Possibility of macroscopic resonant tunneling near the superconductor-insulator transition in $YBa_2Cu_3O_{7-\delta}$ thin films

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Abstract. – Experimental results of the *I-V* characteristics near the superconductor-insulator transition observed for disorder-tuned $YBa_2Cu_3O_{7-\delta}$ thin films are presented. The *I-V* characteristics exhibit new quasiperiodic structures as a function of the current. The current interval, the number of the dI/dV peaks, and the magnetic-field dependence of the peaks are consistent with the theoretical predictions of the *resonant tunneling* of a phase particle in a tilted-cosine potential for a single Josephson junction with small capacitance.

Quantum phase transition in two-dimensional (2D) systems has been the subject of many theoretical and experimental works for its abundant physical implications. In particular, the superconductor-insulator (S-I) transition related to the quantum unit of resistance $h/4e^2 \sim$ 6.45 kΩ has been studied for various materials [1]-[8]. Among them, cuprate superconductors with 2D CuO_2 sheets are suitable to study this phase transition because disorder can easily be controlled by oxygen deficiency. These systems also enable us to investigate the macroscopic quantum tunneling (MQT) [9], in connection with the applicability of quantum mechanics on a macroscopic scale, because of the spontaneous formations of Josephson networks with small capacitances due either to the presence of crystal grains or to oxygen contamination in $YBa_2Cu_3O_{7-\delta}$ thin films, or both. In such a small Josephson junction, the phase difference θ across the junction cannot be considered as a classical variable; it must be treated as an operator that does not commute with the Cooper-pair-number operator $\hat{n}$: $[\hat{\theta}, \hat{n}] = i$. Under current biases, the junction can be represented as a *quantum* particle moving in a one-dimensional tilted cosine potential. The escape from the metastable state by quantum tunneling is thus possible.

Another quantum-mechanical process, resonant tunneling, is possible in Josephson systems. When the charging energy becomes much larger than that of MQT, the quantized energy levels formed in the Josephson potential become important for tunneling. Under the current bias, the alignment of the levels between the adjacent wells rules the tunnel phenomena. This is known as macroscopic resonant tunneling (MRT) [10]. Giordano and Schuler have observed the quasiperiodic structures of current-voltage characteristics due to the resonant features of the tunneling processes, *i.e.* the enhancement and suppression of 2π quantum phase slippages in one-dimensinal superconducting Pb wires [11]. Although the system is similar to Josephson systems, theory remains ambiguous, especially regarding the periodicity of the potential. This letter shows MRT phenomena near the S-I transition in $YBa_2Cu_3O_{7-\delta}$ thin films under magnetic fields. First, we will show that the $YBa_2Cu_3O_{7-\delta}$ thin films can be regarded as a series of Josephson junctions. Next, we present the *I-V* characteristics of the system. We found that the *I-V* curves near the S-I transition exhibit quasiperiodic structures as a function of the current similar to the Giordano and Schuler observation. The structures strongly depend on the magnetic field. Last, we compare our results to theoretical predictions of the *resonant tunneling* of a phase particle in a small Josephson junction.

The $YBa_2Cu_3O_{7-\delta}$ thin films were deposited on MgO (100) substrates by rf-magnetron sputtering using a $YBa_2Cu_3O_{7-\delta}$ disk target. The sputtering gas was a mixture of Ar (50%) and O_2 (50%) with total pressure of 0.5 Pa. The substrate temperature was kept at 650 C during the deposition process. The temperature dependence of resistivities $\rho(T)$ was measured with evaporated gold electrodes by the standard four-terminal method, and the applied current was typically 1 to 10 mA. The differential resistances were measured by a lock-in amplifier with a frequency of 364 Hz. Figure 1 shows the sheet resistances as a function of temperature for six samples (A-F). The average mean of the sheet resistance per CuO_2 layer in $YBa_2Cu_3O_{7-\delta}$ thin films and the parameter representing the intensity were obtained from the relation $R_\square = \rho/d$, where d (= 5.9 Å) is the lattice spacing between CuO_2 layers. Although the disordered parameters in these films were not systematically tuned, the observed normal-state sheet resistances above T_c are different enough that the degree of disorder of these samples is widely distributed. The critical sheet resistance has a value of about 10 kΩ close to the value $h/4e^2 \sim 6.45$ kΩ. The curves B-E show local coherence. Each resistance exhibits a pronounced drop within the 60 to 70 K range, while these samples did not show global coherence and had finite resistance. In addition, a decrease in temperature led to an increase in resistance.

In fig. 2 we plotted the normalized conductivity σ/σ_0 for sample F as a function of $(T - T_c)/T_c$ on a logarithmic scale, where σ_0 is the normal-state conductivity. The data clearly show the power law in the regime $(T - T_c)/T_c \leq 1$, and we have the relation $\sigma \propto (T - T_c)^{-s}$ with $s = 1.36 \pm 0.03$. This estimated value is in good agreement with the theoretical prediction $s = 1.30$ [12]. The agreement indicates that the superconductor in sample F can be regarded as a 2D superconducting percolation system, which is the fundamental model for strongly disordered 2D systems.

