I − V characteristics and THz radiation properties of Bi2212 mesas

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Abstract. Large mesa structures composed of intrinsic Josephson junctions (IJJs) are expected to be one of a promising source of THz electromagnetic wave. In order to study the collective dynamics in large mesas with and without the influence of self-heating effect, two types of mesa structures are fabricated. One is a double-mesa structure which enables the non-uniform bias current distribution to examine the heat-flow in large mesas. We find that the current lead geometry strongly affects the collective switching of IJJs into resistive state even if the number of IJJs in the mesas is the same. Another is a standard rectangular mesa structure used in the emission experiments. In this mesa, we observe THz radiation from IJJs biased at the low bias region, where the self-heating effect is almost negligible, on inner branches of multiple I − V structures and find that all of observed intense inner-branch emissions correspond to the same cavity resonance mode.

1. Introduction

Intrinsic Josephson-junction (IJJ) stacks in Bi₂Sr₂CaCu₂O₈ (Bi2212) are a promising source to emit the intense, continuous, and monochromatic terahertz waves [1, 2, 3]. It is considered that the emission power is characterized by the number \( N \) of synchronizing IJJs in the stack and thus straight way to increase the power is to make mesa consisting of a larger number of IJJs. However, the increase in \( N \) is known to cause the significant heating problem which results in reduction of voltage across the stack. In addition, one of the reasons that a variety of \( I − V \) curves observed for large IJJ stacks may also be due to peculiar heat-generation and heat-flow processes in individual samples because it is clear that such a self-heating induces the spatial variation of critical current and bias current densities. Indeed, at high bias where the \( I − V \) curve shows back bending a hot spot has been observed to be formed inside the mesa and it is considered that the hot spot plays a role for synchronization [4, 5, 6, 7]. Furthermore, a IJJ stack with a large number of junctions have complex dynamical behavior due to coupling effect between adjacent IJJs in the stack, so that in a large IJJ stack switching process of individual IJJs into voltage state is also affected by heating generated from them in the resistive state because of their large critical currents.

In this study, we fabricated the IJJ mesas with different configurations of current injection to produce the spatial distribution of bias current density and found that the \( I − V \) curves of the mesas were strongly influenced by the current lead structure even for the same number of junctions because of different thermal distribution. Furthermore, we present the observation
Figure 1. (a) A photograph of four double-mesa structures and schematic view of the sample. Dimensions of each mesa are listed in Table 1. (b) A photograph of the sample used in emission experiments. Lateral dimensions of the mesa are $L = 275 \, \mu m$, $W = 111 \, \mu m$ and its thickness is $H = 0.84 \, \mu m$ corresponding to the number of junctions of 560.

Table 1. Dimensions of double-mesa structures used in this work. $N_B$ and $N_E$ are the number of IJJs in the base and electrode mesas, respectively.

| Mesa | $L_B$ (µm) | $W_B$ (µm) | $H_B$ (µm) | $N_B$ | $L_E$ (µm) | $W_E$ (µm) | $H_E$ (µm) | $N_E$ |
|------|------------|------------|------------|-------|------------|------------|------------|-------|
| 1    | 270        | 60         | 0.9        | 600   | 263        | 47         | 0.12       | 80    |
| 2    | 270        | 60         | 0.9        | 600   | 68         | 47         | 0.12       | 80 × 2 |
| 3    | 270        | 60         | 0.9        | 600   | 68         | 47         | 0.12       | 80    |
| 4    | 270        | 60         | 0.9        | 600   | 68         | 47         | 0.12       | 80    |

result of THz radiation from the IJJ stack biased at the low bias region, where the self-heating effect is almost negligible, on inner branches of multi-branched $I - V$ curves.

