Andreev Reflection in Ferromagnet/Superconductor/Ferromagnet Structures

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Abstract

We study theoretically the effect of Andreev reflection in ferromagnet/superconductor/ferromagnet structures. The spin-polarized quasiparticle current penetrates to the superconductor in the range of penetration depth from the interfaces, and thus the current depends on the relative orientation of magnetization of the ferromagnets. We show that the current is controlled by the Andreev reflection at the interfaces.

Key words: magnetoresistance, spin-polarized transport, Andreev reflection

The spin-dependent transport through magnetic nanostructures has attracted much interest recently. In a ferromagnet/superconductor (FM/SC) tunnel junction, the superconducting gap is suppressed due to spin accumulation by injection of spin-polarized quasiparticles (QP) [1,2]. The QP's spin transport and relaxation in SC has been studied in detail [3]. In the magnetic point contacts with superconducting electrodes, Andreev reflection [4] has been used to measure the spin polarization of FM [5,6]. When the Andreev reflection occurs at the interface of a normal metal/superconductor (NM/SC) junction, the QP current decays and changes to the supercurrent carried by Cooper pair in the range of the penetration depth ξ_Q from the interface [7]. In a FM/SC junction, the QP current in the SC is spin-polarized because the magnitude of injected QP current with up-spin and one with down-spin are different. A FM/SC/FM junction is particularly interesting because the magnetoresistance is expected due to the penetration of spin-polarized QP to the SC. In this paper, we study the effect of spin injection via Andreev reflection on the magnetoresistance in the FM/SC/FM structure. We consider the system which consists of a SC with thickness L sandwiched by semi-infinite ferromagnets FM1 and FM2. The cross-sectional area of the system is A. The current flows in the z direction and the interfaces between FM1/SC and SC/FM2 are at $z = -L/2$ and $z = L/2$, respectively.

The system we consider is described by the following Bogoliubov-de Gennes (BdG) equation [8]:

$$\begin{pmatrix} H_0 - h_{ex}(z)\sigma & \Delta(z) \\ \Delta^*(z) & -H_0 - h_{ex}(z)\sigma \end{pmatrix} \Psi_\sigma = E\Psi_\sigma, \qquad (1)$$

where $H_0 = -(\hbar^2/2m)\nabla^2 - \mu_F$ is the single particle Hamiltonian, E is the QP energy measured from the Fermi energy μ_F, and $\sigma = +(-)$ for the spin up (down) band. $h_{ex}(z) = h_{1ex}(1 - \theta(z + L/2)) + h_{2ex}\theta(z - L/2)$ is the exchange field in FM's and $\Delta(z)$ is the superconducting gap $\Delta(z) = \Delta(1 - \theta(|z| - L/2))$, where $\theta(x)$ is the step function. We assume the superconducting gap Δ is constant and neglect the proximity effect [9]. In order to consider the scattering effect at the interfaces, we assume the potential $\mathrm{H_B}(z) = \mathrm{H_B}[\delta(z + L/2) + \delta(z - L/2)]$, where $\delta(x)$ is the delta function. Solving the BdG equation (1), the transmission and reflection probabilities for electron and hole from FM's are obtained [7] and the current for the applied voltage V is expressed as

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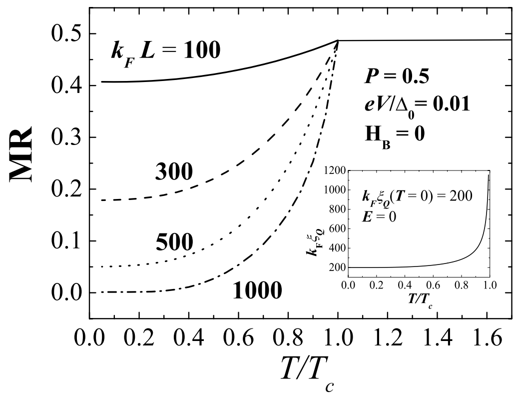

Fig. 1. The magnetoresistance is plotted against temperature normalized by superconducting critical temperature T_c. The cases that the normalized thickness $k_F L$ is 100, 300, 500, 1000, and $k_F^2 A = 10^4$ are shown, where k_F is Fermi wave number. $P = |h_{1ex}|/\mu_F = |h_{2ex}|/\mu_F$ is the polarization of FM's and Δ_0 is the superconducting gap at $T = 0$. Inset shows the temperature dependence of the QP current penetration depth at zero energy ($E = 0$). We take 200 as the value of $k_F \xi_Q$ at $E = T = 0$.

