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Datum: 30.09.2024.

UNIVERZITET CRNE GORE

- Odbor za doktorske studije -

- Senatu -

O V D J E

U prilogu dostavljamo Odluku Vijeća Elektrotehničkog fakulteta sa sjednice od 24.10.2024. godine i obrazac **D2**, sa pratećom dokumentacijom, za kandidata mr **Borisa Markovića**, na dalji postupak.

DEKAN,

Prof. dr Budimir Lutovac

ISPUNJENOST USLOVA DOKTORANDA

OPŠTI PODACI O DOKTORANDU			
Titula, ime, ime roditelja, prezime	mr, Boris, Milenko, Marković		
Fakultet	Elektrotehnički fakultet		
Studijski program	Doktorske studije Elektrotehnike		
Broj indeksa	18/2007		
NAZIV DOKTORSKE DISERTACIJE			
Na službenom jeziku	Uticaj magnetnog polja na THz zračenje generisano sistemima *Josephson*-ovih spojeva		
Na engleskom jeziku	The Influence of Magnetic Fields on THz Radiation Generated by Josephson Junction Systems		
Naučna oblast	THz tehnologija i primjene, Superprovodnost, Elektronika visokih frekvencija, Mikrotalasna tehnika		
MENTOR/MENTORI			
Prvi mentor	Prof. dr Dragan Filipović	Univerzitet Crne Gore, Crna Gora, redovni profesor u penziji	Mikrotalasna tehnika, Elektronika visokih frekvencija
KOMISIJA ZA PREGLED I OCJENU DOKTORSKE DISERTACIJE			
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Prof. dr Zoran Mijanović - član		Univerzitet Crne Gore, Crna Gora	Elektronika visokih frekvencija
Prof. dr Dragan Filipović - član		Univerzitet Crne Gore, Crna Gora, redovni profesor u penziji	Mikrotalasna tehnika, Elektronika visokih frekvencija,

Datum značajni za ocjenu doktorske disertacije	
Sjednica Senata na kojoj je data saglasnost na ocjenu teme i kandidata	22.12.2022. godine Senat je dao saglasnost na ocjenu teme, kandidata i mentora po osnovu materijala od 11.04.2008. godine
Dostavljanja doktorske disertacije organizacionoj jedinici i saglasnost mentora	20.09.2024. godine po Pravilima doktorskih studija iz 2004. godine
Sjednica Vijeća organizacione jedinice na kojoj je dat prijedlog za imenovanje komisija za pregled i ocjenu doktorske disertacije	24.10.2024. godine

ISPUNJENOST USLOVA DOKTORANDA

Po osnovu odredbi člana 122dž stav 1 Zakona o visokom obrazovanju, kojim je dato pravo studentima doktorskih studija da studiraju po zakonu po kojem su upisani do kraja studijske 2023/2024. godine, u skladu sa članom 30 stav 2 Pravila doktorskih studija iz 2004. godine, **kandidat kao autor, ima objavljene radove u renomiranim međunarodnim časopisima sa rezultatima iz teze.**

Spisak radova doktoranda iz oblasti doktorskih studija koje je publikovao u časopisima sa (upisati odgovarajuću listu)

RADOVI PUBLIKOVANI U ČASOPISIMA NA SCI/SCIE LISTI:

[1] Takanari Kashiwagi, Kazuo Nakade, Boris Marković, Yoshihiko Saiwai, Hidetoshi Minami, Takeo Kitamura, Chiharu Watanabe, Kazuo Ishida, Shin Sekimoto, Kentaro Asanuma, Tsubasa Yasui, Yuuki Shibano, Manabu Tsujimoto, Takashi Yamamoto, Jovan Mirković and Kazuo Kadowaki, "Reflection type of terahertz imaging system using a high-Tc superconducting oscillator", Appl. Phys. Lett. 104, 022601 (2014).

Izdavač: Applied Physics Letters, AIP Publishing LLC; Mjesto: Melville, NY, USA; Godina: 2014;
DOI: 10.1063/1.4861602
Link ka radu: https://dx.doi.org/10.1063/1.4861602
Impact faktor https://www.scijournal.org/impact-factor-of-appl-phys-lett.shtml

[2] Takanari Kashiwagi, Kazuo Nakade, Yoshihiko Saiwai, Hidetoshi Minami, Takeo Kitamura, Chiharu Watanabe, Kazuo Ishida, Shin Sekimoto, Kentaro Asanuma, Tsubasa Yasui, Yuuki Shibano, Manabu Tsujimoto, Takashi Yamamoto, Boris Marković, Jovan Mirković, Richard A. Klemm i Kazuo Kadowaki, "Computed tomography image using sub-terahertz waves generated from a high-Tc superconducting intrinsic Josephson junction oscillator", Appl. Phys. Lett. 104, 082603 (2014).

Izdavač: Applied Physics Letters, AIP Publishing LLC; Mjesto: Melville, NY, USA; Godina: 2014;
DOI: 10.1063/1.4866898
Link ka radu: https://dx.doi.org/10.1063/1.4866898
Impact faktor: https://www.scijournal.org/impact-factor-of-appl-phys-lett.shtml

[3] Takanari Kashiwagi, Takashi Yamamoto, Hidetoshi Minami, Manabu Tsujimoto, Ryozo Yoshizaki, Kaveh Delfanazari, Takeo Kitamura, Chiharu Watanabe, Kazuo Nakade, Tsubasa Yasui, Kentaro Asanuma, Yoshihiko Saiwai, Yuuki Shibano, Takuma Enomoto, Hiroyuki Kubo, Kazuki Sakamoto, Takuya Katsuragawa, Boris Marković, Jovan Mirković, Richard A. Klemm i Kazuo Kadowaki, "Efficient Fabrication of Intrinsic-Josephson-Junction Terahertz Oscillators with Greatly Reduced Self-Heating Effects", Physical Review Applied 4, 054018 (2015).

Izdavač: Physical Review Applied, American Physical Society; Mjesto: Ridge, NY, USA; Godina: 2015;
DOI: 10.1103/PhysRevApplied.4.054018
Link ka radu: https://dx.doi.org/10.1103/PhysRevApplied.4.054018
Impact faktor: https://www.scijournal.org/impact-factor-of-physical-review-applied.shtml

RAD PUBLIKOVAN U ČASOPISU NA SCOPUS LISTI:

[4] Jovan Mirković, Itsuhiro Kakeya, Sergey Savel'ev, Takanari Kashiwagi, Boris Marković i Kazuo Kadowaki, "Tilted vortex lattice in irradiate $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals", Journal of Physics: Conference Series, 667, 012007 (2016).

Izdavač: Journal of Physics: Conference Series, IOP Publishing; Mjesto: Bristol, UK; Godina: 2016;
DOI: 10.1088/1742-6596/667/1/012007
Link ka radu: https://dx.doi.org/10.1088/1742-6596/667/1/012007
Impact faktor: https://www.scijournal.org/impact-factor-of-j-of-physics-conf-series.shtml

Obrazloženje mentora o korišćenju doktorske disertacije u publikovanim radovima
Zadatak koji je realizovan u disertaciji je "analiza uticaja magnetnog polja na karakteristike THz zračenja postojećih sistema *Josephson*-ovih spojeva realizovanih korišćenjem $Bi_2Sr_2CaCu_2O_{8+d}$ monokristala, kao i njihovo modifikovanje u cilju postizanja zračenja većih snaga". U cilju realizacije navedenog zadatka, pristupilo se projektovanju i izradi novih terahercnih oscilatora sa *intrinsic Josephson*-ovim spojevima sa znatno smanjenim efektima samogrijanja, koji su opisani u radu [3]. U radu je detaljno opisana tehnologija izrade i proračuni karakteristika, kao i eksperimentalnim putem potvrđene karakteristike THz emitera. Dokazivanje potencijala za praktičnu primjenu THz emitera je urađeno realizacijom refleksionog i transmisionog (Computer tomography) sistema za snimanje, koji sistemi su detaljno opisani, a praktični rezultati njihovog rada su predstavljeni u radovima [1] i [2] respektivno. Superpovodnost predstavlja osnovni uslov za postojanje *Josephson*-ovih spojeva, a samim tim i generisanje THz zračenja iz sistema zasnovanih na njima. Eksperimetima se pokazalo da magnetno polje uzrokuje slabljenje, a daljim pojačavanjem magnetnog polja i gašenje superorovodnosti THz emitera, a posljedično i THz zračenja. Stoga je analizirano složeno vorteksno stanje koje gasi superprovodnost u $Bi_2Sr_2CaCu_2O_{8+d}$ monokristalima i koje je uzrokovano primjenom magnetnog polja, kako je prikazano u radu [4].

Datum i ovjera (pečat i potpis odgovorne osobe)
U Podgorici, 29.10.2024. god. UNIVERZITET CRNE GORE Elektrotehnički fakultet MP DEKAN

Prilog dokumenta sadrži:

1. Potvrdu o predaji doktorske disertacije organizacionoj jedinici
2. Odluku o imenovanju komisije za pregled i ocjenu doktorske disertacije
3. Kopiju rada publikovanog u časopisu sa odgovarajuće liste
4. Biografiju i bibliografiju kandidata
5. Biografiju i bibliografiju članova komisije za pregled i ocjenu doktorske disertacije sa potvrdom o izboru u odgovarajuće akademsko zvanje i potvrdom da barem jedan član komisije nije u radnom odnosu na Univerzitetu Crne Gore

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Broj: 02-1647/4
Datum: 28.10.2024

Na osnovu službene evidencije i dokumentacije Elektrotehničkog fakulteta u Podgorici, izdaje se

POTVRDA

Mr **Boris Marković**, student doktorskih studija na Elektrotehničkom fakultetu u Podgorici, dana 20.09.2024. godine dostavio je ovom Fakultetu doktorsku disertaciju pod nazivom: **„Uticaj magnetnog polja na THz zračenje generisano sistemima Josephson-ovih spojeva“**, na dalje postupanje.

SEKRETAR
mr Valentina Lješević - Dedić

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Broj: 02/1-1992
Datum: 24. 10. 2024

Na osnovu člana 64 Statuta Univerziteta Crne Gore, u vezi sa Pravilima doktorskih studija, na predlog Komisije za doktorske studije, Vijeće Elektrotehničkog fakulteta u Podgorici, na sjednici od 24.10.2024. godine, donijelo je

O D L U K U

Predlaže se Komisija za ocjenu doktorske disertacije **„Uticaj magnetnog polja na THz zračenje generisano sistemima Josephson-ovih spojeva"** kandidata mr **Borisa Markovića,** u sastavu:

1. Dr Jovan Mirković, redovni profesor Prirodno-matematičkog fakulteta Univerziteta Crne Gore,
2. Dr Dragan Filipović, redovni profesor Elektrotehničkog fakulteta Univerziteta Crne Gore, u penziji (mentor),
3. Dr Zoran Mijanović, redovni profesor Elektrotehničkog fakulteta Univerziteta Crne Gore.

-VIJEĆE ELEKTROTEHNIČKOG FAKULTETA-

D E K A N
Prof. dr Budimir Lutovac

Dostavljeno:
- Senatu,
- Odboru za doktorske studije,
- u dosije,
- a/a.

APPLIED PHYSICS LETTERS **104**, 022601 (2014)

Reflection type of terahertz imaging system using a high-T_c superconducting oscillator

T. Kashiwagi,[1,2] K. Nakade,[1] B. Marković,[3] Y. Saiwai,[1] H. Minami,[1,2] T. Kitamura,[1] C. Watanabe,[1] K. Ishida,[1] S. Sekimoto,[1] K. Asanuma,[1] T. Yasui,[1] Y. Shibano,[1] M. Tsujimoto,[4] T. Yamamoto,[5] J. Mirković,[3] and K. Kadowaki[1,2]

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A reflection type of imaging system is shown at sub-terahertz frequencies generated from high-T_c superconducting intrinsic Josephson junction mesa structures fabricated by single crystalline $Bi_2Sr_2CaCu_2O_{8+\delta}$ to demonstrate how the sub-terahertz imaging technique using monochromatic radiation is powerful and unique for the variety of practical applications. Several examples are discussed in detail and are compared to other terahertz imaging systems. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4861602]

Recently, terahertz (THz $= 10^{12}$ c/s) electromagnetic waves have been attracted much attention because of a variety of useful applications such as quality control of industrial products, security, high speed communications, medical diagnosis, biotechnologies, and environmental studies.[1,2] Typical examples of applications involve THz imaging because THz waves can penetrate many packing materials such as paper, cardboard, plastic, wood, etc. In addition, THz waves can be used for the identification and inspection of materials, since many materials usually have their unique fingerprint spectra in this frequency range.[3–6]

The (sub-) THz electromagnetic wave emission can be generated by using high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) mesa structure.[7,8] This emission is unique in operating principle and powerful, so far $\sim 30\,\mu$W, stable and monochromatic characteristics.[7,8] The radiation frequency can be tuned in a frequency range between 0.3 and 1.0 THz.[7,9] The characteristic properties of the superconducting THz emitter have been studied by many researchers.[10–22] In our previous study,[23] we proposed a transmission type of imaging system for application purpose using superconducting THz emitter, where the higher power THz emission is more desirable. It is remarkable and is worthwhile to mention that the 620 μW was recently reported in an array of three mesa structures operated synchronously.[24]

The high-T_c superconductor Bi2212 is well known as a highly anisotropic layered superconductor with a transition temperature of $\sim$90 K. It consists of alternating double layers of superconducting CuO_2 and insulating Bi_2O_2 within a unit cell, which stacks along the crystallographic c-axis with a separation of 15 Å approximately. Therefore, a single crystal of this compound can be regarded as a one-dimensional array of equivalent atomic-scale Josephson junctions along the c-axis and commonly referred to as a stack of intrinsic Josephson junctions (IJJs).[25–27]

The principal mechanism of our THz emitter based on IJJs made of a Bi2212 single crystal, called as the IJJ-THz emitter, is the ac-Josephson effect[28] working in an intrinsic Josephson junction. This is entirely different from the semiconducting or optical ones.[2] According to the ac Josephson effect, the radiation frequency is determined by $f_J = (2e/h)(V/N)$, where e is the elementary charge, h is Planck's constant, V is the applied voltage, and N is the number of the active IJJs. This relation can simply be expressed as f_J [GHz] $= 483.597870$ [GHz/mV] $\times\, v$ [mV/Junction].[29] The THz electromagnetic waves can simply be obtained by applying a suitable bias voltage to IJJs.

Recently, we developed the reflection type (Reflex type) of imaging system, since the transmission type (Trans type) imaging can be used only when THz waves can penetrate through the object. The Trans type can measure the internal information of the sample in accordance with the absorption coefficient of constituent materials, whereas the Reflex type can provide information of the surface structures in accordance with the reflectivity of the surface materials. Therefore, we can exclusively detect the difference of the reflectivity of the constituent materials in the sample. This kind of identification is sometimes much more useful than the Trans type of imaging.

Here, we show the Reflex type of imaging system and demonstrate imaging by comparing performance, quality of images, flexibility, *etc.* as for some practical examples.

Figure 1 shows the measurement system designed for the Reflex type measurement. Our IJJ-THz emitter was placed in a He-flow cryostat (CF1104, OXFORD Inc.). The THz electromagnetic waves generated from the IJJ-THz emitter was transformed to a parallel beam by the first off-axis parabolic mirror, M_1, then the parallel beam was focused to the sample place by the second off-axis parabolic mirror, M_2. These two off-axis parabolic mirrors have the

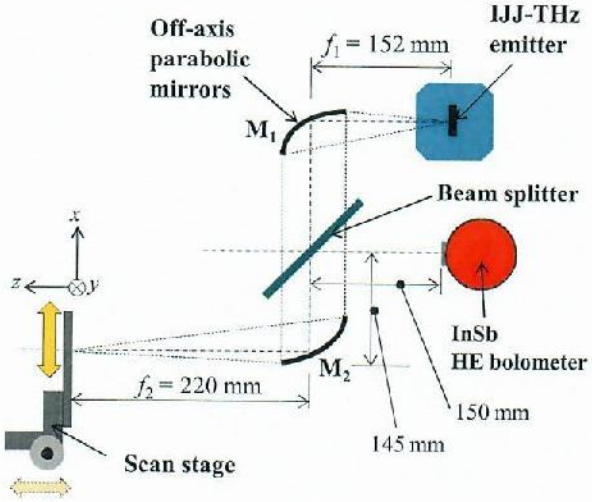

FIG. 1. Schematic top views of the reflection type of measurement system.

