Terahertz radiation imaging of supercurrent distribution in vortex-penetrated YBa$_2$Cu$_3$O$_{7-\delta}$ thin film strips

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We have developed a supercurrent distribution imaging system for high $T_c$ superconductive thin films and demonstrated the visualization of the supercurrent distribution in the vortex-penetrated YBa$_2$Cu$_3$O$_{7-\delta}$ thin film strips. The terahertz (THz) radiation and detection system with a scanning femtosecond laser was employed to visualize the distribution. The imaging system utilizes the principle that the femtosecond optical pulses excite THz radiation into the free space by optical supercurrent modulation, and the radiation amplitude is proportional to the local supercurrent density at the optically excited area. Prior to the observation of the supercurrent distribution, we studied optical excitation effects on the vortices trapped in the strips, calibration of the current density from the THz radiation amplitude, temperature dependence of the THz radiation properties, etc. The laser power dependence of the THz radiation in the remanent state revealed that the excitation with powers larger than the relatively weak finite value (about 10 mW in the present case) strongly affects the vortices trapped in the films. We attributed this behavior to the optically excited depinning effect. We derived a calibration function from the THz radiation images into the supercurrent density distributions by observing the bias-current dependence of the THz radiation, and applied it for the diagnosis of the distributions in the vortex-penetrated strips. The THz radiation images were successfully transferred into the supercurrent density distributions with quantitative agreement. The minimum magnetic flux resolution at the optically excited area was roughly estimated to be 3 $\phi_0$ where $\phi_0$ is a single flux quantum. The measurement of the laser beam profile indicated that the spatial resolution of the THz radiation images is limited by the laser beam diameter: 25 $\mu$m in our case. The observed distributions revealed that the vortices easily penetrate into the strip under an external magnetic field $B_{EX}$ of 0.9 mT, and the persistent supercurrent exists only near the strip edges in the remanent state after removal of the field. The calculations of the convolution between the observed laser pattern and the trial functions suggested that the supercurrent distribution width in the remanent state after removal of the field of 0.9 mT is estimated to be less than 1 $\mu$m. The temperature dependence of the supercurrent distributions revealed that, below 60 K, the thermal activation produces no significant effects on the penetrated vortices at $B_{EX}$=0.9 mT, whereas, the vortices in the remanent state after removal of the field of 15 mT were strongly affected by the thermal activation. The decreasing rate of the supercurrent density at the edge with increasing temperature was larger than that inside the strip. This suggested that the vortices trapped near the edges exhibit rather different behavior from the ones that penetrated into the inner part of the strip.

I. INTRODUCTION

There have been a number of experimental and theoretical studies of magnetic flux and supercurrent distribution in high $T_c$ superconductors (HTSs). This led to the development of a variety of experimental techniques such as scanning Hall probe, scanning superconducting quantum interference device (SQUID) microscope, magneto-optical (MO) imaging method, low-temperature secondary-electron-microscopy (LT-SEM), and scanning laser microscopy. These techniques are categorized mainly into two groups; one is to measure induced voltage and the other is to measure magnetic field. Since voltage detection implies that the phase transition from the superconductive to normal state occurs in an excited area, techniques such as the LT-SEM and the laser imaging would affect the magnetic flux penetrating into the HTSs, which results in destructive evaluation. On the other hand, magnetic field detection techniques such as MO sampling and scanning SQUID microscope can detect the magnetic flux distribution nondestructively. Although the scanning SQUID can detect a single vortex that penetrated the film, the system is too sensitive to evaluate the supercurrent distribution in the films biased with a large amount of current. Thus, the MO sampling method has been widely used as a powerful technique to study the supercurrent distribution in the HTS thin films. The macroscopic pictures in the observed images are generally understandable with theoretical works. However, the MO sampling technique has
some disadvantages. Since the technique utilizes the MO indicator such as an ion garnet film prepared on a gallium gadolinium substrate, the spatial resolution is larger than a few microns. The spatial resolution can be improved to about 1 μm by evaporating EuSe film directly onto the materials, which results in the destructive evaluation. Recently, we developed a technique to visualize supercurrent distribution in HTS thin films by means of terahertz (THz) radiation imaging. The technique can provide a noncontact, nondestructive, and free space evaluation for the supercurrent distribution.

