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Temperature Dependence of Shapiro Steps in Surface Intrinsic Josephson Junctions of $Bi_2Sr_2CaCu_2O_y$ Single Crystals

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Temperature dependence of microwave responses of intrinsic Josephson junctions in $Bi_2Sr_2CaCu_2O_y$ single crystals is investigated and the criterion for the observation of Shapiro steps is discussed. Clear Shapiro steps have been successfully observed in surface IJJ formed on the topmost layer in mesas up to 25 K with the application of microwave of frequencies higher than the Josephson plasma frequency. Power dependence of the step amplitude was slightly different from the conventional Shapiro step and did not show periodicity with the power. We confirm that the intrinsic surface junction has the same criterion for the observation of Shapiro step as the conventional Josephson junction independent of temperature.
Key words: $Bi_2Sr_2CaCu_2O_y$, intrinsic Josephson junctions, Shapiro step, Josephson plasma frequency

1. INTRODUCTION

In the strongly anisotropic cuprate superconductors such as $Bi_2Sr_2CaCu_2O_y$ (BSCCO) and $Tl_2Ba_2Ca_2Cu_3O_y$ (TBCCO), the CuO_2 superconducting layers together with the intervening layers form a stack of Josephson tunnel junctions, the so-called intrinsic Josephson junctions (IJJ's) [1-3]. Recently, the IJJ's have attracted much attention not only from the fundamental physics but also to the high-frequency application because of their large superconducting gaps in a THz region. So far, there have been many high-frequency experiments using IJJ's in BSCCO single crystals and whiskers [1-7]. However, their microwave response is still unclear. For example, although one of straightforward approaches for understanding them is to observe Shapiro steps, most frequentry observed steps are another type of microwave-induced steps which are believed to be due to vortex motion induced by the microwave rather than the Shapiro ones [4-7]. This may be due to relatively large sample size compared with the short Josephson penetration depth of ~1μm and strong electromagnetic coupling between adjacent junctions in a stack of IJJ's.

On the other hand, the main reason for making the observation of the Shapiro step difficult may be the occurrence of chaos in the Josephson junction. It is known that chaos can occur in the rf-driven underdamped low-T_c Josephson junction and lead to instability of Shapiro steps. According to Kautz [8], chaos does not occur for

$$\Omega > \beta^{-1/2}, \qquad (1)$$

where $\Omega=\Phi_0 f_{rf}/I_cR$ is the normalized drive frequency, Φ_0 is the flux quantum, f_{rf} is the drive frequency, I_c is the critical current, R is the normal resistance, $\beta=2\pi I_cR^2C/\Phi_0$ is the McCumber parameter and C is the junction capacitance. This condition can be rewritten by a more practical form of $f_{rf} > f_p$, where $f_p=(eI_c/\pi hC)^{1/2}$ is the Josephson plasma frequency. Therefore, a well-tried principle to avoid chaos is to chose f_{rf} higher than f_p. This may be also available to IJJ's. Then, typical value of f_p for a stack of IJJ's ranges from 50 to 100 GHz. Indeed, Wang *et al.* have succeeded in observing clear Shapiro steps in the stack of 17 IJJ's with THz irradiation [9]. On the other hand, Doh *et al.* observed the steps from the topmost IJJ, or *surface IJJ*, of a mesa formed on the single crystals, irradiating microwave of f_{rf}=76 and 94 GHz [10]. More recently, we have also investigated the microwave response of the surface IJJ in the frequency range 2-20 GHz in detail and confirmed that clear Shapiro steps can appear for $f_{rf} \geq f_p$ at 4.2 K [11]. From these results, it is concluded that the criterion for the observation of Shapiro steps at 4.2 K is the same as that for low temperature Josephson junctions. Until now, however, there is no report on the temperature dependence of the microwave response of surface IJJ and it is not clear whether the above condition is suitable independent of temperature. Therefore, it is hoped to make it clear to open the way for applications of the IJJ and its Shapiro step at high temperature.

In this paper, we have studied the temperature dependence of Shapiro steps in surface IJJ's of BSCCO single crystals and discussed the condition to observe them.

2. EXPERIMENTAL

The BSCCO single crystals with critical temperature of 80-85 K were grown by a conventional melting method [12]. The as-grown single crystal plates were cut in about 1 mm × 1 mm size and were glued onto glass substrates. After cleaving the crystals, Au thin films were then deposited on the fresh surfaces. Mesas with lateral dimensions of 10 μm × 10 μm were fabricated on them using standard photo-lithography and ion milling. SiO_2 films were used as the insulating layer between the crystal and the Au lead layer. In addition, a stripline was interconnected to the top of the mesa in order to apply microwave in the frequency range 2-20 GHz. The experimental configuration is shown in Fig.1. The *I-V* characteristics were measured without and with microwave application at various temperatures. All measurements were performed using a three-terminal configuration. The contact resistance due to this has been subtracted for data evaluation in this paper.

