Influence of inelastic effects on differential conductance of a high-T_c superconductor/metal junction

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Both linear conductance and smeared gaplike structure were observed in differential characteristics measured on point contacts using a gold tip and $Bi_2Sr_2CaCu_2O_{8+y}$ thin films as well as $Bi_2Sr_2CaCu_2O_{8+y}/SrTiO_3$ bilayers with different thickness of $SrTiO_3$. These features were described in terms of inelastic processes. For theoretical description the Blonder-Tinkham-Klapwijk theory extended by Kirtley's model of the inelastic transport of quasiparticles through a normal metal–superconductor interface was used. In addition, we considered the shortening of quasiparticle lifetime τ due to the inelastic scattering in the superconductor near the interface. In agreement with theory a smeared gaplike structure as well as an increase or a decrease of conductance depending on the strength of the potential barrier corresponding to the $SrTiO_3$ was obtained.

The measurement of the differential conductivity of superconductor-insulator-metal (SIN or SN) junctions is a very sensitive method to probe superconducting properties of superconductors. To obtain the basic superconducting parameters such as the superconducting energy gap, critical temperature, superconducting coherence length, etc., a theoretical model is required to deconvolute them from experimental data. While the coincidence between experimental data and theoretical ones is within several percent for conventional low temperature superconductors[1] only qualitative correspondence is achieved for high-T_c superconductors (HTS's).[2,3] The most striking features often observed in differential conductivity of HTS/metal junctions are the broadening and variation of the gaplike structure as well as the linear background at high bias. This fact makes difficult a determination of superconducting parameters from differential characteristics (e.g., $2\Delta/kT_c$ is reported in a wide range from 3 to 10). As was shown by Ekino and Akimitsu[4] the values of Δ depend significantly on the procedure of their determination. The value of Δ determined from the position of the peaks is about 20% higher than that obtained from fitting procedures. This is due to the smeared gaplike structure as well as nonstandard behavior of the background differential conductance. Therefore phenomenological models were elaborated to describe the differential characteristics measured on HTS materials. Cucolo *et al.* assume a model where the superconducting density of states depends linearly on energy[5] or in a later publication the tunneling into the *c* direction of the HTS crystallographic orientation.[6] Similarly, Srikanth *et al.*[7] showed that normal state tunneling conductance in perovskite oxides is linear with bias voltage. Moreover, nonstandard theories [resonant valence bond theory,[8] marginal Fermi liquid (MFL) theory[9]] were elaboratored to explain some interesting experimental features of HTS's as linear dependence of resistance on temperature and linear background of tunneling conductance, too. These theories suppose that the linear tunneling background is an intrinsic property of HTS's. On the other hand, Kirtley[2] pointed out that the nearly linear background can be explained by a conventional model of tunneling if a low tunneling barrier height and small Fermi energy of HTS's is proposed.

However, recently Kirtley *et al.*[10] showed that linear tunneling background has been observed in many different systems (Al-Al_2O_3-Pb, Cr-Cr_2O_3-Pb, $La_{2-x}Sr_xCuO_4$) and can be explained in terms of inelastic tunneling. They elaborated the theoretical background of such inelastic tunneling and also corroborated the theoretical results by experimental ones on the system Al-Al_2O_3-Cr_2O_3-Pb. The origin of inelastic interaction can differ between various systems. Recently Kirtley[11] extended the model of inelastic tunneling to systems with direct conductivity in terms of the Blonder-Tinkham-Klapwijk (BTK) approach.[12] He obtained a linear increase or decrease of conductance depending on the strength of the potential barrier. Both decrease and increase of differential conductance is also predicted by Littlewood and Varma[9] within MFL theory and by Srikanth and Raychaudhuri[16] as an electron confinement effect. From an experimental point of view it is important that the slope of conductance is changed by (a) changing of the tunneling direction for Littlewood's model, (b) changing of the diameter of microconstriction for Srikanth's model, and (c) changing of the strength of the potential

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barrier for Kirtley's model.

In this paper is shown that inelastic processes near the normal metal/HTS interface play a crucial role. We consider the influence of finite quasiparticle lifetime caused by these inelastic processes in BTK theory and in Kirtley's model. The theoretical results are compared with experimental data measured on point contacts using a gold tip and $Bi_2Sr_2CaCu_2O_{8+y}$ thin films as well as $Bi_2Sr_2CaCu_2O_{8+y}/SrTiO_3$ bilayers with different thicknesses of $SrTiO_3$.

