Terahertz Wave Emission from Intrinsic Josephson Junctions of High-T_c Superconductors

L. Ozyuzer, Y. Simsek, H. Koseoglu, F. Turkoglu, C. Kurter, U. Welp, A. E. Koshelev, K. E. Gray, W. K. Kwok, T. Yamamoto, K. Kadowaki, Y. Koval, H. B. Wang, P. Müller

Abstract— **The natural structure of single crystal $Bi_2Sr_2CaCu_2O_{8+d}$ (Bi2212) is considered as c-axis tunnel junctions between sets of superconducting CuO_2 planes, which are called intrinsic Josephson junctions (IJJ). Recently, we experimentally demonstrated that rectangular IJJ mesa structures of Bi2212 can be used as a compact solid state generator of continuous, coherent and polarize terahertz (THz) radiation source, which a reliable source does not exist around this frequency range. The simple voltage-frequency relation in AC Josephson effect is valid and higher frequencies require higher bias for over 600 junctions in series. Since the influence of oxygen doping of on magnitude of energy gap in Bi2212 is known, it is necessary to obtain THz emission before the backbending, which occurs due to local increase of temperature in current-voltage characteristics of mesa. The mesa structures were fabricated on various doping levels of Bi2212, and current-voltage and THz emission characteristics were investigated. We will discuss recent experimental results of THz wave generation from Bi2212 crystals.**

I. INTRODUCTION

TERAHERTZ sensing and imaging is a rapidly developing technology with applications including security, medicine, quality control etc [1]. There is a need for compact continuous wave (CW) solid-state terahertz source with practical power. There are some available CW sources such as quantum cascade lasers that only work above 1.2 THz. Multiplication of Gunn diodes produces low output powers. Backward wave oscillators are bulky and have low output power at higher frequencies. Optically pumped THz gas lasers are also bulky and not tunable.

Single crystal of high temperature superconductors (HTSs) e.g. $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212), forms layered structure and these natural stacks of SIS multi-junctions are called intrinsic Josephson Junctions (IJJs). The experimental observation of IJJ in Bi2212 single crystals was an important achievement because close proximity of tunnel junction couples Josephson junctions [2]. Since the IJJs are naturally stacked along the c-axis of Bi2212 single crystals, they exhibit anisotropic electrical behaviors. The tunneling current-voltage (I-V) characteristics of IJJs along the c-axis of Bi2212 exhibit large hysteresis and multiple branches.

The successful observation of THz emission by our group stimulated studies on THz generation from intrinsic Josephson junctions of Bi2212 mesas [3]. The fundamental frequencies of observed emission were as high as 0.85 THz and radiation power was up to 0.5 μW which are not achieved before. It is shown that the emission frequency is proportional to the 1/w, where w is with of mesa and indicating that Josephson plasma frequency has to match the cavity resonance of mesa for successful emission. Recently, one order larger radiation power (~ 5 μW) and higher harmonics (up to 4^{th} corresponds to 2.5 THz) of resonance have been obtained [4].

Many theoretical studies accomplished to explain mechanism of THz generation from Bi2212 mesas. There is no consensus right now and need more experimental input for complete proof of a theory. In this manuscript, we will present generic properties of THz radiating mesas, such as resistivity versus temperature (R-T) and I-V. After that one of the radiating mesas will be shown that Josephson voltage frequency relation has to be satisfied for the THz emission.

II. EXPERIMENT

In this study, we used floating zone grown single crystals of Bi2212. We underdoped the crystals under getter furnace purified Argon gas flow. The 1x1 mm^2 crystals were glued on 6x6 mm^2 sapphire crystals with silver epoxy. The crystals were cleaved using scotch tape and immediately 100 nm thick Au evaporated under high vacuum. UV optical lithography was used for pattern transfer of mesa patterns with two 400x400 μm^2 contact paths. Argon ion beam etching was applied for mesa creation. The samples were kept cold with flow of LN_2 during etching process. Since the photoresist does not stand firm to long etching period, 1.0-1.5 μm mesa height is the limit for our procedure right now. The fabricated mesas have 600 to 700 junctions. Remaining resist can be removed with acetone. The samples were prepared as 100x300 to 30x300 μm^2 mesas. Third contact is taken from top of the mesa with gold evaporation. THz emission characteristics were obtained by a silicon composite bolometer during I-V trace of mesa.