In a series of our recent works, we have discovered and studied a type of THz radiation from HTSs. The pulsed electromagnetic (EM) radiation with a THz spectral bandwidth (THz radiation) is generated from the current-biased films excited with femtosecond (fs) laser pulses. The THz radiation from semiconductive photoswitches has been intensively studied in the last decade and can be explained by classical EM dynamics. The electric field $E$ observed in the far field is proportional to $dJ/dt$, where $J$ is the photocurrent. The radiation from semiconductors is explained by a transient photocurrent, whereas in superconductors the radiation is explained by the partial supercurrent modulation without phase transition due to optical pair breaking and subsequent quasiparticle recombination. It has been theoretically and experimentally indicated that the detected radiation amplitude is proportional to the local supercurrent density at the optically excited area. We then demonstrated a direct observation of the supercurrent distribution in HTS thin films by means of THz radiation imaging. The images were obtained by scanning the laser beam on the samples and detecting the two-dimensional map of the THz radiation.

In the present work, we apply this technique to observe the supercurrent distribution in vortex-penetrated YBa$_2$Cu$_3$O$_{7-δ}$ (YBCO) thin films and discuss its performance as the supercurrent visualization system. This article is organized as follows. Section II describes experimental details. Section III A demonstrates the visualization of the supercurrent distribution while Sec III B explains the calibration procedures from the THz radiation images to the supercurrent density distributions in the thin film strips. The discussion of the optical and thermal effects on the imaging is in Sec. III C. Sections III D and III E describe experimental results and discussion of the observed supercurrent distribution in the vortex-penetrated thin film strips.

II. EXPERIMENTAL PROCEDURE

Figure 1(a) shows a schematic configuration of the femtosecond time-resolved EM pulse generation and detection system. A mode-locked Ti:sapphire laser operating at a repetition rate of 82 MHz was used to produce 50 fs pulses with a center wavelength of about 800 nm. The fs light pulses were focused by an objective lens onto the sample mounted on a cold finger of a closed-cycle helium cryostat. THz radiation emitted from the opposite side was collimated and focused by a pair of off-axis paraboloidal mirrors onto the detector through a Si hemispherical lens. An Au/Ge/Ni alloy bow-tie antenna fabricated on a low-temperature grown GaAs (LT-GaAs), as shown in Fig. 1(b), was used as a photosensitive detector. The detector was triggered by fs pulses separated from the main beam by a beam splitter. The integrated photocurrent was lock-in detected after being amplified. The EM pulse wave forms in time domain were monitored by changing a delay time between the main and trigger pulses. After fixing the delay time at the maximum amplitude position, the laser beam was scanned to visualize the THz radiation images by translating the sample. The movable sample holder was connected to a cold base of the refrigerator using a metal mesh and also to an exterior X-Z stage controlled by LabView using a thermally insulating polyethylene rod. The spatial resolution is limited by the laser spot size. Using the beam profiler, the minimum full width at half maximum of the beam diameter was measured to be 25 μm. The large beam size is one of the disadvantages of the present system. However, this can be improved by employing the expanded fs laser beam or a lens with a shorter focal length.

Commercially available YBCO films grown on 0.5-mm-thick MgO substrates with a thickness of 100 nm were pat-
terned into a bow-tie antenna structure as illustrated in Fig. 2(a) using conventional photolithographic techniques and Ar ion milling. A hemispherical MgO lens with a diameter of 3 mm was attached to the back side of the substrate with vacuum grease as illustrated in Fig. 2(b) to increase the collection efficiency of the THz radiation. Although the MgO lens enhances the collection efficiency about ten times larger than that without the lens,29 the observable area is limited to about 200 μm in diameter. Thus, we examined the supercurrent distributions only at the center strip line of the antennas.

The orientation of the coordinates is shown in Fig. 2(a).