To account for the shortening of the quasiparticle lifetime we included the inelastic scattering term in the Bogoliubov equations and following the BTK approach[12] we found the Bogoliubov coherence factors $\tilde{u}_0,\tilde{v}_0$ to be[13]

$$\tilde{u}_0^2=\frac{1}{2}\left[1+\frac{\sqrt{(E+i\Gamma)^2-\Delta^2}}{E+i\Gamma}\right], \tag{1a}$$

$$\tilde{v}_0^2=\frac{1}{2}\left[1-\frac{\sqrt{(E+i\Gamma)^2-\Delta^2}}{E+i\Gamma}\right]. \tag{1b}$$

One can see that $\tilde{u}_0,\tilde{v}_0$ are complex in the whole range of energy which differs from the BTK theory where u_0,v_0 are real for $E>\Delta$. The density of states can be expressed by

$$\tilde{N}(E,\Gamma)=\mathrm{Re}[(\tilde{u}_0^2-\tilde{v}_0^2)^{-1}]=\mathrm{Re}\left[\frac{E+i\Gamma}{\sqrt{(E+i\Gamma)^2-\Delta^2}}\right], \tag{2}$$

which is a formula similar to that of Dynes *et al.*[17] Substituting the coefficients $\tilde{u}_0,\tilde{v}_0$ in the relations for the probability of both the Andreev $A(E)$ and the ordinary $B(E)$ reflections derived in Ref. 12 (see Table I), the total elastic current can be expressed as

$$I_{\mathrm{el}}=C\int_{-\infty}^{\infty}[f(E-eV)-f(E)][1+A(E)-B(E)]dE, \tag{3}$$

where $f(E)$ is the Fermi distribution function and C is a constant depending on the junction area. Figure 1 shows the results of a numerical evaluation of the modified BTK theory.

Interesting results are obtained for small values of Z whereas for $Z>1$ the well known Dyne's smeared tunneling conductance is achieved. Our results are different from the result published by Srikanth and Raychaudhuri.[19] They obtained no significant change of differential conductance with variation of the broadening parameter Γ if $Z\rightarrow 0$. From Fig. 1 one can see a dramatic decrease of the differential conductance at $V=0$ if Γ is enhanced so that the ratio G_{NS}/G_{NN} is still not 2 as is expected for Andreev reflection in the case $Z=0$. Also the drop of the conductance at $V=\Delta$ is significantly smeared and therefore the determination of the gap value from differential characteristics is unambiguous. These features were really observed on conventional superconductor/normal metal point contacts.[20] On high-T_c superconductor ($YBa_2Cu_3O_{7-x}$, $Bi_2Sr_2CaCu_2O_{8+y}$)/metal point contacts we have not observed differential characteristics which would resemble those in Fig. 1(a). This is due to the "impedance" imbalance caused by different Fermi velocities in the normal metal (v_{FN}) and HTS (v_{FS}). In such a case the effective value of Z must be taken into account:[14]

$$Z=\left[Z_B^2+\frac{(1-v_{FS}/v_{FN})^2}{4v_{FS}/v_{FN}}\right]^{1/2}, \tag{4}$$

where Z_B is the parameter of strength of the real barrier.

The above modified BTK theory has enabled us to explain the results obtained on $Bi_2Sr_2CaCu_2O_{8+y}/Au$ point contacts.[13] However, well above the gaplike structure a discrepancy between experimental results and theoretical curves occurred. The discrepancy is caused by a linear decrease of the differential conductance at high voltage as one can see from Fig. 2. On the other hand, a linear increase and also constant linear background at higher bias voltage are often observed.[6,20] To explain this experimental fact several models were elaborated as was mentioned above. Since our modification of BTK theory based on inelastic scattering in the surface layer of HTS's described the experimental data very well at $eV<2\Delta$ and it is expected that the density of scattering centers is highest on the surface of HTS's, it is reasonable to suppose that inelastic processes play no negligible role also for the transport of quasiparticles through the N/S interface. Thus the inelastic component of the current must be added to the elastic one. The theory of inelastic transport in metal/superconductor contacts for arbitrary transmittance was recently elaborated by Kirtley.[11] Within first order perturbation theory, and neglecting the influence of the inelastic processes on the distribution

TABLE I. Probability of the Andreev $A(E)$ and the ordinary $B(E)$ reflections, derived in BTK theory [$\gamma=u_0^2(u_0^2-v_0^2)Z^2$].

