Nonequilibrium microwave emission due to tunnel injection of quasiparticles into a high-T_c $Bi_2Sr_2CaCu_2O_y$ superconductor

I. Iguchi, K. Lee,* and E. Kume
Department of Applied Physics and CREST, Tokyo Institute of Technology, 2-12-1 Oh-okayama, Meguro-ku, Tokyo 152-8551, Japan

T. Ishibashi and K. Sato
Faculty of Technology, Tokyo Institute of Agriculture and Technology, 2-24-16 Nakacho, Koganei, Tokyo 184-8588, Japan

(Received 22 March 1999; revised manuscript received 10 September 1999)

Nonequilibrium microwave emission due to tunnel injection of quasiparticles into a high-T_c $Bi_2Sr_2CaCu_2O_y$ (Bi2212) superconducting thin film using an Au/I/Bi2212 tunnel junction is reported. The microwaves were detected by a superheterodyne-mixer technique at a receiver frequency of 47 GHz. With increasing the injection current, the emitted microwave intensity increased almost linearly at relatively low temperatures, in qualitative agreement with the case of $YBa_2Cu_3O_{7-y}$ films. Above 35 K, however, the intensity vs injection current curves exhibited nonlinear behavior. The results were consistently interpreted by the Josephson plasma excitation model due to quasiparticle injection recently proposed by Shafranjuk and Tachiki.

I. INTRODUCTION

Microwave emission from a superconductor has been one of the most attractive subjects due to the basic understanding of physics involved and the application to possible optoelectronic devices. Several measurements have been reported for the generation of microwaves using both low-T_c and high-T_c superconductors. In the steady state of a superconductor, a few methods for the generation of electromagnetic waves from the microwave to millimeter range using dc-biased Josephson junctions are known. The most famous one is the self-radiation method induced by Josephson ac currents.[1] For high-T_c $YBa_2Cu_3O_{7-y}$ (YBCO), $Bi_2Sr_2CaCu_2O_y$ (Bi2212), and $Bi_2Sr_2Ca_2Cu_3O_y$ (Bi2223) superconductors, Josephson self-radiation of the order of picowatts has been detected by a superheterodyne-mixer technique by several groups.[2–7] Another method reported is to generate electromagnetic waves by the flux-flow effect.[8] The flux-flow phenomenon enables the generation of microwaves of several hundred GHz by moving magnetic fluxes in a long Josephson junction in a magnetic field. These two methods provide narrow-band oscillators. On the other hand, with the application of a strong magnetic field parallel to the CuO_2 plane of Bi2212 single-crystal, broadband microwave emission has also been reported.[9] Moreover, the use of a femtosecond laser pulse to excite a superconducting film led to the emission of electromagnetic waves up to the THz region.[10,11]

Quite recently, an emission of microwaves from dc-biased high-T_c YBCO/I/Au tunnel junctions due to quasiparticle injection into the c-axis direction has been reported.[12–14] The phenomenon was observable without applying any magnetic field. Quasiparticle injection phenomena have been intensively studied using high-T_c superconducting tunnel junctions for the past several years.[15–18] The microwave emission appeared in the broadband spectrum, differently from the narrow-band one usually observed for Josephson junctions. To observe nonequilibrium emission, it is essential to establish a strongly perturbed nonequilibrium state by quasiparticle injection. When a large number of quasiparticles are injected into a high-T_c superconducting film through a tunnel barrier, the film is driven to the nonequilibrium state far from the thermal equilibrium. In the nonequilibrium state, the excited quasiparticles decay toward the gap edge and recombine to form Cooper pairs by emitting some excitations such as phonons or plasmons.

