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Andreev reflection in the c-axis transport of $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals near T_c

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임계온도 근처에서 $Bi_2Sr_2CaCu_2O_{8+x}$ 단결정의 c축 방향 전도시 일어나는 안드레에브 반사

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Abstract

An enhancement of the c-axis differential conductance around the zero-bias voltage near the superconducting transition temperature T_c has been observed in $Au/Bi_2Sr_2CaCu_2O_{8+x}$ junctions. We attribute such an enhancement to the Andreev reflection (AR) between the surface Cu-O bilayer with suppressed superconductivity and the next superconducting Cu-O bilayer. The continuous evolution of the differential conductance, from gaplike depression to an AR-like peak structure, around the zero-bias voltage points to weakening of the barrier strength of the nonsuperconducting layer between adjacent Cu-O bilayers as temperature approaches T_c from below. The peak structure disappeared just below the bulk T_c value of underdoped Bi2212 single crystals, whereas it survived up to ~1 K above T_c in junctions prepared on slightly overdoped crystals. According to a recently proposed theoretical consideration, a wider temperature range of the AR above T_c is expected in the underdoped regime when phase-incoherent preformed pairs emerge in the pseudogap state. Our result is in contradiction to the preformed pair scenario.

Keywords : Andreev reflection, preformed pairs, pseudogap, $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals, intrinsic junctions

I. Introduction

The dominant d-wave order parameter (OP) symmetry of the high-T_c superconductors (HTSC's) leads to novel phenomena in the electrical transport properties such as the formation of π-junctions [1] and zero-bias conductance peak (ZBCP) [2,3,4]. The ZBCP is observed in NId (normal-metal/insulator/d-wave-HTSC) junctions when incident quasiparticles (QP's) experience sign changes of the OP upon reflection at the interface of the junction, where a coherent bound state, called the Andreev bound state (ABS) is formed. In contrast to the conventional Andreev reflection (AR) effect [5,6], where maximum conductance enhancement is obtained for zero barrier strength, a finite scattering barrier at the interface is essential for the observation of the ZBCP

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[4].

On the other hand, the c-axis tunneling characteristics of the HTSC's such as $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212) can be well understood in terms of serial stacking of *dId* (*d*-wave-HTSC/insulator/*d*-wave-HTSC) intrinsic Josephson junctions (IJJ's) [7]. Because of the strong barrier strength of the '*I*' layers, however, no AR has been observed to date in an *NId* junction for the c-axis transport. The occurrence of an ABS in such a junction can be ruled out because, in the case of c-axis tunneling, the signs of the OP experienced by the incident and the reflected QP's are always the same.

In this study, we report observation of the conventional AR in the ''surface junction'' of Bi2212 single crystals *for the c-axis transport* at temperatures very close to the bulk transition temperature T_c. In a previous work [8], we showed that the superconductivity of the surface Cu-O bilayer in a Bi2212 single crystal is suppressed when in contact with a normal-metal electrode. Such suppression leads to the formation of a natural *NId* junction at the crystal surface, the ''surface junction'', in the temperature range $T'_c<T<T_c$, where T'_c and T_c are the transition temperatures of the surface and inner Cu-O bilayers, respectively. In this *NId* surface junction, '*N*' represents the surface Cu-O bilayer with suppressed superconductivity including the normal-metallic Au electrode. The fact that the differential conductance (dI/dV) curves evolve in a continuous manner from a gap-like depression at low temperatures to an AR-like peak structure as the temperature approaches T_c from below leads to a conclusion that the nonsuperconducting '*I*' layer between adjacent Cu-O bilayers becomes transparent with vanishing barrier strength at high enough temperatures close to T_c. A simple numerical simulation using the *d*-wave BTK formalism [4] confirms, at least qualitatively, our idea of weakening barrier strength near T_c.

Recently, it has been proposed by Choi, Bang, and Campbell [9] that, if the pseudogap state above T_c in the HTSC's is described in terms of the phase-incoherent preformed pairs (PIPP) [10], the AR can take place from such pairs. They suggest that experimental observation of the resulting conductance enhancement in an *ab*-planar normal-metal/HTSC junction would provide unambiguous confirmation of the PIPP in the pseudogap state. Along with the suggestion of Ref. [9] we utilized the appearance of the AR effect *along the c-axis direction* near T_c to investigate the existence of the PIPP in the pseudogap state. Our result agreed with the recent observation of the nonexistence of the AR effect above T_c *in ab-planar* normal-metal/HTSC junctions by Dagan *et al.* [11] and seems to provide negative perspective to the existence of the PIPP in the pseudogap state.

