Proposal for a correlation induced spin-current polarizer

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We propose a spin polarizer device composed of a quantum dot connected to the spin-polarized leads. The spin control of the current flowing through the device is entirely due to the Coulomb interactions present inside the dot. We show that the initial polarization present in the source lead can be reverted or suppressed just by manipulating the gate voltage acting on the dot; the presence of the external magnetic field is not required. The influence of the temperature and finite bias on the efficiency of the current spin switching effect is also discussed.

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I. INTRODUCTION

The idea of future electronics based on the spin degree of freedom instead of charge has emerged during the last years. The term "spintronics" is one of the most frequently used in modern solid state physics[1] in various aspects. Manipulation of the spin by electric field is an important problem met on the way to achieve a reasonable alternative to traditional charge-based semiconductor electronics. The early work of Datta and Das suggested the electrical control of the spin utilizing the Rashba spin-orbit interaction,[2] which has recently been experimentally realized[3] in a semiconductor heterostructure. Spin transport and gate control has also been realized in carbon nanotubes.[4,5] Recently, half-metallicity has been induced by external electric field applied to the graphene nanoribbon.[6]

In the present work, we focus on small semiconductor quantum dots (QDs) which offer better scalability and are compatible with present semiconductor technology. When operated by the gate voltage in the Coulomb blockade regime, such a QD acts as a single-electron transistor (SET).[7] We will show that in the presence of ferromagnetic leads, SET can invert the spin of the incoming current due to the Coulomb interactions inside the SET.

To date, many theoretical studies of interacting dots with ferromagnetic leads have been reported.[8–10] These ideas have been experimentally realized very recently.[11,12]

We show that in the vicinity of degeneracy points at the Hubbard resonances, where the spin-up and spin-down dot occupancies are equal, the interacting QD in the Coulomb blockade regime can serve as an effective spin polarizer. We predict two experimentally promising conditions for spin switching: (i) the effect is enhanced if the dot is asymmetrically coupled to the leads, an experimentally advantageous condition giving a possibility of different switching fields of the leads;[11,12] (ii) the current flowing into the dot should not be fully polarized because the mechanism of the control of spin polarization is due to the Coulomb interactions between electrons with opposite spins. Thus, within the presented proposal, we take advantage of the inevitably encountered experimental situation, which the resultant current flowing from a spin-polarized electrode into the dot is not 100% polarized.

The tunneling junction between a ferromagnetic metal and two-dimensional electron gas inside the semiconductor heterostructure,[11,12] which the quantum dot is formed of, can be approximated by a ferromagnetic–normal-metal interface (F/N).[13] For such a junction, the degree of polarization of the injected current is dependent on the contact resistance and the characteristic resistances of F and N components, given by the ratio of spin diffusion length and effective bulk conductivity of the corresponding component. Apart from the partial loss of the spin polarization of the injected current at the junction, there are several mechanisms of spin relaxation present on the semiconductor side of the junction.[1,13] For confined structures, they originate mainly from the spin-orbit coupling in the absence of inversion symmetry of the structure and from the hyperfine interaction between magnetic moments of electrons and nuclei. In the following, we will consider the situation where the current injected into the dot partially loses its initial polarization and is not fully polarized even if the source electrode were. Thus, the polarization of the lead, described below in terms of Γ_σ widths of the dot level, should be understood as the effective lead polarization "seen" by the dot localized state after all spin polarization-loss processes took place.