Broadband microwave emission has been observable at least in the microwave detection range of 1.7–47 GHz in our measurements. It has been shown that the nonequilibrium emission differs from the conventional Josephson self-radiation in many ways. One possibility is the Josephson plasma emission due to quasiparticle injection.[19] The Josephson plasma frequency for high-T_c materials lies well below the gap frequency, and the plasma wave transmits without appreciable Landau damping.[20] The detection of microwave emission, however, has been demonstrated only for 1:2:3 oxide compounds such as YBCO (Refs. 12 and 13) and $ErBa_2Cu_3O_{7-y}$ (EBCO).[14] It is very important to determine whether or not the observed phenomenon is characteristic of high-T_c cuprate superconductors and to investigate the relationship between the Josephson plasma phenomenon and high-T_c material properties, since Josephson plasma frequency strongly depends on the material properties.

In this paper, we present our measurements on novel microwave emission from a quasiparticle-injected Bi2212 film. The microwave emission was observable when a tunnel current was supplied to a Bi2212/I/Au junction. The detected microwave intensity at 4.2 K increased almost linearly with increasing the injection current, quite similarly to that observed for the YBCO and EBCO cases.[12–14] At higher temperatures above 35 K, however, the detected characteristics deviated greatly from those of the YBCO and EBCO cases. The observed phenomena may be interpreted by the Josephson plasma excitation model by quasiparticle injection.[19]

II. EXPERIMENTAL DETAILS

Bi2212 films were grown onto MgO(100) substrates by the molecular-beam-epitaxy (MBE) technique.[21] Four differ-

0163-1829/2000/61(1)/689(5)/$15.00

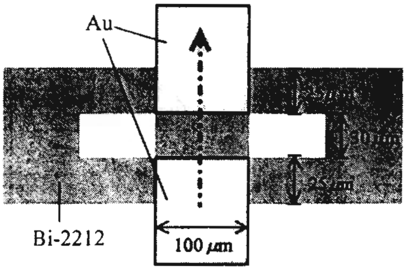

FIG. 1. Sample geometry.

ent elements (Bi, Sr, Ca, and Cu) were evaporated from four *K* cells by introducing an ozone-gas jet of 10% concentration from a nozzle. The background pressure during deposition was 2.5×10^{-3} Pa. The film growth was monitored by reflection high-energy electron diffraction (RHEED) and the good crystallinity of the film was confirmed by the appearance of streak patterns. The deposited film was *c*-axis oriented, as measured by the x-ray-diffraction method. Only 2212 peaks were observable. The film thickness was 300 nm. The film was patterned into a junction, as shown in Fig. 1 in the following way. First, the Bi2212 film was patterned into a geometry with two holes by photolithography and a wet-etching process using HCl. Thereafter, the Au film was deposited and patterned by the lift-off technique. The critical temperature T_c and the critical current density J_c of the Bi2212 film at 4.2 K after microfabrication were 75 K and 10^6 Å/cm^2, respectively, ensuring the high quality of the Bi2212 film grown by the MBE method. The geometry of Fig. 1 was specially designed for studying the injection characteristics as well.

The measurements on the injection characteristics were performed by feeding the injection current through two tunnel barriers, as shown in Fig. 1, and measuring the change in the critical current of the Bi2212 film. The four-terminal method was employed in this measurement. The measurements of microwave detection were performed by a nonresonant superheterodyne-mixer technique with a receiver frequency of 47 GHz (bandwidth: $B=2$ GHz).[7] The generated microwave emission signal was guided to a tapered waveguide at the low-temperature section. The incident signal after passing through a modulator and an attenuator was mixed with a Schottky local oscillator signal, and then the intermediate frequency (IF) signal was amplified and put into an integrator to produce the dc-output signal. The integration time was 1 s. Hence the observed signal corresponds to the integrated power spectrum. The detection sensitivity was 10^{-16} W. To isolate the local oscillator power from the junction, two isolators were used between the sample and the mixer block, providing isolation of more than 60 dB at central frequency, which prevented the local oscillator signal from transmitting to the sample side. The observed magnitude of signal ranged from the subpicowatt to picowatt region.

Figure 2 shows an example of detected Josephson self-radiation signal from a dc-biased YBCO Josephson bicrystal junction using our detection system with the receiver frequency 47 GHz. A sharp peak was found at the current value corresponding to the voltage *V* satisfying the Josephson voltage-frequency (*f*) relation $hf=2$ eV. The detected power was about 1 pW. This result confirms the validity of our measurement system for microwave detection. The measurements of microwave emission due to tunnel injection of quasiparticles were done by feeding the injection current through two tunnel junctions and detecting the microwave signal at the specific receiver frequency.