2. Experimental
The Bi2212 single crystals with critical temperatures $T_c$ of $\sim 85$ K were grown by a conventional melting method [8] and two types of mesa structures were fabricated from them using standard photolithography and Ar ion milling. One is a double-mesa structure which consisting of electrode and base mesas. As shown in Fig. 1(a), four double-mesa structures were formed on the same crystal. Dimensions of each mesa are listed in Table 1. In this case, the bias current is supplied to the base mesa through the electrode mesas. Another is a conventional mesa structure as shown in Fig. 1(b), which was used in emission experiments. Lateral dimensions of the mesa are $L = 275 \, \mu m$, $W = 111 \, \mu m$ and its thickness is $H = 0.84 \, \mu m$ corresponding to the number of junctions of 560. Detail of the fabrication process were described elsewhere [9].

For both samples, the $I - V$ characteristics were measured by two probe method and in emission experiments the radiation from IJJ stacks was detected in situ by using high sensitive IJJ detector [9]. The contact resistance is subtracted in all $I - V$ characteristics presented here.

3. Results and discussion
3.1. Influence of heat-transfer on $I - V$ characteristics
Figure 2 shows the $I - V$ characteristics at 4.2 and 77 K for four mesas of the double-mesa structures as shown in Fig. 1(a). Due to two probe configuration these $I - V$ curves are a sum
Figure 2. $I-V$ characteristics of double-mesa structures as shown in Fig. 1 at 4.2 and 77 K.

of $I-V$ curves of the base and electrode mesas. At 4.2 K the $I-V$ characteristics of Mesa1 and Mesa3 show that all IJJs in the stack switch into the voltage state simultaneously when the bias currents reach to 47.4 mA for Mesa1 and 23.8 mA for Mesa3, respectively, which correspond to the critical current $I_{c}^{(E)}$ of the electrode mesa. This collective voltage jump indicates that the temperature of all IJJs in the mesa increased suddenly although for Mesa3 the bias current injection into base mesa is non-uniform. On the other hand, in the case of Mesa2 and Mesa4 there are several stepwise voltage jumps and the simultaneous switching has occurred only partially in the mesas. For these mesas heat-generation starts from both ends or one end of base mesa at which the bias current was applied and self-heating region may increase with increasing bias current. Therefore, from their $I-V$ curves we can estimate the critical current $I_{c}^{(B)}$ of the base mesa as well as $I_{c}^{(E)}$, whose values are listed in Table 2. However, at 77 K the features of $I-V$ curves for Mesa2, Mesa3 and Mesa4 are different from those at 4.2 K as mentioned above. As seen from Figs. 2(b)-(d), the $I-V$ curves are characterized by two critical currents determined by the ratio of areas of electrode and base mesas but the ratio of the first and second voltage jumps is not consistent with $N_{B}/N_{E} = 7.5$ in all cases. This suggests that the IJJs in the top portion of the base mesa switch into the voltage state simultaneously due to heat-transfer from the electrode mesa when IJJs in electrode mesa switch into the voltage state. Hypothetical temperature distribution inside the mesas presumed from the observed $I-V$ curves is shown in Fig. 3. Furthermore, such a contribution of Joule heating from the electrode mesa to base mesa may increase with increasing $N_{E}$ because the Joule heat generated in the electrode mesa is proportional to the resistance $R_{E}$ of the electrode mesa, i.e., $N_{E}$, in the voltage state. Indeed, we observed that the $I-V$ curves systematically vary depending on $N_{E}$ and will discuss in detail elsewhere.
Table 2. Critical currents of the electrode mesa, $I_c^{(E)}$ and the base mesa, $I_c^{(B)}$ at 4.2 K and 77 K. The data were obtained from Fig. 2.

| Mesa | $I_c^{(E)}$ (mA) | $I_c^{(B)}$ (mA) | $I_c^{(E)}$ (mA) | $I_c^{(B)}$ (mA) |
|------|-----------------|-----------------|-----------------|-----------------|
| 1    | 47.4            | unspecified     | 31.6            | unspecified     |
| 2    | 21.8            | 33.0            | 19.3            | 25.9            |
| 3    | 23.8            | unspecified     | 10.4            | 24.6            |
| 4    | 14.9            | 24.9            | 11.3            | 31.2            |

Figure 3. Hypothetical temperature distribution inside the base mesas immediately after the electrode mesa switches into the voltage state at 4.2 and 77 K.

