Tunneling magnetoresistance effect in ferromagnet-quantum dot-ferromagnet system

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Abstract. We study the tunneling magnetoresistance (TMR) effect in Ferromagnet-quantum dot-Ferromagnet (FM-QD-FM) system by nonequilibrium Green's functions (NGF) method. From the study of TMR-eV curves, we find that the linewidth function has huge influence on the tunneling magnetoresistance effect. The tunneling magnetoresistance effect is also influenced by the relative angle of magnetic moment in the ferromagnetic leads in the quantum dot system.

1. Introduction
With the development of nanotechnology, the field of spintronics has attracted much attention from both fundamental and application points of view [1-4]. One of the phenomena in magnetic tunnel junctions is the so-called tunnel magnetoresistance (TMR) effect. TMR states that the tunneling current through the junction depends sensitively on the relative orientation of the magnetizations of both ferromagnetic electrodes, that is caused by the spin-dependent scattering of conduction electrons.

The tunneling magnetoresistance (TMR) in a spin valve geometry is one of the widely studied spin-dependent transport phenomena in which two ferromagnetic leads are separated by an insulating layer serving as a tunneling barrier. It has recently attracted intensive investigations both experimentally and theoretically [5-12]. The TMR in such system is strongly influenced by the spin dependent single charge tunneling across the system via the discrete levels of the QD. Several authors have analyzed a FM-QD-FM system. It is shown that in both the free and the Coulomb blockade regimes, the presence of the spin-flip interaction may lead to significant reduction in the TMR effect [9]. Previous theoretical works on spin-dependent transport through QDs are mainly focused on the tunnel electrical current and the TMR effect for collinear configuration [13-16] and noncollinear configuration [17-20]. In the presence of an ac field, important transport properties such as the frequency dependent current, differential conductance, and shot noise can be calculated theoretically and measured experimentally.
In this paper, we examine the tunneling magnetoresistance effect of the device with a QD coupled to two ferromagnetic terminals under the irradiation of microwave fields. The spin-polarized electrons absorb and emit photons during their transport under the perturbation of the fields.

The motivation for employing the specific effects of spin in materials naturally enables scientists to contrive novel spintronic nano-devices for magnetoelectrical applications. To construct spintronic devices, one should generate the spin polarized electrons to tunnel through a definite device. Ferromagnetic lead-based spintronic devices have been widely researched in recent years [21-25]. Using ferromagnetic electrodes, the scattering region becomes spin polarized by the local exchange field and we can construct spin filters, spin transistors and spin memories. The spin-valve effect also exists in ferromagnetic leads coupled systems.

In this paper, we examine the TMR of the device with a QD coupled to two ferromagnetic terminals under the irradiation of microwave fields. The spin-polarized electrons absorb and emit photons during their transport under the perturbation of the fields. The current correlations are contributed by both the charge and spin degrees of freedom, and the TMR displays nontrivial behaviours associated with the polarization angle of the ferromagnetic terminals.

This paper is organized as follows. In Sec. 2, we present the Hamiltonian of our system and detailed algebraic expressions by nonequilibrium Green’s functions (NGF), and the matrix form of the current and TMR formulas are given there. The numerical results and analyses are given in Sec. 3. The final section is arranged for conclusion remarks.

2. Model and formalism

We consider the system of a quantum dot coupled to the left and right ferromagnetic terminals in order to present a more general current formula for the mesoscopic transport. We build the spin nano-device prototype as ferromagnet-QD-ferromagnet (FM-QD-FM) structure shown in figure 1. The magnetic moment $M_\gamma$ of the $\gamma$-th electrode is tilted at angle $\theta_\gamma$ to the ez direction, where ez is the unit vector perpendicular to the direction of tunnelling current ex. The Hamiltonian of our system can be written as the usual expression [26].

$$H = \sum_{\gamma=\{L,R\}} \left[ E_{\gamma \sigma} (t) - \sigma M_\gamma \cos \theta_\gamma \right] a_{\gamma \sigma}^+ a_{\gamma \sigma} - M_\gamma \sin \theta_\gamma \left( a_{\gamma \sigma}^+ a_{\gamma \sigma} - \frac{1}{2} \right) + \sum_{\gamma=\{L,R\}} \left[ T_{\gamma \sigma} \right] d_{\gamma \sigma}^+ d_{\gamma \sigma} + \text{H.c.}$$