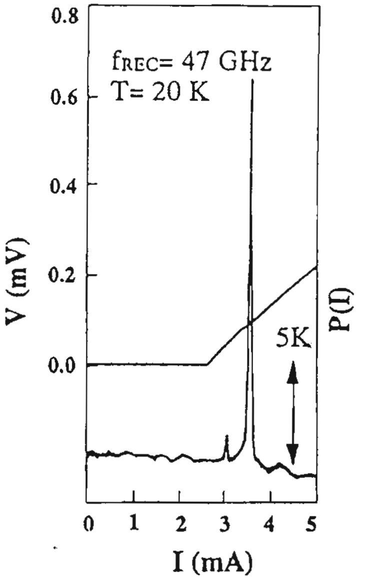

FIG. 2. Josephson self-radiation integrated power spectrum from a YBCO bicrystal junction detected by a superheterodyne-mixer technique.

III. RESULTS AND DISCUSSION

Figure 3 shows the tunnel-conductance characteristics of a Bi2212/I/Au thin-film injector junction at different temperatures. The presence of a pronounced gap structure in the fabricated junction is evident, ensuring that the current injection is held in the tunneling regime. The gap structure exhibited the so-called "gapless" character, being consistent with the *d*-wave nature of high-T_c superconductors. It varied as the bath temperature was raised and diminished near T_c. The gap value at low temperature was $\Delta\sim 20\,\text{meV}$. Above T_c, the nonlinear conductance with some gaplike structure still existed, suggesting the possible existence of a pseudogap state.

Figure 4 shows the observed injector characteristics of a Bi2212 film, i.e., the film's critical current (I_c) vs injection current (I_{inj}) curve at 4.2 K. The critical current for the non-injection case was $I_c=106$ mA. With increasing the injection current I_{inj}, I_c was suppressed, but not as strongly. Note that, because of the geometry given in Fig. 1, the injection characteristics appeared quite symmetrically against the polarity of the current axis (not shown here), in contrast to the case of the junctions using crosstype geometry.[15-17]

The observed average current gain was 1.1, suggesting that the quasiparticle injection into a high-T_c superconductor does not seem to be as effective as that into low-T_c superconductors[22,23] in reducing the energy gap. The results are qualitatively similar to those previously observed for YBCO/I/Au junctions[17,18] and are considered to be charac-

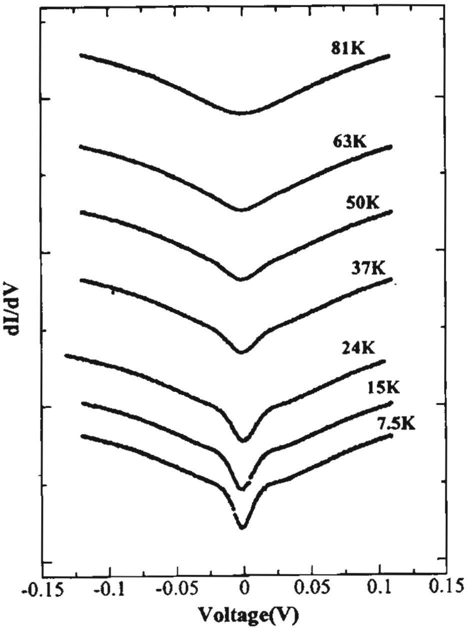

FIG. 3. Tunnel conductance characteristics of a Bi2212/I/Au junction at different temperatures.

