Spin injection and magnetoresistance in ferromagnet/superconductor/ferromagnet tunnel junctions

S. Takahashi, H. Imamura, and S. Maekawa
Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

We theoretically study the spin-dependent transport in a ferromagnet/superconductor/ferromagnet double barrier tunnel junction. The spin-polarized tunneling currents give rise to spin imbalance in the superconductor. The resulting nonequilibrium spin density suppresses the superconductivity with increase of the tunneling currents. We focus on the effect of asymmetry in the double tunnel junction, where the barrier height of the tunnel junction and the spin-polarization of the ferromagnets are different, on spin injection, and discuss how the superconductivity is suppressed in the asymmetric junction. Our results explain recent experimental results on the critical current suppression in high-\(T_c\) SCs by spin injection.

I. INTRODUCTION

Spin-polarized tunneling plays an important role in the spin-dependent transport of magnetic nanostructures \([1]\). First the spin-polarized tunneling causes a large magnetoresistance in ferromagnetic single tunnel junctions \([2]\); the tunnel resistance decreases when the ferromagnetic moments are aligned in a magnetic field \([3]\). Second the spin-polarized tunneling current driven from ferromagnets (FM) into a normal metal (N) or a superconductor (SC) creates a nonequilibrium spin polarization in N or SC \([4,5]\). Recent experiments have shown that a strong magnetoresistance in ferromagnetic single tunnel junctions \([2]\); the spin-polarized tunneling causes a large magnetic nanostructures \([1]\).

A double tunnel junction containing SC sandwiched between two FMs (FM/SC/FM) is a unique system to investigate the nonequilibrium phenomena of spin and charge imbalance in SC caused by the tunneling currents but also the competition between superconductivity and magnetism induced by spin polarization in SC. In a symmetric double junction, where the tunnel barriers and the ferromagnets are the same, we have predicted an intriguing magnetoresistive effect; in the antiferromagnetic (AF) alignment of magnetizations, the spin density accumulated in SC strongly reduces the superconducting gap \(\Delta\) with increase of tunneling currents, while in the ferromagnetic (F) alignment there is no such effect because of the absence of spin population in SC \([11]\). In this paper, we take into account the asymmetry in the junction, and discuss how the spin density is accumulated in SC and suppress the superconductivity of SC, depending on the difference in the tunnel resistance of the barriers and in the spin polarization of FMs.

II. FORMULATION

We consider a FM1/SC/FM2 double tunnel junction as shown in Fig. 1. The left and right electrodes are made of different ferromagnets and the central one is a superconductor with thickness \(d\). The magnetization of FM1 is chosen to point up and that of FM2 is either up or down. In the asymmetric tunnel junction, the height of the tunnel barriers and/or the strength of the ferromagnets are different, which are characterized by the different values of the tunnel resistance and those of the spin-polarization in the junction.

We calculate the tunneling current using a phenomenological tunneling Hamiltonian. If SC is in the superconducting state, it is convenient to rewrite the electron operators \(a_{k\sigma}\) in SC in terms of the quasiparticle operators \(\gamma_{k\sigma}\) using the Bogoliubov transformation

\[
a_{k\uparrow} = u_k \gamma_{k\uparrow} + v_k^* \gamma_{-k\downarrow}, \quad a_{-k\downarrow}^\dagger = -v_k \gamma_{k\uparrow} + u_k^* \gamma_{-k\downarrow},
\]

where \(|u_k|^2 = 1 - |v_k|^2 = \frac{1}{2} (1 + \xi_k/E_k)\) with the quasiparticle dispersion \(E_k = \sqrt{\xi_k^2 + \Delta^2}\) of SC, \(\xi_k\) being the one-electron energy relative to the chemical potential which is chosen to be zero and \(\Delta\) being the gap parameter. Then, using the golden rule formula, we obtain the spin-dependent currents \(I_{j\sigma}\) across the \(j\)th junction:

\[
I_{1\uparrow} = (G_{1\uparrow}/eD_S) \left[ N_1 - S - Q^*/2 \right], \quad (1a)
\]

\[
I_{1\downarrow} = (G_{1\downarrow}/eD_S) \left[ N_1 + S - Q^*/2 \right], \quad (1b)
\]

\[
I_{2\uparrow} = (G_{2\uparrow}/eD_S) \left[ N_2 + S + Q^*/2 \right], \quad (1c)
\]

\[
I_{2\downarrow} = (G_{2\downarrow}/eD_S) \left[ N_2 - S + Q^*/2 \right]. \quad (1d)
\]

