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Microwave oscillation from $Bi_2Sr_2CaCu_2O_y$ intrinsic Josephson junction arrays

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Abstract
We report the novel nonequilibrium microwave emission from current-injected $Bi_2Sr_2CaCu_2O_y$ (BSCCO)/I/Au intrinsic Josephson junctions and two-mesa array of intrinsic Josephson junctions. For the single intrinsic junctions, it appeared as three different modes of oscillations. Among them, two modes are Josephson plasma emissions which appeared at the quasiparticle branches and the gap-edges. The mutual phase interaction between two-mesa structures of BSCCO intrinsic Josephson junctions has been studied. The measured output power of the two-mesa structures of intrinsic Josephson junctions was almost four times larger than that of the single junction, indicating an exact phase-locking state between the two intrinsic Josephson junctions. The maximum detected power was about microwatt level at millimetre-wave range.

1. Introduction

Microwave emission from low- and high-T_c superconductors has attracted considerable attention for both basic studies and electronic applications of high-T_c superconductors. It has been well known that the Josephson junction biased at a finite voltage emits the microwave of the voltage satisfying the Josephson voltage–frequency relation. The phenomena were confirmed for both low- and high-T_c superconductors [1–3]. On the other hand, driving of vortices by a current in a long Nb Josephson tunnel junction under an external magnetic field led to flux-flow devices generating microwaves of around 0.5 THz [4]. Similar microwave emission for high-T_c superconductor has been reported by the Müller group. They attributed the observed phenomenon to the Cherenkov radiation of vortex flow [5]. On the other hand, the nonequilibrium emission from an optically radiated high-T_c thin film using a femtosecond laser has been reported [6].

Recently, it has been reported that when a high-T_c superconductor/insulator/normal metal tunnel junction is biased at a finite current, broadband microwaves are emitted [7–9]. The observed phenomenon is quite different from the Josephson self-emission and has been considered as Josephson plasma emission. When the quasiparticles are injected along the c-axis direction of a high-T_c superconductor, the Josephson plasma modes are excited, which emit electromagnetic emission into a free space. The appearance of the Josephson plasma modes has been demonstrated by the resonant absorption technique [10, 11]. Due to the fact that the c-axis-polarized Josephson plasma modes lie well below the gap energy, the plasma waves are transmitted in the crystal without appreciable Landau damping. Recently, Shafranjuk and Tachiki gave a theoretical basis for the Josephson plasma emission [12]. They showed that the plasma wave was excited by the recombination of quasiparticles and the electron–plasmon scattering process. Assuming the d-wave pairing symmetry, the nonequilibrium quasiparticle distribution function was calculated self-consistently, from which the expression for the frequency-dependent complex dielectric constant was derived.

In this paper, we present the observation of Josephson plasma emission due to quasiparticle injection into the

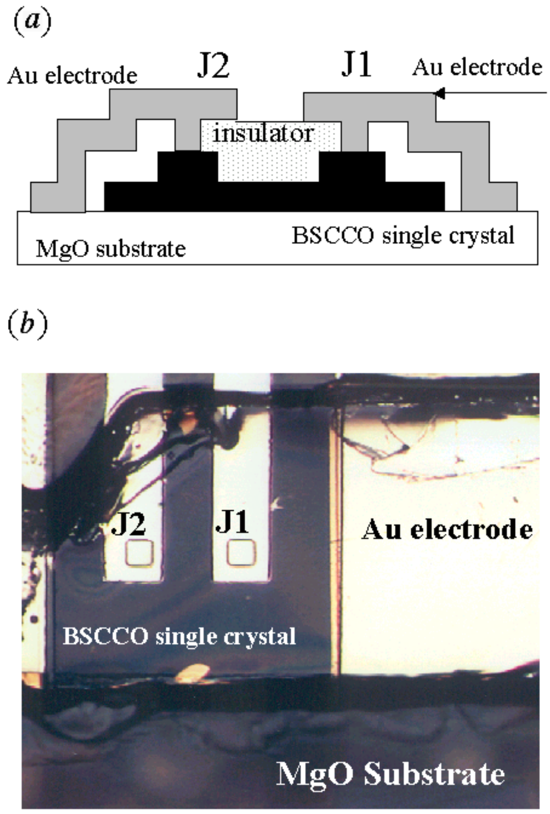


Figure 1. (*a*) Schematic cross-sectional view and (*b*) photograph of two-mesa structures of intrinsic Josephson junctions array on a BSCCO single crystal. The mesa area was $50 \times 50\ \mu m^2$.