teristic of high-T_c cuprates. The value 1.1 is, however, reasonable for our junction geometry in Fig. 1. Let us suppose that there is no tunnel barrier between YBCO and Au (corresponding to current pair breaking only). By assuming that w_1 and w_2 are the widths of an Au film and one channel of a YBCO film in the center region, respectively, the average current gain, as defined by I_c/I_{ic} where I_c is the critical current of the film without injection and I_{ic} is the critical injection current at which I_c becomes zero, is given by $2w_2/w_1$ for the geometry given in Fig. 1 since the film's critical current density $J_c = I_c/2w_2d$ and $J_{ic} = I_{ic}/w_1d$ should be equal. For $w_1 = 100\ \mu\text{m}$ and $w_2 = 25\ \mu\text{m}$, the current gain is 0.5. The value 1.1 is significantly greater than this value. Moreover, in discussing the degree of nonequilibrium effect, the current gain based on the current density should be used. The current gain in this case is given by $J_c/J_{ic} = (I_c/I_{ic})(w_1/2w_2)$, yielding $J_c/J_{ic} = 2.2$, reflecting the significant involvement of the nonequilibrium effect. It is also pointed out that the data points were greatly deviated from the simple heating curve in Fig. 4.

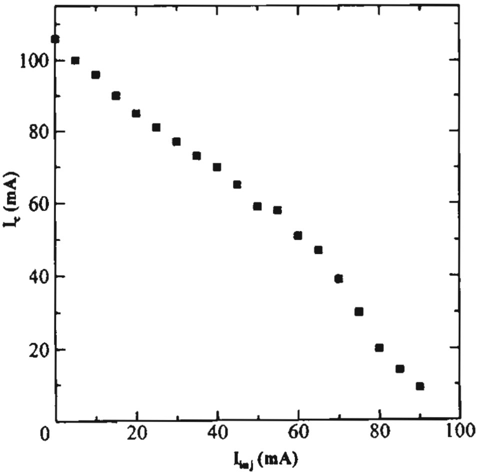

FIG. 4. Critical current of a Bi2212 thin film as a function of injection current at 4.2 K.

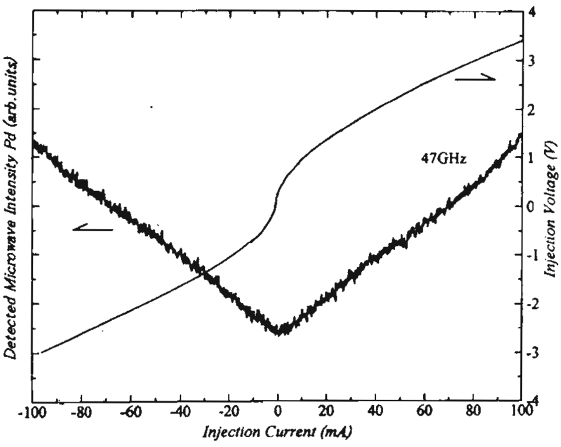

FIG. 5. Detected microwave power at 47 GHz as a function of injection current at 4.2 K, together with the current-voltage characteristic of an injector junction.

Next, we present the results on the detected microwaves. Figure 5 shows the detected microwave power at a receiver frequency of 47 GHz emitted from a Bi2212/I/Au tunnel injector junction as a function of injection current at 4.2 K together with the I-V characteristics of a tunnel junction. The detected microwave power increased almost linearly with increasing the injection current at least up to 100 mA in a qualitatively similar way to those observed in YBCO/I/Au junctions.[12,13] Although the microwaves were detected at 47 GHz only, we consider that the emitted spectrum will extend to a much higher frequency region, as described by the Josephson plasma phenomenon discussed later. In fact, a recent spectroscopic study using the YBCO junctions has determined that the emitted spectra extend up to 10 THz (to be published elsewhere).

Figure 6 shows the result for microwave detection when the current was fed only through a superconducting Bi2212 film and not through the tunnel barrier. No appreciable signal was observable in this measurement, demonstrating that the detected signal was not due to microwave emission from possible weak-coupling granular structures in a film. The result is consistent with the high quality of a Bi2212 film having the critical current density of 10^6 A/cm^2 (4.2 K). Hence, the detected microwave power is considered to arise solely from the quasiparticle injection phenomenon.