FIG. 1. Double barrier tunnel junction consisting of two ferromagnets (FM1 and FM2) and a superconductor (SC) separated by thin insulating barriers.
Here, $G_{i\sigma}$ ($i=1, 2$) is the tunnel conductance of the $i$th junction for electrons with spin $\sigma$ if SC is in the normal state, and is given by $G_{i\sigma} \propto |T_{i\sigma}|^2 D_S D_F$ $P_{i\sigma}$, where $|T_{i\sigma}|^2$ is the tunneling probability of the $i$th junction and $D_S$ and $D_F$ are the spin-subband densities of states in SC and FMi, respectively. The quantity $N_i$ is given by \[ N_i = \frac{1}{2} \sum_k \left[ f_0(E_k - eV_i) - f_0(E_k + eV_i) \right], \] (2)

where $f_0$ is the Fermi distribution function of thermal equilibrium in FM and $V_i$ the voltage drop at the $i$th junction ($V_1 + V_2 = V$). The quantities $S$ and $Q^*$ are quasiparticle spin and charge densities in SC and are defined by

\[ S = \sum_k (f_{k\uparrow} - f_{k\downarrow}), \quad Q^* = \sum_{k\sigma} q_k f_{k\sigma}, \] (3)

where $f_{k\sigma} = \langle \gamma_{k\sigma}^1 \gamma_{k\sigma}^1 \rangle$ is the distribution function of quasiparticles with energy $E_k$ and spin $\sigma$ and $q_k = |u_k|^2 - |v_k|^2$ is the effective charge of a quasiparticle in the state $k$.

The conservation of total charge $Q_{\text{tot}} = \sum_k \langle \gamma_{k\uparrow}^1 \gamma_{k\uparrow}^1 \rangle$ in SC gives $I_{1\uparrow} + I_{1\downarrow} = I_{2\uparrow} + I_{2\downarrow}$, which yields the relation

\[ \left( g_1 P_1 + g_2 \tilde{P}_2 \right) S + Q^*/2 = g_1 N_1 - g_2 N_2, \] (4)

where $g_i = G_i/(G_1 + G_2)$ ($g_1 + g_2 = 1$) is the reduced conductance of $i$th junction, and

\[ P_1 = (G_{1\uparrow} - G_{1\downarrow})/G_1, \quad \tilde{P}_2 = (G_{2\uparrow} - G_{2\downarrow})/G_2, \]

where $\tilde{P}_2 = P_2$ for the F alignment and $\tilde{P}_2 = -P_2$ for the AF alignment of magnetizations. $P_1$ and $P_2$ are the degree of spin-polarization of FM1 and FM2.

The quasiparticle spin density $S$ generated in SC is calculated by balancing the spin injection rate $dS/dt_{\text{inj}} = [(I_{1\uparrow} - I_{1\downarrow}) - (I_{2\uparrow} - I_{2\downarrow})]/2e$ with the spin relaxation rate $S/\tau_S$, where $\tau_S$ is the spin-relaxation time. The result is

\[ S = \frac{g_1 g_2 (P_1 - \tilde{P}_2)}{1 - (g_1 P_1 + g_2 \tilde{P}_2)^2 + \Gamma_S} (N_1 + N_2), \] (5)

where $\Gamma_S = g_1 g_2 (\tau_\uparrow/\tau_S)$, $\tau_\uparrow = 2e^2 D_S (R_1 + R_2)$ is the tunneling time, and $R_1 = 1/G_1$. Note that the spin density in SC is proportional to the difference $P_1 - \tilde{P}_2$ for the F alignment and the sum $(P_1 + \tilde{P}_2)$ for the AF alignment.

The quasiparticle charge density $Q^*$ is obtained by balancing the injection rate $dQ^*/dt_{\text{inj}}$ with the relaxation rate $Q^*/\tau_{Q^*}$ \[ Q^* = -\left( \frac{\tau_{Q^*}}{\tau_\uparrow} \right) \sum_k \frac{\Delta^2}{E_k^2} [g_1 N_{1k} - g_2 N_{2k}] \]

\[ -(g_1 P_1 + g_2 \tilde{P}_2) (f_{k\uparrow} - f_{k\downarrow}), \] (6)

where $N_{ik} = (1/2)[f_0(E_k - eV_i) - f_0(E_k + eV_i)]$.

