A spin switch device based on a triple quantum dots superlattice using the Dicke effect*

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Spin-dependent transport in a triple quantum dots superlattice system with a bridge coupling to two leads is studied. There exists an odd–even parity oscillation of spin polarization at the central dot level $\varepsilon_c = 0$ due to the spin-dependent Fano and Dicke effects induced by the quantum interference and the Rashba spin–orbit interaction. In the case of even numbers of triple quantum dots, the device can be used as a spin switch by tuning the energy difference h between the energies of the central and the lateral dots. These results may be helpful to design and fabricate practical spintronic devices.

Keywords: spin polarization, quantum dots

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1. Introduction

Recently, the spin degree of freedom in quantum dots (QDs) has received increased interest because of its potential application in spintronic devices.[1−9] How to achieve the injection, modulation, and detection of electron spin in mesoscopic systems is the main challenge in the field of spintronics. In 1990, Datta and Das proposed a spin transistor based on the Rashba spin–orbit interaction (RSOI) in a semiconductor sandwiched between two ferromagnetic leads.[10] Since then, a great deal of theoretical and experimental work has been devoted to controlling the electron spin via the electric field due to the difficulties in manipulating the electron spin in practical applications by using magnetic materials or a magnetic field. Sun *et al.* have derived a general second quantization form for the RSOI in the spectral space, which is convenient for handling the RSOI and the electron–electron interactions in QDs systems.[5]

The latest advances in nanotechnology make it possible to fabricate multi-QD structures. Hence, many experimental and theoretical studies concentrate on electron transport through various multi-QD systems. For example, the specific odd–even parity oscillations of conductance have been discussed for systems of an embedded QDs array and of a QDs array side-coupled to a quantum wire or an Aharonov–Bohm (AB) ring.[11−13] The Dicke effect in electron transport through double or triple QDs and through a quantum wire with side-coupled QDs has also been studied.[14−23] Recently, Ojeda *et al.* have proposed a new spin filter device based on a quantum dot array coupled to leads with static magnetic fields applied on the QDs.[11] However, the studies of the spin-polarized odd–even parity oscillations[8] and the Dicke effect in QD configurations consisting of an arbitrary number of QDs are not enough.

In this paper, we investigate the spin-polarized transport through a triple QDs superlattice considering a bridge coupling between the two leads. The system is similar to a triple QDs superlattice embedded in one arm of an AB ring, as shown schematically in Fig. 1. We show that the system can be used as a spin switch device by controlling the Fano and the Dicke effects.

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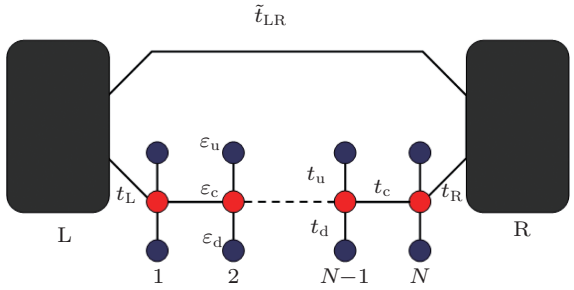


Fig. 1. (colour online) Schematic plot of a triple quantum dots superlattice coupled to two leads with a bridge coupling.

2. Model and method

The device is described by the following noninteracting Anderson Hamiltonian:

$$H = H_{\rm L} + H_{\rm D} + H_{\rm T},$$

where $H_{\rm L} = \sum_{k\alpha\sigma} \varepsilon_{k\alpha} a^{\dagger}_{k\alpha\sigma} a_{k\alpha\sigma}$ describes the lead indexed by α ($\alpha = {\rm L}, {\rm R}$), while $a^{\dagger}_{k\alpha\sigma}$ and $a_{k\alpha\sigma}$ form an orthogonal set of creation and annihilation operators in lead α, and $\varepsilon_{k\alpha}$ is the corresponding single-particle energy. The triple QDs superlattice is described by the Hamiltonian

$$\begin{aligned} H_{\rm D} = & \sum_{i\sigma} (\varepsilon_{\rm u} u^{\dagger}_{i\sigma} u_{i\sigma} + \varepsilon_{\rm c} c^{\dagger}_{i\sigma} c_{i\sigma} + \varepsilon_{\rm d} d^{\dagger}_{i\sigma} d_{i\sigma}) \\ & + \sum_{i\sigma} (t_{\rm c} c_{(i+1)\sigma} c_{i\sigma} + t_{\rm u} u^{\dagger}_{i\sigma} c_{i\sigma} + t_{\rm d} d^{\dagger}_{i\sigma} c_{i\sigma}) \\ & + {\rm H.c.}, \end{aligned} \tag{1}$$

