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Tunable spin-diode with a quantum dot coupled to leads*

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Abstract: Spin-dependent electronic transport through a quantum dot coupled to one ferromagnetic lead and one normal metal lead is investigated by using the master equation approach. Both the intradot spin-flip transition and Coulomb interaction are studied for the current polarization $p = (I_\uparrow - I_\downarrow)/(I_\uparrow + I_\downarrow)$. It is found that p is suppressed to zero for a particular regime of one direction bias, while it is enhanced to a relative maximum value when the bias is reversed, which is called the spin-current diode effect. The bias regime of this effect is determined by the dot level position and the intradot Coulomb interaction strength. We give a physical explanation and several control methods for it. This device is realizable with current nanofabrication technology and should have practical applications in spintronics.

Key words: spin-diode; quantum dot; ferromagnetic lead
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1. Introduction

The discovery of the giant magnetoresistance effect (GMR) in ferromagnetic and nonmagnetic alternating thin-film layers opens a new research region in condensed matter physics, so-called spintronics[1,2]. Since then, spin-biased devices have been both experimentally and theoretically investigated. Compared with conventional charge-based devices, they have many attractive advantages, such as faster data-processing speed, less electric power consumption, and increased integration densities[1,2]. Some devices based on the GMR effect, such as magnetic field sensors and magnetic hard disk read heads, have greatly influenced the recent electronic industry. The rapid progress in nanofabrication technology has stimulated extensive investigations on various low-dimensional semiconductor spintronics structures, such as quantum rings, quantum wells or quantum dots (QDs)[3−5]. In particular, the QD is probably the most attractive one in these nanostructures as it resembles atomic or molecular characteristics, and plays an important role in applications for photoelectric devices, information storage and quantum computing process, etc[6,7].

Devices consisting of a QD coupled to two ferromagnetic electrodes (FM-QD-FM) have been studied for tunnel magnetoresistance (TMR)[8−10], Kondo effect[11,12], spin valve[11,13] or some other spin-relevant phenomena[14]. Intrinsically, the ferromagnetism of the electrodes induces spin-dependent couplings between the QD and the leads, affecting the QD spin and the tunneling current through it. Moreover, tunneling properties and the dot spin are different depending on whether the magnetizations of the two ferromagnetic electrodes are in parallel or antiparallel configurations. Another interesting system is that with a QD coupled to one ferromagnetic electrode and one normal metal electrode (FM-QD-NM)[15], which has seldom been investigated as compared to the FM-QD-FM structure. It was early indicated that in this FM-QD-NM device, the spin-diode effect may arise, that is, the current spin polarization is quite small for all positive bias and is finite for all negative bias[16−19]. A recent work also studied such a system and found that the current polarization is zero in a range of positive bias (not all the positive bias), and is enhanced when the corresponding bias is reversed[15]. Such a diode-like effect was attributed to the spin accumulation $m = n_\uparrow - n_\downarrow$ on the dot, where $n_\uparrow$ ($n_\downarrow$) is the corresponding spin-up (spin-down) electron occupation number.

In the present paper we study the spin-diode effect in the FM-QD-NM device taking the intradot spin-flip transition into account. The spin-flip process affects the dot spin relaxation and decoherence times as well as the spin accumulation[9,16]. It is dominated by spin-orbit interactions and hyperfine coupling between the dot spin and the lattice nuclear spins, providing an effective spin manipulation method. This process has been studied for the TMR in FM-QD-FM structure, and it has been found that it reduces the spin accumulation on the dot and then suppresses the TMR value accordingly[9,16]. We will show later that in the present FM-QD-NM device, the spin-flip transition reduces the current spin polarization p but has no impact on it in the bias range of $p = 0$. The working mechanism of the spin-diode device without the spin-flip transition is illustrated by Figs. 1(a) and 1(b). Assume that the left lead is ferromagnetic and the spin-dependent tunneling rates between the lead and the QD are $\varGamma^{\mathrm{L}}_{\uparrow(\downarrow)} = \varGamma_0(1 \pm p_{\mathrm{L}})$, where p_{L} is the spin asymmetry factor. When the electrons are driven by the positive bias $V = \mu_{\mathrm{L}}/2 = -\mu_{\mathrm{R}}/2$, where $\mu_{\mathrm{L(R)}}$ is the chemical potential of the left (right) lead, into the QD from the left lead with $\varGamma_{\mathrm{L}\uparrow} > \varGamma_{\mathrm{L}\downarrow}$, spin-up electrons will tunnel into the dot faster than spin-down ones providing only ε_{d} is located in the bias window [Fig. 1(a)], while both spin-up and spin-down electrons will tunnel out the dot with the same speed, since the right lead is nonmagnetic and $\varGamma_{\mathrm{R}\uparrow} = \varGamma_{\mathrm{R}\downarrow}$. Then on average the dwell time of the spin-down electrons is longer than the spin-up ones, resulting in $n_\downarrow > n_\uparrow$. So the transportation of the spin-down electrons is more blocked than the spin-up ones and further enlarges the difference between $I_\uparrow$ and $I_\downarrow$. The

