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Meissner effect in diffusive normal metal/superconductor junctions

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Abstract

Meissner effect in the diffusive normal metal/insulator/s-wave superconductor junctions is studied in the presence of the magnetic impurities for various situations, where we have used the Usadel equation with Nazarov's generalized boundary condition. It is shown that the susceptibility of the diffusive normal metal for s-wave superconductor is almost independent of the height of the insulating barrier at the interface.

Keywords: Meissner effect; Proximity effect

1. Introduction

In diffusive normal metal/superconductor (DN/S) junctions, the DN acquires induced superconductivity, i.e. Cooper pairs penetrate into the DN. This proximity effect has been studied since the BCS theory was established. The proximity induced Meissner demagnetization in DN/S junctions was measured experimentally by Oda and Nagano [1] and Mota et al. [2]. It has $T^{-1/2}$ dependence in the dirty limit. The quasiclassical Green's function theory was used earlier to study Meissner effect in proximity structures.

The quasiclassical Green's function theory was developed by Eilenberger [3] and applied by Zaikin [4] and Kieselmann [5] to study the Meissner effect in DN/S junctions. Narikiyo and Fukuyama [6] calculated the Meissner screening length in a

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semi-infinite system containing Anderson impurity. Higashitani and Nagai studied the Meissner effect in the clean limit [7]. Belzig et al. [8] have studied more realistic system assuming a perfectly transparent N/S interface. Up to now the boundary conditions derived by Kupriyanov and Lukichev (KL) [9] were widely used to study proximity effect in DN/S structures.

A more general boundary conditions were derived by Nazarov [10] based on the Keldysh-Nambu Green's function formalism [11] within the framework of the Landauer–Büttiker scattering formalism. The merit of this boundary condition is that the BTK theory [12] is reproduced in the ballistic limit while in the diffusive limit with a low transmissivity of the interface, the KL boundary condition is reproduced. Although almost all of previous papers on Meissner effect in mesoscopic NS junctions are either based on the KL boundary conditions or on the BTK model, in the actual junctions, transparency of the junction is not necessarily small and impurity scattering in the DN is important. Tanaka et al. [13] and Yokoyama et al. [14] calculated tunneling conductance using the Nazarov's boundary condition. The timely problem is to study theoretically the Meissner effect in DN/s-wave junctions using the new boundary conditions [13]. In the present paper, we calculate the susceptibility of the DN layer in DN/s-wave S junctions for various parameters such as the height of the insulating barrier at the interface, resistance R_d in DN, density of states at Fermi energy, the magnetic scattering rate in DN, and the Thouless energy E_{Th} in DN.

2. Formulation

In this section we introduce the model and the formalism. We consider a junction consisting of vacuum (VAC) and superconducting reservoirs connected by a quasi-one-dimensional diffusive conductor (DN) with a length L much larger than the mean free path. We assume that the interface between the DN conductor and the S electrode at $x = L$ has a resistance R_b, the DN/VAC interface at $x = 0$ is specular, and we apply the generalized boundary conditions by Tanaka [13] to treat the interface between DN and S. A weak external magnetic field H is applied in z-direction. The vector potential can be chosen to have only the y component which depends on x.

We model the insulating barrier between DN and S by the delta function $U(x) = H\delta(x - L)$, which provides the transparency of the junction $T_m = 4\cos^2\phi/(4\cos^2\phi + Z^2)$, where $Z = 2H/v_F$ is a dimensionless constant, ϕ is the injection angle measured from the interface normal to the junction and v_F is Fermi velocity.

In the following calculations we apply the Usadel equations [15] and use the standard θ-parameterization, where $\theta(x)$ is a measure of the proximity effect in DN and is determined by the following equation:

$$D\frac{\partial^2}{\partial x^2}\theta(x) - 2(\omega_n + \gamma\cos[\theta(x)])\sin[\theta(x)] = 0, \qquad (1)$$

where γ, D and ω_n denote magnetic scattering rate in DN, the diffusion constant and Matsubara frequency respectively. The boundary condition for $\theta(x)$ at the DN/S interface is given in Ref. [13]. The interface resistance R_b is given by

$$R_b = R_0\frac{2}{\int_{-\pi/2}^{\pi/2} d\phi T(\phi)\cos\phi} \qquad (2)$$

with $T(\phi) = 4\cos^2\phi/(4\cos^2\phi + Z^2)$. Here R_0 is Sharvin resistance $R_0^{-1} = e^2k_F^2S_c/(4\pi^2)$, where k_F is the Fermi wave-vector and S_c is the constriction area. Note that the area S_c is in general not equal to the cross-section area S_d of the normal conductor, therefore S_c/S_d is independent parameter of our theory. The current distribution is given by

$$j(x) = -8\pi e^2N(0)DT\sum_{\omega_n>0}\sin^2\theta(x)A(x), \qquad (3)$$

where $A(x)$, $N(0)$ and T denote vector potential, density of states at Fermi energy and temperature of the system respectively. The Maxwell equation reads

$$\frac{d^2}{dx^2}A(x) = -4\pi j(x). \qquad (4)$$

The boundary conditions for $A(x)$ are

$$\frac{d}{dx}A(0) = H, \quad A(L) = 0, \tag{5}$$

where we have neglected the penetration of the field into the superconductor assuming small penetration depth in S.

