Finite-quasiparticle-lifetime effects in the differential conductance of $Bi_2Sr_2CaCu_2O_y$/Au junctions

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$Bi_2Sr_2CaCu_2O_y$/Au point-contact junctions have been studied. For a description of junction properties we used the Blonder-Tinkham-Klapwijk theory where we included the finite lifetime of the quasiparticles. From the fitting procedures of the experimental differential characteristics, the values of the Fermi velocity $v_F \simeq 5\times10^7$ cm/s, the ratio $2\Delta/k_BT_c \simeq 8$, and the coherence length $\xi_{ab} \simeq 35$ Å for $Bi_2Sr_2CaCu_2O_y$ were obtained.

Recently, a great effort has been made to obtain the basic superconducting parameters of high-T_c superconductors (HTS's). One of the methods successfully applied for such investigation is the measurement of the differential conductance of normal-metal/superconductor (N/S) junctions. The theoretical background of such measurements was elaborated by Blonder-Tinkham-Klapwijk (BTK theory).[1] In the case of low-temperature superconductors the agreement between theoretical and experimental data was very good.[2] However, considerable discrepancy was observed between experimental data measured on HTS materials and theoretical results. In this a smeared gaplike structure was measured. This discrepancy can be caused by shortening of the lifetime of the quasiparticles. A phenomenological model of this idea was given in Ref. 3 where the authors directly put the modified density of states of Dynes *et al.*[4] into the results of BTK theory. Theoretical results obtained by this phenomenological method provided a poor description of the experimental data. However, we believe that the idea of inelastic scattering of quasiparticles near the N/S microconstriction is realistic. As was shown in Ref. 5, the degradation of superconducting properties on the surface layers of HTS's caused by oxygen out-diffusion occurs at room temperature. Randomly distributed oxygen vacancies can destroy the structural coherence in the superconducting plane of HTS's.[6] The structural incoherence can reduce the pair amplitude[7] and/or destroy the phase coherence.[8] Another possible origin of the gaplike-structure broadening can be caused by spin fluctuations arising from the itinerant Cu spins present in the degraded surface layer of cuprate superconductors.[9,10] All the mentioned mechanisms lead to the shortening of the quasiparticle lifetime.

In order to consider the finite lifetime of quasiparticles we have included an inelastic scattering term in the Bogoliubov equations. The theoretical dependencies fit our experimental curves very well. In addition, for $Bi_2Sr_2CaCu_2O_y$ (BSCCO) it is possible to obtain the value of the energy gap, coherence length, and Fermi velocity from the fitting procedure.

The point contacts BSCCO/Au were prepared on the HTS material which was in all cases in the form of thin films. The BSCCO thin films were prepared by the laser ablation technique[11] on single-crystal $SrTiO_3$ substrates with the onset critical temperature $T_{con}=85$ K and the zero-resistance critical temperature $T_c=80$ K. All thin films used in these experiments have a preferential orientation with the c axis perpendicular to the substrate. The surface of the thin films was not cleaned before the point-contact preparation, so a native oxide barrier on the surface was expected. The point contacts were prepared at temperatures lower than 200 K, in order to avoid oxygen diffusion, contributing to the surface degradation, as described in Ref. 5. As an upper electrode bulk Au was used in the shape of a sharp tip. Before measurement the Au tip was mechanically sharpened. At low temperature ($\simeq 10$ K) the resistance of the point contacts was adjusted in the range $1-10^2$ Ω. The differential resistance dV/dI of the point contacts was measured by the standard low-frequency (800 Hz) phase-sensitive detection technique, using a resistance bridge with modulation current $I_{max}=0.5$ μA.

