Large Magnetoresistance Induced by Quantum Charge Fluctuations in Magnetic Double Dots

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We study electron tunneling through two small ferromagnetic dots. Quantum charge fluctuations and interdot coupling make each Coulomb peak of the conductance at zero interdot coupling split across. The interdot tunnel coupling is determined by the relative orientation of magnetization of the two dots, leading to different splitting energies of the Coulomb peaks in parallel and antiparallel magnetization alignments. As a result, a very large tunneling magnetoresistance occurs near the Coulomb peaks, and its sign may be either positive or negative.

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The tunneling conductance of a tunnel junction made of two ferromagnetic (FM) electrodes separated by a non-magnetic (NM) insulating layer may increase by several tens percent, as the magnetizations of the FM electrodes change from antiparallel (AP) to parallel (P) alignment under an external magnetic field [1, 2, 3, 4, 5, 6]. Such a tunneling magnetoresistance (TMR) effect has important applications in magnetic sensors, random access memories, and magnetic imaging. The TMR originates from the spin polarization of tunneling electrons in the FM electrodes. The TMR ratio can be defined in a symmetric form as

\[
\text{TMR} = \frac{G_P - G_{AP}}{G_P + G_{AP}},
\]

where \(G_P\) and \(G_{AP}\) are the conductances for parallel and antiparallel magnetization alignments, respectively. According to the simple model [1, 3], \(\text{TMR} = P_L P_R\) for the magnetic tunnel junctions, where \(P_L(R)\) is the spin polarization factor in the left (right) FM electrode. For electrodes with spin polarization of the same sign, the TMR ratio is usually positive. There is great interest in inverse (negative) TMR [8, 9, 10, 11, 12], which is usually associated with certain hiding mechanisms that affect the spin-dependent transport significantly. The inversion of TMR has been attributed to the reversion of the spin polarization in either of two FM electrodes due to the bonding effect at the FM/NM interface [3, 13, 14], and to the resonant tunneling via localized states on impurities in the insulating barrier [11, 12].

With the advancement of technology, magnetic tunnel junctions are made increasingly small and controllable in recent years. Single electron transistors consisting of FM metals [13] and junctions with small FM islands [14] have been fabricated. Presently, it is of particular interest to study the TMR through small junctions and quantum dots, where the Coulomb interaction plays an important role [15, 16]. It has been suggested that the TMR between two FM leads through an FM dot in the Coulomb blockade regime may be enhanced by higher-order electron tunneling via virtual intermediate states in the dot (cotunneling) [15, 16], or oscillate in magnitude with external voltage [17, 18]. The TMR through an NM dot may be unchanged or in some cases decreased by Coulomb blockade [19, 20].

Nonmagnetic quantum dots have previously been extensively studied, and many features of the tunneling conductance have been well known [20]. The conductance of a quantum dot displays Coulomb peaks at certain gate voltages, and is strongly suppressed elsewhere by the Coulomb blockade [21, 22, 23, 24]. Electron transport through coupled double quantum dots has also been extensively explored. In a double-dot structure, the quantum charge fluctuations can be more directly probed than in a single dot. As has been studied both experimentally [25] and theoretically [26, 27, 28], the interdot coupling and charge fluctuations make each Coulomb peak at zero interdot couplings split across. However, spin-dependent electron transport through coupled FM double quantum dots has not yet been investigated so far. More importantly, we find that, in the FM double quantum dots, a largest TMR effect may occur essentially because of the quantum charge fluctuations between the FM dots.

In this paper, we consider a magnetic tunnel junction consisted of two coupled FM quantum dots. The system is weakly coupled to two reservoirs of electrons. A quantum-circuit description for the charge fluctuations is developed. We show that, with changing the magnetizations of the two FM dots from AP to P alignment, the interdot tunnel coupling increases, which in turn enhances the Coulomb peak splitting. As a consequence, the Coulomb peaks shift to different gate voltages for AP and P alignments, resulting in a very large TMR. Moreover, depending on the gate voltage, the TMR ratio may be either positive or negative.

