Macroscopic quantum tunneling in BiPb2201

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Abstract. We measured the switching probability distributions of the first and second switches in $Bi_{2-x}Pb_xSr_{2-y}La_uCuO_{6+\delta}$ (BiPb2201) intrinsic Josephson junctions. The effective temperature of the first switch is temperature independent below 0.6 K, which is slightly higher than the crossover temperature estimated from the thermal activation model. On the other hand, the effective temperature of the second switch is temperature independent below 2.0 K, which is one-order higher than the crossover temperature. Our study shows that the temperature independent state at high temperature is measured not only in $Bi_2Sr_2CaCu_2O_{8+\delta}$ but also in $Bi_2Sr_2CuO_{6+\delta}$.

1. Introduction

In intrinsic Josephson junction (IJJ) included in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212), macroscopic quantum tunneling (MQT) is an indispensable phenomenon to realize qubits. MQT was observed up to 1 K in Bi2212 IJJs, which is one-order higher than Josephson junction made by metallic superconductors [1]. The result shows that IJJs of Bi2212 can be used as qubits at higher temperatures than Josephson junction made by metallic superconductors.

The current-biased single Josephson junction can be well described by the RCSJ (resistively and capacitively shunted junction) model. In this model, the junction is modeled by the motion of a particle in a tilted washboard potential. The switch of the Josephson junction from zero voltage state to resistive state corresponds the escape from the minima of the potential. The switch is mainly caused by thermal activation (TA) or MQT. TA is described as the escape from the minima by thermal fluctuation. The escape rate is $\sim \exp(-\Delta U/k_{\rm B}T)$, where $\Delta U$is the potential barrier and $k_{\rm B}$ is the Boltzman constant [2]. MQT is described as the quantum tunneling of the particle through the potential barrier. The escape rate is $\sim \exp(-\Delta U/\hbar\omega_{\rm p})$, where $\omega_{\rm p}$ is the current dependent plasma frequency [3]. At high temperatures, TA becomes dominant. The escape rate of TA suppressed with the decreasing temperature. The escape rate of TA and MQT are equal at crossover temperature given by $\sim \hbar\omega_{\rm p}/2\pi k_{\rm B}$. MQT is observed by measuring switching probability distributions which are histogram of currents where a Josephson junction switches from zero voltage state to resistive state. The distribution is temperature independent when MQT is dominant and temperature dependent when TA is dominant. The temperature independent region of the distribution means that MQT is observed.

Recently, several unclear phenomena have been reported in IJJs [4][5][6]. One of the unclear phenomenon is that the temperature independent behavior observed below $\sim$ 8 K for the second switch. The second switch is a phenomenon of the switch another IJJ included in the stack to resistive state subsequent to the first switch. This behavior is not explained by MQT because the temperature is one-order higher than crossover temperature [5][6]. This temperature independent behavior at high temperature is reported only in Bi2212.

In this paper, we measured the switching probability distributions of the first and second switches in the stack of $Bi_{2-x}Pb_xSr_{2-y}La_uCuO_{6+\delta}$ (BiPb2201). BiPb2201 has single CuO_2 layer so that Bi2201 has thiner superconducting layer than Bi2212 with double CuO_2 layer. The difference between Bi2201 and Bi2212 is only the number of CuO_2 layer. The feature of the first switch can be roughly explained by the single Josephson junction model. On the other hand, temperature independent behavior of the second switch is observed at higher temperature than the crossover temperature. This is not due to Pb substitution since the feature of the first switch is not changed by Pb substitution. The temperature independent behavior of the second switch is a common phenomenon observed in Bi2201 and Bi2212.