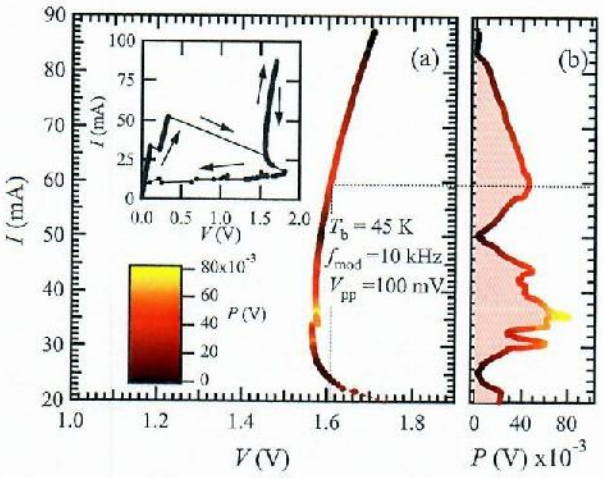

FIG. 2. (a) Current-voltage characteristics of the IJJ THz emitter used for the imaging measurements at $T_b = 45$ K. The curve is potted by using color code according to the output voltage of the InSb HE bolometer. The upper left inset shows the overall I-V characteristics, when the bias current is swept as indicated by arrows. (b) The output voltage of the InSb HE bolometer was plotted as a function of the bias current using the same color code.

focusing lengths of 152 mm and 220 mm, respectively. The sample was placed on the 2D(x, y) scanning stage (SGAHM26-200, SIGMA KOKI Co.) and scanned in X (horizontal) and Y (vertical) directions at a various speed below 130 mm/s.

We introduced a Si-wafer beam splitter (BS) between the two off-axis parabolic mirrors for the purpose of a beam splitting as shown in Fig. 1. A part of beam through the Si-wafer BS is introduced to the xy-scanning stage vertically from the second off-axis parabolic mirror. The vertical component of reflection beam from the sample was collected by the second mirror, and sent back to the Si-wafer BS again. This reflected beam is partially deflected 90° at the Si-wafer BS and was detected by a high-speed InSb hot-electron (HE) bolometer (QFI/2BI, QMC Instruments Ltd.) as shown in Fig. 1.

The detected power from the InSb HE bolometer was measured by using a lock-in amplifier (7265, EG&G instruments.). For this measurement, the output power of the IJJ-THz emitter was modulated by applying a small amplitude of the square wave voltage ($\leq$100 mV) at the frequency of 10 kHz on the constant dc bias voltage by using a function generator (33220A, Agilent). This modulation frequency is determined by minimizing the noise level of the InSb HE bolometer with the time constant of 10 ms. It is noted that this power modulation technique is much better than the optical chopper modulation technique usually used for bolometric THz measurements, because the far-infrared background noise due to the ambient spurious radiation can be completely rejected. The fundamental idea for the detection method was described in the previous imaging system.[23] It is noted that this setup can also be used to take transmission type of images by replacing the HE bolometer and removing the beam splitter.

For this study, we used two IJJ-THz emitters having the radiation frequencies of 440 GHz and 510 GHz, because these emitters show the stable and enough radiation intensities for the bias modulation measurement. Figure 2(a) shows current-voltage (I-V) characteristics of the IJJ-THz emitter used for the present experiment at the bath temperature of 45 K. The dimensions of the mesa device are $80 \times 400 \times 2.4\,\mu m^3$ fabricated by the Ar ion milling technique with a metallic mask.[9] The sub-THz wave radiation with a monochromatic frequency of 440 GHz was estimated by using interference pattern technique developed previously[23] at the bias point of $I = 60$ mA and $V = 1.61$ V as shown by the dotted line in Fig. 2.

According to the responsivity of the InSb HE bolometer of 3.3 mV/nW in the measurement condition, the detected power can be estimated to be about 34 nW, which enables us to take images with the signal to noise ratio $S/N \sim 100$.

We show the first example, where the metallic plate having five holes in a row with different diameters from 1 mm to 5 mm by 1 mm step as shown in Fig. 3(a) was used as an object at 440 GHz. The result is displayed in Fig. 3(b). Although the holes in the metallic plate can be observed, the image becomes invisible as the holes become smaller and smaller and it can no longer noticeable at the 1 mm diameter hole. Since the 2 mm diameter hole can be recognizable rather clearly, it is concluded that the resolution limit is ~1 mm or somewhat larger than that in this system. The images were also taken with the condition of the time constant of 1 ms and the scanning speed of 120 mm/s after checking of the scanning speed effect on the images. In this condition, it will take about 120 s to complete a picture with the size of 120 × 120 pixel at each 1 mm step.

We note that the diameter of the holes shown in Fig. 3 looks somewhat larger than that of the optical picture, and this tendency becomes more exaggerated as the diameter becomes smaller. This effect can be attributed to the spot size of the THz beam and the edge effect of the holes. We noticed that the focusing and collimation of the THz beam are actually very important to make clear images. We estimated the THz beam spot size at the sample plane based on the knife-edge method as described in Ref. 30. In Fig. 3(c), the open symbols show the experimental result of the line profile of the edge of the metallic plate encircled by the

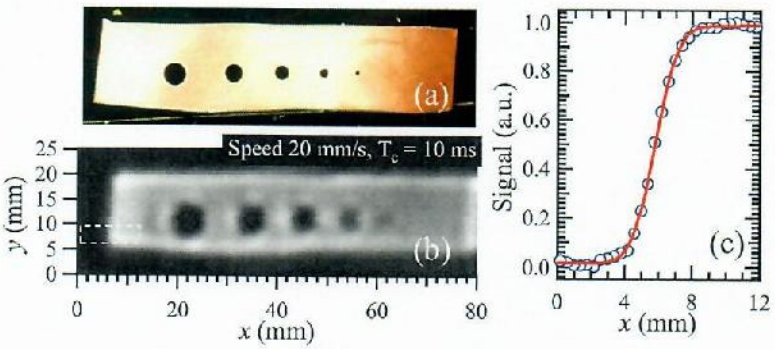

FIG. 3. (a) An optical photograph of the metallic plate (copper) with holes having the diameters of 1 mm, 2 mm, 3 mm, 4 mm, and 5 mm from right to left. (b) The reflection type of the image taken with the speed of the *xy*-scanning stage of 20 mm/s, the time constant of the lock in amplifier of 10 ms and the scanning steps with $x = y = 0.4$ mm. (c) A line scan profile of the edge of the metallic plate encircled by the dotted line in (b). The signal was fitted by an error function.

dotted line in Fig. 3(b) and the solid line is a fit curve using the same function described in Ref. 30. The estimated distribution diameter at half-height is about 2.5 mm. The spatial resolution of the measurement system discussed above may be attributed to this beam spot size. This problem, however, can be improved by using a suitable iris with an appropriate size of aperture and adjusting the position and angle of two off-axis parabolic mirrors as seen later.

In the next example, we show a characteristic feature of the reflection type of imaging and the effect of an aperture. Figure 4 shows the photographs of US quarter and Japanese 5-yen coins (see Fig. 4(a)), and the reflection type of images of these coins taken at 440 GHz (see Fig. 4(b)). These coins were fixed on a quartz glass plate by a double sided adhesive tape. The reflection type of images clearly demonstrates the surface texture of each coin. In addition to that the double sided tape on the quartz glass plate can also be seen behind the coins, which was encircled by the dotted line in Fig. 4(b). We note here that a wooden plate with a thickness of 2.5 mm was used for an aperture in order to catch only the perpendicular component of the reflection in front of the coins. This makes images much sharper than those without aperture plate as seen in Fig. 4(b), where the curved side face of George Washington was rather clearly traced. The letters curved on the surface of US quarter coin cannot be resolved, but the letter of 5-yen coin is legible. It is also noted that this wooden plate is helpful as an absorber to reduce the multiple reflection effect, which makes interference fringes in the imaging picture.

We now compare the images taken by reflection and transmission methods. For a demonstration, an ID card is used. The images are presented and compared in Fig. 5, where both the transmission image and the reflection image from both sides were taken at 440 GHz. It is interesting to note that the reflection images displayed in Figs. 5(b) and 5(c) show different images in front and reverse sides, and the transmission image seems to be a superimposed image of two reflection images. It is noted that the image of (c) is flipped left to right. It may be worthwhile mentioning that this double side technique may be used for checking the wiring and soldering on the electric circuit boards covered by plastic materials in the electronics factory.

Finally, we show an example of our IJJ-THz emitter for the application of security system. Figure 6 shows images of a kitchen knife wrapped by a sheet of newspaper up to five layers taken with frequency of 510 GHz by using a $60 \times 400 \times 1.6\ \mu m^3$ IJJ THz emitter. A clear image can be obtained in the case of the bare knife, whereas the images become blurred as the number of wrapping sheet is increased. We noted that five sheets of paper make images indistinguishable in our present THz imaging setup. The major influence on the reflection image may be the scattering and the decay of the incident THz beam at each paper, which makes multiple reflections. We think that this as a result would cause the fuzzy images.

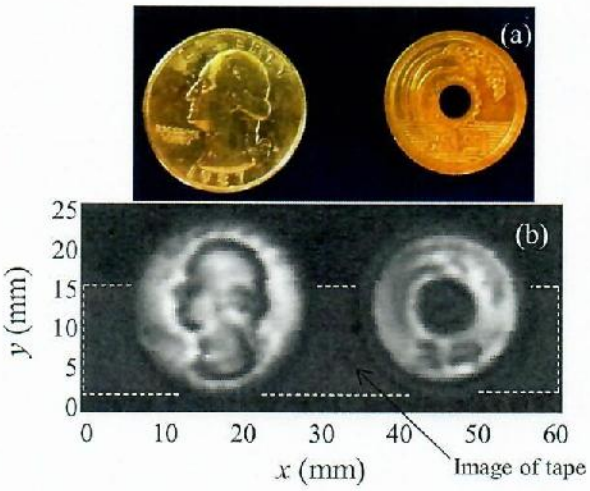

FIG. 4. Photographs of the US quarter coin and the Japanese 5-yen coin (a). (b) Reflection type of images of both coins shown in (a). This image was taken with the speed of the *xy*-scanning stage of 20 mm/s, the time constant of the lock in amplifier of 10 ms and the scanning steps with $x = y = 0.4$ mm.

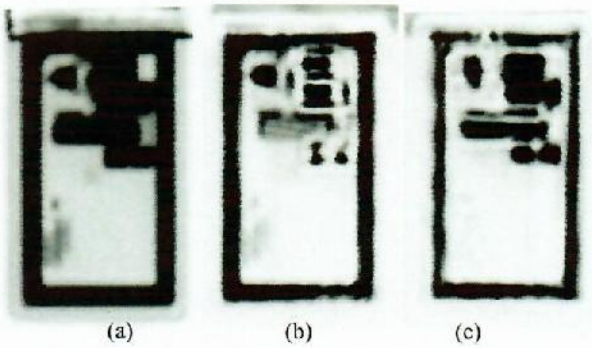

FIG. 5. (a) Transmission type of image of an ID card. (b) and (c) The reflection type of images taken from front and reverse sides, respectively. It is noted that the image of (c) is flipped left to right. These images were taken with the speed of the *xy*-scanning stage of 40 mm/s, the time constant of the lock in amplifier of 3 ms and the scanning steps with $x = y = 0.4$ mm.

Now, we would like to compare our imaging results with the previous reports. An IC card was measured by using continuous wave (CW) transmission technique at 600 GHz generated by BWO (Backward-wave oscillator)[30] and a fiber-coupled multimode laser diode with the frequency of 210 GHz.[31] The quality of our image of the ID card is similar to that of Ref. 31, however, the spatial resolution of the image reported in Ref. 30 is higher than that of ours. This high spatial resolution may be attributed to the good collimation of the focusing beam at the sample position. The reflection image of a surface texture of a coin is also reported by using a hybrid system of CW-Gunn oscillator with a femtosecond Ti:sapphire laser with the frequency of 600 GHz[32] and a CW-THz gas laser with the frequency of 2.5 THz.[33] It is obvious that the spatial resolution taken by using the former source is comparable to ours, whereas the image taken by the latter one seems to exhibits clearer surface textures than ours because it uses shorter wave length of about 120 μm.

Finally, we would make a remark that the acquisition time to take a whole image of the object is another important parameter for the practical applications. In the CW operation with lock-in amplifier system and with xy-scanning stage, it is essentially determined by the scanning speed of the sample

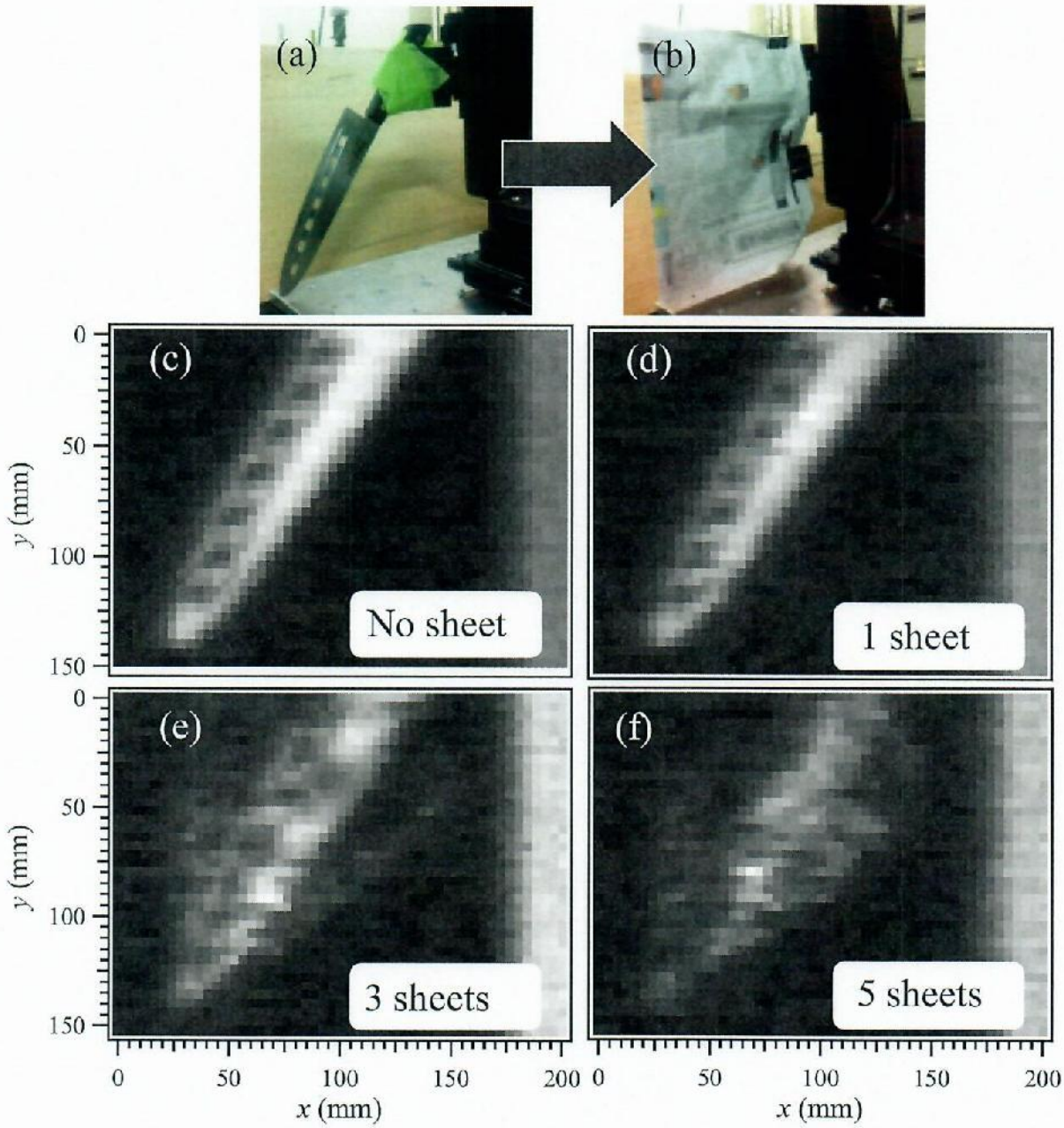

FIG. 6. Photographs of a kitchen knife (a) and wrapped it by a newspaper (b). Reflection type of images of the kitchen knife. (c) Bare, (d), (e), and (f) wrapped by a sheet of newspaper once, three times and five times, respectively. These images were taken with the speed of the xy-scanning stage of 100 mm/s, the time constant of the lock in amplifier of 30 ms and the scanning steps with $x = y = 4.0$ mm.

stage and the time constant of the lock-in amplifier. According to the imaging system by the BWO,[30] an imaging speed is 33 pixels/s, which means that for the scanning size of 100×100 pixels, the total imaging time is about 5 min, being comparable with our measurement.

We have shown the reflection type imaging system by using THz waves generated from high-T_c superconducting mesa structure fabricated from single crystalline $Bi_2Sr_2CaCu_2O_{8+\delta}$. We demonstrated the actual examples such as holes in the metallic plate, coins, IC cards, and knife taken by the reflection type of setup. We convinced that these results are useful enough for the actual applications.

This work had in part been supported by the Grant-in-Aid for challenging Exploratory Research from the Ministry of Education, Culture, Sports, Science and Technology. T.K. thanks the support of the Matsuda foundation.

