Excitation mode characteristics in Bi2212 rectangular mesa structures

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Abstract. The rectangular mesa structure of single crystalline Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ with the dimensions of 64 $\times$ 135 $\times$ 1.35 $\mu$m$^3$ was fabricated by using Ar-ion milling with a metallic mask and focused ion beam. From this mesa, the radiation frequencies of 24.226 cm$^{-1}$ and 17.296 cm$^{-1}$ were observed at the different temperatures of 25 K and 40 K, respectively. The change of the radiation frequencies is also obviously reflected in the radiation pattern measurement. The radiation pattern observed at lower temperature seems to have an asymmetric shape and its intensity as a whole is slightly weak. In the higher temperature, however, the radiation intensity increases and the radiation pattern becomes almost symmetric shape. The radiation characteristics observed at higher temperature is well explained by the fundamental cavity resonance mode expected from the width of the mesa. This result may give us not only the suggestion of the existence of the adequate matching condition between the geometrical cavity and the ac Josephson current in the mesa but also the guide for the designing of the high efficiency of the radiation.

1. Introduction

The theoretical and experimental studies for generating electromagnetic (EM) waves from high temperature superconductors have been performed by a lot of research groups. Among high-T$_c$ superconductors, Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) is an excellent system for studying EM waves generation phenomena at terahertz frequencies because it has unique superconducting characteristics and the layered structure of Bi2212 acts as multi-layered Josephson junctions system known as intrinsic Josephson junctions (IJJs) [1, 2, 3, 4, 5, 6, 7].

The first observation of the EM waves from the mesa structures of Bi2212 single crystal were reported by Ozyuzer et al. with the frequency range from 0.36 to 0.85 THz [8]. Following this result, a lot of interesting radiation characteristics from the Bi2212 mesa structures were reported(for example [9, 10, 11, 12, 13]). Recently, we observed that the several mesas show the large shift of the radiation frequency by changing the bath temperature. According to our previous studies, the mesa structure acts as the resonant cavity and the radiation pattern from the mesa is strongly related to the cavity and the ac Josephson conditions [10, 11]. In order to
understand the relation between the shift of the radiation frequency and the cavity resonance mode, we studied the radiation pattern characteristics for a mesa which shows the large shift of the radiation frequency by changing bath temperatures.

2. Sample preparation and experimental setup

High-quality single crystals of Bi2212 were grown by the traveling solvent floating zone method [14]. The mesa structure discussed here was fabricated by using Ar-ion milling with a metallic mask and focused ion beam (FIB), and its dimensions are 64 × 135 × 1.35 μm³.

For this study, in addition to the radiation measurement setup which was introduced in previous our studies [9, 10, 11], we used another experimental setup shown in Fig. 1. A Si-composite bolometer was placed on a rotating table. We used a cryostat jacket with 2 mm thickness of a cylindrical polyethylene window. The angular θ dependence of the radiation intensity was measured by rotating the position of the Si-composite bolometer. θ is an angle between the top of the mesa (parallel to the crystallographic c axis) and the position of the detector as shown in Fig. 1. For this measurement, we also used a bias modulation technique with the frequency of $f_{\text{mod}} = 70$ Hz and the amplitude of $V_{\text{pp}} = 50$ mV instead of an optical chopper. A FeRh thermometer was placed on a sample holder of a He flow cryostat, so that the measured, T, indicates the temperature of the bath not the temperature of the mesa directly.

3. Experimental results and discussions

The $I$-$V$ characteristics of the mesa obtained at 25 K and 40 K are shown in Fig. 2(a), where contact resistance was subtracted. The $I$-$V$ characteristic has large hysteresis loop and shrinks with increasing the bath temperature. In the resistive state of the $I$-$V$ characteristic, the negative resistance behavior was observed at both temperatures because of the self heating effect [15]. The radiations were observed at around 1.5 V for 25 K and around 0.8–1.0 V for 40 K as shown in Figs. 2(b) and 2(c). As indicated in Fig. 2(d), the radiation frequencies determined by the FT-IR spectrometer at 25 K and 40 K are 24.226 cm⁻¹ (726.27 GHz) and 17.296 cm⁻¹ (518.52 GHz), respectively. Hence, the radiation frequency shifted from the higher one to the lower one with increasing the bath temperature.

In Figs. 3 and 4, we display the $I$-$V$ characteristic, the radiation intensity detected by the Si-bolometer, and the angular θ dependence of the radiation intensity in the $xz$-plane of the mesa for 25 K and 45 K. A sketch of the coordinate system is shown in Fig. 2(e). These data were obtained in another day by using the bias voltage modulation technique, so that both $I$-$V$ and radiation characteristics were slightly changed. The $I$-$V$ characteristics and the relative radiation intensity were measured every 5° from $-105°$ to 95° in the $xz$-plane of the mesa. Then, the 3D plots of the angular θ dependence of the radiation intensity as shown in Fig. 3(d) and 4(d) were obtained by aligning each data with different θ.