The equivalent electrostatic circuit for the double-dot tunnel junction is shown in Fig. 1. For simplicity, the...
two FM dots are assumed identical. For the symmetric capacitors: \( C_L = C_R = C_0 \) and \( C_{G1} = C_{G2} = C_g \), we can confine ourselves to the case of the same gate voltage \( V_{G1} = V_{G2} = V_g \). The qualitative results of this work can be reproduced for nonidentical dots, provided that the two gate voltages \( V_{G1} \) and \( V_{G2} \) are allowed to change differently so that electrons tunneling through the two dots resonate simultaneously. Let \( N_1 \) and \( N_2 \) denote the numbers of excess electrons in the two dots. The model Hamiltonian for the system can be written in the form

\[
H = K + U(N_1, N_2),
\]

where the expression for electron kinetic energy \( K \) will be derived later, and the electrostatic energy of the system is given by

\[
U(N_1, N_2) = E_C(\delta^2 N_1 + \delta^2 N_2) + 2E_C'\delta N_1\delta N_2.
\]

Here \( \delta N_1 = N_1 - N_C \) and \( \delta N_2 = N_2 - N_C \) with \( N_C = C_g V_g/e \). \( E_C = e^2 C_g/2F \) and \( E_C' = e^2 C_{g0}/2F \) with \( C_g = C_0 + C_R + C_L \) and \( F = C_g^2 - C_0^2 \).

The interdot tunnel coupling of electrons is assumed to be much stronger than the tunnel coupling between the dots and the reservoirs. As a result, for given total electron number \( N = N_1 + N_2 \), quantum fluctuations of \( \mathcal{M} = N_1 - N_2 \) are important. In previous treatments of the charge fluctuations, very different assumptions were made on the interdot tunnel matrix elements, e.g., from the thin-shell model with one-to-one level coupling to the thick-shell model with single site-to-site connection. Here we extend the approach developed by Girvin et al. to the charge fluctuations in a Coulomb-blockaded single junction coupled to its environment by long transmission lines. In the approach, the collective motion of the charges is described by inductances, and the charge numbers are treated as quantum canonical coordinates. In this essence, we introduce an inductance \( l \) between the dots to take the inter-dot charge fluctuations into account. The advantage of the approach is that it enables us to capture the essential physics of the charge fluctuations without detailed assumptions about the tunnel matrix elements. It will be shown that a simple connection can be established between our theory and the previous theories.

Since inductance \( l \) essentially describes the charge transfer between the dots, it must depend on the magnetization alignment of the FM dots because of the spin polarization of electrons in the FM dots, just as in an ordinary FM/NM/FM tunnel junction. For the P (AP) alignment, the electron tunneling between the dots is relatively easy (difficult), and so the inductance \( l = l_P \) (\( l = l_{AP} \)) is relatively small (large). According to classical electromagnetism, as a current of \( \dot{I}_g = \mathcal{M}e/2 \) flows through inductance \( l_g \), the energy stored in the inductance is \( K = l_g e^2\mathcal{M}^2/8 \). Its corresponding quantum form is \( K = 2P_m^2/l_g e^2 \) with \( P_m \) the momentum operator conjugate to \( \mathcal{M} \). Projecting \( \mathcal{K} \) into the subspace of integer electron numbers \( N_1 \) and \( N_2 \), we obtain

\[
K = -(D_{M1}^2 + D_{M2}^2 - 2)/2l_g e^2,
\]

where operator \( D_{Mj} = e^{-i\mathcal{M} \eta_j}/\hbar \) increases \( \mathcal{M} \) by two. Subsequently, \( \mathcal{K} \) is transformed into the representation of \( N_1 \) and \( N_2 \), yielding

\[
K = -\kappa_\eta(D_1^2D_2 + D_1D_2^2),
\]

where \( \kappa_\eta = 1/2l_g e^2 \). \( D_{j}^2 = e^{-i\mathcal{M} \eta_j}/\hbar \) increases \( N_j \) by unity with \( \mathcal{M} \), where \( \eta_j = \mathcal{M} \eta_j \), and an irrelevant constant energy \( 1/l_g e^2 \) has been neglected. Equation (4) is a reasonable result, indicating the movement of an electron from one dot to the other.

