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Novel nonequilibrium microwave emission and current -voltage characteristics of $Bi_2Sr_2CaCu_2O_{8+d}$ intrinsic Josephson junction mesas

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Abstract

We have measured the transport properties of $Bi_2Sr_2CaCu_2O_{8+d}$ (BSCCO) intrinsic Josephson junction mesa. Transport measurements with current flow along the c-axis, perpendicular to the layer of mesa showed multi-branch structures on the current-voltage characteristics. For single intrinsic junctions, the microwave radiation appears in the form of three different modes of oscillations, which include Josephson emission, nonequilibrium broad emission and sharp coherent microwave emission. Mutual phase interactions between two-mesas structures of BSCCO intrinsic Josephson junctions were studied. The results were explained within the framework of the Josephson plasma excitation model due to quasiparticle injection.

Keywords : intrinsic Josephson junction, plasma oscillation, nonequilibrium state.

I. Introduction

The investigation of microwave emission from low-T_c 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 microwave signal of the voltage satisfying the Josephson voltage-frequency relation. The phenomena were confirmed for both low-T_c 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 the flux-flow devices generating microwave of around 0.5 THz [4]. Similar microwave emission for high-T_c superconductor has been reported by Muller group [5], who attributed the observed phenomenon to the Cherenkov radiation of vortex flow. Nonequilibrium emission from an optically radiated high- T_c thin film by 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, the broadband microwave are emitted [7]-[9]. The observed phenomenon is quite different from Jopsephson self-emission, and has been attributed to Josephon plasma emission [9]. When the quasiparticles are injected along the c-axis direction of a high-T_c superconductor, the Josephson plasma modes are

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excited, which emits 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 wave travels through 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. The nonequilibrium quasiparticles distribution function was calculated self-consistently with an assumption of the d-wave pairing symmetry, from which the expression for the frequency-dependent complex dielectric constant was derived.

In this paper, we present observations of Josephson plasma emission due to quasiparticle injection into the *c*-axis direction of high-T_c $Bi_2Sr_2CaCu_2O_{8+d}$ (BSCCO) single crystals. For intrinsic Josephson junctions, it had three different emission modes, one may be explained by microwave emission from phase-locked Josephson junctions at a 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 Josephson plasma oscillation in the negative resistance region in 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 from two intrinsic Josephson junctions appeared about four times larger than that from a single intrinsic junction, indicating an exact phase-locking state between two intrinsic Josephson junction.

II. Experimental

The BSCCO single crystals were grown by the solid-state reaction method. Two mesas were patterned using a conventional photolithography using positive photoresist and a Ar ion etching technique. Details on the fabrication method are described in Ref. [13]. The four-probe method was used for the transport measurements with current flow along the *c*-axis, i.e. perpendicular to the layers of mesa. At the frequency of 1.7 GHz, the gap between the top and bottom electrodes could 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}) of 1.7 GHz. The absolute values of the emission power from the junction were calibrated by a standard noise source installed inside the microwave receiver [14].

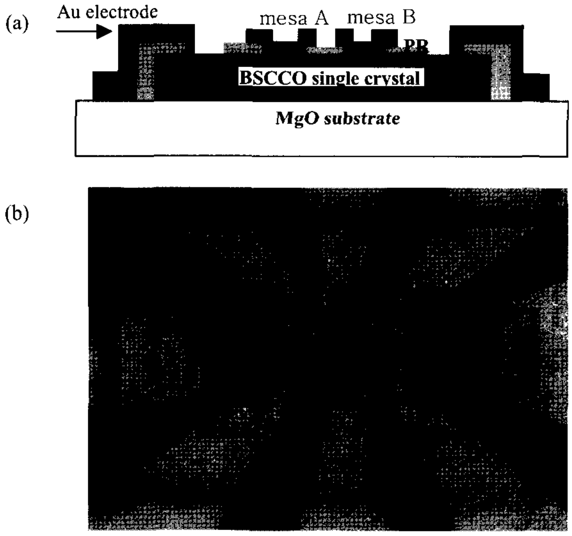

Fig. 1. (a) A schematic cross-sectional view of two-mesas structure, (b) a photograph of two-mesas structure. The small mesa area was 20×5 μm^2

Figure 1(a) shows the schematic cross-sectional view of two-mesas structure. The mesa structure was fabricated by the standard photolithography and ion-milling processes. The mesa area was 20×5 μm^2. The height of mesa was controlled by Ar ion-milling time. Figure 1(b) shows the photograph of two mesas structures of intrinsic BSCCO Josephson junctions.

