Futurum
Tsukuba Science Journal

Superconductor, Josephson junction, hot spot

The study of High-T_c superconducting THz emitting devices and its heating effect

Chiharu Watanabe[1], Hidetoshi Minami[1], Hiroyuki Kubo[1], Kazuki Sakamoto[1], Takuya Katsuragawa[1], Yuki Komori[1], Yuasa Takumi[1], Taiga Tanaka[1], Takanari Kashiwagi[1], Richard A. Klemm[2] and Kazuo Kadowaki[1]

[1]Graduate School of Pure & Applied Sciences, University of Tsukuba, 1-1-1 Ten-nodai, Tsukuba, Ibaraki 305-8571, Japan
[2]Department of Physics, University of Central Florida, Orlando, Florida 32816-2385, USA

ABSTRACT

We have measured simultaneously the spectrum of the electromagnetic wave emitted from and the local temperature of $Bi_2Sr_2CaCu_2O_{8+\delta}$ rectangular mesa devices using a characteristic temperature dependent photo-luminescence (PL) intensity of SiC micro-powders, which is embrocated on the mesa surface. We succeeded in observing clear images of a hot spot where the local temperature becomes higher than T_c. Furthermore, the emission intensity was found to improve drastically, when the hot spot was dragged by the local heating of the mesa surface with a laser beam without significant changes of the emission frequency and the line width. These results strongly suggest that the higher power radiation may be attainable by adjusting the hot spot.

Keywords: Superconductor, Josephson junction, hot spot

Introduction

The electromagnetic waves (EMWs) ranging between that of visible light and micro waves are discerned as THz waves. Especially the frequency range centered at about 1 THz are known as the ‘THz gap’, where there is no available emitters as well as detectors due to the technical difficulties in producing high-power, compact, continuous-wave coherent radiation sources [1]. Filling this THz gap is important because it is the technological challenges using modern semiconducting technology. Among them, so far a resonance tunneling diode [2] and a quantum cascade laser [3] are most promising. Although there two techniques provide monochromatic emission spectra at a fixed frequency, there may be another technique to generate a wide band spectrum in the THz frequency region using an extremely short pulse current (≤ ps) in the time domain spectroscopy technique. This method has a great advantage to variety of potential applications that are related to the study of bio-materials [4], pharmaceuticals [5], and the diagnoses of diseases at the molecular level, *etc.* Therefore, developing sources in the THz frequency range have recently been pushed forward.

In 2007, sub-THz emissions were discovered from mesa structures fabricated from single crystals of the high-transition-temperature T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212). Because the radiation is stable, coherent, continuous and strong, Bi2212 THz emitting device opened up new research opportunities and created the possibility of new devices emitting in this THz gap range [6]. Because Bi2212 crystals are comprised of many equivalent intrinsic Josephson junctions (IJJs) naturally stacked along the *c*-axis direction [7], it is not necessary to fabricate Josephson junctions artificially as previously done by making 2D array network systems of Josephson junctions fabricated using low-T_c superconductor [8]. By further detailed spectroscopic studies it was found that the emission frequency f follows the ac-Josephson relation; f is proportional to biased voltage [6, 9] $f = 2ev/h$, where V is the supplied voltage between the two electrode terminals in the Josephson junction, e is the elementary charge and h is Plank constant. Additionally, it was found that the mesa acts as an electromagnetic cavity similar to the patch antenna. It was also found that the emission intensity is strongly enhanced at specific f values determined by the geometry and dimensions of the mesa structure [6, 10]. For examples, a rectangular mesa structure has a fundamental resonance f_r being proportional to the half of the mesa width $f_r = c_0/2nw$, where n is the refractive index of Bi2212 material, c_0 the velocity of the light, w the width of the mesa [6].

Although the emission intensity of this radiation so far is about several 10 μW [11], it may not be sufficient for many applications [4, 5]. Therefore, drastic improvement of the emission intensity is demanded for application uses. Since the emission intensity is proportional to the squared of number of Josephson junctions: N^2, increasing N (making thicker mesa) could, in principle, be most simple way to enhance emission intensity greatly. However, the Joule heating also becomes larger in the thicker mesas while THz radiation operation. This heating effect has been a very serious problem for high power THz emission. Actually, stronger and broader band THz radiation were observed from the stand alone mesa [12] and the sandwich structure using a stand-alone mesa [13] both of which have less Joule heating than that of conventional mesa structure with Bi2212 substrate [6]. Meanwhile it was found that the local heated region in a mesa, where the local mesa temperature T(r) is higher than the critical temperature T_c arises locally. This is called as `hot-spot' [14]. According to the numerical simulation done by A. Yurgens, it is found that such severe local heating was predicted [15]. Actually, the group of H. B. Wang observed it by Low Temperature Scanning Laser Microscopy (LTSLM) measurements [16]. Although the device temperature can not be observed directly by the LTSLM method, it measures the change in the *c*-axis voltage drop resulting from the temperature modulation created by the laser beam focused on the surface of the mesa. It is worried about the temperature rising by the irradiation of the laser beam. In addition, LTSLM method can not measure the emission characters directly. Therefore, a completely different measurement technique has been needed for the local temperature distribution in rectangular mesas is developed here.

