The influence of electrode position on the current-voltage characteristics and terahertz radiation in a high-T_c superconducting device

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***Abstract*— The influence of electrode position on the current-voltage characteristics (IVC) and broadly tunable terahertz (THz) radiation emitted from two pentagonal mesa structures consisting of the intrinsic Josephson junctions in a high-T_c superconducting device is investigated.**

I. Introduction

BY applying a *dc*-voltage along the *c*-axis of the mesa structures consisting of the intrinsic Josephson junctions (IJJs) in layered high temperature (T_c) superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) single crystal [1], intense and coherent terahertz (THz) electromagnetic (EM) waves are radiated according to the *ac*-Josephson effect [2-12]. Here we investigated the effect of bias electrode position on the current-voltage characteristics (IVC) and broadly tunable THz radiation emitted from two identical pentagonal devices.

II. Sample Preparation Methods

A piece of 800×800 μm^2 in size of Bi2212 crystal was glued onto a sapphire substrate by using Ag paste.

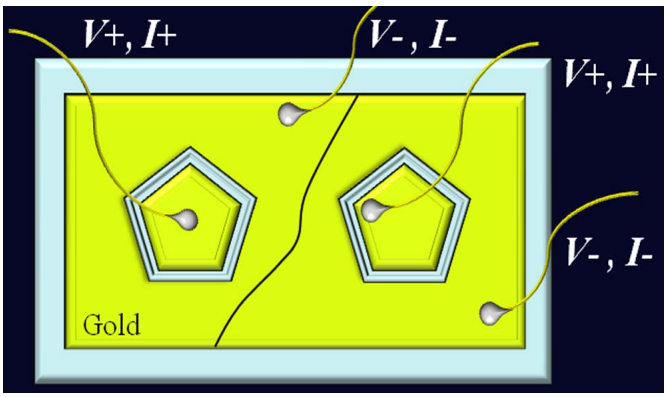

Fig. 1. Schematic view of two identical pentagonal mesas: Sample 1 is the mesa with a current bias feed on its middle (left), and Sample 2 is a mesa with its feed along an edge (right). The crystal surface contains thin layers of Ag and Au. The current is applied along the *c*–axis direction of the Bi-2212 crystal using gold wires.

Two regular pentagonal mesas with top edge length 60 μm [7] were fabricated by using FIB milling. Sample 1, a mesa with a current bias feed on its middle (left), and Sample 2, a mesa with its feed along an edge (right) are schematically shown in Fig. 1. In order to apply the *dc*-current to the mesas, gold wires 10 μm in diameter were attached to the surfaces as electrodes using silver paste.

III. Results

We studied the IVC, emission spectra (by using the Fourier transform infrared (FT-IR) spectroscopy) and angular distribution of the radiation power emitted from two regular pentagonal mesas [7].

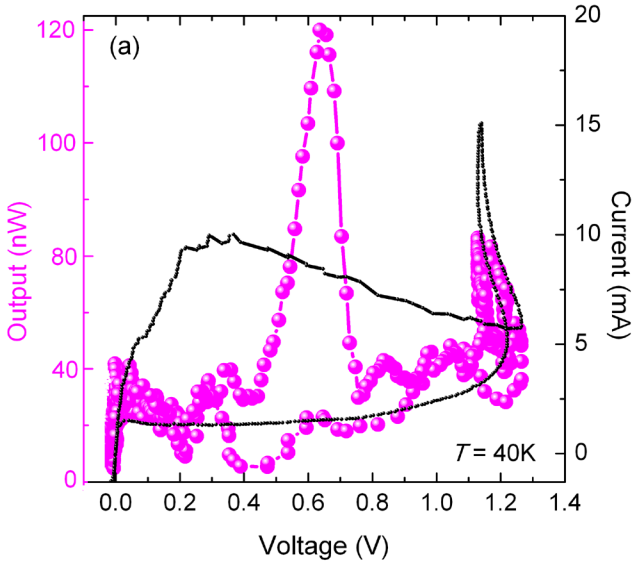

Fig. 2. Experimental results for pentagonal mesa with a current bias feed on its middle: (black) typical IVCs at the bath temperature T = 40.0 K and (Magenta) the emission intensity detected by the Si-bolometer.