(1)

where $\gamma \in \{L, R\}$. In the Hamiltonian, $a_{\gamma \sigma}^+$ and $a_{\gamma \sigma}$ represent the creation and annihilation electron operators of the $\gamma$-th ferromagnetic terminals. $d_{\gamma \sigma}^+$ and $d_{\gamma \sigma}$ are the creation and annihilation electron operators of the QD. $E_{\gamma \sigma} (t) = E_{\gamma \sigma} + \Delta_\gamma \cos (\omega t)$ are the isolated energies of terminals and $E_d (t) = E_d + eV_g + \Delta_g \cos (\omega t)$ is the isolated energy of QD, where $\omega$ is the frequency of the
ac fields. The magnitude $M = \frac{1}{2} g \mu_B \hbar$ is associated with the Bohr magneton $\mu_B$. $T_\gamma$ is the coupling strength of central QD with the $\gamma$-th ferromagnetic terminal. \textit{H. c.} means hermitian conjugation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Schematic diagram of a quantum dot (QD) coupled to two ferromagnetic leads under the perturbation of ac fields.}
\end{figure}

We further make the transformation over the Hamiltonian by introducing the creation and annihilation operators of quasi-particles $\alpha_\gamma^+\sigma$ and $\alpha_\gamma\sigma$ via the unitary transformation $a_{\alpha\sigma} = \alpha_{\alpha\sigma}\cos \frac{\theta_\gamma}{2} - \sigma \alpha_{\alpha\sigma}\sin \frac{\theta_\gamma}{2}$. $\overline{\sigma}$ is also spin which takes the opposite value with $\sigma$. This procedure transforms the spin-flip effect from the ferromagnetic terminals to the tunneling terms.

The interaction terms between the ferromagnetic leads and the QD are now written as the elements $\tilde{T}_{\alpha\gamma\sigma\sigma'}$ of the interaction strength matrix $\tilde{T}_{\alpha\gamma} = \tilde{T}_{\alpha\gamma} R(\theta_\gamma)$ in the spin-space, where the rotation matrix is characterized by the following matrix with its offdiagonal elements describing the spin-flip effect

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

So the total Hamiltonian of the system after the transformation

$$H = \sum_{j\kappa\sigma} \tilde{\varepsilon}_{j\kappa\sigma} a_{j\kappa\sigma}^+ a_{j\kappa\sigma} + \sum_{\sigma} \left[ \varepsilon_d d_\sigma^+ d_\sigma + \frac{1}{2} U n_\sigma n_\sigma \right]$$

$$+ \sum_{\gamma\kappa\sigma\sigma'} \left( a_{\gamma\kappa\sigma}^+ \tilde{T}_{\gamma\kappa,\sigma\sigma'} d_\sigma + H.c. \right)$$

The tunnelling current in the $\gamma$-th lead is determined by the Heisenberg equation and the electron continuity equation

$$i \frac{\delta}{\delta t} N_\gamma = [\hat{N}_\gamma, H] = \dot{\hat{N}}_\gamma H - H \dot{\hat{N}}_\gamma$$

$$\dot{\hat{N}}_\gamma = \sum_{\kappa\sigma} a_{\gamma\kappa\sigma}^+ a_{\gamma\kappa\sigma}$$
where $J_\gamma$ is the current density of the $\gamma$-th terminal. Substituting the Hamiltonian of our system into the corresponding formulas, we arrive at the current operator of the $\gamma$-th terminal. By making the second unitary transformation over the annihilation and creation electron operators, one can write the current operator to be described by the quasiparticles of the $\gamma$-th terminal

$$I_\gamma = \frac{e}{\hbar} \text{Tr} \int d\varepsilon \left( \sum_{\langle \sigma \rho \rangle \text{ even}} J_\gamma^2 (\Lambda_\gamma) J_\rho^2 (\Lambda_\rho) T_{\gamma \rho} (\varepsilon) \times \left[ f_\gamma (\varepsilon - n\hbar) - f_\rho (\varepsilon - n\hbar) \right] \right)$$

The current of the $\gamma$-th terminal is obtained by taking the ensemble average over the tunnelling current operator $I_\gamma = \langle \hat{I}_\gamma (t) \rangle$. The trace Tr is taken over the spin space. The transmission matrix is given by $T_{\gamma \rho} (\varepsilon) = \Gamma_\gamma G^r_\gamma (\varepsilon) \Gamma_\rho (\varepsilon)$. Compared with our former papers [27-28], this formula describes the photon-assisted spin-polarized current, and the spin-flip effect contributes significantly to the current.