$$I = \frac{e}{h} \sum_{nl,\sigma} \int_0^\infty \left(R_{nl,\sigma}^{eh} + R_{nl,\sigma}^{he} + T_{nl,\sigma}^{ee'} + T_{nl,\sigma}^{hh'} \right) \times \left[f_0 \left(E - eV/2 \right) - f_0 \left(E + eV/2 \right) \right] dE, \qquad (2)$$

where $R_{nl,\sigma}^{he(eh)}$ is the Andreev reflection probability for electron (hole) in channel (n, l, σ) from the FM1 and $T_{nl,\sigma}^{ee'(hh')}$ is the transmission probability for electron (hole) in channel (n, l, σ) from the FM2, $f_0(E)$ is Fermi distribution function, e is the electronic charge, and h is the Planck constant. The MR is defined as $(R_{AP} - R_P)/R_P$, where $R_{P(AP)}$ is the resistance when the magnetizations of FM's are in the parallel (anti-parallel) alignment.

Fig. 1 shows the temperature dependence of the MR for several values of the thickness of the SC. The MR decreases with decreasing temperature. In order to understand this behaviour, we consider the temperature dependence of the QP current penetration depth $\xi_Q = \hbar v_F / 2\sqrt{\Delta^2 - E^2}$, where v_F is the Fermi velocity. As shown in the inset of Fig. 1, ξ_Q at zero energy decreases with decreasing temperature. This means that it becomes more difficult to transmit the information of QP's spin from the FM1 to the FM2 at low temperatures because the QP's current with spin changes to the supercurrent carried by Cooper pairs with no spin in the range of ξ_Q from the interfaces. As a result, the MR decreases with decreasing temperature. We also see that the variation of the MR vs temperature becomes stronger for larger L in Fig. 1. This is understood as follows. In the case of $k_F L = 1000$, the QP current almost changes to the supercurrent in the SC at low temperatures since $L \gg \xi_Q \sim 200/k_F$, and therefore the MR becomes nearly zero. On the other hand, in the case of $k_F L = 100$, the QP current is as large as that at the superconducting critical temperature T_c since $L < \xi_Q$, and therefore the MR shows a weak temperature variation. In the above discussion, we neglect the spin-flip scattering in the SC because the spin relaxation length λ_s is much larger than ξ_Q except in the close vicinity to $T = T_c$ [10]. If the MR is measured as a function of the thickness of the SC, the QP current penetration depth ξ_Q and the GL coherence length $\xi(T)$ [11] may be obtained by using the relation $\xi(T) \sim 0.82\,\xi_Q(E = 0)$ [7]. Our theory shows good agreements with recent experimental results [10].

In conclusion, we have studied the magnetoresistance in the ferromagnet/superconductor/ferromagnet structures theoretically. The temperature dependence of the magnetoresistance is understood by considering the penetration of the quasiparticle current to the superconductor via Andreev reflection. It is possible to extract the information of the coherence length from the magnetoresistance.

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References

[1] V.A. Vas'ko *et al.*, Phys. Rev. Lett. **78** (1997) 1134.

[2] S. Takahashi, H. Imamura, S. Maekawa, Phys. Rev. Lett. **82** (1999) 3911.

[3] T. Yamashita, S. Takahashi, H. Imamura, S. Maekawa, Phys. Rev. B **65** (2002) 172509.

[4] A.F. Andreev, Sov. Phys. JETP **19** (1964) 1228.

[5] M.J.M. de Jong, C.W.J. Beenakker, Phys. Rev. Lett. **74** (1995) 1657.

[6] R.J. Soulen Jr. *et al.*, Science **282** (1998) 85.

[7] G.E. Blonder, M. Tinkham, T.M. Klapwijk, Phys. Rev. B **25** (1982) 4515.

[8] P.G. de Gennes, "Superconductivity of Metals and Alloys," chap. 5, W. A. Benjamin, New York (1966).

[9] J. Strijkers, Y. Ji, F.Y. Yang, C.L. Chien, Phys. Rev. B **63** (2001) 104510.

[10] W.P. Pratt, Jr. ; private communication, J.Y. Gu *et al.*, preprint.

[11] V.L. Ginzburg, L.D. Landau, Zh. Eksperim. i Teor. Fiz. **20** (1950) 1064 (Sov. Phys. JETP **20** (1950) 1064).