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Emission of the THz waves from large area mesas of superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ by the injection of spin polarized current

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ABSTRACT

Rectangular $Au/Co/Au/Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) mesa structures with large areas and high thicknesses were fabricated on as-grown Bi2212 single crystals in order to obtain small critical current from as-grown mesas by the injection of spin polarized current and so eliminate the adjustment of doping level for successful THz emission. We have performed *c*-axis resistance versus temperature (*R*–*T*), current–voltage (*I*–*V*) characteristics and bolometer measurements. It is the first time that THz emission has been observed from as-grown mesas due to injection of spin polarized current.

1. Introduction

Although electromagnetic waves in the terahertz frequency region host potential applications such as including imaging, spectroscopy, information technology, environmental monitoring and medical diagnosis, these applications have been limited by the lack of powerful, continuous wave and inexpensive compact solid-state sources [1]. The ac Josephson effect occurring between two superconducting electrodes separated by a thin insulating layer provides a unique way to develop voltage-tunable generators of electromagnetic radiation in the terahertz frequency range, with 1 mV applied voltage to a Josephson junction corresponds to 0.483 THz [2]. However, the operation frequency is restricted by the superconducting gap so it cannot exceed several hundred gigahertz for the devices made of conventional superconductors [3]. Also, the power emitted from a single junction is too small for practical applications, typically in the order of pW. Natural stacks of Josephson tunnel junctions in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) offer very promising alternative for developing powerful, coherent and inexpensive compact sources of THz radiation. Perfectly stacked and dense junction arrays in Bi2212 hold great potential for very high emission power, and the large value of the superconducting gap covers the whole terahertz frequency band [4]. The fundamental emission frequencies up to 0.85 THz and radiation power up to 0.5 μW was detected from the rectangular mesa structure of Bi2212 as the Josephson frequency of the IJJ matches one of the cavity resonance modes of Josephson plasma wave in the mesa [5]. This progress inspired further experimental [6–22] and theoretical [23–35] investigations to achieve completely synchronized THz radiation from Bi2212 intrinsic Josephson junctions and to understand precise nature of the synchronization mechanism. Recently, terahertz imaging was demonstrated by using high-T_c superconducting intrinsic Josephson junction oscillation devices as THz sources [36]. Previous studies also found that all THz emitting mesas are below a certain underdoped level, which has relatively small critical current density in contrast to optimally doped and overdoped Bi2212 [9].

The early experiments involving spin related effects demonstrated that currents flowing through ferromagnets may become spin polarized and spin injection into the superconductor can be performed by applying a potential difference between the ferromagnetic material and superconductor [37]. Cooper pairs in superconductors are formed between up and down spins and so cannot carry a spin current. For a ferromagnet, the DOS at the Fermi energy is different for spin up and spin down electrons where spin up electrons are assumed to be the majority carriers. Since the majority carriers in ferromagnet are spin up electrons, most of the electrons injected into superconductor will have spin up. This nonequilibrium state leads to spin accumulation in superconductor and suppression of superconductivity due to pair breaking effect in CuO_2 layers as a result of excess magnetic moments and quasiparticle redistribution [38–40]. Many times, it was experimentally verified that the injection of spin polarized carriers into high-T_c superconductor is led to reduction of the critical current [38–48].

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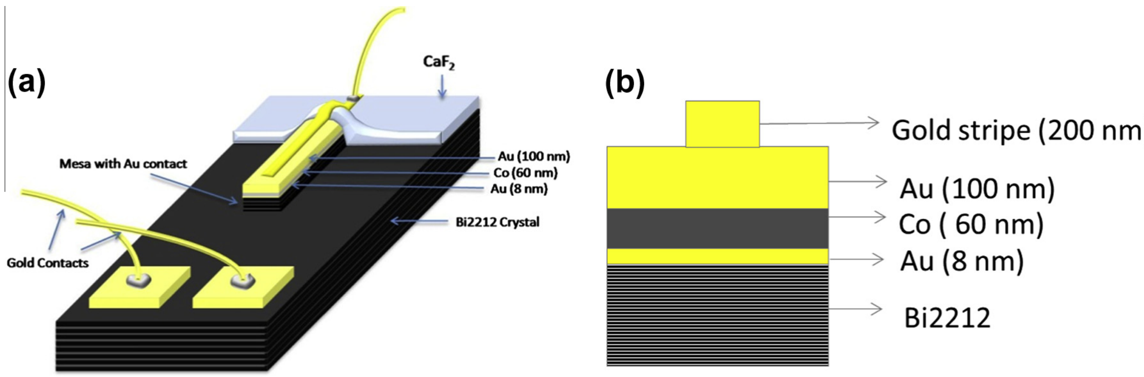

Fig. 1. Measurement configuration of the mesa structure (a) and the cross section of multilayer electrodes (b).