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Computed tomography image using sub-terahertz waves generated from a high-T_c superconducting intrinsic Josephson junction oscillator

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A computed tomography (CT) imaging system using monochromatic sub-terahertz coherent electromagnetic waves generated from a device constructed from the intrinsic Josephson junctions in a single crystalline mesa structure of the high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ was developed and tested on three samples: Standing metallic rods supported by styrofoam, a dried plant (heart pea) containing seeds, and a plastic doll inside an egg shell. The images obtained strongly suggest that this CT imaging system may be useful for a variety of practical applications.
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Recently, compact and powerful generators of electromagnetic waves at terahertz (THz) frequencies based on semiconducting devices such as resonant tunneling diodes (RTDs), unitraveling carrier photo-diodes (UTC-PDs), quantum cascade lasers (QCLs), femtosecond current switching (CS) devices, etc., have been developed very rapidly, because such a frequency domain has became known to be highly useful not only for basic research in science and technology but also for a wide variety of many practical applications, with special emphasis on various kinds of imaging, high-speed communications, security inspections, medical diagnoses, pharmaceutical studies and development, biosciences and technologies, environmental studies, quality control of industrial products, quantum computing, etc.[1,2]

A unique THz source which generates monochromatic coherent continuous radiation was discovered in 2007 using high-transition temperature T_c superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) mesa structures.[3,4] Many characteristics of the THz devices based on Bi2212 sources have been studied experimentally and theoretically.[5–22] The radiation characteristics from this source are entirely different from those of conventional semiconducting and optical sources because of the completely different radiation principle based upon the ac-Josephson effect, whereby the emission frequency $f = f_J = K_J V$, where V is the dc voltage applied across each intrinsic Josephson junction (IJJ) (see below), and $K_J = 2e/h = 483.597891(12)$ [GHz/mV], where e is the electronic charge and h is Planck's constant.[23] Since $f_J \propto V$, it can be varied with V rather arbitrarily. Furthermore, since the superconducting energy gap $2\Delta \approx 60\,\text{meV} \approx 28.8\,\text{THz}$ for Bi2212, these devices can in principle become excellent radiation sources even for f ranging from ~0.3 THz to ~20 THz. These novel sources have therefore accelerated the race to develop powerful, compact, and easy-to-use THz sources.

Bi2212, a highly anisotropic layered superconductor with $T_c \sim 90$ K, consists of alternating and mutually incommensurate double CuO_2 layers responsible for its superconductivity and an insulating Bi_2O_2 block layer within each half crystallographic unit cell c-axis edge of ~15.3 Å. Therefore, a Bi2212 single crystal 1 μm thick corresponds to a c-axis stack of ~653 equivalent atomic-scale IJJs.[24–26]

Recently, we obtained emission with the output power of ~30 μW from a stand-alone mesa structure[27] for f between 0.3 and 1.0 THz.[14,16,18] A synchronized three-mesa array was recently reported to emit with about 600 μW output power.[17] Such remarkable power development is comparable to those from other THz sources, such as RTDs,[28–30] UTC-PDs,[31,32] and QCLs.[33–35] As for QCLs, the competition between the energy level separation and thermal energy forces the limitation $hf > k_BT$, for which 1 THz $\sim 48(k_B/h)$ K, where k_B is Boltzmann's constant.

We developed transmission and reflection types of imaging systems for practical uses of our IJJ-THz emitter.[13,36] The electromagnetic waves in the THz region can easily penetrate through papers and plastic materials, hence hidden objects with high absorption coefficients in the THz region can be detected by THz wave imaging systems. The transmission and reflection types of imaging systems may provide information regarding the bulk and surface structures of a sample, respectively. The different characteristics obtained from those two systems can enable us to identify highly reflective and

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highly absorbing materials within the lightly concealed sample. As discussed in the following, a THz-wave computed tomography (THz-CT) imaging technique can also provide cross-sectional views of the sample's internal structure. By combining these techniques efficiently, one can obtain unique images useful for practical applications based on the characteristic features of THz waves.

In this Letter, we describe a THz-CT imaging system using our IJJ-THz emitter as the source and present THz-CT images of three samples: Three standing metallic rods supported by styrofoam, a dried heart pea (cardiospermum helicacabum) with three seeds inside, and a plastic doll inside an egg shell.

Figure 1 shows a schematic top view of the THz-CT imaging system using our IJJ-THz emitter. The IJJ-THz emitter was placed in a He-flow cryostat (CF1104, OXFORD Instruments) and cooled down to the operating temperature between 10 and 70 K. The THz electromagnetic waves generated from the IJJ-THz emitter are collected and converted to the parallel beam by the first mirror, M_1, then it is focused to the sample by the second mirror, M_2. The focal lengths of M_1 and M_2 are 152 mm and 220 mm, respectively. The samples are placed on a rotating table mounted on a 2D(x, z) scanning stage (SGAHM26-200, SIGMA KOKI Co.). This scanner enables us to take one-dimensional images along the x (horizontal) direction at various speeds below 130 mm/s at various fixed rotation angles θ of the sample table in order to measure the angular and spatial dependencies of the transmission intensity $I(x, y, \theta)$ of the THz radiation. The transmitted THz beam from the sample is detected by a high-speed InSb hot-electron (HE) bolometer (QFI/2BI, QMC Instruments Ltd.), whose detection power was monitored by a lock-in amplifier (Model 7265, EG&G instruments Co.). To facilitate the lock-in detection, the output power of the IJJ-THz emitter is effectively chopped by superposing an ac square-wave voltage of amplitude 80 mV and frequency 10 kHz onto the dc bias voltage with a function generator (33220A, Agilent). We note that lock-in detection using this electronic modulation is superior in noise performance to that of an optical chopper as commonly used for optical and infrared detection, because it essentially eliminates the thermal background noise due to the surrounding environment from the detected signal. Further details of the detection method were described previously.[13]

In order to obtain reliable CT images, it is crucially important to have a THz source beam that is stable throughout the time of the measurements. For the present THz-CT imaging measurements, we selected an IJJ-THz emitter with dimensions $80 \times 400 \times 2.4\,\mu m^3$, due to its stability and output power sufficient for the ac voltage bias modulation measurements. The ratio of the temporal variability $\Delta P(t)$ to that of the temporal average $\overline{P(t)}$ of the output power of the chosen IJJ-THz emitter during the time of each sample measurement was less than $\pm 1\%$. This device was then operated at 45 K and emission $f = 440$ GHz. f was easily estimated using our previous interference pattern technique.[13]

We note that our IJJ-THz emitter has a spatial distribution of its radiation power. Mirror M_1 in Fig. 1 collects a part of this radiation power distribution. We adjusted the dc bias voltage to generate stable radiation, and the voltage of the lock-in detector of the bolometer response is about $V_{det} = 40$ mV at this stable radiation bias point without any sample. According to our previous studies,[18] this corresponds to the incident THz radiation power, $P = 2\sqrt{2}V_{det}/\alpha \approx 34$ nW, where $\alpha = 3.3$ mV/nW is the system optical responsivity calibrated by black body radiation.

We note that the THz-CT images shown here are constructed by superposing the θ dependence of the 2D matrix $I(x, y, \theta)$ from each line scan along the x direction based on the primitive filtered back projection CT imaging technique.[37]

We first made a simple check using a trivial test sample. Figure 2 shows the THz-CT imaging picture of the three standing metallic rods with the diameter of 2 mm supported by a styrofoam base. The inset of Fig. 2 shows an optical photograph of the sample. This THz-CT image was constructed by superposing the θ-dependent images taken from $\theta = 0$ to 360° in 10° steps, which were obtained by horizontal (x) line scanning at the speed of 10 mm/s in scanning steps

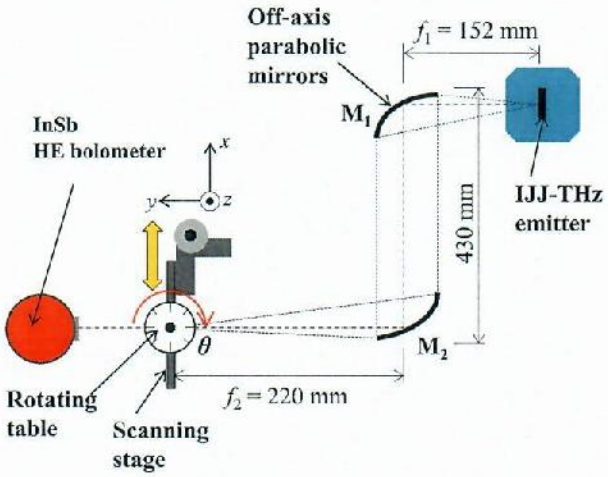

FIG. 1. A schematic top view of the THz-CT imaging system using an IJJ-THz emitter.

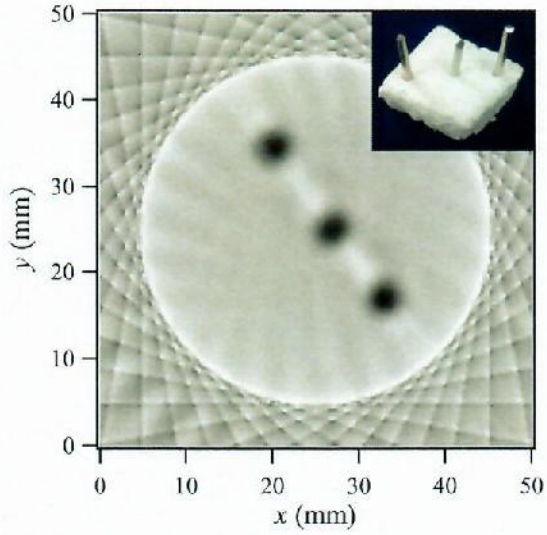

FIG. 2. A THz-CT image of three metallic rods each 2 mm in diameter supported by a styrofoam base. Inset: An optical photograph of the same supported metallic rods.

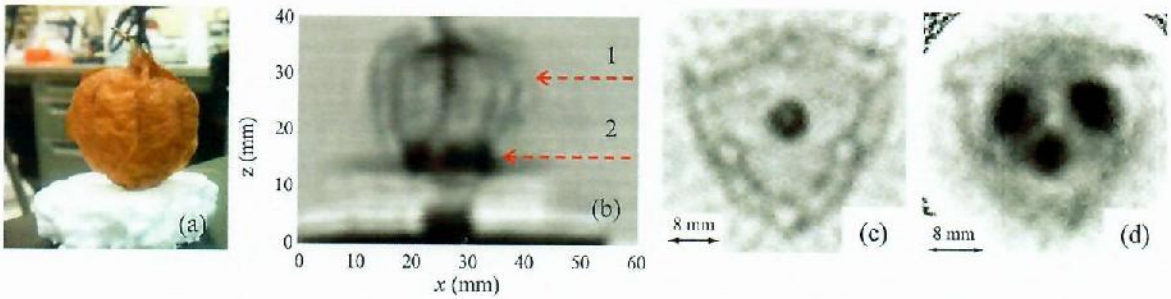

FIG. 3. (a) Optical photograph of the exterior of a dried heart pea. (b) Transmission image of the dried heart pea. (c) and (d) THz-CT horizontal planar images taken at fixed z values indicated by dashed red arrows 1 and 2 in Fig. 3(b).

of 0.2 mm. It took about 10 min to collect all angular dependent data. The resulting composite image shown in Fig. 2 clearly demonstrates the sample characteristics of the positions, the distances, and the diameters of three rods. From this image, we estimate the spatial resolution of our transmission imaging system to be on the order of or somewhat larger than 1 mm. We note that the two upper left THz-CT rod images appear to have slightly larger diameters than that of the other rod, although they all have the same diameter. This may be due to the fact that the rods are not all standing parallel to the rotation axis. Moreover, the THz-CT detected diameters of all three rods are considerably bigger than 2 mm. This is probably due to the resolution limit of our system, ~1 mm, obtained using monochromatic THz electromagnetic waves.

We now present the results of a THz-CT scan of a sample that is more relevant to the utility of the imaging system: A dried heart pea with three seeds inside. An optical photograph of the heart pea placed on a styrofoam base is shown in Fig. 3(a). The 2D transmission THz-image is displayed in Fig. 3(b). The three dark spots at the bottom of the heart pea are images of the three seeds located in three different inflated ventricles (or chambers) inside the heart pea that are separated by thin-shelled walls, an exterior view of which is seen in Fig. 3(a). The faint vertical lines connected at the top and bottom are the images of the three walls separating the ventricles of the heart pea. The THz-CT images of the heart pea constructed by 36 transmission 2D images at the horizontal planes indicated by the red dashed arrows 1 and 2 in Fig. 3(b) are shown in Figs. 3(c) and 3(d), respectively. Note that the horizontal images for the CT image are taken at a scanning speed of 10 mm/s along x in measurement steps of 0.4 mm. It is remarkable that Fig. 3(c) clearly shows the characteristic features of a heart pea: Three ventricles, each consisting of an inflated thin-walled, balloon-like triangular capsule, that are pressed together. In Fig. 3(d), three ball-like seeds located in separate ventricles are also clearly visualized at the bottom of the heart pea. These results provide strong evidence that the THz-CT imaging technique is extremely useful to investigate the internal structures, distributions, textures, etc., of the object containing different THz absorption coefficients.

Next, we examine a sample consisting of a small plastic doll placed in an egg shell by the THz-CT technique. Figure 4(a) shows an optical photograph of the egg shell placed on and supported by the paper holder on the sample stage. A plastic doll was placed in the egg shell upside down as shown in Fig. 4(b). Then the egg shell is closed and the transmission image was taken. This result is shown in Fig. 4(c), where the head of the small doll, egg shell, and the paper holder can be seen rather vividly, although plastics in general have a very low absorption coefficient. It is clear that the THz waves easily penetrate through the egg shell, whereas the plastic doll has a slightly larger absorption coefficient than does the egg shell as seen in Fig. 4(c). The THz-CT image obtained at the red dashed line in Fig. 4(c) is displayed in Fig. 4(d). This CT imaging picture was obtained with the line scanning speed of 10 mm/s in steps of 0.2 mm. We emphasize that the image in Fig. 4(d) clearly detects the characteristics of the body and hands of the doll, the position of the doll in the egg shell, and the edge of the egg shell. These remarkable results will accelerate further detailed studies of this THz-CT imaging technique, especially for the variety of applications such as in bio- and life-sciences.

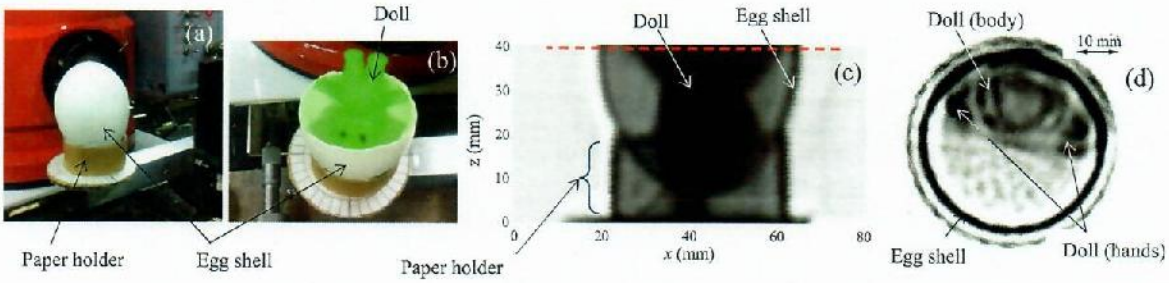

FIG. 4. (a) and (b) Optical photographs of an egg shell supported by a paper holder on the sample stage and of a doll placed upside down inside the egg shell. (c) Transmission image of the doll in the egg shell. (d) THz-CT image of the doll in the egg shell.

In conclusion, we have shown three different CT images taken by the home-made THz-CT image scanning system at a sub-THz frequency (440 GHz) generated from the mesa structure fabricated from single crystalline high-T_c superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$. We demonstrated with three different examples that our IJJ-THz emitter may be employed in transmission THz-CT imaging systems and, thereby, also vividly demonstrated the utility of the THz-CT scanning technique in future imaging applications.

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Efficient Fabrication of Intrinsic-Josephson-Junction Terahertz Oscillators with Greatly Reduced Self-Heating Effects

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The intrinsic Josephson junctions (IJJs) in the high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) are shown to have great potential for the construction of an oscillator emitting in the terahertz-frequency f regime. However, earlier devices with Bi2212 substrates exhibit strong self-heating effects detrimental to their operation and limiting the maximum f to approximately 1 THz. Here we describe an efficient fabrication procedure for a stand-alone-mesa IJJ terahertz oscillator with considerably reduced self-heating effects, greatly expanding the tunability and maximum value of f, potentially even to 15 THz. Their typical current-voltage characteristics, radiation tunability and power, and some practical uses are also presented.

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I. INTRODUCTION

Recently, the generation and detection of electromagnetic waves (EMWs) in the terahertz-frequency range have been fascinating areas of research, with both infrared optical and microwave techniques being used to attempt to fill the so-called "terahertz gap" existing only in a narrow range of this part of the electromagnetic spectrum. These frequencies are thought to be useful for practical applications in medical diagnoses, pharmaceutical drug development, bioscience and biotechnologies, environmental studies, imaging techniques, ultra-high-speed communications, quantum computers, etc. [1,2].

