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Continuous 30 μW terahertz source by a high-T_c superconductor mesa structure

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Using a modified mesa structure of high-T_c superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ with a thin underlaying base superconductor ($\sim$3 μm), the effective working temperature of the continuous and monochromatic terahertz emitter is extended up to 70 K, and the maximum power of $\sim$30 μW at 0.44 THz is achieved at the relatively high temperature of $T_b = 55$ K in a low bias current retrapping region. The diverging behavior of the intensity occurring at 55 K in the low current regime without hot spot formation may provide us an important clue for the stronger THz radiation from intrinsic Josephson junction devices. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4827094]

Terahertz (THz) electromagnetic (EM) waves are very useful not only for studying fundamental physics associated with the low-energy excitations in molecules and solids but also for many applications such as chemical identification, various kinds of physical imaging, and high-speed communication.[1,2] However, development of coherent, continuous, and high power solid-state sources with a compact size have not been achieved by both fundamental and technical difficulties known as the "*terahertz gap*."[2] Much effort has been put to improve the high frequency characteristics in semiconducting electronics devices such as resonant tunneling diodes[3] or to extend the low frequency characteristics in laser devices such as quantum cascade lasers.[4]

In 2007, a novel EM emission phenomenon at THz frequencies from a mesa structure fabricated from a piece of high-T_c superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) single crystals has been discovered in zero magnetic field.[5,6] This compound is known as the intrinsic Josephson junction (IJJ) system,[7] where the atomic thin insulating Bi_2O_2 layers are sandwiched by the CuO_2 double layers responsible for superconductivity. Although the distance between double CuO_2 planes is only 1.533 nm separated by insulating Bi_2O_2 layers, the superconducting coupling is extremely weak consisting of two IJJs in a unit cell along the *c*-axis. Therefore, this system is known to behave as a multi-stack of IJJ's.

The actual mesa is usually constructed on top of the large single crystal surface. In the case of the rectangular mesa, the emission occurs when the following two conditions are fulfilled: one is that the width of the mesa, w, obeys a relation of $f = c_0/n\lambda = c_0/2nw$, where f is the radiation frequency, c_0 is the speed of light in vacuum, λ is the wavelength, and n is the refractive index.[5] The another one is the ac Josephson relation,[8] expressed as $f = (2e/h)(V/N)$, where e is the elementary charge, h is the Planck constant, N is the number of the layers of IJJ, and V is the voltage applied to the mesa.

In the early stage of the development,[5,6] the radiation power was small, about 0.5 μW, with a frequency range from 0.36 to 0.85 THz. Since then up to now, two orders of magnitude higher power have been achieved, in particular, in a rectangular mesa with very complicated current-voltage behavior,[9] and a rectangular parallelepiped Bi2212 placed on a normal good conductor (stand-alone mesa).[10–12] Turkoglu *et al.* has succeeded in observing 60 μW output power from the rectangular mesa.[13] Just recently, Benseman *et al.* has announced more than 600 μW in a synchronized three mesa array system.[14] This power level is 10^5–10^8 orders of magnitude larger than that observed in single Josephson junctions, such as Sn-SnO-Sn and Nb-AlO-Nb, with power of 1 pW to 0.1 nW at most in the 1960s–1970s.[15–17] It might be possible to make 1 mW level of power emission even by making an array of conventional Josephson junctions, if the number of 10^4–10^5 of identical Josephson junctions were made to be synchronized.[18–22] This is technically formidable, hindering high power generation using conventional Josephson junctions. Furthermore, the superconducting gap 2Δ is only a few mV, so that it cannot, in principle, go beyond $\sim$1 THz in conventional Josephson junctions. On the contrary to this, high-T_c superconductors have a large superconducting gap of $\sim$50–70 mV, so that there is no fundamental obstacle to go beyond 1 THz in high-T_c superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$.

