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Resonant spin transport through a double quantum-dot system with ferromagnetic electrodes and tunable magnetic field

Abstract*.*
The resonant spin transport in a double quantum-dot (QD) system with ferromagnetic electrodes and tunable magnetic field was investigated by non-equilibrium Green function method. It is clearly seen that, in contrast to the steplike or baisnlike behaviors of the spin (electrical) current in the single quantum dot with ferromagnetic electrodes system [Phys. Rev. B 73, 054414 (2006)], the resonant tunneling determines the main features of the spin (electrical) current in the double quantum-dot with ferromagnetic electrodes system. It should 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. On the other hand, for two identified QDs, the tunable external magnetic field has profound effect on the current for different spins in the QDs. Especially for different magnetic fields, the threshold voltage for up spin shifts higher as the difference increasing, while it for down spin is lower. It is suggested that the system is a favorable candidate for spintronic devices or external field detectors.

Streszczenie. *Analizowano przewodzenie spinowe systemów z podwójnym kwantowaniem QS z elektrodami ferromagnetycznymi i strojonym polem magnetycznym. Wykorzystano funkcję Greena. Właściwości przewodzenia są głównie zdeterminowane przez rezonansowe tunelowanie spinowe. Zbada no wpływ pola magnetycznego na różne struktury. (****Mechanizm przewodzenia z rezonansem spinowym z w systemie z podwójną kropką kwantowa, elektrodami ferromagnetycznymi i zmiennym polem magnetycznym****)*

Keywords: resonant spin transport; coupled-double-quantum-dot (CDQD); ferromagnetic electrodes; tunable magnetic field
Słowa kluczowe: rezonansowe przewodzenie spiniowe, kropka kwantowa, tunelowanie.

Introduction

Because spintronics [1-2] hold promise for quantum computing, spin, as another character of electron, has been investigated extensively. One of the key problems is how to effectively control and manipulate spin, and then obtain spin polarization as well as spin-polarized currents. Meanwhile, due to the advance of nanotechnology one of the most important spin-based electronic devices—a mesoscopic quantum dot (QD) system are fabricated, in which the electron transport is restricted in three dimensions and the spin coherence time for electrons or nuclei is relatively long [3-4] Hence, there have been increasing interests in spin transport in the QD systems [5] . Recently, a series of research also have demonstrated that spin transport in QD system obviously present novel properties. It has been shown theoretically [6] and demonstrated experimentally [7] that a QD system will function as a phase-coherent spin pump in the presence of sizable Zeeman splitting. Mu et al. [8] 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. Very recently, Spin-dependent transport through two coupled single-level quantum dots weakly connected to ferromagnetic leads with collinear magnetizations is considered theoretically. Negative tunnel magnetoresistance have been found in the case of serial geometries [9].

However, the previous works mainly focus on the spin-polarized transport in the magnetic nanostructure consisted of only one QD. To date, little work pays attention to the investigation of the spin-polarized transport in magnetic nanostructure with a coupled-double-quantum-dot (CDQD). The CDQD with ferromagnetic electrodes system possesses two most prominent merits: (1) Electrons with different spins experience effectively modulated potentials. (2) Compare 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 transporting in it.

So in this paper, the characteristics for spin-polarized transport in CDQD (in serial) with ferromagnetic electrodes (FM-CDQD-FM) system (see Fig.1a) have been symmetrically studied. The results show that, in contrast to the steplike or baisnlike behaviors of the spin (electrical) current in the FM-QD-FM system [8], the resonant tunneling determines the main features of the spin (electrical) current in the FM-CDQD-FM system. Furthermore, the effects of the orientation of the magnetization and the spin polarization of the electrodes on spin-polarized transport have been discussed. In addition, it is another simplest mean to manipulate its spin when electron transports in magnetic field due to dependence of the Zeeman effect on spins. But in single-dot system the occurrence of spin polarization is in the presence of stronger magnetic field [11]. Accordingly, its application is declined. In our work, at zero polarization, using a coupled double quantum-dot system in series, which has been experimentally fabricated, we found that the magnetic field which induces spin polarization is only the tenth of that applied on single-dot system.