II. THEORETICAL APPROACH

The device is described by the Anderson Hamiltonian,[14] where the dot takes the role of magnetic impurity and the (polarized) leads are analogs of the host metal,

$$H = \epsilon_d d_\sigma^+ d_\sigma + U n_\sigma n_{\bar{\sigma}} + \sum_{k,\sigma,\alpha=L,R} [t_\alpha c_{k\alpha,\sigma}^+ d_\sigma + \text{H.c.}] + \sum_{k,\sigma,\alpha=L,R} \epsilon_{k\alpha,\sigma} c_{k\alpha,\sigma}^+ c_{k\alpha,\sigma}. \quad (1)$$

The first two terms describe the dot with the presence of the Coulomb interactions U. The bare dot level is shifted by the gate voltage acting on the dot capacitatively, $\epsilon_d \equiv \epsilon_d - V_g$, and its initial position is assumed to coincide with the Fermi level $\epsilon_d = \epsilon_F = 0$. The third term describes the tunneling between the dot and the leads, represented by the last term in Eq. (1). The electron energy in the leads is spin dependent, $\sigma = \uparrow, \downarrow$, because the leads are assumed to be spin polarized. We neglect the spin dependence of the tunneling matrix elements t_α ($\alpha = L, R$) which are rather dependent on the potential barrier between the dot and a given lead. Thus, the spin dependence of the QD level width $(\Gamma_\sigma/2)=(1/2)\Sigma_\alpha\Gamma_{\alpha\sigma}$; $\Gamma_{\alpha\sigma}=2\pi|t_\alpha|^2\rho_{\alpha\sigma}$ is caused by the coupling to the leads with different spectral densities $\rho_{\alpha\uparrow}\neq\rho_{\alpha\downarrow}$, which are assumed to be featureless and constant.

Let us define the polarization of the quantity X, $P_X=(X_\uparrow-X_\downarrow)/(X_\uparrow+X_\downarrow)$. For the lead α, it is $P_\alpha=(\rho_{\alpha\uparrow}-\rho_{\alpha\downarrow})/(\rho_{\alpha\uparrow}+\rho_{\alpha\downarrow})$, which can be expressed by the spin-dependent QD widths: $P_\alpha=(\Gamma_{\alpha\uparrow}-\Gamma_{\alpha\downarrow})/(\Gamma_{\alpha\uparrow}+\Gamma_{\alpha\downarrow})$.

The retarded dot Green's function $G^r_\sigma(t-t')=-i\theta(t-t')\langle d_\sigma(t)d^\dagger_\sigma(t')+d^\dagger_\sigma(t')d_\sigma(t)\rangle$ is obtained by solving the set of equations of motion of the Green's functions in the Hubbard approximation.[15] Within this approximation, the two-particle Green's functions describing spin-flip processes (generating the Kondo effect) on the localized level are neglected. The Green's functions that describe the normal scattering of band electrons on an impurity are approximated by decoupling of band electrons from impurity electrons. The Hubbard approximation is valid for large U/Γ ratio, when the Hubbard subbands are well separated in the energy scale. It is the simplest scheme which describes correlated electrons, placed on the approximation scale between Hartree-Fock approximation for interacting but uncorrelated electrons, and the schemes for strongly correlated electrons, leading to Kondo physics. Thus, it is most suitable for the description of a spin-degenerate QD level in the Coulomb blockade regime of the lead-dot coupling. The Fourier-transformed expression for QD Green's function with the spin $\sigma=\uparrow,\downarrow$ has the form

$$G^r_\sigma(\omega)=\left[\frac{\omega-\epsilon_d}{1+\dfrac{\langle n_{\bar\sigma}\rangle U}{\omega-\epsilon_d-U}}+\frac{i\Gamma_\sigma}{2}\right]^{-1} \simeq \frac{1-\langle n_{\bar\sigma}\rangle}{\omega-\epsilon_d+\dfrac{i\Gamma_\sigma}{2}}+\frac{\langle n_{\bar\sigma}\rangle}{\omega-\epsilon_d-U+\dfrac{i\Gamma_\sigma}{2}}. \quad (2)$$