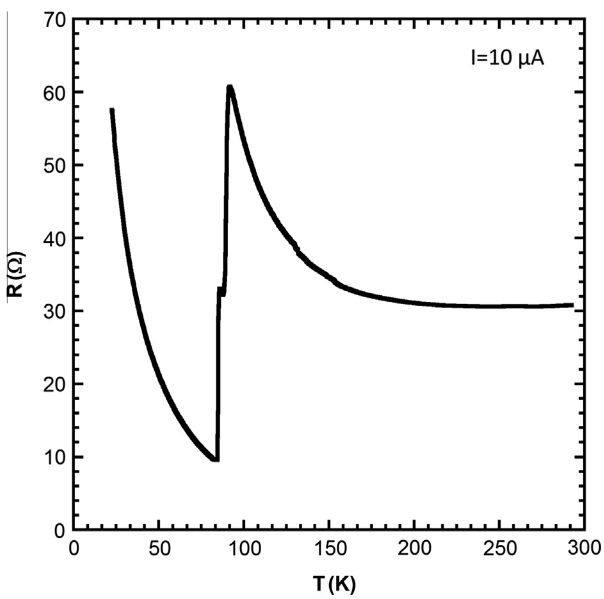

Fig. 2. Resistance versus temperature behavior of as-grown mesa for a bias current 10 μA.

In this work, we demonstrated that small critical current from rectangular mesa structures fabricated by as-grown Bi2212 single crystals can be obtained by the injection spin polarized current and the adjustment of doping level for THz emission can be eliminated.

2. Experiment

Au/Co/Au/Bi2212 tunnel junction is used in this work. Single crystal of Bi2212 is glued onto a sapphire substrate from its smooth a–b surface by silver epoxy. In order to get a fresh and smooth surface on Bi2212, the crystal was then cleaved with an adhesive tape and Au layer with the thickness of 8 nm was thermally deposited on the cleaved crystal surface immediately to prevent the chemical reactions between Co layer and Bi2212 crystal. Increasing thickness of the Au layer causes the reduction of spin polarization of the quasiparticles [41] so thin Au layer was used to keep polarization of spins. After that 60 nm Co layer was deposited on thin Au layer as a spin injector and then in order to prevent oxidation 100 nm thick Au layer was deposited on the top of Co layer using magnetron sputtering technique. $55 \times 100\ \mu m^2$ mesa structures with heights approximately 800 nm were fabricated on crystals by standard optical photolithography and Ar ion beam etching techniques. Since the photoresist does not stand well and etched with ions rapidly, the samples were cooled by liquid N_2 during the etching process. Because of the difficulties in making a contact on small area of the mesa, firstly CaF_2 insulating layer is deposited by evaporation onto crystal and small area of the mesa then a shadow mask whose split lying along the mesa and insulating layer is placed on substrate and a gold stripe with the width of 30 μm is deposited by evaporation on insulating layer and mesa. Finally three gold probe wires are connected on two path and mesa

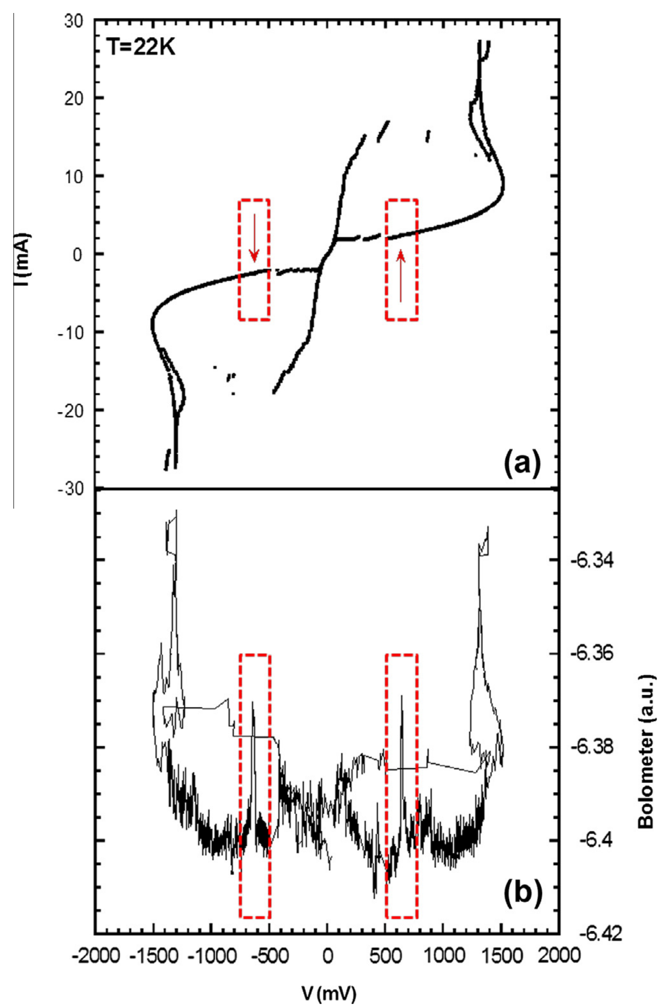

Fig. 3. *I–V* (a) and bolometer (b) measurements of mesa at 22 K.

