2008

Subterahertz Josephson plasma emission in layered high-T-C superconducting tunnel junctions

Gustavo A. Alvarez
University of Wollongong, gustavo@uow.edu.au

T Puzzer
University of New South Wales

Xiaolin Wang
University of Wollongong, xiaolin@uow.edu.au

Roger A. Lewis
University of Wollongong, roger@uow.edu.au

Carey A. Freeth
University of Wollongong, carey@uow.edu.au

See next page for additional authors

https://ro.uow.edu.au/engpapers/1145

Recommended Citation

Alvarez, Gustavo A.; Puzzer, T; Wang, Xiaolin; Lewis, Roger A.; Freeth, Carey A.; and Dou, S. X.: Subterahertz Josephson plasma emission in layered high-T-C superconducting tunnel junctions 2008.
https://ro.uow.edu.au/engpapers/1145

Authors

Gustavo A. Alvarez, T Puzzer, Xiaolin Wang, Roger A. Lewis, Carey A. Freeth, and S. X. Dou

JOURNAL OF APPLIED PHYSICS **103**, 07C719 (2008)

Subterahertz Josephson plasma emission in layered high-T_C superconducting tunnel junctions

G. A. Alvarez,[1,a)] T. Puzzer,[2] X. L. Wang,[1] R. A. Lewis,[1,3] C. Freeth,[1,3] and S. X. Dou[1]
[1]*Institute for Superconducting and Electronic Materials, University of Wollongong, New South Wales 2522, Australia*
[2]*Centre of Excellence in Advanced Silicon Photovoltaics and Photonics, University of New South Wales, Sydney, New South Wales 2052, Australia*
[3]*School of Engineering Physics, University of Wollongong, New South Wales 2522, Australia*

(Presented on 9 November 2007; received 17 September 2007; accepted 19 December 2007; published online 15 April 2008)

We investigated the emission of subterahertz frequency electromagnetic radiation from high-T_C superconducting c-axis $NdBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}/NdBa_2Cu_3O_{7-\delta}$ trilayer thin film tunneling junctions when external electric and magnetic fields are applied. The current-voltage characteristics under applied ab-plane magnetic fields H (up 8 T) exhibit well defined steps, V_n, such that $eV_n \approx h\omega_p/(2n\pi)$, where the plasma frequency $\omega_p \approx 0.4$ THz and $n=1,2,3,\ldots$.. These steps may be interpreted using Josephson plasma dynamics. The applied voltage creates oscillating currents via the Josephson coupling energy E_J ($E_J=hI_J/4\pi e$, where I_J is the Josephson current and h is Planck's constant) and the charge energy E_C ($E_C=e^2/2C$, where C is the junction capacitance). Thus the Josephson plasma becomes excited by the tunneling current, with some of the energy being emitted as subterahertz frequency radiation. Our results provide a new insight into a solid-state quantum system with considerable potential for new solid-state terahertz emission sources. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2840019]

I. INTRODUCTION

Superconducting electromagnetic emission is an attractive application of optoelectronic devices. In the superconducting steady state, the generation of electromagnetic waves with wavelengths varying from the microwave to the millimeter range is attainable using four distinct methods related to dc-biased Josephson junctions.

First, the self-radiation induced by Josephson ac currents has been widely used.[1] For high-temperature superconductors (HTS) $YBa_2Cu_3O_{7-\delta}$ (YBCO) and $Bi_2Sr_2CaCu_2O_y$ (Bi2212), the Josephson self-radiation in the picowatt range has been detected by using a superheterodyne-mixer technique.[2–7]

Second, the irradiation of samples with a femtosecond laser pulse led to the emission of electromagnetic waves in the terahertz region.[8,9]

Third, quasiparticle injection has been intensively studied using HTS tunneling junctions and the emission of microwave radiation from dc-biased HTS YBCO/Insulator/Au tunneling junctions.[10–13] Here, microwave emission was observed in the absence of an external applied magnetic field, and was broadband, in contrast to the narrow-band emission usually observed from Josephson junctions.

The flux-flow effect[14] is the fourth method of generating electromagnetic waves. It produces microwave radiation of several hundred gigahertz by applying strong Lorentz forces to the magnetic fluxes. Broadband microwave emission has been observed[15] using this method by applying strong magnetic fields parallel to the CuO_2 plane of Bi2212 single crystals.

In this paper, we discuss the emission of subterahertz electromagnetic radiation from high-T_C superconducting c-axis $NdBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}/NdBa_2Cu_3O_{7-\delta}$ (NBCO/PBCO/NBCO) multilayer thin film tunneling junctions when external bias and magnetic fields are applied. The current-voltage characteristics (I–V) under applied ab-plane magnetic fields H exhibit sharply defined steps at applied bias voltages V_n, so that

$$V_n = eV/n \approx h\omega_p/(2n\pi), \tag{1}$$

where the plasma frequency $\omega_p=0.4$ THz, and $n=1,2,\ldots$.