Equation (2) has been written as the sum of two Hubbard resonances, whose spectral weights are controlled by the dot level occupancy with the opposite spin $\bar\sigma$. This feature, caused by the Coulomb interactions between electrons with opposite spins, is crucial for the spin switching effect. The occupancies of spin ↑ and ↓ can be very different for the given gate voltage in spite of degeneracy $\epsilon_{d\uparrow}=\epsilon_{d\downarrow}$ because of the different widths of $\epsilon_{d\uparrow}$ and $\epsilon_{d\downarrow}$ levels introduced by polarized electrodes. Occupancies have been calculated self-consistently from the set of coupled equations,

$$\langle n_\sigma\rangle=-\frac{i}{2\pi}\int G^<_\sigma(\omega,\langle n_{\bar\sigma}\rangle)d\omega,$$

$$\langle n_{\bar\sigma}\rangle=-\frac{i}{2\pi}\int G^<_{\bar\sigma}(\omega,\langle n_\sigma\rangle)d\omega. \quad (3)$$

The "lesser" dot Green's function $G^<$ can be expressed by the spectral density of the dot,[16] $\rho_\sigma(\omega)=-(1/\pi)\Im G^r_\sigma(\omega)$ and $G^<_\sigma(\omega)=2i\pi\bar f(\omega)\rho_\sigma(\omega)$. Nonequilibrium distribution function $\bar f=[\Gamma_{L\sigma}f_L+\Gamma_{R\sigma}f_R]/(\Gamma_{L\sigma}+\Gamma_{R\sigma})$ has a two-step profile defined by the chemical potential in the leads: $f_{L/R}\equiv f(\omega\mp eV)$ and collapses into the equilibrium Fermi-Dirac distribution function $f\equiv f_L=f_R$ in the limit of zero bias between the leads, $eV\to 0$. The current is calculated within the Landauer formalism from the relation[16]

$$J=\frac{e}{\hbar}\sum_\sigma\int d\omega[f_L-f_R]\frac{\Gamma_{L\sigma}\Gamma_{R\sigma}}{\Gamma_{L\sigma}+\Gamma_{R\sigma}}\rho_\sigma(\omega). \quad (4)$$

In the limit of zero bias, the conductance has the form

$$G=\frac{\partial J}{\partial V}=\frac{2e^2}{\hbar}\sum_\sigma\int d\omega\left(-\frac{\partial f}{\partial\omega}\right)\frac{\Gamma_{L\sigma}\Gamma_{R\sigma}}{\Gamma_{L\sigma}+\Gamma_{R\sigma}}\rho_\sigma(\omega). \quad (5)$$

III. RESULTS AND DISCUSSION

When the leads are unpolarized, $P_L=P_R=0$, the occupancy curves for $n_\uparrow$ and $n_\downarrow$ coincide and the usual plateau of the width $\sim U$ appears when the first ϵ_d and second ϵ_d+U Hubbard levels are filled with electrons when the gate voltage changes [see the solid curve in Fig. 1(a)]. An introduction of the spin-polarized leads changes the situation. The nonmonotonicity of the dot spin-up and spin-down occupations appears with the increase of the left electrode polarization (we focus on the case when right lead polarization $P_R=0$ and asymmetric QD lead coupling $\Gamma_{R\uparrow}=0.1\Gamma_{L\uparrow}$ is assumed in the present discussion, unless differently stated[17]). Now, the spin-dependent widths of the ϵ_d level $\Gamma_\uparrow\neq\Gamma_\downarrow$, which introduces the difference in the $n_\uparrow$ and $n_\downarrow$ as calculated from the integration of the corresponding spectral densities [see Eq. (3)]. The weights of the spectral peaks of $\rho_\uparrow$ and $\rho_\downarrow$ become different as controlled by the occupancy of opposite spins [Eq. (2)].

The present model is formally equivalent to the model of the spinless electron double-dot system with the Coulomb interaction between the dots[18] for the case of dot level degeneracy and anisotropy of the levels coupling to the leads. Within this model, nonmonotonicity in the occupancy has also been encountered.