Theoretical models

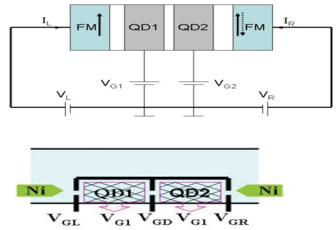

Fig.1. (a) Schematic diagram of the model.

For a central part double QDs is in serial, the energy bands of the single-level dots are sketched in Fig. 1b. If the left (L) and right (R) electrodes are connected with the bias voltage V and 0, respectively and the single-particle state is above the equilibrium Fermi energy of the electrodes [10,12-16], the whole system can be described by a Hamiltonian of the general form $H = H_\beta + H_d + H_t$, where

H_β ($\beta = L, R$) describe the left (L) and right (R) electrodes as reservoirs of noninteracting quasiparticles, H_d is the dots Hamiltonian, and tunneling processes between the electrodes and dots, and between the dots are included in H_t. Therefore, the main difference of the Hamiltonian between the double quantum-dot (QD) system with ferromagnetic electrodes and tunable magnetic field and single QD system is the tunneling term H_t. For the double QDs system this term can be expressed as $H_t = H_t^0 + H_t^{'}$, and

(1) $$H_t^0 = \sum_{k,\sigma} \widetilde{V}_k^L d_{1\sigma}^+ c_{k\sigma} + \sum_{p,\sigma} \widetilde{V}_{p\sigma}^R d_{2\sigma}^+ c_{p\sigma} + H.c$$

where $\widetilde{V}_k^L = V_k^L$, $\widetilde{V}_{p\sigma}^R = V_p^R (\cos\frac{\theta}{2} - \sigma \sin\frac{\theta}{2})$; whereas the second term corresponds to tunneling between the two dots

(2) $$H_t^{'} = \sum_\sigma V_d d_{1\sigma}^+ d_{2\sigma} + H.c.$$

Here, $c_{k\sigma}^+$ ($c_{k\sigma}$) and $c_{p\sigma}^+$ ($c_{p\sigma}$) are the creation (annihilation) operators of the electrons in the left and right FM electrodes; $d_{i\sigma}^+$ ($d_{i\sigma}$) ($i = 1,2$) 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^L (V_p^R) and V_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_L of the left FM and M_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 $I_S = I_{i\beta}^\uparrow - I_{i\beta}^\downarrow$ [17]. Adopting the Keldysh formalism [18], the currents carried by spin-up or -down electrons from the electrode L(R) into the dot 1(2) can be calculated

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

with the lesser Green functions $\langle\langle c_{k(p)\sigma} | d_{i\sigma}^+ \rangle\rangle^<$ and $\langle\langle d_{i\sigma} | c_{k(p)\sigma}^+ \rangle\rangle^<$. By applying the Langrenth theorem $[AB]^< = A^r B^< + A^< B^a$ [19] and Fourier transform, we may obtain the following equation:

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

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 $g_{k(p)\sigma}^< = 2\pi i f_{L(R)}(\varepsilon) \delta(\varepsilon - \varepsilon_{k(p)}^\beta - \sigma M_\beta)$ and $g_{k(p)\sigma}^r = (\varepsilon - \varepsilon_{k(p)}^\beta - \sigma M_\beta + i\eta)^{-1}$. The parameters ε_k^L and ε_p^R are the single-electron energies in the FM electrodes.