II. Experiment

As-grown overdoped Bi2212 single crystals were prepared by the conventional solid-state-reaction method. Underdoped crystals were grown first by traveling solvent floating zone methods and the doping level was reduced by annealing the crystals in a low-concentration (~0.1 %) N_2 mixed O_2 gas. Details of the mesa fabrication are described elsewhere [8,12]. The temperature dependence of the c-axis resistance $R_c(T)$ and the differential conductance dI/dV were obtained by standard ac lock-in technique.

III. Results and Discussion

Fig. 1 displays the typical c-axis tunneling resistance $R_c(T)$ of a mesa (UD2) fabricated on the surface of an underdoped Bi2212 single crystal and measured in a three-terminal configuration as shown in the right inset. The bulk transition temperature T_c ($\approx$82.5 K) was defined as the peaking temperature of the $R_c(T)$ curve. As Kim *et al.* [8] argued earlier, the superconductivity of the surface Cu-O bilayer in Bi2212 single crystals is strongly suppressed when it is in contact with a normal metal layer. The resulting characteristics from the *NId* surface junction in Fig. 1 is apparent as the strongly semiconducting part of the $R_c(T)$ curve below T_c. However, no superconducting transition of the surface Cu-O bilayer was observed down to ~4.2 K in contrast to the results in as-grown slightly overdoped crystals [8,12], where the surface bilayers usually show the superconducting transition at $T'_c\approx$30–40 K. In this underdoped crystal UD2, the

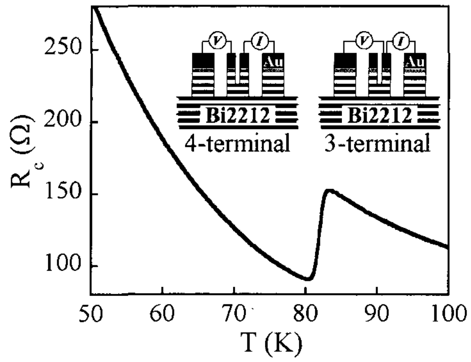

Fig. 1. Typical $R_c(T)$ curve measured in a three-terminal configuration of the mesa UD2, prepared on an underdoped Bi2212. The maximum $R_c(T)$ takes place at about 82.5 K ($\approx T_c$). The finite resistance below T_c was from the surface junction. Insets are schematic views of the sample geometry and the configuration for the three- and four-terminal measurements.

reduced hole doping of the surface Cu-O bilayer [13] may have contributed to the suppression of the superconductivity in addition to the proximity-induced suppression.

A set of *dI/dV* curves of the mesa UD2 for various temperatures are shown in Fig. 2. The conductance was measured *in the first branch* of the current-voltage characteristics (*IVC*), which was from the *NId* surface junction of the mesa. The *dI/dV* curves at the lower temperature range in Fig. 2(a) display distinct gaplike features. Since the *IVC* of IJJ's in the supercurrent branch switches to the QP branch before the bias voltage reaches the gap edge, sudden jumps appear in the *dI/dV* curves in Fig. 2(a), where the coupling of the IJJ's broke down before the gap edge of the inner Cu-O bilayer in the *NId* surface junction was reached. Details of the situation are illustrated in the inset of Fig. 2(b) for $T \approx 65.2$ K, in which the shaded area approximately marks the region of the voltage jump in the *IVC*. As the temperature is raised the gaplike depression of the differential conductance becomes shallower [Fig. 2(a)], and gradually exhibits a peak structure [Fig. 2(b)]. However, as shown in Fig. 2(b), in the middle of the superconducting transition slightly above 79.6 K, the magnitude of the peak decreases with increasing temperature and finally vanishes near T_c. The oscillations of the *dI/dV* curve with rather

