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Physica C 463–465 (2007) 198–201
PHYSICA C
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Effect of magnons on the 0–π transition in a superconductor/half-metallic ferromagnet/superconductor junction

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Accepted 5 April 2007
Available online 24 May 2007

Abstract

We study the Josephson effect in an s-wave superconductor/dirty half-metal/s-wave superconductor (SC/HM/SC) junction by taking account of the spin dynamics due to the magnon excitation in the HM. Using the fourth order perturbation theory for the tunneling Hamiltonian and Green's function method, we formulate the Josephson critical current in a SC/HM/SC junction. In the tunneling process from the SC to the HM and vice versa, we consider the effect of spin flip tunneling due to the magnon excitation at the interface. As a result, it is found that the spin triplet pair correlation propagates into the HM and the Josephson current flows. We find that the Josephson critical current shows the damped oscillation as a function of the thickness of the HM and the 0–π transition occurs. Moreover, we show that the 0–π transition occurs by changing temperature. The 0–π transition results from magnon excitations in the HM. This proposes a new mechanism with respect to the 0–π transition.

PACS: 74.45.+c; 74.50.+r

Keywords: Josephson effect; Superconductor; Ferromagnet; Tunnel junction; Nanostructure

In a Josephson junction composed of a weak ferromagnet (FM) and s-wave superconductors (SC's), the singlet Cooper pairs penetrate into the FM, and have a finite momentum proportional to the magnetic exchange splitting (h_{ex}) between the up- and the down-spin bands in the FM. As a result, the singlet pair-amplitude (Ψ_s) oscillates along the direction perpendicular to the interface in FM [1–3]. Therefore, Ψ_s has either the same sign (0-state) or different sign (π-state) at the interfaces depending on the thickness (d_{FM}) of FM. Several experimental observations of the 0- and π-state have been reported [4–10].

The Josephson effect has been observed in the s-wave superconductor/half-metal/s-wave superconductor (SC/HM/SC) junction, where NbTiN was used as a SC and CrO_2 as a HM [11]. In the case of completely spin-polarized materials called HM, the spin singlet Cooper pairs cannot penetrate into the HM, and the Josephson current can not flow in the SC/HM/SC junction. Therefore, the experiment suggests that a spin triplet pair correlation may be induced in CrO_2 and the Josephson current is carried by the triplet pair correlation. The experiment shows that the correlation of Cooper pair in HM is rather long compared with that in FM.

There are some theoretical studies on SC/HM/SC junctions [12,13]. They showed that the spin triplet pairs are induced by the spin flip scattering at the interface of SC/HM and the Josephson current is carried by the triplet pair

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doi:10.1016/j.physc.2007.04.251

correlation. In these theoretical studies, the spin dynamics in HM is not treated.

In this paper, we study the Josephson effect in a SC/HM/SC junction by taking account of the spin dynamics due to magnon excitation in HM. We propose a new mechanism of Josephson effect in the SC/HM/SC junction. Moreover, we show that the 0–π transition occurs by changing the thickness (d_{HM}) of HM and temperature (T) in this system. The 0–π transition is obtained by the magnon excitation in HM.

We consider a junction composed of a dirty HM with the thickness d_{HM} sandwiched by s-wave SCs. The SCs and the HM are connected by tunneling Hamiltonian. The total Hamiltonian is

$$H^{\mathrm{L(R)}}_{\mathrm{BCS}} = \sum_{\boldsymbol{k},\sigma} \xi_{\boldsymbol{k}} c^{\dagger}_{\boldsymbol{k},\sigma} c_{\boldsymbol{k},\sigma} + \sum_{\boldsymbol{k}} \Delta \mathrm{e}^{\mathrm{i}\theta_{\mathrm{L(R)}}} c^{\dagger}_{\boldsymbol{k}\uparrow} c^{\dagger}_{-\boldsymbol{k}\downarrow} + \mathrm{h.c.}, \tag{1}$$

$$H_{\mathrm{HM}} = \sum_{\boldsymbol{p}} \xi_{\boldsymbol{p}} a^{\dagger}_{\boldsymbol{p},\uparrow} a_{\boldsymbol{p},\uparrow} + \frac{1}{V} \sum_{\boldsymbol{p},\boldsymbol{s}} u(\boldsymbol{s}) a^{\dagger}_{\boldsymbol{p}+\boldsymbol{s},\uparrow} a_{\boldsymbol{p},\uparrow}, \tag{2}$$

$$\begin{aligned} H_{\mathrm{T}} = {} & T_0 \sum_{\boldsymbol{k},\boldsymbol{p}} [c^{\dagger}_{\boldsymbol{k}\uparrow} c_{\boldsymbol{p}\uparrow} \mathrm{e}^{-\mathrm{i}(\boldsymbol{k}-\boldsymbol{p})\boldsymbol{R}_{\mathrm{L}}} + \mathrm{h.c.}] + (\mathrm{L} \to \mathrm{R}) \\ & + T_1 \sum_{\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}} [S^{+}(\boldsymbol{q}) c^{\dagger}_{\boldsymbol{k},\downarrow} a_{\boldsymbol{p},\uparrow} \mathrm{e}^{-\mathrm{i}(\boldsymbol{k}-\boldsymbol{p}-\boldsymbol{q})\boldsymbol{R}_{\mathrm{L}}} + \mathrm{h.c.}] + (\mathrm{L} \to \mathrm{R}), \end{aligned} \tag{3}$$

