Spin-relaxation and magnetoresistance in FM/SC/FM tunnel junctions

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The effect of spin relaxation on tunnel magnetoresistance (TMR) in a ferromagnet/superconductor/ferromagnet (FM/SC/FM) double tunnel junction is theoretically studied. The spin accumulation in SC is determined by balancing of the spin-injection rate and the spin-relaxation rate. In the superconducting state, the spin-relaxation time \( \tau_s \) becomes longer with decreasing temperature, resulting in a rapid increase of TMR. The TMR of FM/SC/FM junctions provides a useful probe to extract information about spin-relaxation in superconductors.

Spin-polarized tunneling plays an important role in the spin-dependent transport of magnetic nanostructures [1]. The spin-polarized electrons injected from ferromagnets (FM) into nonmagnetic metals (NM) such as a normal metal, semiconductor, and superconductor creates a nonequilibrium spin polarization in NM [2, 3]. The efficient spin injection and weak spin-relaxation during transport across the junctions are required for practical applications. A number of experiments for observing the spin relaxation time \( \tau_s \) in SCs has been reported by using a spin-injection device [4] and by the conduction electron spin resonance [5, 6].

A double tunnel junction FM/SC/FM containing superconductor (SC) sandwiched between two FMs is a unique system to investigate nonequilibrium phenomena caused by spin injection, especially the magnetoresistive effects by competition between superconductivity and spin accumulation [1, 7]. The pronounced magnetoresistance effects is brought about by a long spin relaxation time \( \tau_s \) in SC, which corresponds to a long spin-diffusion length. In this article, we take into account the coherence effect of superconductivity on the spin-relaxation due to spin-orbit scattering by impurities [8].

Spin-relaxation in SCs has been reported [9, 10], particularly the magnetoresistive effects by competition between superconductivity and spin accumulation [11, 12]. In the following we consider the case that the bias voltage \( V \) is much smaller than the superconducting gap parameter \( \Delta \). In this case, the shift of chemical potential \( \delta \mu \) for up-spin (down-spin) electrons due to spin accumulation is much smaller than \( \Delta \), so that the tunnel current \( I_s \) across the junction \( (i = 1, 2) \) becomes

\[
\begin{align*}
I_s^1(V) &= G_s^1 \chi(T) \left[ V/2 - \delta \mu/e \right], \\
I_s^2(V) &= G_s^2 \chi(T) \left[ V/2 + \delta \mu/e \right], \\
I_s^3(V) &= G_s^3 \chi(T) \left[ V/2 + \delta \mu/e \right], \\
I_s^4(V) &= G_s^4 \chi(T) \left[ V/2 - \delta \mu/e \right].
\end{align*}
\]

Here, \( G_i^\sigma \chi(T) \) \((i = 1, 2)\) is the tunnel conductance for electrons with spin \( \sigma \) in the superconducting state, \( G_i^\sigma \) is that in the normal state, and \( \chi(T) \) is given by

\[
\chi(T) = 2 \int_\Delta^\infty \frac{E_k}{\sqrt{E_k^2 - \Delta^2}} \left( -\frac{\partial f_0}{\partial E_k} \right) dE_k,
\]

where \( f_0(E_k) \) is the Fermi distribution function and \( E_k = \sqrt{\xi_k^2 + \Delta^2} \) the dispersion of quasiparticles, \( \xi_k \) being one-electron energy relative to the chemical potential.

The spin density \( S \) accumulated in SC is determined by balancing the spin injection rate \( (dS/dt)_{\text{inj}} \) with the spin relaxation rate \( S/\tau_s \):

\[
(I_{1\uparrow} - I_{1\downarrow}) - (I_{2\uparrow} - I_{2\downarrow}) = 2eS/\tau_s,
\]
where $\tau_s$ is the spin relaxation time and

$$S = \frac{1}{2} \sum_k [f_\uparrow(E_k) - f_\downarrow(E_k)] \approx N(0) \chi(T) \delta \mu,$$  \hspace{1cm} (7)

where $f_\sigma(E_k) \sim f_\sigma(0) - (\partial f_\sigma/\partial E_k) \sigma \delta \mu$ is the distribution function of quasiparticles with spin $\sigma$ and $N(0)$ is the normal-state density of states in SC.

It follows from Eqs. (1)-(7) that the tunnel currents for the parallel (P) and antiparallel (AP) alignments are given by

$$I_P = \chi(T)V/R_T,$$  \hspace{1cm} (8)

$$I_{AP} = \left[1 - \frac{P^2 + x_s}{1 + x_s}\right] \chi(T)V/R_T,$$  \hspace{1cm} (9)

where $R_T = 1/G_T$ is the tunnel resistance and $\Gamma_s$ is the relaxation parameter

$$\Gamma_s = e^2 N(0) R_T A d / \tau_s,$$  \hspace{1cm} (10)

with $A$ being the junction area. Therefore, we have the TMR ratio at low bias ($V \ll \Delta$)

$$TMR = \frac{I_P - I_{AP}}{I_{AP}} = \frac{P^2}{1 - P^2 + \Gamma_s},$$  \hspace{1cm} (11)

where $P = (G_1^\uparrow - G_1^\downarrow)/(G_1^\uparrow + G_1^\downarrow)$ is the tunneling spin polarization. For a weak spin relaxation ($\Gamma_s \ll 1$), $TMR = P^2/(1 - P^2)$, while for a strong spin-relaxation ($\Gamma_s \gg 1$), $TMR = P^2/\Gamma_s \ll 1$.

