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Tunneling Spectra in Organic Cu-Pc/$Bi_2Sr_2CaCu_2O_{8+\delta}$ Tunnel Junctions

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Abstract

We report the current transport properties of a normal metal/organic conductor/ superconductor tunnel junction as a novel high-T_c superconducting three terminal device. The organic copper (II) phthalocyanine (Cu-Pc) layer was used for a polaronic quasiparticle (QP) injector. The injection of polaronic QP from the Cu-Pc interlayer into a superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) thin film generated a substantially larger nonequilibrium effect as compared to the normal QP injection current. The tunneling spectroscopy of an Au/Cu-Pc/BSCCO junction exhibited a zero bias conductance peak which may be due to Andreev reflection at a Cu-Pc/*d*-wave superconductor junction.

Keywords: Organic copper (II) phthalocyanine, Andreev reflection, polaronic quasiparticle injection.

I. Introduction

The investigation of a nonequilibrium superconductivity has been studied for the application to superconducting three terminal devices [1]. The nonequilibrium state in a superconductor can be induced by injecting photons or phonons with energy greater than the superconducting energy gap, so that the number of quasiparticle (QP) becomes greater than that in thermal equilibrium. Effective ways to induce a strongly perturbed nonequilibrium state have been investigated by injecting QP into the tunnel junction with a high-T_c superconductor (HTSC) [2-6]. Comparing with quasipaticle injection into low-T_c superconductor, the carrier density of HTSC is smaller than low-T_c superconductor, thus, the higher gain was expected. However a small current gain has been measured [2-4]. In order to get higher current gain, recently, many authors have reported spin-polarized QP injection from a ferromagnetic injector into a HTSC has caused a strong nonequilibrium effect [7-8].

In this letter, we report the nonequilibrium effects in a HTSC due to the injection of polaronic QP from organic copper (II) phthalocyanine (Cu-Pc) interlayer into a $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) thin film. When the organic material is interlaid between normal metal and high-T_c superconductor, the QP incoming from a metal will be perturbed by the polaron in the organic material where the charge transport occurs by polaron hopping [9]. The perturbed QP in organic conductor will act as QP injector at the interface between the organic conductor and the HTSC. The QP injection from Cu-Pc into a HTSC is expected to form a strong nonequilibrium state due to the interaction between polarons and Cooper-pairs. Thus, we observed that the current gain of N/Or/S tunnel junctions was higher than that of S/N junctions, which behavior is interpreted by the nonequilibrium

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effect due to the organic interlayer. The dependences of the differential conductance of Au/Cu-Pc/BSCCO (N/Or/S) tunnel junctions on the voltage bias have been studied. We observed a zero bias conductance peak (ZBCP) which may be interpreted as a scattering process at an organic Cu-Pc/*d*-wave superconductor junction.

II. Experimental

The BSCCO thin films were prepared by a molecular beam epitaxy with a sequential deposition technique on MgO (110) substrates [10]. The growth temperature and the growth rate of BSCCO thin film were 740 °*C* and 29 *nm/h*, respectively. The fabricated BSCCO thin film has the cleaved surface which include the *ab* plane. Note that, the surface morphology of the superconductor is crucial in N/Or/S tunnel junction experiment. For N/S junction, Au layer was deposited on BSCCO thin film. For N/Or/S junction, the organic Cu-Pc thin film interlayer between normal metal Au and BSCCO thin film was deposited by thermal evaporation. The interl ayer thickness of Cu-Pc thin film was 100 *nm*. The polaronic QP injector, an organic Cu-Pc has the fourfold symmetry and a copper lies at the center of the phthalocyanine ring. This ring structure has long hydrocarbon chains which play an important role in t he formation of polarons [11]. The normal metal Au was deposited as an electrode on a Cu-Pc film and BSCCO thin film. The junction area is $1\times1 mm^2$. The device geometry is depicted in Fig. 1. Two currents were fed into the superconductor film: one is the injection current (I_{inj}) and the other is the transport current (I_T) through a superconductor thin film. The I_{inj} goes from the organic Cu-Pc thin film to the BSCCO. The current-voltage (*I-V*) characteristics of the junctions were measured using a dc four-probe method and the conductance spectra were measured using a lock-in amplifier.

III. Results and discussion

The measured critical temperature of the BSCCO thin film was about 72 *K* as shown in Fig. 2. For Au/Cu-Pc/BSCCO tunnel junction, the temperature dependence of the junction resistance in BSCCO also showed a distinct resistive transition at 72 *K*,

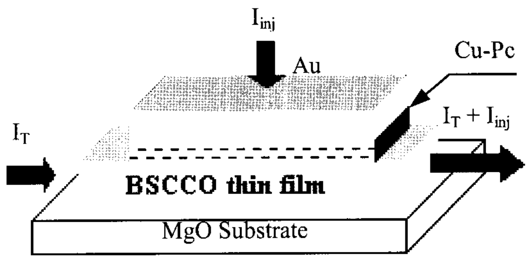

Fig. 1. The geometry of an Au/Cu-Pc/BSCCO tunnel junction.

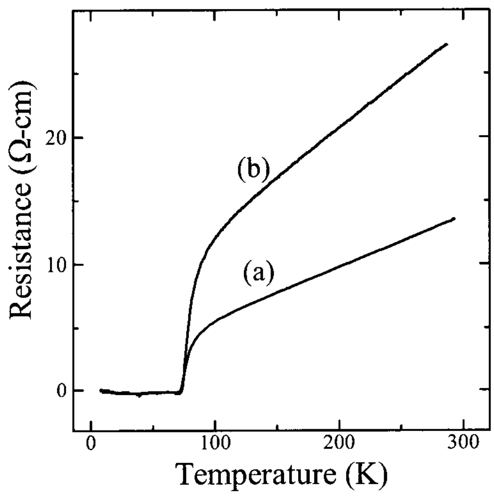

Fig. 2. The resistive transition of an Au/Cu-Pc/BSCCO tunnel junctions (a) without a Cu-Pc interlayer and (b) with $d_{Cu\text{-}Pc}$=100 *nm*.

independent on the thickness of Cu-Pc film; $d_{Cu\text{-}Pc}$. This means that there is no degradation by the deposition of the Cu-Pc layer while a ferromagnet/HTSC tunnel junction always degrades superconductivity [7].

