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Dynamic tunneling magnetoresistance in quantum dot system under the perturbation of phonon

Lili Zhao*, Ying Liu, Chun mei Liu and Rui Yang

Department of Fundamental Courses, Army Academy of Armored Force, Beijing, 100072,China

*Corresponding author e-mail: Zhao_lili219@163.com

Abstract. We theoretically investigate the tunneling magnetoresistance(TMR) effect in a center quantum dot (QD) connected simultaneously to two Ferromagnets and a local phonon bath. By using the nonequilibrium Keldysh Green's function technique, we obtain the formula of the TMR contained the effects of phonon. The linewidth function and angle θ influence the TMR curves significantly.

1. Introduction

With the further miniaturization of semiconductor devices, traditional electronic devices using electronic charges have reached their limits. Nowadays, Mesoscopic electronic transport has attracted researcher's attention. [1-4].Nanoelectronic devices have important application prospects. Their development will greatly promote the society and science and technology. In the field of Microelectronics, the charge characteristics of electrons are mainly used to carry and process information. Therefore, the main function of various electronic devices is to control the electronic storage and transport by manipulating and controlling the charge freedom of electrons. The study of magnetic mesoscopic system has been paid more and more attention .Tunnel magnetoresistance (TMR) effect is one of the most significtant issues about spin-dependent transport phenomena. The tunneling current depends on the relative the magnetizations of angle θbetween two ferromagnets. The TMR effect studies in quantum system have been carried out both in theoretical and experimental.Experiments show that the resistance depends on whether the average magnetization directions of the two ferromagnetic films are parallel or antiparallel. Previous investigations of the effect in Coulomb blockade region show that spin-flip transitions may lead to the reduction of TMR .[5,6]. Yun-Qing Zhou team focused on the TMR effect for collinear configuration with the spin-dependent transport through QDs [7,8]. Spintronics devices have potential advantages over traditional devices.It can improve data processing speed, reduce electronic energy consumption, increase the integrated density and so on. The TMR effect can be widely used .The most important magnetic memory effect discussed at present is its application in the field of magnetic memory. The use of spin properties to prepare memory in ferromagnetic materials, charge and spin are used separately. The development of spintronics makes it possible to use both aspects of electrons in semiconductor technology. In this work we investigate the dynamic TMR effects in quantum dot system under the perturbation of phonon. On one hand we reveal the physical mechanism and laws of new effects in mesoscopic systems , and to provide a physical model and theoretical basis for the design and implementation of quantum devices with excellent performance on the other.

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The rest of this article is structured as follows. In section 2 we give the Hamiltonian of the system and the derivation of the current. Then in section 3 we numerically study the TMR as well as the current formula .A brief summary is given in section 4.

2. Model and formalism

The system is composed of three parts: the center QD, the ferromagnetic terminals and the tunneling term. The Hamiltonian of the our system can be written as [9–11]:

$$\begin{aligned} H = &\sum_{\gamma\kappa\sigma}\left\{\left[\varepsilon_{\gamma\kappa}(t) - \sigma M_\gamma \cos\theta_\gamma\right] a^+_{\gamma\kappa\sigma} a_{\gamma\kappa\sigma} - M_\gamma \sin\theta_\gamma a^+_{\gamma\kappa\sigma} a_{\gamma\kappa\bar{\sigma}}\right\} + \\ &\sum_\sigma \left[\varepsilon_d + \lambda_q (a^+_q + a_q)\right] d^+_\sigma d_\sigma + \sum_{\gamma\kappa\sigma}\left(T_{\gamma\kappa} a^+_{\gamma\kappa\sigma} d_\sigma + H.\,c.\right) + \sum_q \omega_q a^+_q a_q \end{aligned} \tag{1}$$

In the Hamiltonian above, $H.\,c.$ means hermitian conjugation. a_q (a^+_q) is the annihilation (creation) operator of a phonon and ω_q is the vibrational frequency. λ_q is the coupling strength of electron–phonon interaction. $M_\gamma = ½ g\mu_B h_\gamma$

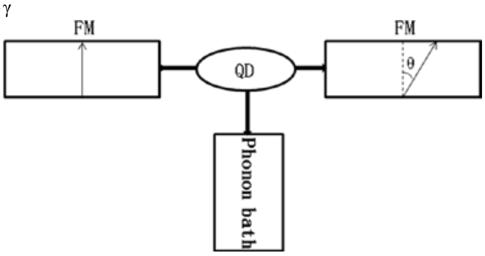

Figure 1 The graphic structure schematically illustrates the system.