The Green’s function matrix can be expressed using the Green’s functions of the terminals and the QD by employing the equation of motion (EOM) method and Langreth relations [27-30]. The retarded Green’s function has been obtained in the studies of transport.

$$G^r_{\sigma \sigma'} (\varepsilon) = \frac{\nu_{\sigma \sigma'} (\varepsilon) \xi_{\sigma \sigma'} (\varepsilon) \delta_{\sigma \sigma'} + \eta_{\sigma \sigma'} (\varepsilon) \xi_{\sigma \sigma'} (\varepsilon) \delta_{\sigma \sigma'}}{\nu_{\sigma \sigma'} (\varepsilon) \nu_{\sigma \sigma'} (\varepsilon) - \eta_{\sigma \sigma'} (\varepsilon) \eta_{\sigma \sigma'} (\varepsilon)},$$

where we have used the notations $\xi_{\sigma \sigma'} (\varepsilon) = \varepsilon - \varepsilon_d - U \left( 1 - \langle n_\sigma \rangle \right)$, $\nu_{\sigma \sigma'} (\varepsilon) = \zeta_{\sigma \sigma'} (\varepsilon) \kappa (\varepsilon) - U \langle n_\sigma \rangle \Sigma^r_{\sigma \sigma'} (\varepsilon)$, $\eta_{\sigma \sigma'} (\varepsilon) = \Sigma^r_{\sigma \sigma'} (\varepsilon) \left[ \kappa (\varepsilon) + U \langle n_\sigma \rangle \right]$, and $\zeta_{\sigma \sigma'} (\varepsilon) = \varepsilon - \varepsilon_d - \Sigma^r_{\sigma \sigma'} (\varepsilon)$. The occupation number of the QD is denoted by $\langle n_\sigma \rangle$, which should be calculated self-consistently through the equation $\langle n_\sigma \rangle = \frac{1}{2\pi} \int d\varepsilon G^<_{\sigma \sigma'} (\varepsilon)$. We wish to show the angle dependence of the tunneling conductance and the effect of the external perturbation of ac fields on the tunnel magnetoresistance (TMR). The angle-dependent TMR ratio is defined as

$$\text{TMR} \equiv \frac{[I_0 - I(\theta)]}{I_0}$$

where $I(\theta)$ and $I_0$ are the tunneling currents with the lead magnetizations at angle $\theta$ and parallel to each other ($\theta = 0$), respectively.
3. The numerical calculations

In this section we perform numerical calculations to examine the current and the TMR in FM-QD-FM system in the Coulomb blockade regime perturbed by ac fields. We only consider a single level QD system by setting $\epsilon_a = 0$ to study the behaviour of current around a single level. We take $\Delta = \hbar \omega = 1.0\text{meV}$ as the energy scale in the numerical calculation, which indicates all of the energy quantities are compared to it. The linewidths are considered to be energy independent in the wide-band limit, but to be spin-dependent. The parameters are chosen as $\Gamma_{L \uparrow} = \Gamma_{R \uparrow} = 0.3\Delta$, $\Gamma_{L \downarrow} = \Gamma_{R \downarrow} = 0.09\Delta$, $T = 0$, $U = 3.0\Delta$, $\Lambda_L = \Lambda_R = \Lambda = 1.0$. We set the polarization angle of the left terminal to be zero $\theta_L = 0$, and examine the heat generation variation at arbitrary polarization angle of the right terminal by denoting $\theta_R = \theta$. The chemical potential of the right lead is chosen as the energy zero point $\mu_R = 0$, and then the bias voltage is $eV = \mu_L$. The current and the derivative of the current are scaled by $e \Delta / h$ and $e^2 \Delta / h$, respectively.

The tunnelling current $I$ and the derivative of current $dI/dV$ versus source-drain bias $eV$ as the gate voltage $eV_g = 0$. (b) The derivative $dI/dV$ of the curves presented in (a).

The tunnelling current $I$ and the derivative of current $dI/dV$ versus source-drain bias $eV$ with different polarization angle $\theta$ are depicted in figure 2(a) and 2(b), respectively. We consider the situation that the system is applied by the ac fields with the same magnitudes for $\Lambda_L = \Lambda_R = \Lambda = 1.0$.

In diagram (a) we present the tunnelling current $I$ versus the source-drain bias $eV$ as the gate voltage $eV_g = 0$. The tunnelling current increases rapidly by increasing the source-drain bias. One
can see that there are many small substeps emerge in the current curves because of the photon-assisted tunneling processes. The differential conductance provides more detailed information about the ferromagnet system, and is presented in figure 2(b) for a changing source-drain bias. Many side-peaks emerge around $eV = 0$ and $eV = U$ due to the photon irradiation. The heights of the peaks are intimately related to the polarization angle in FM-QD-FM system.