There are three degeneracy points where $n_\uparrow=n_\downarrow$ shown in Fig. 1(a). Two of them are for the gate voltages when the levels ϵ_d ($V_g=0$) and ϵ_d+U ($V_g=U$), respectively, coincide with the Fermi energy. They are the most advantageous for the spin control. The third point, when $\langle n_\uparrow\rangle=\langle n_\downarrow\rangle\cong 0.5$, appears when the Fermi level is placed between the Hubbard levels. For unpolarized electrodes, it corresponds to the symmetric Anderson model when $\epsilon_d=-U/2$ ($V_g=U/2$).[14]

For the remaining gate voltages, $\langle n_\uparrow\rangle\neq\langle n_\downarrow\rangle$. In the limiting case of $P_L=1$, the occupancy curves do not change much, the spin down electrons are still supplied to the dot from the right, unpolarized lead to modify the spectral density $\rho_\uparrow$ [see Eq. (2)] and $\langle n_\uparrow\rangle$ occupancy as a result of Coulomb interactions.

Panel (b) of Fig. 1 shows the change of the dot occupancy polarization P_n with decrease of the asymmetry of the coupling to the leads. The efficiency of the switching of the initial polarization decreases for more symmetric dot-lead coupling, but the device is still operational even for symmetric coupling.

Panel (c) shows P_n for various right lead polarizations P_R. P_n is robust in the range of V_g where the Coulomb interac-

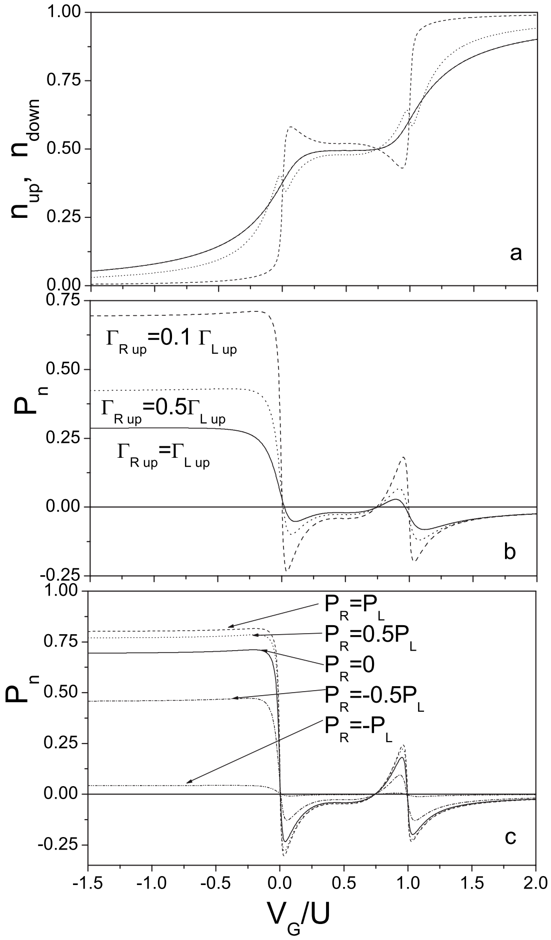

FIG. 1. Panel (a): occupancies $\langle n_\uparrow \rangle$ and $\langle n_\downarrow \rangle$ vs gate voltage for zero temperature, $P_L=0.8$ and $P_R=0$ and asymmetric coupling to the leads $\Gamma_{R\uparrow}=0.1\Gamma_{L\uparrow}$ (dotted curve $n_\uparrow$, dashed curve $n_\downarrow$). The solid curve shows the occupancy $n_\uparrow = n_\downarrow$ for unpolarized leads. Panel (b) shows the polarization of the dot for the same lead polarization as in (a), but with the decrease of the asymmetry of the coupling to the leads. Panel (c) shows the polarization of the dot for the same parameters as for (a), but when the right lead polarization changes.