Our observations may be interpreted in terms of the quantization of the Josephson plasma (subterahertz) emission in layered HTS tunnel junctions.

II. EXPERIMENTAL

For the fabrication of HTS tunneling junctions, very high quality thin films with atomically flat surfaces and interfaces are required. Because of the close lattice match and growth conditions in PBCO oxide superconductors, a very promising approach is to epitaxially grow nonsuperconducting PBCO thin films on lattice matched superconducting NBCO films and vice versa. The oxygen diffuses readily through PBCO so that fully oxidized NBCO/PBCO structures can be formed by the same *in situ* process. The structural quality at the interface plays a crucial role in the observation of quantum phenomena. The NBCO/PBCO structures are crucial in establishing the intrinsic behavior, for they cir-

---

[a)] Author to whom correspondence should addressed. Electronic mail: gustavo@uow.edu.au.

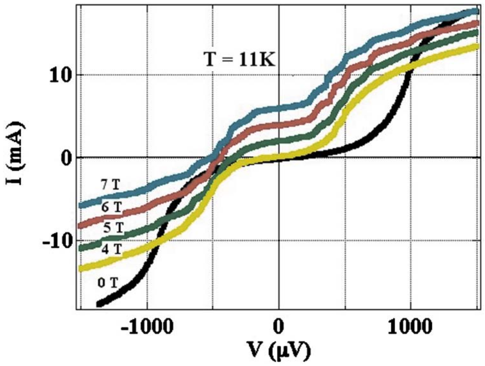

FIG. 1. (Color online) *I-V* characteristics at 11 K and applied magnetic fields of 0, 4, 5, 6, and 7 T in the *ab* plane for a *c*-axis NBCO/PBCO/NBCO tunneling junction (Sample SNPN1). The curves at 5, 6, and 7 T have been displaced vertically for clarity.

cumvent the crystal growth interface inhomogeneity that otherwise could mask the intrinsic physics.

The NBCO/PBCO/NBCO trilayer junctions used in this study were fabricated by pulsed laser deposition. Single-layer thin film deposition is described elsewhere.[16] A very high degree of crystal *c*-axis orientation was shown in x-ray diffractometer and Rutherford backscattering analyses. Atomic force microscopy studies showed a very smooth surface morphology with only a few angstrom roughness.[17] Transmission electron microscopy and transport data on a variety of multilayers and trilayers demonstrated virtually atomic-level perfection of the NBCO/PBCO/NBCO interfaces.[16] Planar junctions with widths varying from 1 to 10 μm were fabricated from the *c*-axis-oriented NBCO/PBCO/NBCO thin film trilayers using standard photolithographic and ion milling techniques.[18] The devices were contacted with Au bonding pads. The junctions were placed in the center of an 8 T superconducting solenoid with the magnetic field aligned in the *ab* plane. The subterahertz radiation was detected from the second sample (SNPN2) using a superheterodyne radiometric receiver at a frequency of 36 GHz.

III. RESULTS AND DISCUSSION

A standard experimental approach was used to measure the tunneling conduction through the PBCO barrier as a function of the voltage applied between the two NBCO electrodes. In Fig. 1, the current is plotted versus the voltage for $H=0$, 4, 5, 6, and 7 T. In zero field, the usual superconductor-insulator-superconductor tunneling characteristic is obtained. When the applied field H is increased to 3 T, the steps appearing in the *I-V* curve are noticeably broadened. As H increases further, this broadening develops into well resolved steplike structures. The formation of the step structure can be clearly observed in Fig. 2 for an in-plane magnetic field of 6 T. The steps arise from the quantization of the Josephson plasma emission and may be interpreted using Josephson plasma dynamics to give Eq. (1). The steplike structures reveal Josephson plasma emission from the quasiparticle density of states and have components originating from the charge E_C, Zeeman E_Z, and superconducting gap energies, and spatial quantization in the tunneling barrier (this will be published elsewhere).

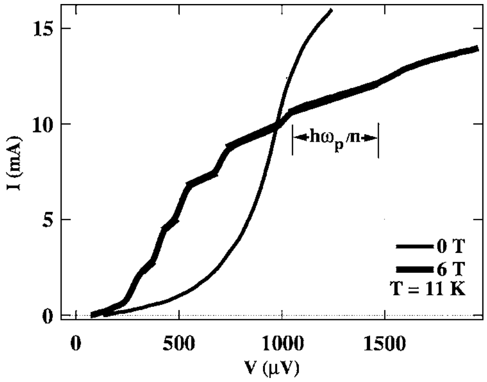

FIG. 2. *I-V* characteristics at 11 K and 6 T for a *c*-axis NBCO/PBCO/NBCO tunneling junction (Sample SNPN1).