Manuscript received 8 May 2009. This work was supported in part by the TUBITAK (Scientific and Technical Council of Turkey) project number 108T238. L. Ozyuzer acknowledges support from Turkish Academy of Sciences and Alexander von Humboldt foundation.

L. Ozyuzer, H. Koseoglu and F. Turkoglu are with the Department of Physics, Izmir Institute Technology, 35430 Izmir, Turkey (e-mail: ozyuzer@iyte.edu.tr).

Y. Simsek, Y. Koval and P. Müller are with the University of Erlangen-Nurnberg, Germany.

C. Kurter, U. Welp, A. E. Koshelev, K. E. Gray and W. K. Kwok are with the Argonne National Laboratory, Illinois USA.

T. Yamamoto and K. Kadowaki are with the University of Tsukuba, Japan.

H. B. Wang is with the National Institute for Materials Science, Tsukuba, Japan.

III. RESULTS

Fig. 1 shows R-T measurements of radiating mesas represented in the same graph. Onsets of critical temperatures of mesas are between 75 and 87 K. The contact resistance is below 5 ohm except one of the sample (w=40 μm). R-T exhibits semiconductor like curve which is observed below certain oxygen concentration in Bi2212 crystals. Due to our three point measurement configuration, c-axis resistivity cannot be exactly found and compared with previous studies. On the other hand, $R(T_c)/R(300)$ values from Fig. 1 give a clue that they have $R(T_c)/R(300) > 4$. This indicates a certain doping range which is δ~0.22 for THz emission.

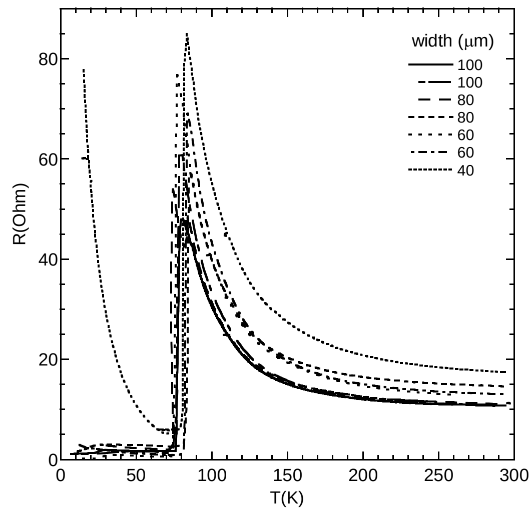

Fig. 1. Resistivity versus temperature behavior of THz emitting mesas with various widths. I=10 μA is used as a constant current and note that the resistance below T_c is due to contact resistance.

Fig. 2 shows I-V curves of THz emitting mesas plotted together. The current is swept back and forward to obtain each I-V curve. Some of the quasiparticle braches can be seen. All of the curves show backbending above 1.5 V. Using the simple Josephson voltage-frequency relation, 1.5 V corresponds to 2 mV per junction which indicates 1 THz possible before heating severely affects the mesa. Since the backbending voltage depends on doping level of Bi2212, number of junctions and surface area of mesa, exciting 1 THz seems a challenge.