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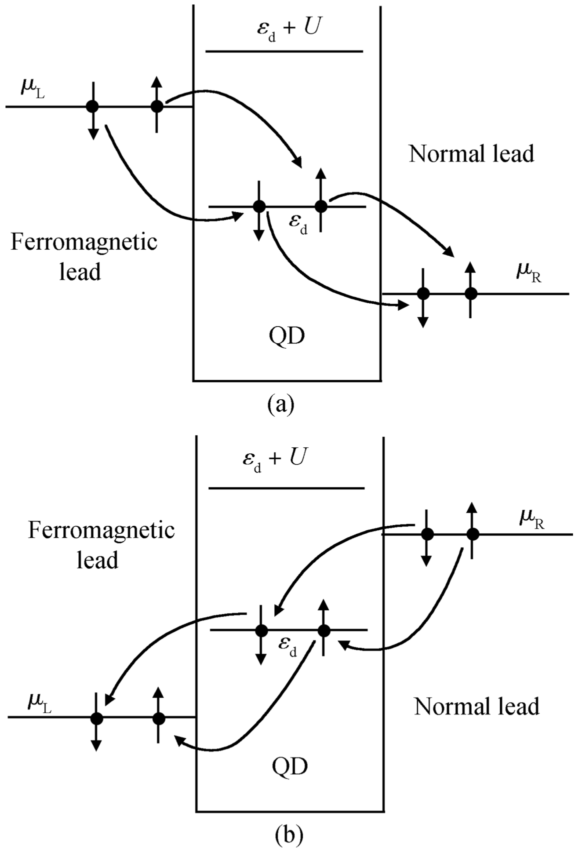

Fig. 1. Schematic diagram for the proposed device, in which a QD is coupled to one ferromagnetic and one normal metal lead. (a) and (b) are level diagrams for the positive and negative bias cases, respectively.

corresponding current polarization $p = (I_\uparrow - I_\downarrow)/(I_\uparrow + I_\downarrow)$ may reach a maximum value in the dot level or bias range of $\varepsilon_d < \mu_L < \varepsilon_d + U$. For $\mu_L > \varepsilon_d + U$, the double-occupancy channel $\varepsilon_d + U$ enters into the bias window and will suppress the difference between $n_\downarrow$ and $n_\uparrow$ (spin accumulation), and then the current polarization will be reduced accordingly. For the negative bias case [Fig. 1(b)], the nonmagnetic right lead operates as the source lead and the ferromagnetic left lead as a drain one; the current is spin unpolarized in the bias range of $\varepsilon_d < |\mu_R| < \varepsilon_d + U$, thus resulting in zero current polarization.

2. Model and method

The device can be described by the following Hamiltonian[15, 16]:

$$H = \sum_\sigma \varepsilon_d d_\sigma^\dagger d_\sigma + U d_\uparrow^\dagger d_\uparrow d_\downarrow^\dagger d_\downarrow + R(d_\uparrow^\dagger d_\downarrow + d_\downarrow^\dagger d_\uparrow) + \sum_{\kappa,\sigma,\alpha} \varepsilon_{\kappa\alpha\sigma} c_{\kappa\alpha\sigma}^\dagger c_{\kappa\alpha\sigma} + \sum_{\kappa,\sigma,\alpha} (t_{\alpha d} c_{\kappa\alpha\sigma}^\dagger d_\sigma + H.c.), \qquad (1)$$