Finally we get the following expression for the susceptibility of the DN;

$$-4\pi\chi = 1 + \frac{A(0)}{HL}. \tag{6}$$

In the following we denote $K = 16\pi e^2 N(0) D^2$ and $\Delta(T)$ is the magnitude of pair potential at a given temperature T. It should be remarked that in the present circuit theory, R_d/R_b can be varied independently of T_m, i.e., independently of Z, since one can change the magnitude of the constriction area S_c independently. In other words, R_d/R_b is no more proportional to $T_{av}(L/l)$, where T_{av} is the averaged transmissivity of the barrier and l is the mean free path in the diffusive region. Based on this fact, we can choose R_d/R_b and Z as independent parameters.

3. Results

Figs. 1–4 show $T^{-1/2}$ dependence of the susceptibility of the DN. It is linear in the intermediate region. Let us first focus on the low transparent junctions with $Z = 10$ and $R_d/R_b = 10$ for various $\gamma/\Delta(0)$ (Fig. 1). As T increases, the magnitude of $-4\pi\chi$ is reduced and finally becomes zero. Magnetic scattering suppresses the Meissner effect. As K decreases, this suppression is enhanced. The susceptibility is enhanced with an increase in $E_{Th}/\Delta(0)$ at relatively high temperature. For $Z = 10$ and $R_d/R_b = 1$ (Fig. 2), the magnitude of $-4\pi\chi$ is somehow reduced compared to those for corresponding parameters in Fig. 1. As R_d/R_b increases, Meissner effect is enhanced while the suppression on Meissner effect by magnetic scattering becomes weak. For $Z = 0$ (Figs. 3 and 4), line shapes are almost the same as those for corresponding parameters in Figs. 1 and 2, that is, Z dependence of the susceptibility is very weak. The saturated value of the susceptibility is determined by K, R_d/R_b.

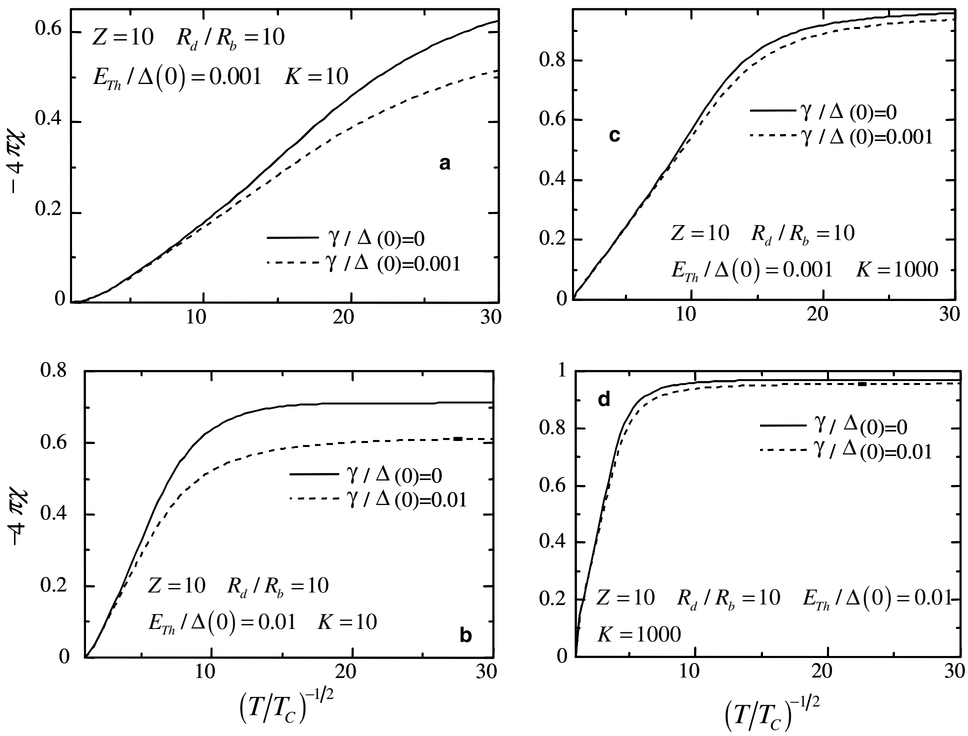

Fig. 1. Susceptibility for low transparent junctions with $Z = 10$ and $R_d/R_b = 10$.