In the regime illustrated by the *I-V* curves in Fig. 3, the current is suppressed at voltages below the threshold value $V=e/2C$, where C is the tunneling capacitance ($\sim 10^{-18}$ F). This *I-V* response is suggestive of the Coulomb blockade effect, observed in tunnel junctions, in which the charging energy E_C dominates. At low voltages, charge is trapped in the electrodes and the dynamic resistance is very large. For $V > e/2C$, the microwave emission intensity from the junction was measured using a superheterodyne radiometric receiver at a frequency (f) of 36 GHz. The observed maximum emitted spectrum power was about 10 pW for an integrating time of 1 s.

When the current jumps to a quasiparticle current branch on the *I-V* curve shown in Fig. 3, broadband microwave emission power was detected. A series of incoherent microwave emissions were observed from branch to branch up to the high bias voltage region, probably due to the electron-plasmon scattering process. However, when the current was varied along the quasiparticle branch, a continuous change of the emission power was observed. These emissions are qualitatively different from Josephson self-emission since they appeared at bias voltages much higher than the expected bias

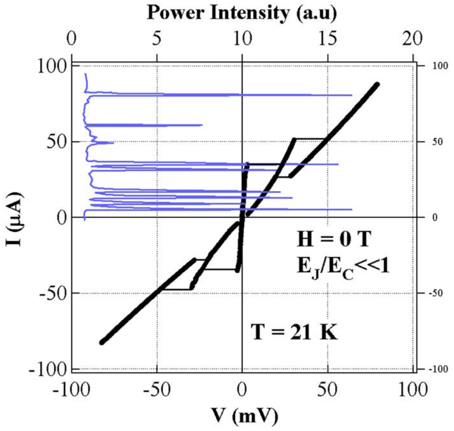

FIG. 3. (Color online) *I-V* characteristics at 21 K for a NBCO/PBCO/NBCO tunneling junction (Sample SNPN2) with the corresponding detected Josephson microwave power shown for a receiving frequency of 36 GHz. Here $E_J/E_C \ll 1$.

voltage given by the Josephson voltage-frequency relation $hf = 2$ eV. The emissions are similar to those observed in S/I/N thin film tunneling junctions.[19] The emitted power was found to be greater at lower temperatures. The results indicate that the dynamics of the Coulomb blockade (when E_C dominates) may be essential for microwave emission arising from a coherent Josephson plasma mode.

IV. SUMMARY

Future development of the generation of subterahertz electromagnetic waves in high T_c superconducting c-axis NBCO/PBCO/NBCO trilayer thin film tunneling junctions may provide a continuous and frequency tunable source in this region. The coherency of the terahertz emission from the NBCO/PBCO/NBCO configuration is another advantage. Our results provide a new insight into a solid-state quantum system with considerable potential for new solid-state terahertz emission sources that will eventually help bridge the terahertz gap.

ACKNOWLEDGMENTS

This work was partially supported by the Australian Research Council.

[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] M. Hangyo, S. Tomozawa, Y. Murakami, M. Tonouchi, M. Tani, Z. Wang, K. Sakai, and S. Nakashima, Appl. Phys. Lett. **69**, 1948 (1996}.
[9] C. Jaekel, H. G. Roskos, and H. Kurz, Phys. Rev. B **54**, R6889 (1996).
[10] I. Iguchi, K. Nukui, and K. Lee, Phys. Rev. B **50**, 457 (1994).
[11] S. Shafranjuk and M. Tachiki, Phys. Rev. B **59**, 14 087 (1999); M. Tachiki, T. Koyama, and S. Takahashi, *ibid.* **50**, 7065 (1994).
[12] Q. Wang and I. Iguchi, Physica C **228**, 393 (1994).
[13] H. Arie, E. Kume, and I. Iguchi, Phys. Rev. B **56**, 2387 (1997).
[14] T. Nagatsuma, K. Enpuku, F. Irie, and K. Yoshida, J. Appl. Phys. **56**, 3284 (1984); M. Tachiki, M. Iizuka, K. Minami, S. Tejima, and H. Nakamura, Phys. Rev. B **71**, 134515 (2005).
[15] G. Hechtfishcer, R. Kleiner, A. V. Ustinov, and P. Muller, Phys. Rev. Lett. **79**, 1365 (1997).
[16] G. A. Alvarez, J. G. Wen, F. Wang, and Y. Enomoto, Jpn. J. Appl. Phys., Part 2 **35**, L1050 (1996).
[17] G. Alvarez, T. Utagawa, and Y. Enomoto, Physica C **282**, 1483 (1997).
[18] M. Konishi and Y. Enomoto, Jpn. J. Appl. Phys., Part 2 **34**, L1271 (1995).
[19] K. Lee, H. Yamaguchi, W. Wang, E. Kume, and I. Iguchi, Appl. Phys. Lett. **74**, 2375 (1999).