Using semiconductor technology, compact terahertz emitters such as resonant tunneling diodes (RTDs) and quantum cascade lasers (QCLs) have recently been developed and have attracted much attention. For example, the radiation frequency f ranging from 0.4 to 1.4 THz can be obtained at room temperature by using RTDs [3,4], although the output power P decreases strongly with increasing f, becoming about 1 μW at 1.42 THz. As for QCLs, a milliwatt level of P was obtained at 3.2 THz at temperatures below 200 K. However, f below 2 THz cannot be generated at sufficient P (approximately microwatts) without cooling below 40 K [5–7].

In 2007, continuous monochromatic coherent terahertz waves generated from a mesa structure made from single-crystalline high-transition-temperature T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) were first reported [8], and their basic properties were studied in order to understand this entirely new type of terahertz-emitting device. The fundamental principle of the operation is based on the coherent synchronization of the emission from the many intrinsic Josephson junctions (IJJs) existing in a single Bi2212 crystal. It is well known that Bi2212 with $T_c \sim$ 90 K consists of alternating double layers of superconducting CuO_2 and insulating Bi_2O_2 within a unit cell, which stack along the crystallographic c-axis with an effective repeat distance of approximately 1.533 nm, corresponding to one IJJ and one-half of a unit-cell c-axis edge. Therefore, atomic-scale IJJs are intrinsically formed with

crystallographic precision in this compound [9–11]. $N \sim 660$ of essentially identical IJJs are present in a Bi2212 single crystal 1 μm thick.

When a Bi2212 mesa is biased by a current I and a voltage V applied across it, an oscillating current is generated across each IJJ, each of which emits electromagnetic radiation. According to the ac Josephson relation [12], this EMW has a definite frequency f given by $f = f_J = (2e/h)\ v$, where $v = V/N$ is the voltage applied across each IJJ, and e and h are the electric charge and Planck constant, respectively, provided that $hf < |2\Delta|$ for an isotropic superconducting gap $|2\Delta|$ on each side of the IJJ [12]. Here, it is emphasized that the electromagnetic-radiation power is enhanced greatly due to the coherent synchronization of emission from the N (approximately 10^3) IJJ layers in the mesa structure. Then the output power is expected to be proportional to N^2 [8,13,14], resulting in a power of approximately 10^6 times larger than the single junction [15–17].

If each superconducting layer in the bulk of Bi2212 has an isotropic gap of magnitude 60 meV, the ac Josephson effect will potentially allow f to be tunable up to 15 THz. However, we note that both anisotropic gap functions due to competing charge-density waves and two superconducting gaps have been observed in the transition-metal dichalcogenides [18]. For example, scanning tunneling microscopy of 2H-$NbSe_2$ resulted in a low-temperature gap that was about 40% of the peak-to-peak value [19] and Josephson tunneling with Pb tips led to values of the product I_cR_n of the critical current times the c-axis normal resistance that were considerably less than the Ambegaokar-Baratoff result [20,21], even when I_c was estimated using this minimum (real) gap value, whose behavior those authors claimed was similar to that seen in cuprates [22]. Since Bi2212 also exhibits charge-density wave ordering, if it were to have an anisotropic superconducting gap function of magnitude $|2\Delta_n(\boldsymbol{k})|$ for Cooper pairs of intralayer wave vector $\boldsymbol{k}$ within the nth superconducting layer counting from the mesa top, in order for monochromatic emission from each of the IJJs to occur and for their overall coherent phase synchronization to occur, this gap function must have a minimum constant value $|2\Delta_{\min}| > 0$ in the bulk layers with $1 \ll n \ll N$, and strong emissions will be limited by $hf < |2\Delta_{\min}|$.

The very recent observations of emissions up to 1.6 THz [23] and, more recently, up to 2.4 THz [24] with strong emissions at 1.0 THz and rather strong emissions at 1.6 THz seem to suggest that the minimum bulk gap in the quasiparticle spectrum $|2\Delta_{\min}| \sim 4.1$ to 6.5 meV or greater, whose values are roughly consistent with earlier bulk c-axis twist Josephson-junction experiments on overdoped Bi2212 [25,26]. However, since such experiments were not carried out on underdoped Bi2212 samples, it is not clear if those results will be relevant to the gap in terahertz-emitting samples, all of which are underdoped. In addition, according to studies of Josephson junctions in conventional s-wave superconductors (Al, Nb) in high-frequency mixers and radiation detectors, those junctions support electromagnetic oscillations at frequencies well above the gap 2Δ frequency $f_g = 2\ \mathrm{eV}/h$, albeit at the expense of increasing losses [27,28]. Therefore, further studies of the radiation frequency of Bi2212 IJJ terahertz oscillators might provide a more accurate way to estimate the bulk minimum gap value.

In order to understand the characteristic features of present and earlier IJJ terahertz oscillators, experimental [8,23,24,29–64] and theoretical [65–89] studies have been actively performed. The development of earlier IJJ terahertz oscillators was reviewed recently [90].

The radiation power emitted from single IJJ terahertz oscillators has steadily increased to about 30 μW to date by improving the fabrication process and by optimizing the radiation conditions [49–51,61]. Although such power levels were unattainable with the conventional mesa structures used in the first terahertz-emission experiments [8], such high-power emission is now reproducibly obtained from stand-alone mesa structures. Sketches of conventional and stand-alone mesa structures are, respectively, shown in Figs. 1(a) and 1(b) and photographs of them are shown in Figs. 1(c) and 1(d), respectively. The high-power performances of stand-alone mesa structures were, in fact, proposed theoretically prior to their fabrication [81,82].

It is noted that an output power at the 610 μW level was recently reported from the synchronization of an array of three conventional rectangular mesa structures [48]. This result should encourage further studies to develop the synchronization of stand-alone mesa-structure arrays, with the goal of achieving an overall output power of 1 mW.

We have so far mainly studied the device characteristics of rectangular mesa structures. In actual mesa structures, there is another very important condition for the strong emission of radiation in addition to the ac Josephson effect

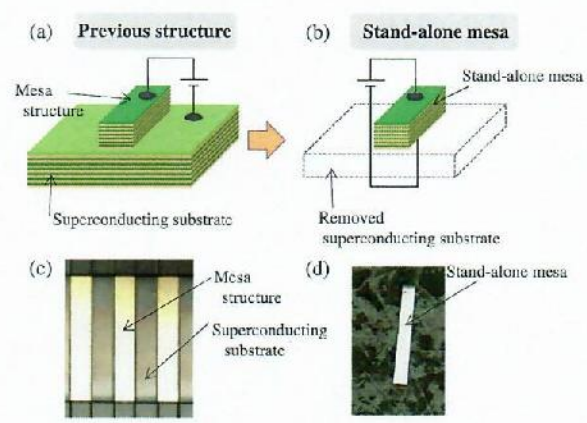

FIG. 1. (a),(b) Respective sketches of a conventional and a stand-alone type of rectangular mesa structure. (c),(d) Respective optical photographs of three conventional mesa structures and one stand-alone mesa structure.

and the requirement that hf be less than the minimum value of the magnitude of the bulk superconducting gap. That is the cavity resonance condition $f = f_c(m, p)$ [8,29,30] for the transverse-magnetic (TM) mode indexed by the integers (m, p) for the particular geometry of the thin mesa behaving as an electromagnetic cavity. In actual operation of terahertz radiation, it is very important to match both conditions [$f = f_J$ and $f = f_c(m, p)$] simultaneously to obtain strong emission. This match is actually difficult to optimize due to a number of effects that deteriorate the overall synchronized operation of the many IJJs. The most significant deleterious effect is that of the Joule self-heating arising from the applied I bias.

According to recent experimental results, the inhomogeneous temperature distribution $T(\boldsymbol{r})$ of the mesa structure has been observed experimentally by low-temperature scanning laser microscopy [39–41], a Eu^{3+} fluorescence line in a europium chelate [31,55,56], and a photoluminescence technique using SiC micropowders [32,53,54], and was predicted *a priori* and studied *a posteriori* by numerical simulations [84,85]. These experimental results and simulations clearly indicate that the Joule heating strongly affects the radiation characteristics and conditions.

After observing and studying such undesired effects, we develop a method to significantly reduce their magnitudes. The central idea is that a stand-alone mesa structure, such as that shown in Fig. 1(c), is well suited for resolving the self-heating problem because the very poor thermally conducting Bi2212 superconducting substrate beneath it in conventional mesas is surgically removed by cleavage. Instead, the remaining Bi2212 mesa is directly contacted on both top and bottom surfaces with far superior thermal conductors such as sapphire, gold, or copper. To date, such and similar stand-alone mesa structures have allowed for output powers greater than approximately 30 μW and emission frequencies tunable from approximately 0.3 to 1.6 THz and from approximately 0.5 to 2.4 THz [23,24,51,52]. Therefore, it is important to understand the radiation characteristics of stand-alone mesa structures to further improve the characteristic radiation properties for practical uses of high-power IJJ terahertz oscillators.

Recently, we developed a simple procedure for stand-alone mesa-structure fabrication and device assembly. The highlights of the experimental results of the simple device structure were reported [23,24]. Here, we provide more details of the device structure and its characteristics.

We first describe the simple technique for fabricating stand-alone mesa structures. Second, we describe an easy and reliable device-assembly procedure for efficient heat removal and electric wiring, etc. Third, the physical properties of several samples contained within the assembled device structure are presented.

II. SAMPLE PREPARATIONS

A. Fabrication processes of stand-alone mesa structures

High-quality single crystals of Bi2212 are grown by a traveling-solvent floating-zone method using a modified infrared-image furnace [91,92]. A piece of an as-grown Bi2212 single crystal is then annealed overnight to obtain an appropriate doping level [8,29,30,33,43].

Both surfaces of the piece of the annealed Bi2212 single crystal are cleaved to obtain fresh surfaces, with a resulting thickness on the order of a few micrometers. Both cleaved fresh surfaces are coated with Ag and Au films 50 to 100 nm in thickness by evaporation.

Figure 2(a) is a sketch of the preassembly of the milling rig used in fabricating the stand-alone mesa structures. The dual-metallic doubly deposited thin crystal of Bi2212 is placed between two metallic masks (4 and 5) by using two metallic plates (2) and two covers (1 and 3). Each metallic plate and cover has a hole in its center large enough to allow for Ar ion milling of the doubly coated Bi2212 crystal into mesas. A cross-sectional sketch of the assembled milling-rig components prior to Ar ion milling is shown in Fig. 2(b).

Two different types of metallic masks are used to fabricate the stand-alone mesa structures by Ar ion milling, as shown in Fig. 2(a). The top mask (4) defines the length, and the bottom mask (5) determines the width of the mesa structures [33]. We first limit the lengths of the mesa structures by Ar ion milling from the top of the assembled milling rig, as shown in Fig. 2(b), and then the rig is turned

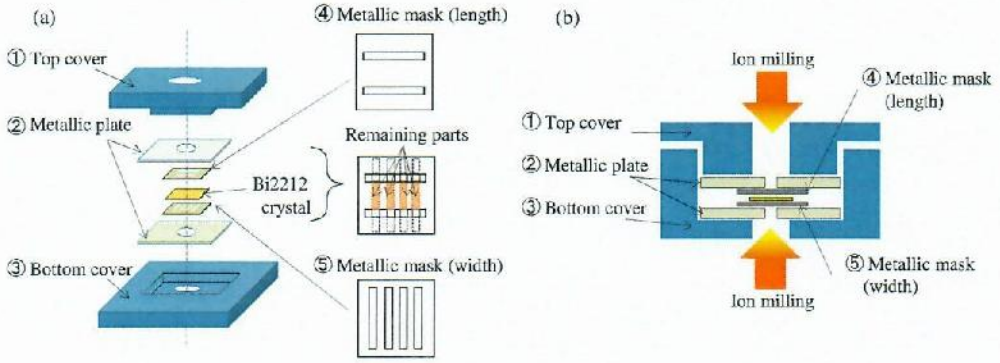

FIG. 2. (a) Sketch of the preassembly of the milling-rig components used in fabricating stand-alone mesa structures. (b) Cross-sectional sketch of the assembled milling-rig components prior to Ar ion milling from above and below.

upside down and the mesa widths are fabricated by Ar milling from the rig bottom. After these two milling processes, the remaining stand-alone mesa structures are carefully removed from the metallic masks.

We note that during both milling processes, the active milling mask must be held in close contact with the sample. If this close contact is not kept, the surfaces of the resulting stand-alone mesa structures might become covered by the milling debris, greatly increasing the difficulty in forming electrical contacts onto them.

The number of mesa structures that can be fabricated simultaneously depends only upon the number of slot lines in the bottom metallic mask (5). This milling process is potentially well suited for the simultaneous mass production of stand-alone mesa structures. To date, we have succeeded in fabricating eight stand-alone mesa structures at once.

B. Wiring and fixing of the stand-alone mesa structures

After fabrication of a stand-alone mesa structure, electrical contacts have to be attached to both its top and bottom surfaces for the application of the dc bias voltage V across it. In our previous studies of stand-alone mesa structures, the electric contact was made on one surface by a crimping connection and/or an electrical conductive paste such as silver paste to attach the surface to the gold metal deposited onto a sapphire substrate. The electric contact on the other surface of the mesa structure was made by a gold wire ($d = 10\ \mu$m) with silver paste [44,50,51]. We emphasize that the quality of the resulting electrical contacts in those previous constructions depended on the skill and technique of the researcher.

To overcome this human skill limitation, we develop a simple mechanical electrical-contact-formation procedure. Figure 3(a) is a sketch of the preassembly of the contact rig used for mechanical electrical-contact attachments onto the stand-alone mesa surfaces. We first prepare two sapphire substrates of dimensions $7.0 \times 7.0 \times 0.5$ mm^3. Then thin Au strips with thicknesses of 50 to 100 nm and widths of 100 to 200 μm are deposited across the sapphire substrates, and the substrates are placed together face to face with the metallic strips on the sapphire plates in order to sandwich the stand-alone mesa to provide both mechanical and electrical contacts, as sketched in Figs. 3(a) and 3(b). Optical photographs of the stand-alone mesa before and after sandwiching by gently pressing the two sapphire substrates with the deposited metal film strips are shown, respectively, in Figs. 3(c) and 3(d). Although, in principle, high-Q resonances are possible with this structure, the details of this effect have not yet been well studied. Therefore, the experimental results shown in the following will be discussed without considering the possible resonances caused by the surrounding mesa structure.

In order to tighten the gold-gold contacts above and below each stand-alone mesa in the overall sandwich structure described above and pictured in Fig. 3(d), we loosely insert four screws to mechanically press together the rear and front covers of the contact rig sketched in Figs. 3(a) and 3(e). Prior to tightening the screws, Au wires are also attached to both thin-film metal strips deposited on the sapphire substrates to complete the electrical contacts to the external voltage source. Finally, a hemispherical-shaped Si lens with a diameter of 4 mm is attached to the top of the front sapphire substrate and held in place with a spacer, as

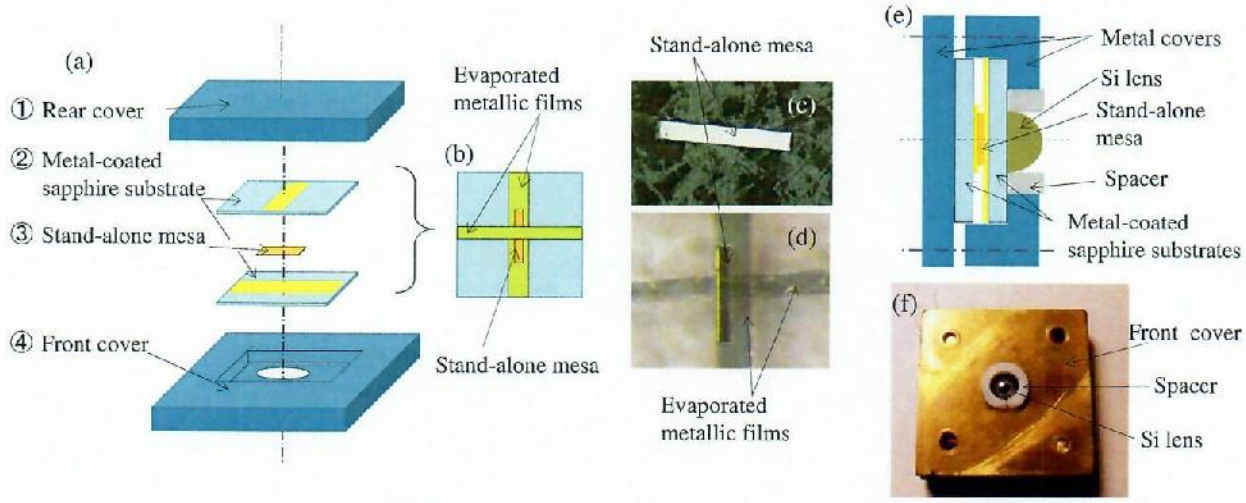

FIG. 3. (a) Sketch of the preassembly of the contact-rig components used for mechanical attachment of the electrical contacts onto the stand-alone mesa structure. The Au strips are deposited on the sapphire-substrate surfaces in eventual contact with the Bi2212 mesa. (b) Sketch of the stand-alone mesa structure sandwiched between two partially-metal-coated sapphire substrates. (c),(d) Respective optical photographs of the stand-alone mesa structure and its sandwiched structure using two sapphire substrates with metallic contact thin-film strips. (e),(f) Side sketch of an assembled contact-rig structure and a top optical photograph of it, respectively.

indicated in a cross-sectional sketch pictured in Fig. 3(e). During the final tightening of the four screws, the contact resistance across the sample is monitored in order to ensure good electrical contacts.