where $H^{\mathrm{L(R)}}_{\mathrm{BCS}}$ is the BCS mean field Hamiltonian of the left (right) SC, ξ_k is the kinetic energy of an electron, $c^{(\dagger)}_{\boldsymbol{k},\sigma}$ is the annihilation (creation) operator of the electron with wave vector $\boldsymbol{k}$ and spin σ, and Δ is a superconducting gap and $\theta_{\mathrm{L(R)}}$ is the phase variable in the left (right) SC. H_{HM} is the Hamiltonian of the HM, which has only up-spin electrons and non-magnetic impurity scattering term. The first term in H_{HM} is the kinetic energy of electrons, and the second term is a non-magnetic impurity scattering component, where u is a non-magnetic impurity potential, and V is the volume of HM. H_{T} is the tunneling Hamiltonian, in which T_0 is a tunnel matrix element without spin flip, T_1 is a tunnel matrix element with spin flip accompanied with a spin-wave. $S^{+} = S_x + \mathrm{i}S_y$ is a spin operator of a local moment in the HM. S_x and S_y are the x and y components of the local spin operator, respectively. $\boldsymbol{R}_{\mathrm{L(R)}}$ is the position of the left (right) interface of the SC/HM junction.

We calculate the fourth order term of the tunneling Hamiltonian and formulate the Josephson critical current in the SC/HM/SC junction. The Feynman diagram for this tunneling process is shown in Fig. 1. The wavy lines represent a magnon propagator. The total free energy corresponding to the Josephson current is a sum of two diagram in Fig. 1. The diffusive motion of a Cooperon in the HM is indicated by the vertex Γ. The Feynman diagram for Γ is shown in Fig. 2, where the averaged impurity potential is represented by the cross and the dashed lines represent impurity scattering. The double solid lines represent a Green function in the HM including the self-energy of non-magnetic impurity scattering within the Born approximation. The self-energy is given by

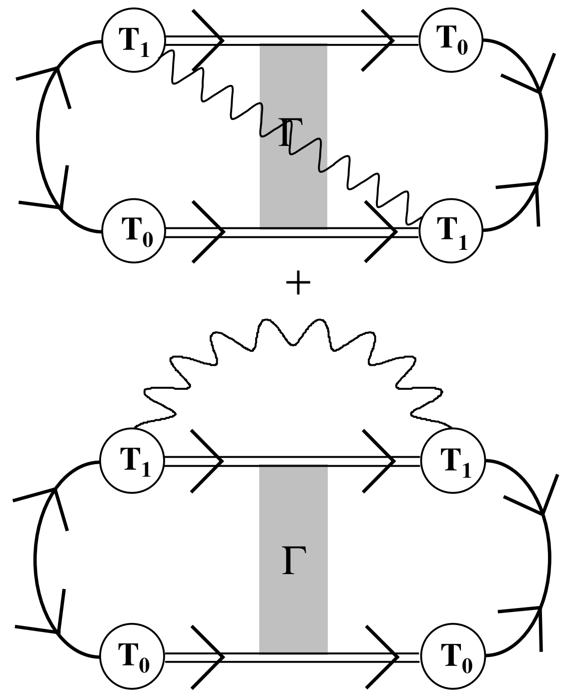

Fig. 1. Fourth order diagram contributing to the Josephson current. T_0 is the matrix element of non spin flip tunneling and T_1 is that of spin flip tunneling due to the magnon. The wavy lines represent the magnon propagator. The total free energy in SC/HM/SC junction is the sum of the two diagrams.

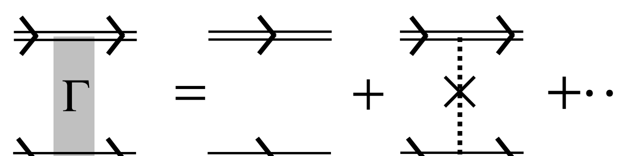

Fig. 2. Vertex part of non-magnetic scattering. The averaged impurity potential is represented by the cross and the dashed lines represent impurity scattering.

$$\Sigma(\omega_n) = -\mathrm{i}\frac{1}{2\tau}\mathrm{sgn}(\omega_n), \tag{4}$$

$$\tau^{-1} = 2\pi N_{\mathrm{F}} n_{\mathrm{i}} u^2, \tag{5}$$

where τ is the relaxation time of non-magnetic impurity scattering, $\omega_n = (2n+1)\pi T$ is a Matsubara frequency of electron, N_{F} is the density of states on the Fermi level in the HM, and n_{i} is the density of impurities. By taking the limit of $\omega_n\tau$, $v_{\mathrm{F}}Q\tau \ll 1$, one can obtain the following equation as,

$$\Gamma \approx 2\pi N(0) \sum_{\boldsymbol{Q}} \begin{cases} \frac{\mathrm{e}^{\mathrm{i}QR}}{DQ^2 + 2|\omega_n| + v_\ell}, & \omega_n(\omega_n - v_\ell) > 0, \\ 0, & \omega_n(\omega_n - v_\ell) < 0, \end{cases} \tag{6}$$

where $D = v_{\mathrm{F}}^2\tau/3$ is the diffusion constant, v_{F} the Fermi velocity, and $v_\ell = 2\ell\pi T$ is the Matsubara frequency of