c-axis direction of high-T_c $Bi_2Sr_2CaCu_2O_y$ (BSCCO) single crystals. For the intrinsic Josephson junction, it appeared as three different emission modes; one may be explained by microwave emission from phase-locked Josephson junctions at the low bias voltage range, and the others may be caused by the injection of quasiparticle current into the layered intrinsic Josephson junction at high bias voltage. We present the observation of Josephson plasma oscillation in the negative resistance region of the current–voltage characteristics. We also investigate the mutual phase interaction of plasma oscillations between BSCCO intrinsic Josephson junctions. The measured phase-locked output power of two intrinsic Josephson junctions was almost four times larger than that of the single intrinsic junction, indicating an exact phase-locking state between two intrinsic Josephson junctions.

2. Experimental section

The $Bi_2Sr_2CaCu_2O_8$ single crystals were grown by the travelling solvent floating zone technique. Typical dimensions of these single crystals were 4×8 mm^2 in the *ab* plane, with thickness of 50–100 μm. Large single crystals were cut into small sizes, then a 50 nm thick Au film was deposited on the cleaved surface of the crystal by electron beam evaporation. In order to increase the anisotropy and reduce the contact resistance, the crystal was annealed at 400–600 °C for 1–20 h. Epoxy was used to mount the sample on a MgO substrate. The insulating layer was made by depositing a 200 nm CeO_2 thin film at room temperature and was patterned by the lift-off technique. To obtain good coupling at high frequency, disk-shaped electrodes were formed by depositing Au thin films on the bottom surface of crystal and the top of the mesa, followed by patterning by Ar-ion milling. The three-terminal method was used for the transport measurements with current flow along the *c*-axis, i.e perpendicular to the layers of the mesa. At the frequency of 11.6 GHz, the gap between the top and bottom electrodes can be used as a resonator to improve the coupling. The radiation power from the intrinsic junction was measured by a superheterodyne detection technique with a non-resonant broadband matching system at the receiving frequency $f_{rec} = 11.6$ GHz. The absolute values of the emission power from the junction were calibrated by a standard noise source installed inside the microwave receiver [13]. Figure 1(*a*) shows the schematic cross-sectional view of the mesa structures of two-junction array. The mesa structures were fabricated by standard photolithography and ion-milling processes. The mesa area was $50 \times 50\ \mu m^2$. The height of the mesa was controlled by the milling time of an Ar ion gun. Figure 1(*b*) shows the photograph of the two-mesa structures of intrinsic BSCCO Josephson junction.

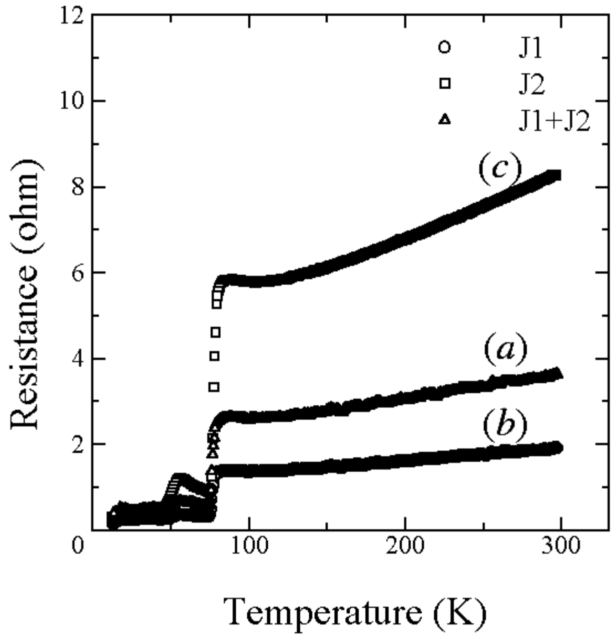
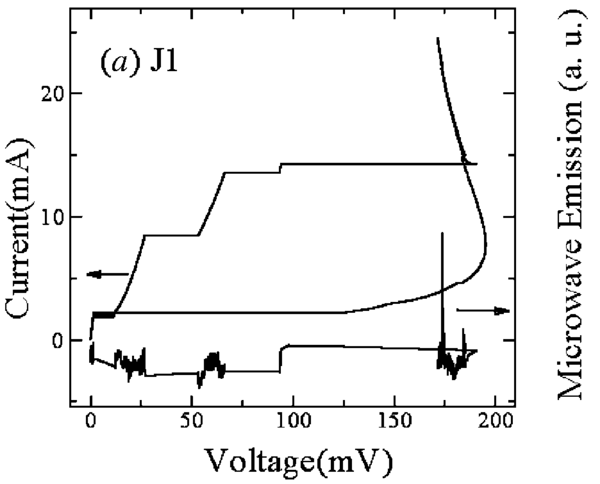


