TMR Effect in a FM-QD-FM System

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Using the Keldysh nonequilibrium technique, we study current and the tunnelling magnetoresistance (TMR) in a quantum dot coupled to two ferromagnetic leads (FM-dot-FM). The current is calculated for both parallel and antiparallel lead alignments. Coulomb interaction and spin-flip scattering are taken into account within the quantum dot. Interestingly, we find that these interactions play a contrasting role in the TMR: there is a parameter range where spin flip suppresses the TMR, while Coulomb correlations enhance it, due to Coulomb blockade.

1 Introduction

Tunnelling magnetoresistance (TMR) describes the change in the resistance of a FM-insulator-FM system when the ferromagnet leads switch their relative polarization alignments from a parallel (P) to an anti-parallel (AP) configuration. This effect was discovered by Julliere [1] in a Co/Ge/Fe junction; he observed a resistance change $\Delta R/R$ of nearly 14% at 4.2K and zero applied bias. This effect, however, was significantly suppressed when a voltage of few meV was applied across the junction. In 1995 Moodera *et al.* [2] succeeded in significantly improving the TMR ratios: values of $\Delta R/R$ close to 11% at 295K and 24% at 4.2K were reported. In addition, $\Delta R/R$ remained almost independent of the dc bias up to about 100 mV in this experiment. The TMR is important for several technological applications. These encompass magnetic-field sensors [3], hard-disk read heads [4], and non-volatile storage devices [5].

Here we use a quantum dot in between the ferromagnetic leads, instead of the usual insulator layer as in the standard TMR setup. In a FM-QD-FM system the quantum dot plays a role in the transport properties, thus giving rise to new physics not present in the usual FM-I-FM junction. For example, this system can exhibit Coulomb blockade [6]-[8] and the Kondo effect [9]-[11]

In this work, we are particularly interested in the interplay of spin-flip scattering and electron-electron interaction effects on the TMR. We assume that both the spin flip and Coulomb correlations act only within the dot. In addition, the tunnelling processes from the leads into the dot and vice versa are assumed spin conserving [12]. Our approach is based on the Keldysh nonequilibrium technique [13]. Within this framework, we develop a set of coupled equations involving the retarded, advanced, and lesser Green functions. We then express the current in the leads η = L (Left), R (Right) for both P and AP configurations in terms of these Green functions. We calculate the TMR ratio from the usual definition

$$TMR = \frac{I_P - I_{AP}}{I_{AP}}, \quad (1)$$

where I_P (I_{AP}) is the current in the parallel (antiparallel) configuration.

Our main results are as follows. We find that both the Coulomb interaction and the spin flip scattering within the dot play crucial roles in the transport properties of our FM-QD-FM system. On the TMR, for instance, spin flip tends to wash out this effect, which is consistent with experimental findings [12]. On the other hand, Coulomb interaction tends to enhance the TMR in the Coulomb blockade regime [14].

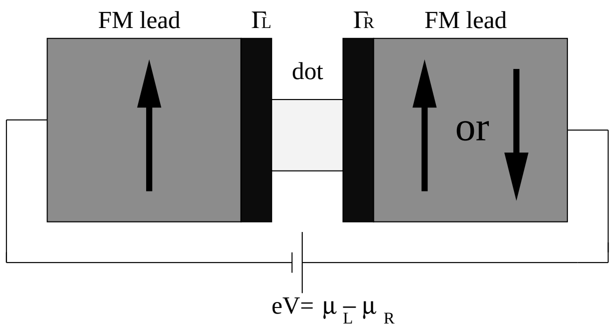

Figure 1. Schematics of the system investigated: two ferromagnetic leads attached to a quantum dot via tunnelling barriers. An applied bias V across the system gives rise to a lead chemical potentials imbalance, $eV = \mu_L - \mu_R$, which produces a net current through the device.

2 Model Hamiltonian

Our FM-QD-FM system consists of two FM leads coupled to a quantum dot via tunnelling barriers, Fig. 1, with tunnelling rates Γ_σ^L and Γ_σ^R, where σ is the spin index and L and R denote left and right leads, respectively. The lead chemical potentials differ by $eV = \mu_L - \mu_R$ due to the applied bias V (here $e > 0$). The dot is supposed to have only one spin-degenerate level ϵ_d in the absence of interactions. We assume a linear voltage drop across the system so that $\epsilon_d = \epsilon_0 - eV/2$, where ϵ_0 is the energy level position for zero bias. This assumption does not account for charging effects in the dot, which in general give rise to a non-linear variation of ϵ_d with the bias voltage [15].

*Hamiltonian.*The FM-QD-FM Hamiltonian we use has the form

$$H = H_L + H_D + H_R + H_T. \tag{2}$$

In the above, $H_L = \sum_{k\sigma} \epsilon_{k\sigma L} c_{k\sigma L}^\dagger c_{k\sigma L}$ (H_R) describes the left (right) lead; the operator $c_{k\sigma L}$ ($c_{k\sigma L}^\dagger$) destroys (creates) an electron in the lead L with wave vector k and spin component σ, whose energy dispersion is $\epsilon_{k\sigma L}$. For a parabolic-band ferromagnet ("Stoner model"), $\epsilon_{k\sigma L} = \hbar^2 k^2/2m + \sigma\Delta$, where Δ denotes the exchange-induced spin splitting of the bands.

