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# Tunneling effect due to UV irradiation in organic Cu-Pc/$Bi_2Sr_2CaCu_2O_{8+\delta}$ tunnel junction

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**Abstract**

We studied the nonequilibrium superconductivity due to tunnel injection of polaronic quasiparticle (QP) from organic photoconductor. The transport properties of an organic copper (II) phthalocyanine (Cu -Pc)/d-wave superconductor were investigated in dark and under ultraviolet (UV) radiation for performance of a novel high-$T_c$ superconducting three terminal device. We observed that the injection of polaronic QP from the organic Cu -Pc film into the $Bi_2Sr_2CaCu_2O_{8+\delta}$ film generated a substantially larger nonequilibrium effect as compared to the normal QP injection current. We could increase the current gain by UV excitation of the organic photoconductor injector. The tunneling spectroscopy of a Cu -Pc/BSCCO junction exhibited a small enhancement of the zero bias conductance peak under the UV excitation. The above phenomena are of importance in developing optically controlled three terminal superconducting device.

*Keywords* : Organic Copper (II) phthalocyanine, $Bi_2Sr_2CaCu_2O_{8+\delta}$, polaronic quasiparticle injection, nonequilibrium state.

## I. Introduction

Recently, the tunnel injection of quasiparticles (QP) [1]-[3] or spin-polarized QP [4]-[6] into superconductor has been extensively investigated for the application of high-$T_c$ superconductivity (HTSC) to three terminal devices. Such a tunnel injection creates a nonequilibrium state in superconductor which suppresses the superconducting order parameter and depresses the critical current density [7].

The generation of a strong nonequilibrium state in the HTSC leads to the high current gain of the device. In order to get higher current gain in HTSC, many authors have reported that the spin-polarized QP injection from a ferromagnet injector into a HTSC has caused a strong nonequilibrium effect [4]-[6].

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In this context, using an organic photoconductor, we investigated injection of polaronic QP from an organic material to get an effective nonequilibrium state. Note that polaronic quasiparticle injection from an organic photoconductor, unlike spin injection from a ferromagnet, can open the possibility of optical control of superconductivity as well as high current gain.

For effective tunnel injection, we used an organic injector; copper (II) phthalocyanine (Cu-Pc). The organic Cu-Pc is known to be a *p*-type semiconductor and the molecular formula is $C_{32}H_{16}CuN_8$. As shown in Fig. 1(a), A copper lies at the center of the phthalocyanine ring and this ring structure has long hydrocarbon chains which play an important role in the formation of polarons [8].

Fig. 1 (b) shows the optical absorption spectra of Cu-Pc thin film. At low temperature it was found that an exciton peak that is formed by an electron and hole pair bound together with molecular vibrations

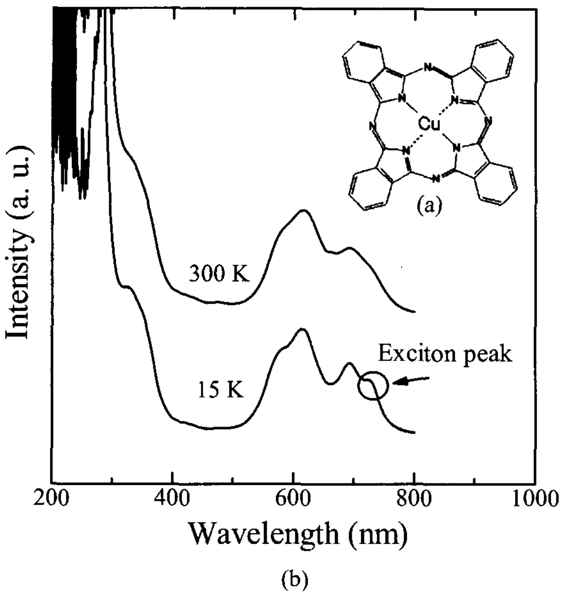


Fig. 1. (a) Molecular structure of Cu-Pc. (b) Absorption spectra of Cu-Pc at 15K and 300K.

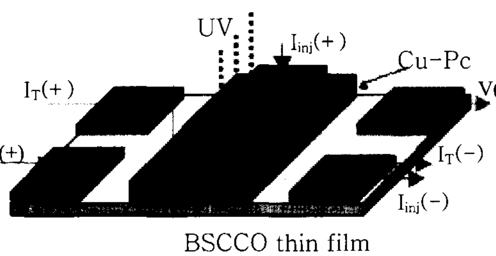


Fig. 2. The schematic structure of Au/Cu-Pc/BSCCO tunnel junction

within a single molecule. This is the evidence that the carriers in Cu-Pc are dressed by lattice vibrations, forming polarons as in an ionic crystal [9]. The polaronic QP injection from Cu-Pc into the HTSC is expected to form a strong nonequilibrium state due to the interaction between polaronic QPs and Cooper pairs.

