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Journal of Physics and Chemistry of Solids 67 (2006) 132–135
JOURNAL OF PHYSICS AND CHEMISTRY OF SOLIDS
www.elsevier.com/locate/jpcs

Interface density of states in d-wave superconducting proximity effect through Andreev reflections

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Abstract

Tunneling spectra via Andreev bound states between a normal metal (N)/$d_{x^2-y^2}$-wave superconductor (S) (in the presence of a subdominant *s*-wave pair potential) junction are investigated. In the present work, we employ quasiclassical Green's function methods in order to study the role of the proximity effect in detail. In the case of a high transparent contact to the (100) interface of the *d*-wave superconductor, the pair potential penetrates into the inside of the N due to the proximity effect, where the i*s*-wave is not indeed at all. Then, the tunneling spectra has a very sharp zero-energy peak (ZEP). This ZEP originates from the fact that quasiparticles feel different sign of the pair potentials between normal metals and *d*-wave superconductors through Andreev reflections. On the other hand, in the N/S junction with the (110) interface, the induction of i*s*-wave component in the S side leads to an induced i*s*-wavepair potential also in the N side due to the proximity effect. In this case, the interface density of states has a dip structure. We show that the spatial dependence of pair potentials is significantly sensitive to the transparency of the junction.

PACS: 74.50.+r; 74.20.Rp; 74.72.-h

1. Introduction

Nowadays, most promising symmetry of superconducting state of high-T_c cuprates is *d*-wave. One of the important features of the *d*-wave symmetry is the so-called zero-bias conductance peak (ZBCP) [1,2] due to the formation of Andreev bound states (ABS's) in normal metal/*d*-wave superconductor (N/S) junctions. The ABS's originate from the interference effect in the predominant $d_{x^2-y^2}$-wave symmetry through reflection at a surface or an interface [3]. Up to now, the consistency between the theories and experiments has been checked in details [1,4–7]. On the other hand, the reduction of the $d_{x^2-y^2}$-wave state at the surface or interface allows the coexistence of different symmetry of pair potentials. The subdominant interaction induces the broken time reversal symmetry state (BTRSS), i.e. $d+\mathrm{i}s$-wave state [8,9]. The splitting of ZBCP in tunneling spectra at low temperatures may be one of the evidence for the BTRSS. However, as regards this point, tunneling experiments are still controversial. Some experiments report the splitting of ZBCP, others do not show the splitting even in low temperatures [10,11]. More recently, it is proposed that the induced *s*-wave component of the pair potential by proximity effect in the N side may enhance the magnitude of the subdominant *s*-wave component in the S side, which forms the BTRSS based on the analysis of the tunneling experiments [12]. The proximity effect in N/S junction without the BTRSS was theoretically studied by Ohashi [13]. In order to understand the actual tunneling spectroscopy quantitatively, we must study the proximity effect in detail. Motivated by this point, we extend our previous formula [6] to take into account the induced pair potential in the N side. In the present paper, we study the local density of states at the interface of N/S junctions based on the self-consistently determined pair potentials by changing the transmission probability of the junctions.

2. Formulation

We consider the normal metal (N)/*d*-wave superconductor (S) junctions separated by an insulating interface at $x=0$, where the normal metal is located at $x<0$ and the $d_{x^2-y^2}$-wave superconductor extends elsewhere In order to study the proximity effect in the N/S junction, we determine the spatial variation of the pair potentials self-consistently. For this purpose, we make use of the quasi-classical Green's function

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0022-3697/$ - see front matter
doi:10.1016/j.jpcs.2005.10.034

procedure [14] developed by Nagai and co-workers [15,16]. Here a cylindrical Fermi surface is assumed and the magnitude of the Fermi momentum and the effective mass are chosen to be equal both in the N and S sides. The pair potential in S [N] side will tend to the bulk value [zero] $\Delta^{s}(\phi_\alpha,\infty)$ [$\Delta^{N}(\phi_\alpha,\text{-}\infty)$] at sufficiently large x. We introduce the quasiclassical Green's functions in N and S regions given by

$$\hat{g}^{S}_{++}(\phi_+,x)=\frac{i}{1-D^S_+(x)F^S_+(x)}\begin{pmatrix}1+D^S_+(x)F^S_+(x) & 2iF^S_+(x)\\ 2iD^S_+(x) & -1-D^S_+(x)F^S_+(x)(2)\end{pmatrix}, \quad (1)$$

$$\hat{g}^{N}_{--}(\phi_-,x)=\frac{i}{1-D^N_-(x)F^N_-(x)}\begin{pmatrix}1+D^N_-(x)F^N_-(x) & 2iF^N_-(x)\\ 2iD^N_-(x) & -1-D^N_-(x)F^N_-(x)\end{pmatrix}. \quad (2)$$