$A(E)$	$B(E)$
$A(E)=aa^*$	$B(E)=bb^*$
$a=u_0v_0/\gamma$	$b=-(u_0^2-v_0^2)(Z^2+iZ)/\gamma$

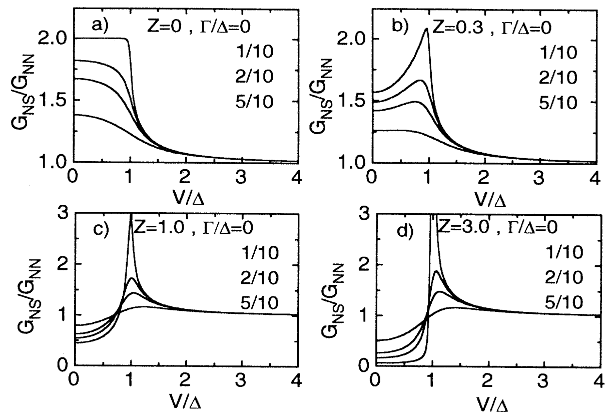

FIG. 1. Normalized elastic differential conductance of the superconductor/metal point contact evaluated for various values of the barrier strength parameter Z and of the broadening parameter Γ.

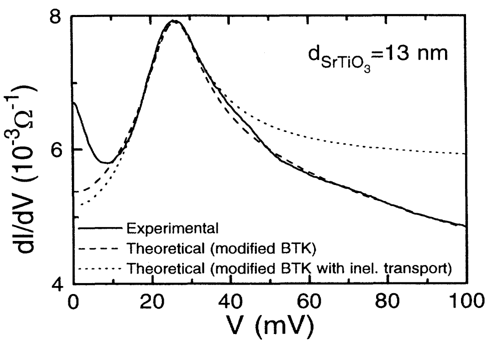

FIG. 2. Comparison of experimental data (solid line) measured on $Bi_2Sr_2CaCu_2O_{8+y}/SrTiO_3$(13 nm)-Au point contact at temperature 4.2 K with theoretical curves evaluated from modified BTK theory (dotted line) and modified BTK theory extended by the inelastic component of conductivity (dashed line). Fitting parameters are $\omega_c = 200$ mV, $N = 100$, $T = 4.2$ K, $Z = 0.7$, $\Gamma = 7$ meV, and $\Delta = 27$ meV.

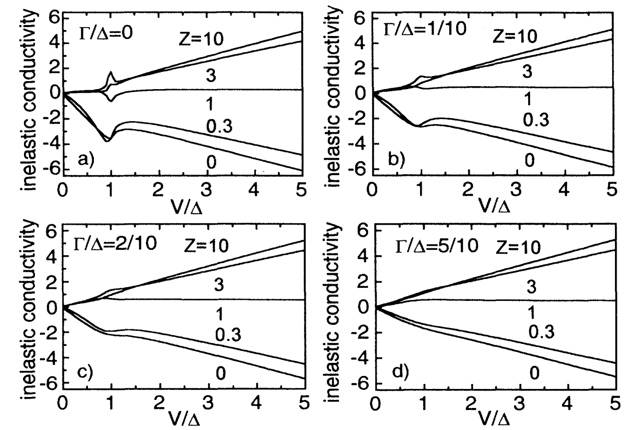

FIG. 3. Inelastic differential conductance of the superconductor/metal point contact evaluated for various values of the barrier strength parameter Z and of the broadening parameter Γ ($\omega_c = 10\Delta$, $N = 100$).

function of quasiparticles, he derived the relation for the inelastic component of the current

$$I_{\text{inel}}(V,\hbar\omega) = I_A(V,\hbar\omega) + I_B(V,\hbar\omega) + I_C(V,\hbar\omega) + I_D(V,\hbar\omega) , \tag{5}$$

where I_A, I_B, I_C, I_D are the Andreev scattering, normal reflection, direct transmission, and the branch crossing inelastic currents, respectively, given in Ref. 11.

These current components depend on the quantities $u_0(E), v_0(E)$, strength Z, and $a(E)$ and $b(E)$ [which depend on the above quantities $u_0(E)$, $v_0(E)$, and Z as given in Table I] as well as on inelastic-energy loss level $\hbar\omega$. For a broad inelastic-energy loss distribution (IELD), the total inelastic conductance can be expressed as

$$G_{\text{inel}} \sim \sum_{j=1}^{N} \frac{\partial I_{\text{inel}}(V,\hbar\omega_j)}{\partial V} . \tag{6}$$

For simplicity we will suppose an equidistant IELD from zero to the cutoff energy $\hbar\omega_C$, i.e.,

$$\hbar\omega_j = \frac{j}{N}\hbar\omega_C , \tag{7}$$

where N is the number of energy levels relevant for the inelastic losses. The results obtained from Kirtley's model are shown in Fig. 3(a).