The superconducting gap $\Delta$ in SC is determined by $f_{k\sigma}$ through the BCS gap equation

\[ \frac{1}{V_{\text{BCS}}} = \sum_k \frac{1 - f_{k\uparrow} - f_{k\downarrow}}{E_k}. \] (7)

It follows from Eqs. (5) and (6) that, if the junction is symmetric, both $S$ and $Q^*$ vanish for the F alignment, while $S \neq 0$ and $Q^* = 0$ for the AF alignment. In the asymmetric case, $S$ and $Q^*$ become finite for both alignments. In the following, we restrict ourselves to the case $\tau_{Q^*} \ll \tau_\uparrow \ll \tau_S$, where the charge imbalance is very small ($Q^* \sim 0$), so that the nonequilibrium effect is dominated by the spin imbalance. In addition, the thickness of SC $d$ is much smaller than the spin diffusion length $l_S = \sqrt{D_S/\tau_S}$, $D$ being the diffusion constant, so that the distribution of quasiparticles is spatially uniform in SC. Then, the distribution function $f_{k\sigma}$ is described by $f_0$, but the chemical potentials of the spin-up and spin-down quasiparticles are shifted oppositely by $\delta \mu S$ from the equilibrium one to generate the spin density;

\[ f_{k\uparrow} = f_0(E_k - \delta \mu S), \quad f_{k\downarrow} = f_0(E_k + \delta \mu S). \] (8)

We solve self-consistently Eqs. (3) - (6) with respect to $\Delta$, $\delta \mu S$, and $V_i$, and obtain $\Delta$ and $S$ as functions of $V$. The results are used to calculate the total tunneling current $I_{\text{inj}} = I_{1\uparrow} + I_{1\downarrow}$:

\[ I_{\text{inj}} = \frac{1}{eD_S} \left( \frac{N_1 + N_2}{R_1 + R_2} \right) \left[ 1 - (g_1 P_1^2 + g_2 \tilde{P}_2^2) + \Gamma_S \right] \]

\[ 1 - (g_1 P_1 + g_2 \tilde{P}_2)^2 + \Gamma_S, \] (9)

which we call the injection current.

### III. RESULTS

We briefly discuss the tunnel magnetoresistance (TMR) in the normal state ($T > T_c$), in which $N_1 + N_2 = D_S eV$, so that the TMR ratio, $\Delta R/R_F = (R_A - R_F)/R_F$, has the form

\[ \frac{\Delta R}{R_F} = \frac{4g_1 g_2 P_1 P_2}{1 - (g_1 P_1 + g_2 \tilde{P}_2)^2 + \Gamma_S}. \] (10)

The TMR is degraded in the case of strong asymmetry in the conductances ($G_1 \ll G_2$ or $G_1 \gg G_2$). A large TMR ratio is obtained when the following conditions are satisfied; the tunnel barriers are similar ($R_1 \sim R_2$) and the spin relaxation time in SC is long compared with the tunneling time ($\tau_\uparrow/\tau_S < 1$). The latter condition is $\left( \rho_N/R_1 \right) + \left( \rho_N/R_2 \right) > \left( Ad/l_S^2 \right)$, where $\rho_N$ is the resistivity of SC in the normal state and $A$ the junction area, which requires a low junction resistance and/or a thin SC with $d$ much smaller than $l_S$. If these conditions are satisfied, we have the optimum ratio $\Delta R/R_F \sim P_1 P_2/(1 - P_1 P_2)$ in the normal state.
According to the Ginzburg-Landau theory, \( J_c \) in the AF alignment steeply decreases and vanishes at a small value of \( I_{\text{inj}} \), whereas \( J_c \) in the F alignment shows no dependence on \( I_{\text{inj}} \). In the case that FM1 and FM2 are different (middle panel), the critical current decreases with increase of injection current in both alignments but in different way; \( J_c \) decreases more slowly in the F alignment than in the AF alignment. If one of the ferromagnets, FM2, is replaced by a normal metal (N), we have a heterostructure junction FM1/SC/N, which corresponds to the junction with \( P_2 = 0 \) (top panel). The calculated result for \( P_2 = 0 \) explains the critical current suppression by spin injection observed in the heterostructure junctions consisting of a high-\( T_c \) SC and a ferromagnetic manganite with \( P \sim 100 \) [6-10].

**ACKNOWLEDGEMENTS**

This work is supported by a Grant-in-Aid for Scientific Research Priority Area for Ministry of Education, Science and Culture of Japan, CREST, and NEDO, and by the supercomputing facilities in IMR, Tohoku University.

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