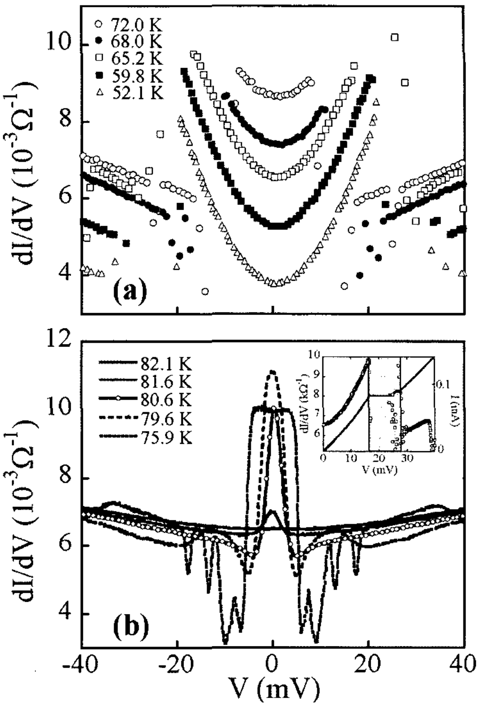

Fig. 2. *dI/dV* curves of the *NId* surface junction (a) at relatively low temperatures and (b) at high temperatures near T_c. Inset shows the *IVC* (–) and the *dI/dV* (○) vs. voltage at $T \approx 65.2$ K. The shaded area marks the region of the voltage jump to the QP branch due to the premature switching of the surface junction.

regular periodicity at $T \approx 75.9$ K are believed to be caused either by the fluctuating Josephson coupling in the IJJ's underneath the surface junction or by the coherent interference of boundary-reflected QP's in the normal-metal electrode of the *NId* surface junction [14].

The appearance of the zero-bias enhancement of the *c*-axis *dI/dV* is quite surprising and in clear contrast to most of earlier results of *c*-axis tunneling measurements in HTSC's [3,15,16,17], where only gap-like features have been observed. In some exceptions reported, however, the conductance peak was attributed to the possible existence of *ab*-planar tunneling components due to some surface defects [2,11,18].

The transition from a gaplike structure to a peak in the *dI/dV* curves was also observed previously in scanning tunneling microscopy (STM) measurements

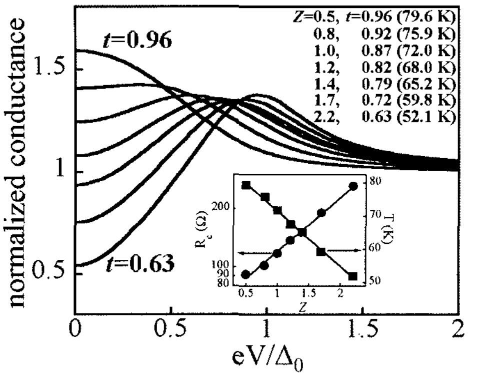

Fig. 3. $\sigma(E)$ calculated using Equation (3). Fixing $\sigma(E=0)$ at various temperatures ($t=T/T_c$) to the corresponding measured values, a continuously decreasing Z gives the best qualitative fit to the measured dI/dV curves of Fig. 2. Inset: Temperature dependence of Z (□) and the Z dependence of $R_c(T)$ ( ). Z is linearly proportional to $\log_{10}[R_c(T)]$ and T. Lines are guides to the eye.

on conventional superconductors [19,20]. Reduction the distance between the normal (superconducting) STM tip and superconducting (normal) sample surface turned the conduction characteristics of the system from tunneling-like into weak-link behavior with the tunneling resistance and the corresponding barrier strength Z decreasing. Also, in a c-axis *NId* junction fabricated by using a sequential deposition of a $Bi_2Sr_2CuO_6$ (Bi2201) thin film and an Au layer on the surface of a Bi2212 single crystal, Matsumoto *et al.* [21] observed an enhancement of the conductance when the temperature approached T_c from below. The increase in the conductance was explained due to the conventional AR effect, where the value of the effective barrier strength parameter Z was reduced with increasing temperature by the semiconducting temperature dependence of the Bi2201 film. We suppose that a similar situation took place in the nonsuperconducting '*I*' layer between the surface Cu-O bilayer and the superconducting next bilayer in the *NId* surface junction. AR between the Au electrode and the surface Cu-O bilayer can be ruled out, however, since the latter is nonsuperconducting at all the temperatures under consideration.