2. Experimental method

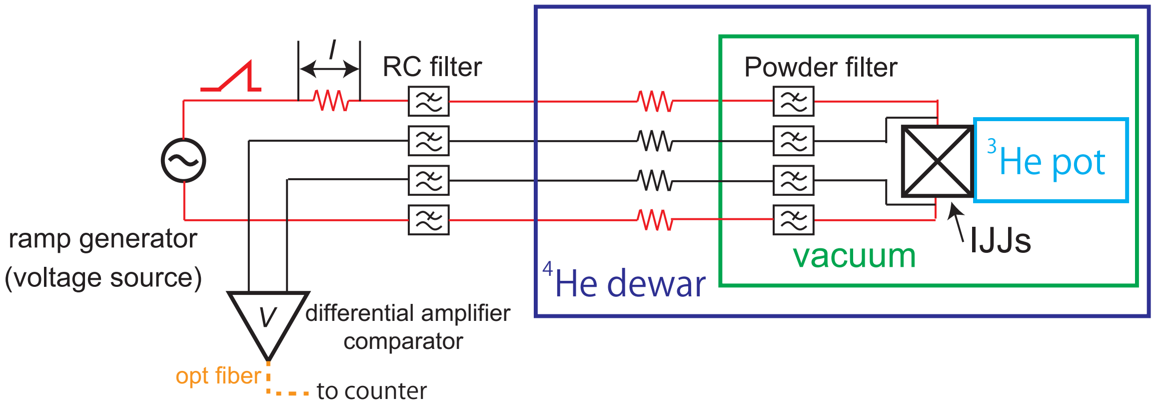

Figure 1. Schematic of the measurement system for the switching probability distribution

We used BiPb2201 single crystal grown by the traveling solvent floating zone method. The single crystal was grown as follows. Powders of Bi_2O_3, PbO, $SrCO_3$, La_2O_3 and CuO were mixed in the nominal compositions of $Bi_{1.8}Pb_{0.3}Sr_{1.5}La_{0.4}Cu_{1.0}$. Mixed powders were calcined twice at 740 °C for 24 hour. Calcined powders were put into rubber tube and pressed under 50 MPa for 1 hour. The pressed rod was sintered at 840 °C for 24 hour. The rod was pre-melted at a velocity of 10 mm/hour. After that, the crystal was grown by the rate of 0.5 mm/hour. The analyzed composition of the crystal by EDS is $Bi_{1.9}Pb_{0.1}Sr_{1.4}La_{0.6}Cu_{1.0}O_{6+\delta}$.

The mesa structure can be fabricated easily by two dimensional processing, and the number of the IJJs include in the mesa structure can be changed by the milling time. In this study, we fabricated the mesa structure on BiPb2201 single crystal with the size of 1×1 μm^2 by using electron-beam lithography and Ar-ion milling. The detail of the fabrication is described elsewhere [7].

switching probability distributions were measured down to 0.4 K by using ^{3}He cryostat. The measurement system is shown in Fig. 1. We used current source which is same as that described in Ref [8] before. However the critical current of the first switch is the largest among the branches in this mesa structure. In this case, all IJJs are switched to voltage state simultaneously if IJJs are biased by current source because the current does not decrease by the switch. We connected the home-made current-controlled voltage source to the output of the current source. The voltage source consists of three operation amplifiers (Burr-Brown OPA 277) and chip resistors. Two operation amplifiers are used for the inverting amplifier and another operation amplifier is used as the voltage follower. The stack of IJJs is biased by the output of the inverting amplifier.

The bias current is monitored by means of the voltage drops across a series of chip resistors (100 ohm). The power source of these home-made circuits is supplied by a DC stabilized voltage source. Two low-pass filters are inserted in this circuit, one is a RC filter at room temperature and another is powder filter inside the vacuum space of the cryostat. The cut-off frequency of the RC filter is 300 kHz and that of powder filter is 1 MHz. The voltage source and the IJJs are separated from digital electronics connected to the PC by the optical fiber to reduce the noise of the commercial power supply. We measured the switch current about 10,000 times to obtain its distribution.

We calculated the effective temperature ($T_{\rm eff}$) to fit the switching probability distribution by thermal activation model. $T_{\rm eff}$ is a parameter indicating the distribution. If $T_{\rm eff}$ shows temperature independent, it is considered that MQT is the dominant switching process.