In this paper we only discuss the IVC and the strong THz radiation detected by the Si-bolometer. For sample 1 THz radiation was detected on the return branch region where the current is relatively low. A clear irreversible (IR) type THz radiation at bath temperature 40 K for this sample was seen. The IVC and THz radiation on the return branch region of IVC of sample 1 detected by the Si-bolometer are shown in Fig. 2. Along with the rapid jump in the voltage, a small hysteresis in the outermost branch of the IVCs for currents

between about 8 and 12 mA appears (right vertical scale). The negative differential resistance due to Joule heating is seen in the IVCs of Sample 1 for voltage range 1.1-1.25 V. The left vertical scale indicates the intensity of the THz emission detected by the Si-bolometer. The detailed calculation of emission power detected by Si-bolometer was discussed in Ref. [8].

Figure 3 shows THz radiation from Sample 2 which I_c is around 8 mA and THz radiation was observed for I = 2~3 mA. The maximum bias voltage for Sample 2 is 0.98 V, lower than that of Sample 1. As a result, the negative resistance and backbending behavior that appeared above 1 V in the IVCs of Sample 1 are almost absent. These results suggest that when the bias feed is along an edge, the mesa doesn't over heat as much, resulting in higher output emission power.

To better understand the effect of the bias feed position on the IVC of mesas, we have also studied the temperature dependence of *c*-axis resistance (R-T) of both samples [7]. In both cases the contact resistance of few Ohm due to two terminal measurements was seen. The difference between the transition temperatures of two samples was a small amount. This indicates that the contact resistance (between gold wires and mesas) and the thermal contact between the sample substrate and the sample holder (cryostat) do not influence the IVC.

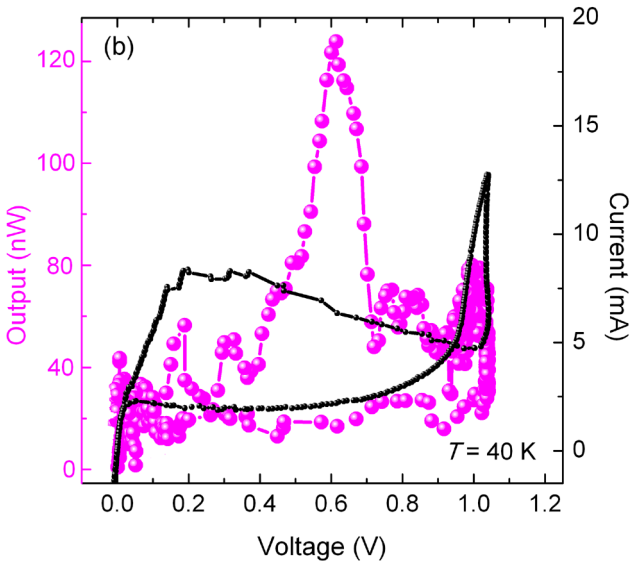

Fig. 3. Experimental results for pentagonal mesa with a current bias feed along an edge: (black) typical IVCs at the bath temperature T = 40.0 K and (Magenta) the emission intensity detected by Si-bolometer.

IV. Summary

The effect of the bias current position on the radiation of intense and tunable THz radiation from pentagonal IJJs devices of superconducting Bi-2212 was investigated in this paper. The common backbending in the IVC due to Joule heating was not seen for the device with a current bias feed along an edge. We attribute this to the effect of the bias feed position on the THz radiation from pentagonal mesas.

References

[1]. R. Kleiner, F. Steynmeyer, G. Kunkel, and P. Müller, "Intrinsic Josephson effects in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals," *Phys. Rev. Lett*., vol. 68, pp. 2394–2397, 1994.

[2]. U. Welp, K. Kadowaki, and R. Kleiner, "Superconducting emitters of THz radiation," *Nat. Photon*., vol. 7, pp. 702–710, 2013.