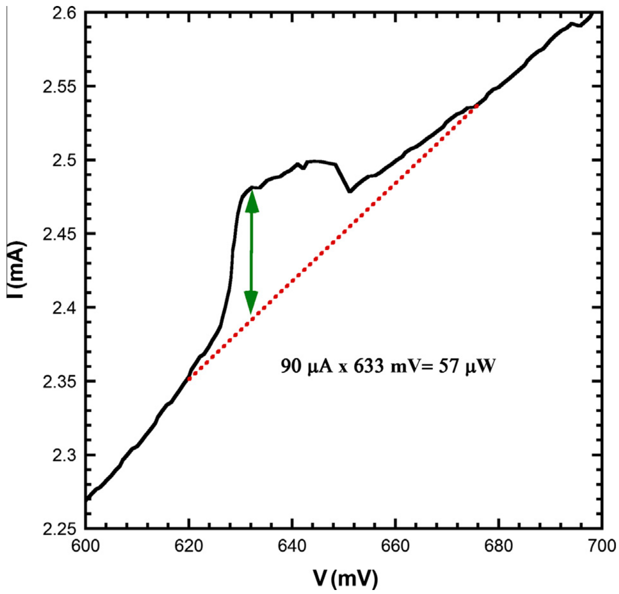

Fig. 4. Close-up of the return branch of I–V curve.

by silver epoxy. The final measurement configuration of the mesa structure with three point probe can be seen in Fig. 1a and the cross section of multilayer electrodes can be seen in Fig. 1b.

We have performed c-axis resistance versus temperature (R–T), current–voltage (I–V) characteristics and bolometer measurements to characterize the Bi2212 mesas. In order to determine the emission frequency Michelson interferometer setup was used.

3. Results

c-Axis resistance versus temperature (R–T) characteristics of the as-grown Bi2212 mesa was measured in a He flow cryostat system. As seen in Fig. 2 both temperature dependence of the c-axis resistance and the superconducting transition temperature (T_c = 91.5 K) of the mesa indicate that this mesa is in the slightly optimally-doped state of the Bi2212 crystals. The ratio of $R(T_c)/R(300\text{ K})$ is 1.97 for this mesa. As the necessity of certain doping level for THz radiation from Bi2212 studied by Ref. [9], this mesa has high doping level for THz emission.

Fig. 3a and b shows THz emission characteristics and current–voltage (I–V) characteristics of the mesa with $55 \times 300\ \mu m^2$ at T = 22 K. I–V data shows that the magnitude of Josephson critical current is 18 mA when spin polarized current is injected through the c-axis of the as-grown mesa. The Josephson critical current density, J_c, is 120 A/cm^2 at 22 K which is 2–3 times smaller than as-grown Bi2212 crystals due to injection of spin polarized current and it is comparable to other THz emitting mesas [9]. Decrement in J_c due to the spin injection was also demonstrated by previous works in our group by comparing spin degenerate and spin polarized cases [46]. At high bias voltages, when I–V curve shows back-bending, the bolometer detects the heating of the mesa in the form of unpolarized black body radiation. Polarized emission peaks were observed at ±0.64 V for positive and negative bias voltages in the return branches.

We show that the necessity of small critical current density for THz emission can be satisfied by driving spin polarized current through the c-axis of the as-grown mesas and adjustment of doping level can be eliminated. Since Co has some parallel-aligned spins into its magnetic domains even without applied magnetic field, injection of spin polarized current can suppress the superconductivity in some degree resulting in decrease in J_c. However, we cannot limit decrease in critical current due to self-field of ferromagnetic Co layer. For further work, we will investigate the emission characteristics of over-doped samples with magnetic field which enhances the spin directionality inside the Co.

As it can be seen in Fig. 4, which shows the close-up of emission region (arrows in Fig. 3a), there is a bump in return branch of I–V curve because radiation can change the character of the charge-time dependence [49]. That is emission persist over an extended voltage range around the resonance condition as a result of the slightly inclined side walls of the mesa [6]. This property makes the design of tunable THz sources possible by varying the bias voltage. However, we believe that while the frequency tunability of the mesa increases as the angles between the basal plane and the mesa sides decreases, intensity of emission power decreases [14]. Because trapezoidal cross section leads to a gradient in the critical currents of the IJJs and variations of junction parameters may cause desynchronization and significant drop in emission power. The emission frequency is found to be tunable by up to 8.75% for the fabricated mesa with trapezoidal cross section, being