Figure 3(f) is a photograph of the front view of the assembled contact rig with the four screws in the holes near the corners. The role of the Si lens is to focus the terahertz waves generated from the stand-alone mesa structure. The Si lens enhances the response at the detector at least by several times and focuses the beam, which may be useful for terahertz-imaging applications, for example.

III. MEASUREMENT SETUP

For the measurements of the radiation properties of the stand-alone mesa structures, we use a ^{4}He flow cryostat (CF1104, Oxford Instruments) for sample cooling, a Si bolometer (Infrared Laboratories), and a high-speed InSb hot-electron (HE) bolometer (QFI/2BI, QMC Instruments Ltd.) for detecting terahertz waves from the stand-alone mesa structures. The absolute radiation power is measured by a submillimeter power meter (Model PM4, Virginia Diodes, Inc.). For determining the radiation frequencies, a Fourier-transform infrared (FTIR) spectrometer (FARIS-1, JASCO) is used. An FeRh thermometer is placed on the sample holder inside the ^{4}He flow cryostat to measure the bath temperature T_b of the sample. For measurements of the current-voltage characteristics (I-V characteristics), a voltage source and a standard resistance $R_s = 10\ \Omega$ are used to apply the dc voltage V and to measure the dc current I applied to the mesa structure, respectively. Block diagrams and the details of the experimental setup are the same as reported previously [29,44].

IV. RESULTS AND DISCUSSION

A. Sample characteristics

The metallic masks described in Sec. II A and sketched in Fig. 2 are used to fabricate several stand-alone mesa structures of dimensions 350 μm in length, 58–66 μm in width (top to bottom in a trapezoidal cross section), and 4.7 μm in thickness, including the electrode pads of the Ag and Au metallic layers. The thickness of each mesa structure is estimated with a scanning electron microscope. Electrical contacts are applied mechanically, as described in Sec. II B and sketched in Fig. 3.

Figure 3(f) is a photograph of the assembled contact-rig (device) structure with the focusing Si lens. After its assembly, the entire device's dimensions are about $20 \times 20 \times 5$ mm^3. This fully assembled terahertz oscillator is sufficiently compact and easy to handle for many practical uses.

To date, we confirm that four mesa devices with the structures described above reproducibly emit coherent terahertz radiation. In the following, we mainly describe the radiation characteristics and applications of these new devices with the results obtained from sample no. 1, the strongest emitter of the four devices. Sample no. 2 is fabricated in the same batch as was sample no. 1, and its properties are compared with those of sample no. 1.

B. Current-voltage and radiation-frequency characteristics

Figure 4(a) displays the T_b dependence of the c-axis resistance $R_c(T_b)$ of sample no. 1. The superconducting transition temperature T_c is about 76 K, and the contact resistance is about 75 Ω in this device. This contact resistance can be decreased by tightening the four contact rig screws, but excessive tightening can damage the mesa structure. The contact resistance of sample no. 1 is subtracted from the data, as discussed in the following.

Figure 4(b) shows the typical bath-temperature T_b dependence of the outer I-V characteristic branch of stand-alone mesa sample no. 1 obtained at $T_b = 15$, 50, and 70 K. It is remarkable that at 15 K, the bias V is as high as 7 V even though the mesa is 3–4 times thicker than those previously studied [8,29,30]. This fact can be attributed to the more-efficient heat transfer away from the device through the sapphire plates that sandwich the stand-alone mesa structure. This notion is further supported by the fact that the I-V characteristics in Fig. 4(b) do not show a clear backbending behavior with negative differential resistance, indicative of self-heating commonly observed in previous mesa structures with Bi2212 substrates. Although the mesa temperature T of sample no. 1 may be considerably higher than T_b, the maximum voltage that can be applied across each IJJ is increased from that allowed in previous mesas due to the more-efficient cooling of sample no. 1. Because of this efficient cooling effect, the I-V characteristics show large hysteresis as the bias current is cycled as in Fig. 4(b). This hysteresis of the I-V characteristics shrinks rapidly as T_b increases close to T_c.

The radiation-output power detected by the InSb HE bolometer at the T_b values 15, 50, and 70 K is plotted in Figs. 4(c) and 4(d). Note the logarithmic scale of the bolometer output voltage $V_{\rm out}$. As seen in Figs. 4(c) and 4(d), the radiation occurs at bias voltages around 4 and 6 V with $T_b = 15$ K, where the I-V characteristics are in the vicinity of an instability prior to the retrapping phenomenon. It is remarkable that the radiation-output power at 50 K and bias V of 2.2 V is nearly 1 order of magnitude larger than the radiation at 15 K around the bias V of 3.5 V, as displayed in Figs. 4(c) and 4(d). The emission from sample no. 1 is still strong around the bias point of 1.3 V even up to $T_b = 70$ K, just a few kelvin below $T_c = 76$ K.

Figure 4(e) shows the radiation spectra obtained at $T_b = 13$ K for two different bias points. Note that the spectra shown in Figs. 4(e)–4(g) are measured at slightly different temperatures than the I-V characteristics and the bolometer responses shown in Figs. 4(a)–4(c). At the lower bias point of approximately 4.1 V, a radiation spectral peak centered at 0.75 THz is observed. On the other hand, at the higher-V bias point of approximately 6.4 V, radiation with both a

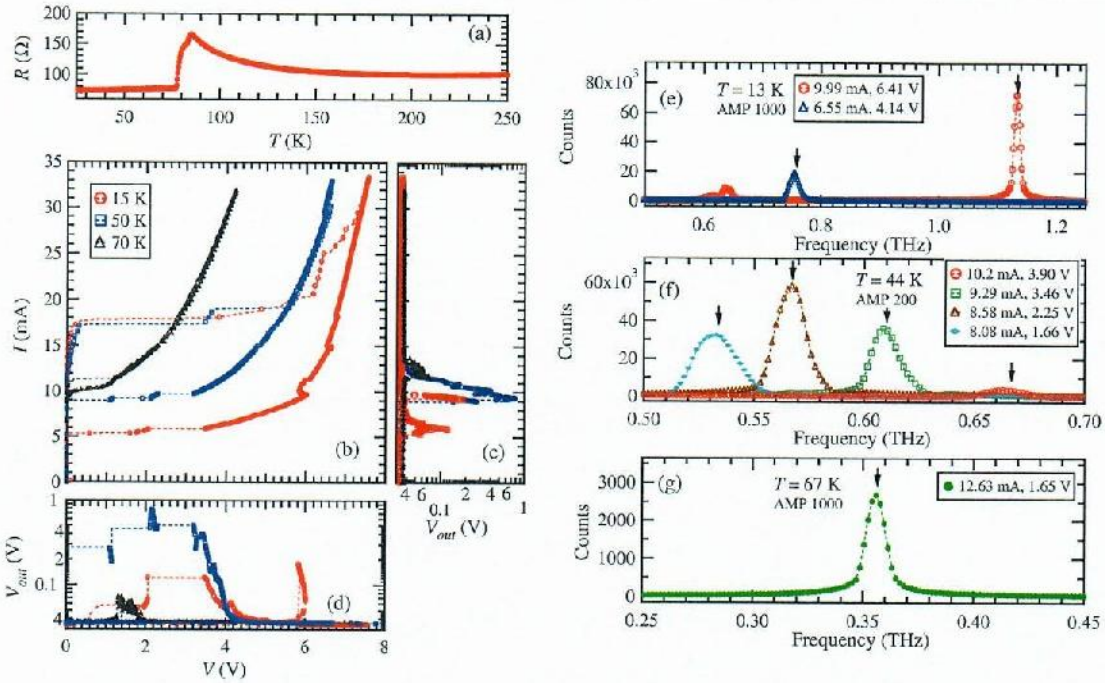

FIG. 4. (a) $R_c(T_b)$ of sample no. 1. (b) Typical I-V characteristics of sample no. 1 obtained at $T_b = 15$, 50, and 70 K. (c), (d) Semilogarithmic plots of the output voltages $V_{\rm out}$ of the InSb hot-electron bolometer versus the current I and voltage V applied to sample no. 1, respectively. (e),(f),(g) The radiation spectra at the bias points indicated in the legends observed at $T_b = 13$, 44, and 67 K, respectively, and at amplifier (AMP) gain values of 1000, 200, and 1000, respectively.

sharp peak at 1.14 THz and a small peak at 0.63 THz is observed. Similar behavior is also observed from sample no. 2; however, the difference between the two frequencies is smaller than between the analogous two observed from sample no. 1 shown in Fig. 4(e). Although it may be related to the thick mesa height of 4.7 μm and the sandwich structure of the mesa, the precise reason for the two radiation frequencies at a single bias point is presently unclear. It seems that neither the emission at 0.75 THz from the lower bias point nor that at 1.14 THz from the higher bias point can be easily explained by the excitation of a half-wave-length cavity mode with the measured width of 58–66 μm (0.62–0.54 THz) across the rectangular mesa structure, as is usually observed in rectangular mesa structures [8,29,30,43,44].

Figures 4(f) and 4(g) present other examples of unusual emission characteristics obtained at different T_b values. Sometimes the spectra observed at a fixed I-V position exhibit additional peaks, as seen in Fig. 4(e), or a broad line as found in Fig. 4(f). Note that the frequency scale in the abscissa is different in Fig. 4(e) from those in Figs. 4(f) and 4(g). Since the frequency resolution of our FTIR spectrometer is approximately 7.5 GHz, the line widths observed in Fig. 4(f) are wider than the limit of our FTIR resolution. This sort of rather broad line width is also observed in the case of radiation in the low-bias-current region [45]. It is also evident that the line widths can be both frequency and temperature dependent. In addition, the squeezing of the two sapphire plates sandwiching the present mesa structure can cause inhomogeneous stress broadening. This stress effect, in fact, seems to appear as rather small jumping irregularities in the I-V characteristics.

Next, we measure the T_b dependence of the radiation frequencies and their intensities at several bias points. These are displayed in Fig. 5. The data in Fig. 5 are mainly obtained from the outermost I-V characteristic branch and include the experimental points in the retrapping (low-I bias) I-V characteristic region. The details of the radiation-frequency data obtained from the multibranching I-V characteristic structure is discussed in Sec. IV D.

In Fig. 5(a), a plot of the bias current I versus voltage V at the color-coded T_b values is presented for all the measured outer-branch I-V characteristic data points for which terahertz radiation is observed. Since the I-V characteristic hysteresis decreases with increasing T_b, the bias points where terahertz radiation is observed gradually shift from higher V and lower I bias to lower V and higher I bias with increasing T_b.

In Fig. 5(b), the radiation frequencies f obtained from the various bias points shown in Fig. 5(a) are plotted as a function of T_b. A strongly-T_b-dependent emission frequency is observed: higher frequencies are observed at lower T_b values, and lower frequencies are observed at higher T_b values. The maximum frequency detected here

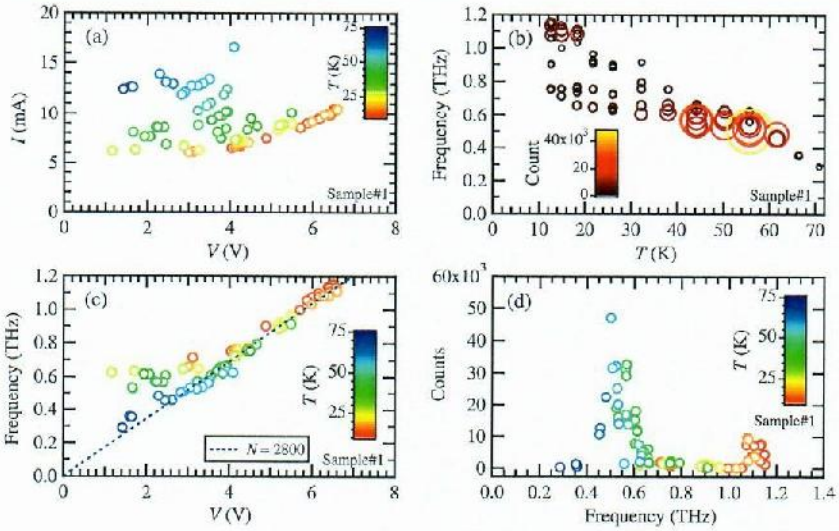

FIG. 5. Emission characteristics observed from sample no. 1. (a) The relationship between the bias current I and voltage V for all observed electromagnetic-wave radiation data at various T_b values described by the color code. (b) The relationship between the observed radiation frequencies and T_b. The observed terahertz-radiation intensity measured by the FTIR spectrometer is both color coded and depicted by the sizes of the circles. (c) The relationship between the observed radiation frequencies and the applied bias voltages V and the color-coded T_b. The dotted line shows the ac Josephson relation with $N = 2800$. (d) The relationship between the observed spectrum radiation intensities and its frequencies at the color-coded T_b.

is 1.14 THz at $T_b = 13$ K, whereas the lowest frequency observed is 0.30 THz at $T_b = 71$ K. Such temperature-dependent behavior has been reported previously by Wang *et al.* [40] and Benseman *et al.* [42]. The overall behavior of the data shown in Fig. 5(b) agrees very well with their data. The T_b dependence of the terahertz-radiation frequency f is attributed to the T_b dependence of the I-V characteristics shown in Fig. 4(b). The changes in the emission-bias V value with T_b changes are consistent with f obeying the ac Josephson relation, $f = f_J = (2e/h)V/N$. This behavior is clearly seen in Fig. 5(c), where f is plotted versus V. As seen in Fig. 5(c), most of the experimental data are consistent with $f \propto V$, in agreement with the ac Josephson relation for a particular N value. Those data are obtained from the I-V characteristic outer branches, which have the same N values.

However, there are data points in Fig. 5(c) that deviate from the linear dotted line, especially below $f = 0.75$ THz. These data points arise from inner-branch I-V characteristics, not from the outermost I-V characteristics. Although at first sight they appear to violate the ac Josephson relation, in reality they do not, because in the inner branches, the number N_{act} of active intrinsic Josephson junctions is reduced from the total number N of the mesa device, so that the bias V is proportionately reduced. Hence, the ac Josephson relation is still valid for N_{act} active junctions, even for the inner-branch I-V characteristics [43].

In Fig. 5(d), the FTIR spectroscopic peak intensity is plotted with the color-coded T_b values versus the emission frequency f. As clearly seen, the observed spectral intensity depends strongly upon f. The emission spectrum exhibits two distinct peaks at 0.5 and 1.1 THz, which correspond, respectively, to the transverse magnetic TM(1,0) and TM (2,0) cavity resonance modes of the mesa with the width range of 58–66 μm (0.62–0.54 THz). This correspondence means that those particular rectangular-cavity modes appear to enhance the emission power. Similar behavior is also seen in other measurements [51].

Most of the above radiation characteristics are well reproduced by those obtained from sample no. 2, as shown in Fig. 6. However, the f versus V data obtained from sample no. 2 and shown in Fig. 6(c) exhibit a wider V (or f) range of strong deviations from the linear ac Josephson relation than do the data shown in Fig. 5(c) obtained from sample no. 1. These sample no. 2 radiation data are obtained from the higher-I-bias points in the I-V characteristics. For the data points obtained near to $T_b = 20$ K in Fig. 6(c), different f values are observed at similar V biases. The f values observed at low-I biases are higher than those obtained at higher-I biases. This result might be caused by increases in the effective temperature T of the mesa structure due to self-heating effects, because a decrease in the effective bias V by self-heating causes a decrease in the central radiation f. Similar behavior was also discussed by Benseman *et al.* [64].

C. Estimation of radiation power

As shown in Figs. 5(b) and 5(d), the strongest radiation is observed from sample no. 1 at around $T_b = 55$ K. We estimate the radiation power by using the power meter at $T_b = 56$ K. A schematic side view of the experimental setup for power measurements is shown in Fig. 7(a). The power meter is placed at a distance of approximately 30 mm from the emitter and is near to the polyethylene optical window of the He flow cryostat.