The rotation matrix is employed:

$$\boldsymbol{R}\left(\theta_\gamma\right) = \begin{pmatrix} \cos\theta_\gamma/2 & \sin\theta_\gamma/2 \\ -\sin\theta_\gamma/2 & \cos\theta_\gamma/2 \end{pmatrix} \tag{2}$$

Herein, we obtain the Hamiltonian of the system:

$$\begin{aligned} H = &\sum_{\gamma\kappa\sigma} [\varepsilon_{\gamma\kappa}(t) - \sigma M_\gamma \cos\theta_\gamma] a^+_{\gamma\kappa\sigma} a_{\gamma\kappa\sigma} + \sum_\sigma [\varepsilon_d + \lambda_q (a^+_q + a_q)] d^+_\sigma d_\sigma \\ &+ \sum_{\gamma\kappa\sigma\sigma'} (a^+_{\gamma\kappa\sigma} \tilde{T}_{\gamma\kappa\sigma\sigma'} d_{\sigma'} + H.c.) + \sum_q \omega_q a^+_q a_q \end{aligned} \tag{3}$$

We define Green's functions [12,13]:

$$G^r_{q\sigma}(t,t') = -i\theta(t-t')\left\langle\left[d^+_\sigma(t) d_\sigma(t), a^+_q(t')\right]\right\rangle \tag{4}$$

$G^r_{q\sigma}(t,t')$ is the retarded Green's function.

$$\tilde{G}^r_{\sigma\sigma'}(\omega) = \frac{\zeta_{\bar{\sigma}\bar{\sigma}}(\omega)\delta_{\sigma\sigma'} + \Sigma^r_{\sigma\bar{\sigma}}(\omega)\delta_{\bar{\sigma}\sigma'}}{\zeta_{\sigma\sigma}(\omega)\zeta_{\bar{\sigma}\bar{\sigma}}(\omega) - \Sigma^r_{\sigma\bar{\sigma}}(\omega)\Sigma^r_{\bar{\sigma}\sigma}(\omega)} \tag{5}$$

where $\zeta_{\sigma\sigma'}(\omega) = \varepsilon - \varepsilon_d - \Sigma^r_{\sigma\sigma'}(\omega)$.

We determine the elements of the matrix $\tilde{\Gamma}_\gamma$:

$$\tilde{\Gamma}_{\gamma\sigma\sigma} = \cos^2\frac{\theta_\gamma}{2}\tilde{\Gamma}_{\gamma\sigma} + \sin^2\frac{\theta_\gamma}{2}\tilde{\Gamma}_{\gamma\bar{\sigma}}$$

$$\tilde{\Gamma}_{\gamma\sigma\bar{\sigma}} = \sigma\cos\frac{\theta_\gamma}{2}\sin\frac{\theta_\gamma}{2}\left(\tilde{\Gamma}_{\gamma\sigma} - \tilde{\Gamma}_{\gamma\bar{\sigma}}\right) \tag{6}$$

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The linewidth function is $\tilde{\Gamma}_{\gamma\sigma} = \Gamma_{\gamma\sigma}\exp\left[-\left(\lambda_\theta/\omega_\theta\right)^2\left(2N_q+1\right)\right]$.

Here we present the obtained current as following formula:

$$I_L = \frac{e}{h}\sum_n Tr\int d\omega L_n \tilde{\Gamma}_L \tilde{G}^r(\omega - n\omega_\theta)\tilde{\Gamma}_R \tilde{G}^a(\omega - n\omega_\theta)\left[f_L(\omega) - f_R(\omega)\right] \tag{7}$$

Here $L_m = e^{-g(2N_{ph}+1)} I_m\left(2g\sqrt{N_{ph}\left(N_{ph}+1\right)}\right)e^{m\omega_q\beta/2}$, $\beta = 1/(k_B T_{ph})$, I_m is the m-th Bessel function of the complex argument. T_{ph} means the temperature of the phonon bath.

At zero temperature, as $m \geq 0$: $L_m = e^{-g} g^m / m!$ (8)

As $m < 0$, $L_m = 0$.

The TMR ratio of the system is defined as

$$\mathrm{TMR} \equiv [I_0 - I(\theta)]/I_0 \tag{9}$$

The tunneling currents at angle θ is $I(\theta)$.

3. The numerical calculations

Now we discuss the numerical results for the current and the TMR in the system under the perturbation of phonon. From the study of the currents flowing through the center QD and the ferromagnetic terminals we can find that they have different behaviors. The current depends on the spin-flip effect related to the polarization angle. The spin-flip effect leads to TMR effect in the magnetic tunnel junction between the quantum dot and the lead. The understanding of TMR is very complicated due to the micro tunneling process and the spin correlation of multi - bodies. For simplicity , we consider a single level QD by using $\varepsilon d = 0$ .We choose $\Delta = 1.0$ meV as the energy unit in the following numerical calculation. We set the polarization angle of the terminals to be zero $\theta_L = 0$ and$\theta_R = \theta$. The temperature of electron and phonon are chosen as Tq = Te = T. We choose the chemical potential of the right lead $\mu_R = 0$, and the bias voltage eV = μ_L. The current is scaled by *eΔ/h*. The parameters in our numerical calculations are chosen as eV = 2.5Δ, $K_B T = 0.1$. $\Gamma_{L\uparrow} = \Gamma_{R\uparrow} = 0.3\Delta$, $\Gamma_{L\downarrow} = \Gamma_{R\downarrow} = 0.09\Delta$,$\lambda = 1.0\Delta$, $\omega_q = 1.0\Delta$.