As for the emission power, it was found that a stand-alone mesa can reproducibly generate powerful THz radiation with several tens of μW so far, but the fabrication process is rather complicated.[11] More powerful radiation can be obtained by making synchronized operation of a large number of N IJJ's, since the total emission power $P \propto N^2$, where N is the number of IJJ. This is, in principle, true, however, an injected large current to the mesa (several 10 mA) also generates a considerable amount of Joule heat (several 10 mW/mesa = a few MW/cm^3), resulting in severe self heating of the mesa. In fact, the stand-alone mesa has been developed because of not only larger far field emission intensity but also more efficient cooling of the mesa by removing the underneath poorly thermal conducting superconducting substrate. Actually a power of $\sim$600 μW was recently claimed from an array of three mesas synchronized simultaneously,[14] but it should be mentioned that the operation of the three mesa synchronization is not easy because of unstable bias conditions due to thermal interferences between three mesas.

In this paper, we demonstrate a method to achieve $\sim$30 μW without complicated fabrication processes from a modified mesa structure whose underlying superconductor is practically removed. Since the process used here is much easier, applying this method to making large arrays may give a clue for generating much higher power of the THz radiation.

High-quality single crystals of Bi2212 were grown by a traveling solvent floating zone method.[23] The crystal was annealed to obtain a slightly underdoped state.[24] Five mesas with an identical rectangular shape were prepared on a thin Bi2212 single crystal by argon ion milling technique with a metal mask as follows. First of all, a piece of the single crystal with $\sim$1 mm^2 in size and a few tens of μm thick was cut out of an annealed larger crystal, then it was glued on the polished surface of a sapphire substrate by very thin PIX.[25] After drying completely, it was further cleaved to a few μm thick. Then, the crystal was deposited by thin Ag and Au layers ($\sim$30 nm and $\sim$40 nm, respectively) on the surface. Second, the mesa was etched out by using a metal mask twice to determine the width and the length of the mesa by Argon milling technique. During the second process, a part of crystal is completely milled out and reached down to the sapphire substrate. Next, in order to electrically isolate the top electrode of the mesa from the bottom crystal, CaF_2 ($\sim$60 nm thick) was deposited on $\sim$30% of the mesa including approximately half of the whole crystal. Then, Au ($\sim$80 nm thick) was again deposited on the mesa and on CaF_2 as a current lead to the top of the mesa. For more detailed sample fabrication process, refer to the reports by Kashiwagi *et al.*[11] and Minami *et al.*[24,26]

Figure 1(a) shows a photograph of the three mesas out of five used for the present study. The stereographic view of the mesa is given in Fig. 1(b) to explain the details as described above. The size of mesas was measured using an atomic force microscope, and the dimensions of 87 μm (top and bottom were 82 and 92 μm, respectively) $\times$ 400 μm $\times$ 2.8 μm (including Ag and Au layers). Since the underlying superconductor has a thickness of $\sim$3.0 μm, rather thin compared with the typical mesas used for the previous studies, and the rest of base crystal is removed, this method can be regarded as the modified (simplified) stand-alone mesa fabrication method, in which we found that the emission power improves significantly.

The sample was mounted on a copper finger cooled by a ^{4}He flow cryostat (Oxford Instruments, CF1104), and its electrical properties were measured by two terminal method, and the THz radiation was detected by three different detectors: a Si composite bolometer (Infrared Laboratories), an InSb hot electron (HE) bolometer detector (QMC Instruments, QFI/2BI), and a commercial power meter (VDI, Erickson PM4). The former two detectors were used with a chopper modulation technique and a lock-in detection with a frequency of 70 Hz and the pre-amplifier gain of 200 and 1000, respectively, while the latter one detects directly the absolute power. The InSb HE bolometer has been calibrated by black body radiation, and the optical responsivity is known to be 3.3 mV/nW. The radiation spectra between 3 and 300 cm^{-1} were measured by a FT-IR spectrometer (JASCO, FARIS-1) with the resolution of 7.5 GHz.

In Figs. 2(a)–2(c), we present an example of the c-axis I–V characteristics and the radiation power output detected by the InSb hot electron bolometer at 40 K and 55 K for the comparison. For 40 K, the THz emission is observed in the reversible (R-type) region at currents between 31.4 and 55.2 mA and at voltages around 1.8 V, whereas for 55 K, it is observed in the irreversible (IR-type) return branch at lower currents between 11.7 and 25.0 mA and at voltages between 0.28 and 1.64 V, where the maximum radiation power is observed around 1.1 V. It is noted that the radiation power shown in Figs. 2(b) and 2(c) are shifted by 50 mV for the abscissa and the ordinate, respectively. In Fig. 2(d), the spectral intensities obtained at 40 K and at 55 K at the maximum intensities measured by the FTIR spectrometer were compared. Although the center frequencies of both radiation at 40 K and at 55 K are 0.395 THz and 0.438 THz, respectively, both emissions lie in the range of frequency satisfying the cavity resonance condition $f = c_0/n\lambda = c_0/2nw$ where $w = 82$–92 μm. The full width at half maximum of the observed emission line is restricted by the instrumental resolution of 7.5 GHz. It is