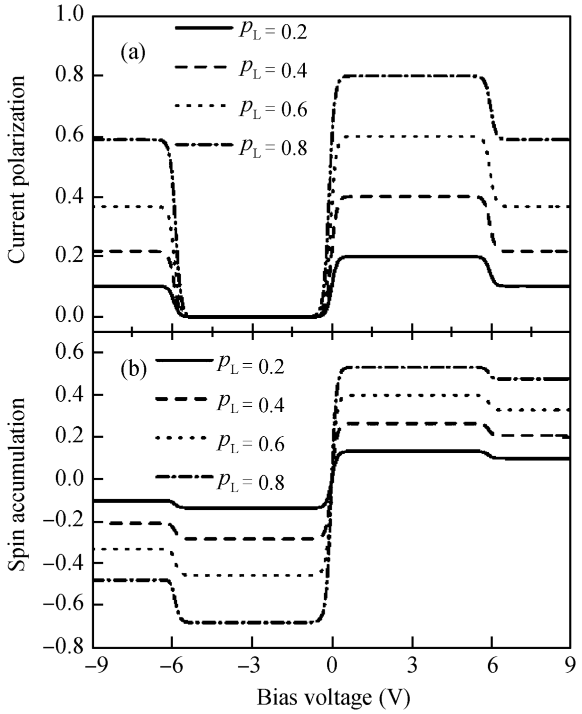

Fig. 2. (a) Current polarization and (b) spin accumulation as a function of bias for different p_L and fixed $p_R = 0$. K_B is set to be 0.05 meV.

where $d_\sigma^\dagger (d_\sigma)$ creates (annihilates) an electron in the QD with spin σ, $c_{\kappa\alpha\sigma}^\dagger (c_{\kappa\alpha\sigma})$ is the creation (annihilation) operator of the electrons with momentum k, spin σ and energy $\varepsilon_{\kappa\alpha\sigma}$ in the $\alpha (\alpha = L, R)$ lead; R denotes the spin-flip relaxation processes; $t_{L(R)d}$ describes the energy-independent QD-lead tunneling coupling. We limit our consideration to the sequential tunneling regime, in which the tunneling of an electron is in a sequence of two incoherent processes. Higher-order tunneling process such as the subtle Kondo effect is then neglected. To find the tunneling current we use the master equation method. Following the method developed by Glazman and Matweev[16, 20], the spin-dependent current through the α-th lead is given by ($\hbar = 1$):

$$I_\sigma^\alpha = e[\Gamma_{\alpha\sigma}^-(n_\sigma - n_d) - \Gamma_{\alpha\sigma}^+(1 - n_\sigma)(1 - n_{\bar\sigma})] + e[\widetilde{\Gamma}_{\alpha\sigma}^- n_d - \widetilde{\Gamma}_{\alpha\sigma}^+(n_{\bar\sigma} - n_d)], \qquad (2)$$

where $n_\sigma = \langle d_\sigma^\dagger d_\sigma \rangle$, $n_d = \langle n_\uparrow n_\downarrow \rangle$ are the single and double average occupancies on the dot, respectively. The tunneling rates in the above equation are $\Gamma_{\alpha\sigma}^\pm = \Gamma_{\alpha\sigma} f_\alpha^\pm$, $\widetilde{\Gamma}_{\alpha\sigma}^\pm = \Gamma_{\alpha\sigma} \widetilde{f}_\alpha^\pm$, with the coupling strengths between the dot and the lead as $\Gamma_{\alpha\sigma} = 2\pi |t_{\alpha d}|^2 \rho_{\alpha\sigma}(\varepsilon_d)$ and $\widetilde{\Gamma}_{\alpha\sigma} = 2\pi |t_{\alpha d}|^2 \rho_{\alpha\sigma}(\varepsilon_d + U)$. Here $\rho_{\alpha\sigma}(\varepsilon)$ denotes the spin-dependent density of states of lead α. To describe the spin dependence of the coupling strengths more quantitatively, we introduce the spin asymmetry factors p_L and p_R for the left and right leads, respectively, $\Gamma_{\alpha\uparrow(\downarrow)} = \Gamma_0(1 \pm p_\alpha)$, where Γ_0 is a parameter. The Fermi distribution functions f_α^+ and $\widetilde{f}_\alpha^+$ are

