Terahertz electromagnetic radiation from Bi$_2$Sr$_2$CaCu$_2$O$_y$ intrinsic Josephson junction stack

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Abstract

We have observed terahertz (THz) electromagnetic wave radiation from Bi$_2$Sr$_2$CaCu$_2$O$_y$ intrinsic Josephson junction (IJJ) stacks using high sensitive detector made of a small IJJ mesa. In this study, we focused on the THz radiation from a few hundred IJJs. We fabricated the IJJ oscillator and detector. The oscillators consist of 55 ~ 300 IJJs with the lateral dimensions of 290 × 50 µm$^2$. The current-voltage characteristics of the IJJ oscillators showed a negative resistance accompanied with large hysteresis. The THz radiation was observed for several samples when the oscillator was biased at some current in the negative resistance region. We attribute the observed radiation to synchronized emission from many IJJs in the stack and find the emission frequency corresponds to the in-phase cavity resonance frequency.

Keywords: intrinsic Josephson junctions; Josephson effect; THz radiation

1. Introduction

Intrinsic Josephson junctions in layered high-$T_C$ superconductors such as Bi$_2$Sr$_2$CaCu$_2$O$_y$ (BSCCO) have been extensively studied as one of possible candidates for compact solid-state THz sources because the energy gap frequency of BSCCO lies in the THz frequency range and high power radiation can be expected due to synchronized phenomenon of a large number of junctions [1-4]. Recently, coherent THz emission from stacks consisting of several hundreds of IJJs has been demonstrated [5-8]. Intense radiation from such IJJ stacks is considered to be associated with cavity resonance modes. However, little attention has been given to the THz radiation from the stack with a few hundred IJJs. In order to understand the THz radiation mechanism of IJJs, it is important to study the emission properties of a few hundred IJJs or less.

In this paper, we have investigated THz emission properties in stacks of thickness less than 450 nm by using a high sensitivity IJJ detector.

2. Samples

BSCCO single crystals with critical temperature of ~ 85 K were grown by self-flux melting method [9]. The IJJ oscillator mesas with length $l = 290$ µm, width $w = 50$ µm and height $h = 90 - 420$ nm (corresponding to the number of
junctions $N = 50 - 280$) were fabricated on the crystals by photolithography and Ar ion milling. The electrical contact to the mesa was provided Au layer deposited by vacuum evaporation. The optical image of the fabricated IJJ oscillator is shown in Fig. 1 (a).

Figure 1 (b) shows the current-voltage ($I_{\text{OSC}}-V_{\text{OSC}}$) characteristics of three oscillators with different numbers of IJJs ($N = 55, 100, 170$) at 4.2 K. Due to two terminal measurement the characteristics include a few dozen ohms of contact resistance. The maximum critical currents of IJJs in these samples have the values around 30 mA because of the same lateral dimensions. In contrast, as increasing the number of junctions the negative resistance appeared on the quasi particle branches becomes larger due to the heating effect.

3. Results and discussion

Detection experiments were performed at 4.2 K. Experimental setup is shown in Fig. 2 (a). The THz radiation from IJJ oscillator was detected by the IJJ detector consisting of a small mesa with lateral dimensions of $5 \times 5 \mu m^2$ and bow-tie antenna. The IJJ detector was fabricated by using the same method reported previously [10]. The optical image of the IJJ detector is shown in Fig. 2 (b). The IJJ detector was placed about 1.5 cm away from the IJJ oscillator. During experiment, the detector was biased at a constant current and the driving current of the oscillator was swept at 2 mHz. Figure 2 (c) shows principle of the EM wave detection with the IJJ detector. As well-known, the critical current of a surface IJJ formed on the top surface of the IJJ stack is very small [11] and is sensitive to EM wave. Therefore, the output voltage of the IJJ detector biased just below the critical current of the surface IJJ can be modulated by the EM wave radiation from the IJJ oscillator depending on the emission power. In experiment, the $I_{\text{OSC}}-V_{\text{OSC}}$ characteristic of

Fig. 2. (a) Experimental setup for detection of THz radiation from the IJJ oscillator. (b) The optical image of the fabricated IJJ detector. (c) Principle of EM wave detection by using the IJJ detector.
the oscillator and the $V_{\text{DET}}$ were recorded by a personal computer connected to digital multimeters.