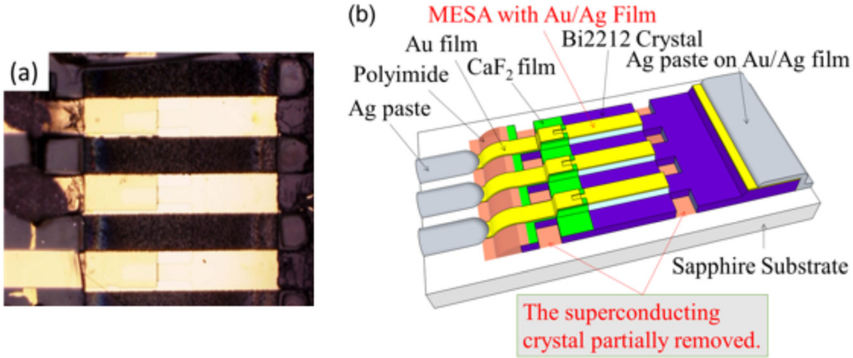

FIG. 1. (a) A photograph of three mesas in an array of five mesas fabricated on a Bi2212 single crystal surface. The mesa located at the center was used for radiation experiment. (b) A stereographic view of the THz emitter fabricated by the modified method on a sapphire substrate. The superconducting base crystal is partially removed.

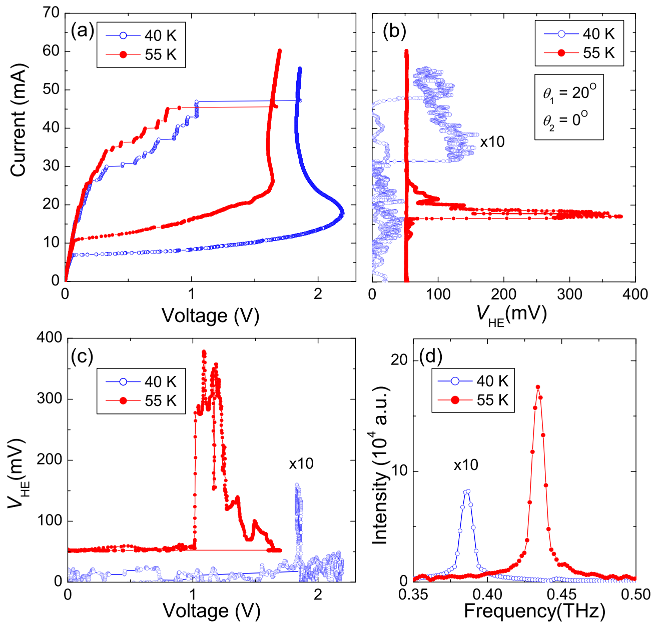

FIG. 2. (a) The current-voltage (I–V) characteristic curves as a function of voltage at 40 K (blue) and 55 K (red). (b) and (c) The radiation power detected by the InSb hot electron bolometer is plotted as a function of the current and as a function of the voltage, respectively, at 40 K (blue) and 55 K (red). Note that the power between 0.28 V and 1.02 V is an order of magnitude smaller than that between 1.02 V and 1.64 V. (d) An example of the power spectra of the radiation from the present modified mesa measured at 40 K and 55 K by a FT-IR spectrometer with the 7.5 GHz resolution. The radiation power shown in (b) and (c) and the spectral intensity shown in (d) measured at 40 K was presented by multiplying a factor of 10.