The visualized images contain 40×20 pixels with a pixel size of 5 μm×5 μm. External magnetic field \( B_{\text{EX}} \) of 0.9 or 15 mT was applied perpendicular to the sample surface by placing the permanent magnet outside the cryostat after the sample being cooled without an intentional external field, which corresponds to a zero-field-cool (ZFC) state. The transition temperature \( T_c \) of the sample was 79 K. Since we measured the temperature at the cold finger, the observed temperatures differ from the center of the bridge, which is the other disadvantage for our system at present. The difference between the monitored temperature and the actual sample temperature was roughly estimated to be about 5 K. This was done by comparing \( T_c \) measured using the mapping system and that of the four point probe method.

III. RESULTS AND DISCUSSION

A. THz radiation images

Figure 3 shows an example of the THz radiation wave form emitted from YBCO thin films observed with a laser power \( P_{\text{probe}} \) of 10 mW and a bias current \( I_B \) of 100 mA. The wave form shows that the radiation has the maximum amplitude at around 6.3 ps. The THz radiation wave form measured by a dipole antenna detector, which is explained by the time derivative of the supercurrent,24 is equal to the time derivative of the signal measured by the bow-tie antenna detector.33 Thus, the observed wave form corresponds to the transient response in the supercurrent: at the maximum position, the supercurrent density becomes minimum at the excited area. After fixing the time delay at 6.3 ps as indicated by the dashed line in Fig. 3, the sample is scanned along the \( x \) and \( z \) directions. Figure 4 shows an example of the THz radiation peak amplitude distribution near the center of the device at 16.5 K when a current of 30 mA is biased. The image indicates that the supercurrent flows along the antenna edge, which is qualitatively explained by the Bean’s critical state model.20 Since the LT-GaAs bowtie antenna mainly detects the radiation polarized in the \( x \) direction as expected from the antenna structure in Fig. 2(b), the radiation from the center strip is larger than that from the inclined antenna edges. However, the difference in the radiation amplitude was much larger than expected, which is presumably attributed to the difference in the collection efficiency. We will report details of the supercurrent observation elsewhere.22,34

The results suggest that the observable region is limited within an area of 200 μm in diameter. Thus we characterize the supercurrent distribution only at the center strips.

Figure 5 shows the three-dimensional plots of the radiation amplitude emitted from the strip under \( B_{\text{EX}} \) of 0.9 mT, and after removal of the field. The images indicate that the supercurrent under the magnetic field flows in opposite directions along each edge, which corresponds to the conventional shielding current. The supercurrent direction is reversed after the removal of the field. This reveals that the vortices are trapped near the strip edges. The results indicate that the THz radiation imaging technique can be used for observation of the supercurrent in the vortex-penetrated strip. In order to discuss the supercurrent distributions quantitatively, we examine calibration procedures from the detected THz radiation amplitude to the supercurrent density.

FIG. 2. (a) Schematic structure of the fabricated YBCO antenna and orientation of the coordinates. (b) Schematic configuration of the sample mount.

FIG. 3. A typical waveform of the THz radiation emitted with a bias current of 30 mA and a laser power of 30 mW.

FIG. 4. Two-dimensional plot of the THz radiation amplitude near the center of the device.

FIG. 5. Three-dimensional plots of the radiation amplitude emitted from the strip under \( B_{\text{EX}} \) of 0.9 mT, and after removal of the field.
B. Calibration procedures

We estimate the local current density from the detected THz radiation amplitude in the following manner. We first estimate the conversion function to change the amplitude distribution mirror symmetric at the center of the bridge to avoid a slight distortion in the images due to the misalignment of the system. We then estimate the current density by calibrating the distribution so that the integrated amplitude becomes identical to the bias current. Figure 6 shows the estimated supercurrent density distribution along the $z$ direction for various bias currents. The origin $z=0$ is set at the center of the strip hereafter, and the bridge is located between $z=-50 \mu m$ and $z=+50 \mu m$. We thus determine the calibration function from the observed THz radiation amplitude images to the current density distribution. The supercurrent density distribution in the vortex-penetrated films is then estimated using the calibration function.

