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Simultaneous Observation of Three Types of Terahertz Radiation from Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ Intrinsic Josephson Junctions

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Abstract. Terahertz radiation from mesa structures of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ is detected at various bias points with a Si-bolometer. These radiations are classified into these types: W observed at a current close to the critical current, R and IR observed reversibly and irreversibly, respectively. The type W is the most intense among the three and the radiating condition is complicated. Temperature dependence of radiation voltage of the type R and IR is much more significant than ever seen.

1. Introduction
There are much less prevailing light sources than in two general paradigms for generating electromagnetic waves below and above the terahertz gap[1]. Powerful and compact solid-state terahertz sources have been desired for a long time. Bismuth based high temperature superconductors have been expected as materials potentially used for THz sources because the superconducting energy gap is sufficiently large and intrinsic Josephson junction (IJJ) involved in its crystal structure is suitable for intense electromagnetic radiation through a synchronization of huge number of stacked IJJs[2][3]. Recently, coherent and continuous THz waves from a rectangular mesa formed on the surface of a single crystal of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) was observed by Ozyuzer et al.[4][5]. Since then, many experimental and theoretical efforts have been made in order to reveal the mechanism of the radiation[6]-[14]. So far, it is considered that the radiation is described as a cavity resonance inside the mesa structures: spatially varying phase differences of stacked IJJs synchronized along the c-axis yield alternating electric field at the edge of the mesa[15]. However, the mechanism of the synchronization remains unclear because of lack of systematic experimental results with carefully controlled junction parameters.

In this paper, we report observations of three types of terahertz emissions from one mesa in a current-voltage cycle. The most intensive, which is referred as type W here, is found at a current wandering above the critical current from scan to scan. The other two are identical to type IR and R reported previously[4][5]. We report the experimental results of the W radiation in detail. Furthermore, we refer to the temperature dependency of the resonance voltage. The applied voltage to the mesa at a radiation implies an excitation of not a half-wavelength mode usually observed but a one-wavelength mode.
2. Experiments
Three devices used in this study were prepared by following procedure. A Bi2212 single crystal grown by the TSFZ method was annealed at 650 °C for 75 hours in Ar atmosphere to reduce the oxygen concentration. In order to decrease contact resistance between an electrode and a crystal, the single crystal was cleaved in a vacuum and a 30 nm Ag layer was immediately evaporated on the surface cleaved in a vacuum. The mesa structures were fabricated by photolithography and Ar ion milling and the size of the mesa was 80 × 400 × 1.1 μm³. Since the thickness of an IJJ is 1.5 nm, the mesa includes N = 730 IJJs. After forming the mesas, Stycast 1266 epoxy was applied to an edge of the mesas for insulation. Afterward, additive upper Ag electrodes with thickness of 30 nm were formed by thermal evaporation and Ar milling methods in order to extend the electrodes on the mesa to the outside of the crystal. The width of the electrodes on the mesa is 30 μm and the electrodes were positioned at the center of the mesa, as one of the used samples is shown in Fig. 1.

![Figure 1](image_url). The optical image of the rectangular mesas fabricated on the Bi2212 single crystal. Ag electrodes with a width of 30 μm were formed on the mesas and the total thickness of the electrodes was 60 nm.

The device is mounted on the stage of Oxford CF1204 He flow cryostat. A mesa connected in series to a 10 Ω resistor is biased by triangularly oscillating voltage with a period of ∼ 1 mHz. The THz waves emitted from the mesa are chopped with a frequency of 40 Hz and detected by a Si-bolometer with a 1 THz low-pass filter. The output signal of the bolometer is amplified by high-pass preamplifier and a lock-in amplifier, and recorded on a computer.

