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Spin-polarized transport in a coupled-double-quantum-dot system with ferromagnetic electrodes

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Abstract
Based on the Keldysh non-equilibrium Green function method, the spin-polarized transport properties in a coupled-double-quantum-dot (CDQD) system with ferromagnetic electrodes (FM–CDQD–FM) are investigated. It is clearly seen that, in contrast to the steplike or basin-like behaviors of the spin (electrical) current in the FM–QD–FM system (Mu *et al* 2006 *Phys. Rev.* B **73** 054414), the resonant tunneling determines the main features of the spin (electrical) current in the FM–CDQD–FM system. It must originate from the coupling effect between two dots, which destroys the Coulomb blockade (CB) effect and makes electron spin transport mainly depend on the cotunneling. Furthermore, it is also found that spin-polarized transport in the system is evidently modulated by the coupling strength between two dots, which results from the non-equilibrium spin accumulation and the spin precession for the presence of ferromagnetic electrodes.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In the last decade, due to its potential applications in spintronics [1] and quantum computing [2], spin-polarized transport in quantum dots (QDs) coupled to a ferromagnetic electrode system [3–9] has attracted much interest. Sergueev *et al* [3] reported on a theoretical analysis of transport characteristics of a spin-valve system formed by a quantum dot connecting to two ferromagnetic electrodes whose magnetic moments are oriented at an angle θ with respect to each other. The results suggest that the Kondo peaks in the local density of states and in the conductance can be modulated by θ. Then, the group of Martinek [4] further investigated the interplay of charge and spin degrees of freedom in these systems in

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the sequential tunneling, cotunneling and strong coupling regimes. It is found that in the Coulomb blockade limit a large enhancement of the tunnel magnetoresistance (TMR) at low temperatures is observed, especially for higher order tunneling processes. It is also shown that apart from charge fluctuations there are also large spin fluctuations, which influence the transport current and enhance the current noise. Related to this subject is the work of Rudziñski *et al* [5], who demonstrated that Coulomb correlations on the dot and strong spin polarization of the electrodes significantly enhance precession of the average dot spin around the effective molecular field created by the external electrodes. Afterwards, Weymann *et al* [6] addressed the problem of second-order (cotunneling) spin-dependent transport through quantum dots coupled to ferromagnetic leads with arbitrary configuration of the in-plane magnetic moments of external electrodes. The results show that, in the case of an empty dot, TMR was found to be roughly independent of the bias voltage, but strongly dependent on the angle between magnetic moments. Recently, Mu *et al* [7] advocated that in a ferromagnet–quantum dot–ferromagnet coupled system the spin current shows quite different characteristics from its electrical counterpart, and by changing the relative orientation of both magnetizations, it can change its magnitude and even sign. Subsequently, spin-dependent electronic transport through a quantum dot in the Kondo regime was also calculated [8]. It is shown that in symmetrical systems the splitting of the Kondo anomaly in differential conductance decreases monotonically with an increasing angle between magnetizations and vanishes in the antiparallel configuration. The corresponding behavior in asymmetrical systems may be different; i.e., the splitting of the anomaly can vary non-monotonically with the angle between magnetizations and can remain finite in the antiparallel configurations. More recently, Braun *et al* [9] studied the frequency-dependent current noise through a single-level quantum dot connected to ferromagnetic electrodes with non-collinear magnetization. It is found that the shape of the resonance in the current–current correlation can either have an absorption or dispersion line shape, depending on the relative angle between the electrode magnetizations.

However, the previous works mainly focus on the spin-polarized transport in the magnetic nanostructure consisting of only one QD. To date, little work has paid attention to the investigation of the spin-polarized transport in a magnetic nanostructure with a coupled double quantum dot (CDQD). The system of a CDQD with ferromagnetic electrodes possesses two most prominent merits: (1) electrons with different spins experience effectively modulated potentials; (2) compared with the individual QD system, the CDQD forms the simplest artificial systems showing molecule-like correlations at the nanoscale. As a consequence, it has been proposed as a feasible two-qubit system for quantum computation [10]. The interdot coupling effectively modulates the single-particle level of two dots and introduces novel characteristics for electron transport in it.

So in this paper, the characteristics for spin-polarized transport in a system of a CDQD (in series) with ferromagnetic electrodes (FM–CDQD–FM) (see figure 1(a)) have been symmetrically studied. The results show that, in contrast to the steplike or basin-like behaviors of the spin (electrical) current in the FM–QD–FM system [7], the resonant tunneling determines the main features of the spin (electrical) current in the FM–CDQD–FM system. Furthermore, it is also found that spin-polarized transport in the system is effectively modulated by the coupling strength between two dots. In addition, the effects of the orientation of the magnetization and the spin polarization of the electrodes on spin-polarized transport have been discussed.

