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Microwave plasma emission from tunnel-injected nonequilibrium high-Tc superconductors

Kiejin Lee
Sogang University, Seoul, Korea

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Abstract

We report on the novel nonequilibrium microwave emission from quasiparticle-injected high-Tc superconductors. The phenomena have been observed for the current-injected YBCO/I/Au or BSCCO/I/Au thin-film tunnel junctions and BSCCO single-crystal intrinsic Josephson mesa junction samples. For the thin-film tunnel junctions, the emitted radiation appears as broadband. For the intrinsic BSCCO mesa samples, the radiation appears as three different modes of emissions depending on the bias point in the hysteretic current-voltage characteristics; Josephson-emission, nonequilibrium broad emission and sharp coherent microwave emission. The results were interpreted by the Josephson plasma excitation model due to quasiparticle injection.

Keywords: Josephson plasma, high-T_c tunnel junction, intrinsic junction, nonequilibrium state, quasiparticle injection

I. Introduction

Microwave emission from low-T_c and high T_c superconductor have attracted considerable attention for both basic studies and electronic applications of high-Tc superconductors. It has been well known that the Josephson junction based at a finite voltage emits the microwave for the voltage satisfying the Josephson voltage–frequency relations. The phsenomena were confirmed for both low-Tc and high-Tc superconductors [1-3]. On the other hand, the driving of vortices by a current in the long Nb Josephson tunnel junction under an external magnetic field led to the flux flow devices generarting microwave of around 0.5 THz[4]. Similar microwave emission for high-Tc YBCO superconductors has reported by Muller 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 YBCO thin film using a femtosecond laser has been reported[6].

Recently, it has been reported that when a high-Tc superconductor/insulator/normal metal tunnel junction is biased at a finite current, the broadband microwave are emitted[7-11]. The observed phenomenon is quite different from Jopsephson self-emission and has been considered as Josephon plasma emission. When the quasiparticle are injected along the c-axis direction of a high-T_c superconductor, the Josephson plasma modes has been so far demonstrated by the resonant absorption technique[8]. Due to the fact that the c-axis polarized Josephson plasma modes lie well below the gap energy, the plasma wave are transmitted in the crystal without appreciable Landau Damping [9]. Recently, Shafranjuk and Tachiki gave a theoretical basis for the Josephson plasma emission [9]. They showed that by quasiparticle injection, the plasma wave is excited by the recombination of quasiparticle

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Corresponding author. Fax: + 82 2 705 8429
e-mail: klee@ccs.sogang.ac.kr

distribution function was calculated self-consistently, from which the expression for the frequency-dependent complex dielectric constant was derived. When the real part of the dielectric constant becomes zero, it gives a plasma frequency. The calculated plasma emission spectra contain the bradband Josephson plama oscillation spectruma and the coherent Josephson plasma emission.

In this paper, we present the observation of Josephson plasma emission due to quasiparticle injection into the c-axis direction of high-Tc thin films and single crystals. The emission appeared in broadband for the thin film samples. For intrinsic single crystal samples, it appeared as three different emission modes, one may be explained by microwave emission from phase-locked Josephson junctions, and the other may be caused by the injection of quasiparticle current into the layered intrinsic Josephson junction. It interpreted that that sharp coherent peak may be interpreted by the electromagnetic interaction between thw Josephson plasma modes in the negative resistance region in the current-voltage characteristics.

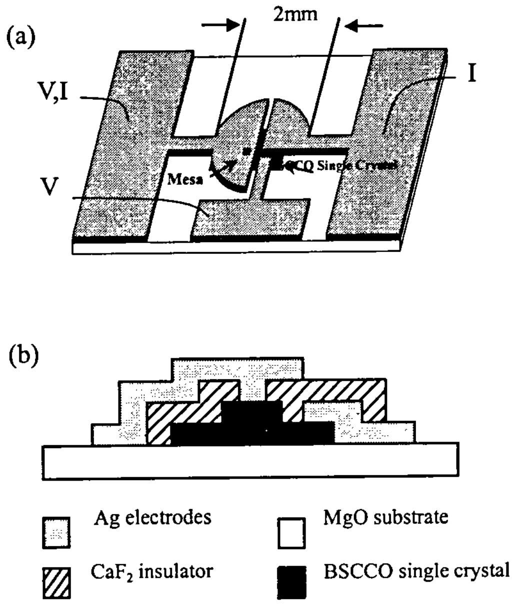

Fig. 1. Sketch of the sample geometry. (a) Shape of the electrodes. (b) Schematic cross-sectional view of mesa structure.