Figure 4. (a) $I – V$ characteristic of the emitter sample at 4.2 K as shown in Fig. 1. (b) Response of IJJ detector as a function of bias current of the emitter. (c) Multi-branching $I – V$ characteristics in the low bias region denoted by the dashed circle in Fig. 4 (a) and the emission properties of the emitter biased at inner branches.
3.2. Emission properties

A large mesa structure has been used in most studies of the THz emission from IJJs and it is known that two types of emissions have been observed. One is the emission in low current region and another is in high current region. The difference between these emission is the magnitude of contribution of the self-heating. The high-bias emission have been observed under the situation where a hot spot is formed while in the case of the low-bias emission the influence of self-heating is almost negligible. In this paper we focus on the low-bias emission because the self-heating effect makes the analysis of the emission properties complicated.

Figures 4(a) and 4(b) show $I-V$ characteristic and the response of IJJ detector as a function of bias current, respectively, for the sample $(N = 560)$ as shown in Fig. 1(b) at 4.2 K. The critical current is 45 mA and the maximum voltage of 830 mV is appeared at $I = 8.3$ mA. It is found that from the response of IJJ detector the sample emitted the electromagnetic wave at the current range between 4.3 and 5.7 mA in the low bias region. The largest response of the detector was observed at the bias point of $I = 5.64$ mA and $V = 700$ mV. Although the emission frequency could not be measured directly in our experimental system, it is roughly estimated to be 0.6 THz from the Josephson voltage-frequency relation $f = V/(N\Phi_0)$ using the values of $V = 700$ mV and $N = 560$, where $\Phi_0$ is the flux quantum. Here, we assumed that all IJJs in the mesa participate in the emission because the corresponding bias point is on the outermost branch. Although it is difficult to distinctly determine the cavity mode, the estimated emission frequency of 0.6 THz is qualitatively consistent with the cavity resonance frequency of $f(2,0) = 0.64$ THz or $f(2,1) = 0.66$ THz calculated by a general expression of the geometrical resonance for rectangular mesa, given by [10]

$$f(m,n) = \frac{c_0}{2n_f} \sqrt{\left(\frac{m}{W}\right)^2 + \left(\frac{n}{L}\right)^2}, \quad (1)$$

where $c_0$ is the speed of light in vacuum, $n_f = 4.2$ is the refractive index of Bi2212 [2], $m$ and $n$ are integers. On the other hand, multiple-branch structure can be observed in the $I-V$ characteristics by sweeping up and down the bias current in the low bias region. Figure 4(c) shows the observed inner branches and corresponding detector responses displayed with the same color. The filled circles on the inner branches indicate the bias point at which the detector signal becomes maximum.

We roughly estimated the number of active IJJs for each inner branches from the ratio of

![Figure 5](image-url)
the minimum voltage of the outermost branch and inner ones shown in Fig. 4(c). Figure 5 shows the emitter voltage ranges on each inner branches, at which the intense emission was observed, as a function of estimated the number of active IJJs. From this, we found that all of observed intense emission on inner branches also correspond to the cavity resonance mode of \((m, n) = (2, 0)\) or \((2, 1)\) and the smallest number of IJJs contributing to the emission is estimated to be 189, which corresponds to 34% IJJs in the mesa. This may be not strange because only voltage corresponding to such a mode is suitable for the voltage range of each inner branch and the expected bias points for other modes deviate from the low bias region of each inner branch.

4. Conclusion
We have fabricated large IJJ mesas with different configurations of current injection and have discussed heat-flow in them. We observe that \(I - V\) characteristics are strongly influenced by the current lead geometry even for the mesas with the same number of junctions because of different thermal distribution. Furthermore, we observe the THz radiation from the IJJ emitter mesa biased at inner branches of multiple-branched \(I - V\) characteristics. We find that all of observed intense emissions on inner branches correspond to the same cavity resonance mode and in the case of the observed innermost branch 34% IJJs in the mesa contribute to such emission.

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