2. Theoretical models

For the central part CDQD in series, the energy bands of the single-level dots are sketched in figure 1(b). If the left (L) and right (R) electrodes are connected with the bias voltage

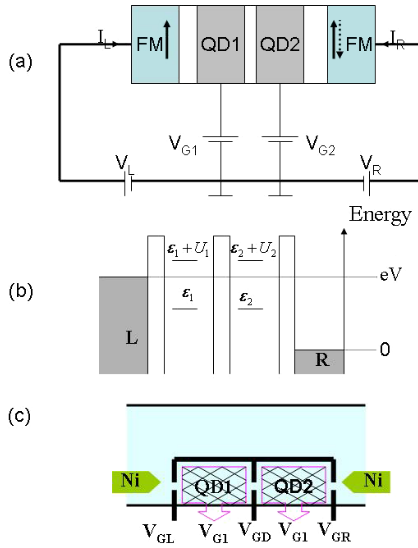

Figure 1. (a) Schematic diagram of the model. The central part CDQD is in series. The orientation of magnetization of each part can be independently controlled. (b) The relative energies of the dots. (c) Schematic diagram for our proposed experimental device fabricated in 2DEGs. The dark regions are the split gate to control the coupling coefficients $V_k^{\rm L}$ ($V_p^{\rm R}$) and $V_{\rm d}$. The inclined lattice region is the gate that controls the level ε_i. Green regions are the nickel (Ni) electrodes. ε_i is the single-electron energy level and U_i is the on-site Coulomb repulsion in the ith dot, respectively.

V and 0, respectively, and the single-particle state is above the equilibrium Fermi energy of the electrodes [10–15], the whole system can be described by a Hamiltonian of the general form $H = H_\beta + H_{\rm d} + H_{\rm t}$, where H_β ($\beta = {\rm L,R}$) describe the left (L) and right (R) electrodes as reservoirs of non-interacting quasiparticles, $H_{\rm d}$ is the dots' Hamiltonian, and tunneling processes between the electrodes and dots, and between the dots, are included in $H_{\rm t}$. Therefore, the main difference of the Hamiltonian between the FM–CDQD–FM and FM–QD–FM systems is the tunneling term $H_{\rm t}$. For the FM–CDQD–FM system this term can be expressed as $H_{\rm t} = H_{\rm t}^0 + H_{\rm t}'$, and

$$H_{\rm t}^0 = \sum_{k,\sigma} \tilde{V}_k^{\rm L} d_{1\sigma}^\dagger c_{k\sigma} + \sum_{p,\sigma} \tilde{V}_{p\sigma}^{\rm R} d_{2\sigma}^\dagger c_{p\sigma} + {\rm H.c.} \tag{1}$$

where

$$\tilde{V}_k^{\rm L} = V_k^{\rm L}, \qquad \tilde{V}_p^{\rm R} = V_p^{\rm R}\left(\cos\frac{\theta}{2} - \sigma\sin\frac{\theta}{2}\right);$$

whereas the second term corresponds to tunneling between the two dots

$$H_{\rm t}' = \sum_\sigma V_{\rm d} d_{1\sigma}^\dagger d_{2\sigma} + {\rm H.c.} \tag{2}$$

Here, $c_{k\sigma}^\dagger(c_{k\sigma})$ and $c_{p\sigma}^\dagger(c_{p\sigma})$ are the creation (annihilation) operators of the electrons in the left and right FM electrodes; $d_{i\sigma}^\dagger(d_{i\sigma})$ ($i = 1, 2$) is the creation (annihilation) operator of the electrons in the ith dot; σ is the electron spin direction (here, up spin $\sigma = 1$ is labeled $\uparrow$ and down spin $\sigma = -1$ is labeled $\downarrow$); $V_k^{\rm L}$ ($V_p^{\rm R}$) and $V_{\rm d}$ denote the tunneling amplitude between the left (right) non-ferromagnetic electrode and dot 1 (2) and the interdot coupling, respectively. θ is the angle between the magnetic moment $M_{\rm L}$ of the left FM and $M_{\rm R}$ of the right FM. In the present case, we only consider the collinear Magnetization; i.e., the magnetization of the two electrodes is either parallel (P, $\theta = 0$) or antiparallel (AP, $\theta = \pi$), and thus σ can be labeled 'up' or 'down'.