The above model is essentially a quantum LC circuit, whose general eigenstates can be determined from the complicated Mathieu equation \([31]\). In this work, under the assumption of \( E_C \gg E_C' \) and \( E_C \gg \kappa_\eta \) and so to a good approximation, we project the Hamiltonian into the subspace spanned by the lowest-energy states for all possible \( N \). The eigenstates of \( N_1 \) and \( N_2 \), \( |n_1, n_2\rangle = (D_1^N)|N_1\rangle (D_2^N)|N_2\rangle |0, 0\rangle \), can be used as the base wave vectors, where \(|0, 0\rangle \) stands for the state without excess electrons in the dots. For even \( N = 2k \), the low-energy state is the single state \( |k, k\rangle \) with electrostatic energy \( E_\mathcal{N} = U(k, k) \); and for odd \( N = 2k + 1 \), the low-energy states are the two degenerate states \( |k, k + 1\rangle \) and \( |k + 1, k\rangle \) with electrostatic energy \( E_\mathcal{N} = U(k + 1, k) \). Since the kinetic energy given by Eq. (4) conserves the total electron number \( \mathcal{N} \), the only nonzero matrix elements of \( K \) in the low-energy subspace are those between the two degenerate states for odd \( \mathcal{N} = 2k + 1 \), namely,

\[
|k + 1, k\rangle K |k, k + 1\rangle = \langle k + 1, k|k, k + 1\rangle = -\kappa_\eta.
\]

It is thus easy to obtain the eigenstates of the system. For an even electron number \( \mathcal{N} = 2k \), the eigenstate is \( |N\rangle = |k, k\rangle \) with eigenenergy \( E_\mathcal{N} = E_{\mathcal{N}} \). For an odd electron number \( \mathcal{N} = 2k + 1 \), there are two eigenstates, which will be distinguished from each other by symbols \( \uparrow \) and \( \downarrow \), symmetric state \( |N\uparrow\rangle = (|k + 1, k + 1\rangle + |k, k + 1\rangle)/\sqrt{2} \) with lower eigenenergy \( E_{\mathcal{N} \uparrow} = E_\mathcal{N} - \kappa_\eta \), and antisymmetric state \( |N\downarrow\rangle = (|k + 1, k\rangle - |k, k + 1\rangle)/\sqrt{2} \) with higher
eigenenergy $E_{Nk} = E_N + \kappa_\eta$.

The total excess electron number $N$ in the ground state is determined by the minimum of system eigenenergy. Therefore, tunneling of an electron into or out of the dots usually causes an increase of the system energy and so the tunneling rate is suppressed, leading to the Coulomb blockade effect. At certain values of the gate voltage, however, the system eigenenergies are degenerate for different $N$, i.e., $E_{2k} = E_{(2k+1)}$ or $E_{2k+2} = E_{(2k+1)}^\uparrow$, in which there appear Coulomb peaks of linear conductance. The positions of the Coulomb peaks are obtained as

$$V_G = V_{G,\eta} = \frac{e}{C_G} \left( k + \frac{1}{2} \pm \frac{\delta_\eta}{2} \right) ,$$

where $\delta_\eta = (E_C^0 + \kappa_\eta)/E_C$ describes the correction to the peak position due to interdot electrostatic coupling $E_C^0$ and interdot tunnel coupling $\kappa_\eta$. According to Eq. (4), if the interdot coupling is absent, the conductance peaks occur periodically, whenever the gate voltage is equal to half-integer times $e/C_G$. The presence of the interdot coupling splits each peak into two, the distance between them given by $\delta_\eta e/C_G$. It is interesting to notice that our result recovers the previous result for the NM dots obtained in the weak-tunneling regime [27, 28], if we set $\kappa_D = (\hbar \ln 2/\pi)g_D/\hbar\Sigma$ with $g_D$ the interdot conductance. It then follows that, for the FM dots, $\kappa_D$ does depend on the relative orientation of their magnetizations, for tunneling conductance $G_D$ between two FM dots must be orientation dependent.

According to Eq. (5), there is a position shift of the Coulomb peaks with changing the magnetization alignment from AP to P. This effect originates from the quantum charge fluctuations and results in a very large TMR. To evaluate the conductance and TMR, we will confine ourselves to the vicinities of the Coulomb peaks, where real tunneling processes of the electrons dominate. In the strongly Coulomb-blockaded region, higher-order tunneling processes of electrons via virtual intermediate states (cotunneling) may be important [17, 18], which will not be considered here. Let us consider the first pair of resonant peaks for positive gate voltage $V_G$, whose positions are determined from Eq. (5) by setting $k = 0$. The physics around other peaks is completely similar. The conductance is given by [28]

$$G_\eta = \frac{G_0}{2Z} \left[ g(V_G - V_{G,\eta}^-) + g(V_{G,\eta}^+ - V_G) \right] ,$$

where $G_0$ is the conductance of the dot-reservoir barrier, $Z = 2 + e^{-\alpha(V_G - V_{G,\eta}^-)} + e^{-\alpha(V_{G,\eta}^+ - V_G)}$ is the partition function with $\alpha = 2C_G E_C/ek_B T$, and $g(x) = \alpha x/(e^{\alpha x} - 1)$.