There have been another method to measure the local temperature of a superconductor. It is a photo-luminescent (PL) technique developed by group of Univ. of Oslo who has measured the local temperature of Bi2212 film as an indicator by detecting the PL emission intensity from Eu complex compound imbedded in the coated film on the surface of the sample. Since the absorption peak of the Eu complex compound exists in the range of 360–500 nm in the wave length. The intensity of the luminescence after UV light excitation can be detected by the indicator [17]. Using such a technique, the clear image of a hot-spot was observed with high spatial and temperature resolution. The similar technique has been used for detector of the hot-spot in the mesa device [18].

More recently, we succeeded in observing the mesa temperature using the SiC photoluminescence intensity of the coated SiC microcrystals while the simultaneous spectroscopical investigations of the THz radiation were measured from the Bi2212 devices. The SiC powders with micro size emit sufficiently strong temperature dependent PL light below 150 K by irradiated by UV-light. The advantages to use SiC are as follows: firstly, it has chemical stability and reproducibility so that we can use it many times down to liquid He temperatures. Secondly, it is easy to make on the device surface by coating SiC micro-powder solution dissolved into water on the sample surface homogeneously, then drying it. Thirdly, most importantly, the emission intensity shows strong temperature dependence between 0 and 140~150 K so that after the intensity *vs*. temperature calibration, it can be used as a sensitive thermos meter below 150 K within accuracy of ∓5 K. By this measurement technique we found clearly that a hot spot forms in the higher current I bias region of the I–V characteristics (*IV*Cs), where the temperature at a hot-spot exceeds T_c of Bi2212 single crystals [19, 20]. Furthermore, we observed that sudden jumps of the position of the hot spot often occur with small current change. It is also noted that such a sudden jump seems to cause the strong changes in the emission intensity. These observations strongly suggest that the THz emission intensity from the mesa may be sensitive to the hot-spot position, and therefore may have a potential to be enhanced by adjusting hot-spot position.

The similar behavior (improvement of the emission intensity by changing the heating condition) was also found in the numerical simulations of local heating effects on Bi2212 mesas by H. Asai and others [21]. In their simulation, the THz emission intensity from a mesa device was investigated under heated condition of the device locally and the heating position was varied. Interestingly, enough they found that when the edge of a mesa was heated locally and the emission intensity was drastically improved. The temperature distribution shows a large asymmetric behavior against the center position of a mesa.

Since we found a possibility of an improvement of emission intensity by adjusting heating condition not only theoretically but also experimentally, we tried to control the heating condition by the focused laser beam.

Here, we used the blue laser to heat a mesa and at the same time we recorded the PL emission intensity by the comercial CCD camera and measure the emission spectra by the FTIR spectro-meter.

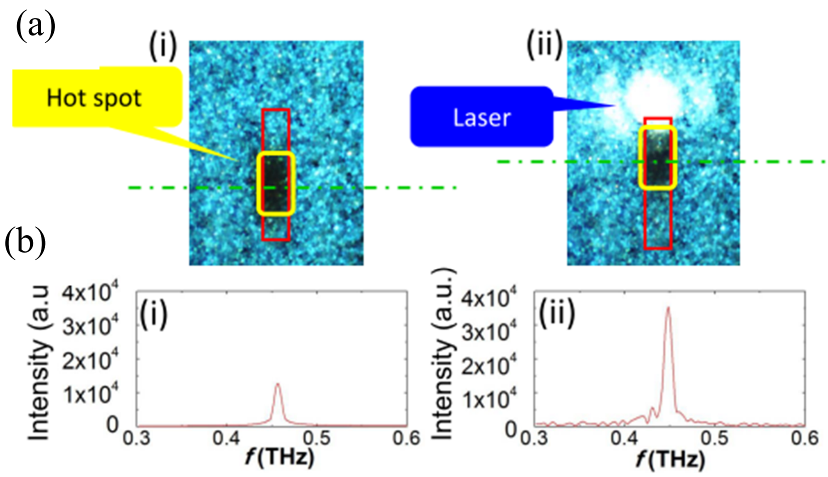

Fig. 1. (a) Photos of the PL emission intensity distribution from SiC micro-powders observed at 25 K. Hot spot (dark area) is indicated by yellow rectangles. When the laser beam is turned off, the hot spot is located at the center position of the mesa (i). On the other hand, the hot spot moves toward the heated region when the mesa is heated by the focused laser beam (ii). (b) (i) and (ii) indicate the emission spectra with and without LASER beam, respectively. Panels (i) and (ii) have a one-to-one correspondence with panels (i) and (ii) in Fig. 1(a). The emission intensity is drastically improved by adjusting the heating condition.