In our calculations, the tunneling electrical current of the system is defined by the sum of the currents carried by spin-up and down electrons $I_C = I_{i\beta}^{\uparrow} + I_{i\beta}^{\downarrow}$, and its spin current is defined by the difference between the electrical currents through the spin-up and down channels $I_S = I_{i\beta}^{\uparrow} - I_{i\beta}^{\downarrow}$ [16]. Adopting the Keldysh formalism [17], the currents carried by spin-up or down electrons from electrode L (R) into dot 1 (2) can be calculated

$$I_{i\beta}^{\sigma} = \frac{e}{h}\sum_{k(p)}\int (\tilde{V}_{k(p)\sigma}^{\beta}\langle\langle c_{k(p)\sigma}|d_{i\sigma}^{\dagger}\rangle\rangle^{<} - \tilde{V}_{k(p)\sigma}^{\beta *}\langle\langle d_{i\sigma}|c_{k(p)\sigma}^{\dagger}\rangle\rangle^{<})\,\mathrm{d}\varepsilon \qquad (\beta = \mathrm{L,R}) \tag{3}$$

with the lesser Green functions $\langle\langle c_{k(p)\sigma}|d_{i\sigma}^{\dagger}\rangle\rangle^{<}$ and $\langle\langle d_{i\sigma}|c_{k(p)\sigma}^{\dagger}\rangle\rangle^{<}$.

By applying the Langrenth theorem $[AB]^{<} = A^{r}B^{<} + A^{<}B^{a}$ [18] and the Fourier transform, we may obtain the following equation:

$$\langle\langle d_{i\sigma}|c_{k(p)\sigma}^{\dagger}\rangle\rangle^{<} = \tilde{V}_{k(p)}^{\mathrm{L(R)}}\langle\langle d_{i\sigma}|d_{i\sigma}^{\dagger}\rangle\rangle^{r} g_{k(p)\sigma}^{<} + \tilde{V}_{k(p)}^{\mathrm{L(R)}}\langle\langle d_{i\sigma}|d_{i\sigma}^{\dagger}\rangle\rangle^{<} g_{k(p)\sigma}^{r*} \tag{4}$$

where $g_{k(p)\sigma}^{<}$ and $g_{k(p)\sigma}^{r}$ are the free-electron Green functions in the two electrodes and have the relations $g_{k(p)\sigma}^{<} = 2\pi \mathrm{i} f_{\mathrm{L\,(R)}}(\varepsilon)\delta(\varepsilon - \varepsilon_{k(p)}^{\beta} - \sigma M_{\beta})$ and $g_{k(p)\sigma}^{r} = (\varepsilon - \varepsilon_{k(p)}^{\beta} - \sigma M_{\beta} + \mathrm{i}\eta)^{-1}$. The parameters $\varepsilon_k^{\mathrm{L}}$ and $\varepsilon_p^{\mathrm{R}}$ are the single-electron energies in the FM electrodes.

For the equation of motion method (EOM) and the Hartree–Fock approximation, they may fail to account properly for the interplay between Kondo correlations and ferromagnetism even in a single-quantum-dot case [19, 20]; however, when the temperature is sufficiently higher than the Kondo temperature, they will be valid for studying the present CDQD system with a higher temperature [21]. Recently it is also reported that at high enough temperature the decoupling approximations agree to the relevant order with direct perturbation expansions [22]. By using the EOM and the Hartree–Fock approximation without considering the Kondo effect, the retarded (lesser) Green function can be written as

$$G_{i\sigma}^{r}(\varepsilon) = \langle\langle d_{i\sigma}|d_{i\sigma}^{\dagger}\rangle\rangle_{\varepsilon}^{r} = \frac{G_{i0\varepsilon}^{r}}{1 - |V_{\mathrm{d}}|^2 G_{i0\varepsilon}^{r} G_{\bar{i}0\varepsilon}^{r}} \tag{5}$$

$$G_{i\sigma}^{<} = \langle\langle d_{i\sigma}|d_{i\sigma}^{\dagger}\rangle\rangle^{<} = 2\mathrm{i}\frac{f_{\beta}(\varepsilon)\Gamma_{\beta\sigma}(\varepsilon) - 2f_{\bar{\beta}}(\varepsilon)|V_{\mathrm{d}}|^2\,\mathrm{Im}\,G_{\bar{i}0\varepsilon}^{r}}{\Gamma_{\beta\sigma}(\varepsilon) - 2|V_{\mathrm{d}}|^2\,\mathrm{Im}\,G_{\bar{i}0\varepsilon}^{r}}\,\mathrm{Im}\,G_{i\sigma}^{r} \tag{6}$$