[3]. M. Tsujimoto, T. Yamamoto, K. Delfanazari, R. Nakayama, T. Kitamura, M. Sawamura, T. Kashiwagi, H. Minami, M. Tachiki, K. Kadowaki, R. A Klemm, "Broadly tunable sub-terahertz emission from internal branches of the current-voltage characteristics of superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals," *Phys. Rev. Lett*., vol. 108, 2012, Art ID 107006.

[4]. K. Delfanazari, H. Asai, M. Tsujimoto, T. Kashiwagi, T. Kitamura, T. Yamamoto, M. Sawamura, K. Ishida, C. Watanabe, S. Sekimoto, H. Minami, M. Tachiki, R. A. Klemm, T. Hattori, and K. Kadowaki, "Tunable terahertz emission from the intrinsic Josephson junctions in acute isosceles triangular $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesas," *Opt. Express*, vol. 21, pp. 2171–2184, 2013.

[5]. M. Tsujimoto, H. Kambara, Y. Maeda, Y. Yoshioka, Y. Nakagawa, and I. Kakeya, "Dynamic control of temperature distributions in stacks of intrinsic Josephson junctions in $Bi_2Sr_2CaCu_2O_{8+\delta}$ for intense terahertz radiation," *Phys. Rev. Appl.*, vol. 2, 2014, Art ID 044016.

[6]. T. Kashiwagi, T. Yamamoto, T. Kitamura, K. Asanuma, C. Watanabe, K. Nakade, T. Yasui, Y. Saiwai, Y. Shibano, H. Kubo, K. Sakamoto, T. Katsuragawa, M. Tsujimoto, K. Delfanazari, R. Yoshizaki, H. Minami, R. A. Klemm, K. Kadowaki "Generation of electromagnetic waves from 0.3 to 1.6 terahertz with a high-T_c superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ intrinsic Josephson junction emitter," *Appl. Phys. Lett*., vol. 106, 2015, Art ID 092601.

[7]. K. Delfanazari, H. Asai, M. Tsujimoto, T. Kashiwagi, T. Kitamura, T. Yamamoto, W. Wilson, R. A. Klemm, T. Hattori, K. Kadowaki, "Effect of Bias Electrode Position on Terahertz Radiation from Pentagonal Mesas of Superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$," *IEEE Trans. THz Sci. and Techno.*, vol. 5 (3), pp. 505-511, 2015.

[8]. T. Kitamura, T. Kashiwagi, T. Yamamoto, M. Tsujimoto, C. Watanabe, K. Ishida, S. Sekimoto, K. Asanuma, T. Yasui, K. Nakade, Y. Shibano, Y. Saiwai, H. Minami, R. A. Klemm, and K. Kadowaki, "Broadly tunable, high-power terahertz radiation up to 73 K from a stand-alone $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesa," *Appl. Phys. Lett*., vol. 105, 2014, Art ID 202603.

[9]. V. M. Krasnov, "Terahertz electromagnetic radiation from intrinsic Josephson junctions at zero magnetic field via breather-type self-oscillations," *Phys. Rev. B*, vol. 83, 2011, Art ID 174517.

[10]. Y. M. Shukrinov, I. R. Rahmonov, A. Plecenik, P. Seidel, E. Il'ichev, and W. Nawrocki, "Phase dynamics of two parallel stacks of coupled Josephson junctions," *Supercond. Sci. Technol*., vol. 27, 2014, Art ID 124007..

[11]. S. Savel'ev, V. A. Yampol'skii, A. L. Rakhmanov, and F. Nori, "Terahertz Josephson plasma waves in layered superconductors: spectrum, generation, nonlinear and quantum phenomena," *Rev. Prog. Phys*., vol. 73, 2010, Art ID 026501.

[12]. X. Hu and S. Lin, "Cavity phenomena in mesas of cuprate highsuperconductors under voltage bias," *Phys. Rev.* B, vol. 80, 2009, Art ID 064519.