As the temperature is reduced, the superconducting network gradually extends. At the critical temperature T_c, the superconducting path extends from top to bottom and from left to right of the sample, and the whole sample becomes globally coherent. The superconducting percolation network is comprised of links —one-dimentional chains— and blobs —dense regions with more than one connection between two points. If one link is cut at T_c, the global coherence is broken and this link constitutes a backborn structure. Compared with globally coherent sample F, the superconducting path is reduced considerably in the large-disordered samples B-E. Therefore, links are regarded as Josephson junctions in series and blobs are regarded as superconductors with zero resistivity. Locally coherent samples B-E with large disorders
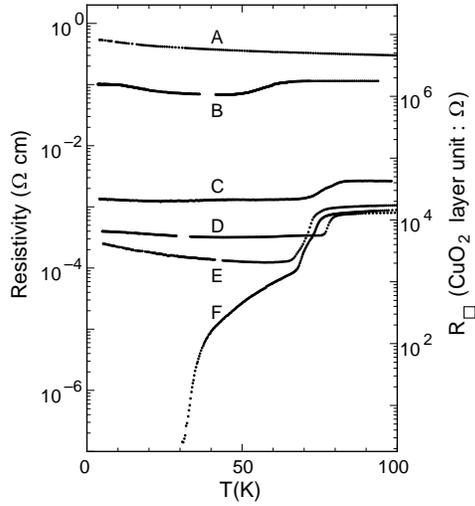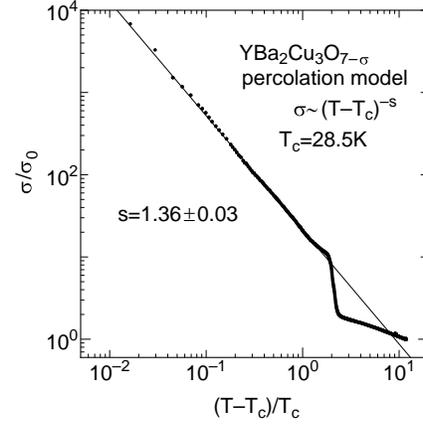
Fig. 1   Fig. 2

Fig. 1. – The temperature dependence of the resistivity of disorder-tuned $YBa_2Cu_3O_{7-\delta}$ thin films. Film thickness were 300 Å (A, B), 1000 Å (C, D, E, F).

Fig. 2. – The temperature dependence of the conductivity of sample F. The solid lines show the power law with $s = 1.36 \pm 0.03$.

are considered ultrasmall Josephson junctions in series, *I-V* characteristics are determined by the smallest Josephson junction. The multi-junction system is nonetheless preferable for observing the behavior of a *single* Josephson junction because the junctions in series provide high resistance and suppress the effect of the electromagnetic environments [13].

We measured the *I-V* characteristics near the S-I transition under various magnetic fields (fig. 3). We found that the dV/dI-I curves exhibit quasiperiodic structures as a function of the current. These structures are similar to the Giordano and Schuler observation, which strongly depends on the magnetic field. Let us explain these new structures from the standpoint of MRT. First we calculated E_J using the Ambegaokar-Baratoff equation [14], $E_J = \pi\hbar\Delta/4e^2R_N$, at zero temperature, where Δ is the gap energy and R_T is the tunnel resistance. The R_T is roughly given by the normal resistance of the system, $R_T \simeq R_N$, which is different from $R_\square$. In sample E, the resistance is $R_N = 120\ \Omega$, and the gap energy $\Delta = 20$ meV. Thus, the Josephson coupling energy E_J is about 8.6×10^{-20} J. In contrast to the Josephson coupling energy, it is dificut to estimate the charging energy E_c of the junction because no techniques have been established for estimating the capacitance of the junctions in random media. The junction capacitance is usually evaluated from the junction geometry or the Coulomb gap in *I-V* characteristics. We applied the Coulomb gap technique to our system, but we could not obtain the junction capacitance because sample E does not satisfy the Coulomb blockade conditions, $R_N > h/e^2 \sim 25$ kΩ. Thus we were obliged to infer the capacitance from the value of the other samples. Fortunately, the capacitance of sample B, with large resistance $R_N = 40$ kΩ, can be obtained. Figure 4 shows the *I-V* characteristics of sample B. The curve clearly shows the Coulomb gap due to single-electron tunneling, indicating the formation of small junctions in the sample and strongly supporting our Josephson model for $YBa_2Cu_3O_{7-\delta}$ thin films. The capacitance of the junction in sample B, estimated from the Coulomb gap ($e/2C = 71$ mV), is $C = 1.1 \times 10^{-18}$ F. The charging energy E_c is about 1.1×10^{-20} J. The capacitance of sample
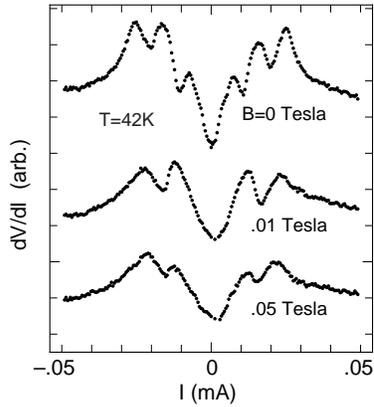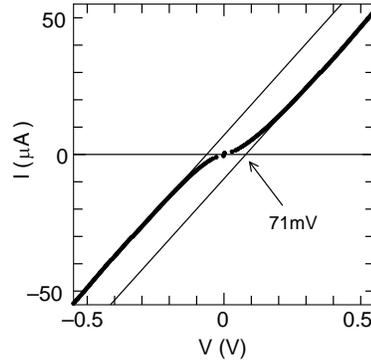
Fig. 3