($\bar{i} = 1, 2$; if $i = 1$, $\bar{i}$ is equal to 2 and vice versa), where $f_{\beta}(\varepsilon) = \{\exp[(\varepsilon - \mu_{\beta})/k_{\mathrm{B}}T] + 1\}^{-1}(\mu_{\mathrm{L}} = V, \mu_{\mathrm{R}} = 0)$ are the Fermi distribution functions of the electrodes; $G_{i0\varepsilon}^{r}$ denoting the retarded Green function without coupling between the two dots can be written as

$$G_{i0\varepsilon}^{r} = \langle\langle d_{i\sigma}|d_{i\sigma}^{\dagger}\rangle\rangle_{0\varepsilon}^{r} = \frac{\varepsilon - \varepsilon_i - U_i(1 - n_{i\bar{\sigma}})}{(\varepsilon - \varepsilon_i)(\varepsilon - \varepsilon_i - U_i) - [\varepsilon - \varepsilon_i - U_i(1 - n_{i\bar{\sigma}})](\sum_{k(p)}|\tilde{V}_{k(p)}^{\beta}|^2 g_{k(p)}^{r}(\varepsilon))} \tag{7}$$

where ε_i is the single-electron energy level in the ith dot, which can be tuned by gate voltage V_{Gi} [23]; U_i is the on-site Coulomb repulsion in the ith dot; $n_{i\sigma} = d_i^{\dagger}d_i$ is the average occupation in the ith dot, which can be obtained self-consistently by means of the relation $n_{i\sigma} = \frac{1}{2\pi}\int \mathrm{Im}\langle\langle d_{i\sigma}|d_{i\sigma}^{\dagger}\rangle\rangle^{<}\,\mathrm{d}\varepsilon$.

The spin-dependent coupling strengths to the ferromagnetic electrode β are described as $\Gamma_{\beta\sigma}(\varepsilon) = 2\pi\sum_{k(p)\sigma}|\tilde{V}_{k(p)}^{\beta}|^2\delta(\varepsilon - \varepsilon_{k(p)}^{\beta} - \sigma M_{\beta})$. Further, in the wide band limit, the energy dependence of $\Gamma_{\beta\sigma}(\varepsilon)$ can be neglected, evaluating it at $\varepsilon = E_{\mathrm{F}}$. Then the spin-dependent coupling strengths are related to the spin polarization of the electrodes by

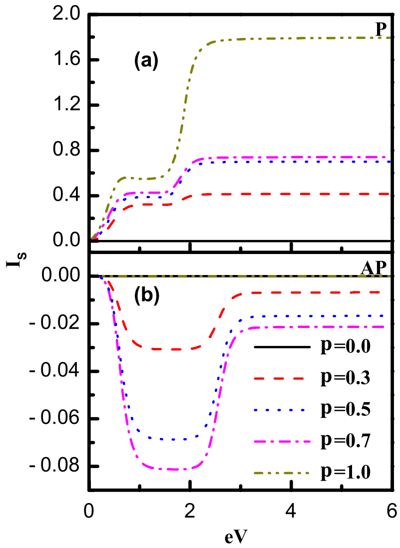

Figure 2. Bias dependence of the spin current of FM–QD–FM system for different spin polarizations p of electrodes, in the case of the parallel (P, $\theta = 0$) (a) and antiparallel (AP, $\theta = \pi$) (b) alignments. The parameters are taken as $\varepsilon_0 = 0.5$, $U = 1.0$, $\Gamma_0 = 0.1$, $k_B T = 0.125$, and $p = 0.3$.

$p_\beta = (\Gamma_{\beta\uparrow} - \Gamma_{\beta\downarrow})/\Gamma_0$, where $\Gamma_0 \equiv \Gamma_{\beta\uparrow} + \Gamma_{\beta\downarrow}$. Under these considerations and the Dyson equations

$$\langle\langle c_{k(p)\sigma}|d^\dagger_{i\sigma}\rangle\rangle^< = \tilde{V}^{\mathrm{L(R)}}_{k(p)}\langle\langle d_{i\sigma}|d^\dagger_{i\sigma}\rangle\rangle^< g^r_{k(p)\sigma} + \tilde{V}^{\mathrm{L(R)}}_{k(p)}\langle\langle d_{i\sigma}|d^\dagger_{i\sigma}\rangle\rangle^{r*} g^<_{k(p)\sigma},$$

we finally get

$$I^\sigma_{i\beta} = -\frac{4e}{h}\int \frac{\Gamma_{\beta\sigma}\,|V_{\mathrm{d}}|^2\,\mathrm{Im}\,G^r_{\bar{i}0\varepsilon}}{\Gamma_{\beta\sigma} - 2\,|V_{\mathrm{d}}|^2\,\mathrm{Im}\,G^r_{\bar{i}0\varepsilon}}\,\mathrm{Im}\,G^r_{i\sigma}(\varepsilon)[f_{\mathrm{L}}(\varepsilon) - f_{\mathrm{R}}(\varepsilon)]\,\mathrm{d}\varepsilon. \quad (8)$$