where $u^{\dagger}_{i\sigma}$, $c^{\dagger}_{i\sigma}$, and $d^{\dagger}_{i\sigma}$ ($u_{i\sigma}$, $c_{i\sigma}$, and $d_{i\sigma}$) create (annihilate) an electron in the upper, the central, and the down dots with spin σ and energies $\varepsilon_{\rm u}$, $\varepsilon_{\rm c}$, and $\varepsilon_{\rm d}$, respectively; $t_{\rm c}$ is the interdot tunneling coupling between the i-th and the $(i+1)$-th dots in the central QDs array; and $t_{\rm u}$ ($t_{\rm d}$) is the tunneling coupling between the central and the upper (down) dots. The tunneling processes between the two leads and between the leads and the QDs superlattice are taken into account via the tunneling Hamiltonian

$$\begin{aligned} H_{\rm T} = & \sum_{k\sigma} (\tilde{t}_{\rm LR} a^{\dagger}_{k{\rm L}\sigma} a_{k{\rm R}\sigma} + t_{\rm L} a^{\dagger}_{k{\rm L}\sigma} c_{1\sigma} + t_{\rm R} a^{\dagger}_{k{\rm R}\sigma} c_{N\sigma}) \\ & + {\rm H.c.}, \end{aligned} \tag{2}$$

where $\tilde{t}_{\rm LR} = t_{\rm LR}\, {\rm e}^{-{\rm i}\sigma\varphi_{\rm R}}\, {\rm e}^{{\rm i}\phi}$, $t_{\rm L}$ ($t_{\rm R}$) is the tunneling coupling between the left (right) lead and the QDs superlattice. As the RSOI exists in one arm of the AB ring and the magnetic flux Φ threads through the AB ring, an extra spin-dependent phase $-\sigma\varphi_{\rm R}$ and a familiar spin-independent phase factor $\phi = 2\pi\Phi/\Phi_0$ are added to the tunneling coupling $t_{\rm LR}$ between the two leads.

We calculate quantum transport properties of the system using the standard nonequilibrium Green's function formalism. The Green's functions are identical to those in Ref. [5] except that they are all $(3N+2)\times(3N+2)$ matrices in the present case. The retarded Green function can be calculated using the Dyson equation $\boldsymbol{G}^{\rm r}_{\sigma} = \boldsymbol{g}^{\rm r}_{\sigma} + \boldsymbol{g}^{\rm r}_{\sigma}\boldsymbol{\Sigma}^{\rm r}_{\sigma}\boldsymbol{G}^{\rm r}_{\sigma}$, where $\boldsymbol{g}^{\rm r}_{\sigma}$ is the Green's function of free electron in the leads and the QDs, and $\boldsymbol{\Sigma}^{\rm r}_{\sigma}$ is the retarded self-energy. After solving $\boldsymbol{G}^{\rm r}_{\sigma}$, the lesser Green's function $\boldsymbol{G}^{<}_{\sigma}$ can be obtained straightforwardly from the standard Keldysh equation $\boldsymbol{G}^{<}_{\sigma}(\omega) = \boldsymbol{G}^{\rm r}_{\sigma}(\omega)\boldsymbol{\Sigma}^{<}_{\sigma}\boldsymbol{G}^{a}_{\sigma}(\omega)$, where $\boldsymbol{\Sigma}^{<}_{\sigma}$ is the lesser self-energy, and $\boldsymbol{G}^{a}_{\sigma} = (\boldsymbol{G}^{\rm r}_{\sigma})^{\dagger}$ is the advanced Green's function. The spin-dependent current flowing from the left lead into the device can be derived as

$$I_{\sigma} = \frac{2e}{\hbar}\int \frac{{\rm d}\omega}{2\pi}\, {\rm Re}[\tilde{t}_{\rm LR} G^{<}_{{\rm RL}\sigma} + t_{\rm L} G^{<}_{1L\sigma}]. \tag{3}$$

The spin-dependent linear conductance and the spin polarization can be defined as $G_{\sigma} = {\rm d}I_{\sigma}/{\rm d}V\ |_{V=0}$ and $P = (G_{\uparrow} - G_{\downarrow})/(G_{\uparrow} + G_{\downarrow})$, respectively.