Panels (i) and (ii) show the photos of PL emission observed from the rectangular mesa as an example. The red solid rectangles represent the position of the mesa (80 μm x 400 μm x 2.4 μm) in Fig. 1(a). Since the PL emission intensity from the SiC powder decreases strongly with increasing temperature, the hot spot is observed in Fig. 1(a) as the dark regions indicated by the yellow rectangles. The green dashhed lines represent the central position of the hot-spot. When the external laser beam is switched off, the hot-spot is located at the almost center position as shown in panel (i) in Fig. 1(a). On the other hand, as soon as the laser beam is switched on and is focused on the top edge of the mesa (white bright area) in panel (ii) of Fig. 1(a), the position of the hot-spot changes sensitively and has moved slightly up toward the laser beam. Astonishnigly, the remarkable feature observed here is that the THz radiation intensity increased several times by simply adjusting the hot-spot positions by additional external LASER beam. This is seen in the spectral intensity data shown in Fig. 1(b), for which panels (i) and (ii) have a one-to-one correspondence with panels (i) and (ii) in Fig. 1(a). It is clear that the emission intensity of panel (ii) is much higher than that of (i) as seen in Fig. 1(b): The emission intensity seems to become larger when the edge of the mesa is heated. This behavior is consistent with the numerical simulation [21]. Although it is not clear why the emission intensity becomes larger when the edge of the mesa was heated, one may guess that the area of the superconducting region(s) influences the emission intensity. The maximum emission intensity was observed when the hot-spot position is nearest to the top of the mesa as pictured in panel (ii) of Fig. 1(b) [22].

Conclusions

In conclusion, we reported simultaneous experimental observations of the inhomogeneous temperature distribution (hot-spot) by the SiC micro-powders method, which has been developed newly in our Lab. and the emission spectra by FTIR spectroscopy under controlling the heating condition using the focused laser beam. Astonishingly, when the mesa was heated at the edge, the emission intensity is drastically improved by LASER beam. Although the mechanism of the enhancement of the THz emission is still not well understood and the continuous study is needed to fully understand it, it is evident that the area and location of the normal part of the mesa plays very important roles for the high power emission.

Acknowledgments

This work was supported by the Japan Society for the Promotion of Science (JSPS) through the respective KAKENHI (Grant-in-Aid Numbers 15H01996 and 15K04688) for Scientific Research (A) and (C). C Watanabe is a JSPS Fellow supported for young scientists from the Japan Society for the promotion of Science (Grant-in-Aid Number 263097).

References

1. M. Tonouchi, Nat. Photon. **1**, 97 (2007).
2. S. Suzuki *et al.*, Appl. Phys. Lett. **97**, 242102 (2010)
3. M. L. Silva *et al.*, Appl. Phys. B **81**, 705–710 (2005).
4. T. R. Globus *et al.*, J. Biol. Phys. **29**, 89 – 100 (2003).
5. B. M. Fischer, M. Walther and P. Jepsen, Phys.
6. L. Ozyuzer *et al.*, Science **318** 1291(2007).
7. R. Kleiner *et al.*, Phys. Rev. Lett. **68**, 2394 (1992).
8. P. Barbara *et al.*, Phys. Rev. Lett. **82**, 1963 (1999).
9. C. Watanabe *et al.*, Supercond. Sci. Tech. **29**, 065022 (2016).
10. M. Tsujimoto *et al.*, Phys. Rev. Lett. **105**, 037005 (2010).
11. S. Sekimoto *et al.*, Appl. Phys. Lett. **103**, 182601 (2013).
12. T. Kitamura *et al.*, Appl. Phys. Lett. **105**, 202603 (2014).
13. T. Kashiwagi *et al.*, Appl. Phys. Lett. 107, 082601 (2015).
14. A. Gurevich and R. G. Mints, Rev. Mod. Phys. **59**, 941 (1987).
15. A. Yurgens, Phys. Rev. B **83**, 184501 (2011).
16. H. B. Wang, *et al.*, Phys. Rev. Lett. **102**, 017006 (2009).
17. Niratisairak
18. T. M. Benseman *et al.*, J. Appl. Phys. **113**, 133902 (2013).
19. H. Minami *et al.*, Phys. Rev. B **89**, 054503 (2014).
20. C. Watanabe *et al.*, J. Phys.: Condens. Matter **26**, 172201 (2014).
21. H. Asai and S. Kawabata, Appl. Phys. Lett. **104**, 112601 (2014).
22. C. Watanabe *et al.*, Appl. Phys. Lett. **106** , 042603 (2015).

Received: 25 December, 2016.
Accepted: 26 December, 2016.

*E-mail: s-chiharu@ims.tsukuba.ac.jp (C. Watanabe)