III. Results and discussion

The measured critical temperature of BSCCO single crystal was about 77 K. The junction resistances of mesas A, B and mesa A+B were 17. 6 Ω, 10.5 Ω, and 29.6 Ω at 300 K, respectively.

Figure 2 shows the c-axis current-voltage (I-V) characteristics of mesa A at 13 K. Typical branch structures with large hysteresis were observed. This multi-branch structure can be explained by individual switching of the intrinsic Josephson junctions to the resistive state [9]. On the I-V characteristics of Fig. 2, periodic voltage jumps could be observed with the first jump voltage was observed at about 7.4 mV. With increased the bias current, 21 branches could be traced out. For large bias current, at a characteristic voltage V_c of 209.7 mV, all the intrinsic junctions contained in the stack structure were switched to the resistive state. In case of mesa B, the multi-branches were also observed and about 17 branches could be traced out with the characteristic voltage of about 150.9 mV. The value of V_c/N is about 9.98 mV for mesa A and 8.87 mV for mesa B, where N is the number of branches in the corresponding I-V curves. It is generally believed that V_c/N and first jump voltage are basically proportional to the gap of CuO_2 bilayer. However, our result appeared smaller than the gap voltage of 40-50 mV. The suppression of the gap value and the negative resistance effect are likely due to the nonequilibrium effect.

It is noted that the microwave emission properties of mesa A and B are not attributed to the Josephson self-emission. It is because the microwave since it appeared at a voltage far above that expected for a series array of Jopsephson junctions [14]. The presence of the microwave plasma emission peak and the negative resistance suggest that the system be driven into the strongly perturbed nonequilibrium state due to self-injection of quasiparticles. As shown in Figs. 3(a) and 3(b), in addition to the Josephson self-emission at low-bias voltage about a few millivolts range, a sharp emission peak was observed

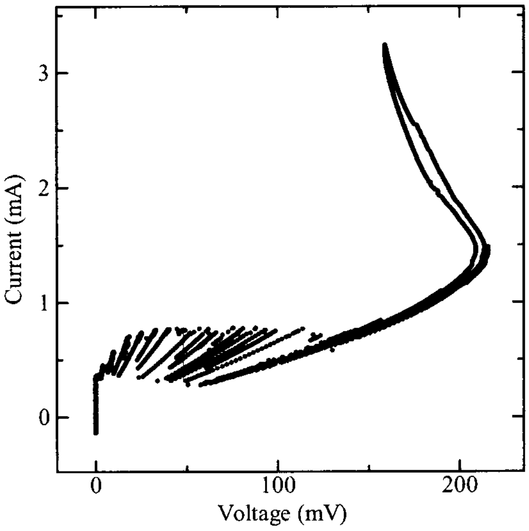

Fig. 2. Quasiparticle branches on the I-V characteristics of mesa A.