3. RESULTS AND DISCUSSION

3.1 Surface intrinsic Josephson junctions

The remarkable feature of the *I-V* characteristics of IJJ's is multiple quasiparticle branches with very large hysteresis, where the number of branches corresponds to the number of IJJ's in the resistive state. Usually, in the well-defined IJJ's such as a mesa structure formed on the single crystal these branches have the almost same amplitude, *i.e.*, uniform critical currents. However, in the measurements using a three-terminal configuration, a branch with a critical current much smaller than the former ones is often observed [10,11,13,14]. This branch is considered to be attributed to the surface IJJ because such branch has not observed by the four-terminal configuration. Accordingly, IJJ's in a mesa can be classified into one surface and inner IJJ's.

Fig. 2(a) shows a typical *I-V* characteristic of a 10μm × 10μm mesa (#1) at 4.2 K without microwave application. It is found that this mesa includes one surface and 14 inner IJJ's from the number of branches. As can be seen in the figure, critical current of inner IJJ's has the almost same value and the average value of I_c is about 190 μA, corresponding to the current density of 190 A/cm^2. The voltage spacing between adjacent branches is ~ 34 mV. On the other hand, the *I-V* characteristic of surface IJJ is shown in Fig. 2(b), which is an enlargement near the origin of Fig. 2(a). Its critical current is 11 μA, which is much lower than that of inner ones. From these critical currents, f_p of surface and inner IJJ's are estimated to be 12.8 and 53.2 GHz, respectively, using the value of dielectric constant of ε=7 [15].

Kim *et al.* proposed that such smaller I_c is attributed to the proximity effect induced by Au which is in contact with the topmost layer of a mesa because such reduced I_c dose not follow the Ambegaoka-Baratoff relation and is observed below $T_c/2$ [14]. We have also observed the critical current of surface IJJ only in low temperature range (T<30-40 K) independent of the value of I_c. As reported in our previous paper,

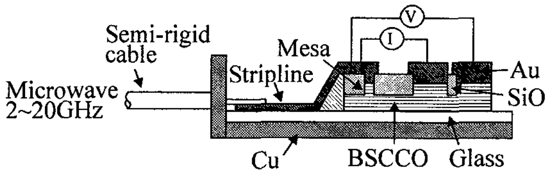

Fig. 1 Schematic drawing of the experimental configuration. The microwave is applied to a BSCCO mesa through a stripline and the *I-V* characteristics are measured by a three-terminal method.

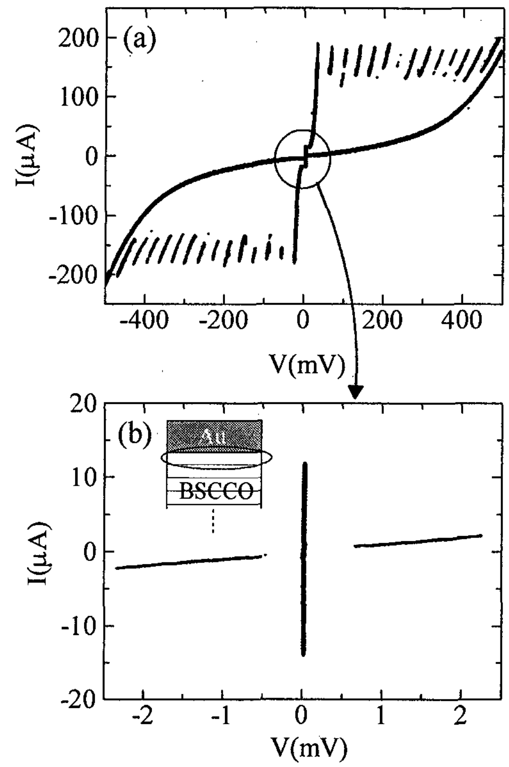

Fig. 2 *I-V* characteristics of a BSCCO mesa (#1) with an area of 10 × 10 μm^2 at 4.2 K; (a)the inner IJJ's and (b)the surface IJJ. The inset in Fig. 2(b) is schematic structure of a mesa near the surface.

however, the gap structure related to the surface IJJ is observed up to the bulk T_c [16]. This implies that the CuO_2 superconducting electrode in the surface IJJ has the same superconducting feature as that in inner IJJ. We can not now explain the origin of the small critical current of surface IJJ but the reduction of I_c seems to be not due to the proximity effect.