In these calculations, we consider for the parallel (P, $\theta = 0$) and antiparallel (AP, $\theta = \pi$) alignments of the two electrodes. For the sake of simplicity, we further suppose that the two ferromagnets are made of the same materials, namely, in the P case ($p_{\mathrm{L}} = p_{\mathrm{R}} \equiv p$) we have $\Gamma_{\mathrm{L}\uparrow} = \Gamma_{\mathrm{R}\uparrow} = (1+p)\Gamma_0/2$ and $\Gamma_{\mathrm{L}\downarrow} = \Gamma_{\mathrm{R}\downarrow} = (1-p)\Gamma_0/2$; whereas the AP case ($p_{\mathrm{L}} = -p_{\mathrm{R}} \equiv p$) yields $\Gamma_{\mathrm{L}\uparrow} = \Gamma_{\mathrm{R}\downarrow} = (1+p)\Gamma_0/2$, $\Gamma_{\mathrm{L}\downarrow} = \Gamma_{\mathrm{R}\uparrow} = (1-p)\Gamma_0/2$. In our calculation, the two dots are completely identical using $10^{-2}e/h$ as the unit, where $\varepsilon_1 = \varepsilon_2 = 0.5$ and $U_1 = U_2 = 1.0$, and the other parameters are set as $\Gamma_0 = 0.1$ and $k_B T = 0.125$.

3. Resonant spin transport through CDQD

In figure 2, the spin current I_{S} in the FM–QD–FM coupled system has been examined. It is obvious that, for the case of parallel alignment, the spin current exhibits two step features, which corresponds to the resonant tunneling of electrons through the QD at energy levels ε_0 and $\varepsilon_0 + U$; for the case of antiparallel alignment, it exhibits behaviors similar to a basin-like shape. Similar results have also been obtained in [7]. These results should be attributed to the Coulomb blockade (CB) effect. Due to the CB effect, both the spin-up and spin-down currents should present the two step features for electron transport through the parallel and

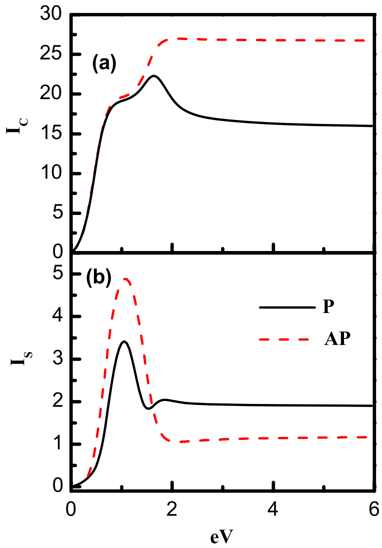

Figure 3. Bias dependence of the electrical current I_C (a) and the spin current I_S (b) of the FM–CDQD–FM system. The parameters are taken as $\varepsilon_1 = \varepsilon_2 = 0.5$, $U_1 = U_2 = 1.0$, $\Gamma_0 = 0.1$, $k_B T = 0.125$, $V_d = 0.05$, and $p = 0.3$.

antiparallel configurations. However, for an antiparallel FM–QD–FM, with increasing bias voltage the spin current decreases steeply at the QD energy level ε_0, and then keeps a constant till the other resonant level $\varepsilon_0 + U$, where the spin current I_S increases sharply. It is obvious for the case of antiparallel alignment that the spin current shows a basin-like characteristic in figure 2(b). In addition, the effects of the polarizations on the spin current in parallel and antiparallel configurations [7] are also reproduced in our calculations.

Next, we investigate the spin-polarized transport in an FM–CDQD–FM system. Compared with the FM–QD–FM, some novel and different phenomena are presented. (1) For the case of parallel alignment, the electrical current I_C shows a resonant peak at the bias voltage of about 1.6 eV instead of the two step behaviors observed in previous studies [5], then decreases exponentially and gradually approaches a constant with the bias voltage increasing (as shown in figure 3(a)). (2) The spin current presents a resonant peak corresponding to the bias voltage 1.0 eV for spin-polarized transport through both the parallel and antiparallel configurations (figure 3(b)). It is noticed that, with the orientation of magnetization in the two electrodes switching from parallel to antiparallel, at the bias voltage lower than 1.6 eV the amplitude of spin current is enhanced; while at the bias voltage higher than 1.6 eV the spin current is reduced and then keeps invariable. (3) In figure 4(a), for spin-polarized transport through the P configuration, the resonant peak of the spin current disappears at the polarization $p = 1.0$. (4) Moreover, it is found that in figure 4(b), in the case of antiparallel alignment, on the lower bias voltage side, the spin current enhances firstly at $p = 0.5$, and then decreases at $p = 0.7$, and the position of the resonant peak does not shift; however, on the higher bias voltage side, the larger the polarization p is, the smaller the spin current is; even at $p = 0.7$ the spin current declines to zero. These results suggest that, for spin-polarized transport in the FM–CDQD–FM system, when the two electrodes possess the AP magnetization, the spin current is uniquely tuned by the spin polarization of the electrode.