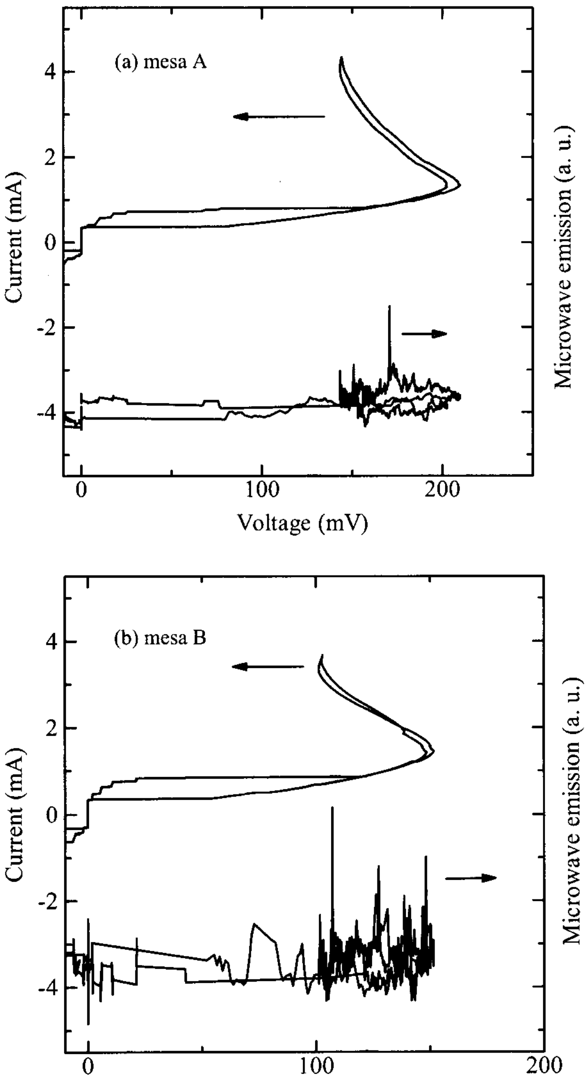

Fig. 3. Detected microwave emissions at a receiving frequency of 1.7 GHz and the I-V characteristics for the BSCCO intrinsic Josephson junction for (a) mesa A and (b) mesa B.

at the high bias voltage in the gap edge region, exhibiting a negative differential resistance behavior. In the negative resistance region, the phase differences of all junctions are in phase, inducing the same static voltage in all the junctions. The electric field E in the intrinsic Josephson junction is given by [9], [15]

$$E = E_0 + E_p \cos \omega_p t \qquad (1)$$

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 mesa A+B. For a large bias current, at a characteristic voltage V_c of 293.9 mV, all 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 = 304.4 mV for mesa A+B. Figure 4 shows the microwave emission peak for mesa A+B, which is caused by the interaction between two-mesas structures of intrinsic junctions. These results provide an evidence that the phase coherent state of two-mesas 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 is proportional to the load with the maximum power P_{max} expressed by $P_{max}=(1/8)NI_c^2R_L$. With a matching load, available power is proportional to N^2. In this context, the two-mesas array need to deliver the maximum power of 245 μW into the matching load.

However, the observed emission power of the two-mesas array was only about 4.7 μW at 1.7 GHz. From the theoretical estimate of mismatch between the array impedance and the load impedance of a receiver, the transmission power loss is expected about 30 dB smaller than the above value. Meanwhile, the observed microwave emission power of mesa A+B was about two orders smaller than that of the expected. Without matching load, the observed power indicated that the phase differences of two-mesas junctions are in phase, inducing the same static voltage in all junctions, which would result in increased transmission power [16]. Thus, as shown in Fig. 4, our results imply the phase-locking between the two-mesas of BSCCO intrinsic Josephson junctions.

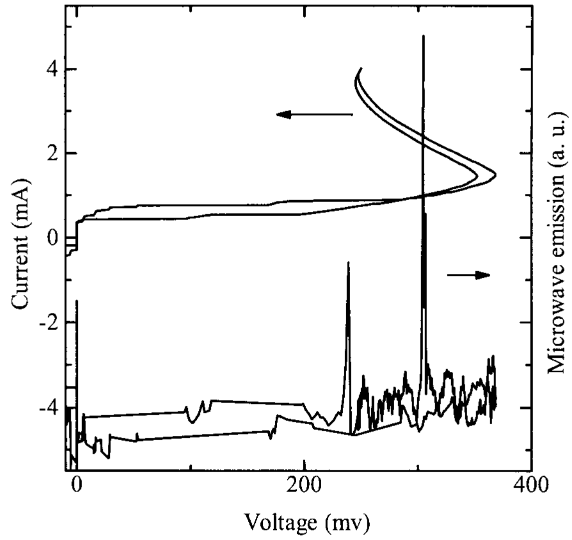

Fig. 4. Detected microwave emission at a receiving frequency of 1.7 GHz and the *I-V* characteristics for the BSCCO intrinsic Josephson junction for mesa A+B.

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 from intrinsic Josephson junctions are found to have three different modes including 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 two-mesas structure of BSCCO intrinsic Josephson junctions showed about microwatt power level, indicating an exact phase-locking state between two-mesa structures of intrinsic Josephson junctions.

Acknowledgments

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