II.Experimental

The $Bi_2Sr_2CaCu_2O_8$ single crystals were grown by the traveling solvent floating zone technique. Typical dimensions of these single crystals are 4× 8 mm^2 in the a-b plane, with thickness of 50-100μ m. The large single crystals were cut into small size, then a 50nm 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℃ for 1-20 hrs. Epoxy was used to mount the sample on a MgO substrate. The insulating layer was made by depositing a 200nm CaF_2 thin film at room temperature and was patterned by lift-off technique. To obtain good coupling at high frequency, disk shaped electrodes were formed by depositing Ag thin films on the bottom surface of crystal and the top of mesa, then patterning by Ar-ion milling as shown in Fig. 1. The mesa structures were fabricated by the standard photolithography and ion-milling processes. The mesa area was 50× 50μ m^2. The height of mesa was controlled by the milling time of an Ar ion gun. Figure 2 shows the meas structure of intrinsic Josephson junction at BSCCO single crystal.

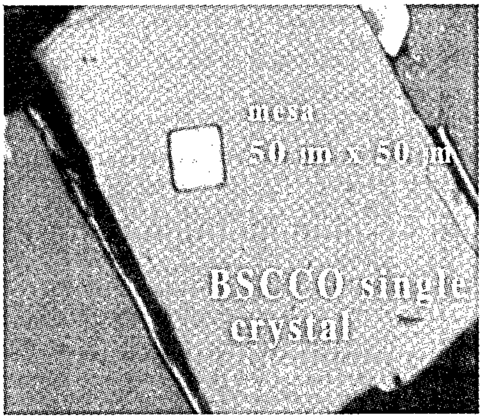

Fig. 2. A meas structure of intrinsic Josephson junction on a BSCCO single crystal. The mesa area was 50× 50 m^2.

Table 1. Variable parameters for the intrinsic Josephson junctions.

Sample	Mesa size (μm^2)	Branch number	R(300K) (Ω)	T_c(K)
A	50x50	25	10	86
B	50x50	30	13	86
C	50x50	20	17	86

The three terminal method was used for the transport measurements with current flow along along the c-axis, i.e. perpendicular to the layers of mesa. At the frequency between 12GHz and 47GHz, the gap between the top and bottom electrodes can be used as a resonator to improve the coupling. In the microwave measurements, the whole sample holder was mounted at the center of a waveguide with a cross section of 1 Ĭ1mm^2 which was connected to a K-band rectangular waveguide with a two-step quarter-wave standard matching transformer. The radiation power from the junction array was measured by a superheterodyne detection technique with a non-resonant broad-band matching system at receiving frequencies f_{rec}=12 GHz, 36GHz and 47GHz. The receiver was operated in a two band

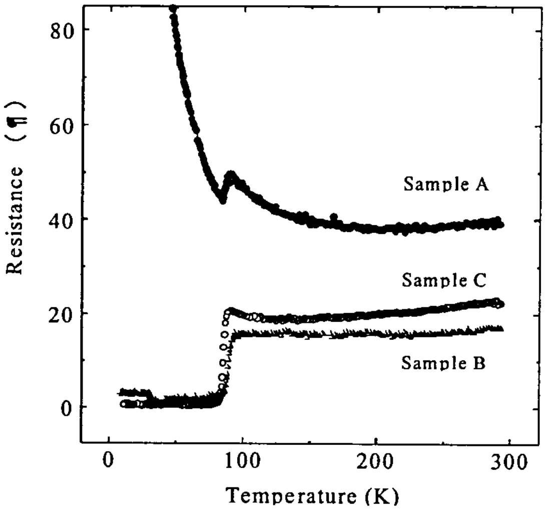

Fig. 3. Temperature dependence of junction resistance for sample A, sample B and Sample C. Sample A, B and C were fabricated without annealing process, annealed at 400 C for 1 h and annealed at 600 C for 4 h, respectively.

