Local heating effects on the radiation intensity of high-$T_c$ superconducting terahertz emitters

K Nakamura$^1$, H Minami$^{1,2}$, R Ota$^1$, K Murayama$^1$, Y Ono$^1$, S Kusunose$^1$
T Kashiwagi$^{1,2}$, M Tsujimoto$^{1,2}$ and K Kadowaki$^{2,3}$

$^1$ Graduate School of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Ten-nodai, Tsukuba, Ibaraki 305-8571, Japan
$^2$ Division of Materials Science, University of Tsukuba, 1-1-1 Ten-nodai, Tsukuba, Ibaraki 305-8573, Japan
$^3$ Algae Biomass and Energy System (ABES) Research and Development Center, University of Tsukuba, 1-1-1, Tennodai, Tsukuba Ibaraki 305-8572, Japan

E-mail: minami@bk.tsukuba.ac.jp

Abstract. The terahertz electromagnetic waves can be generated by the mesa device made of a piece of high-$T_c$ superconductor Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ single crystal, which is known to be comprised of multi-stacks of intrinsic Josephson junctions. In the case of a thick mesa containing the large number of junctions, large amount of Joule heat is generated, resulting in the formation of the inhomogeneous temperature distribution $T(r)$ in the mesa. It is known from previous studies that $T(r)$ strongly affects the emission intensity and line width. When the mesa is irradiated partly by a focused laser beam, the terahertz radiation intensity grows almost two times as compared with the standard biases without laser irradiation as was found previously. It is also found that the enhanced emission remains without losing the intensity even after switching off the laser power. This result suggests that the normal current distribution in the mesa is modified irreversibly when the device is biased under laser irradiation, according to the thermoreflectance measurement.

1. Introduction

Recently, terahertz (THz) electromagnetic waves have attracted much attention because of various potential applications such as molecular level spectroscopic identification, inspection of products, pharmaceutical studies, medicine, etc. [1]. However, the research field has not been progressed much because of the lack of high performance THz emitters and detectors so far available. Coherent and continuous THz emission has been discovered from the mesa device made of high transition temperature $T_c$ superconductor Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ (Bi2212) single crystal comprised of multi-stacks of intrinsic Josephson junctions (IJJs) [2-4]. The IJJs consist of the atomic thin insulating Bi$_2$O$_2$ layers sandwiched by superconducting CuO$_2$ double layers stacking along the $c$-axis direction. The device has attracted much attention to be as the new type of THz emitters because the emission mechanism is completely different from the conventional ones.

The THz emission from the following two conditions are fulfilled. One is the ac-Josephson effect expressed as $f = (2e/h) (V/N)$, where $f$ is the radiation frequency, $e$ the elementary charge, $h$ the Planck’s constant, $V$ the voltage applied to the mesa and $N$ the total number of the IJJ stacking in the mesa [5]. Another is the cavity resonance condition expressed as $f = c / n λ = c / 2 n w$, where $c$ is the
speed of light in vacuum, $n$ is the refractive index of Bi2212, $\lambda$ is the wavelength and $w$ is the width of the mesa [2]. The power of THz emission from IJJs mesa is at present of $\sim 30 \mu W$ at its best [6], which is not sufficient to the practically required power of $\sim 1$ mW. Stronger emission power has been desired for various applications.

An idea to generate stronger emission power is to increase the number of Josephson junctions using thicker mesas because the emission power $P \propto N^2$. However, a thicker mesa containing the larger number of junctions produces larger amount of Joule heat, so that the temperature of the mesa in the lateral direction of the Josephson junctions increases inhomogeneously. At high bias currents, the heated area abruptly shrinks and simultaneously the normal currents concentrate in there, which is known as the formation of a hot-spot in which the temperature is extremely increased to even higher than $T_c$ [7-10]. That shows that this system has an instability on the normal current flow. Dynamic fluctuation due to the instability may impede the development of the in-plane phase synchronization in the mesa. Actually, the emission line width is known to be strongly changed by the bias current, especially it is strikingly improved after the hot-spot was formed [11]. The emission intensity and frequency have also been observed to be affected by the formation of the hot-spot and also the size and position as well [12]. According to the computer simulation that the hot-spot position can be easily changed by the local heating, they have shown that artificial local heating by a focused laser beam makes the emission power almost double of the largest one in the standard bias process without laser beam [13].

In a theoretical model, the intense THz emission is expected from IJJs by using an external local-heating source [14]. The THz emission is investigated there by solving the sine-Gordon, Maxwell, and thermal diffusion equations simultaneously, when the top electrode of the mesa is heated locally by the external heat source. It is interesting to point out that the local temperature increase by laser heating to just below $T_c$ is more effective for high-power emission.

In the present study, we have investigated the effect of local heating on the emission intensity by using a focused laser beam and measuring temperature distribution of the mesa using a thermoreflectance microscopy observation [15]. From these results, a clue to produce higher power emission can be found.