To obtain the linear background a continuous broad IELD is necessary. When the shortening of the quasiparticle lifetime caused by inelastic scattering is taken into account, the discrete spectrum will be smeared and the linear background can also be obtained in the case of a noncontinuous distribution. To include the shortening of the quasiparticle lifetime in the model of Kirtley we substitute for $u_0(E)$, $v_0(E)$, and $N_S(E)$ used in Ref. 11 the relations (1a), (1b), and (2). The slope of the linear background depends on both the barrier strength Z and the density of inelastic-energy losses. But only variations of the parameter Z can change the linearly increasing conductance to a linearly decreasing one. From Fig. 3 one can see that the shortening of the quasiparticle lifetime causes a significant suppression of the gaplike structure in the inelastic component of the differential conductivity, considerably larger than for the elastic one (see Fig. 1). Thus a linear dependence of the differential conductivity without a gaplike structure should be observed when inelastic processes play a crucial role. Such a type of differential characteristic was really observed by various authors.[21,15]

In order to verify whether the above inelastic mechanism takes place in the surface layer of HTS's we measured the differential resistance (dV/dI vs V) of thin film $Bi_2Sr_2CaCu_2O_{8+y}/SrTiO_3$-Au tip point contacts. The type of conductivity depended on the thickness d of $SrTiO_3$ and it was changed from metallic (without $SrTiO_3$) to tunneling (for $d > 18$ nm) type. The thin $Bi_2Sr_2CaCu_2O_{8+y}$ films were deposited by laser ablation onto single crystalline $SrTiO_3$ substrates.[22] The $Bi_2Sr_2CaCu_2O_{8+y}$ deposition was carried out at a substrate temperature 720 °C and at an oxygen partial pressure 20 Pa. The critical temperature of these thin films was > 80 K and the critical current density $j_c(60\text{ K}) > 10^6$ A/cm^2. Onto the $Bi_2Sr_2CaCu_2O_{8+y}$ surface, thin films of $SrTiO_3$ were deposited *in situ* at a substrate temperature of 600 °C and at an oxygen partial pressure 20 Pa. The thicknesses of these $SrTiO_3$ top layers were 13 nm, 18 nm, and 23 nm, respectively. The thickness of the $Bi_2Sr_2CaCu_2O_{8+y}$ films was 100 nm. On these bilayer structures point contact junctions were prepared and measured at a temperature 4.2 K. A Au wire was used as a point contact tip. The differential characteristics dV/dI vs V were measured by the standard low-frequency phase-sensitive detection technique using a resistance bridge.

Typical measured differential characteristics are given in Fig. 4. A broadened gaplike structure, linear background, and often the conductance peak at zero bias voltage were observed. The origin of the zero-bias anomaly

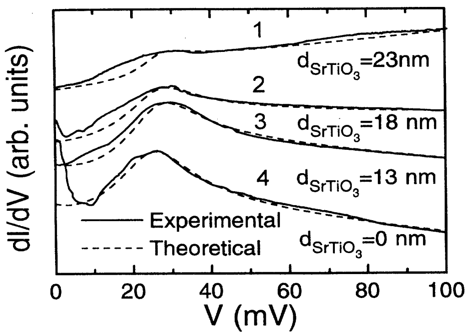

FIG. 4. dI/dV V characteristics measured on $Bi_2Sr_2CaCu_2O_{8+y}/SrTiO_3$-Au point contacts with thickness of $SrTiO_3$ (curve 4), 13 (curve 3), 18 (curve 2), and 23 nm (curve 1) at temperature 4.2 K. The experimental data (solid lines) are fitted by the modified BTK theory extended by the inelastic component of conductivity (dashed lines). Fitting parameters are $\omega_c = 200$ mV, $N = 100$, $T = 4.2$ K, and curve (1) $Z = 3$, $\Gamma = 7$ meV, $\Delta = 27$ meV, curve (2) $Z = 1$, $\Gamma = 7$ meV, $\Delta = 27$ meV, curve (3) $Z = 0.7$, $\Gamma = 7$ meV, $\Delta = 29$ meV, curve (4) $Z = 0.6$, $\Gamma = 7$ meV, $\Delta = 26$ meV.