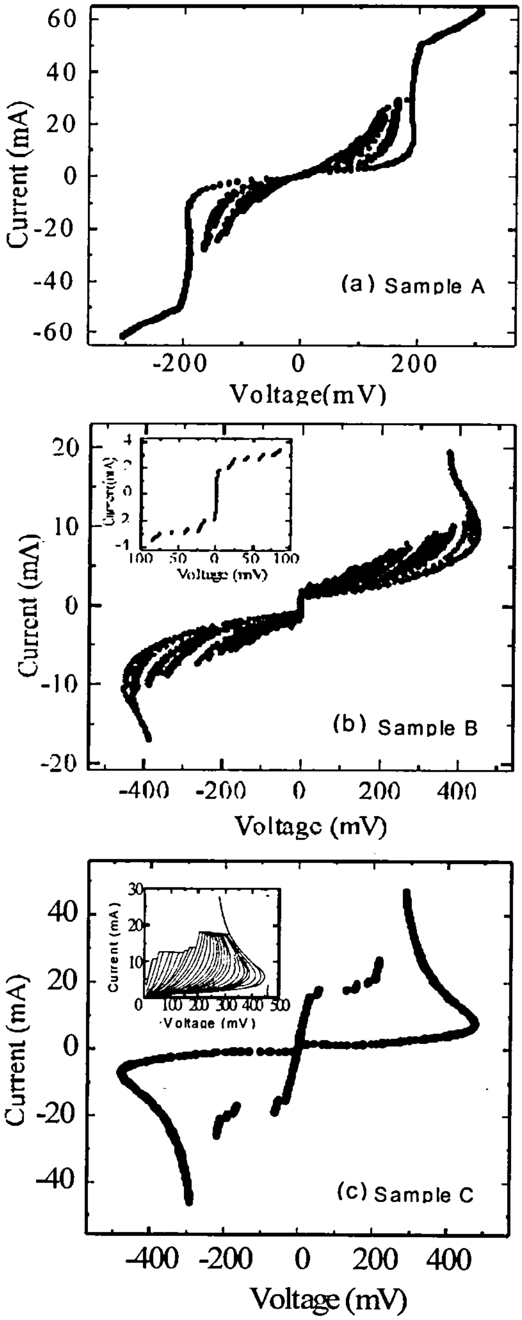

Fig. 4. Typical *I-V* characteristics of three intrinsic Josephson junctions for (a) sample A, (b) sample B, and sample (C). The inset in (b) and (c) shows quasiparticle branches.

regime with a bandwidth • B=2GHz. The sensitivity of the receiver was • S≈3 Ĭ0^{-24}W/Hz at an integrating time $\tau = 1$s. The absolute values of the self-radiation power emitted from the junctions was calibrated by a standard noise source installed inside the microwave receiver system. All electrical connections were carefully filtered by a low pass filter and a dc bias was used as an analog low-noise source. The sample was magnetically shielded by superconducting Pb and μ-metal. More details of the microwave measuremental setup are described in Ref. [10].

III. Results and Discussion

The observed current - voltage (*I-V*) characteristics for the meas sample exhibited multibranch structures accompanying negative resistance behavior due to self-injection of quasiparticles. For example for sample C, the presence of 25 multibranch structures was confirmed. Figure 4 shows the Josephson microwave emission at low bias voltage range at different receiving frequencies f= 36 GHz and 47 GHz. The results are consistent with the occurrence of phase-locked Josephson microwave emission from a series connected Josephson junction array. The Josephson emission at frequency ω with a bias voltage, $S_v(\omega)$ can be obtained by the RSJ model and the Josephosn equation $\omega = (2e/\hbar)V$, as

$$S_v(\omega) = \sum_{i=1}^{n} S_0 \exp\left(\frac{\omega - n\omega_J}{\Delta\omega}\right)^2 \qquad (1)$$

where, n is the number of junctions and $\Delta\omega$ is the linewidth due to the thermal fluctuations.

Note that, to observe he Josephson microwave emission at low bias range, it was necessary to fabricate the sample with low tunnel resistance so that a large amount of quasiparticles might be injected at the gap-sum voltages. This could be done by controlling the annealing condition. In fact, we obtained the samples with the contact resistance of order of 10 Ω.

When the *I-V* characteristic jumped to one of quasiparticle current branch, a broadband microwave emission power was observed. A Series of incoherent broadband microwave emissions were observed from branch to branch up to the high bias voltage region. Note that, a series of broadband emissions were observable from branch to branch at the high bias voltage region. Figure 5 shows such results. When the current was increased or decreased along the quasiparticle branch, a continuous change of the emission power was observed. These emissions are qualitatively different from Josephson self-emission since it appeared at the bias voltages much greater than the expected bias voltage according to the Josephson voltage-frequency relation. The emissions were quite similar to those observed in S/I/N thin film tunnel junctions[11]. Note that, the emitted microwave emission power depends linearly on the injection current. It increased with the injection current approximately linearly up to the next quasiparticle branch. These behaviors were common to all temperatures T<T_c. The emitted power was found to be greater at low temperature and diminished near T_c. The results indicate that the dynamic

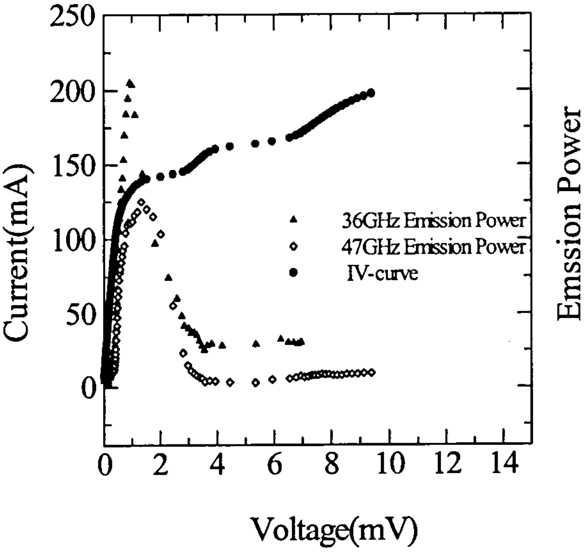

Fig. 5. Detected Josephson microwave power and the *I-V* characteristics at low bias voltage range at receiving frequencies f=36 GHz and 47 GHz at 4.2 K for a BSCCO intrinsic junction.