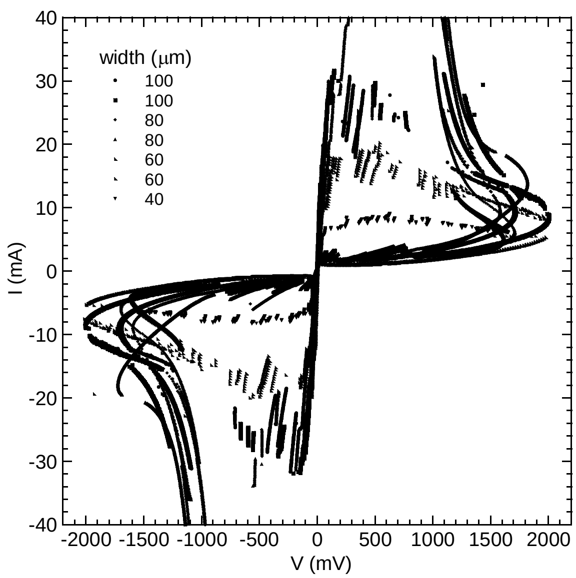

Fig. 2. Current versus voltage behavior of THz emitting mesas with various widths. Temperature is kept below 12 K for all curves. These mesas emit radiation between 0.35 and 0.85 THz.

Fig. 3 shows THz emission characteristics of one of the 100x300 μm^2 mesa at 20 K. At high bias (> $\pm$1 V), I-V curve shows backbending and bolometer detects the heating of the mesa. It can be seen Fig. 3b that above $\pm$1 V bolometer signal is increasing. It indicates that local mesa temperature is increasing. When the bias reduced in positive part of the curve, THz emission peak shows up. After that a retrapping occurs. The frequency of the emission is found 0.35 THz by examining emission with set of cut-off filters.

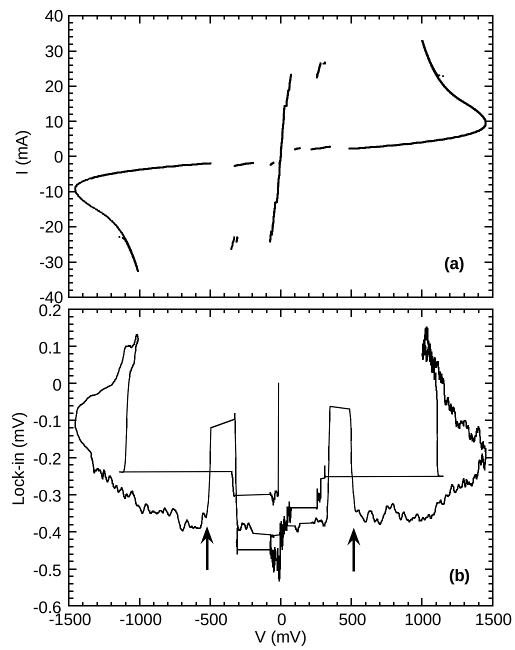

Fig. 3. Current-Voltage (a) and bolometer output versus voltage (b) graph of one of the 100x300 μm^2 mesa. The arrows correspond to emission bias voltages.

IV. CONCLUSION

In this study, we show that the THz emitting mesas have a certain doping range for mesa dimensions we used. The doping level sets Josephson plasma frequency and limits the dimensions of mesas that we have to fabricate for successful THz emission.

REFERENCES

[1] M. Tonouchi, "Cutting-edge terahertz technology," Nature Photonics, vol. 1, pp. 97-105, Feb. 2007.

[2] R. Kleiner, F. Steinmeyer, G. Kunkel, and P. Müller, "Intrinsic Josephson effect in $Bi_2Sr_2CaCu_2O_8$ single crystals." Phys. Rev. Lett., vol. 68, pp. 2394-2397, 1992.

[3] L. Ozyuzer, A. E. Koshelev, C. Kurter, N. Gopalsami, Q. Li, M. Tachiki, K. Kadowaki, T. Yamamoto, H. Minami, H. Yamaguchi, T. Tachiki, K. E. Gray, W.-K. Kwok, U. Welp, "Emission of Coherent THz Radiation from Superconductors," Science, vol. 318, pp. 1291-1293, Nov. 2007.

[4] K. Kadowaki, H. Yamaguchi, K. Kawamata, T. Yamamoto, H. Minami, I. Kakeya, U. Welp, L. Ozyuzer, A. E. Koshelev, C. Kurter, K. E. Gray, and W.-K. Kwok, "Direct observation of terahertz electromagnetic waves emitted from intrinsic Josephson junctions in single crystalline $Bi_2Sr_2CaCu_2O_{8+d}$," Physica C, vol. 468, pp. 634-639, March 2008.