For the equations 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 [20-21], however, when the temperature is sufficiently higher than the Kondo temperature, they will be valid for studying the present double QDs system with a higher temperature [22]. Recently it is also reported that at high-enough temperature the decoupling approximations agree to the relevant order with direct perturbation expansions [23]. By using the EOM and the Hartree-Fock approximation without considering the Kondo effect, the retarded (lesser) Green function can be written as:

(5) $$G_{i\sigma}^r(\varepsilon) = \langle\langle d_{i\sigma} | d_{i\sigma}^+ \rangle\rangle_\varepsilon^r = \frac{G_{i0\varepsilon}^r}{1 - |V_d|^2 G_{i0\varepsilon}^r G_{\bar{i}0\varepsilon}^r}$$

(6) $$G_{i\sigma}^< = \langle\langle d_{i\sigma} | d_{i\sigma}^+ \rangle\rangle^< = 2i \frac{f_\beta(\varepsilon)\Gamma_{\beta\sigma}(\varepsilon) - 2 f_{\bar{\beta}}(\varepsilon)|V_d|^2 \operatorname{Im} G_{\bar{i}0\varepsilon}^r}{\Gamma_{\beta\sigma}(\varepsilon) - 2|V_d|^2 \operatorname{Im} G_{\bar{i}0\varepsilon}^r} \operatorname{Im} G_{i\sigma}^r$$

($\bar{i} = 1,2$. If i=1, $\bar{i}$ is equal to 2; vice versa)

where $f_\beta(\varepsilon) = \{\exp[(\varepsilon - \mu_\beta)/k_B T] + 1\}^{-1}$ ($\mu_L = V, \mu_R = 0$) 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

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

where ε_i is the single-electron energy level in the ith dot, which can be tuned by gate voltage V_{Gi} [24]; U_i is the on-site Coulomb repulsion in the ith dot; $n_{i\sigma} = d_i^+ d_i$ is the average occupation in the ith dot, which can be got self-consistently by means of the relation $n_{i\sigma} = \frac{1}{2\pi} \int \operatorname{Im} \langle\langle d_{i\sigma} | d_{i\sigma}^+ \rangle\rangle^< d\varepsilon$.

The spin-dependent coupling strengths to the ferromagnetic electrode β are described as $\Gamma_{\beta\sigma}(\varepsilon) = 2\pi \sum_{k(p)\sigma} |\widetilde{V}_{k(p)}^\beta|^2 \delta(\varepsilon - \varepsilon_{k(p)}^\beta - \sigma M_\beta)$. Further, in the wide band limit, the energy dependence of $\Gamma_{\beta\sigma}(\varepsilon)$ can be neglect, evaluating it at $\varepsilon = E_F$. Then the spin-dependent coupling strengths are related to the spin polarization of the electrodes by $p_\beta = (\Gamma_{\beta\uparrow} - \Gamma_{\beta\downarrow})/\Gamma_0$, where $\Gamma_0 \equiv \Gamma_{\beta\uparrow} + \Gamma_{\beta\downarrow}$. Under these considerations and the Dyson equations $\langle\langle c_{k(p)\sigma} | d_{i\sigma}^+ \rangle\rangle^< = \widetilde{V}_{k(p)}^{L(R)} \langle\langle d_{i\sigma} | d_{i\sigma}^+ \rangle\rangle^< g_{k(p)\sigma}^r + \widetilde{V}_{k(p)}^{L(R)} \langle\langle d_{i\sigma} | d_{i\sigma}^+ \rangle\rangle^{r*} g_{k(p)\sigma}^<$, we finally get

(8) $$I_{i\beta}^\sigma = -\frac{4e}{h} \int \frac{\Gamma_{\beta\sigma} |V_d|^2 \operatorname{Im} G_{\bar{i}0\varepsilon}^r}{\Gamma_{\beta\sigma} - 2|V_d|^2 \operatorname{Im} G_{\bar{i}0\varepsilon}^r} \operatorname{Im} G_{i\sigma}^r(\varepsilon)[f_L(\varepsilon) - f_R(\varepsilon)] d\varepsilon$$