$$f_\alpha^+ = \frac{1}{1 + \exp[(\varepsilon_d - \mu_\alpha)/k_B T]}, \qquad (3)$$

and

$$\widetilde{f}_\alpha^+ = \frac{1}{1 + \exp[(\varepsilon_d + U - \mu_\alpha)/k_B T]}, \qquad (4)$$

where k_B and T are the Boltzmann constant and the temperature, respectively. μ_α stands for the electrochemical potential of the lead α. The other two functions are $f_\alpha^- = 1 - f_\alpha^+$ and $\widetilde{f}_\alpha^- = 1 - \widetilde{f}_\alpha^+$.

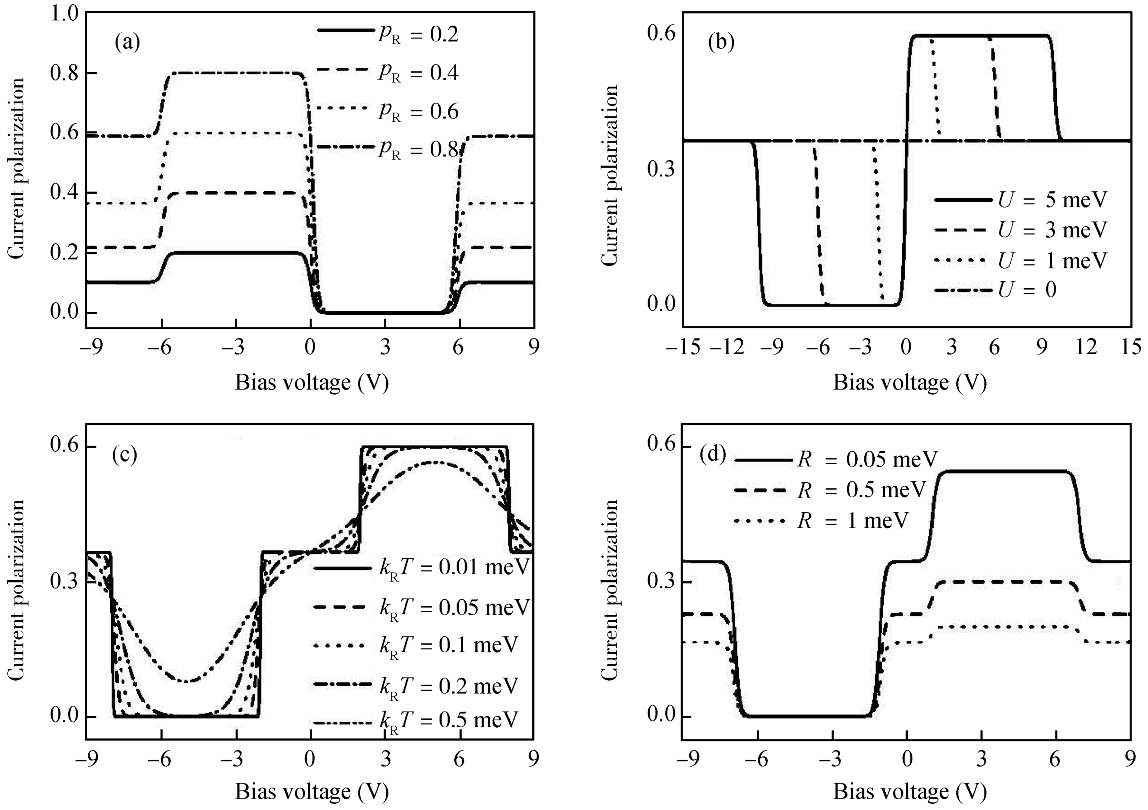

Fig. 3. Current polarization as a function of bias voltage under different conditions. The parameters are the same as those in Fig. 2 unless noted.