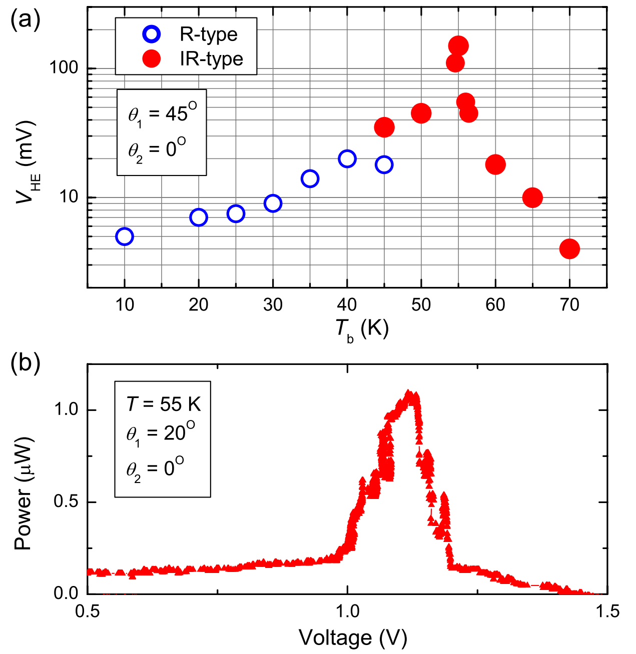

FIG. 3. (a) The temperature dependence of maximum radiation power detected by the InSb hot electron bolometer. A sharp peak indicating a diverging phenomenon of the radiation intensity is observed at 55 K. The radiation shifts a character from reversible (R) type to irreversible (IR) type at 45 K as the temperature is increased. (b) The radiation power as a function of voltage detected by the power meter at 55 K.

remarkable that the spectral intensity at 55 K is much larger (more than 20 times) than the one at 40 K as seen in Fig. 2(d), and the maximum power reached at about 30 μW in total after the correction of directivity of radiation. We found the similar behavior for other two mesas shown in Fig. 1(a). The high power radiation of ~30 μW reported in our previous report[9,10] was also obtained at low current IR retrapping region.

The typical temperature dependence of the emission intensity was shown in Fig. 3(a). It is surprising that the emission intensity has a sharp peak centered around 55 K, then it is rapidly diminishing above 55 K. Here, we note that the similar temperature dependence has been observed in other types of stand-alone mesa.[10] Although the reason for the diverging peak behavior is not understood well at this moment, the logarithmic divergent character suggests strongly a kind of instability in the energy flow process from dc power to THz EM radiation occurring in the coherently coupled intrinsic Josephson junction system. The sharp decrease of the intensity after the peak seems to occur due to the high temperature effect near T_c, which rapidly weakens the synchronization by the Joule heating. We remind here that the cross-over like phenomenon from reversible to irreversible radiation takes place around 45 K, when the temperature is raised. This is clearly shown in Fig. 3(a) by plotting the intensities with blue (reversible region) and red (irreversible region) colors. This cross-over like behavior can be understood as a natural consequence of the temperature shift of the I–V curve with temperature as long as the two conditions for the THz radiation are kept effective. It seems from our empirical observation that the intensity in the irreversible region is rather stronger than the one in the reversible region. This may be related to the fact that the emission in the reversible region occurs with severe Joule heating, forming a hot-spot in the mesa,[27] whereas the emission in the irreversible region takes place without hot-spot, forming rather uniform temperature distribution in the mesa.[28] This casts a serious question concerning the suggested radiation mechanism that the hot-spot or the severe temperature inhomogeneity might help the synchronization.[27–29] The absolute radiation power measured directly by the power meter is shown in Fig. 3(b) as a function of voltage V at 55 K.

In order to estimate the absolute power emitted from the mesa, the angular distribution of the THz radiation intensity is measured in two major directions of the rectangular mesa for the xz-plane (perpendicular) and for the yz-plane (parallel) defined as θ_1 and θ_2, respectively. The results are presented in Figs. 4(b) and 4(c) and the coordinate used here is shown in Fig. 4(a). This angular dependence can be understood rather well by considering the dual source model developed previously.[30,31]

We estimated the total radiation power from the modified mesa prepared here in three different ways using three different detectors as mentioned before. First, using the HE bolometer, as the maximum detected output voltage was $V_{det} = 380$ mV at 55 K, this corresponds to the incident THz radiation power, $P_{det} = 2\sqrt{2}V_{det}/\alpha = 0.33\,\mu$W, where $\alpha = 3.3$ mV/nW is the system optical responsivity calibrated by black body radiation. Taking a value of 0.02 sr for the solid angle of detection and the attenuation factor of the cryostat window made of quartz glass of 0.75, the total power integrated, assuming a spatial distribution of the radiation power as seen in Figs. 4(b) and 4(c), is estimated to be ~30 μW.