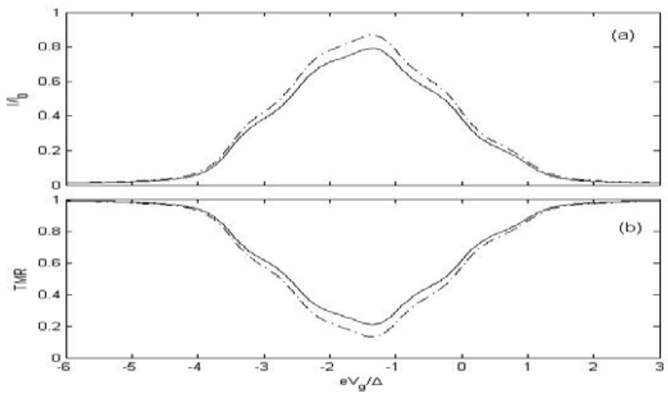

Figure 2 The current (a) and TMR ratio (b) versus the gate voltage V_g .
e$V = 0.8\Delta$, $\theta = 0.5\pi$ (dotted line) , $\theta = 0.7\pi$ (solid line).

In Fig. 2 the curves of the current and TMR versus the gate voltage V_g are presented. We plot two different lines for TMR and current at $\theta = 0.5\pi$ (dotted line) , $\theta = 0.7\pi$ (solid line).The spin-polarized current through the device can produce very interesting behavior. The current increase with the increase of the magnitudes of θ. It means that TMR is complex depending on the polarization angle and the magnitude of the gate voltage. The phonon-assisted behaviors strongly modify the mesoscopic transport. The spin-polarized tunneling current component flowing through the center QD and the terminals is related to both spin-up and spin-down current components. This spin flip effect links to the transfer matrix. It makes TMR complex to associate with the polarization angle of the magnetic moment. In the picture above we can see that TMR decrease with increasing the polarization angle.

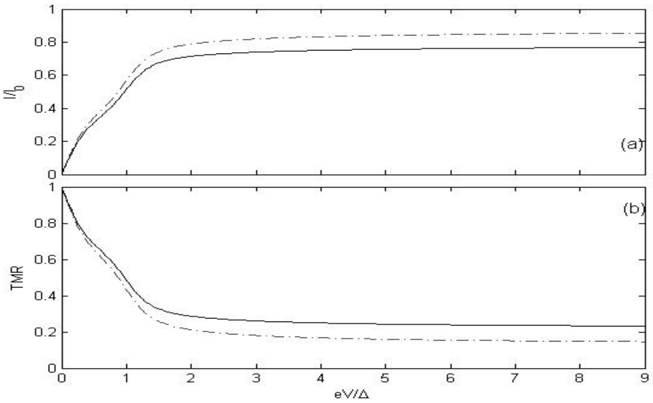

Figure 3 The electronic current (a) and TMR ratio (b) versus the source-drain bias eV . $\theta = 0.5\pi$ (dotted line) , $\theta = 0.7\pi$ (solid line).

We study the influence of the bias voltage on the electronic current and TMR with different angles. The numerical results we obtained are plotted in Fig. 3. At $eV_g = 0$,two curves are plotted. When the bias voltage is adjusted high enough, the curves become plat. As the polarization angle increases, the TMR steps are flattened. It is found that the magnitude of TMR is closely related to the polarization angle. The TMR ratio decreases obviously with the increase of the source-drain bias eV . Interestingly, the TMR ratio presents a step like curves. This is caused by many small substeps that appear in the current curve. The results show that electron-phonon interaction can lead to the emergence of companion peaks, which are pinned at positions where the energy is equal to an integer multiple of the phonon frequency. The phonon absorption andandemission process may cause many small substeps in the current curve.

4. Conclusion

To summarize, We give the quantum transport theory of current and TMR in mesoscopic ferromagnetic system under phonon perturbation. The current and Green function theoretical derivation in our research is based on NGF technology. The TMR ratio of the system can be controlled through adjusting the external parameters, such as the angle θ between the two leads, and source-drain bias. The phonon absorption andemission process may cause many small substeps in the current curves. And the substeps in the current may lead the TMR appears the same substeps like curve. We also find the suppression effect in the current and TMR because of the increase of the polarization angle. The present calculated results show that the TMR complicatedly depend on the polarization angle of the leads, gate voltages of QD and the source-drain bias eV .

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