Previously we reported that THz radiation efficiency depends on temperature. The effect is mainly attributed to the temperature dependence of the EM wave transmittance in the THz region. Figure 7 shows the radiation distribution along the $z$ direction for various temperatures observed in the strip at $I_B=10 mA$ and $P_{probe}=5 mW$. The radiation amplitude increases with increasing temperature without significant deformation in the distributions below 60 K. Therefore one has to take the temperature dependence of the radiation efficiency into account to evaluate the temperature dependence of the current distribution. We derive the calibration function from the temperature dependence of the maximum amplitude of the distribution as indicated by the solid line in Fig. 8. Here we normalize the radiation amplitude by the value at 16.5 K to define the radiation efficiency. Above 60 K, the bias current of 10 mA induced dc voltages at the bridge due to flux flow and we observed the anomaly of the radiation. This implies that the flux creep affects the THz radiation and the detected signals would be also affected. The anomaly strongly depends on the measurement conditions such as the bias current and the laser power. The details will be discussed elsewhere.

FIG. 5. Three-dimensional plots of the THz radiation amplitude emitted near the center strip (a) under $B_{ex}=0.9 mT$, and (b) in the remanent state. The distributions are visualized in the area of 100 $\mu m$ in the x direction and 200 $\mu m$ in the z direction. The images are observed with $P_{probe}$ of 2 mW.

FIG. 6. Distributions along the $z$ direction of the calibrated supercurrent density for various bias current. The profiles are measured at 16.5 K with $P_{probe}$ of 2 mW.

FIG. 7. THz radiation amplitude distribution along the z direction for various temperatures. The profiles are measured with $I_B$ of 10 mA and $P_{probe}$ of 2 mW.

FIG. 8. Temperature dependence of the maximum THz radiation amplitude. The solid line is a fit by the function $c_0+c_1T+c_2T^2+c_3T^3$, which gives $c_0=0.91$, $c_1=0.014$, $c_2=-7.8 \times 10^{-4}$, and $c_3=2.0 \times 10^{-5}$ when the radiation amplitude at 16.5 K is set unit.
C. Laser exposure influence

The fs laser exposure strongly affects the THz radiation wave forms and the vortices trapped in the YBCO thin films. This indicates that there exists a heating effect on the radiation.25,35,36 Thus, one has to study the optical excitation effects prior to the evaluation of the vortex penetration. Figure 9 shows the probe power dependence of the radiation peak amplitude at around the strip edge. The magnetic flux is trapped with $B_{EX}$ of 0.9 or 15 mT in the ZFC state. The peak amplitude is expected to increase proportionally with increasing probe power.26 This is confirmed in the current-biased dipole antenna regardless of $P_{probe}$, and in the vortex-trapped strip below $P_{probe}$ of about 2 mW as indicated by the dashed and solid lines, respectively. Above this value, however, deviation from the linear dependence is observed in the remanent state. This suggests that probing with higher laser power induces the photoassisted flux creep in the strip. The closed and open symbols represent the data obtained by the initial scan and the second scan, respectively, indicating that the amount of the trapped flux decays by the laser scanning using large probe power. The attenuation ratio is defined as the value of the maximum amplitude for the second scan divided by the one for the first scan and is summarized in Fig. 10. A slight decay is observed below $P_{probe}$ of 10 mW, whereas probing above this value remarkably decreases the amount of the trapped magnetic flux. The fact that THz radiation can be excited with $P_{probe}$ larger than 150 mW,29,36 and the YBCO thin film loops can keep the magnetic flux after irradiation with $P_{probe}$ of 100 mW,37 suggests that the temperature rise $\Delta T$ (K) due to the laser exposure is expected to be smaller than 0.4 $P_{probe}$ (mW). Therefore, the laser exposure effect with a power greater than 10 mW cannot be explained by the simple heating, and the detrapping effect of the flux would originate in the optical excitation with the laser energy of about 1.6 eV. To avoid the optical effect in the imaging procedure, one has to reduce $P_{probe}$ below the critical power. In the present work, we examine the distribution with $P_{probe}$ smaller than 5 mW.