For the above results, the resonant peak characteristics may be understood from the coupling effect between the two QDs. When electrons tunnel between the two dots,

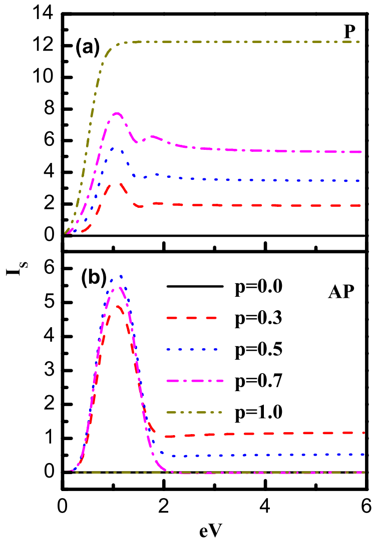

Figure 4. I_S–V curves for different spin polarizations p of the electrodes. The other parameters are taken the same as in figure 3.

single-particle levels in dot 1 and dot 2 couple with each other, and form two 'molecular' states [23–27] $\varepsilon_\pm = \varepsilon_i \pm 2V_d$, where there appears a gap $\Delta\varepsilon = 4V_d$ between them. The gap destroys the CB effect, and results in the electron transport in the FM–CDQD–FM system being mainly dependent on the cotunneling. Therefore, as spin-polarized transport in the FM–CDQD–FM system, the resonant peak determines the main features of the spin (electrical) current. Owing to the on-site Coulomb interaction, the resonant peak is located at $\varepsilon_i + U_i + 2V_d$, which is the exact position of the resonant peak, 1.6 eV, for the calculated parameters selected in figure 3.

The reduction of the electrical current for parallel configuration may be interplayed as follows: in the heterostructure that consists of a non-magnetic sandwiched structure with the ferromagnetic electrodes, the concept of spin accumulation becomes important. Once the spin diffusion length is larger than the size of the non-magnetic region, the information about the relative orientation of the electrodes' magnetization is mediated through the middle part. In the parallel configuration an applied bias voltage leads to a pile-up of spin in the non-magnetic center, since electrons with one type of spin (say spin up) are preferentially injected from the source electrode, while electrons with the other type of spin (spin down) are pulled out from the drain electrode. This piling up of spin splits the chemical potentials for spin-up and spin-down electrons in the center regime such that electrical transport through the whole device is reduced.

The increase of the polarization and bias voltage will lead to a novel change of the spin current in both configurations (P and AP) but for different reasons. Let us consider P and AP configurations separately. When the electrodes are in a P configuration (figure 4(a)), an increase of the polarization elevates the tunneling rates for the spin-up electrons and decreases the tunneling rates for the spin-down electrons. This will increase the spin-up current and decrease the spin-down current, thereby it will enhance the spin current through the system, which is equal to the difference between the spin-up and spin-down currents. In this limit where the Coulomb interaction prevents a double occupancy of the dots, there will be competition between tunneling processes for electrons with the spin-up current and those with the spin-down current. The characteristic time for these two processes, due to polarization, is unequal:

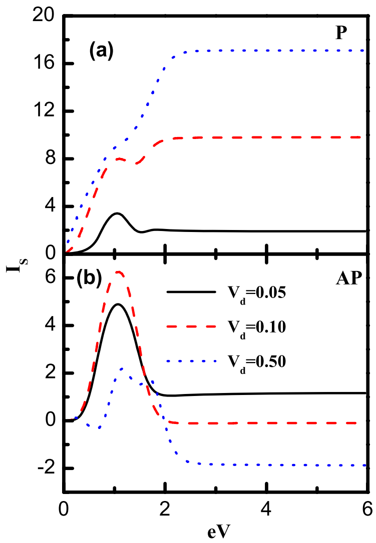

Figure 5. Spin current versus bias voltage for different interdot coupling V_d: (a) the P case; (b) the AP case. The other parameters are taken the same as in figure 3.

there is fast tunneling of spin-up electrons and slow tunneling of spin-down electrons through the system. The spin-down electrons, which spend a long time on the dot, block the fast tunneling of the spin-up electrons (so-called dynamical spin blockade) [16–18]. Eventually, for a large value of polarization, it leads to an effective bunching of tunneling events. Increasing the bias voltage above the Coulomb blockade regime, i.e. for $eV/2 > \tilde{\varepsilon} + U$, opens one more conducting channel and removes spin blockade. In this regime, spin-up and spin-down electrons are tunneling through the different channels and there is no more competition between these two tunneling events. This leads to a reduction of the spin current after the bias voltage is higher than a certain value.