Figure 2. Temperature dependence of junction resistance for (*a*) sample J1, (*b*) sample J2 and (*c*) sample J1 + J2.

3. Results and discussion

Before testing the mutual phase interaction between two junctions, we separated our device and tested the microwave properties of the single intrinsic Josephson junction and the two-junction array of intrinsic Josephson junctions which can be separately biased. In table 1, we present the characteristic parameters of the two single-junctions and the array junction. Figure 2 shows the temperature dependence of junction resistance for sample J1, sample J2, and sample J1 + J2. For sample J1 + J2, the current was biased from J1 to J2. The three-terminal method was used for the transport measurements with



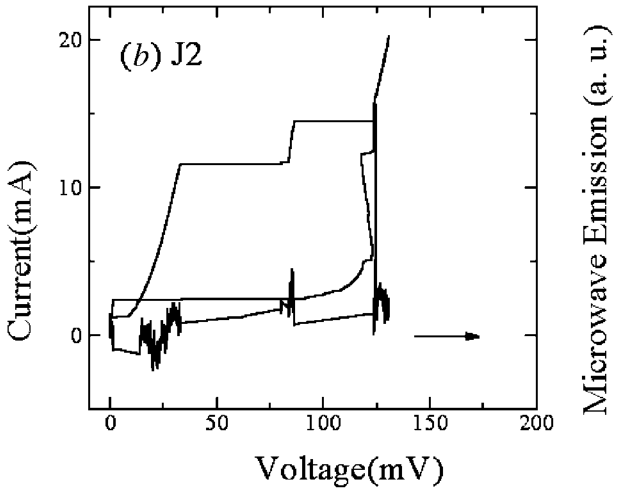


Figure 3. Detected Josephson microwave power at receiving frequency $f = 11.6$ GHz and the *I–V* characteristic for the BSCCO intrinsic junction for (*a*) sample J1 and (*b*) sample J2.

Table 1. Parameters for intrinsic BSCCO junction array.

Sample	Mesa size (μm^2)	Branch number	R(300 K) (Ω)	T_c(K)	V_c (mV)
J1	50×50	22	3.6	77	195
J2	50×50	17	1.9	77	125
J1 + J2	–	23	8.2	77	300

current flow along the *c*-axis, i.e. perpendicular to the layers of the mesa. Sample J1 shows low junction resistance below T_c, while sample J2 shows a relatively high junction resistance.

Figures 3(*a*) and (*b*) show the *I–V* characteristics and the microwave emission power for samples J1 and J2, respectively. Typical branch structures with large hysteresis were observed (not shown in the graph). This multi-branch structure can be explained by individual switching of the intrinsic Josephson junctions to the resistive state [9]. For sample J1, a periodic voltage jump could be observed and the first jump voltage was observed at about 25 mV. Increasing the bias current, 22 branches could be traced out. For large bias current, at a characteristic voltage V_c of 195 mV, all of the intrinsic junctions contained in the stack structure were switched to

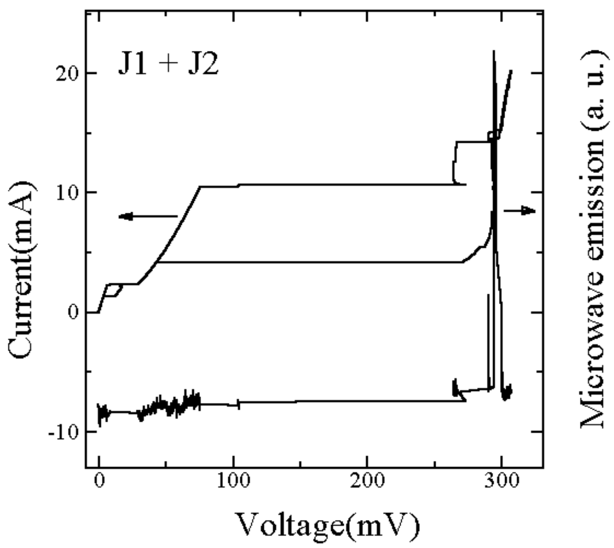


Figure 4. Detected Josephson microwave power at receiving frequency $f = 11.6$ GHz and the *I–V* characteristic for the BSCCO intrinsic junction for sample J1 + J2.