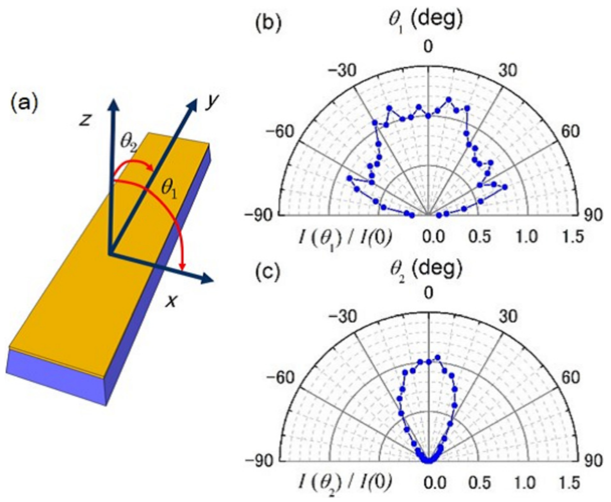

FIG. 4. (a) The coordinate system. (b) Polar plots of the radiation intensity $I(\theta_1)$ normalized at $I(0)$ measured in the *xz*-plane at 55 K. (c) Polar plots of $I(\theta_2)$ normalized at $I(0)$ measured in the *yz*-plane at 55 K.

Similarly, using the Si composite bolometer, the observed maximum intensity from the mesa is about $V_{det} = 280$ mV at $\theta_1 = 20°$ and $\theta_2 = 0°$ at the detecting solid angle of 0.005 sr. This corresponds to the incident power $P_{det} = 2\sqrt{2}V_{det}/\beta = 0.072\,\mu$W, where the system optical responsivity $\beta = 11$ mV/nW, assuming that the attenuation factor inside the Si composite bolometer is 0.25. Taking the radiation angular dependences into account, the resulting total radiation power can be estimated to be $\sim 30\,\mu$W.

Third, as the most reliable method, the power meter was used for the measurement of absolute value of the emission power. The maximum obtained intensity from the mesa was about $P_{det} = 1.1\,\mu$W at $\theta_1 = 20°$ and $\theta_2 = 0°$ with the detecting solid angle of 0.12 sr as shown in Fig. 3(b). Taking the radiation pattern into account, the total power can be estimated to be $\sim 25\ \mu$W. By comparing these three values measured by three different detectors, the agreement is rather good.

We demonstrated significant improvement of the emission power from a single mesa to $\sim 30\,\mu$W using the modified fabrication method. This method is not only much easier in the fabrication processes but also provides an excellent heat transfer from mesa to thermal bath. This can be achieved by removing superconducting material underneath the mesa as much as possible. The mesa without superconducting material, *i.e.*, the stand alone mesa, would be ideal. Because of this improvement of thermal management, the temperature range where the THz emission is observable expanded from ~ 50 K in the conventional mesas to ~ 70 K, which is close to T_c. In such a condition, it is observed that the radiation power shows a diverging behavior, just below T_c. It is very curious to mention that the intensity of the THz radiation increases rapidly with increasing temperature up to 55 K, not other way around. The reason for this is not understood yet, but it is rather convincing that hot spot does not play any essential roles for the large power emission or instability, because at 55 K there is no hot spot and the temperature of the mesa become more or less uniform temperature.[28] We remind that the hot spot is generated because $\rho_c(T)$ has a very steep negative temperature coefficient with decreasing temperature.[32,33] This experimental result may leads an interesting consequence that in order to make the stronger emission more homogeneous temperature may be required contradicting the previous thought.[27,29]

In summary, we have demonstrated high power THz emission of $\sim 30\,\mu$W by using a modified fabrication method of the mesa for the THz emitter in such a way that a underlying superconducting Bi2212 single crystal is very thin and is also partially removed. The detailed fabrication technique of such a mesa was given. We also showed the diverging behavior of the THz radiation intensity at ~ 55 K, above which it rapidly diminishes. This experimental fact strongly suggests a possible new dynamical phase instability in the synchronized intrinsic Josephson junction systems.

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