In the above, $D^l_\alpha(x)$ and $F^l_\alpha(x)(l=\text{N,S},\alpha=\pm)$ obey the following Riccati-type equations

$$\hbar v_{Fx}\frac{\partial}{\partial x}D^l_\alpha(x)=\alpha[2\omega_m D^l_\alpha(x)+\Delta^l(\phi_\alpha,x)D^l_\alpha(x)^2-\Delta^l(\phi_\alpha,x)^*], \quad (3)$$

$$\hbar v_{Fx}\frac{\partial}{\partial x}F^l_\alpha(x)=-\alpha[2\omega_m F^l_\alpha(x)+\Delta^l(\phi_\alpha,x)^*F^l_\alpha(x)^2-\Delta^l(\phi_\alpha,x)], \quad (4)$$

where v_{Fx} is the x component of the Fermi velocity and $\hat{\tau}_3$ is the Pauli matrix. Here $\omega_m=\pi T(2m+1)$ with integer m is the Matsubara frequency. Initial conditions of these equations are

$$D^S_+(\infty)=\frac{\Delta^S(\phi_+,\infty)^*}{\omega_m+\Omega^S_+},D^N_-(-\infty)=0, \quad (5)$$

with $\Omega^l_\alpha=\sqrt{\omega_m^2+|\Delta^l(\phi_\alpha,\infty)|^2}$. Moreover, the boundary conditions of the $G^l_\alpha(0)$ and $F^l_\alpha(0)$ at the interface $x=0$ are

$$F^S_+=\frac{RG^N_+-G^N_-+(1-R)G^S_-}{G^S_-[G^N_+-RG^N_-]-(1-R)G^N_+G^N_-}, \quad (6)$$

$$F^N_-=\frac{RG^S_--G^S_++(1-R)G^N_+}{G^N_+[G^S_--RG^S_+]-(1-R)G^S_-G^S_+}. \quad (7)$$

The pair potentials are given by [6,13,16]

$$\Delta^l(\phi,x)=\sum_{0\le m<\omega_c/2\pi T}\frac{1}{2\pi}\times\int_{-\pi/2}^{\pi/2}d\phi'\sum_\alpha V^l(\phi,\phi'_\alpha)[\hat{g}^l_{\alpha\alpha}(\phi'_\alpha,x)]_{12}, \quad (8)$$

where ω_c is the cutoff energy and $[\hat{g}^l_{\alpha\alpha}(\phi'_\alpha,x)]_{12}$ denotes the 12 element of $\hat{g}^l_{\alpha\alpha}(\phi'_\alpha,x)$. Here $V^l(\phi,\phi'_\alpha)$ is the effective interelectron potential of the Copper pair. In our numerical calculations, a new $\Delta^l(\phi,x)$ is calculated using Eq. (8) and $\hat{g}^l_{\alpha\alpha}(\phi_\alpha,x)$ is obtained again from Eqs. (1)–(7). We reiterate this process until the convergence is sufficiently obtained.

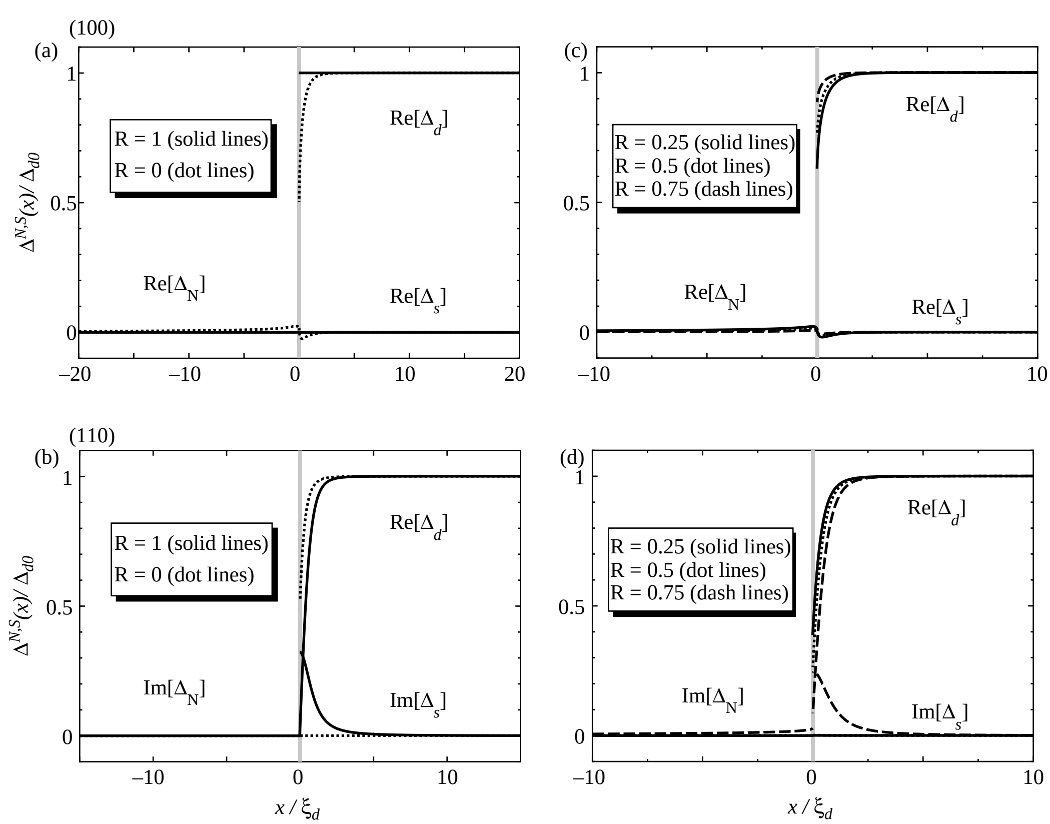

Fig. 1. Spatial dependence of the pair potentials in the N/D junctions for various R. (a) (100) interface [$\theta=0$], (b) (110) interface [$\theta=\pi/4$].