To calculate the current in Eq. (2) we use the following master equations to find the average occupancies[16, 20],

$$\frac{\mathrm{d}}{\mathrm{d}t}n_\sigma = \Gamma_\sigma^+[(1-n_\sigma)(1-n_{\bar\sigma})] - \Gamma_\sigma^-(n_\sigma - n_\mathrm{d}) + \widetilde{\Gamma}_\sigma^+(n_{\bar\sigma} - n_\mathrm{d}) - \widetilde{\Gamma}_\sigma^- n_\mathrm{d} - R(n_\sigma - n_{\bar\sigma}), \quad (5)$$

and

$$\frac{\mathrm{d}}{\mathrm{d}t}n_\mathrm{d} = \widetilde{\Gamma}_\uparrow^+(n_\downarrow - n_\mathrm{d}) - \widetilde{\Gamma}_\uparrow^- n_\mathrm{d} + \widetilde{\Gamma}_\downarrow^+(n_\uparrow - n_\mathrm{d}) - \widetilde{\Gamma}_\downarrow^- n_\mathrm{d}, \quad (6)$$

where $\Gamma_\sigma^\pm = \Gamma_{\mathrm{L}\sigma}^\pm + \Gamma_{\mathrm{R}\sigma}^\pm$ and $\widetilde{\Gamma}_\sigma^\pm = \widetilde{\Gamma}_{\mathrm{L}\sigma}^\pm + \widetilde{\Gamma}_{\mathrm{R}\sigma}^\pm$ are the total tunneling rates. Equations (5) and (6) determine the time dependence of the average occupation numbers. Here we are only interested in the stationary case and the time differentials of n_σ and n_d are all zero. So the occupation numbers can be obtained by solving three coupled equations, allowing us to calculate the tunneling current through the system.

3. Numerical results

In the following numerical calculations, we set $\Gamma_0 = 1$ meV as the energy unit. The chemical potential is $\mu_\mathrm{L} = -\mu_\mathrm{R} = V/2$ with the bias voltage V. Figure 2 shows the current polarization p and the spin accumulation $m = n_\uparrow - n_\downarrow$ versus the bias voltage V for fixed dot level $\varepsilon_\mathrm{d} = 0$ and various p_L. p_R is set to be zero. As is seen from Fig. 2(a), for positive bias voltage (electrons transporting from the left ferromagnetic lead to the right normal lead), the current polarization first reaches a maximum value of $p = p_\mathrm{L}$ in a bias range of about $\varepsilon_\mathrm{d} < V < \varepsilon_\mathrm{d} + 2U$, and then decreases to a constant value with increasing bias. The current polarization is zero for the corresponding negative bias regime. This phenomenon is analogous to that observed in Ref. [15] except that the widths of the current polarization enhancement and suppression bias regimes are doubled. This is because that the bias in the present paper is set to be $V = 2\mu_\mathrm{L} = -2\mu_\mathrm{R}$, whereas it is $\mu_\mathrm{L} = 0$ and $\mu_\mathrm{R} = V$ in Ref. [15]. Moreover, the dot level is fixed to be zero in the present paper, whereas it was tuned to vary with respect to the bias voltage in their work. This indicates that the spin-diode effect can also been observed in a self-assembled QD device, in which the dot level is somewhat difficult to tune as compared to the gated QD. As shown by Fig. 2(b), the corresponding spin accumulation on the QD is always positive for $V > 0$ and negative for $V < 0$. The maximum absolute value of m emerges in the bias range of $\varepsilon_\mathrm{d} < |V| < \varepsilon_\mathrm{d} + 2U$, in which the spin-diode effect is observed for the current polarization. The reason for this has been given previously and we do not discuss it again.

Figure 3 presents various tunings of the diode effect. First, as shown by Fig. 3(a), when $p_\mathrm{L} = 0$ and $p_\mathrm{R} \neq 0$, i.e., the ferromagnetism of the leads is interchanged, the suppression and enhancement bias regions of p are exactly reversed as compared with Fig. 2(a). This confirms that the enhancement or the suppression of the current polarization is determined by the magnetism of the source lead. More precisely, when the electrons are driven by the bias from the ferromagnetic lead to the nonmagnetic one, p can reach a maximum value in the bias range of $\varepsilon_\mathrm{d} < V < \varepsilon_\mathrm{d} + 2U$. In contrast, when the nonmagnetic lead operates as the source lead and the ferromagnetic leads as the drain lead, the current is spin-unpolarized in the corresponding bias regime. Figure 3(b) shows the current po-