In order to confirm the appearance of the AR in pure c-axis conduction we followed the formalism by Tanaka and Kashiwaya [4]. In this case the BTK kernel is given by

$$1+|A|^2-|B|^2=\frac{16(1+|\Gamma|^2)+4Z^2(1-|\Gamma^2|^2)}{|4+Z^2(1-\Gamma^2)|^2}, \qquad (1)$$

where $\Gamma=E/\Delta(T,\phi)-\sqrt{[E/\Delta(T,\phi)]^2-1}$. The d-wave symmetry of Bi2212 was accounted by $\Delta(T,\phi)=\Delta(T)\cos(2\phi)$ [22], with ϕ as the azimuthal angle in the Cu-O layer and the temperature dependence of OP magnitude was chosen as [23]:

$$\Delta(T)=\Delta(0)\tanh(3.2\sqrt{T_c/T-1}). \qquad (2)$$

The expression of Eq. (2), which agrees very well with the numerical solution of the BCS gap function except near T_c where underdoped crystals are known to have a larger gap size [16,17], was obtained by fitting the $\Delta(T)$ of Ref. [23] to the data of the underdoped Bi2212 crystal with T_c=83 K in Ref. [17] with $\Delta(T=0)\approx 40$ meV [24]. Using these parameters the normalized conductance was calculated according to the BTK formula [4,6] as

$$\sigma(E)=\frac{4}{4+Z^2}\int_{-\infty}^{\infty}\frac{1}{2\pi}\int_0^{2\pi}\left[1+|A|^2-|B|^2\right]d\phi \times\left(-\frac{\partial f(E-eV)}{\partial eV}\right)dE, \qquad (3)$$

where $f(E)$ is the Fermi distribution function. The values of Z at different temperatures were chosen by fixing $\sigma(E=0)$ of Eq. (3) to the measured dI/dV in Figure 2. As shown in the inset of Fig. 3 the values of Z determined in this way are proportional to $\log_{10}[R_c(T)]$ consistent with earlier observations [20]. In addition, the temperature dependence of Z agrees with the scenario of gradually weakening barrier strength as temperature is increased.

Fig. 3 displays the results of Eq. (3) corresponding to the dI/dV curves of Fig. (2) for T=52.1–79.6 K. The overall qualitative features of the calculated $\sigma(E)$ have almost one to one correspondence to the experimental data of Fig. 2. At low temperatures, where Z is supposed to be relatively large, the

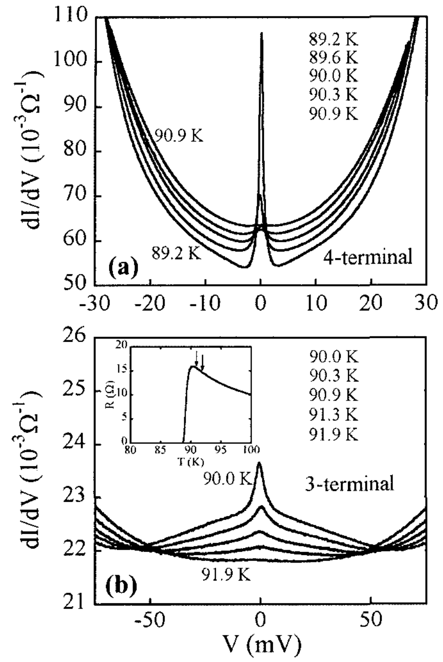

Fig. 4. (a) *dI/dV* curves of the mesa OD3 measured in the four-terminal configuration and (b) in the three-terminal configuration. Inset: $R_c(T)$ of mesa OD3 obtained in the four-terminal configuration. The two arrows denote the temperatures above which the zero-bias peak of the *dI/dV* curves in the four- (the left one) and three-terminal (the right one) configurations disappears.

calculated curves show gaplike features that are qualitatively similar to the observed ones. With increasing temperature Z decreases and both the calculated $\sigma(E)$ and experimental *dI/dV* curves develop to an AR-like enhancement near the zero-bias voltage in a continuous manner. However, at higher temperatures the measured peak widths are significantly narrower than the calculated ones, which seems to be due to the above-mentioned premature switching to the QP branch of the IJJ's below the *NId* surface junction. This switching effectively decreases the conductance inside the gap and results in a narrower width of the AR peak. Other possibilities are a decrease in the AR process itself due to thermal excitation of QP's with energies lower than the gap and the thermal smearing of the gap edge very close to T_c. Both effects decrease the effective OP magnitude experienced by the QP's to a value smaller than that of Equation (2).

