Magnetic field effects and dynamic control of terahertz electromagnetic wave emission from high-$T_c$ superconducting Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ mesa structures

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Abstract. Terahertz electromagnetic waves are very useful for a number of security and medical applications. Recently, intense and coherent terahertz emission from high-$T_c$ superconducting Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) intrinsic Josephson junctions (IJJs) has been intensively investigated. In this paper, we report magnetic field effects and dynamic control of terahertz electromagnetic wave emission generated by the rectangular mesa structure of Bi2212. The magnetic field affects anisotropically the emission intensity at $T = 25$ K. Terahertz emission is strongly suppressed by an external magnetic field (less than 200 Oe) parallel to the c axis. In contrast, a 20% enhancement of radiated power is observed when an appropriate magnetic field ($H = \Phi_0$) is applied parallel to the ab plane. This anisotropy seems to result from the anisotropic vortex formation inside Bi2212. We also demonstrate that the intensity of terahertz emission can be controlled dynamically by applying a weak magnetic field, suggesting that we can modulate the continuous power of terahertz emission by applying weak magnetic field pulses.

1. Introduction

High-temperature superconductors are typically constructed from a stack of several intrinsic Josephson junctions (IJJs) because they have a peculiar crystal structure, in which the superconducting ($\text{CuO}_2$) and insulating layers are alternately stacked within a unit cell of the crystal [1]. A typical example is the well-known Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212). Although there have been many theoretical suggestions proposing electromagnetic (EM) wave emissions from this type of multilayered Josephson junction [2], the EM wave emission from high-$T_c$ superconductors has not been observed experimentally in more than ten years. There are a few exceptions where low-intensity emissions have been detected [3].

Recently, continuous and monochromatic terahertz radiation generated from rectangular mesas of Bi2212 IJJs has been successfully observed [4]. Both the geometrical resonance condition and the EM wave condition inside the mesa have been intensively investigated [5]. Several tens of microwatts of the radiated power have already been achieved [6].

The effect of magnetic fields on emission is another key issue for understanding the mechanism. It is well known that in Bi2212, various interesting vortex states, such as a vortex
liquid state, a vortex glass state, a Bose glass state, or a pancake vortex state, can easily be realized in relatively low magnetic fields [7]. Experimentally, strong suppression of radiation power was observed when a magnetic field was applied parallel to the \(c\) axis, whereas a weaker suppression effect was observed when a magnetic field was applied parallel to the \(ab\) plane [8]. Nonomura showed theoretically that the in-plane magnetic field dependence of terahertz wave emission was controlled by surface impedance [9]. Rakhmanov asserted that the application of a moderate dc magnetic field could significantly increase synchronized terahertz emission from stacks of intrinsic Josephson junctions (SJJs) [10]. In this paper, we study dynamic control and magnetic field effect of electromagnetic wave emission, such as its effect on FT-IR spectra.

2. Experiments

Single crystals of Bi2212 were grown using the TS-FZ method. The crystals were annealed under a reduced atmosphere. Two rectangular-shaped mesas, 400 \(\mu\)m long, 80 \(\mu\)m wide, and 1.2 and 1.5 \(\mu\)m thick, were fabricated using an argon ion milling technique.

A static magnetic field was applied to the sample by two Nd permanent magnets located with axial symmetry. The two magnets were equally spaced from the sample, and the magnet system could be rotated within an accuracy of \( \pm 0.5^\circ \). The magnitude of the magnetic field can be varied from 0 to 150 Oe by changing the distance between the two magnets. Both the magnitude and the homogeneity of the magnetic field were calibrated by a miniature Hall sensor prior to the experiments.