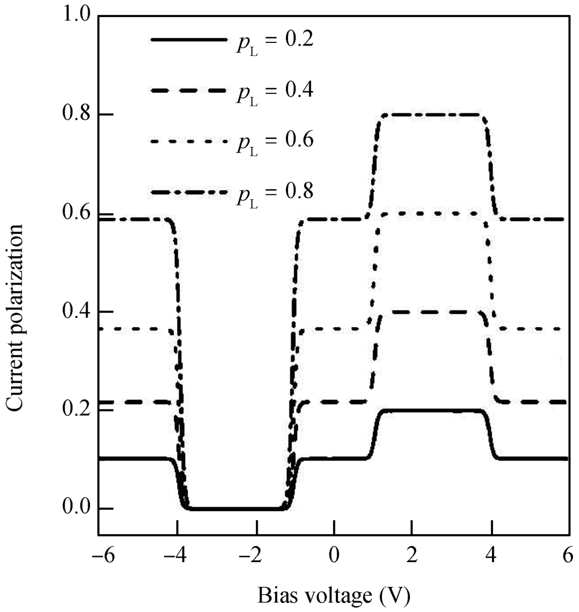

Fig. 4. Current polarization as a function of bias voltage for the varying dot level case. Other parameters are the same as those in Fig. 2.

larization as a function of the bias voltage for various intradot Coulomb interactions. Experimentally, the e–e Coulomb interaction can be changed by tuning the dot shape by gate voltages[5]. It is shown that the widths of the current polarization suppression and enhancement bias regions remain about $2U$ except for the $U = 0$ case, of which p is a constant for all the bias. This is because when there is no intradot Coulomb repulsion interaction ($U = 0$), the dwell times of the spin-up and spin-down electrons are respectively determined by their own tunneling rates, and the spin accumulation on the dot has no impact on the current, resulting in a constant current polarization. Figure 3(c) shows the temperature dependence of the spin-diode effect with $p_L = 0.4$, $\varepsilon_d = 2$ meV and $U = 5$ meV. It is found that the boundary regions of the suppression and the enhancement of p become steeper with decreasing temperature. At lower temperature, as indicated by the solid line, the suppression and enhancement of p are exactly in the bias region of $\varepsilon_d < V < \varepsilon_d + 2U$. But in the high temperature regime (dash-dot-dotted line), p cannot be suppressed to zero. This is because, at higher temperature, the Coulomb blockade in the dot is weakened by the random thermal motion of the electrons.

The influence of the intradot spin-flip processes on the spin-diode effect is studied in Fig. 3(d) for $\varepsilon_d = 1$ meV and $U = 5$ meV. The spin-diode effect is robust in the presence of the spin-flip transition but the magnitude of p is reduced except for the case of the $p = 0$ bias region. The asymmetric impact of the spin-flip transition on the current-voltage property in the present FM-QD-NM device is similar to that in Ref. [16], where the FM-QD-FM structure was studied. The reason is that for negative bias the spin-flip processes play a minor role, since now the double occupation probability n_d is very small.

Finally we study the case when the dot level depends on the bias voltage according to $\varepsilon_d = \varepsilon_d^0 - 0.5V$, where ε_d^0 is tunable via gate voltages and is set to be 1 meV. Figure 4 shows that the behavior of the current polarization is similar to that for the fixed dot level case. It is suppressed to zero and enhanced to a maximum value in a particular range of negative and positive biases, respectively. But the widths of the suppression and enhancement bias regions are all U now, which is consistent with the result obtained in Ref. [15]. This phenomenon again confirms that the diode effect emerges under the condition of only the singly occupied dot level being in the bias window.

4. Conclusions

Based on the master equation method we studied the spin-diode effect in a FM-QD-NM device. It is found that the current polarization can be suppressed to zero for one bias direction, and is enhanced to a maximum value when the corresponding bias is reversed. The suppression or the enhancement of it is determined by the magnetism of the source lead. We clarify that the widths of the current polarization suppression and enhancement regions are $2U$ for a fixed dot level case, and they are U if the dot level is arranged as $\varepsilon_d = \varepsilon_d^0 - 0.5V$. The diode effect can be found in either self-assembled or gated QD devices, and can be tuned in terms of the arrangement of the magnetisms of the leads, the dot shape (intradot Coulomb interaction) or the intradot spin-flip transition.

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