the resistive state. For sample J2, the multi-branches were also observed and about 17 branches could be traced out and the characteristic voltage was about 125 mV. Comparing with sample J2, large contact resistance of sample J1 could be seen. It is pointed out that, in both the samples, negative resistance behaviour was observable in the last few branches.

Note that these microwave emission properties of sample J1 and J2 are quite different from the Josephson self-emission since it appeared at a voltage far above that expected for a series array of Josephson junctions. As shown in figures 3(*a*) and (*b*), in addition to the Josephson self-emission at low-bias voltage about a few millivolts range, a sharp emission peak was observed at the high bias voltage in the gap-edge region, exhibiting a negative differential resistance behaviour [13]. The presence of a microwave plasma emission peak and negative resistance suggests that the system was driven into the strongly perturbed nonequilibrium state due to self-injection of quasiparticles. In the negative-resistance region, the phase differences of all junctions are in phase, inducing the same static voltage in all junctions. The electric field E in the intrinsic Josephson junction is given by [9, 14]

$$E = E_0 + E_p \cos \omega_p t \tag{1}$$

where ω_p is the Josephson plasma frequency, E_0 is the static voltage and E_p is the amplitude of the Josephson plasma oscillation induced in the nonequilibrium state. It is consistent with the experimental observation of a coherent plasma oscillation peak. The sharp Josephson plasma peak was only observed for the intrinsic junctions exhibiting strong negative resistance accompanying large gap reduction.

Figure 4 shows the *I–V* characteristics and the microwave emission power for sample J1 + J2. Typical branch structures with hysteresis were also observed. Increasing the bias current, about 23 branches could be traced out. For large bias current, at a characteristic voltage V_c of 300 mV, all of the intrinsic junctions contained in the stack structure were switched to the resistive state. A sharp emission peak was observed at the bias voltage $V = 294$ mV for J1 + J2. Figure 4 shows the microwave emission peak for sample J1 + J2, which is caused by the interaction between the two-mesa structures of intrinsic junctions. These results provide the evidence that the phase coherent state of two-mesa structures of intrinsic junctions was enhanced by the mutual phase interaction. Note that, for a single intrinsic junction, the observed emission power was about several nW. For the series-connected junction array, if the number of junctions N is chosen such as $NR_J = R_L$, where R_J is the resistance of a single intrinsic Josephson junction and R_L is the load impedance. The available power proportional to the load is approximately $P_{max} = (1/8)NI_c^2R_L$, where N is the number of junctions. With a matching load, available power is proportional to N^2. The two-mesa array should deliver the maximum power of 280 μW into the matching load. The observed emission power of the two-mesa array was about 5 μW at the receiving frequency of 11.6 GHz. From the theoretical estimate of mismatch between the array impedance and the load impedance of a receiver, the transmission power loss would be expected to be about 30 dB smaller than the above value. The observed microwave emission power of sample J1 + J2 was about two orders smaller than that of the expected value. Without matching load, the observed power indicated that the phase differences of the two-mesa junctions are in phase, inducing the same static voltage in all the junctions and increasing the transmission power [15]. Thus, as shown in figure 4 our result showed the phase-locking of the two-mesa structures of BSCCO intrinsic Josephson junctions.

In summary, we have reported novel microwave emissions due to tunnel injection of quasiparticles into the c-axis direction of BSCCO single crystal. The observed microwave emission form intrinsic Josephson junctions are found to have three different modes; Josephson self-emission at low bias voltages, a nonequilibrium incoherent broadband emission in the quasiparticle branches and a coherent plasma emission in the negative-resistance region at the gap edge. The mutual phase interaction between the two intrinsic junction arrays has been studied. The observed output power of the two-mesa structures of BSCCO intrinsic Josephson junctions showed a microwatt power level, indicating an exact phase-locking state between two-mesa structures of intrinsic Josephson junctions.

Acknowledgments

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