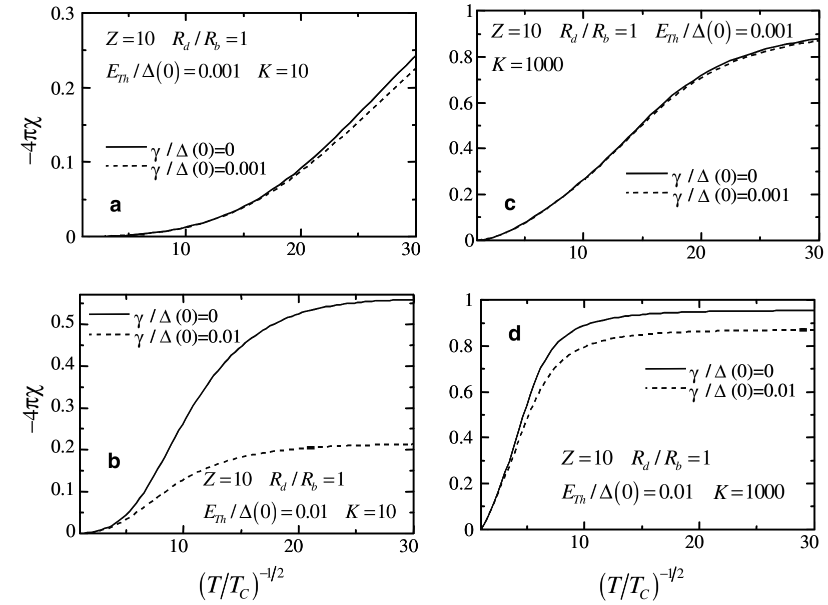

Fig. 2. Susceptibility for low transparent junctions with $Z = 10$ and $R_d/R_b = 1$.

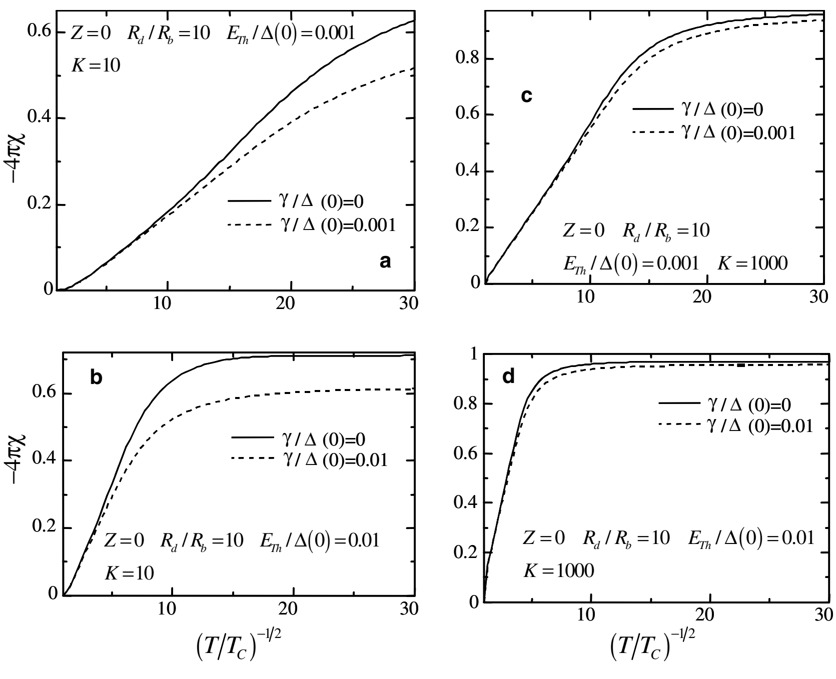

Fig. 3. Susceptibility for high transparent junctions with $Z = 0$ and $R_d/R_b = 10$.