3.2 Shapiro steps in the surface IJJ

We focus on the microwave response of the surface IJJ because the plasma frequency of surface IJJ is about 4-5 times lower than that of the inner IJJ as mentioned above, so that the Shapiro step can be observed for surface IJJ even by application of microwave in the frequency range of 10-20 GHz. Figure 3(a) shows the *I-V*

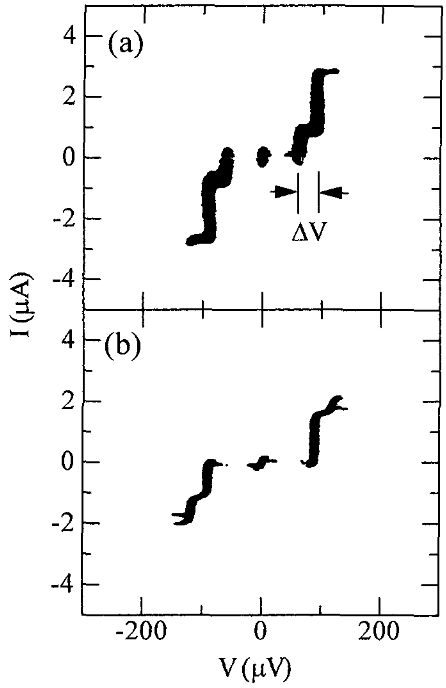

Fig. 3 The *I-V* characteristics of the surface IJJ (#2) with 15 GHz microwave application at (a)4.2 K and (b) 11 K.

characteristic of a surface IJJ (#2) with the application of the 15 GHz microwave at 4.2 K. This specimen has a critical current of 8.5μA, which corresponds to f_p=11.3 GHz, without the microwave application. One can see that the critical current is reduced into almost zero and clear four voltage constant steps appear at ±61μV and ±92μV. The voltage difference between the steps of ΔV=31μV is in good agreement with the expected value of $\Delta V=hf/2e$ [17]. Thus, the observed steps are recognized to be the second and third order Shapiro steps. These steps behave like a one-valued function of current. In addition, it is found that the second step crosses the zero-current axis, so-called zero-crossing step, which occurs commonly in high-capacitance Josephson junction [16]. By increasing the microwave power, the steps shifted to higher voltage keeping the Josephson voltage-frequency relation. Consequently, we observed the Shapiro steps up to the order of n=7. Such steps were observed at various drive frequencies above f_p. Furthermore, we were able to observe the Shapiro steps up to ~ 20 K for this sample. Figure 3(b) shows the *I-V* characteristic at T=11 K for f_{rf} =15 GHz. Without microwave, the value of I_c was 4 μA, which corresponds to f_p=7.7 GHz. One can also see clear steps by applying microwave. The behavior of the steps was similar to that observed at 4.2 K. As a result, the Shapiro steps were observed for $f_{rf} > f_p$. For T > 20 K, although I_c was suppressed to zero with microwave application, no Shapiro steps were observable for this sample due to thermal noise.

For the surface IJJ's having relatively large I_c at 4.2 K, we also measured the *I-V* characteristics with microwave application. Fig. 4(a) shows the *I-V* characteristic of a

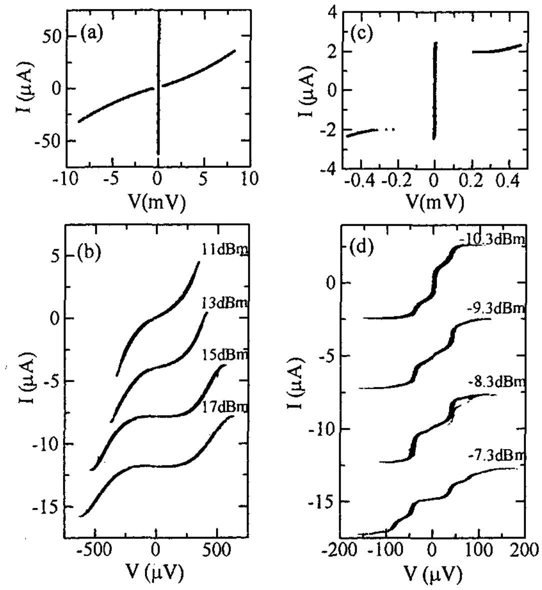

Fig. 4 *I-V* characteristics of a surface IJJ (#3), (a) without microwave at 4.2 K, (b)with 20.5 GHz microwave at 4.2 K, (c)without microwave at 25 K, and (d)with 20.5 GHz microwave at 25 K.

