Microwave response of long intrinsic Josephson junctions fabricated on Bi-2212 single crystals

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Abstract. The microwave response properties of Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ long intrinsic Josephson junctions have been experimentally and theoretically investigated. We fabricated a mesa structure consisting of 14 junctions, 50 µm long and 4 µm wide, and observed the microwave-induced steps in the $I$–$V$ characteristics under irradiation with microwaves in the range 5–8 GHz. The step voltages were proportional to the square root of the microwave power, implying that the steps were produced by the motion of fluxons created by the microwaves. The Josephson frequency corresponding to the maximum step voltage was estimated to be 570 GHz. The step voltage decreased with increasing temperature, which can be explained by the decrease of the Swihart velocity. We performed a numerical simulation using coupled sine-Gordon equations and obtained a power dependence of the step voltage similar to the experimental result, and demonstrated standing waves of electric fields with in-phase plasma oscillation in all the junctions. These facts suggest that the steps observed in the experiment were produced by plasma resonance excited by the external microwaves.

1. Introduction
Recently, terahertz (THz) electromagnetic wave emission from high-$T_c$ Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ (Bi-2212) intrinsic Josephson junctions (IJJs) has been reported [1], [2]. This oscillator is expected to have several advantages, namely, featuring continuous waves, tunability, and a maximum power of the order of several mW, some of which are experimentally investigated [1], [2].

The mechanism of THz emission can be explained as follows: Bi-2212 IJJs are biased in a voltage state by applying a static magnetic field parallel to the CuO$_2$ superconducting layers in Bi-2212 or by irradiating with microwaves; the AC Josephson effect excites Josephson plasma waves in the IJJs; decay of the plasma causes THz waves to be emitted from the IJJs. Most experimental studies of plasma excitation have used a flow of dense fluxons, introduced by an applied field greater than 1 Tesla [1]-[4]. In contrast, using a low-temperature scanning electron microscopy (LTSEM) for Bi-2212 IJJs, Clauss et al. have demonstrated plasma resonance excited by microwaves of approximately 5 GHz, which is much lower than the Josephson plasma frequency [5]. This demonstrates that THz oscillators can be produced using a standard microwave signal generator, rather than requiring an expensive high-field magnet.

To realize THz oscillators based on microwave excitation, the microwave response properties of Bi-2212 IJJs must be investigated. Microwave-induced steps observed in the $I$–$V$ characteristics (IVCs) are an important property. The observed step voltage is much larger than the Shapiro step...
voltage estimated from the microwave frequency. For IJJs whose shape is a columnar mesa with a diameter of the order of a few µm, the step voltage monotonically increases with microwave power and saturates at high powers [6]. From the experimental result and numerical simulation using coupled sine-Gordon equations (CSGEs), this power dependence of the step voltage can be explained by a Josephson current with harmonics of the microwave frequency and the inverse AC Josephson effect [7].

On the other hand, a submillimeter oscillator with a junction much longer than the Josephson penetration depth \( \lambda_j \) exhibits high output power, since the oscillation of the voltage signal in the junction is amplified by the motion of fluxons [8]. For long IJJs or IJJs larger than \( \lambda_j \) in the junction plane, the step voltage is proportional to the square root of the power [9], [10]. Irie and Oya have interpreted this dependence as being due to the collective motion of fluxons introduced by the magnetic component of the external microwaves [9].

In this study, we investigate the microwave power and temperature dependence of the microwave-induced steps experimentally measured in Bi-2212 long IJJs. Moreover, to clearly understand the mechanism producing the steps, we investigate the power dependence and electromagnetic distribution in long IJJs by a numerical simulation using CSGEs under microwave irradiation.

2. Observation of microwave-induced steps in Bi-2212 long intrinsic junctions
To begin, we briefly describe the Bi-2212 IJJ fabrication method. An underdoped Bi-2212 single crystal was grown by a flux method. The critical temperature of the crystal was 63.4 K. A 50-nm Au passivation layer was evaporated on the crystal after cleaving the crystal in vacuum in order to reduce the contact resistance between the Bi-2212 and the Au layer. A mesa 50 µm long and 4 µm wide was fabricated on the crystal by an electron beam lithography and ion-milling technique. The mesa can be regarded as a stack of 14 intrinsic junctions. A 100-nm SiO insulating layer was evaporated and contact holes were formed by a self-align method. Finally, a second Au layer was evaporated on the sample and etched to form a three terminal configuration.