The radiation pattern obtained at 25 K seems to have an asymmetric shape with some peak.
structures around $\theta = -30^\circ$ as seen along the two dotted lines denoted by A and B in Fig. 3(d). On the contrary, the almost symmetric radiation pattern was clearly observed at 45 K around 9 mA denoted by the dotted line of C. The scattering of the radiation intensity below 6 mA at 45 K as seen along the dotted line of D originates from the radiation at the re-trapping region. The $I-V$ characteristic at re-trapping region is easily varied by the different measurement runs, so that the radiation intensity in the re-trapping region also depends on the measurement runs.

According to the cavity condition for the thin rectangular mesa, the resonance frequency of the fundamental mode along the width of the mesa (TM$_{1,0}$ mode) is described as $f_{1,0} = \frac{c_0}{2\pi n w}$, where $c_0$ is the speed of light in vacuum, $n$ the refractive index of Bi2212, and $w$ the width of the mesa [8, 10, 16]. The frequency of the TM$_{1,0}$ mode for this mesa is estimated as $f_{1,0} = 557.76$ GHz by using $n = 4.2$ [10] and $w = 64$ μm. The observed radiation frequency of 518.52 GHz at 40 K is almost consistent with the above estimation. It is noted that the 5−10% tuning of the center frequency of the radiation is possible by changing the applied voltage to the mesa. In addition to that, the characteristic of radiation pattern observed at higher temperature has good agreement with the result reported by Kadowaki et al. [10] for the TM$^z$(1,0) mode of a rectangular mesa.

The radiation frequency observed at 25 K is 1.4 times higher than that at 40 K and the applied voltage in the radiation point at 25 K is about 1.5 times larger than that at 40 K. These facts suggest that the higher cavity mode might be excited by the higher frequency of the ac Josephson current at lower temperature. However, the matching condition between the geometrical cavity and the ac Josephson current in the mesa may not be enough for appropriate generation of the higher cavity modes. Therefore, the radiation intensity at lower temperature is weaker than that of higher temperature and the radiation pattern at lower temperature can be unclear.

One convincing reason for this result is the low $Q$-value of the mesa structure because it has a slightly trapezoidal shape. In general for a resonator, a higher excitation mode is more sensitive to the geometrical conditions than a lower one. Therefore, by improving the geometrical structure, it might be obtained higher efficiency of the radiation for lower excitation modes as well as for higher excitation modes. Another possible reason is the change of mixing ratio of the radiation sources. According to the previous study [10, 11], the mixing of two radiation sources such as the nodal electric field component of the cavity mode and the uniform electric field component of the ac Josephson current were proposed to explain the radiation pattern from
mesas. It is known that the mixing ratio of those two sources depends on each mesa. This sort of thing might be related to the radiation pattern characteristic for this mesa.

In conclusion, we discussed the radiation characteristics at different temperatures for the Bi2212 rectangular mesa structure. The experimental results suggest that the existence of the adequate matching condition between the geometrical cavity and the ac Josephson current.

Acknowledgments

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References

[1] Sakai S, Bodin P and Pedersen N. F 1993 J. Appl. Phys. 73 2411
[2] Tachiki M, Koyama T and Takahashi S 1994 Phys. Rev. B 50 7065
[3] Koyama T and Tachiki M 1995 Sol. St. Comm 96 367
[4] Hechtischer G, Kleiner R, Ustinov A. V and Müller P 1997 Phys. Rev. Lett. 79 1365
[5] Lee K, Wang W, Iguchi I, Tachiki M, Hirata K and Mochiku T 2000 Phys. Rev. B 61 3616
[6] Batov I E, Jin X Y, Shitov S V, Koval Y, Müller P and Ustinov A V 2006 Appl. Phys. Lett. 88 262504
[7] Kleiner R, Steinmeyer F, Kunkel G and Müller P 1992 Phys. Rev. Lett. 68 2394
[8] Ozyuzer L et al. 2007 Science 318 1291
[9] Kadowaki K et al. 2008 Physica C 468 634
[10] Kadowaki K, Tsujimoto M, Yamaki K, Yamamoto T, Kashiwagi T, Minami H, Tachiki M and Klemm R A 2010 J. Phys. Soc. Jpn. 79 023703
[11] Tsujimoto M, Yamaki K, Deguchi K, Yamamoto T, Kashiwagi T, Minami H, Tachiki M, Kadowaki K and Klemm R A 2010 Phys. Rev. Lett. 105 057005
[12] Wang H B et al. 2010 Phys. Rev. Lett. 105 057002
[13] Guénon S et al. 2010 Phys. Rev. B 82 214506
[14] Mochiku T and Kadowaki K 1994 Physica C 235–240 523
[15] Kurter C, Ozyuzer L, Prolier T, Zasadzinski J F, Hinks D G and Gray K E 2010 Phys. Rev. B 81 224518
[16] Klemm R A and Kadowaki K 2010 J. Phys.: Condens. Matter 22 375701