2. Experimental details

2.1. Fabrication of Bi2212 mesa devices

High-quality single crystals of Bi2212 were grown by a traveling solvent floating zone method [16]. Rectangular mesas were fabricated on a thin Bi2212 crystal as follows. A piece of Bi2212 single crystal was cleaved to several $\mu$m thick, deposited immediately by thin Ag and Au (~20 nm and ~10 nm, respectively) on the surface, and glued on a alumina substrate by thin polyimide. Then, mesas were fabricated by Ar ion milling technique using metal masks twice to determine the width and the length. The second milling reached down to the alumina substrate and some parts of crystal were milled out completely, as shown in figure 1 (a) and it is illustrated in figure 1 (b). In order to attach a current lead to the top of the mesa, polyimide and CaF$_2$ were first deposited to avoid current leakage, and then thin Ag and Au films were deposited as current leads. Figure 1 (a) shows a photograph of the mesa devices. One of the mesas is highlighted by the yellow rectangle. The stereographic view of the fabricated mesa devices is given in figure 1 (b) to show the details as described above. The dimensions of the mesa are 80 $\mu$m in width, 400 $\mu$m in length and 3.0 $\mu$m in thickness, and a thickness of the underlying superconductor is less than 3.0 $\mu$m.

2.2. Experimental setup

A schematic view of the experimental setup is shown in figure 1 (c). We used a red color laser beam with the wave length of 660 nm and with a maximum power of 80 mW. The laser spot can be focused in a circular form with a diameter of 30 $\mu$m on the sample surface by using a beam expander and a focusing lens. The sample was mounted on a Cu cold finger cooled by a He flow cryostat (Oxford Instruments, CF1104). THz radiation was detected by a modulation technique using an InSb hot-electron
bolometer and a lock-in amplifier. In addition, the temperature distribution of the surface of the mesa device was measured by thermoreflectance microscopy (TRM) [15]. This thermography technique is based on the experimental fact that the relative change of the reflectance at the device surface takes place with the temperature. Weak green light was irradiated on the whole surface of the device, and the reflected light was detected by a 12-bit CCD camera. The TRM image is presented as \( \Delta I / I_0 \) that indicates the change in reflectance from zero bias, where \( I_0 \) is the intensity of the green component in the RGB image data at zero bias and \( \Delta I \) is the difference of that between at biased and zero bias conditions on the \( I-V \) characteristics. In order to improve the image quality, the obtained images were averaged 100 times by a computer. Although the TRM image does not tell directly the temperature distribution at the mesa surface, it provides qualitative but useful information of relative change of the surface temperature. The microscope and the camera were also used to observe the position where the laser beam was irradiated.

3. Results and discussion
The current-voltage (\( I-V \)) characteristics, emission intensity, and TRM measurements were all performed by continuously sweeping up and down the bias points, while keeping the power of the laser beam to the irradiation position. The laser beam was moved at nine different positions on a mesa. When the laser beam was located at some corners or at the center of a mesa for example, we did not observe significant enhancement of the emission intensity. Only when the laser beam is irradiated at a position indicated by a red dot in figure 2 (a), significant enhancement of the radiation intensity was observed. It is a corner opposite to the current injection point in the mesa. This is in contradiction to the previous result in which the enhancement of emission was observed when it was irradiated near the current injection point [13]. The reason of the contradiction is not clear at this moment.
Figure 2. (a) A red dot indicates a position where a laser beam of the diameter of 30 μm was irradiated. (b) The I-V characteristics and the emission intensity as a function of the applied voltage at $T_b=40$ K when the mesa is biased with (red) and without (purple) laser irradiation at the red dot position shown in (a). (c) The maximum emission intensity as a function of $T_b$. The mesa is biased with (filled circles) and without (open circles) laser irradiation. (d) The TRM images of the mesa surface at $T_b=40$ K and $V=2.9$ V. The surface temperature is high at the position where the reflectance decreases.

Figure 2 (b) shows the I-V characteristics and the emission intensity as a function of the applied voltage at bath temperature $T_b=40$ K, when the mesa is biased with (red) and without (purple) laser irradiation of the power of 80 mW focused at the red dot position in figure 2 (a). As the laser is irradiated on the Ag/Au film, only a few percent of the laser power must be absorbed [8]. Although no significant difference was observed in the I-V characteristics, the emission intensity observed is increased more than three times under laser irradiation. Interestingly, at $T_b=35$ K and 40 K, the enhanced emission is observed without losing the intensity even after the laser is switched off at the fixed bias point where the emission intensity is at its maximum. In contrast to this phenomenon, in the case that the mesa is irradiated at the same bias point after biasing without irradiation, the enhancement was not observed in the intensity.

Figure 2 (c) shows the $T_b$ dependence of the maximum emission intensity, where the mesa is biased with (filled circles) and without (open circles) laser irradiation at the power of 80 mW located at the red dot position in figure 2 (a). It is clear that at $T_b=35$ K, 40 K and 45 K, the emission intensity is enhanced with laser irradiation.