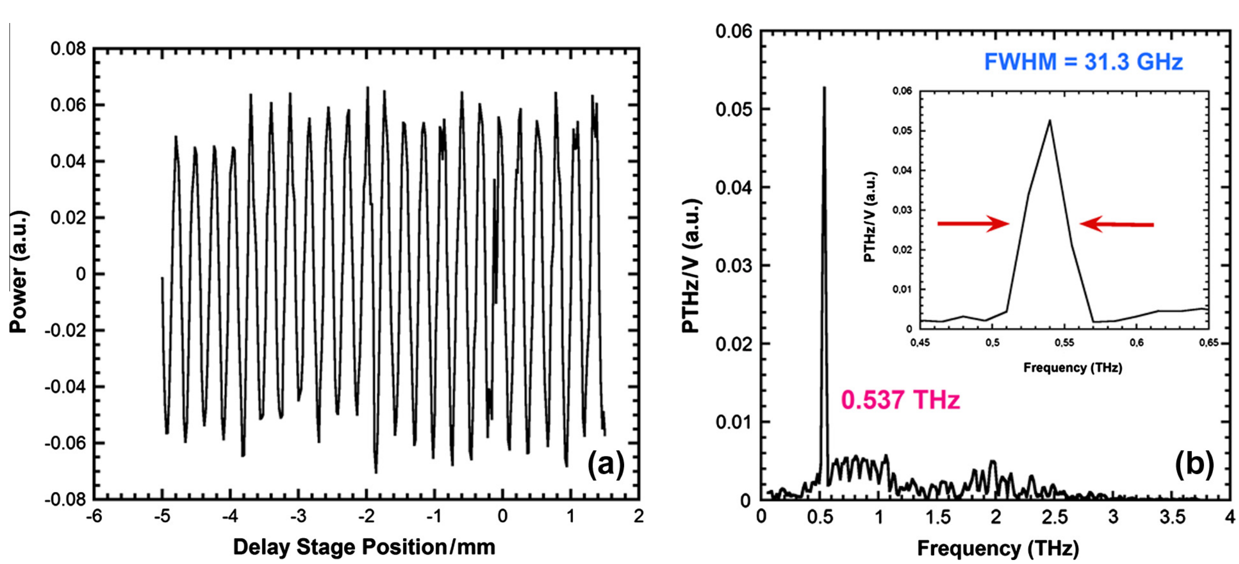

Fig. 5. (a) Interference patterns detected by bolometer inside the emission region and (b) the Fourier transform of the interference data.

wider at the bottom by 5%. It is not so large compared to other works [18,22], because in these works the difference between the lengths of the top sides and the bottom sides of the mesas are considerably high. We did not observe re-trapping event in the emission region, this indicates that there is no loss of emission. The power pumped into the in-phase resonance determined as 57 μW by establishing a baseline of the current.

Michelson interferometer setup was used to determine the emission frequency of mesa. The mesa is biased at optimum emission voltage and interferometric data were taken. Fig. 5a shows the signals detected by bolometer. The emission frequency was found taking the fast Fourier transform (FFT) of this wave form using Labview program. Fig. 5b shows the Fourier transform of the data and the peak in this figure indicates that emission frequency of the mesa is 0.537 THz which is consistent with Josephson frequency–voltage relation for 534 junctions when the contact resistance subtracted from *I*–*V* curve. However, this frequency value is not good agreement with the fundamental cavity resonance, $f = c_0/2nw$, where w is the width of the mesa and n is the c-axis refractive index of Bi2212, which for w = 55 μm yields f = 0.77 THz for $n \approx 3.5$ [5]. The fundamental frequencies of the low bias emission generally do not match the fundamental cavity resonance and this behavior has not been clarified yet. The full width at half maximum (FWHM) of the peak is 31.3 GHz. This quite large value is attributed to the instrumental origin because instrumental resolution is not good enough. Moreover, there are some technical difficulties, for example, we cannot keep the voltage constant during the measurement.

4. Conclusion

In this work, rectangular Au/Co/Au/Bi2212 mesa structures were fabricated on as-grown Bi2212 single crystals. *R*–*T*, *I*–*V* and bolometer measurements of mesas were analyzed. For the first time, THz emission was achieved from as-grown mesas due to injection of spin polarized current. We observed that emission persists over an extended voltage range around the resonance condition. This property makes the design of tunable THz sources possible. Re-trapping events were not observed in the emission region, indicating that all junctions are tightly locked to the resistive state and so there is no loss of emission. The emission frequency calculated by a Fourier transformation of the interference data is consistent with Josephson frequency–voltage relation. We demonstrated that the necessity of small critical current density for decreasing the influence of heating effect on emission can be satisfied by driving spin polarized current through the c-axis of the as-grown mesas and the adjustment of doping level for THz emission can be eliminated.

Acknowledgments

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