Taking the presence of *c*-axis AR for granted, we also investigated the *c*-axis *dI/dV* curves near T_c in *NId* surface junctions made on slightly overdoped Bi2212 single crystals (mesa OD3). The inset of Fig. 4(b) shows the resistive transition of mesa OD3, taken in a four-terminal configuration as illustrated in the left inset of Fig. 1. The temperature of maximum $R_c(T)$, which should be close to T_c, is about 90.3 K and since measurements in a four-terminal configuration do not include the surface effect, the inset of Fig. 4(b) displays the properties of the IJJ's. Fig. 4(a) illustrates the *dI/dV* curves measured in the four-terminal configuration. The zero-bias peak at each temperature was caused by the Josephson pair tunneling over the stacked IJJ's. With slightly increasing temperature the peak reduces rapidly and disappears completely at 90.9 K, which is defined as the intrinsic value of T_c of the crystal and marked slightly above the temperature of maximum $R_c(T)$ by the left arrow in the inset of Fig. 4(b). The concave background conductance implies the existence of the pseudogap in this temperature range [25]. The *dI/dV* curves measured in a three-terminal configuration from the same central mesa are shown in Figure 4(b). One should note that in this case the properties of the *NId* surface junction as well as that of the IJJ's were measured. At 90.9 K, where the conductance peak completely vanishes in the corresponding four-terminal measurements, a clear peak structure in the *dI/dV* curves still persists, although its magnitude is much smaller than the four-terminal counterpart. Increasing temperature the peak height gradually decreases and disappears completely around T=91.9 K as marked by the right arrow in the inset of Fig. 4(b). Thus, in the three-terminal configuration, one has a 1-K temperature window of AR above the T_c measured by the four-terminal configuration. In a different mesa (OD2) fabricated on another overdoped crystal, a 2-K temperature window of AR above T_c was obtained (data not shown). Since the inner Cu-O bilayer is no more superconducting above 90.9 K, the AR in Fig. 4(b) is either from the thermally fluctuating superconducting order or from the PIPP in the pseudogap state as proposed in Ref. [9]. If the AR was genuinely from the PIPP, the temperature window of the AR above T_c should be wider in underdoped crystals than in overdoped ones as pointed out by the authors of Ref. [9]. However, contrary to the theoretical expectation, in the case of underdoped crystals, we observed no appreciable AR above T_c as shown in Fig. 2, whereas a clear temperature window of the AR has been observed in crystals in the overdoped regime.

In summary, we report that an AR has been observed in Au/Bi2212 single crystal junctions with the transport current along the *c* axis of the Bi2212 HTSC's, in both underdoped and overdoped states. The features of the *dI/dV* curves changed from gaplike depression at low temperatures to an AR-like enhancement near T_c. We attribute such continuous evolution to the AR between the proximity-suppressed surface Cu-O bilayer and the superconducting inner one as the barrier potential decreases with the temperature approaching T_c from below. We utilized this appearance of the AR to investigate the existence of the PIPP in the pseudogap state above T_c. In as-grown overdoped mesas we have observed maximally a 2-K temperature range where the three-terminal measurements exhibit the AR-induced conductance peaks above T_c that was determined in a four-terminal configuration. On the other hand, no appreciable AR above T_c has been detected in single crystals that were in the underdoped regime, although theoretical consideration [9] suggests a wider temperature range of AR above T_c. Therefore the AR above T_c in overdoped crystals may have been resulted from the thermal fluctuation effect of the superconducting order. If that is the case no AR due to PIPP in the pseudogap state has been observed in this work. Our results then agree with the recent report in *ab*-planar junctions [11] where no AR was observed in the pseudogap state. However, more rigorous examination is required on the validity of the suggested observation [9] of the AR effect from PIPP.

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