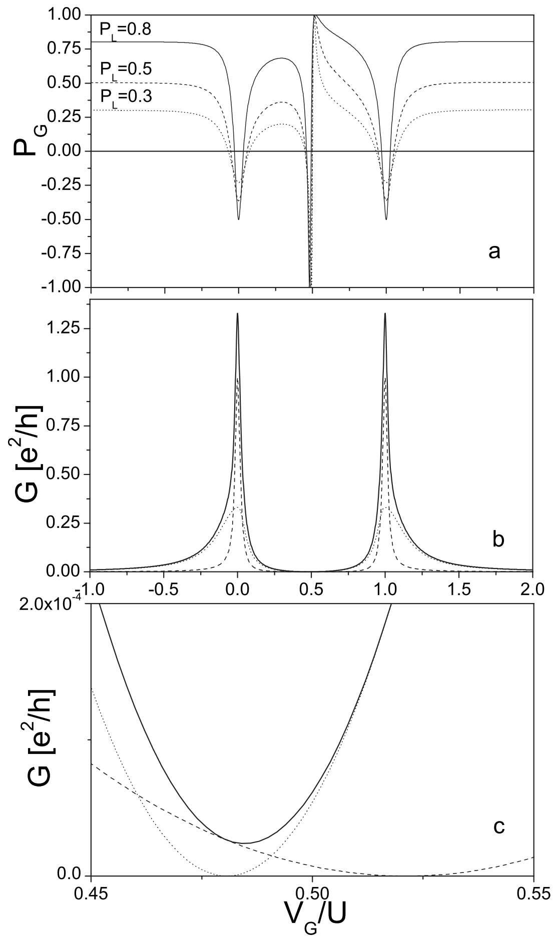

FIG. 2. Panel (a): zero-bias conductance polarization calculated for the same parameters as for Fig. 1(a) but for various initial source lead polarizations. Panel (b) shows the conductance for $P_L=0.8$ with its spin-dependent components: dashed line—spin down and dotted line—spin-up components, respectively. Bold solid line is the total conductance. Panel (c): magnification of the region in-between conductance peaks shown in (b); note the change of the gate voltage scale.

tion inside the dot plays the role in the spin switching until the right lead has an opposite polarization with respect to the left one. In such a case, the effect is strongly diminished.[17]

Zero-bias conductance polarization P_G is shown in Fig. 2(a) for various P_L values. There are three gate voltage ranges for which the polarization of the initial current flowing from the source can be reverted. The most favorable for operation are the values $V_g=0$ and $V_g=U$, which correspond to high values of conductance at the Coulomb peaks [see panel (b)]. The third point at $V_g=U/2$ is less favorable because it is placed in-between Coulomb blockade peaks, where the conductance is very small. In this point, regardless of the initial P_L, P_G reaches the value of -1 and then switches to the value of +1. This feature can be understood when analyzing the expression for zero-bias conductance. At $T=0$, its σ component has the form

$$G_\sigma = \frac{2e^2}{h} \frac{\Gamma_{L\sigma}\Gamma_{R\sigma}}{\left(\dfrac{\epsilon_d(\epsilon_d+U)}{\epsilon_d + U(1-\langle n_{\bar{\sigma}}\rangle)} \right)^2 + (\Gamma_\sigma/2)^2}. \tag{6}$$

It reaches zero value when the denominator $\epsilon_d + U(1-\langle n_{\bar{\sigma}}\rangle) = 0$, which for unpolarized leads gives the symmetric case: $\epsilon_d = -U/2$ and $\langle n_{\bar{\sigma}}\rangle = \langle n_\sigma \rangle = 0.5$. For polarized leads, the position of ϵ_d giving $G_\sigma = 0$ is different for each conductance spin component because $\langle n_\sigma \rangle \neq \langle n_{\bar{\sigma}}\rangle$. In our case, for $P_L > 0$, $n_\downarrow > n_\uparrow$ [Fig. 1(a)] in-between Coulomb blockade (CB) peaks and $G_\uparrow = 0$ for smaller value of V_g than $G_\downarrow = 0$, which implies $P_G = -1$ for such gate voltage [see Fig. 2(c)]. When the gate voltage increases further, $G_\downarrow$, in turn, reaches zero value and the conductance polarization jumps to the value of +1. The values of $n_\downarrow$ and $n_\uparrow$ in the region between CB peaks are weakly dependent on the initial P_L polarization and the difference between them is small. It causes the same weak de-