3. Results and discussion

In the following, we take $\rho = 1$, $k_{\rm B}T = 0.0001$, and all the tunneling matrix elements as constants $t_{\rm L} = t_{\rm R} = t_{\rm u} = t_{\rm c} = t_{\rm d} = 0.4$. The energies will be given in the units of parameter $\Gamma \equiv 2\pi\rho|t_{\rm L}|^2 \approx 1$. We set the site energies of the upper and the down dots as $\varepsilon_{\rm u} = \varepsilon_{\rm c} + h$ and $\varepsilon_{\rm d} = \varepsilon_{\rm c} - h$, respectively, where the asymmetry parameter h is the energy difference between the site energies of the central and the lateral dots.

Figure 2 displays the spin-dependent conductance as a function of the central dot level $\varepsilon_{\rm c}$ and the energy difference h for $t_{\rm LR} = 0.3$ with $\varphi_{\rm R} = \phi = \pi/2$. In the symmetric configuration ($h = 0$), the spin-dependent conductance shows two antiresonant peaks for $N = 1$. For larger values of N, the antiresonances evolve into antiresonant minibands due to the Fano effect which arises from the interference between the localized states of the QDs superlattice and the continuous states of the bridge coupling in our device. In the asymmetric configuration ($h \neq 0$), a narrow dip emerges in the conductance at $\varepsilon_{\rm c} = 0$ for a small value of h. This phenomenon resembles the Dicke resonance in optics, in which a strong narrow emission line appears when the distance between a pair of atoms is smaller than the wave length of the corresponding radiation. In our case, the energy difference h plays the

role of the distance between atoms. For increasing values of h, the dip evolves into a new antiresonant miniband, while the two side antiresonant minibands become more and more narrow and finally disappear for a very large value of h. This behavior is quite reasonable, with increasing h, the states of the upper and the down dots that are not coupled directly become more and more antilocalized and localized, respectively. In addition, the Fano antiresonances of the spin-up and the spin-down conductances have opposite Fano factors for $N = 1$ and $N = 3$ (odd numbers of triple QDs), while the curves of the spin-dependent conductance are symmetric with respect to $\varepsilon_c = 0$ for $N = 2$ and $N = 4$ (even numbers of triple QDs). It is important that the odd–even behavior of the spin-dependent conductance can result in an odd–even parity oscillation of spin polarization at $\varepsilon_c = 0$ for a finite value of h.

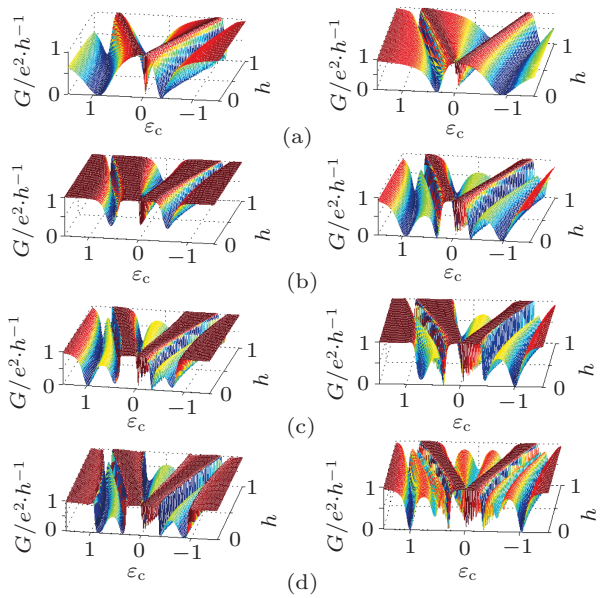


Fig. 2. (colour online) Spin-dependent conductances vs ε_c and h for (a) $N = 1$, (b) $N = 2$, (c) $N = 3$, and (d) $N = 4$ with $t_{LR} = 0.3$ and $\varphi_R = \phi = \pi/2$. Left and right panels correspond to spin-up and spin-down conductances, respectively.

In order to investigate the odd–even parity oscillation of spin polarization, we respectively plot the spin-dependent conductance and the spin polarization in Figs. 3 and 4 as a function of h and t_{LR} for $\varepsilon_c = 0$ and $\varphi_R = \phi = \pi/2$. In the case of $t_{LR} = 0$, because of the shut down of the bridge coupling, the antiresonance of the conductance rapidly becomes resonance with slightly increasing h for both the spin-up and spin-down electrons. In the case of $h = 0$, both the spin-up and spin-down conductances increase first and are followed by a slight reduction with a gradual opening of the bridge coupling, i.e., the gradual raising of t_{LR}. Then the transport current has no spin polarization at $\varepsilon_c = 0$, so $P = 0$ and $G_\uparrow = G_\downarrow$ if either one of the two parameters h and t_{LR} vanishes, as shown in Fig. 4. In Fig. 3, we also find that the spin-up or the spin-down electrons reach the fully destructive interference at $t_{LR} = 0.4$ with a small value of h for $N = 2$ and $N = 4$ (even numbers of triple QDs), so the spin polarization can reach 100%.