Figure 2 (d) shows the TRM images of the mesa when the mesa is biased at $V=2.9$ V at $T_b=40$ K. The hot-spot is clearly observed at the position slightly left from the center of the mesa. This may be due to Joule heat produced by the contact resistance at the current injection point. In the lower image, the mesa was biased while irradiating a laser beam at the red dot position in figure 2 (a), whereas it was
biased without irradiation in the upper image. Each image shows the change of the reflected light intensity from zero bias current. Therefore, the heating by the laser beam itself should not be included in the lower image. A hot spot appeared at the laser irradiation point is thus due to the concentration of the normal current flow guided by local heating. Actually, the temperature slightly decreases at other parts because of the decrease of normal currents. That may be a reason why the emission is enhanced with irradiation. In the previous experiment, we have demonstrated that the position of a hot-spot can be reversibly controlled by local heating using a laser beam [13]. In the present case, however, the hot spot remains at the source position even after switching off the laser, so the emission also remain without losing the intensity.

In summary, we have observed that the emission intensity from the high-\textit{T}\textsubscript{c} superconducting terahertz emitting device is enhanced by local heating with a laser beam irradiation. The emission intensity reaches up to twice as large as the largest one obtained without laser irradiation, similar to the previous research. However, the enhanced emission is observed to remain without losing the intensity even after the laser power is switched off. This result suggests that the distribution of the normal current strongly influences the emission intensity. We have reconfirmed that the terahertz emitting phenomenon of this device is deeply related to the temperature distribution, \textit{i.e.}, normal current flow in the mesa.

\textbf{Acknowledgments}

This work was supported by JSPS KAKENHI Grant Number 15K04688 and 15H01996, and University of Tsukuba Basic Research Support Program Type B.

\textbf{References}

[1] Tonouchi M 2007 \textit{Nature Photon.} 1 97
[2] Ozyuzer L, Koshelev A E, Kurter C, Gopalsami N, Li Q, Tachiki M, Kadowaki K, Yamamoto T, Minami H, Yamaguchi H, Tachiki T, Gray K E, Kwok W-K and Welp U 2007 \textit{Science} 318 1291
[3] Welp U, Kadowaki K and Kleiner R 2013 \textit{Nature Photon.} 7 702
[4] Kadowaki K, Yamaguchi H, Kawamata K, Yamamoto T, Minami H, Kakeya I, Welp U, Ozyuzer L, Koshelev A, Kurter C, Gray K E and Kwok W-K 2008 \textit{Physica C} 468 634
[5] Josephson B D 1962 \textit{Phys. Lett.} 1 251
[6] Sekimoto S, Watanabe C, Minami H, Yamamoto T, Kashiwagi T, Klemm R A and Kadowaki K 2013 \textit{Appl. Phys. Lett.} 103 182601
[7] Skocpol W J, Beasley M R and Tinkham M 1974 \textit{J. Appl. Phys.} 45 4054
[8] Wang H B, Guénon S, Gross B, Yuan J, Jiang Z G, Zhong Y Y, Grünzweig M, Ishii A, Wu P H, Hatano T, Koelle D and Kleiner R 2010 \textit{Phys. Rev. Lett.} 105 057002
[9] Benseman T M, Koshelev A E, Vlasko-Vlasov V, Hao Y, Kwok W-K, Welp U, Keiser C, Gross B, Lange M, Kölle D, Kleiner R, Minami H, Watanabe C and Kadowaki K 2015 \textit{Phys. Rev. Appl.} 3 044017
[10] Minami H, Watanabe C, Sato K, Sekimoto S, Yamamoto T, Kashiwagi T, Klemm R A and Kadowaki K 2014 \textit{Phys. Rev. B} 89 054503
[11] Li M, Yuan J, Kinev N, Li J, Gross B, Guénon S, Ishii A, Hirata K, Hatano T, Koelle D, Kleiner R, Koshelets V P, Wang H and Wu P 2012 \textit{Phys. Rev. B} 86 060505(R)
[12] Watanabe C, Minami H, Yamamoto T, Kashiwagi T, Klemm R A and Kadowaki K 2014 \textit{J. Phys.: Condens. Matter} 26 172201
[13] Watanabe C, Minami H, Kitamura T, Asanuma K, Nakade K, Yasui T, Saiwai Y, Shibano Y, Yamamoto T, Kashiwagi T, Klemm R A and Kadowaki K 2015 \textit{Appl. Phys. Lett.} 106 042603
[14] Asai H and Kawabata S 2014 \textit{Appl. Phys. Lett.} 104 112601
[15] Kashiwagi T, Tanaka T, Watanabe C, Kubo H, Komori Y, Yuasa T, Tanabe Y, Ota R, Kuwano G, Nakamura K, Tsujimoto M, Minami H, Yamamoto T, Klemm R A and Kadowaki K 2017 \textit{J. Appl. Phys.} 122 233902
[16] Mochiku T and Kadowaki K 1994 \textit{Physica C} 235 523