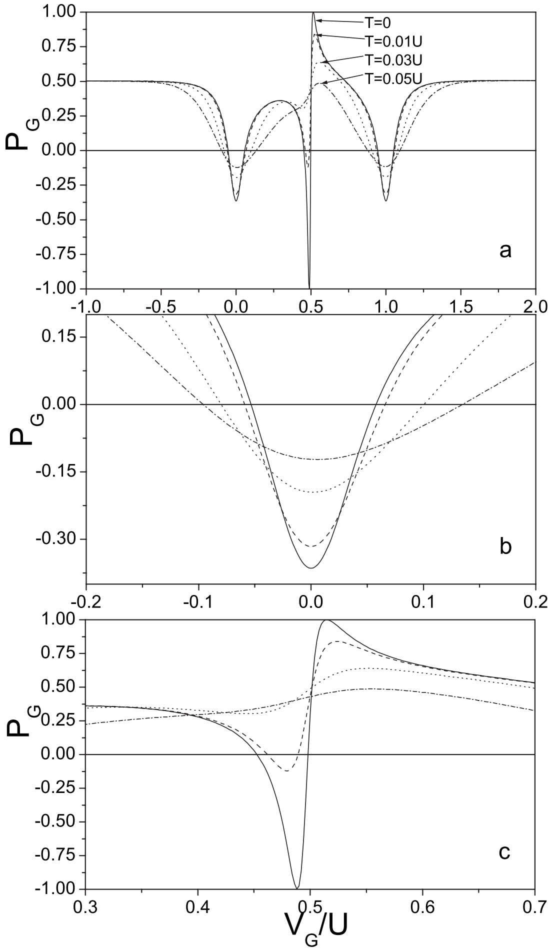

FIG. 3. Panel (a): zero-bias conductance polarization calculated for various temperatures, $P_L=0.5$, $P_R=0$, and $\Gamma_{L\uparrow}=0.1\Gamma_{R\uparrow}$. Panels (b) and (c) show the magnification of regions in the vicinity of $V_g=0$ and $V_g=0.5U$, respectively. Note the changes of the gate voltage scale.

pendence on P_L of the zero-bias conductance polarization in this region.

Panel (b) of Fig. 2 shows the conductance with its spin-dependent contributions for $P_L=0.8$ and $\Gamma_{R\uparrow}=0.1\Gamma_{R\downarrow}$. The total conductance does not reach the unitary limit because of the asymmetry of the coupling of the dot to the leads. The conductance peaks are very asymmetric due to the peculiar behavior of the occupancies and coupling asymmetry. When the sign of P_L is changed, the obtained polarization curves are reverted with respect to the conductance polarization $P_G=0$ line (not shown).

The effect of conductance polarization switching is more pronounced when the dot is asymmetrically coupled to the leads, promoting better control of the lead polarizations by different switching fields.[11,12] Moreover, the asymmetric coupling is naturally experimentally accessible, contrary to the fully symmetric coupling which needs some tuning of the quantum point contacts between the leads and the dot.