The situation is completely different in the AP configuration (figure 4(b)). An increase of the polarization enhances the spin-down electron tunneling rates but suppresses the spin-up electron tunneling rates. An electron with the spin up, which has tunneled from the left electrode into the QD, remains there for a long time because the tunneling rate is reduced by the polarization. This decreases the spin-up current. An increase of the polarization also decreases the spin-down current because it reduces the probability for tunneling of the spin-down electrons into the QD. This will decrease the total current through the system. The enhancement of the spin current in the AP configuration is due to the asymmetry in the tunneling rates into and out of the QDs (but) for each spin separately. For large voltage, both conducting channels become available, which results in reduction of the spin current compared with the Coulomb blockade regime.

4. Resonant tunneling modulated by the interdot coupling effect

Furthermore, in order to explore the effect of the interdot coupling V_d on spin-polarized transport in the FM–CDQD–FM nanostructure, in figure 5 the spin currents are plotted with different V_d. The results show that, in the parallel configuration, the spin current is advanced, and the main characteristics of the curves are gradually varied from resonant to step-like with the interdot coupling V_d strengthened (figure 5(a)). It must originate from the two independent dots being closely correlated with the enhancement of the interdot coupling V_d, where at a strong enough interdot coupling V_d the two dots will be incorporated into one dot [28]. This indicates that the behavior for spin-polarized transport in the FM–CDQD–FM system resembles that in the FM–QD–FM system when a strong enough interdot coupling is applied. More interestingly, in the antiparallel configuration (figure 5(b)), except that the spin current curves still preserve the resonant properties with increasing the interdot coupling V_d, there exhibit some novel peculiarities, such as, for $V_d = 0.1$ the position of the resonant peak of the spin current is unchanged, but its amplitude is advanced at low bias voltage and is decreased at bias voltage higher than 2.0; for $V_d = 0.5$ the resonant peak is split into two peaks corresponding to the positions of 1.0 and 2.0, respectively, and its amplitude declines holistically; at bias voltage about 2.0 the sign of the spin current is reversed from positive to negative. These properties can be understood from the tunneling degree being the direct ratio of the energy difference between the bonding and antibonding states of a covalent-like bond system [19]. For $V_d = 0.5$, there comes into being a covalent-like bond between the two dots, bringing the electron to tend to locate in a single QD, thereby the spin current declines holistically. At the same time, the energy split is $\Delta\varepsilon = [(\varepsilon_1 - \varepsilon_2)^2 + (2V_d)^2]^{1/2}$; there are two resonant energy levels at the positions of 1.0 and 2.0, respectively.

It is clearly found from the above results that under the modulation of the interdot coupling V_d the spin current has quite different behaviors in parallel and antiparallel configurations. The difference for spin-polarized transport through the P and AP configuration may be caused by the different magnitude and direction of the quantum-dot spin for the two structures [9], which is determined by the interplay of two processes: non-equilibrium spin accumulation due to spin injection from the electrodes, and spin precession due to an exchange field generated by the tunnel coupling to spin-polarized electrodes [29]. In the parallel configuration the more spin-up electron injects into dot 1 from the left electrode, while the more spin-up electron migrates to the right electrode from dot 2. However, in the antiparallel configuration, in both dot 1 and dot 2 the spin-up electrons are accumulated. As a result, electrical current is increased as the magnetization of electrodes changes from parallel to antiparallel.

Finally, it should be pointed out that spin-polarized transport in the configuration with the center part including two dots in parallel or in the higher order tunneling regime may display some complicated behaviors. Thus, the peculiarities of spin-polarized transport in these systems need further investigation.

5. Conclusions

By means of the Keldysh non-equilibrium Green functions, we have investigated the spin-polarized transport properties through a FM–CDQD–FM system with a series coupled double QD. The results show that compared with the steplike or basin-like behaviors of the spin (electrical) current in the FM–QD–FM system [7] the resonant tunneling determines the main features of the spin (electrical) current in the FM–CDQD–FM system, in particular for the spin current. This means that the FM–CDQD–FM system is a more feasible candidate for the quantum computing devices than the FM–QD–FM. Furthermore, it is also found that spin-polarized transport in the system is effectively modulated by the coupling strength between two dots and by the orientation of the magnetization and the spin polarization of the electrodes. In particular, in the antiparallel configuration, with augmentation of the interdot coupling V_d, the position of the resonant peak of the spin current is unchanged, but its amplitude is modulated appropriately; even for $V_d = 0.5$ the resonant peak is split. In addition, it is found that the effect of the spin polarization of the electrodes on spin current becomes a bit complicated in the case of antiparallel alignment. When $p = 0$ and 1 the spin current is zero, while for $p \neq 0, 1$, on the lower bias voltage side, the spin current enhances firstly at $p = 0.5$, and then decreases at $p = 0.7$, but the position of the resonant peak does not shift. These results may indicate an effective approach for tunable spintronic devices.