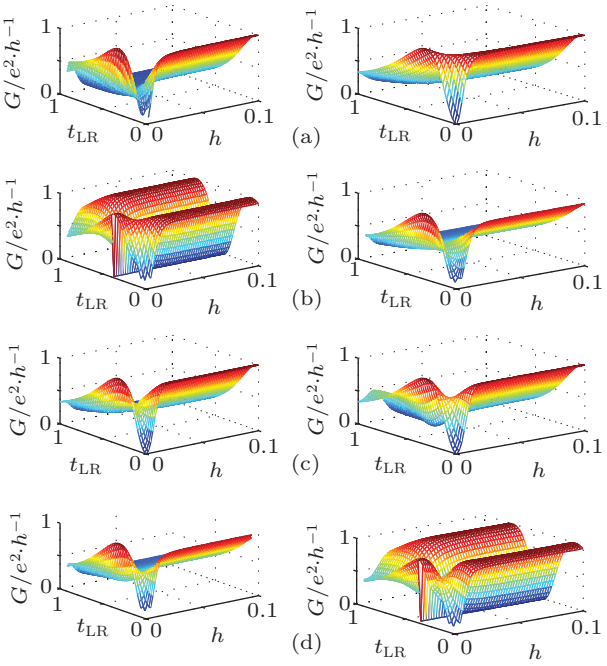


Fig. 3. (colour online) Spin-dependent conductances vs t_{LR} and h for (a) $N = 1$, (b) $N = 2$, (c) $N = 3$, and (d) $N = 4$ with $\varepsilon_c = 0$ and $\varphi_R = \phi = \pi/2$. Left and right panels correspond to spin-up and spin-down conductances, respectively.

The odd–even parity oscillation of spin polarization can be clearly observed in Fig. 4 as h increases, especially for $t_{LR} = 0.4$. Namely, the spin polarization vanishes for an odd number of triple QDs, while it emerges for an even number. In the case of an even N, the polarization abruptly emerges and reaches 100% at $t_{LR} = 0.4$ by changing a small amount of h from zero. This means that the spin switching mechanism can be realized by slightly adjusting h using the gate voltages on the lateral dots in the experiment. Moreover, the polarization strongly varies from a large positive value to a negative one by tuning N, that is, the directions of spin polarization can be switched and easily controlled by varying the number of triple QDs.

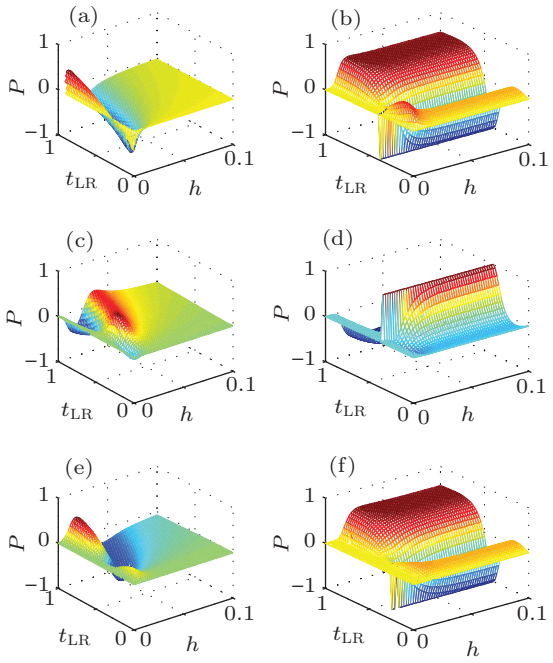


Fig. 4. (colour online) Spin polarization vs t_{LR} and h for (a) $N = 1$, (b) $N = 2$, (c) $N = 3$, (d) $N = 4$, (e) $N = 5$, and (f) $N = 6$. All parameters are the same as those of Fig. 3.

4. Conclusion

In summary, we have proposed a novel spin switch device based on spin-dependent Fano and Dicke effects in a triple QD superlattice by utilizing the RSOI and a bridge coupling between two leads. There exist odd–even parity oscillations of spin polarization at $\varepsilon_c = 0$ as the energy difference h between the energies of the central and the lateral dots increases. For an even number of triple QDs, the spin polarizations have a switching effect by adjusting the asymmetry parameter h using the gate voltages on the lateral QDs. The strength and the direction of spin polarization in the present device are easily controllable by varying the system parameters, which are experimentally accessible. These properties are interesting from a theoretical point of view, but also due to their potential technological applications.

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