The current polarization change at the resonances for $V_g=0$ and for $V_g=U$ offers an electron correlation-based mechanism for the change of the sign of tunneling magne-

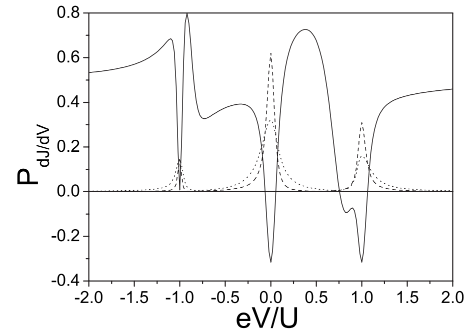

FIG. 4. Bias dependence of the differential conductance polarization (solid line) calculated for $V_g=0$ and temperature $T=0.01U$, $P_L=0.5$, $P_R=0$, and $\Gamma_{L\uparrow}=0.1\Gamma_{R\uparrow}$. The spin-dependent contributions to the conductance are shown: spin down—dashed line and spin up—dotted line.

toresistance by the gate voltage, which has recently been observed.[12] The polarization P_G dependence vs gate voltage does not exactly match the quantum dot polarization, especially in the gate voltage range where the dot is occupied by one electron. This is due to the fact that the conductance polarization is not directly related to the dot polarization but rather to the value of the spin-dependent QD spectral densities at the Fermi level.

In the limiting case of $P_L=1$, the conductance polarization is always $P_G=1$ (contrary to the dot occupancy polarization discussed above) because $\Gamma_{L\downarrow}=0$ and the spin-down contribution to the conductance is switched off. The effectiveness of current polarization switching by the Coulomb blockaded SET is operative in realistic situations, when the electrons incoming to the dot are not 100% polarized. The current polarization switching is robust to the temperature increase in the regions of the operation of the device for $V_g\sim 0$ and $V_g\sim U$, as compared to the point of $V_g\sim U/2$. It is shown in Fig. 3 for the source lead polarization $P_L=0.5$. For the temperature $T=0.01U$ [=174 mK for $U=15$ meV (Ref. 12)], which is a typical range for the SET operation in the Coulomb blockade,[7,11,12] $P_G\simeq -0.35$ at $V_g=0$ shown in panel (b) of Fig. 3. For $T=0.05U$, the switching is less efficient, but still present. The effect is limited rather by the temperature value for which the Coulomb blockade becomes visible, $k_BT<\Gamma<U$. Contrary, the P_G is sensitive to the temperature change in the region close to $V_g=0.5U$ [panel (c) of Fig. 3]. The increase of thermal broadening of the conductance peaks causes the decrease of the difference between spin-up and spin-down components in this region, which is reflected in the rapid decrease of polarization.

The dependence of the differential conductance polarization $P_{dJ/dV}$ on the applied bias voltage calculated at $V_g=0$ is shown in Fig. 4 along with conductance spin-dependent components for the temperature $T=0.01U$ and $P_L=0.5$. At $V_g=0$, the dot ϵ_d level matches the effective chemical potential in the leads for zero bias. The switching effect decreases for finite bias and approaches $P_{dJ/dV}=0$ for $eV\sim\pm 0.05U$. There are additional $P_{dJ/dV}$ polarization anomalies, which appear for larger values of applied bias, $eV=\pm U$. Namely, for $eV=-U$, the chemical potential in the left lead comes into resonance with the ϵ_d+U level, which is reflected by the maxima shown in Fig. 4 of spin components of conductance for such a bias. Similarly, for $eV=U$, the chemical potential of the right lead is in resonance with the ϵ_d+U level. The large bias spin transport has indeed been very recently observed.[11] The anomalies at large bias are sensitive to the lead polarization arrangement and asymmetry of the dot-lead coupling.[17]

In conclusion, we have shown that the spin polarization of the current can be electrically inverted by the gate voltage acting on the SET in the Coulomb blockade regime. The effect is purely due to the Coulomb interactions present inside the QD. Current polarization switching is robust to the temperature change and favored by inevitably encountered experimental conditions: asymmetry of the dot-lead coupling and partial loss of the initial current polarization at the dot-lead interface. The model also sheds light on layered spin-polarized heterostructures[19] operated by external electric field, where the bound states can be formed inside the interface due to the spatial confinement and energy structure mismatch of heterostructure components.

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