Fig. 4

Fig. 3. – $\mathrm{d}V/\mathrm{d}I$-I curves of sample E. The temperature was 4.2 K.

Fig. 4. – I-V characteristics of sample B. The threshold voltage was 71 mV.

E can be evaluated through the ratio of resistance between the junctions on different samples, since both capacitance and resistance are characterized by the junction's cross-section [15]. The charging energy of sample E is of the order of 4.2×10^{-21} J.

Now let us explain our experimental results in terms of macroscopic resonant tunneling. First, we check whether our experimental conditions were such that MRT occurred. MRT requires quantized energy levels in the Josephson potential. The number of quantum levels (n) in the potential is obtained as the ratio of the height of the Josephson potential $2E_\mathrm{J}$ to the level spacing, roughly $\hbar\omega_\mathrm{J}$, in the harmonic approximation of the potential:

$$n \sim \frac{2E_\mathrm{J}}{\hbar\omega_\mathrm{J}} = \sqrt{\frac{E_\mathrm{J}}{2E_\mathrm{c}}}. \tag{1}$$

Here ω_J is the Josephson plasma frequency. The number of levels n is at least more than 2 for MRT to occur. Moreover, the temperature must be held low enough to prevent masking by the thermal fluctuations, *i.e.* $k_\mathrm{B}T \ll \hbar\omega_\mathrm{J}$. In sample E, all of the above conditions are satisfied: $n \simeq 3$ and $T = 4.2$ K. In fact, we observed that periodic structures are broadened as the temperature increases, and disappear at $T = 55$ K. This implies that the origin of the structures stems from the quantum-mechanical effects.

Next, we have compared our results to the MRT predictions. MRT occurs when the energy levels in adjacent wells are coincident. These coincidences occur at special values of bias currents which reflect the quantized energy levels. First, we checked the periodicity of the oscillations in $\mathrm{d}V/\mathrm{d}I$-I curves. The current intervals can be determined by setting the level spacing equal to the energy gain from the battery, $\hbar\omega_\mathrm{J} = \hbar\Delta I/2e$; thus,

$$\Delta I = \frac{2e}{h}\sqrt{8E_\mathrm{c}E_\mathrm{J}}, \tag{2}$$

where we use the relation $\omega_\mathrm{J} = \sqrt{8E_\mathrm{c}E_\mathrm{J}}/\hbar$. The current interval is $\Delta I \sim 2.4$ µA. This is close to the experimental value $\Delta I \sim 6$ µA, in spite of the rough estimation of the capacitance. Second, the number of the observed peaks is consistent with the number of quantum levels in the potential calculated above. Third, the upper peak position is also consistent with

the MRT predictions; as the current bias increases, the tunneling mechanism changes from MRT to usual MQT. We can determine the threshold current by considering the potential's arrangement [10]. In our case, $E_c/E_J = 0.07$ and the threshold current is therefore about $0.17 I_c = 44$ µA, where I_c is the Josephson critical current. The current of third peak, 25 µA, is less than the threshold current. Furthermore, the magnetic-field dependence of the dV/dI-I curves is also consistent with the theoretical predictions; as the magnetic field was increased, the number of peaks reduced from three to two and the intensity of the peaks gradually weakened. Hence, the strong magnetic field reduces the Josephson coupling energy E_J and prevents the occurrence of the MRT. Finally, the structure disappeared at 0.25 T. Just as with the temperature, this reflects quantum-mechanical effects. Thus, we have concluded that the new quasiperiodic structures in I-V characteristics are due to the MRT.

In summary, we have found that the I-V characteristics near the universal critical sheet resistance exhibit new quasiperiodic structures as a function of the current in $YBa_2Cu_3O_{7-\delta}$ thin films. The periodic structures are in good agreement with theoretical predictions of the MRT in small Josephson junctions.

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[14] AMBEGAOKAR V. and BARATOFF A., *Phys. Rev. Lett.*, **10** (1963) 486.
[15] In general, both the capacitance and the resistance of the junction are the function of both tunnel distance d and cross-section S, and can be described by $C \sim S/d$ and $R_N \sim e^{-d}/S$, respectively. Our 2D Josephson networks are made by introducing oxygen deficiencies in the CuO_2 planes of $YBa_2Cu_3O_{7-\delta}$. Since the deficiency has the same effect as cutting the bonding, only the cross-section of the junction is changed while tunneling distance seems to be constant.