## II. Experimental

Fig. 2 shows the device geometry of the Au/Cu-Pc/BSCCO tunnel junction as an organic conductor/superconductor (Or/S) junction structure. The BSCCO thin films were prepared by molecular beam epitaxy (MBE) on MgO (001) substrates [10]. The fabricated BSCCO thin film includes the *ab* plane as well as surface oriented along the *c* direction. The BSCCO film of thickness 150 nm has an average roughness of about 5 nm. The organic Cu-Pc thin film interlayer between the Au and BSCCO thin films was deposited by thermal evaporation and the thickness was 100 nm.

For an experiment of tunnel injection, two currents were fed into the superconductor film as shown in Fig. 2: one is the injection current ($I_{inj}$) and the other is the transport current ($I_T$). The $I_{inj}$ goes from the organic Cu-Pc thin film to the BSCCO thin film. The response of the critical current of a film to injected current is exhibited as the current gain:

$$G = -\frac{dI_c}{dI_{inj}} \qquad (1)$$

The minus sign is included to make the gain positive since the critical current is expected to decrease with injection.

A xenon discharge lamp (300 W) was used as the exciting UV light source. The current-voltage (*I-V*) characteristics were measured using a *dc* four-probe method. The conductance spectra were measured using a lock-in amplifier.

## III. Result and discussion

For ordinary current injection, the order parameter of the superconductor is perturbed from its equilibrium state near the injector. The superconducting energy gap (Δ) in a thin film decreases with increasing injection current as [11]:

$$\frac{d\Delta}{dJ_{inj}} \cong -\frac{\tau_{eff}}{2eN(0)d} \qquad (2)$$

Where *N(0)* is the single-spin density of states in the superconductor, $J_{inj}$ is the injected current density ($J_{inj}=I_{inj}/A$, where $A$ is the contact area), $\tau_{eff}$ is the effective quasiparticle recombination time including phonon trapping effects and $d$ is the thickness of the perturbed region. This means that both the nonequilibrium quasiparticle density and the suppression of the gap increase linearly with increasing $\tau_{eff}$.

The polaronic quasiparticle tunneling generates an effective nonequilibrium state in the HTSC by Eq. (2), because the net relaxation time $\tau_{eff}$ is increased due to inelastic tunneling (described below). For the Or/S tunnel junction, the charge transport in organic Cu-Pc layer involves polarons consisting of electrons dressed with phonons [12]. These injected polarons involve a phonon component with the recombination time $\tau_p$ of $\sim 10^{-15}$-$10^{-14}$ sec, which is faster than that of QP ($\sim 10^{-12}$ sec) relaxation time $\tau_R$ in HTSCs [13], [14]. Since the phonon recombination time of Cu-Pc is shorter than that of the QP ($\tau_p < \tau_R$), it is expected that the polarons in Cu-Pc split into electrons and phonons at the interface and only the electrons tunnel into BSCCO thin film leaving phonons at the interface due to inelastic tunneling processes. Therefore the $\tau_{eff}$ is increased due to the phonon contribution at the interface. Thus, electrical impedance is created by phonons at the boundary between the Cu-Pc and the HTSC BSCCO film and generates a nonequilibrium state in the HTSC.

The experimental transport properties of a Au/Cu-Pc/BSCCO junction at 30 K is shown in Fig. 3 (a). This result demonstrates the critical current suppression due to the current injection only has the effect of raising the film temperature. The qualitative discrepancy of the experimental data from the heating curve in Fig. 3 (b) is evident, indicating a nonequilibrium state different from simple heating. Note that, in the absence of a nonequilibrium effect, a current gain of unity arises solely from current pair breaking. Without UV irradiation, the measured current gain was over 2.75, which may be attributed to a nonequilibrium effect due to suppression of superconductivity by the polaronic QP injection. With a UV excitation, the measured current gain was increased to 3.03, which may be attributed to an additional nonequilibrium effect by the polaronic QP injection due to the photogenerated current in the Cu-Pc.

For the investigation of tunneling properties at the boundary, we studied the tunnel conductance of a Cu-Pc/BSCCO tunnel junction. Fig. 4 shows the differential conductance spectra of a Cu-Pc/BSCCO junction with and without UV irradiation.