The sample was mounted on a sample holder in a liquid He dewar and irradiated with microwaves in the range 1–26.5 GHz using a semi-rigid cable with an open end, connected to a signal generator.

Figure 1 (a) shows IVCs of the fabricated mesa without microwave irradiation at 4.2 K. The junction critical current density, the number of junctions and McCumber parameter were approximately 260 A/cm², 14 and 4200, respectively, estimated from the IVCs. It should be noted that the mesa showed uniform distribution of the critical currents for all the branches except the 0th branch.

![Figure 1](image_url)

**Figure 1.** (a) \( I-V \) characteristics of the fabricated mesa at 4.2 K with no microwave irradiation. (b) 0th and 1st branches at the same temperature.
The 0th and 1st branches at the same temperature are shown in figure 1 (b). The vertical slope of the 0th branch indicates the contact resistance, giving a contact resistivity of less than $10^{-6}$ Ω cm$^2$.

Figure 2 (a) shows IVCs under irradiation with 6.9-GHz microwaves. The 0th branch in figure 1 is split into two parts, both crossing the horizontal axis in figure 2 (a). These distinct steps are the so-called microwave-induced zero-current-crossing (ZCC) steps. An enlarged picture in the positive bias region is shown in figure 2 (b). As seen in this figure, multiple microwave-induced steps, marked by arrows, are observed at several bias points. In the higher bias region, the mesa made voltage jumps to the quasiparticle branches. Clauss et al. have observed cavity resonant steps in Bi-2212 long IJJs under the microwaves below 10 GHz and LTSEM suggested that the steps are due to plasma resonance [5]. In this study, the observed steps including the ZCC steps may be caused by the resonance, since they are quite similar to the resonant steps verified by LTSEM.

![Figure 2](image-url)

**Figure 2.** (a) $I$−$V$ characteristics under microwave irradiation at 6.9 GHz. (b) Enlargement in the positive bias region. The measurement temperature is 4.2 K and microwave power is 15 dBm, measured by a signal generator. Multiple microwave-induced steps are marked by arrows.

Figure 3 shows the microwave power dependence of the step voltage measured at 6.9 GHz. The vertical and horizontal axes show the step voltage $V_s$ and the square root of the power $P$, respectively. Six steps are observed for the whole power region. $V_s$ is proportional to $P^{1/2}$ for all the steps, indicating that the observed steps originate from the motion of fluxons created by the magnetic component of the microwaves. A maximum step voltage of 18 mV was obtained for the 6th step. The step voltage per junction was approximately 1.2 mV if the step voltage was produced by all of the junctions. This gives a Josephson frequency at the maximum step voltage of 570 GHz.

We next investigated the relationship between the step voltage and measurement temperature. Figure 4 shows the temperature dependence of the step voltage measured for the 3rd step at 7.4 GHz. The step voltage gradually decreases with increasing temperature and vanishes at 35 K. The temperature dependence for the other steps is similar to that for the 3rd step. When the observed steps can be caused by cavity resonance [11], the step voltage is given by

$$V_s = \frac{\phi_0 c_n}{2L} n_x$$  \hspace{1cm} (1)

where $\phi_0$ is the quantum flux, $L$ the junction length and $n_x$ the mode number of the resonance along the long junction axis. $c_n$ is the velocity of the plasma mode and is given by [12]
\[ c_s = \frac{\bar{c}}{\sqrt{1 + 2S \cos \left( \frac{n_z \pi}{N + 1} \right)}} \]  

(2)

where \( N \) is the total number of junctions, \( S \) the coupling constant including the thickness of the superconducting and insulating layers, and \( n_z \) the mode number along the \( c \)-axis in Bi-2212. \( \bar{c} \) is the Swihart velocity of IJJs and is assumed to be given by the following expression [13] in this study:

\[ \bar{c} \approx \frac{d}{\lambda_{ab}} \frac{c}{\sqrt{2\varepsilon_r}} \]

(3)

where \( d \) is the interlayer spacing, \( \lambda_{ab} \) the London penetration depth for a shielding current flowing in the \( ab \)-plane and \( \varepsilon_r \) the relative dielectric constant. The Swihart velocity is important for understanding the temperature dependence. Temperature-dependent variables in (3) are \( d \), \( \varepsilon_r \) and \( \lambda_{ab} \). We assume that the temperature dependence of \( \bar{c} \) is due to only \( \lambda_{ab} \) and its temperature variation is \([1 - (T/T_c)^4]^{1/2}\) using the two-fluid model. The solid line in figure 4 shows the step voltage calculated using (1)-(3). Since this line gradually decreases in the low temperature region, similar to the experimental results, the decrease of the observed step voltage can be explained by the decrease of Swihart velocity.