Typical point-contact spectra obtained on BSCCO/Au junctions have the shape of the curve in Fig. 1 (solid line). These characteristics are typical for junctions with high transparency of the tunneling barrier or for junctions where the tunneling barrier is absent. Such types of junctions were described by the BTK theory[1] of microconstricted contacts. In the BTK model one considers transmission and reflection of quasiparticles on the N/S interface. In this case the expression for the total current is given as

$$I_{NS}=C\int_{-\infty}^{\infty}[f(E-eV)-f(E)][1+A(E)-B(E)]dE \;, \tag{1}$$

where $f(E)$ is the Fermi distribution function, $A(E)$ and $B(E)$ are coefficients giving the probability of Andreev and ordinary reflection, respectively, and C is a constant dependent on the area of the junction and the density of states, as well as on the Fermi velocity. The fitting curve corresponding to this theory is shown in Fig. 1 (dashed line). The difference between the experimental and the theoretical curves is evident. The differential-resistance dips are smeared out and this fact leads to the idea of the existence of inelastic scattering near the N/S interface as a consequence of degradation processes in the surface layer. This inelastic scattering contributes to the shortening of the quasiparticle lifetime near the N/S interface and this mechanism can lead to a smearing of the dips in the differential characteristic. Employing such an idea enabled us to explain the results presented in this paper.

We considered an inelastic scattering term in the expressions for functions $F(x,t)$ and $G(x,t)$ in the Bogoliubov equations, i.e.,

$$i\hbar\left[\frac{\partial F(x,t)}{\partial t}\right]=i\hbar\left[\frac{\partial F(x,t)}{\partial t}\right]_{\text{field}}+i\hbar\left[\frac{\partial F(x,t)}{\partial t}\right]_{\text{inel}} \quad (2)$$

and in the linear approach:

$$i\hbar\left[\frac{\partial F(x,t)}{\partial t}\right]_{\text{inel}}=-\frac{i\hbar}{\tau}F(x,t) , \quad (3)$$

where τ is the lifetime of the quasiparticles between collisions. Similar considerations were used for the function $G(x,t)$. After substitution of $\Gamma=\hbar/\tau$ the Bogoliubov equations may be written:

$$i\hbar\frac{\partial F(x,t)}{\partial t}=\left[-\frac{\hbar^2\nabla^2}{2m}-\mu-i\Gamma+V\right]F(x,t)+\Delta G(x,t) , \quad (4)$$

$$i\hbar\frac{\partial G(x,t)}{\partial t}=\left[\frac{\hbar^2\nabla^2}{2m}+\mu+i\Gamma-V\right]G(x,t)+\Delta F(x,t) . \quad (5)$$

Taking the solution for $F(x,t)$ and $G(x,t)$ in the forms $F(x,t)=u_0\exp(ikx-iEt/\hbar)$ and $G(x,t)=v_0\exp(ikx-iEt/\hbar)$ we find for the Bogoliubov coherence factors u_0 and v_0:

$$u_0^2=\frac{1}{2}\left[1+\frac{\sqrt{(E+i\Gamma)^2-\Delta^2}}{E+i\Gamma}\right]=1-v_0^2 . \quad (6)$$

For the density of states we can write

$$N(E,\Gamma)=\text{Re}[(u_0^2-v_0^2)^{-1}]=\text{Re}\left[\frac{E+i\Gamma}{\sqrt{(E+i\Gamma)^2-\Delta^2}}\right] , \quad (7)$$

which is a formula similar to that of Dynes *et al.*[4] For a more simple expression of $A(E)$ and $B(E)$ we write u_0 and v_0 as

$$u_0^2=\alpha+i\eta,\quad v_0^2=\beta-i\eta , \quad (8)$$

and for $A(E)$ and $B(E)$ we can write

$$A(E)=aa^*=\frac{\sqrt{(\alpha^2+\eta^2)(\beta^2+\eta^2)}}{\gamma^2} , \quad (9)$$

$$B(E)=bb^*=Z^2\frac{[(\alpha-\beta)Z-2\eta]^2+[2\eta Z+(\alpha-\beta)]^2}{\gamma^2} , \quad (10)$$

$$\gamma^2=\gamma\gamma^*=[\alpha+Z^2(\alpha-\beta)]^2+[\eta(2Z^2+1)]^2 , \quad (11)$$