The black symbols in Fig. 7(b) depict the multibranching I-V characteristic structure from sample no. 1 obtained at $T_b = 56$ K. The radiation intensities on the I-V characteristics are color coded according to the scale on the right ordinate axis. The strongest radiation is observed at the bias

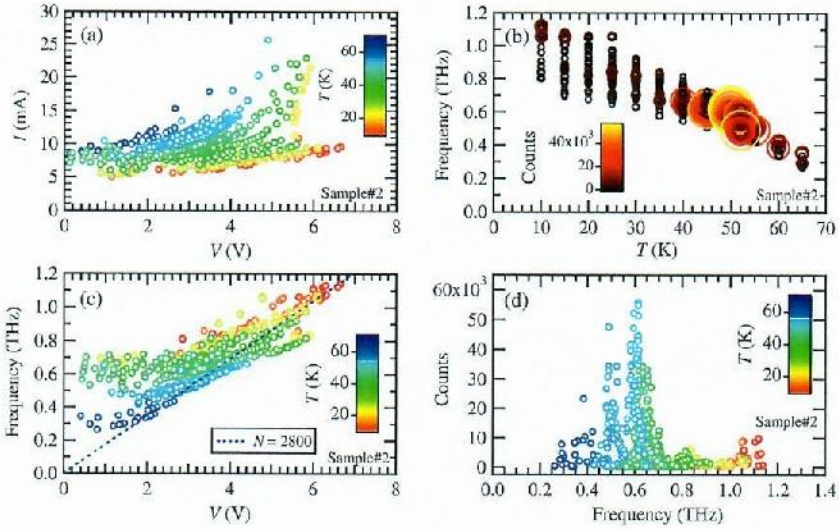

FIG. 6. (a)–(d) The same emission characteristics of sample no. 2 as those shown in Fig. 5 for sample no. 1.

point of around 12 mA and 2.2 V. Figure 7(c) details this high-intensity I-V characteristic region with I (left axis) and the radiation intensities detected by the power meter (right axis), at the same V bias values. The maximum output power from this sample is detected to be about 6.5 μW at the bias point of around 2.2 V. According to the radiation pattern from sample no. 1 discussed in the following section and the losses at the detector, the total radiation-power level is estimated to be on the order of a few tens of microwatts, which is comparable to the maximum power of approximately 30 μW that is observed from other stand-alone mesa structures. The maximum output power observed from a single stand-alone mesa by our group is presently approximately 30 μW [49–51].

This radiation-intensity value is also checked using the response of the InSb HE bolometer. The output voltage of the bolometer at the same bias point is about $V_{\mathrm{det}} \sim 2.5$ V. According to previous studies [49], this corresponds to the incident terahertz-radiation power, $P = 2\sqrt{2}V_{\mathrm{det}}/\alpha \approx 2.1\ \mu$W, where $\alpha = 3.3$ mV/nW is the system optical responsivity calibrated with black-body radiation. Therefore, the output-power estimates obtained from the power meter and from the InSb HE bolometer are consistent.

D. The radiation characteristics on the multibranching structure of I-V characteristics

Figures 8(a)–8(d) show the temperature dependence of the multibranching structure of the I-V characteristics displayed by their related color-coded radiation intensities for the T_b values 10, 30, 40, and 50 K. In these figures, the background-signal levels of the right power color codes are 0.06–0.07 in arbitrary units.

As seen in Figs. 8(a)–8(d), the hysteresis of the I-V characteristic loops shrinks gradually with increasing T_b, as is commonly observed. In examining the radiation intensity in detail as T_b is varied, a dramatic change in the radiation behavior is found. At 10 K, there are two current regions around 6 and 10 mA where the radiation intensity is strong. In the higher-current-bias region, a higher radiation frequency around 1.1 THz corresponding to the cavity

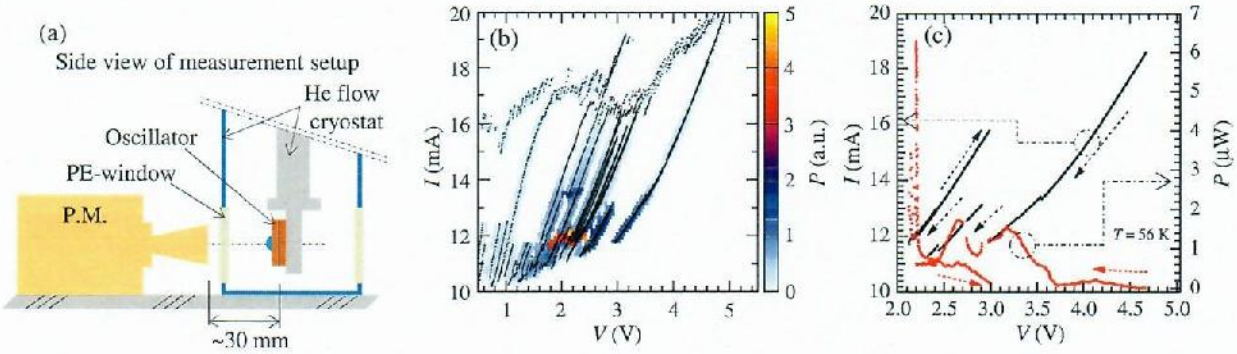

FIG. 7. (a) Schematic side view of the setup for the radiation-power measurements. (b) Multibranching I-V characteristic behavior obtained at $T_b = 56$ K. The radiation intensity is color coded on the I-V characteristics. (c) Some details of the I-V characteristics shown in (b) (black, left axis) and the corresponding radiation power (red, right axis) detected by the power meter (P.M.).

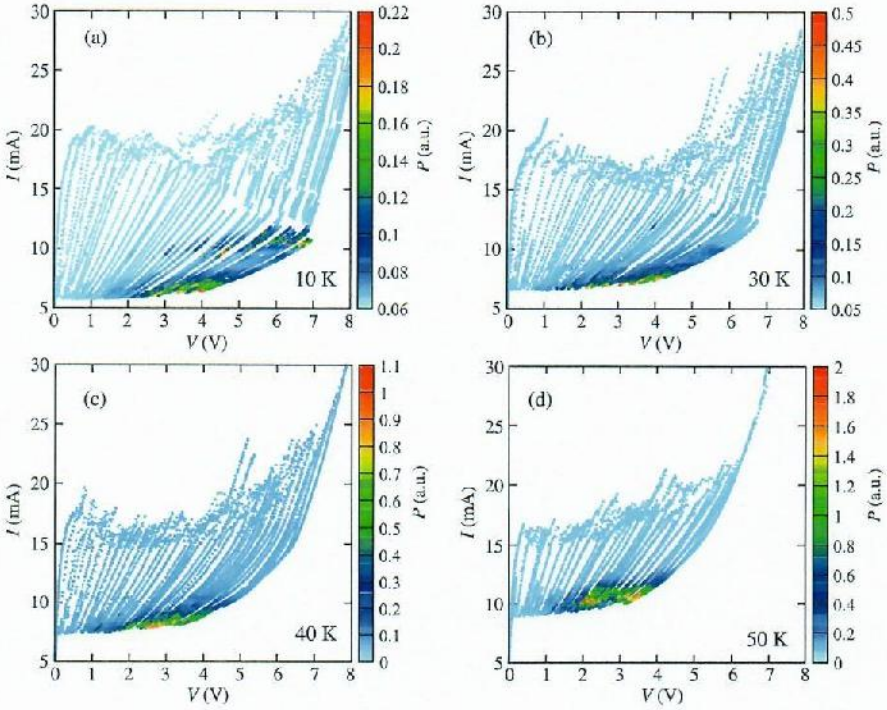

FIG. 8. Temperature dependence of the multibranching structure of the I-V characteristics displayed by their related color-coded radiation intensities for 10 K in (a), 30 K in (b), 40 K in (b), and 50 K in (d).

TM(2,0) mode is observed as discussed in the previous section. At 30 K, a drastic change in the radiation behavior is seen, although the overall I-V characteristics do not change significantly. This change is found in Fig. 8(b), where the radiation intensity that is seen for $I \sim 10$ mA at 10 K is no longer observed, and the radiation in the lower-current region grows and dominates the output despite little changes in the multibranching I-V characteristic structure. With further increases in T_b, the radiation intensity from the lower-current-bias points increases, and the bias region of radiation appears to be extended over a wider I range at higher T_b values.

It is interesting to note that there is very little evidence for possible hot-spot behavior seen in the I-V characteristics. For "conventional" mesas with Bi2212 substrates, hot-spot behavior is evidenced by sudden jumps in the I-V characteristics and in strong I-V characteristic backbending behavior. In the I-V characteristics exhibited in Fig. 8, the only features that might be attributable to overheating are the I-V characteristic kinks seen in Fig. 8(a) at 10 K and in Fig. 8(b) at 30 K, but the I-V characteristic data taken at 40 and 50 K do not show significant kinks.

Besides the overall decreases in the I-V characteristic hysteresis area with T_b increases, another notable feature evident in the four I-V characteristics shown in Fig. 8 is the increase with T_b of the return I value. Note that in Fig. 8(a) at 10 K, the final return I is about 6 mA, and this value increases monotonically with T_b to 9 mA in Fig. 8(d) at 50 K. According to the resistively-and-capacitively-shunted-Josephson-junction model, the return current $I_R(T)$ is proportional to $I_c(T)/\sqrt{\beta_c}$, where $\beta_c \propto I_c(T)R^2(T)$ is the McCumber parameter. Thus, $I_R(T) \propto \sqrt{I_c(T)}/R(T)$. Since both $I_c(T)$ and $R_c(T)$ decrease with increasing T, the return current increases with increasing temperature. Strictly speaking, the direct application of the RCSJ model for the high-T_c IJJs is difficult, since there is no well-defined R value in this case. However, the observed behavior seems to be well explained by the RCSJ model.

In order to understand additional details of the radiation characteristics on the multibranching I-V characteristic structure, extensive measurements of the frequencies of the radiation from the inner I-V characteristic branches are made at three different T_b values. Color-coded maps of the radiation frequency results obtained at the typical T_b values 10, 49, and 55 K are displayed in Fig. 9.

The primary characteristic features of the radiation at 10 K seen in the three panels of Fig. 9(a) are summarized in the following.

(1) Very wide frequency tunability is observed, ranging from about 0.69 to 1.63 THz over the entire multibranching I-V characteristic structure. The radiation intensity has a sharp peak at about 1.14 THz, as seen in Fig. 9(a-3).

(2) The radiation frequencies observed from the innermost I-V characteristic branches are higher than those observed from the outer I-V characteristic branches. The highest radiation frequency of 1.63 THz is observed from an inner branch at the bias point of 4 V and 15 mA.

(3) The radiation frequencies obtained from the same I-V characteristic branch generally increase with

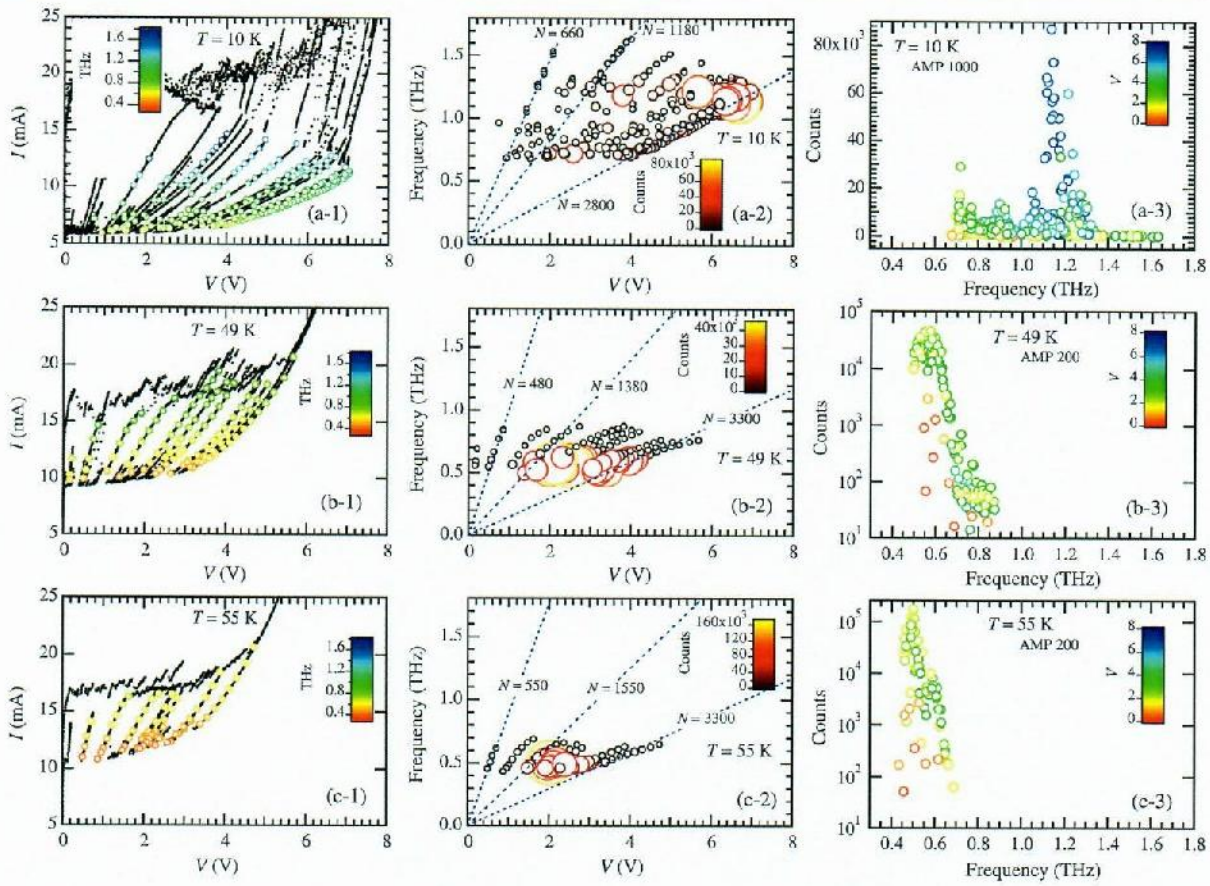

FIG. 9. Plots of three radiation features from the inner I-V characteristic branches at $T_b = 10$, 49, and 55 K. (a-1), (b-1), and (c-1) are the plots of the multibranching I-V characteristics and the related radiation frequencies on the I-V characteristics displayed by the color code. (a-2), (b-2), and (c-2) are the plots of the relationships between the observed radiation f values and the applied bias V values. The color code and the size of the symbols correspond to the radiation intensities. The dotted lines show the ac Josephson relation with different N values. (a-3), (b-3), and (c-3) are the plots of the relationships between the observed radiation intensities and the observed radiation f values. The color code indicates the applied bias V to the mesa structure. The respective detector amplifier gains in (a-3), (b-3), and (c-3) are 1000, 200, and 200.

the applied bias voltage. As shown in Fig. 9(a-2), the observed radiation frequencies are proportional to the applied bias voltages, and this behavior is maintained for all of the inner I-V characteristic branches.

(4) The strongest radiation at the frequency of approximately 1.14 THz is observed at the bias voltage of approximately 6.3 V on the outermost I-V characteristic branch. Similar behavior is observed from the I-V characteristic inner branches.

Next, the characteristic features of the terahertz radiation at 49 K are summarized in the following.

(1) Emission frequencies ranging from about 0.48 to 0.9 THz are observed on the multibranching I-V characteristic structure, as seen in Fig. 9(b-1). This frequency range observed at 49 K is narrower than that observed at 10 K. On the other hand, the radiation intensity at 49 K is much stronger over the broad peak centered at about 0.54 THz than that observed at 10 K. This is shown in Fig. 9(b-3).

(2) The radiation frequencies observed from the inner I-V characteristic branches are higher than those observed from the outer I-V characteristic branches, as is seen at 10 K, and this relative behavior may be common to the inner and outer branch radiation.

(3) The observed radiation f values are mostly proportional to the applied bias V values, as for the results of 10 K. However, a slight deviation from this linearity is observed in the higher-f region, as seen in Fig. 9(b-2). This deviation might possibly be due to the effects of complicated branching structures at the high-voltage branch ends. Another possible reason for the nonlinearities may be the self-heating effects at the higher-bias I values, as discussed in the previous section for the radiation from sample no. 2.

(4) The strongest intensity at approximately 0.54 THz occurs on the inner I-V characteristic branches around 2.1 V. This is a rather rare case, because in most of the previous cases, the outer branch shows the strongest power.

Finally, the characteristic features of the radiation at 55 K are summarized in the following.

(1) Radiation f values ranging from about 0.42 to 0.69 THz are observed on the multibranching I-V characteristic structures as shown in Fig. 9(c-2). The radiation intensity has a peak at about 0.50 THz, as seen in Fig. 9(c-3).

(2) The observed radiation f values are mostly proportional to the applied bias V values, as for the radiation observed at 10 and 49 K. However, deviations from this linearity are also observed in the higher-f region, as seen in Fig. 9(c-2). This behavior is also similar to the results obtained at 49 K.

(3) Very strong radiation with a frequency of about 0.50 THz is observed over the very narrow-bias region around 2.0 V and 12 mA of the inner I-V characteristic branches. This strong emission can be attributed to the TM(1,0) cavity mode of sample no. 1.