D. Supercurrent distribution at 16.5 K

Supercurrent density distributions along the $z$ direction, averaged in the $x$ direction $J_x(z)$, corresponding to the current distributions in Figs. 5(a) and 5(b), are summarized in Fig. 11(a). The maximum supercurrent density and distribution, respectively, under $B_{EX}$ of 0.9 mT are about three times larger and slightly wider than those observed after removal of the field. Furthermore, the maximum current density under this field is observed at the slightly inner portion of the strip, whereas the one with the flux-trapped strip is observed just at the edges. These results suggest that the vortices under this field penetrate into the inner part of the strip compared to the ones after removal of the field. It is also found that al-

FIG. 9. The probe power dependence of the maximum THz radiation amplitude emitted from the strip in the remanent state. The circles and the triangles represent the data for $B_{EX}=15$ and 0.9 mT, respectively. The closed and open symbols represent the data for the initial scan and the second scan, respectively. The closed diamonds represent the data for the radiation from the 20-μm-wide strip with a bias current of 100 mA. The solid and dashed lines are drawn to indicate the trend, both of which have the same slope.

FIG. 10. The probe power dependence of the attenuation ratio. The open and closed symbols represent the data for $B_{EX}=15$ mT and 0.9 mT, respectively. The solid line is drawn as a guide to the eye.

FIG. 11. (a) Supercurrent density distributions along the $z$ direction. Closed and open circles represent the distribution measured under $B_{EX}=0.9$ mT and after removal of the field, respectively. (b) Calculated magnetic field distributions corresponding to the supercurrent density distributions. The solid and dashed lines are drawn as a guide to the eye.
though the maximum current density in the flux-trapped state coincides roughly with the one in the current biased strip at $I_B=80\,\text{mA}$, the supercurrent distributions are quite different from each other. The supercurrent in the current biased strip at $I_B=30\,\text{mA}$ is observed to flow even at the center of the strip as shown in Fig. 6, whereas no supercurrent flows at the center in the remanent state.

The magnetic field distribution for a thin strip can be calculated by solving Biot-Savart’s law. The $y$ component of the magnetic flux density $B_y(z)$ is expressed by the following formula:

$$B_y(z) = \frac{\mu_0}{2\pi} \int_{-\infty}^{\infty} \frac{j_y(z')dz'}{z-z'} + B_{EX},$$ (1)

where $d$ is a film thickness. Figure 11(b) shows the calculated flux density profiles across the strip corresponding to the distributions in Fig. 11(a). The distribution under the magnetic field indicates that the field is compressed near the strip edge, and no flux penetrates into the center of the strip as shown in the closed symbol. This profile agrees with the distribution observed by other techniques. The results indicate that the calibration from the detected THz radiation sensitivity by employing a spiral antenna detector and a thinner optical window, the value could be reduced less than $\phi_0$.

Since the obtained distributions are visualized by the convolution between the laser beam pattern and the supercurrent distribution, we here examine the laser beam profiles, and discuss the actual distribution speculatively. A solid line in Fig. 12 represents the measured laser beam profile along the $z$ direction. The closed circles represent the observed distributions measured after removal of the field of $0.9\,\text{mT}$. The intensity is normalized with respect to the maximum value.

The supercurrent distribution functions used in the calculation. The solid and dashed lines represent the functions for the fits with the data under $B_{EX}=0.9\,\text{mT}$ and in the remanent state, respectively.
E. Temperature dependence of the distribution

Although it is obvious that the temperature dependence of the vortex behavior is an important subject, and much research has been done, to our knowledge, there is no systematic study on the temperature dependence of the supercurrent distribution in the vortex-penetrated strips. One of the advantages of the present observation technique is that once the calibration from the THz amplitude to the current density is made in the well-aligned system, one can diagnose the temperature dependence of the supercurrent distribution easily. Here we demonstrate the observation of the temperature dependence of the supercurrent distribution in the flux-penetrated strip.