Figure 7 shows the measurements of the detected microwave power as a function of injection current at different temperatures. The microwave emission disappeared above T_c, assuring that the phenomenon is of superconductive nature. The nearly linear dependence of the microwave power on injection current at 4.2 K suggests that the microwave emission is incoherent, since the detected power P_d was not

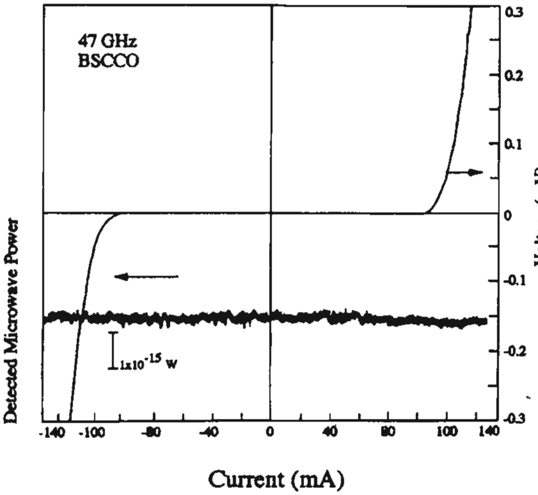

FIG. 6. Detected microwave signal as a function of transport current in a Bi2212 film only, together with its current-voltage characteristic. Note that no signal was detected by feeding the current in a Bi2212 thin film only, assuring that the signal obtained in Fig. 5 is not due to granular structures in the film itself.

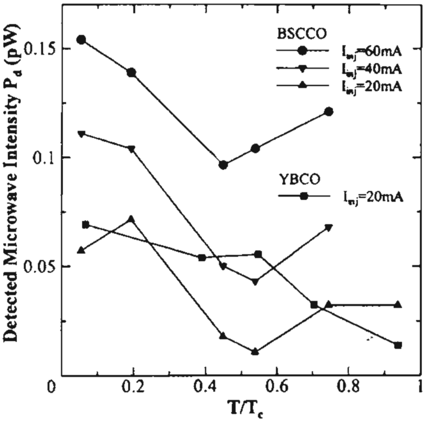

FIG. 8. Detected microwave intensity as a function of temperature for Bi2212 and YBCO films at several injection currents.

proportional to the injected power P_{inj}. With increasing the bath temperature, the linear current-dependent incoherent behavior disappeared and the P_d vs I_{inj} curves changed to nonlinear power-dependent behavior. This result differs from those previously reported for the YBCO films,[12,13] suggesting the additional contribution in going from incoherent nature of emission to coherentlike nature of emission. In fact, looking at the data at 15 K, we see some transient region from current-dependent incoherent behavior to power-dependent coherent behavior with increasing the injection current, i.e., for I_{inj} less than 20 mA, the P_d vs I_{inj} curve exhibits linear behavior, whereas above 20 mA, it tends to become nonlinear.

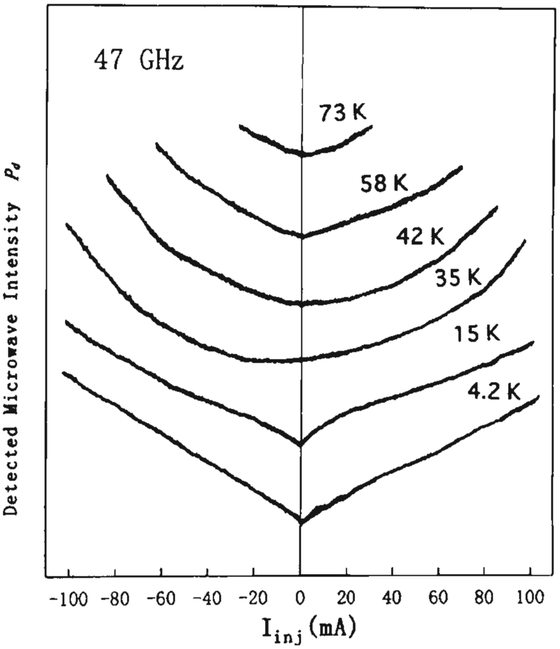

FIG. 7. Detected microwave power at 47 GHz as a function of injection current at different temperatures.