In addition to these characteristic features, a few further remarks are warranted. As seen in Figs. 9(a-2), 9(b-2), and 9(c-2), the N values are not the same because the radiation from the inner branches is detected intentionally. Note that the dotted lines, which in Figs. 9(a-2), 9(b-2), and 9(c-2) are just guides for the eye, are for the data obtained from some of the inner I-V branches and the outermost I-V curves. The N's are estimated from the slope of the dotted line, and they are given in Figs. 5, 9(a-2), 9(b-2), and 9(c-2). All N values are not given there, but the frequencies are measured at the points located at all the circles shown in Figs. 9(a-2), 9(b-2), and 9(c-2). For the emissions from the same I-V branch, no matter which branch, the slopes of the straight lines passing through the origins on the frequency versus voltage plots allow one to obtain the effective number N of operating junctions from the ac Josephson relation $hf = 2\ \mathrm{eV}/N$. According to the slope of the frequency-voltage plot in Fig. 9, the maximum number of operating junctions $N_{\max}$ increases from $N_{\max} = 2800$ (10 K) to $N_{\max} = 3300$ (50–55 K) with increasing T_b. This different number of emitting JJs at various T_b might be caused by a temperature distribution along the c-axis of the Bi2212 mesa structure that can vary with T_b, because at lower T_b, the IJJs adjacent to the sapphire substrates might be in a superconducting state at all bias currents with this experimental condition [42,64].

Second, the emission frequencies generally shift from higher values at lower-T_b values to lower values at higher-T_b values. However, the radiation intensity is sometimes greatly enhanced by even an order of magnitude. In particular, stand-alone mesa sample no. 2 exhibits two strong radiation peaks at around 0.54 and 1.14 THz. These results are consistent with the double peak shown in Fig. 5(d). These results clearly indicate and reconfirm that the cavity-enhancement mechanism for the terahertz radiation is working properly, but its peculiar T_b dependence is still unresolved. As for the radiation f, it is basically proportional to the applied bias V as seen in Figs. 9(a-2), 9(b-2), and 9(c-2), reminiscent of the ac Josephson effect widely considered to be the driving force of terahertz radiation from IJJs. Although considerable deviations from the linear relation at higher-T_b values are observed, some possible reasons for these deviations are discussed.

Finally, one interesting feature to be emphasized is that the strongest radiation is observed at a particular inner I-V characteristic branch at 55 K, as shown in Figs. 9(c-2) and 9(c-3). In most cases, the strong radiation occurs at a relative high-T_b value on an outermost I-V characteristic branch point or on an inner-branch point that is rather close to the outermost I-V characteristic branch. As shown in Figs. 9(b-2) and 9(c-2), at biasing on the inner I-V characteristic branches, some IJJs are in operation, and these IJJs can be well synchronized only at some frequencies (e.g., 0.5 and 1.1 THz, where cavity resonances take place). These results suggest that there may be an optimal number of intrinsic Josephson junctions for strong radiation from a particular stand-alone mesa structure.

It is noted that the highest radiation $f = 1.63$ THz is also observed from an inner branch. In previous studies, the creation of a hot spot or/and the overheating of the mesa caused a clear V-bias jump with small I changes [32,53,54]. Therefore, the radiation frequency at the high-bias-I region above the bias V jump on the I-V characteristic is lower than that of the low-bias-I region because of the reduction of applied bias V to the mesa due to the Joule heating. In addition, by decreasing V further into the inner branches and into the low-I-bias region, the total Joule heat decreases. Therefore, the V-bias jump is suppressed on the inner I-V characteristic branches and in the low-I-bias current, and since the number of active junctions N_{act} decreases faster than V, f increases. These effects may partly explain the increase in f in the inner I-V characteristic branches. These points are important for the design of high-frequency IJJ terahertz emitters.

E. Radiation patterns

Figure 10 shows the angular (θ) radiation patterns obtained at 10 and 49 K with the Si lens. A sketch of the angle θ is given in Fig. 10(a). Simultaneous Si-bolometer measurements of the radiation intensities at fixed θ values and the I-V characteristic bias voltages as in Figs. 4(b) and 4(c) are made. The radiation at each angle θ is obtained from the output voltages of the bolometer taken at a fixed bias point on the I-V characteristics, and the combined results are shown in Fig. 10. The radiation frequencies at the fixed bias points at 10 and 49 K are measured with the FTIR spectrometer. The angular

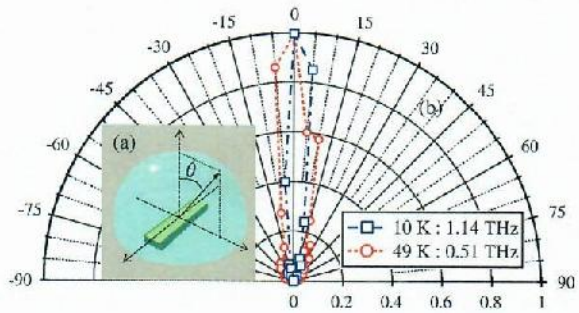

FIG. 10. Inset (a) Schematic definition of the angle θ. (b) Respective θ (in degrees) dependences of the radiation intensities observed by the Si bolometer at 10 K (approximately 1.14 THz) and 49 K (approximately 0.51 THz).

distribution patterns at both $T_b = 10$ and 49 K are sharply peaked within $\pm 10° - 15°$ of $\theta = 0°$ (perpendicular to the mesa device), as shown in Fig. 10(b), due to the strong focusing effect of the hemispherical Si lens attached onto the sapphire plate just above the mesa structure, as sketched in Figs. 10(a) and 3(e), a photograph of which is shown in Fig. 3(f). Note that the peak of the radiation patter at $\theta = 0°$ may also be due to the effect of the sapphire substrates and the metallic structures around the mesa.

F. Applications of the IJJ terahertz oscillator

Finally, we demonstrate a few examples of imaging applications of the stand-alone mesa device characterized in this work.

First, we show an example of a terahertz-transmission image of an integrated-circuit (IC-)embedded card, which is taken with a moving sample stage. The terahertz beam is focused onto the sample with two off-axis mirrors, and the transmitted terahertz beam is detected by the InSb hot-electron bolometer with a lock-in amplifier. To facilitate the lock-in detection, the output power of the IJJ terahertz oscillator is modulated by superposing an ac square-wave voltage of amplitude 90 mV and frequency 10 kHz onto the dc bias voltage with a function generator. This power-modulation (PM) technique allows for much greater detection sensitivity than does the conventional PM method using an optical chopper, because the background noise mostly originating from thermal fluctuations can be essentially removed. Further details of the detection method were described previously [57].

Figures 11(a) and 11(b) display two transmission images of the card taken at 1.01 and 0.56 THz, respectively. These pictures are taken by using stand-alone mesa sample no. 1 as the source. The imaging data at 1.01 and at 0.56 THz are taken with two samplings per millimeter and one sampling per millimeter, respectively. Figure 11(c) represents an optical photograph of the IC card used for transmission imaging.

For the generation of EMWs at 1.01 THz, the sample is cooled to 10 K. On the other hand, for the generation of

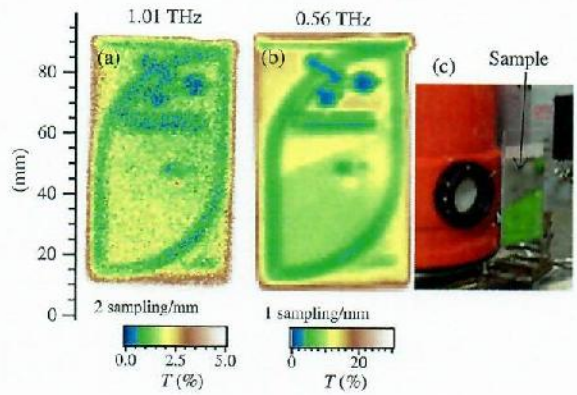

FIG. 11. Transmission images of the sample taken (a) at 1.01 THz with two samplings per millimeter and (b) at 0.56 THz with one sampling per millimeter. (c) Optical photograph of the IC card sample.

0.56 THz waves, T_b is controlled at 50 K. In this way, the frequency-dependent data can be accumulated by simply adjusting T_b of the mesa and the I-V characteristic point. Figures 11(a) and 11(b) are plotted with different transmittance scales. In comparing Figs. 11(a) and 11(b), it appears that the transmittance at the higher frequency is lower than that at the lower frequency. Thus, the results shown in Fig. 11 clearly indicate that there is a frequency dependence to the transmission characteristics of the sample. Hence, by taking transmission images at many fixed frequencies by changing the device emission conditions, it is, in principle, possible to measure the transmission-frequency spectrum of the object.

Next, we show a reflection type of imaging of an identification (ID) card as a second example of terahertz imaging, by again using stand-alone mesa sample no. 1 as the source. Figures 12(a) and 12(b) display the reflection images taken from the front and back sides of the ID card at 0.56 THz and $T_b = 50$ K. The images are plotted with the normalized reflectivity scale by using the metallic part of the moving sample stage. It is noted that the image of

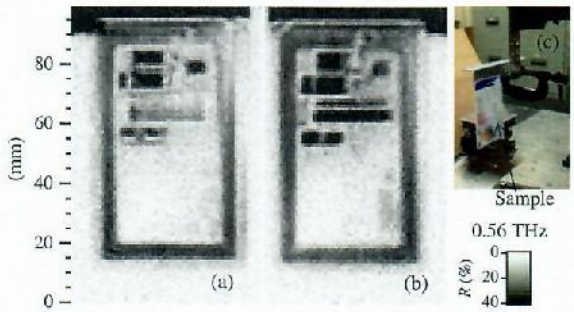

FIG. 12. Reflection images of the ID card taken from the front (a) and back (b) sides measured at 0.56 THz with one sampling per millimeter. (c) Optical photograph of the ID card sample.

Fig. 12(b) is flipped left to right. Figure 12(c) shows an optical photograph of the object. The details of the experimental setup were reported previously [58].

The reflection-type images shown in Figs. 12(a) and 12(b) appear to contain more information regarding the detailed internal structure of the object than do the transmission images, especially concerning the hidden structure located in the interior of the card. Since the ID card used here is the same one studied previously [58], the reflection images obtained here reproduce very well the previously reported ones.

The combined information from both transmission and reflection images is very helpful to investigate the internal structure of the object. Therefore, the transmission and reflection types of measurements play complementary investigation roles. These techniques may be useful for quality control of factory production of certain objects.

V. CONCLUSIONS

We develop a simple process for the mechanical fabrication of stand-alone mesa structures. Using a stand-alone mesa structure with a simple assembly method, we generate electromagnetic-wave radiation and present its characteristic features over the very wide frequency range from 0.3 to 1.63 THz. The device prepared here is easy to handle and is well suited for practical uses of an IJJ terahertz oscillator. To demonstrate the properties of this new type of device, we show its radiation characteristics and images of an object obtained from the actual device developed here. The results presented here will overcome the terahertz gap and provide the strong promise and fruitful features for terahertz applications such as spectroscopy, imaging (transmission, reflection, and computed tomography types), etc.

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Tilted vortex lattice in irradiate $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals

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Abstract. In order to enlighten the structure of vortex matter in irradiated layered $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals, the interaction of Josephson vortices and pancake vortices in was investigated by means of the local ac-magnetic permeability measurements by using the miniature local coils, while vortex matter in pristine crystals was studied by in-plane resistivity measurements. The transition anomaly, separating the strong pinning phase and the weak pinning vortex phase was found by both techniques deep in the vortex solid phase solid near ab-plane, indicating crossover from the vortex chains + lattice phase to tilted vortex chains phase. While the columnar defects affect strongly the first-order vortex-lattice melting transition, the magnetic permeability anomaly, associated with the crossover from vortex chains + lattice phase to tilted lattice, is surprisingly still clear, deep in the vortex solid phase. However, the stronger columnar defects eventually affect the crossover anomaly that it disappears too.

1. Introduction

Vortex matter in layered superconductors, such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals, differs from vortex lattices in moderately anisotropic superconductors, such as $YBa_2Cu_3O_{7-\delta}$. In tilted magnetic fields, $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples have two types of vortices: the c-axis component H_c of the magnetic field produces (2D) pancake vortices (PVs) [1], while the in-plane field component H_{ab} generates Josephson vortices (JV) between the CuO_2 planes [2,3]. Interacting crossing PV and JV lattices have been studied theoretically [3]-[7] and recently were observed by using Lorentz microscopy [8,9], scanning Hall probe microscopy [10], and magneto-optical imaging [11]. There are two reasons of this surge of the interest to vortex matter and in particular crossing vortex lattice in layered superconductors. First, crossing vortex lattices exhibit non-trivial and fascinating dynamical behavior (see,e.g., [12,13]) which allows us to manipulate [14]-[18] one vortex lattice via another one (or in more general interacting nanoparticles), as well as non-standard thermodynamic properties [19-25]. For instance, in contrast to the Ginzburg–Landau (GL) approach, the first-order melting transition line (the boundary separating the vortex-solid and vortex-liquid phases) exhibits a 'step-wise' shape [19] (i.e., approximately linear decay interrupted by two flat-plateau) if plotted in the H_c–H_{ab} plane.

Namely, the c-axis component H_{trans} of magnetic field at the phase transition decays linearly when increasing H_{ab}, followed by a plateau. A similar stepwise shape of the phase boundary was observed [26] at a much lower temperature, where disorder plays an essential role and the transition is smooth, in contrast to first-order. Thus, this suggests that the shape of the transition line is controlled by general thermodynamic properties, rather than the precise statistical features of the vortex-solid-phase, including vortex-glass, Bragg-glass, or Bose-glass. The second reason of huge interest to vortex phase diagram in Bi-compounds is related to possible application of this material for superconducting THz electronics [27-38].

In this article we report recent measurements of the vortex-solid phase diagram in $Bi_2Sr_2CaCu_2O_{8+\delta}$ pristine and irradiate samples and observation of the phase boundary deep in the vortex solid phase which can be attributed to a vortex structure transition. This transition smears out for strongly irradiated samples. We discuss this transition based on the vortex phase diagram having both tilted and crossing vortex lattice structures.

2. Experiment

The two $Bi_2Sr_2CaCu_2O_{8+\delta}$ as-grown single crystals with T_c = 89 and 88.9 K were used . These samples had defects along c-axis introduced by heavy-ion irradiation ($_{127}I_{28+}$,650 Mev), with doses of B_Φ = 0.1 and 0.02 T, respectively. The vortex phases were probed via local ac mutual-inductance measurements by using a set of two miniature coils. The size of the coils was 0.35 mm, which was sufficiently smaller than the size of the samples (~3mm × 3mm) in order to diminish the surface barrier.

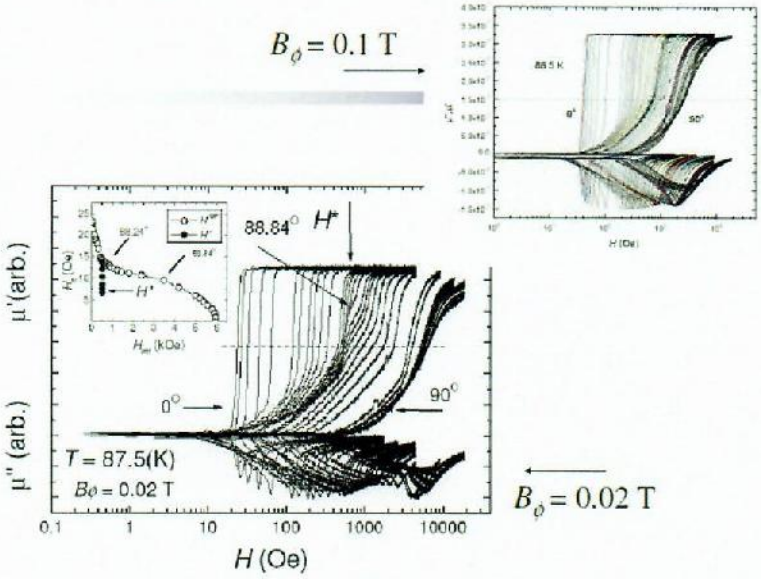

Figure 1. The magnetic field dependence of the real and imaginary parts of the ac-local magnetic permeability μ for irradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$, with two doses B_Φ = 0.1 T (upper) and B_Φ = 0.02 T (lower) with corresponding phase diagram (left).

The dc magnetic field, generated by a 70 kOe split coil magnet, was rotated with a fine angular resolution of 0.01°. A representative set of data (ac-local magnetic permeability versus dc magnetic field for different angles) is shown in Fig. 1. In order to construct the phase boundary, we used the voltage level of 15μV (approximately middle point between zero and the saturation value of the real part of the permeability, μ).

3. Discussion

Comparison of the free energies of crossing and tilted vortex lattices result in a complicated picture of phase transitions between these vortex structures. The proposed phase diagram [4] is shown in Fig. 2.