was discussed in Ref. 18 but the explanation of this zero-bias anomaly remains open up to now. The experimental curves are compared with theoretical ones calculated from the above theories. Although modified BTK theory[13] fitted the experimental curves well at voltages near the energy gap, a considerable departure occurs at higher voltages. When the inelastic component of the differential conductance is added to the elastic one a very good correspondence between experimental and theoretical data was obtained. From the fitting procedure we obtained the maximal value of the energy gap $\Delta = 29$ meV. The ratio was $2\Delta/kT_c = 7.7$ if the bulk value of the critical temperature is considered. The next fitting parameter Z was obtained from 0.6 ($d = 0$ nm) to 3 ($d = 23$ nm). Thus the lower limit of the value of the Fermi velocity ($v_{FS} \geq 4.5 \times 10^7$ cm/s) and superconducting coherence length ($\xi \geq 35$ Å) can be calculated from relations (4) and $\xi = \hbar v_{FS}/\pi\Delta$, respectively. If $Z_B = 0$ is supposed for $Bi_2Sr_2CaCu_2O_{8+y}$ without $SrTiO_3$ covering, the parameters $v_{FS} = 4.5 \times 10^7$ cm/s and $\xi = 35$ Å are obtained. The slope of the linear background depends on the effective strength of the barrier (parameter Z) as a result of the above theory. Also the large parameters of broadening Γ (about 7 meV) indicate the presence of inelastic scattering caused by structural disorder (oxygen vacancies, grain boundaries, magnetic impurities) near the HTS/metal interface. As was shown by photoemission spectroscopy[23] as well as other methods[24] a strong degradation of a HTS surface layer caused by oxygen depletion occurs at room temperature. A similar effect was observed in the time immediately after the preparation of the HTS/metal contact.[25–27] These facts imply a relatively high mobility of oxygen ions in the HTS materials at room temperature. The results shows that the surface layer of HTS's is oxygen deficient within a depth of several tens of Å.[28] Thus the randomly distributed oxygen vacancies can destroy the structural coherence in the superconducting planes of HTS's (Ref. 29) and consequently reduce the pair amplitude[30] and/or destroy the phase coherence.[31] In addition, local fluctuation of Cu spins can be present in the oxygen deficient surface layer and produces local moments acting as paramagnetic impurities.[32] Thus the degraded surface layer of the HTS influences the pair potential Δ and produces the inelastic scattering of quasiparticles. This inelastic scattering contributes to the shortening of the quasiparticle lifetime near the N/S interface and this mechanism can lead both to a smearing of the gaplike structure in the differential characteristic and to inelastic transport through the N/S or N-I-S interface. As already mentioned the change of slope of the linear background from increasing to decreasing was also predicted by Littlewood and Varma within MFL theory and Srikanth *et al.* in terms of electron confinement. The latter effect probably does not play a substantial role. The reasons that lead us to this conclusion are the following: (a) the contacts were prepared in the same way so there is no reason to expect that the active junction area could be changed by covering the $Bi_2Sr_2CaCu_2O_{8+y}$ with a $SrTiO_3$ thin film; (b) the diameter of the contact area required to lead to electron confinement is extremely small in HTS materials ($\simeq 5$ Å). As regards the MFL model we cannot exclude that the effects described by this model take place in HTS's. This model corroborates also experiments carried out by Mandrus *et al.*,[33] where a decrease of the differential conductivity on break junctions in the *a-b* direction was shown. But our results show that the slope of the linear background is changed by changing the barrier strength. Thus the inelastic effects play a dominant role that prevail over the effect predicted by Littlewood and Varma.

In conclusion, we have shown that both the linear background at high bias and the smeared gaplike structure can be explained by inelastic processes in the HTS/normal metal interface. We obtained good agreement between experimental and theoretical curves if both the inelastic transport through the interface as well as the inelastic scattering in the surface layer of the HTS are considered. We have found that the slope of the linear background of the differential conductance is changed from increasing to decreasing depending on the strength of the barrier. From the experimental curves the energy gap value $\Delta = 29$ meV, $v_{FS} = 4.5 \times 10^7$ cm/s, and $\xi = 35$ Å were determined. Our results indicate that the most striking features often observed in the differential conductivity of HTS/metal junctions, such as broadening and variation of the gaplike structure, or the linear background at high bias, are not intrinsic properties of HTS's, but can be explained by inelastic processes in the degradated surface layer of the HTS.

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