The second term in Eq. (2) is the dot Hamiltonian $H_D = \sum_\sigma \epsilon_d d_\sigma^\dagger d_\sigma + U n_\uparrow n_\downarrow + R(d_\uparrow^\dagger d_\downarrow + d_\downarrow^\dagger d_\uparrow)$ with d_σ ($d_\sigma^\dagger$) being the destruction (creation) operator for electrons in the dot, U the Coulomb interaction strength, and R the spin flip rate. The last term in (2) is the tunnelling Hamiltonian $H_T = \sum_{k\sigma\eta} \{t_{k\sigma} c_{k\sigma\eta}^\dagger d_\sigma + h.c.\}$, where $t_{k\sigma}$ is the coupling matrix. We neglect spin flip process in the tunnelling process, hence $t_{k\sigma}$ is spin conserving and does not mix different spin components. Note that H_T drives the system out of equilibrium when an external voltage is applied.

3 Non-equilibrium current

The current in lead η is given by $I_\eta = -e\langle \dot{N}_\eta \rangle$, where $N_\eta = \sum_{k\sigma} c_{k\sigma\eta}^\dagger c_{k\sigma\eta}$ is the total electron number operator and $\langle ... \rangle$ denotes a thermodynamic average. Using the Heisenberg equation of motion, we find $I_\eta = -ei\langle [H_T, N_\eta] \rangle$. This average is carried out in the non-equilibrium framework, which yields [16]

$$I_\eta = ie \int \frac{d\omega}{2\pi} \sum_\sigma \Gamma_\sigma^\eta [G_{\sigma\sigma}^< + n_\eta (G_{\sigma\sigma}^r - G_{\sigma\sigma}^a)], \tag{3}$$

where $\Gamma_\sigma^\eta = 2\pi \sum_k |t_{k\sigma}|^2 \delta(\epsilon - \epsilon_{k\sigma\eta})$ is the line-width function, which is proportional to the density of states $\rho_\sigma^\eta(\epsilon)$ of the lead η. The function Γ_σ^η defines also the tunnelling rates between the leads and the dot. $n_\eta(\omega)$ is the Fermi distribution function of the lead η. $G_{\sigma\sigma}^r$, $G_{\sigma\sigma}^a$, and $G_{\sigma\sigma}^<$ are the retarded, advanced, and lesser Green functions, respectively. They are all obtained via analytical continuation [17] and Fourier transform of the contour time-ordered Green function $G(\tau, \tau') = -i\langle T_c d_\sigma(\tau) d_\sigma^\dagger(\tau') \rangle$, where T_c is the contour time-ordering operator and τ and τ' are complex times running along the Keldysh contour. From Eq. (3) we determine the current in both P and AP cases, and then calculate the TMR which we discuss in the next section. Note that current is strictly conserved in our system, i.e., $I_L = -I_R$ which gives either I_P or I_{AP} depending on the lead alignment considered.

In our actual calculation, we assume that the density of states in the leads $\rho_\sigma(\epsilon)$ is energy independent (wide-band limit) and equal to $\rho_\sigma(\epsilon_F)$, where ϵ_F is the Fermi energy. Note that the spin imbalance in the leads translates into $\rho_\uparrow(\epsilon_F) \neq \rho_\downarrow(\epsilon_F)$ which in turn yields $\Gamma_\uparrow^L \neq \Gamma_\downarrow^L$ (incidentally, this gives rise to spin-polarized transport in the system). Hence, spin up electrons tunnel into the dot with a rate different from that for spin down electrons. More explicitly, in the parabolic band model the line-width function becomes

$$\Gamma_\sigma^L = \Gamma_0 \sqrt{1 + \sigma \frac{\Delta}{\epsilon_F}}. \tag{4}$$

By Taylor expanding Γ_σ^L in $\Delta/\epsilon_F < 1$ we find $\Gamma_\sigma^L \simeq \Gamma_0(1 + \sigma p)$ to lowest order, where $p = \Delta/2\epsilon_F$ is the degree of polarization of the leads and Γ_0 is the strength of lead-dot coupling. To simulate the P and AP alignments in our calculation, we use $\Gamma_\sigma^R = \Gamma_\sigma^L$ and $\Gamma_\sigma^R = \Gamma_{\bar{\sigma}}^L$, respectively, where $\bar{\sigma} = -\sigma$.

4 Results

In our numerical calculation we set Γ_0=10 μeV and $p = 0.4$ (40%). The temperature used is $k_B T = 0.17$ meV and the charging energy is $U = 1$ meV. We take $\mu_L = 0$ as the reference of zero energy so that $\mu_R = -eV$. We also assume $\epsilon_0 = 0.25$ meV. For zero bias we have $\epsilon_0 > \mu_L$, so that the dot is only slightly populated by electrons in this case. This small population arises from thermal excitations. The electrons start to resonantly tunnel into the dot when the level ϵ_d lines up with μ_L (the emitter lead), thus generating a net current.