where $a=u_0v_0/\gamma$, $b=-(u_0^2-v_0^2)(Z^2+iZ)/\gamma$, $\gamma=u_0^2+(u_0^2-v_0^2)Z^2$, and a^*,b^*,γ^* are the complex conjugate quantities, derived in Ref. 1. Substituting parameters $A(E)$ and $B(E)$ in the expression (1) we obtain the expression for the current flow through the N/S boundary. A fitting procedure based on modified BTK theory leads to good agreement of experimental and theoretical results (dotted line in Fig. 1). The identification of differential-resistance dips with the energy gap of BSCCO is demonstrated in Fig. 2, showing the temperature dependence of a BSCCO/Au junction prepared at 4.2 K. The curves for higher temperatures were shifted up by a value of differential resistance $n\delta R_D$ for clarity. In our case the temperature increased from 4.2 to 60 K and the fitted values of the energy gap Δ decreased from 27 meV to 18 meV. The best agreement of experimental and theoretical (fitting) data was obtained in the overwhelming majority of cases for $Z=\langle 0.45-0.6\rangle$. The examples of fitted curves are shown in Fig. 1 (dotted line) with fitting parameters $\Delta=24$ meV, $\Gamma=12$ meV, and $Z=0.56$ for temperature 11 K, and in Fig. 2 (dashed lines) with $\Delta=27$ meV, $\Gamma=7$ meV, and $Z=0.54$, for temperature 4.2 K. Values of Γ in the range 5–12 meV were obtained, indicating that the idea of scattering centers is reasonable.

Thus we can conclude that such a large shortening of the quasiparticle lifetime is not an intrinsic property of HTS's. This is evident from the sharper gaplike structure measured on break junctions,[12] which follows from the method of the junction's preparation. Usually these junctions are prepared at low temperature and the problems of surface degradation and/or contamination are avoided. It is evident also from the measurement of the Δ value. The values of Δ measured on break junctions are usually 30 meV or more ($\Delta\simeq 36$ meV in Ref. 12) while the values of Δ obtained from our measurements and by other authors[13] on point contacts are less than 30 meV. This difference can be caused by reduction of the order parameter Δ in the degraded surface layer of HTS's indicated also by enhancement of the Γ parameter.

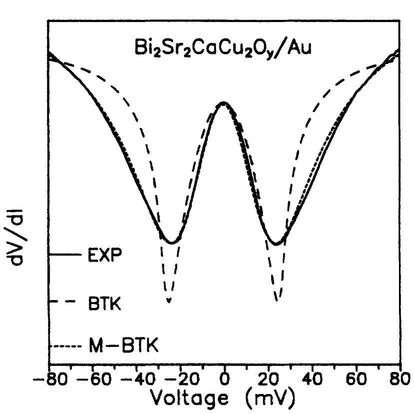

FIG. 1. dV/dI-V characteristics measured on a BSCCO/Au point-contact junction. Experimental, solid line; fitted by BTK theory, dashed line; fitted by modified BTK theory, dotted line.

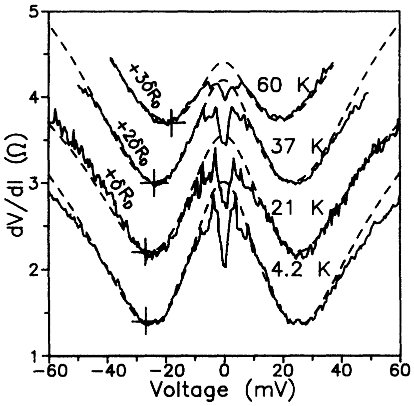

FIG. 2. Temperature dependence of dV/dI-V characteristic measured on a BSCCO/Au point-contact junction. Curves at higher temperatures are shifted by $n\delta R_D$ for clarity.

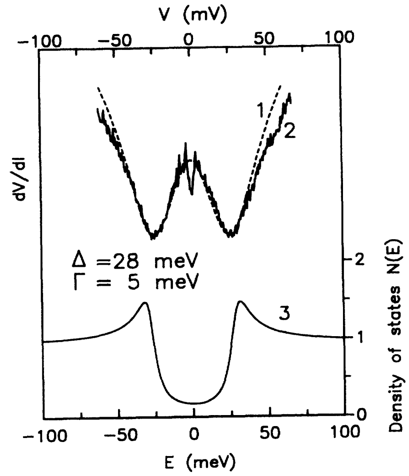

FIG. 3. Restoration of superconducting density of states of BSCCO (curve 3) from theoretical fitting (curve 1) of experimental data (curve 2).