3. Results
3.1. Radiation above critical current
I-V characteristics and radiation power of sample #1 at 25 K is shown in Fig. 2. Color of plots represents I-V cycle: detector response represented by different color was obtained at another scan. As seen in Fig. 2, a radiation accompanied with a jump between branches is found in the retrapping region, and a radiation at which the I-V curve is continuous and reversible is found in negative dI/dV region of the I-V curve. These two radiations have similar features as those previously reported, so called as type IR and R for the former and the latter. We found another type of radiations, at currents higher than those of IR and R radiations. For some occasions, the radiations are even higher than the critical current \( I_c \approx 20 \) mA. The third type emerges from time to time at different current and voltage with a certain range (10 < I < 25 mA). This is in contrast to the type IR and R, where the radiations are observed at specific current and voltage points for every I-V cycle. Thus we refer to the type of radiations as type W (wandering). The W radiation is excited even with increasing bias voltage and multiple emission points are found in an I-V cycle at 20 K. With increasing temperature, excitation of the type W becomes less frequent, meaning that the type W is found once for several cycles, whereas the type IR and R always appear at certain voltage ranges. The type W was not observed in mesa #2 and #3, in which the other types were reproducibly found.
These experiments suggest that the type W would rely on a delicate disequilibrium state of the temperature distribution of the mesa. In low temperature, where thermal conductivity of the HTSC is low, temperature inhomogeneity due to current injection through the electrode is significant\cite{16}. Assuming that the difference between \#1 and the others is the position of an electrode and insulation against the mesa volume, which affects heat-escape-paths of the devices, the difference of the temperature distribution would be severe. Now we consider that the type W would have different origin from the type R and IR.

![Figure 2](image-url)

**Figure 2.** The $I$-$V$ characteristics (a) of sample \#1 at 25 K, the current dependency of the radiation power detected by Si-bolometer (b), and the voltage dependency (c). Black and red lines indicate different scan cycles. The radiations different from the type IR and R were observed at higher currents in the reversible region.

3.2. Temperature dependency of resonance voltage
The R and IR radiations found in \#2 and \#3 show quite strong temperature dependence between 20 and 50 K. In \#3, both R and IR radiations are found at $V_r = 0.8$ V, at which the bias voltage for an individual IJJ is approximately $V = V/N = 1.1$ mV. According to the ac Josephson relation $2e\nu = h\nu$, excited frequency is estimated as $\nu = 0.53$ THz. This is slightly larger than a reported value in a mesa with the same width\cite{4}\cite{6}. With increasing temperature, the radiation voltage $V_r$ linearly decreases to 0.4 V and the radiation is not observed below 0.4 V. Behavior of $V_r$ in \#2 is more peculiar. At 20 K, radiations are found at $V_r = 1.3$ V, which gives $\nu = 0.86$ THz with the same procedure as above. The frequency is closer to the value of the one-wavelength cavity mode of the mesa than the half-wavelength mode usually observed in this field. With increasing temperature, $V_r$ of the R and IR radiation decreases linearly and the radiation is not found below 0.4 V as well as in \#3. The decrease rate of $V_r$ is considerably higher in the type IR, resulting that the IR radiation disappears at higher temperature than the R radiation. Here, we found that $V_r$ decreases more than 30 % and 60 % for \#3 and \#2, respectively. Wang et al. reported that radiation frequency decreases from 0.65 to 0.45 THz with increasing temperature from 10 to 60 K\cite{9}. Assuming the change in $V_r$ directly means change in radiation frequency, their argument to explain the decrease of the radiation frequency in the context of the hot spot scenario may be invalid. So far, we do not have clear suggestion to explain these two peculiarities; one is the strong temperature dependence of $V_r$ and the other is the lower threshold voltage of 0.4 V. Further research will uncover links between these phenomena and the mechanism of the terahertz radiation.

4. Conclusions
We observed another THz radiation referred as type W from a rectangular mesa in addition to the two types of radiations which have reported previously. The behavior of the W radiation is
Figure 3. The temperature dependency of the instantaneous voltage at the peak of the radiation power. The samples #2 and #3 were fabricated on the same crystal but their properties are quite different.

unlike that of the others and the radiating condition for the type W is very severe. Since the appearance of the type W depends on $I-V$ history, we consider that the radiating condition is greatly influenced by the heat generated in the mesa and the temperature inhomogeneity is a key component of terahertz radiations. Moreover, we found quite strong temperature dependency of R and IR radiations to the radiation voltage $V_r$. The fact that $V_r$ varies dramatically with respect to the variation of bath temperature means that the radiating frequency is possibly regulated broadly by changing the bath temperature. The phenomena we observed in this work have peculiar features as above, additive measurements will figure out the whole picture of terahertz emission from IJJs.

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