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References

[1] Prinz G A 1998 *Science* **282** 1660
[2] Recher P, Loss D and Levy J 2001 *MQC2 2000: Proc. Macroscopic Quantum Coherence and Quantum Computing* ed D Averin, B Ruggiero and P Silvestrini (New York: Kluwer–Academic/Plenum)
[3] Sergueev N, Sun Q-F, Guo H, Wang B G and Wang J 2002 *Phys. Rev.* B **65** 165303
[4] Martinek J, Barnas J, Fert A, Maekawa S and Schon G 2003 *J. Appl. Phys.* **93** 8265
[5] Rudziñski W, Barnas J, Swirkowicz R and Wilczyñski M 2005 *Phys. Rev.* B **71** 205307
[6] Weymann I and Barnas J 2005 *Eur. Phys. J.* B **46** 289–99
[7] Mu H-F, Su G and Zheng Q-R 2006 *Phys. Rev.* B **73** 054414
[8] Swirkowicz R, Wilczynski M, Wawrzyniak M and Barnas J 2006 *Phys. Rev.* B **73** 193312
[9] Braun M, König J and Martinek J 2006 *Phys. Rev.* B **74** 075328
[10] Loss D and DiVincenzo D P 1998 *Phys. Rev.* A **57** 120
[11] Sukhorukov E V, Burkard G and Loss D 2001 *Phys. Rev.* B **63** 125315
[12] Engel H A and Loss D 2004 *Phys. Rev. Lett.* **93** 136602
[13] Thielmann A, Hettler M H, König J and Schön G 2005 *Phys. Rev. Lett.* **95** 146806
[14] Belzig W 2005 *Phys. Rev.* B **71** 161301(R)
[15] Weymann I, Barnas J, König J, Martinek J and Schön G 2005 *Phys. Rev.* B **72** 113301
Weymann I, König J, Martinek J, Barnas J and Schön G 2005 *Phys. Rev.* B **72** 115334
[16] Maekawa S 2004 *J. Magn. Magn. Mater.* **272–276** 1459(E)
[17] Meir Y and Wingreen N S 1992 *Phys. Rev. Lett.* **68** 2512
Cottet A and Belzig W 2004 *Europhys. Lett.* **66** 405
Cottet A, Belzig W and Bruder C 2004 *Phys. Rev. Lett.* **92** 206801
Cottet A, Belzig W and Bruder C 2004 *Phys. Rev.* B **70** 115315
[18] Jauho A P, Wingreen N S and Meir Y 1994 *Phys. Rev.* B **50** 5528
Haug H and Jauho A-P 1998 *Quantum Kinetics in Transport and Optics of Semiconductors* (Berlin: Springer)
[19] Martinek J, Sindel M, Borda L, Barnas' J, König J, Schön G and von Delft J 2003 *Phys. Rev. Lett.* **91** 247202
[20] Kashcheyevs V, Aharony A and Entin-Wohlman O 2006 *Phys. Rev.* B **73** 125338
[21] Lacroix C 1981 *J. Phys. F: Met. Phys.* **11** 2389
[22] Kashcheyevs V, Schiller A, Aharony A and Entin-Wohlman O 2007 *Phys. Rev.* B **75** 115313
[23] Pioro-Ladriére M, Ciorga M, Lapointe J, Zawadzki P, Korkusin'ski M, Hawrylak P and Sachrajda A S 2003 *Phys. Rev. Lett.* **91** 026803
[24] Yoffe D A 2001 *Adv. Phys.* **50** 1
[25] Laraa G A, Orellanab P A, Ya'ñeza J M and Anda E V 2005 *Solid State Commun.* **136** 323–7
[26] Brusheim P and Xu H Q 2006 *Phys. Rev.* B **73** 045313
[27] Zitko R, Bonca J, Ramsak A and Rejec T 2006 *Phys. Rev.* B **73** 153307
[28] Maekawa S and Shinjo T (ed) 2002 *Spin Dependent Transport in Magnetic Nanostructures, Advances in Condensed Matter Science* (London: Taylor and Francis)
[29] König J and Martinek J 2003 *Phys. Rev. Lett.* **90** 166602
Braun M, König J and Martinek J 2004 *Phys. Rev.* B **70** 195345