The nonequilibrium effect in Au/Cu-Pc/BSCCO tunnel junction can arise by polaronic QP injection from organic Cu-Pc layer, which is quite different from QP injection effect in normal metal/supercond uctor tunnel junction. The charge transport in Cu-Pc layer involves polarons consisting of electron dressed with phonon [12]. Thus, the QP incoming from a m etal will be perturbed with polaron in the organic material where the charge transport occurs by polaron hopping. When the polaronic QPs are injected into superconductor, it can be expected that

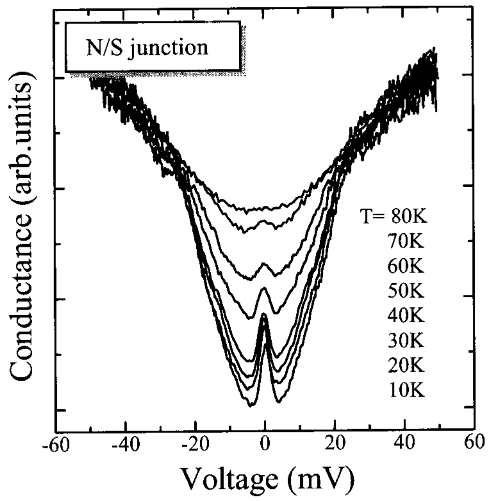

Fig. 3. Temperature dependence of the differential conductance for an Au/BSCCO tunnel junction.

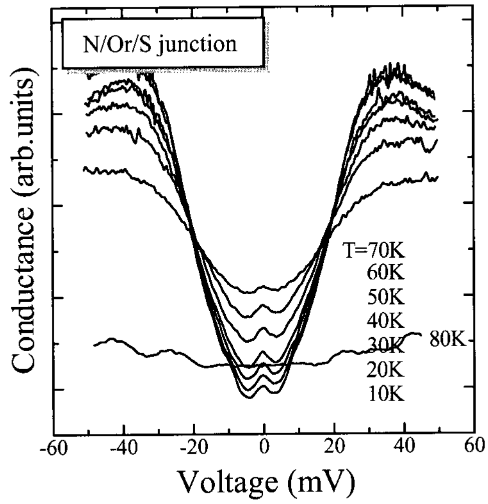

Fig. 4. Temperature dependence of the differential conductance for an Au/Cu-Pc/BSCCO tunnel junction with $d_{Cu\text{-}Pc}$=100 *nm*.

the polarons in Cu-Pc split into electrons and phonons at the interface because the recombination time of phonon component in Cu-Pc ($\sim10^{-15}$-10^{-14} sec) is shorter than that of the QP ($\sim10^{-12}$ sec) relaxation time and only the electrons tunnel into the BSCCO thin film leaving phonons at the interface due to inelastic tunneling process [13-14]. Thus, electrical impedance is created at the boundary between the Cu-Pc and the HTSC BSCCO film and generates a nonequilibrium state at the interlayer. These similar nonequilibrium effects could be observed in a superconductor/metal/ ferromagnetic tunnel devices [7].

Fig. 3 shows the conductance spectra of Au/BSCCO tunnel junction. Conductance spectra exhibit ZBCP. It was explained by Andreev reflection at N/S interface. The Andreev reflection caused by the rotation of the internal state of an excitation spectrum from particle-type to hole-type and vice versa leads to the Andreev bound states at a zero energy on the Fermi surface. It can be directly detected by ZBCP. Thus, the appearance of the ZBCP implies that the anisotropic high-T_c superconductor has *d*-wave pairing symmetry for their pair potential since such ZBCP does not appear at the *s*-wave superconductor. This effect is consistent with the observed features in many QP tunneling experiment performed by many groups [15-18]. The change of ZBCP heights as a function of temperature increased nonlinearly as bath temperature was reduced. Alff et al. reported a $1/T$ dependent of ZBCP using bicrystal junction and our results had a similar tendency against temperature [19].

Fig. 4 shows the temperature dependence of the differential conductance spectra for organic Cu-Pc/BSCCO *d*-wave superconductor interface. The ZBCP was observed up to 70 K. Note that, according to theory [20-23], a ZBCP is expected when the tunnel boundary in formed at the (110) surface of a *d*-wave superconductor. At an organic conductor/ HTSC interface, the differential conductance characteristics were also affected by the same effective interfacial boundary condition. For organic Cu-Pc/BSCCO *d*-wave superconductor interface, a ZBCP is also expected for a non-*c*-axis oriented interface. Thus, the observed ZBCP may be interpreted as the Andreev boundary state of polaronic QP from the Cu-Pc film into *d*-wave superconductor.

In summary, we have reported the transport properties of Au/BSCCO and Au/Cu-Pc/BSCCO tunnel junctions. For Au/BSCCO tunnel junctions, a clear ZBCP directly related to the Andreev bound states was observed. The conductance spectra between an organic Cu-Pc and BSCCO thin film also showed a ZBCP, reflecting the charge transport in the [110] surface due to an Andreev bound state. The above phenomena are of importance in developing nonequilibrium three-terminal superconducting devices.

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