In these calculations, it is considered 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 ($p_L = p_R \equiv p$), there are $\Gamma_{L\uparrow} = \Gamma_{R\uparrow} = (1+p)\Gamma_0/2$ and $\Gamma_{L\downarrow} = \Gamma_{R\downarrow} = (1-p)\Gamma_0/2$; whereas the AP case ($p_L = -p_R \equiv p$) yields $\Gamma_{L\uparrow} = \Gamma_{R\downarrow} = (1+p)\Gamma_0/2$, $\Gamma_{L\downarrow} = \Gamma_{R\uparrow} = (1-p)\Gamma_0/2$. In our calculation, the two dots are completely identical with using $10^{-2} e/h$ as the unit, which $\varepsilon_1 = \varepsilon_2 = 0.5$ and $U_1 = U_2 = 1.0$, and the other parameters are set $\Gamma_0 = 0.1$ and $k_B T = 0.125$.

Results and discussions

Firstly, we investigate the spin-polarized transport in a double quantum-dot with ferromagnetic electrodes system. Compared with single quantum-dot with ferromagnetic electrodes system, 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 about 1.6 eV instead of the two-step behaviors observed in previous studies [25], then decreases exponentially and gradually approaches to a constant with the bias voltage increasing (as shown in Fig.2(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 (Fig. 2(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 Fig. 3(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 Fig.3 (b), in the case of antiparallel alignment, in 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, in 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 double quantum-dot with ferromagnetic electrodes system, when the two electrodes possess the AP magnetization, the spin current is uniquely tuned by the spin polarization of the electrode.

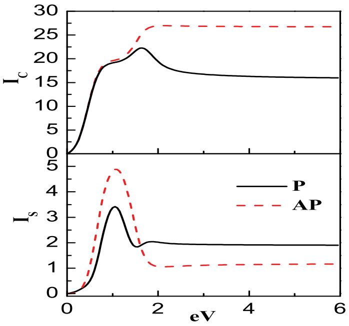

Fig.2. Bias dependence of the tunnel current I_C (a) and the spin current Is (b) of double quantum-dot (QD) with ferromagnetic electrodes system.

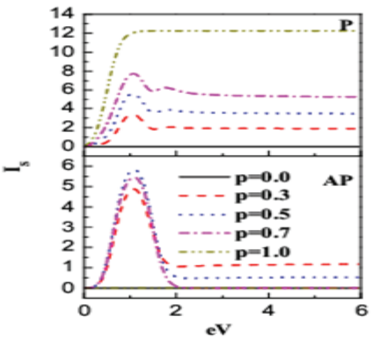

Fig.3. I_S-V curves for different spin polarization p of the electrodes.

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, single-particle levels in dot1 and dot2 couple each other, and form two “molecular” states [24,26-29] $\varepsilon_{\pm} = \varepsilon_i \pm 2V_d$, where appears a gap $\Delta\varepsilon = 4V_d$ between them. The gap destroys the CB effect, and results in that the electron transport in the double quantum-dot with ferromagnetic electrodes system is mainly dependent on the cotunneling. Therefore, as spin-polarized transport in the double quantum-dot with ferromagnetic electrodes system, the resonant peak determines the main features of the spin (electrical) current. Owing to the on-site Coulomb interaction, the resonant peak locates 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 Fig. 2.

The reduction of the electrical current for parallel configuration may be interplayed as follows: in the heterostructure that consists of a nonmagnetic 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 nonmagnetic 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 nonmagnetic 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 [Fig. 3(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: 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) [17]–[19]. 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 being higher than a certain value.

The situation is completely different in the AP configuration (Fig. 3(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 a 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 comparing with the Coulomb blockade regime.

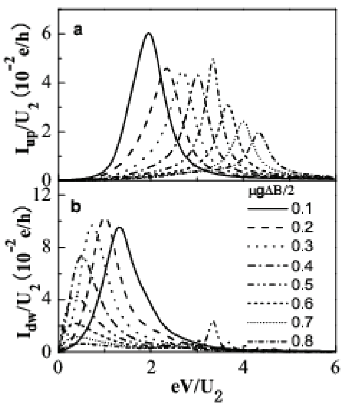

Fig.4. I_s-V curves for the double quantum-dot system consisting of two identified dots with various differences of magnetic fields applied on dot 1 and 2. (a) up spin (b) down spin.