3. Results and discussion

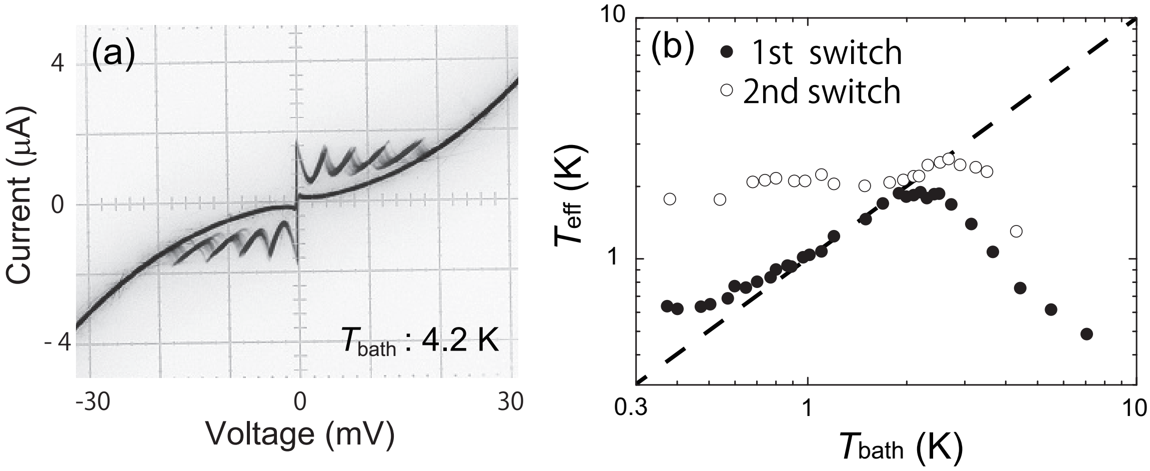

Figure 2. (a) I-V characteristics in Bi2201 at 4.2 K. (b) Effective temperature versus bath temperature in Bi2201 for the first (solid symbol) and second (open symbol) switches.

Fig. 2(a) shows an oscilloscope image of I-V characteristics for the IJJ stack, measured at 4.2 K. One can find five branches separated equally in voltage of 4 mV at I = 1.6 μA. The critical current densities are found to be 180 A/cm^2 and the critical current of the first switch is the largest among branches of the I-V characteristics. Thus we consider that the number of the IJJs is five and these five IJJs are uniform. Fig. 2(b) shows the $T_{\rm eff}$ vs bath temperature($T_{\rm bath}$) plots. Below 0.6 K, $T_{\rm eff}$ of the first switch is temperature independent. $T_{\rm eff}$ corresponds with $T_{\rm bath}$ between 0.6 K and 2.0 K. This result can be explained that MQT is dominant below 0.6 K so that $T_{\rm eff}$ shows temperature independent behavior. The crossover temperature is $\sim$ 0.35 K. The temperature independent state is observed at a little higher temperature. The feature of $T_{\rm eff}$ between 0.6 K and 2.0 K can be explained by the TA model. We conclude that the first switch in the stack of IJJs can be roughly explained by the single Josephson junction model.

The switching probability distribution of the second switch is different from that of the first switch. $T_{\rm eff}$ shows temperature independent behavior below 2.0 K. $T_{\rm eff}$ corresponds with $T_{\rm bath}$ between 2.0 K and 3.0 K. The crossover temperature of the second switch is $\sim$ 0.30 K. The temperature independent behavior is observed one-order higher than the crossover temperature. This can not be explained by MQT of the single Josephson junction model. The behavior of $T_{\rm eff}$between 2.0 K and 3.0 K can be explained by the TA model because $T_{\rm eff}$ and $T_{\rm bath}$ shows good agreement in this region.

We consider this temperature independent state at high temperatures is not due to Pb substitution by following reasons. This peculiar behavior of $T_{\rm eff}$ is not observed at the first switch. The first switch is well described single Josephson junction model as well as in $\rm Bi_2Sr_{2-y}La_uCuO_{6+\delta}$ (Bi2201) [9]. This means that Pb substitution does not affect the switch dynamics in Bi2201. Second, same tendency has been observed in Bi2212 despite of the no Pb substitution [5][6][10]. Therefore, we conclude that the fluctuation of the second switch is much larger than that of the first switch in IJJs consist of $\rm Bi_2Sr_2Ca_{n-1}Cu_nO_{4+2n+\delta}$ (BSCCO) with single and double $\rm CuO_2$ layer. Someone considers that the behavior of the second switch is attributed to heating effect [5]. However, we consider that the self-heating is too small to raise temperature. The mesa structure is fabricated to measure the switching probability distributions in this report. In the mesa structure, the heating in the IJJs is removed by the thick Ag electrode covering the top of the IJJs. Moreover, the previous report calculated the temperature increase due to the self-heating in Bi2212 [6]. In mesa structure of Bi2212, the temperature rise is estimated about ~ 0.14 K which is one-order smaller than the $T_{\rm eff}$ of the second switch at 0.38 K. The large fluctuation of the second switch is attributed to the charge coupling between IJJs because the $T_{\rm eff}$ of the first and second switches of $\rm Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ IJJs are almost identical [10].

4. Conclusion

We measured switching probability distributions of the first and second switches in the stack of IJJs in BiPb2201. The first switch can be explained by the single Josephson junction model. This result is consistent with the previous report in Bi2201. Pb-substitution does not affect the switch mechanism of the first switch in Bi2201. However, the temperature independent behavior of the second switch was observed at high temperatures in comparison with the first switch. The large fluctuation of the second switch is a peculiar phenomenon in BSCCO IJJs with superconducting layer being less than 0.3 nm.

Acknowledgments

We thank Professor Osamu Sakai for allowing us to use the electron-beam lithography facility.

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