In SC, the spin relaxation is caused by the spin-orbit scattering from impurities or grain boundaries. The spin-orbit interaction $H_{\text{so}}$ via impurity potential $V_{\text{imp}}(r)$ is given by

$$H_{\text{so}} = -i \hbar/(2mc)^2 \hat{\sigma} \cdot [\nabla V_{\text{imp}}(r) \times \nabla],$$  \hspace{1cm} (12)

where $\hat{\sigma}$ is the Pauli spin matrix. The scattering matrix elements over quasiparticle states $|k\sigma\rangle$ have the form:

$$\langle k'\sigma'\mid H_{\text{so}} \mid k\sigma\rangle = i \lambda_{\text{so}} \vec{V}_{k'k} \left[ \hat{\sigma}_{\sigma'\sigma} \cdot (\vec{k} \times \vec{k'} \mid) \right],$$  \hspace{1cm} (13)

where $\lambda_{\text{so}}$ is the spin-orbit coupling parameter, $\vec{V}_{k'k} = (u_{k'k} u_k - v_{k'k} v_k) V_{\text{imp}}$, $|u_k|^2 = 1 - |v_k|^2 = k^2/(1 + \xi_k/E_k)$, and $\vec{k} = \vec{k}/|k|$. Using the golden rule formula, we obtain the spin-relaxation rate due to the spin-flip scattering by $H_{\text{so}}$:

$$\frac{\partial S}{\partial t}_s \approx \frac{2\pi}{\hbar} n_i \sum_{k'k} |\langle k'\downarrow\mid H_{\text{so}}\mid k\uparrow\rangle|^2 \delta(E_k - E_{k'})$$

$$\times \int_\Delta \left[ f_\uparrow(E_{k'}) - f_\downarrow(E_k) \right] dE,$$  \hspace{1cm} (14)

where $1/\tau_{\text{imp}} = (2\pi/\hbar) n_i V_{\text{imp}}^2 N(0)$ is the scattering rate by impurities and $n_i$ is the impurity concentration.

From Eqs. (12) and (13), we determine the relaxation time $\tau_s$ from $(\partial S/\partial t)_s = -S/\tau_s$, and obtain

$$\tau_s = \tau_{sf} \frac{\int_\Delta E \epsilon - \Delta S}{\epsilon - \Delta \int_\Delta \left[ f_\uparrow(E) - f_\downarrow(E) \right] dE},$$  \hspace{1cm} (15)

where $\tau_{sf} = 9 \tau_{\text{imp}}/8\lambda_{\text{so}}^2$ is the spin-flip scattering time in the normal state. Note that the expression of Eq. (15) is valid for $\epsilon - \Delta \gg \hbar \omega$. For $\delta \mu \ll \Delta$, Eq. (15) reduces to

$$\tau_s = \left[ \chi(T) / 2f_0(\Delta) \right] \tau_{sf},$$  \hspace{1cm} (16)

which is the same as the result of Yafet [15], but differs from the result of Zhao and Hershfield [16].

Equation (15) is a generalization of Yafet to the case of arbitrary value of $\delta \mu$.

The temperature dependence of the spin-relaxation parameter $\Gamma_s$ is scaled to the normalized spin-relaxation time $\tau_s/\tau_{sf}$ by the relation $\Gamma_s = (\tau_{sf}/\tau_s)^N$, where $\Gamma_s = e^2 N(0) R_T A d / \tau_{sf}$ is the relaxation parameter in the normal state. Figure 1 shows the temperature dependence of $\tau_s/\tau_{sf}$.
\[ \frac{\tau_s}{\tau_{sf}}. \] Above \( T = T_c \), the spin relaxation time \( \tau_s \) becomes longer with decreasing \( T \) and behaves as \( \tau_s \sim (\pi \Delta / 2 k_B T)^{1/2} \tau_{sf} \) at low \( T \).

Figure 2 shows the temperature dependence of the normalized TMR for different values of \( \Gamma_N^S \). The inset shows the TMR versus \( \Gamma_N^S \) in the normal state. In the case of \( \Gamma_N^S > 1 \), which corresponds to the case that the spin-relaxation rate is larger than the spin-injection rate in the normal state, the TMR above \( T_c \) is suppressed compared with the optimal value 33% for \( \Gamma_N^S = 0 \) and \( P = 0.5 \) as shown in the inset of Fig. 2. However, in the superconducting state below \( T_c \), the TMR increases rapidly with decreasing \( T \) due to the increase of \( \tau_s \), and recovers the optimal TMR in the limit of \( T \to 0 \). If one uses the values of \( R_T A = 100 \Omega \mu m^2 \), \( \tau_{sf} = 10^{-10} \text{sec} \), \( d = 10 \text{ nm} \), and \( N(0) = 10^{22}/(eV\text{cm}^3) \), then one obtains \( \Gamma_N^S = 10 \). Notice that in the case of strong spin-relaxation \( (\Gamma_N^S \gg 1) \), the TMR becomes proportional to \( \tau_s \), so that the temperature dependence of \( TMR/TMR(T_c) \) coincides with that of \( \tau_s/\tau_{sf} \) as shown by the dashed curve in Fig. 2. The result indicates that the TMR of FM/SC/FM junctions provides a method to extract important information about spin-relaxation in superconductors.

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