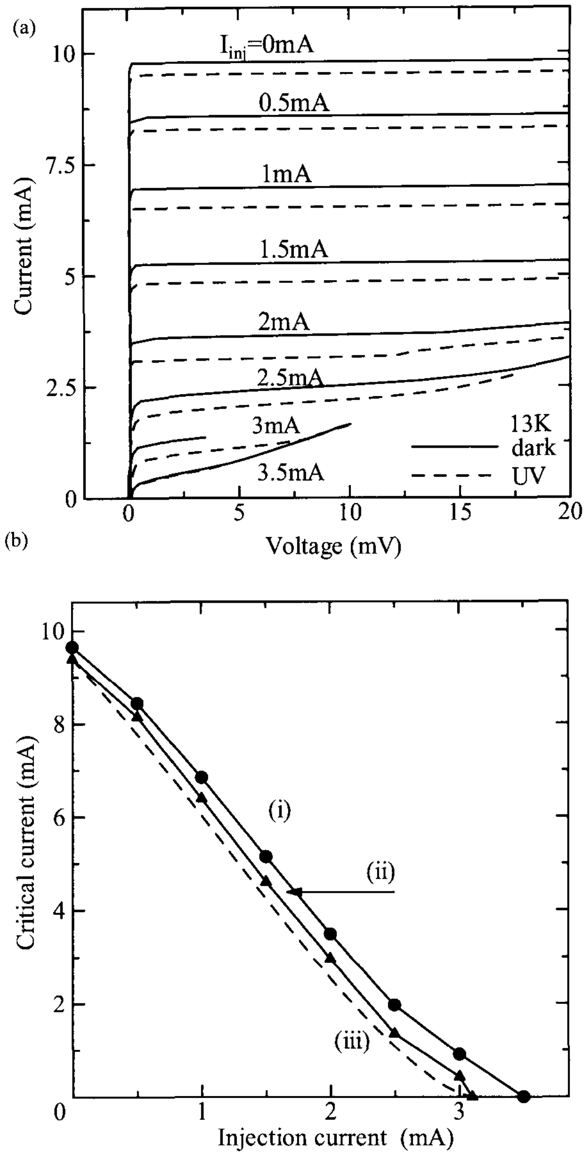


Fig. 3. (a) I-V characteristics due to injection current with and without UV irradiation at 13 K. (b) BSCCO film critical current as a function of injection current for Au/Cu-Pc/BSCCO junction (i) without and (ii) with UV irradiation. (iii) The dashed line corresponds to the calculated curve for a simple heating model.

The typical conductance spectra for a normal metal/*d*-wave superconductor tunnel junction including the (110) interface show the zero bias conductance peak (ZBCP) [15]-[18] and have been observed in QP tunneling experiment performed by

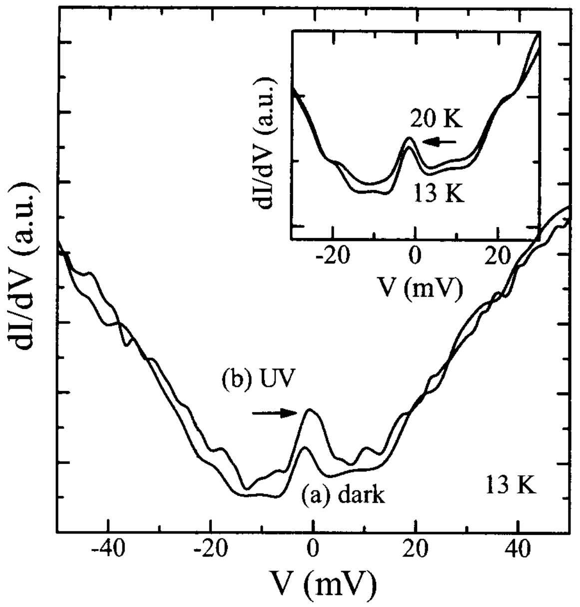


Fig. 4. Differential conductance for Au/Cu-Pc/BSCCO tunnel junction (a) in dark and (b) with He-Ne laser at 13 K. The inset shows the ZBCP at 13 K and 20 K.

many groups [19]-[21]. At the Or/S interface, the differential conductance characteristics are affected by the same interfacial boundary condition with the N/S junction and 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 a polaronic QP from the Cu-Pc film into a BSCCO *d*-wave superconductor.

For a Cu-Pc/BSCCO junction, it was observed that the ZBCP as compared to Au/BSCCO junction was slightly broadened and observed up to 70 K [22]. These behaviors may be due to an injection of polaronic QP carries from the Cu-Pc into a superconductor. The most striking difference of the Or/S junction from a normal metal/superconductor (N/S) junction was observed under the UV irradiation. Note that, in the large absorption wavelength region from 260 to 800 nm, the Cu-Pc film has a high photogenerated carrier density. When the UV was irradiated to the sample, the magnitude of the ZBCP was enhanced as shown in fig. 4 (b). These facts indicate that when the junction is illuminated the number of charge carriers becomes larger in Cu-Pc and the height of the ZBCP increases.

Previous calculations in [23] have indicated that features at low energy in N/S junctions are very sensitive to having different Fermi energies (Fermi wave vector mismatch) on the two sides of the junction. That is, before illumination, the Fermi wave vector in Cu-Pc is much smaller than the Fermi wave vector in BSCCO and the mismatch suppresses the ZBCP. By generating charge carriers one decreases the wave vector difference and the height of the ZBCP increases.

## IV. Conclusion

We have reported the nonequilibrium transport properties of Cu-Pc/BSCCO tunnel junctions as a novel HTSC three terminal device. The organic Cu-Pc layer as a polaronic QP injector played an important role in the generation of a substantially larger nonequilibrium effect as compared to the normal QP injection current. The tunneling spectroscopy of a Cu-Pc/BSCCO junction exhibited the enhancement of ZBCP under the UV excitation; this effect is caused by Andreev reflection of photogenerated charge carriers. The above phenomena are of importance in developing optically controlled three-terminal superconducting devices.

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