Figure 8 compares the results of the detected microwave intensity at several injection currents as a function of temperature for Bi2212 and YBCO films. The general features of these two data are qualitatively different. For a YBCO film, the overall detected power decreases monotonically as the bath temperature is raised while keeping the linear relation between P_d and I_{inj} suggesting the decrease of the plasmon emission probability at higher temperatures. At high temperatures near T_c, the injected nonequilibrium state becomes closer to the simple heating state in which most of excitations are emitted in terms of phonons. On the other hand, for a Bi2212 film, the detected intensity takes a minimum value at about $T/T_c = 0.5\,(T = 35\ \mathrm{K})$.

In the nonequilibrium state of a superconductor, the injected high-energy quasiparticles decay toward the gap energy via electron-phonon and electron-plasmon interactions. The quasiparticles near the gap edge recombine to form Cooper pairs by emitting phonons or plasmons. By considering nonequilibrium kinetics only, it is difficult to interpret the qualitative difference between the observed phenomena for YBCO and Bi2212 materials. Here, we interpret the observed results in terms of Josephson plasma emission effect in a high-T_c d-wave superconductor by quasiparticle injection as discussed by Shafranjuk and Tachiki quite recently.[19] According to their model, when a large number of quasiparticles are injected into a high-T_c superconductor along the c axis using a superconductor/insulating-barrier/normal-metal (S/I/N) tunnel junction, the Josephson plasma wave is excited by the processes of recombination of quasiparticles and electron-plasma scattering and the plasma wave polarized along the c axis is emitted. The nonequilibrium effect appears as a change in the electronic distribution function. The resultant nonequilibrium state depends on various injection conditions such as the injection voltage, injection current, and phonon escape time. It has been pointed out that the plasma-emission spectral mode depends strongly on the injection rate and injection voltage. For a relatively smaller injection rate, the spectrum forms a peak around the plasma frequency. For strong quasiparticle injection, the plasma mode is washed away by nonresonant electron-plasmon and electron-phonon collisions.

Based on the Josephson plasma physics, we interpret the observed results as follows. The Josephson plasma frequency ω_p largely differs in the above two materials. For Bi2212, it is around 100 GHz, whereas it is about 2 THz for YBCO.[24] The receiver frequency (47 GHz) is rather close to the Josephson plasma frequency of Bi2212, but far from that of YBCO. ω_p strongly depends on the temperature and decreases with increasing temperature. When the quasiparticle injection is held, the effective temperature of the system is raised, and ω_p decreases as well. Hence, the decrease of ω_p is determined by the sum of two effects, i.e., the rise of bath temperature and the increase of system temperature due to quasiparticle injection. Theoretically, as calculated by Shafranjuk and Tachiki,[19] the emitted spectrum due to quasiparticle injection consists of a coherentlike peak around Josephson plasma frequency ω_p with some width determined by the real part of the c-axis ac conductivity and a broadband spectrum due to incoherent plasmons arising from the electron-plasmon interaction. The decrease of Josephson plasma frequency causes a spectral shift of this peak spectrum toward lower frequency, hence raising the signal intensity at the receiver frequency site. At high temperature and in the presence of quasiparticle injection, ω_p is considerably reduced so that the plasma peaking edge may meet with the detector window. For Bi2212, since ω_p lies near the receiver frequency, this effect is large, and the contribution of plasma peak behavior appears as the increase of the detected power at higher temperatures (Fig. 8). On the other hand, ω_p is much greater than the receiver frequency for YBCO; hence, such a contribution is too small to be observed. The slight displacement of a minimum point between the data for $I_{\mathrm{inj}} = 40\,\mathrm{mA}$ and $I_{\mathrm{inj}} = 60\,\mathrm{mA}$ in the temperature axis in Fig. 8 reflects that the spectrum displacement with increasing I_{inj} indeed happens.