Figure 2 shows the average current I against eV for both the P and AP cases and different spin flip rates. Note that the current increases initially due to the emergence of the on-resonance condition $\epsilon_d = \mu_L$. For temperatures much smaller than the level width, this enhancement of the current is very sharp and happens exactly at $\epsilon_d = \mu_L$. But here we use a temperature $k_B T$ much greater then Γ_σ ("level width"), so this enhancement is broadened as seen in Fig. 2. When the level ϵ_d is below μ_L the current tends to saturate in the Coulomb blockade regime between 1 and 2 meV in Fig. 2. However, at even higher biases the level $\epsilon_d + U$ comes in resonance with the emitter conduction band, thus giving rise to a new enhancement of the current. The current finally saturates when the two levels ϵ_d and $\epsilon_d + U$ are below μ_L. Note that the second resonance involves double occupancy in the dot.

For $R = 0$ Fig. 2 shows that $I_P > I_{AP}$. This is related to the distinct transmission coefficients of the P and AP configurations, which gives rise to the TMR effect. We show I_P only for $R = 0$ because it is basically insensitive to spin flip, while I_{AP} is dramatically affected by spin flip processes. Note also that I_{AP} tends to I_P as the spin flip rate increases.

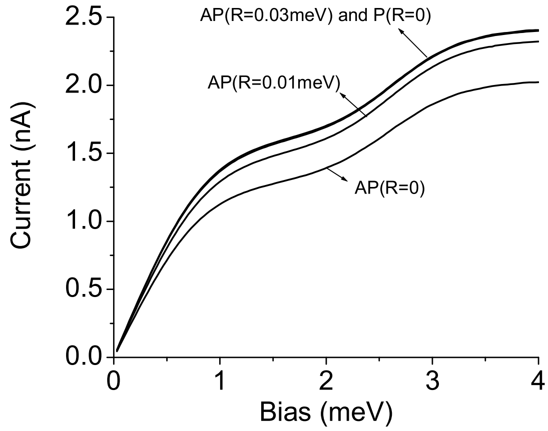

Figure 2. Current against eV for both the P and AP alignments and three spin flip rates. The two broad steps correspond to the levels ϵ_d and $\epsilon_d + U$. Observe that $I_P > I_{AP}$. This is due to the resistance difference between the two magnetic configurations. When spin flip takes place this difference is reduced, thus revealing that spin flip suppresses the resistance difference between the P and the AP cases.

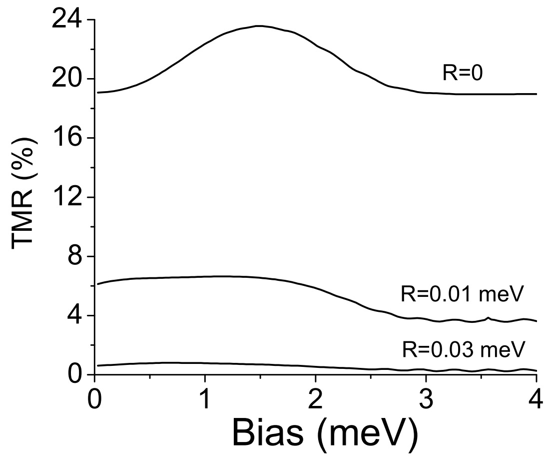

Figure 3. Tunnelling magneto resistance against eV for three spin flip rates. The TMR is strongly suppressed due to spin flip, approaching zero for $R = 0.03$ meV.

Figure 3 shows the TMR signal for three spin flip rates. For $R = 0$ the TMR is enhanced in the bias range $[0.5, 2.5\mathrm{meV}]$, peaking at 1.5 meV. This enhancement is due to Coulomb correlations which shift one spin channel to $\epsilon + U$, thus reducing the current which flows through the level ϵ, and increasing the resistance of the system. For $R = 0.01$ meV the TMR is significantly suppressed and for $R = 0.03$ meV it is close to zero. This shows that spin flip washes out the TMR. The effect of spin flip scattering on the TMR was reported experimentally in a FM-I-FM system, where the spin flip takes place in the insulator layer [12]. This experiment shows that the TMR is suppressed due to spin flip. Even though our system is different than that studied experimentally, the role of spin flip – which in our system is strictly confined to the dot – on the TMR presents a similar trend.

5 Conclusion

We have briefly described the effects of spin-flip scattering and the electron-electron interaction on the TMR of a quantum dot coupled to two ferromagnetic leads. We find that I_P is essentially insensitive to spin flip, while I_{AP} is dramatically affected by these processes thus tending to I_P as the spin flip rates increase. Hence spin flip suppresses TMR. On the other hand, electron-electron interaction in the dot enhances the TMR due to Coulomb blockade.

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