Figure 14(a) shows the current density distributions in the strip near the edge for various temperatures measured at $B_{\text{EX}} = 0.9 \, \text{mT}$ with $P_{\text{probe}}$ of 2 mW. The maximum current density decreases, the width of the distribution increases, and the peak position at the maximum current density shifts to the inner part of the strip with increasing temperature. The results indicate that the amount of the vortex decreases and the distribution spreads at high temperature. The deviation from the symmetric distribution is also observed above 60 K. The supercurrent in the minus region flows more than that in the plus region, which suggests that the vortex penetration depth in the minus region is deeper than that in the plus one. The laser beam scanned from the minus region to the plus region might assist the vortex penetration in the minus region more than that in the plus region. We then examine the temperature dependence of the distributions in the strip in the remanent state after removal of the external magnetic field of 0.9 mT. Figure 14(b) shows the distributions for various temperatures measured with $P_{\text{probe}}$ of 5 mW. Since the excitation brought about by the laser power is expected to affect the distributions due to the optical excitation, we monitored the distribution after the sample temperature was elevated to a finite value, kept for 5 min at that temperature, and then cooled down to 16.5 K. Although the maximum current density decreases with increasing temperature similar to that of Fig. 14(a), the broadening and center shift of the distribution are not observed within our experimental resolution. This suggests that some of the vortices escape from the strip due to thermal activation and the rest remain near the edge regardless of the temperature.

Figure 14(c) shows the distributions for various temperatures in the strip measured with $P_{\text{probe}}$ of 0.75 mW after the vortices were trapped with $B_{\text{EX}}$ of 15 mT. The maximum current density is approximately ten times larger than that measured in the remanent state after removal of the magnetic field of 0.9 mT. The maximum current density decreases, the width of the distribution increases, and the peak position at the maximum current density shifts inner to the strip with increasing temperature. Although this behavior is similar to the results in Fig. 14(a), the depinning rate for the temperature increase is much larger than the other.

The temperature dependence of the maximum current density for the various conditions is summarized in Fig. 15. Both the strips, that with applied $B_{\text{EX}}$ of 0.9 mT and that with trapped vortices after removal of $B_{\text{EX}}$, show weak temperature dependence of the maximum supercurrent density below 60 K. However, above this value the supercurrent density rapidly decreases with increasing temperature. The rate of decrease of the supercurrent density in the strip under the field above 60 K is larger than that in the vortex-trapped strip. This would be attributed to the optical excitation effects. By neglecting those effects, one can expect similar behavior in both cases. Namely, the supercurrent distribution and the trapped-vortex distribution are not affected by the thermal activation below around 60 K. On the other hand, the temperature dependence in the strip with trapped vortices under $B_{\text{EX}}$ of 15 mT remarkably differs from the above dependencies. The rate of decrease of the maximum supercurrent density below 60 K is observed to be much larger than

\[ \text{FIG. 14. Supercurrent density distributions in the half of the strip for various temperatures. The measurements were carried out under the conditions: (a) applied with } B_{\text{EX}} = 0.9 \, \text{mT, (b) in the remanent state after removal of } B_{\text{EX}} = 0.9 \, \text{mT, and (c) in the remanent state after removal of } B_{\text{EX}} = 15 \, \text{mT, with } P_{\text{probe}}'s \text{'s of 2, 5, and 0.75 mW, respectively. The distributions in (b) were measured at 16.5 K after the temperature was elevated to a finite value, and kept for 5 min, and cooled down without optical excitation.} \]
FIG. 15. Temperature dependence of the maximum supercurrent density. Open circles, closed triangles, and closed circles represent the data measured under the conditions (a) applied with $B_{EX}=0.9$ mT, (b) in the remanent state after removal of $B_{EX}=0.9$ mT, and (c) in the remanent state after removal of $B_{EX}=15$ mT, respectively. The other conditions are the same in Fig. 14. The three open triangles represent the data measured at temperatures of 16.5, 35, and 16.5 K, in that order. The two closed diamonds represent the data measured at 16.5 K before and after the sample temperature is elevated to 35 K from the initial-flux-trapped state, and then cooled down to 16.5 K without imaging. The closed diamonds and the open triangles are also shown in the inset. The solid lines are drawn as a guide to the eye; the dashed line represents the fit to the data with a power law.

that in the former cases. This thermal effect was confirmed by measuring the maximum current density at temperatures of 16.5, 35, and 16.5 K, in that order, as indicated by the open triangles in Fig. 15. We were able to obtain almost same current density in the last two cases. It is also confirmed that the maximum current densities in the strip before and after the sample temperature is elevated to 35 K from the initial-flux-trapped state, and then cooled down to 16.5 K without imaging at 35 K, are identical to the first and the last, respectively, as indicated by the closed diamonds. The results indicate that the decrease in the maximum current density with increasing temperature below 60 K originates in the thermal activation effect.