In the following we confine ourselves to $\gamma = 0$. Now we look at the K, R_d/R_b and Z dependence of the susceptibility at $T/T_c = 0.01$. We will plot the K and R_d/R_b dependence of the susceptibility

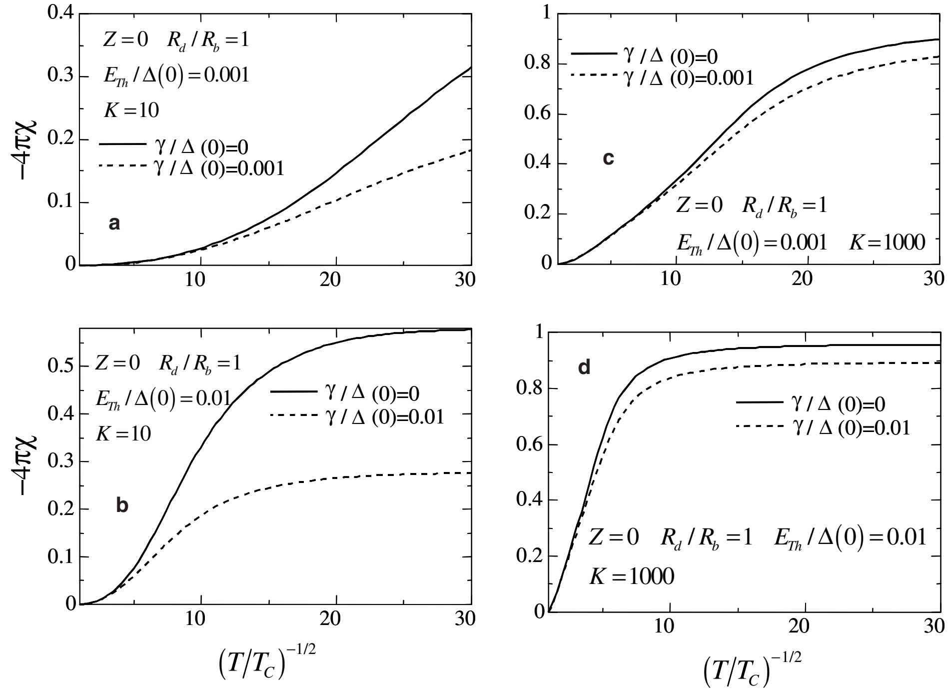

Fig. 4. Susceptibility for high transparent junctions with $Z = 0$ and $R_d/R_b = 1$.

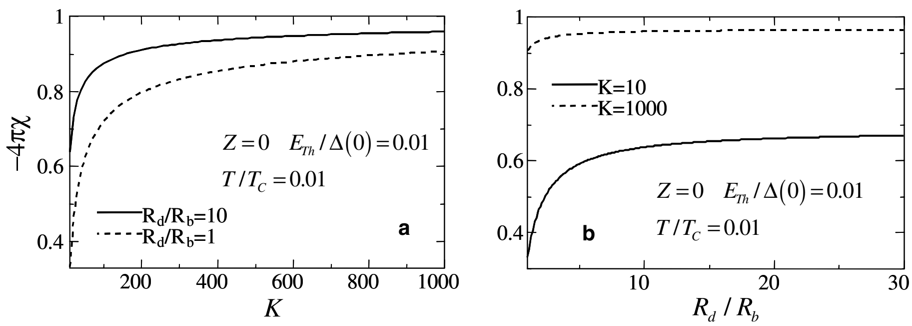

Fig. 5. K (left panel) and R_d/R_b (right panel) dependence of the susceptibility.

in Fig. 5. The magnitude of $-4\pi\chi$ is an increasing function of K and R_d/R_b. For sufficiently large K and R_d/R_b, it becomes constant. Fig. 6 shows the Z dependence of the susceptibility. Z dependence of the susceptibility is very weak especially for large R_d/R_b.

Finally let us make a brief explanation for the above results. As shown in Ref. [14], where retarded Green's function is used, magnetic impurity scattering suppresses proximity effect, i.e., θ whereas θ increases with an increase in R_d/R_b and is almost independent of Z. We can regard $\omega_n/\cos\theta(x) + \gamma$ as effective magnetic scattering rate in the Usadel equation with retarded Green's function at zero energy. So the proximity effect and the magnitude of $-4\pi\chi$ are suppressed with an increase in T, increased with an increase in R_d/R_b and almost independent of Z.

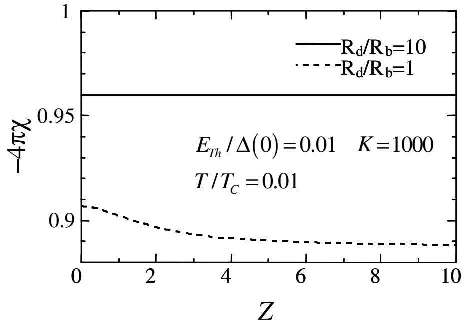

Fig. 6. Z dependence of the susceptibility.

4. Conclusions

In the present paper, a detailed theoretical investigation of the susceptibility of diffusive normal metal/s-wave superconductor junctions in the presence of magnetic impurity is presented. We have clarified that Z dependence of the susceptibility for s-wave superconductor is very weak especially for large R_d/R_b.

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