![Figure 2](image)

**Figure 2.** Angle dependence of the electronic current (a) and TMR ratio (b) versus the source-drain bias $eV$ for the gate voltage $eV_g = 0$ with $\theta = 0.5 \pi$ (dotted line) and $\theta = 0.7 \pi$ (solid line).

In figure 3 we show angle dependence of the electronic current and TMR ratio versus the source-drain bias $eV$. Different curves are plotted for different polarization angles, and the magnitude of TMR is intimately related to the polarization angle in FM-QD-FM system. It is interesting to see that the $\theta$ dependence of the TMR ratio shows a step like curves. That is induced by the many small substeps emerge in the current curves because of the photon-assisted tunneling processes. The TMR ratio decreases rapidly by increasing the source-drain bias. The heights of the steps are intimately related to the polarization angle in FM-QD-FM system. The tunnelling current and TMR are contributed to by the spin-splitting and spin-flip effects described by the spin-diagonal and offdiagonal elements of linewidths in the terminals. This causes the transmission of electrons to be described by the spin-flip transport strongly adjusted by the polarization angle.
Figure 4. (a) The tunnelling current $I$ versus the gate voltage $V_g$ as the source-drain bias $eV = 0.8\Delta$. (b) The derivative $dI/dV_g$ of the curves presented in (a).

In figure 4 we show the tunnelling current $I$ and the derivative of current $dI/dV$ versus the gate voltage $V_g$ with different polarization angle. In diagram (a) we present the pumping current $I$ with respect to the gate voltage $V_g$. A photon induced step emerges on the left side of the peak located at $eV_g = 0$, and two left steps emerge on the second peak located at about $eV = U$. One observes that the current decreases with increasing the spin polarization angle, in diagram (a). The heights of the steps and peaks are dependent on the polarization angle. Diagram (b) is the derivative of the tunnelling current $dI/dV_g$, which displays a peak-valley structure at $eV_g = 0$ and $3\Delta$ accompanied by the side peaks located at $eV_g = n\hbar\omega$. The spin polarization effect is clearly exhibited at the peaks and valleys.

In order to make further investigation on the spin polarization originated from the ferromagnetic terminals, we present the TMR versus the gate voltage $V_g$ at different magnitudes of $\theta$ in figure 5. It is clear seen that the TMR varies with polarization angle. The TMR decreases with increasing the magnitudes of $\theta$ in the regime $-2\Delta < eV_g < 1.5\Delta$. The TMR increases with increasing the magnitudes of $\theta$ in the regime $1.5\Delta < eV_g < 5\Delta$. This means that the suppression and enhancement of TMR for different absorption and emission cases are sensitively dependent on the magnitudes of the gate voltage and the polarization angle. The spin polarized tunnelling current components are correlated with both of the spin-up and spindown current components. This spin-flip effect contributes to the
transmission matrix, and hence makes the noise complicatedly rely on the polarization angle of the magnetic moment.

\[
\begin{align*}
\text{Figure 5.} \quad \text{Angle dependence of the electronic current (a) and TMR ratio (b) versus the gate voltage } V_g \\
\text{for } eV = 0.8\Delta \text{ with } \theta = 0.5\pi \text{ (dotted line) and } \theta = 0.7\pi \text{ (solid line).}
\end{align*}
\]

4. Conclusions
We have investigated the tunnel magnetoresistance (TMR) effect in Ferromagnet-quantum dot-Ferromagnet system by nonequilibrium Green's functions method. The spin polarized electrons are driven by the source-drain bias and the polarization angle associated with the orientation of polarized magnetic moment of electron in the ferromagnetic terminals contributes significant effect to TMR effect. There are many small substeps emerge in the current curves because of the photon-assisted tunneling processes. The suppression effect due to increasing the polarization angle can also be found in the current and TMR. The tunnelling current and TMR are contributed to by the spin-splitting and spin-flip effects described by the spin-diagonal and off-diagonal elements of linewidths in the terminals. This causes the transmission of electrons to be described by the spin-flip transport strongly adjusted by the polarization angle. The spin polarized tunnelling current components are correlated with both of the spin-up and spin-down current components. This spin-flip effect contributes to the transmission matrix, and hence makes the current complicatedly rely on the polarization angle of the magnetic moment. The photon-assisted spin-splitting and spin-polarization effect contributes a photon-assisted spin valve to adjust the electron tunneling current and the correlation of spin-polarized currents. These concrete effects indicate that the spin and photon controllable current exhibits significant features associated with spintronic devices.
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