One may expect that the thermal effect can be attributed to the temperature dependence of the critical current density $J_C(T)$ in the YBCO thin film. Here, we discuss the temperature dependence of the maximum current density in the strip in the remanent state trapped with $B_{EX}$ of 15 mT. At temperatures below the near-temperature regime, $J_C(T)$ has been explained by the nearly linear $(1-T/T_C)$ dependence, or by a flux-creep-controlled transport current with the form

$$J_C = J_0 \exp(-A \sqrt{T/T_C}),$$

where $A$ is a constant. However, this relationship also failed to explain the dependence. We then tried to explain it by a power-law dependence. The dashed line in Fig. 15 is a fit to the data below 65 K with a power law of the form

$$J = J_0 (1-T/T_C)^n,$$

which yields $n = 1.5$ and $J_0 = 15$ MA/cm². The nonlinear behavior with $n = 1.5$ is explained by the Ginzburg–Landau theory. In the HTS thin films, however, this dependence is usually observed only near $T_C$. Therefore, the observed temperature dependence of the maximum current density in the remanent state cannot be simply explained by the temperature dependence of the critical current density. Cukauskis et al. reported that the composite thin films of Au and YBCO prepared on various substrates have large $n$, which strongly depends on the substrates and the deposition conditions. They suggested that the grain boundary plays an important role in determining the temperature dependence. In Sec. III D, we suggested that the vortex behavior near the film edges differs from that inside the film. As shown in Fig. 14(c), the rate of decrease of the maximum current density with increasing temperature at the edges is larger than that at the inner part of the strip. This suggests that the edge has weaker pinning force than the inner part of the strip, and may be originated in the process damage, which would affect the coupling properties between the grains. The coexistence of this edge effect and the intrinsic one in the strip would account for the observed temperature dependence.

Above around 60 K, we observed abrupt deviation from the power law dependence in the maximum current density. Cao et al. found the logarithmic decrease of the critical current density with increasing temperature near $T_C$, and explained it by the pinned vortex liquid. The weak trapped magnetic field in the remanent state might be responsible for the pinned vortex-liquid regime formation. More work such as the extraction of the optical excitation effect from the observed data remains to be undertaken to discuss the vortex behavior near $T_C$.

IV. CONCLUSION

We have developed a novel supercurrent distribution imaging system for HTS thin films and demonstrated the visualization of the supercurrent density distribution in the vortex-penetrated YBCO thin film strips. The THz radiation and detection system with a scanning femtosecond laser was employed to visualize the distribution. The imaging system utilizes the principle that the femtosecond optical pulses excite THz radiation into the free space by optical supercurrent modulation, and that the radiation amplitude is proportional to the local supercurrent density at the optically excited area.

The calibration function was determined by the THz radiation images obtained from the current-biased strips to investigate the supercurrent density distribution. The magnetic field profile calculated using Biot–Savart’s law suggested that the THz radiation images obtained from the vortex-penetrated strip can be transferred into the supercurrent density distribution with quantitative agreement. The minimum
magnetic flux resolution at the optically excited area was roughly estimated to be 3 \( \phi_0 \). The measurement of the laser beam profile indicated that the spatial resolution of the THz radiation images is limited by the laser beam diameter: 25 \( \mu m \) in our case.

The temperature dependence of the THz radiation amplitude emitted from the current-biased strip confirmed that the radiation coefficient increases with increasing temperature. The calibration function to study the temperature dependence of the supercurrent distribution in the vortex-penetrated strips was determined from this dependency.

Since the radiation amplitude due to the optical supercurrent modulation increases linearly with increasing laser power, the system became more sensitive with higher laser power. However, the laser power dependence of the THz radiation coefficient increases with increasing temperature. The calculations of the convolution between the observed current distribution width in the remanent state after removal of their helpful discussions, and to H. Saijo

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