The value of $Z \simeq 0.5$ obtained in the majority of cases indicates high transparency of the tunneling barrier. However, in the case of junctions consisting of materials with different Fermi velocities normal reflection of quasiparticles occurs even if no barrier is present. In this case the value of Z is shifted to a higher effective value:[2]

$$Z_{\rm eff} = [Z^2 + (1-r)^2/4r]^{1/2} \,, \tag{12}$$

where $r = v_{F_1}/v_{F_2}$ is the ratio of the Fermi velocities. If we consider $Z=0$ (N/S interface without tunneling barrier) and $Z_{\rm eff} \simeq 0.5$ (obtained from the fitting procedure) then the Fermi velocity of BSCCO, $v_F = v_F\,(\mathrm{Au})/2.6 = 5\times10^7$ cm/s, where the factor 2.6 comes from Eq. (12). For marginal values of $Z_{\rm eff}$ we obtain $v_F = 5.8\times10^7$ cm/s for $Z_{\rm eff}=0.45$, and $v_F = 4.5\times10^7$ cm/s for $Z_{\rm eff}=0.6$, which are in good agreement with published data,[14] demonstrating that in the case of BSCCO one measures the direct N/S interface without any tunneling barrier; thus the surface of BSCCO is superconducting, allowing measurement of the energy gap of BSCCO. From the known values of the energy gap and the Fermi velocity of BSCCO we can determine the coherence length ξ of this material. Substitution of $v_F = 5\times10^7$ cm/s and $\Delta = 30$ meV into the well-known relation $\xi = \hbar v_F/\pi\Delta(0)$ yields $\xi = 35$ Å. This value is in agreement with the published value in Ref. 15. Using our parameters the ratio $2\Delta/k_B T_c$ is about 8. Similar results were obtained by tunneling spectroscopy on point contact [13] and break junctions [12].

From the fitting parameters we can restore the density of states of BSCCO by substituting the parameters Δ and Γ into the expression (7). In Fig. 3 an experimental curve 2 fitted by a theoretical curve 1, using fitting parameters $\Delta = 28$ meV, $\Gamma = 5$ meV, and restored superconducting density of states (curve 3) are shown.

A serious problem is the determination of the "tunneling" direction into HTS's. In Ref. 16 results are presented obtained on BSCCO (2:2:1:2) by scanning tunneling microscopy and tunneling spectroscopy. They showed that the BiO plane is nonmetallic and the CuO_2 layer is responsible for the quasi-two-dimensional superconductivity. In our case, if the tunneling is realized in the c-axis direction, we would obtain much larger values of the Z parameter from the fitting procedure. We conclude that we measured the conductivity of the junction in a direction parallel to the CuO_2 plane and the values of the coherence length and energy gap obtained are in the ab direction, i.e., $\xi = \xi_{ab}$ and $\Delta = \Delta_{ab}$.

In this work we showed that the differential characteristics measured on BSCCO/Au point-contact junctions can be described by BTK theory, but we obtained better agreement between experimental and theoretical curves when the existence of scattering centers in the junction interface was considered, i.e., in the expression for the time derivative of the wave functions one considers the inelastic scattering processes. Since Fermi velocities are different for the two junction electrodes, we used a formula valid for the effective value of the Z parameter. From the fitted parameters of $Z_{\rm eff}$ we determined the Fermi velocity for BSCCO $v_F \simeq 5\times10^7$ cm/s, the ratio $2\Delta/k_B T_c \simeq 8$, and the coherence length $\xi_{ab} \simeq 35$ Å. In this paper we have shown that in our BSCCO/Au junctions $Z=0$, i.e., the tunneling barrier is absent in these junctions and the surface layer remains in the superconducting state or only partially crosses into the normal state.

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