![Figure 3. Microwave power dependence of the observed step voltage.](image1)

![Figure 4. Temperature dependence of the observed step voltage.](image2)

3. Numerical simulations for long intrinsic Josephson junctions

To investigate the observed steps in detail, we performed a numerical simulation using CSGEs for long IJJs under microwave irradiation. The simulation model takes account of inductive coupling [14] originating from the high anisotropy in Bi-2212. The model and simulation procedure have been described in detail elsewhere [7]. In this paper, we only detail the boundary conditions for solving the CSGEs, namely the continuity condition that the electromagnetic fields expressed using the CSGEs must be equal to the external microwaves in the TEM mode at the junction edges. For simplicity and to reduce computation time, the following parameters were used: \( L = 4 \lambda_j \), \( N = 3 \), \( S = -0.444 \) and \( \varepsilon_r = 10 \). Also, the external microwave \( f \) was constant at 0.02 \( f_p \), where \( f_p \) is the Josephson plasma frequency. The junction voltage \( V \), current \( I \) and the amplitude of the microwave field \( E_a \) were normalized by \( V_p = \)
$\phi_0 f_p$, the critical current $I_c$ and $V_p/d$, respectively.

The total IVCs of all the junctions calculated using the CSGEs under microwave irradiation are shown in figure 5 and an enlarged view is shown in the inset of the figure. The amplitude of the microwave field $E_a$ is 1.6. Two distinct ZCC steps are seen in the inset. As seen in the main figure, a large broad step appears outside the ZCC steps in both the positive and negative bias regions. In the high bias region, voltage jumps to the quasiparticle branches are evident. Both the ZCC step and the large step can correspond to resonant steps as shown in figure 2, though the number of steps obtained by the simulation is smaller than that measured in the experiment. It should be noted that every step voltage in figure 5 is much higher than the Shapiro step voltage of 0.02.

Figure 6 shows the relationship between the calculated step voltage $V_s$ and the amplitude of the electric field $E_a$. $V_s$ is defined as the voltage at $I = 0.2$ and is proportional to $E_a$, which corresponds to the square root of the microwave power. This indicates that the calculated steps originate from the motion of fluxons created by the microwaves.

Finally, we investigated the electric field distribution in each junction at a bias point where a step

![Figure 5](image1.png)  
**Figure 5.** Total $I$–$V$ characteristics of three IJJs calculated using CSGEs under microwave irradiation.

![Figure 6](image2.png)  
**Figure 6.** Relationship between the calculated step voltage and microwave field.

![Figure 7](image3.png)  
**Figure 7.** Snapshots of the electric field distribution in three IJJs.
appears. Figure 7 shows snapshots of the field distribution in the top, middle and bottom junctions at $I = 0.2$. The solid and broken lines are the field distribution at $0.390T_0$ and $0.394T_0$, respectively, where $T_0$ is the microwave period. As seen in the figure, the electric fields in all the junctions are standing waves with fundamental oscillation and the distributions show in-phase oscillation [11]. LTSEM measurements clearly demonstrate a standing wave pattern at bias points of the microwave-induced steps, which indicates plasma cavity resonance excited by the microwaves [5]. Accordingly, it can be concluded that it is likely that the standing waves shown in figure 7 exhibit plasma resonance.

4. Conclusion
We have fabricated Bi-2212 long IJJs 50 µm long and 4 µm wide and observed microwave-induced steps. The step voltage was proportional to the microwave power, indicating that the steps are caused by the motion of fluxons induced by the microwaves. The Josephson frequency at the maximum step voltage, obtained for the 6th step at the highest power in the experiment, was 570 GHz. The decrease of the step voltage with increasing temperature can be explained by the decrease of the Swihart velocity, which is related to cavity resonance.

Numerical simulations for long IJJs under microwave irradiation give IVCs and power dependence of the step voltage similar to the experimental results. In addition, the simulations produce standing waves in the electric fields with in-phase oscillation in the junctions. This may indicate plasma resonance excited by the microwaves.

We conclude therefore, that the steps observed in our experiment were probably produced by plasma resonance of frequency greater than 500 GHz. This finding can be useful for practical applications such as THz oscillators using microwave excitation.

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