected through measuring the charge current with different values of the energy level $\epsilon_d$.

4. Summary and conclusions

In summary, we have investigated the electron transport induced by a spin bias through a quantum dot coupled to a ferromagnetic lead and a nonmagnetic semiconductor lead. The spin bias in the nonmagnetic semiconductor lead can be applied by spin injection from a spin-polarized quantum point contact in combination with magnetic focusing. The occupation number of electrons $n_\sigma$ in the quantum dot presents different variation trends through adjusting the position of the energy level of the quantum dot for the two cases $\mu_{L\uparrow} > \mu_{L\downarrow}$ and $\mu_{L\downarrow} > \mu_{L\uparrow}$. The physical origin of the different occupation number arises from the interplay of the ferromagnetic lead and the Coulombic repulsion, which finally affect the charge current induced by the spin bias. Therefore, the charge current shows different variation trends for the two cases $\mu_{L\uparrow} > \mu_{L\downarrow}$ and $\mu_{L\downarrow} > \mu_{L\uparrow}$ when the energy level of the quantum dot is adjusted. The variable characteristic of the current can be utilized to detect the magnitudes and polarization direction of the spin bias. It is found that the charge current is basically temperature-dependent. And the charge current will become larger with increment of the tunneling rates. According to numerical analysis, the spin-bias-induced current is suggested to be measured in systems with low temperature and high tunneling rates. Even with a low tunneling rate, however, the spin bias can still be detected through adjusting the energy levels of the quantum dot because the total variable trends keep consistent. Thus the model proposed in this paper may be a promising device to detect spin bias through measuring the charge current.

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