3. Results and discussion

Typical \(I-V\) characteristics and detected radiation signals are shown in figure 1. An emission from the mesa was observed in the retrapping region of the return branch at \(V = 0.7\) V. The corresponding \(I-V\) curve where emission occurs is magnified in figure 2(a). Figure 3(a) shows typical emission spectra from the Bi2212 mesa structure. Each spectrum was observed at a different bias voltage. A shift to higher frequency with increasing applied voltage was seen. The integrated intensity of the spectra decreases with decreasing \(c\)-axis current. The frequency tunability for one branch is almost 3\%–5\%, and the voltage change corresponds to the change in frequency. Figure 3(b) shows emission spectra in a magnetic field. The voltage at which emission occurred was applied to the sample, and then, a magnetic field was applied to the sample. The emission intensity simply decreased and dropped to zero with increasing external magnetic field. The emitted frequency is the same for the applied external magnetic field as is observed in the data. Figure 2(b) shows the change in the \(I-V\) curve when the two magnets approach the sample.

The magnetic field dependence of the maximum intensity of emission shown in figure 4 is not trivial. The output power was normalized to an initial value of 100 at an intensity of \(H = 0\) Oe. In the case of the \(H \parallel ab\) plane, the radiation power increased by 20\% with increasing external magnetic field (when the two magnets approached the sample) up to 46 Oe. This value is almost equal to one flux quantum \(\phi_0\) per layer. This enhancement of maximum intensity for the \(H/\parallel ab\) plane was observed only when the accuracy of the angle for the \(ab\) plane was within \(\pm 0.5^\circ\). Any misalignment of the field angle seems to be important for adjusting the radiation condition. However, when a magnetic field was applied parallel to the \(c\) axis, a strong suppression of radiation power was observed. Since the crystal structure of Bi2212 is anisotropic, large anisotropic magnetic field effects are observed in Bi2212. Accordingly, a Josephson vortex is realized in the case of the \(H \parallel ab\) plane. In contrast, a pancake vortex penetrates the \(CuO_2\) layer in the case of the \(H \parallel c\) axis. As a result, the emission condition is interrupted by the pancake vortices. Since a Josephson vortex affects the interlayer coupling of the Josephson junction, this modulation of coupling might result in the enhancement of the radiation intensity.

Figure 5 shows the modulation of radiated power with the simultaneously observed \(c\)-axis
Figure 1. Typical $I$–$V$ characteristics and detected radiation signals from a bolometer.

Figure 2. Magnified $I$–$V$ characteristics (a) for changing biased voltage without a magnetic field and (b) when two magnets approach the sample.

Figure 3. Emission spectra observed (a) without a magnetic field and (b) in a magnetic field. (a) The frequency is shifted from 508 to 524 GHz by increasing the applied voltage shown in figure 2(a). (b) The frequency remains at 483 GHz, although the intensity has dropped to zero with increasing external magnetic field.

current and voltage in the presence of an applied external magnetic field. We apply a voltage at which emission occurs to the sample with a voltage source, and then apply a magnetic field to the mesa by changing the distance of the magnets. The radiated power was strongly suppressed with increasing external magnetic field (when the two magnets approached the mesa). The changes in the $I$–$V$ curve are estimated to be only 0.5% for current and 2% for voltage when the two magnets approached the sample. However, these small changes in the $I$–$V$ curve do not suppress the terahertz emission, as is observed in figure 3(a) and in figure 2(a). When the two magnets approach the sample, pancake vortices start to interrupt the resonance condition. Hence, a reproducible novel dynamic effect that can control the on (emitting) and off (nonemitting) states of the terahertz radiation by an external magnetic field has been unambiguously discovered here for the first time.
4. Summary

In this study, we investigated the magnetic field effects and dynamic control of terahertz electromagnetic wave emission from high-$T_c$ superconducting Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ mesa structures. Our experimental results clearly demonstrate that the terahertz emission is strongly suppressed by applying an external magnetic field along the $c$ axis. In contrast, the highest intensity is achieved when an appropriate magnetic field ($H \sim \phi_0$) is applied parallel to the $ab$ plane. The intensity of emission can be controlled by the external magnetic field. This phenomenon would be useful for realizing high-frequency switching devices based on high-$T_c$ cuprates.

References

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