The calculated conductances for P and AP magnetization alignments as functions of normalized gate voltage for several temperatures are shown in Figs. 2a and 2b, respectively. As expected, the position of the resonant peaks depends on the magnetization alignment. The distance between the split peaks is greater in the P alignment than in the AP alignment, the resulting TMR ratio plotted in Fig. 2c. On either side of the two peaks for $G_{AP}$, the TMR is positive, exhibiting the same sign as that in normal FM/NM/FM junctions. At low temperatures, e.g., $k_B T = 0.01E_C$, the positive TMR may reach about 98%, corresponding to $G_P/G_{AP} \simeq 100$. It forms a striking contrast to the much smaller ratio $\kappa_P/\kappa_{AP} = 2$ used in the calculation. Actually, for gate voltage $V_G$ on either side of the two peaks for $G_P$, one can obtain $G_P/G_{AP} \simeq \exp[(\kappa_P - \kappa_{AP})/k_B T]$, increasing exponentially with the temperature lowered. More interestingly, in the region between the two peaks of $G_{AP}$, the TMR is not only very large in magnitude but also inverted in sign. For gate voltage $V_G$ in this region, the conductance ratio $G_P/G_{AP} \simeq \exp[-(\kappa_P - \kappa_{AP})/k_B T]$ decreases exponentially with the temperature lowered. With increasing temperature, both positive TMR and negative TMR decrease in magnitude. As energy $k_B T$ is increased so as to be comparable with the energy separation $(\kappa_P - \kappa_{AP})$ of the left (or right) two Coulomb peaks for $G_{AP}$ and $G_P$, the TMR ratio becomes very small.

In Fig. 3, the conductance ratio $G_P/G_{AP}$ is plotted as
FIG. 3: Conductance ratio \( G_{P}/G_{AP} \) as a function of normalized temperature \( k_{B}T/E_{C} \) for different \( \kappa_{P} \) and \( C_{D} \). Here \( C_{0} = C_{G} \) and \( \kappa_{P} = 2\kappa_{AP} \). The gate voltage is \( V_{G} = V_{G,P}^{+} \) for the upper three curves, and \( V_{G} = (V_{G,P}^{+} + V_{G,P}^{-})/2 \) for the lower three curves.

a function of temperature for different interdot electrostatic couplings \( C_{D} \) and interdot tunnel coupling \( \kappa_{P} \). We note that \( G_{P}/G_{AP} > 1 \) corresponds to positive TMR, and \( G_{P}/G_{AP} < 1 \) corresponds to negative TMR. So far, we have confined ourselves to the simple case of zero interdot capacitor \( C_{D} \). The interdot capacitor represents the effect of the excess charges in one dot on the electrical potential of the other dot. According to Eq. (5), a nonzero \( C_{D} \) mainly enhances the splitting of the Coulomb peaks. The two dotted lines in Fig. 3 are obtained for nonzero \( C_{D} \). By comparing them with the solid curves, we find that an increased interdot capacitance does not change the TMR significantly.

Finally, we wish to make a discussion on experimental realization of the present theory. With today’s fabrication technology, it is possible to connect two FM dots by using short narrow conductor (quantum wire) [31], and keep the FM dots sufficiently separated in space. In this manner, relatively strong electron hopping coupling can be ensured, and in the meantime magnetic dipolar interaction can be avoided between the FM dots. As a result, the RKKY interaction caused by electron hopping between the dots may induce an AF alignment, if the dots are suitably distanced. The P alignment can be achieved simply by applying an external magnetic field. As a simplified model of the real systems, we have omitted the complexities such as spin-flip scattering and electron virtual tunneling in the Coulomb blockade regime. These effects could reduce the TMR measured experimentally. However, it is believed that they will not change the results qualitatively.

In summary, we have investigated the charge fluctuations and conductance peak splitting in magnetic double quantum dots. The characteristic energy of the Coulomb peak splitting is shown to depend on the magnetization alignment. Therefore, the change in the magnetization alignment causes very large TMR effect. The TMR ratio may be either positive or negative, depending on the value of gate voltage.

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