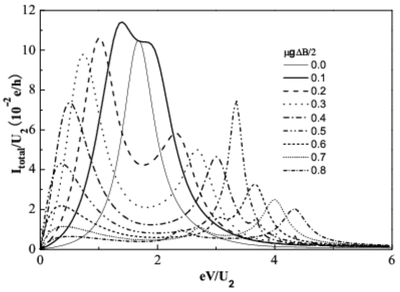

Fig.5. The total current curves for up spin and down spin electron transport in the double quantum-dot system consisting of two identified dots with various magnetic fields

To realize the spin controllable, another useful tool is external magnetic field. Therefore at the polarization p=0.0, the up spin and down spin currents versus bias voltage with several differences of magnetic fields applied on dot 1 and 2 are shown in figure4. In Fig. 4(a) one can see that with the difference increasing the resonant peaks of up spin current are shift to higher bias voltage. The results indicate that for up spin electron the threshold voltage is elevated. While in Fig. 4(b) one can find that with the gap of magnetic field between two dots adding the resonant peaks of down spin current are moved to lower bias voltage. It demonstrates that the threshold voltage of down spin electron is depressed. In a word, the above results suggest that in the presence of the tunable magnetic field the strength of the spin polarization is well controllable and manipulatable by simply varying the bias. This also implies that the total current ($I_{total} = I_{up} + I_{dw}$) possess the interesting behaviors with the changeable magnetic fields. So in Figure 5 the total current curves for up spin and down spin electron transport in the double quantum-dot system consisting of two identified dots with various magnetic fields are plotted. It is found that if the same magnetic fields are applied on the two dots (shown as $\mu g\Delta B/2 = 0.0$) one resonant peak is presented in the current curve. With the difference between the magnetic fields added on the two dots elevated the resonant peak split into two peaks. For $\mu g\Delta B/2$ smaller than 0.5, the resonant peak at the lower bias is higher than that at higher bias, whereas for $\mu g\Delta B/2$ bigger than 0.5, the resonant peak at the lower bias is suppressed lower than that at higher bias. This result suggests that for $\mu g\Delta B/2$ smaller than 0.5 the spin electron inclines to occupy the lower level, but for $\mu g\Delta B/2$ bigger than 0.5 it likes to occupy the higher level. In other word, $\mu g\Delta B/2 = 0.5$ is a critical point. The reason may be as following: for smaller $\mu g\Delta B/2$ the up spin electron into the double quantum-dot and the levels of two dots $\varepsilon_1, \varepsilon_2$ are aligned. However, with the difference more than 0.5 the down spin electron into the double quantum-dot and the levels of two dots $\varepsilon_1, \varepsilon_2 + U$ are aligned. Thereby in the controllable system a critical magnetic field exists. The fascinating phenomena imply it can be as a favorable spin-selected device.

Conclusions

In summary, we have proposed a simple and practical method to generate the spin polarized electrons in double QDs system by utilizing the ferromagnetic electrodes and tunable magnetic fields. The results show that compared with the steplike or baisnlike behaviors of the spin (electrical) current in the single quantum dot with ferromagnetic electrodes system [8], the resonant tunneling determines the main features of the spin (electrical) current in the double quantum dots with ferromagnetic electrodes system, in particular, for the spin current. This means that the double quantum dots with ferromagnetic electrodes system is a more feasible candidate for the quantum computing devices than the single quantum dot with ferromagnetic electrodes. 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 $p \neq 0,1$, in 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. Furthermore, at p=0 for the double QDs system, in contrast to spin transport in single-dot system, the spin electrons are easily polarized, and a large spin polarization can be produced in presence of smaller magnetic fields. The above novel phenomena indicate that it can be adopted to mark spin in the qubit used in quantum computing [30]. Or, it can be a candidate of a magnetic field detector based on its sensitiveness to the external magnetic fields.

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