surface IJJ (#3) of I_c=62 μA at 4.2 K without microwave and Fig. 4(b) shows the *I-V* characteristics at different powers of the 20.5 GHz microwave. In this case, the microwave-induced step with finite slope can be seen in the *I-V* characteristics but distinct step structures such as Shapiro steps have not been observed because of f_p=30.4 GHz at 4.2 K. The observed step may be related to the vortex flow induced by the microwave [4-7]. The *I-V* characteristic of the same sample at 25 K is shown in Fig. 4(c). By increasing temperature, the values of I_c and f_p decreased to 2.5 μA and 6.1 GHz, respectively, so that clear Shapiro steps can be observed even for f_{rf}=10-20.5 GHz as shown in Fig. 4(d). From these results, we conclude that the criterion for the observation of Shapiro steps is $f_{rf} \geq f_p$ independent of temperature below T_c of surface IJJ.

To understand the behavior of the Shapiro steps observed in surface IJJ's, the power dependence of the step amplitude was measured using the sample #2. In Fig. 5, we show the normalized step amplitudes obtained at 4.2 K and 11 K as a function of the square root of the microwave power, $P^{1/2}$, for f_{rf}=15 GHz together with the expected one, which is given by

$$\frac{\Delta I_n}{I_c} = \left| J_n\left(\frac{v_{ac}}{f_{rf}\Phi_0}\right) \right|, \tag{2}$$

where J_n is the nth Bessel function, v_{ac} is alternative voltage across junction due to microwave [17]. The data are fitted to the theoretical curves at two points denoted by arrows. It is found that experimental power dependences of the step amplitudes slightly differ from the expected ones (solid lines) although they seems to approach to the Bessel function with an increase in temperature. At low microwave power, the zeroth step,

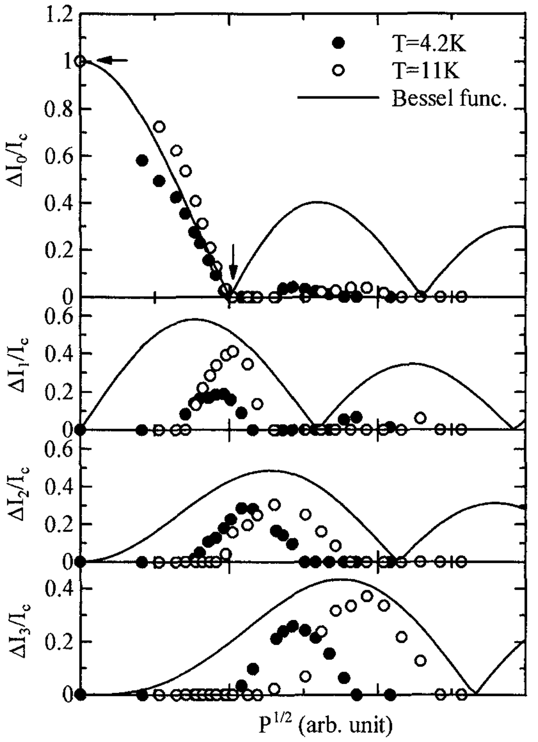

Fig. 5 Normalized step amplitudes obtained at 4.2 K and 11 K as a function of the square root of the microwave power $P^{1/2}$ for f_{rf}=15 GHz. The solid ;ines are the calculated step amplitude by Eq. (2).

i.e., critical current, is suppressed obeying the Bessel function, while the other steps did not appear. Furthermore, in contrast with the conventional Shapiro step, each step did not appear periodically with increasing $P^{1/2}$ and appeared only in the small power range. The similar result was observed for the sample #3 at 25 K and was also reported by several authors[1,11]. Therefore, the power dependence as shown in Fig. 5 seems to be a feature common to the steps observed in IJJ's. The observed one-valued and tunable Shapiro steps depending on the microwave power may be useful to device application like the voltage standard.

4. CONCLUSIONS

We have investigated microwave response of intrinsic Josephson junctions in mesa-shaped $Bi_2Sr_2CaCu_2O_y$ single crystals as a function of temperature. Each mesa consisted of a stack of one surface IJJ and inner IJJ's. Clear Shapiro steps were successfully observed in only surface IJJ up to 25 K independent of temperature when the applied microwave frequency was higher than the Josephson plasma frequency. This indicates that the Shapiro step response of the surface IJJ's can be also observed on the same condition as that of low-T_c Josephson junctions, over a wide range of temperature. However, the power dependence of the step amplitude was slightly different from the Bessel functionlike behavior and steps appeared only in a certain power region of applied microwave.

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