IV. CONCLUDING REMARKS

We have reported the microwave emission from a quasiparticle-injected Bi2212 film using a Bi2212/I/Au tunnel junction. The microwave signal was detected by a superheterodyne-mixer technique at a receiver frequency of 47 GHz. With increasing the injection current, the microwave power increased almost linearly against the injection current at 4.2 K, consistently with those reported for YBCO films. At higher temperatures above 35 K, however, a nonlinear increase of microwave power against the injection current was observed. The results were interpreted by the excitation of the Josephson plasma mode due to quasiparticle injection into a Bi2212 film having a low plasma frequency of approximately 100 GHz.

---

*Present address: Department of Physics, Sogang University, C.P.O. Box 1142, Seoul 121-742, Korea.

[1] B. D. Josephson, Adv. Phys. **14**, 419 (1965).

[2] W Reuter, M. Siegel, K. Herrmann, J. Schubert, W. Zander, and A. I. Braginski, Appl. Phys. Lett. **62**, 2280 (1993).

[3] R. Kleiner and P. Muller, Phys. Rev. B **49**, 1327 (1994).

[4] R. Kleiner, F. Steinmeyer, G. Kunkel, and P. Muller, Phys. Rev. Lett. **68**, 2394 (1992).

[5] K. Lee, I. Iguchi, T. Hikata, and K. Sato, Appl. Phys. Lett. **64**, 1729 (1994).

[6] K. Lee and I. Iguchi, Appl. Phys. Lett. **66**, 769 (1995).

[7] K. Lee and I. Iguchi, IEICE Trans. Electron. **E78-C**, 490 (1995).

[8] T. Nagatsuma, K. Enpuku, F. Irie, and K. Yoshida, J. Appl. Phys. **54**, 3302 (1983); **56**, 3284 (1984).

[9] G. Hechtfishcer, R. Kleiner, A. V. Ustinov, and P. Muller, Phys. Rev. Lett. **79**, 1365 (1997).

[10] M. Hangyo, S. Tomozawa, Y. Murakami, M. Tonouchi, M. Tani, Z. Wang, K. Sakai, and S. Nakashima, Appl. Phys. Lett. **69**, 1948 (1996).

[11] C. Jaekel, H. G. Roskos, and H. Kurz, Phys. Rev. B **54**, R6889 (1996).

[12] I. Iguchi, K. Lee, H. Arie, and E. Kume, in *Advances in Superconductivity X*, edited by K. Osamura and I. Hirabayashi (Springer-Verlag, Tokyo, 1998), p. 1181.

[13] K. Lee, I. Iguchi, H. Arie, and E. Kume, Jpn. J. Appl. Phys., Part 2 **37**, L278 (1998).

[14] K. Lee, H. Yamaguchi, W. Wang, E. Kume, and I. Iguchi, Appl. Phys. Lett. **74**, 2375 (1999).

[15] I. Iguchi, K. Nukui, and K. Lee, Phys. Rev. B **50**, 457 (1994).

[16] Yu. M. Boguslavskij, K. Joosse, A. G. Sivakov, F. J. G. Roesthuis, G. J. Gerritsma, and H. Rogalla, Physica C **220**, 195 (1994).

[17] Q. Wang and I. Iguchi, Physica C **228**, 393 (1994).

[18] H. Arie, E. Kume, and I. Iguchi, Phys. Rev. B **56**, 2387 (1997).

[19] S. Shafranjuk and M. Tachiki, Phys. Rev. B **59**, 14 087 (1999).

[20] M. Tachiki, T. Koyama, and S. Takahashi, Phys. Rev. B **50**, 7065 (1994).

[21] T. Ishibashi, Y. Okada, and M. Kawabe, Jpn. J. Appl. Phys., Part 2 **33**, L763 (1995).

[22] I. Iguchi, Phys. Rev. B **16**, 1954 (1977).

[23] T. Wong, J. T. C. Yeh, and D. N Langenberg, Phys. Rev. Lett. **37**, 150 (1976).

[24] H. Shibata and T. Yamada, Physica C **293**, 191 (1997).