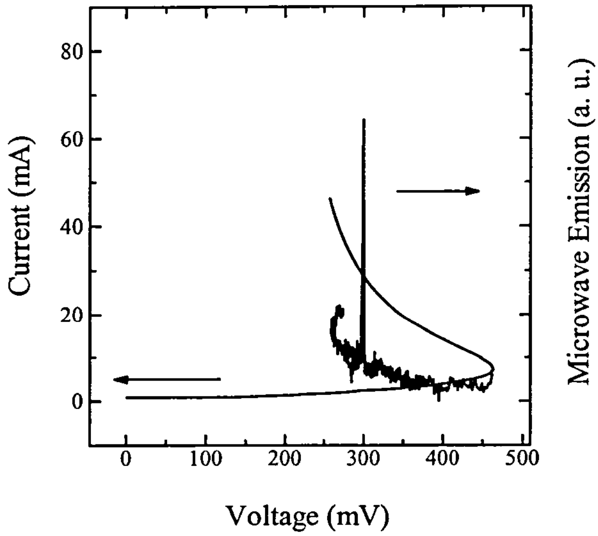

Fig. 6. Detected microwave emission power of f=11.6 GHz and the I-V characteristic in the negative resistance region at the gap edge for sample C.

of nonequilibrium superconductivity is essential for microwave emission arises from incoherent Josephson plasma emission. The Josephson plasma frequency for YBCO material lies 0.5 THz depending on the oxygen deficiency. It should be noted that the quasiparticle injection into the ab-plane did not generate electromagnetic radiation. The microwave emission was only observable foe quasiparticle injection along c-axis. Incidentally, the strong nonequilibrium state was found to be established only for the quasiparticle injection along the c-axis[11].

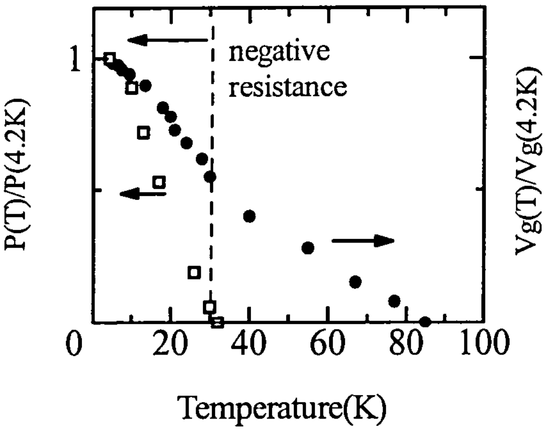

Fig. 7. Temperature dependence of he Josephson plasma peak(□) and the normalized gap-edge voltage(•).

For the observation of microwave emission power at the gap edge, we pick up one specific cycle in the I-V characteristics of intrinsic Josephson junction for sample C. Figure 6 shows such on specific cycle, in which the I-V characteristic exhibited hysteretic behavior which can be divided into the gap-edge region. In addition to the Josephson emission at low bias voltage as shown in Fig. 5, a sharp emission peak was observed at the bias voltage V=300 mV in the gap edge region exhibiting a negative resistance behavior. This peak is quite different from the Josephson self-emission since it appeared at voltage far above that expected for a series array of Jopsephson junctions. The presence of microwave plasma emission peak and negative resistance suggest that the system was driven into the strongly perturbed nonequilibrium state due to self-injection of QP. 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 [5]

$$E = E_o + E_p \cos \omega_p t \tag{2}$$

where, ω_p is the Josephson plasma frequency, E_o is the static voltage and Ep 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 observable for the intrinsic junctions exhibiting strong negative resistance accompanying large gap reduction. In Fig. 7, it is plotted the temperature dependence of the intensity of the sharp Josephson plasma peak. It also shows the measured temperature dependence of the normalized gap edge voltage. We note that the Josephson plasma peak shifted gradually toward a larger current region, reflecting that the resultant system is responsible for he nature of

Josephson plasma.

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 the intrinsic Josephson junction are found to have three different modes; Josephson self-emission at low bias voltage, a nonequilibrium incoherent broadband emission in the quasiparticle branches and a coherent plasma emission in the negative resistance region at the gap edge.

Acknowledgments

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