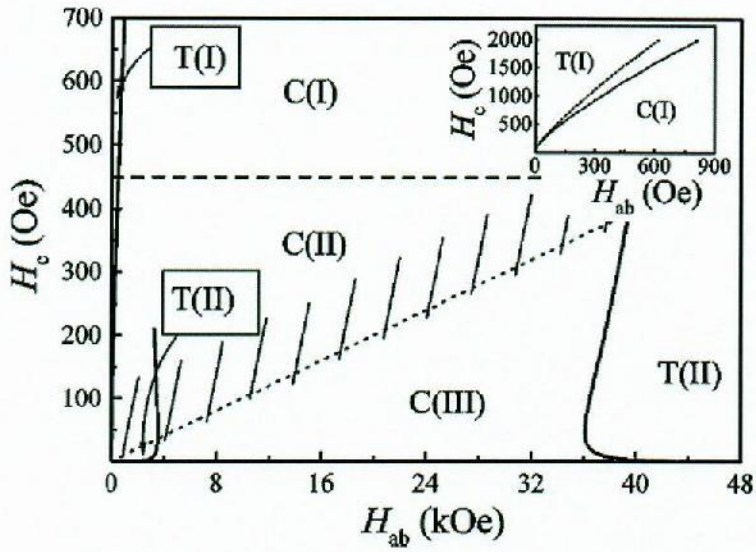

Figure. 2. The proposed phase diagram of the vortex-solid phase in the oblique magnetic fields [4].

The tilted vortex structure TI of inclined PV stacks can be replaced by the crossing lattice quite close to the c axis (see phase diagram obtained for $\gamma = 500$, inset in Fig. 2). The crossing lattice, which exists in a wide angular range, can have different substructures. At high enough out-of-plane fields, the ''shifted'' PV sublattice is realized in the crossing-lattices structure where the PVs are shifted from their equilibrium positions by currents generated by JVs.

In this substructure, the JV currents shift the PV's mostly along the x axis. The ''shifted'' phase can transform into the ''trapped'' PV lattice CII when the energy gain related to the ''crossing-lattice pinning'' exceeds the energy needed for the additional shear deformation (the dashed line in Fig. 2 separating CI and CII). Around the this line, the lattice CII can be changed by the tilted lattice TII with JV strings linked by PV kinks Fig. 2 bottom panel or by the crossing-lattice structure CIII at which all PV stacks are placed on a few JV's. As one can see, the vortex phase diagram in layered superconductors is very complicated even with no disorder or pinning. Disorder can affect this by both shifting phase boundaries from their no-disorder position and smear or even destroy phase boundaries. The experiments discussed here seems to be related to phase boundary between TII and CII (or CIII) phase boundary. This boundary is defined by the condition of the balance between the free energy F_t of the tilted lattice and the free energy of the crossing lattice F_c: $F_t(H_c,H_{ab}) = F_c(H_c,H_{ab})$. In the presence of pinning, we have to include the term, describing the interaction of vortices with disorder, which by itself is very non-trivial procedure. In the naive approach, we could just add a term F_p (H_c, H_{ab}, H_T), where H_T describes the dose of irradiation. One would expect the spreading $<[H_{ab}^{tran}(H_c)]^2> - <[H_{ab}^{tran}(H_c)]>^2$ of the phase line $H_{ab}^{tran}(H_c)$ to be proportional to H_T^2, which is consistent with our experimental results.

In conclusion, we study the deformation of vortex matter phase diagram of irradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples. The result is consistent with proposed earlier phase diagram for layered superconductor. However, a detailed description of disordered layered superconductors might require more detailed theoretical studies.

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PhD teza: "*Experimental study of static and low-frequent electromagnetic properties of ceramic and melted high-temperature superconductors.*", Moscow State University "M.V. Lomonosov", Russia, 1996.

Projekti

- Responsible Research & Innovation for Sustainable Ecosystems in Europe – SeeRRI / Network of Affiliated Territories member (HORIZON2020 - SwafS14-2018, coordinator: Nord University, Norway)
- Development of the E-Mobility Feasibility Study for Montenegro (United Nations Development Programme, coordinator: Energy Institute "Hrvoje Pozar", Croatia)
- "Superconducting Nanotechnologies", Ministry of Science, Montenegro, 2018-2019
- Antioxidant activity determination device "BLIZAR", Ministry of Science of Montenegro, 2018
- Production of lithium perchlorate, POLIEX together with partners, the Montenegrin Science Promotion Foundation – PRONA and Faculty of Science and Mathematics, University of Montenegro
- *Youth Science Forum / Debate Science* – HORIZON2020 / 2018-2020
- "Nanoscale Coherent Hybrid Devices for Superconducting Quantum Technologies" (NANOCOHYBRI) CA16218, 2017-2020
- „Physics of Nanostructures", Ministry of Science, Montenegro, 2013-2016
- „Physical properties of layered superconductors", Ministry of Science, Montenegro, 2008-2011
- "Montenegro in XXI Century - in the Era of Competitiveness: Science and Technology", Coordinator, Montenegrin Academy of Sciences and Arts, Podgorica 2009 - 10
- „Science and Youth", Montenegrin Science Promotion Foundation PRONA, 2009
- Science Festival - Researchers' Night 2009-2015, Podgorica, Montenegro (Program Coordinator)
- Summer Physics School 2008-2010; Summer School of Physics and Mathematics 2011, Summer Science School 2012-2013, Ivanova Korita (President of the Program Committee)
- Summer School *Planet in Your Hands* 2011-2013
- Inquiry based science education methods program, 2011
- Students Impact on Quality Assurance of High Education in Montenegro, 2009-10
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- „Theoretical and experimental investigation of thermodynamic and transport properties of superconductors", Ministry of Education and Science", Montenegro, 2005-2007
- „Introduction to Experimental Physics", Course development program (CDP+), WUS-Austria, 2004
- Multidisciplinary Centre for Experimental Study, World University Service - Austria, 2003.

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ODLUKU
O IZBORU U ZVANJE

Dr **JOVAN MIRKOVIĆ** bira se u akademsko zvanje **redovni profesor** Univerziteta Crne Gore za predmete: Osnovi fizičkog eksperimenta I i II, Istorija i filozofija fizike na **Prirodno-matematičkom fakultetu** i Fizika na nematičnim fakultetima.

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Rođen je 19. 03. 1950. god. u Gornjoj Ržanici, opština Plav. Diplomirao je na Tehničkom fakultetu u Titogradu (Podgorica) 1972. god., a magistrirao na Elektrotehničkom fakultetu u Beogradu 1975. god. sa temom "Efekat blizine u slučaju trakastih provodnika". Doktorsku disertaciju "Prilog mrežnom modelu difrakcije na planarnoj periodičnoj metalnoj rešetki" odbranio je 1996. god. na Elektrotehničkom fakultetu u Podgorici. Na fakultetu je od diplomiranja 1972. god.

Na posljednjem izboru 2010. god. izabran je za nastavnika na predmetima Mikrotalasna tehnika, Mikrotalasna kola i Mikrotalasna mjerenja. Ranije je držao predavanja iz Osnova elektrotehnike I i Teorijske elektromagnetike, Osnova elektrotehnike (na Fakultetu za proizvodnju i menadzment u Trebinju), Osnova informatike na Visokoj medicinskoj školi u Beranama i iz Mikrotalasne tehnike (na Fakultetu za pomorstvo u Kotoru). Naučne oblasti kojima se bavi su Teorijska elektromagnetika i Mikrotalasna tehnika. U periodima 1991 – 1992 i 1996 – 2000 bio je prodekan za nastavu.

Bio je na naučnom usavršavanju na Sirakuškom univerzitetu (SAD) u periodu 1975 – 1977 i na Moskovskom državnom univerzitetu (MGU) 1989. god.

Član je Naučnog komiteta Međunarodne konferencije za primjenjenu elektromagnetiku (International conference on applied electromagnetics), koja se od 1990. god. održava u Nišu svake druge godine.

Objavio je preko 40 radova u stranim i domaćim časopisima i na stranim i domaćim konferencijama.

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Naučna oblast: Teorijska elektromagnetika i Mikrotalasna tehnika

Spisak najvažnijih referenci

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12. **D. Filipović**, B. Lutovac, **Mikrotalasna tehnika**, Akademska misao, Beograd, 2019. godine, ISBN: 978-86-7466-818-4.
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ODLUKU
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Dr **DRAGAN FILIPOVIĆ** bira se u akademsko zvanje **redovni profesor** Univerziteta Crne Gore za predmete: Mikrotalasna tehnika, Mikrotalasna mjerenja i Mikrotalasna kola na **Elektrotehničkom fakultetu.**

REKTOR

Prof.dr Predrag Miranović

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Europass Curriculum Vitae

Lični podaci

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Datum rođenja	24.02.1959.
Pol	Muški
Oblast kojom se bavi	**Elektronika, Nastava, Inovacije, Konstruisanje i projektovanje, Inženjerstvo**

Radno iskustvo

Naziv i adresa poslodavca	**Elektrotehnički fakultet, Univerzitet Crne Gore, ul. Džordža Vašingtona, 81000 Podgorica, Crna Gora**
Vrsta posla ili sektor	**Javni sektor, državni univerzitet**
Vrijeme	Od 1984 do danas
Zanimanje ili pozicija	Redovni profesor
Glavne aktivnosti i odgovornosti	Nastava iz predmeta: 1) Elektronika, 2) Računarski interfejsi i periferije, 3) Projektovanje mikrokontrolerskih uređaja, 4) Identifikacioni sistemi, 5) Dizajn mehatroničkih uređaja, 6) Inteligentni senzori i aktuatori
Naziv i adresa poslodavca	**Institut "Mihajlo Pupin", Beograd, Srbija**
Vrsta posla ili sektor	Istraživački institut
Vrijeme	1981-1984
Zanimanje ili pozicija	Istraživač - saradnik
Glavne aktivnosti i odgovornosti	Projektovanje i razvoj hibridnog računara

Obrazovanje i treninzi

Vrijeme	**1989**
Titula stečene kvalifikacije	**Doktor nauka iz oblasti elektrotehnike**
Glavne teme / vještine koje je stekao	Elektro-inženjerstvo - "Tranzistorki invertori za vektorsko upravljanje asinhronim motorima"
Ime i tip organizacije u kojoj je stekao obrazovanje i trening	Beogradski unverzitet, Elektrotehnički fakultet
Nivo u nacionalnoj i međunarodnoj kvalifikaciji	Doktor nauka, Ph.D.
Vrijeme	**1983**
Titula stečene kvalifikacije	**Magistar nauka iz oblasti elektrotehnike**
Glavne teme / vještine koje je stekao	Elektro-inženjerstvo - "Generatori proizvoljnih funkcija"
Ime i tip organizacije u kojoj je stekao obrazovanje i trening	Beogradski unverzitet, Elektrotehnički fakultet
Nivo u nacionalnoj i međunarodnoj kvalifikaciji	Magistar nauka, M.Sc.
Vrijeme	**1981**
Titula stečene kvalifikacije	**Diplomirani elektro-inženjer**
Glavne teme / vještine koje je stekao	Elektro-inženjerstvo - elektronika
Ime i tip organizacije u kojoj je stekao obrazovanje i trening	Univerzitet Crne Gore, Elektrotehnički fakultet
Nivo u nacionalnoj i međunarodnoj kvalifikaciji	Diplomirani inženjer, B.Sc.

Lične vještine i kompetencije

Uglavnom saradnja sa privredom koja je rezultirala obiljem originalnih rješenja i sistema iz oblasti elektronike. Dobitnik nagrade Privredne komore Crne Gore za inovativnost 2008. godine.

Matemji jezik: Srpsko-hrvatski

Ostali jezici

Self-assessment	Understanding				Speaking				Writing	
European level (*)	Listening		Reading		Spoken interaction		Spoken production			
English	C1	Expert	C2	Mastery	C1	Expert	C1	Expert	C2	Mastery
Russian	B2	Communicator	C1	Expert	B2	Communicator	B2	Communicator	C1	Expert

(*) Common European Framework of Reference for Languages

Socijalne vještine i kompetencije: Zoran Mijanović je radio u velikom broju projekata koji su uključivali obrazovanje mladih ljudi, posebno i oblastima koje se tiču elektronike i inovacija. Član je predsjedništva "Mladih pronalazača Crne Gore" - fondacije koja je pomagala mladim učenicima srednjih škola da razviju sopstvenu inovativnost i izlože svoje pronalaske na godišnjem sajmu mladih pronalazača Crne Gore.

Računarske vještine i kompetencije: Računarske vještine:

- Operativni sistemi: Linux, Windows, Android
- Automatizacija dokumentacije: Office (Word, Excel, itd.), MS Project, Open office
- Vještine prezentacije: Libre Office Impress, MS PowerPoint
- Programski jezici: C, C++, Javascript, Node js, Python, Perl, Basic, Pascal, PHP

Vozačka dozvola	B kategorija
Dodatne informacije	Objavljeni naučni radovi – pogledaj Dodatak 1 Učešće u realizaciji mnogih projekata - pogledaj Dodatak 2:
Dodaci	Dodatak 1: Mijanović Zoran: Bibliografija Dodatak 2: Mijanović Zoran: Spisak projekata

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K 3.2. Radovi u časopisu medjunarodnog značaja

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K 3.3 Radovi u časopisu nacionalnog značaja

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3. Nedjeljko Lekic, **Zoran Mijanovic**, Desa Gobovic and Rada Dragovic –Ivanovic, The simple RS232 Hub to interface Microcontroller Peripheral Devices with the Central Processor, Proceedings of 10th IEEE International Conference on Electronics, Circuits and Systems - ICECS 2003, December 14-17, 2003, Sharjah, United Arab Emirates, ISBN: 0-7803-8164-5, pp. 1208-1211.
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K 6.1. Doktorska disertacija

Doktorat odbranjen na Elektrotehničkom fakultetu u Beogradu.

K 6.2. Magistarska teza

Magistarski rad odbranjen na Elektrotehničkom fakultetu u Beogradu.

K.8.1 Novi proizvod ili tehnologija u proizvodnji, programski sistem, sorta, linija, soj

1. RF identifikacioni sistem za praćenje nastavnih aktivnosti. Realizaciju sistema finansiro je Ekonomski fakultet iz Podgorice i krajem septembra 2009. godine, sistem je montiran u njihovim učionicama. Sistem služi za evidenciju prisutnosti studenata nastavi, kao i za evidenciju izvođenja nastave nastavnika.

2. RF sistem za evidenciju radnog vremena (RF EVIRAD). Realizaciju sistema finansirala je firma EMI (Elektromašinski inženjering) iz Podgorice. Sistem je do nivoa primjene razvijen krajem ljeta 2004. godine i od tada je montiran u više od 50 radnih organizacije u Crnoj Gori.

3. RF sistem za evidenciju i kontrolu točenja goriva na benzinskoj pumpi MUP-a Crne Gore. Realizaciju sistema je finansirao MUP Republike Crne Gore i sredinom 2005. godine montiran je na njihovoj benzinskoj pumpi u Zagoriču, Podgorica.

4. Off-line MIFARE sistem za kontrolu pristupa. Realizaciju sistema finansirao je OSCE Podgorica. Sistem je u martu 2004 godine montiran i kontroliše pristup prostorijama OSCE-a u Podgorici. Druga generacija ovog sistema montirana je i kontroliše pristup parkinzima u više radnih organizacije u Crnoj Gori (parking Ekonomskog fakulteta, parking Aerodroma Podgorica, ...).

5. Vib Bas, Nikšić – pogon za izvlačenje žice.

6. Galenika, Podgorica – mašina za pakovanje blistera u kartonske kutije.

7. Arsmedica, Podgorica – razni korisni uređaji za vanmateričnu oplodnju

8. T-Mobile CG – upravljanje agregatima na osnovu stanja mreže i napunjenosti baterija.

K 9.1. Koordinacija medjunarodnih projekata

1. World University Center Austria (WUS), CDP+ No-06/2006, rukovodilac

K 10.1. Doktorske disertacije

1. *Nedjeljko Lekić, «Doprinosi razvoju savremenih identifikacionih sistema», Elektrotehnički fakultet, teza je odbranjena decembra 2006. godine.*

K 10.2. Magistarske teze

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Na osnovu člana 97. Zakona o Univerzitetu ("Sl.list RCG", br. 27/92 i 6/94) i člana 94. Statuta Univerziteta Crne Gore, Naučno-nastavno vijeće Univerziteta Crne Gore, na sjednici održanoj, 4.05.2001.godine donijelo je

ODLUKU
O IZBORU U ZVANJE

Dr ZORAN MIJANOVIĆ bira se u zvanje **redovnog profesora** Univerziteta Crne Gore za predmete: **Elektronika I i Elektronika II** na Elektrotehničkom fakultetu u Podgorici.

PRAVNA POUKA: Protiv ove odluke može se uložiti žalba Naučno-nastavnom vijeću Univerziteta Crne Gore u roku od 15 dana od dana prijema iste.

REKTOR,

Prof.dr Predrag Obradović