An example of the THz radiation from IJJ stack is shown in Fig. 3 (a). The $I_{\text{OSC}}$-$V_{\text{OSC}}$ characteristic is shown together with the $V_{\text{DET}}$. Here, the voltage drop of contact resistance is subtracted from the measured voltage. The number of IJJs in this sample is 210. One can see that the $V_{\text{DET}}$ shows clear peak at 225 mV. Furthermore, the $V_{\text{DET}}$ peak position was reproducible independent on the sweep direction of $I_{\text{OSC}}$. This means that strong EM wave emission occurs when the oscillator is biased at 42 mA on the fully resistive branch (point A). As well-known, a Josephson junction can act as a voltage-frequency converter. Therefore, we can estimate the emission frequency $f_{\text{OSC}}$ by using the Josephson relation,

$$ f_{\text{OSC}} = \frac{V_{\text{OSC}}}{(N \Phi_0)}, $$

where $\Phi_0$ is flux quantum ($2.07 \times 10^{-15}$ Wb) and obtain $f_{\text{OSC}} = 0.52$ THz.

In previous studies for thick IJJ stacks of $N \geq 500$, it has been pointed out that the THz emission occurs when the in-phase cavity resonance mode is excited by the Josephson oscillation, i.e., the Josephson frequency matches the in-phase cavity resonance [5-7]. Therefore, it is interesting to compare $f_{\text{OSC}}$ with the cavity resonance frequency $f_c = c/2w$, where $c$ is the propagation velocity of EM wave in the stack. It is well known that $N$-junction stack has $N$ mode velocities [12]. For $N > 500$ the in-phase mode velocity $c_1$ approximately equals $c_0/n$, where $c_0$ is the light velocity in vacuum and $n$ is the refractive index. However, for $N < 400$ $c_1$ depends on $N$ and is given by the following approximation formula [13].

$$ c_1 \approx c_0 \sqrt{\frac{d(d+t)}{\varepsilon_r \lambda_{ab}}} \frac{N+1}{\pi}. \quad (1) $$

Here, $\varepsilon_r$ is the relative dielectric permittivity, $d$ is the barrier thickness, $t$ is the superconducting electrode thickness and $\lambda_{ab}$ is the London penetration depth. From equation (1), the in-phase mode velocity for the sample shown in Fig. 3 (a) is estimated to be $5.1 \times 10^7$ m/s by using typical values of $\varepsilon_r = 7$, $d = 1.2$ nm, $t = 0.3$ nm and $\lambda_{ab} = 200$ nm for BSCCO.
IJJ. From this we obtain $f_C = c/2w = 0.51$ THz which is comparable to $f_{OSC}$ estimated above. Accordingly, we may say that the emission peak seen in Fig. 3 (a) is due to the fundamental cavity resonance of the in-phase mode.

Another example of THz radiation detection is shown in Fig. 3 (b). The number of IJJs in this sample is 170. One can see two emission peaks. The large peak was observed at $I_{OSC} = 33$ mA (point B) which is above $I_C$, while small peak was observed at $I_{OSC} = 22$ mA (point C) which is below $I_C$. From $V_{OSC}$ of these peaks the emission frequencies are estimated to be 0.79 and 0.99 THz. Thus, the in-phase velocity $c_1$ and fundamental cavity resonance frequency for this sample are calculated to be $4.1 \times 10^7$ m/s and 0.41 THz, respectively. Therefore, we find that the large peak corresponds to the second harmonics of the in-phase cavity mode. On the other hand, the small peak does not correspond to the cavity resonance mode. At present the origin of the small peak seen in Fig. 3 (b) is an unsettled question but it may be due to the heating effect because the negative resistance of this sample is rather large compared with that of the sample shown in Fig. 3 (a).

We also measured the emission stability of the sample shown in Fig. 3 (a). Figure 4 shows the time development of $V_{DET}$ measured when the sample was biased at 42 mA (point A) where the $V_{DET}$ became maximum. From this result, we find that the emission is very stable over 5min or more and the estimated power fluctuation is less than ±5 % because the $V_{DET}$ depends on the power of detected EM wave.

We have successfully observed the emission for 20 samples with different number of IJJs ($N = 55$~280).

4. Conclusion

We have observed terahertz electromagnetic wave emission from stacks consisting of a few hundred IJJs using IJJ detector. The reproducible strong emission was observed by biasing at some current in the negative resistance region. The radiation detected was characterized by the in-phase cavity mode. Furthermore, it was conformed that the radiation was very stable over a long time.

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