# Fabrication of Double Mesa Structures by E-Beam Lithography from High Temperature Superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) for Powerful Terahertz Emission

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## Abstract

We work on a frequency tunable solid state device to meet the needs of continuous, coherent, powerful terahertz emission sources that fill practically important terahertz gap. High temperature superconducting (HTS) coherently oscillating Josephson junctions in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) crystal make this approach very promising. Since doping dependence of Bi2212 is an important parameter, Bi2212 crystals are annealed in vacuum or purified argon gas flow at 425 $^oC$. For further processing we pattern both single and double rectangular mesa structures by using electron beam lithography on the cleaved surface of the crystal. Resistance- temperature (*R–T*), and current–voltage behavior (*I –V)* measurements achieved.

## 1. Introduction

Terahertz radiation is part of the electromagnetic spectrum lying between microwaves and the far-IR. This region has frequencies ranging from 0.1 – 10 THz and wavelengths from 3 mm to 0.03 mm. This spectral region is often referred to as the "THz gap" as these frequencies fall between electronic and optical means of generation [1].

Among the cuprates, single crystal of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) is a potential candidate of compact solid state devices designed for generating electromagnetic waves in terahertz frequency range. Bi2212 crystals are consisting of natural arrays in the form of identical layers called intrinsic Josephson junctions (IJJ). Since the IJJs are homogeneous in the atomic scale along the c-axis of Bi2212 single crystals (Fig. 1), highly-uniform junction arrays hold great potential for very high emission power [2]. Each single junction has small emission power which is not enough for practical applications so we fabricate a terahertz oscillator in a rectangular mesa shaped containing large series arrays of IJJs. Therefore, they can provide much more power. Also fabricated mesa structures can operate at frequencies well exceeding those obtainable with low $T_c$ superconductors due to the Josephson effect between these stacks, their large superconducting gap and other unique properties. Many researches were proposed to achieve synchronized THz radiation from intrinsic Josephson junctions such as applying a magnetic field to induce coherent Josephson vortex flow [3].

Recently, Ozyuzer et al. [4] succeeded in observing directly the strong emission of terahertz electromagnetic waves using a mesa of Bi2212 single crystal in the absence of an external magnetic field. Mesa shaped terahertz light device with sizable power works as a dc voltage to high-frequency converter and in principle, this is based on the dynamics of intrinsic Josephson junctions- ac Josephson effect. The general mechanism for the emission is as follows, when an external current is applied along the c-axis, the ac Josephson current in the resistive state excites a cavity resonance mode of Josephson plasma wave and converted to a terahertz wave at the mesa surfaces [5].

Bi2212 crystals have a large energy gap and wide doping range [6], which is suitable for the THz region. It is shown that THz emitting mesas are below a certain underdoped level, which has relatively small critical current in contrast to optimally doped and overdoped Bi2212 [7]. More recently, emission powers of 5 μW and frequencies at the higher harmonics up to 2.5 THz have been obtained. Wang et al. [8] reported that as in the low bias regime, also at high bias cavity modes are important for synchronizing the Josephson currents. Experimental results clearly demonstrate the validity of the cavity resonance model for the fundamental frequency mode of thin square and cylindrical mesas [9].

## 2. Experiment

Previous studies provided that electromagnetic wave generated mesas are all in below a certain underdoped level of Bi2212 [7]. In this study, under optimized doping conditions we aimed to investigate powerful terahertz emission. THz emission in the μW range can be obtained fabricating rectangular-shaped mesa structures on the Bi2212 crystal. In the experimental procedure, in order to obtain various doping levels, we annealed the high temperature superconducting Bi2212 single crystals at 425 $^oC$ in vacuum or under argon flow. In the first annealing procedure, Argon gas is purified in the gettering furnace and flowed through the crystals at the rate of 100 sccm. Second system has a turbo molecular pump for high vacuum as $10^{-6}$ and under vacuum conditions we annealed the crystals for different

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time intervals. Then the single crystal having a smooth surface (the a-b plane) was glued onto a sapphire substrate by silver epoxy. Sapphire substrate and silver epoxy were preferred since they are good thermal conductors. In order to get a fresh and smooth surface on Bi2212, the crystal was mechanically cleaved with adhesive tape. After the cleaving process, gold layer with thickness of 100 nm is immediately deposited by a vacuum evaporation technique on fresh surface of the crystal in order to keep the surface against deterioration and to protect the crystal surface from water and chemicals during the experimental processes. We describe a mesa patterning process, which makes it possible to measure current–voltage characteristics along the c-axes of the films. To obtain natural IJJ stacks with various size and height, mesa on Bi2212 have been fabricated using e-beam lithography and argon ion beam etching techniques. After the mesa fabrication, in order to establish electrical contact to the gold layer on top of the mesa, $CaF_2$ layer was evaporated through a shadow mask onto the top part of the crystal including a small section of the mesa for the electrical isolation purpose. Subsequently, lift off technique is used for fabrication of gold stripes by e-beam lithography onto the mesa and the $CaF_2$. Finally, a gold wire was attached to the strip over the $CaF_2$ and 2 pads with silver epoxy for the electrical connection of the mesa and two contact pads.

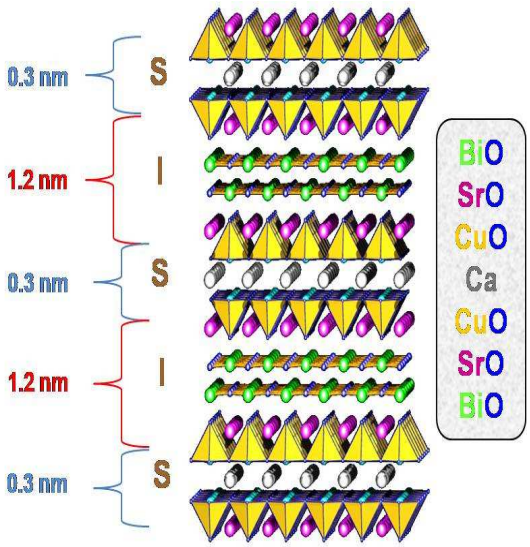


Fig. 1 Generic view of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) crystal.

We first fabricated a set of samples with various doping levels and sizes. The heat treatment duration is varied to change the $T_c$ and critical current of crystals. Figure 2 shows our annealing systems. After doping process by using the vacuum thermal evaporation, e-beam lithography, reactive ion beam etching techniques, both single and double mesas with various sizes have been fabricated

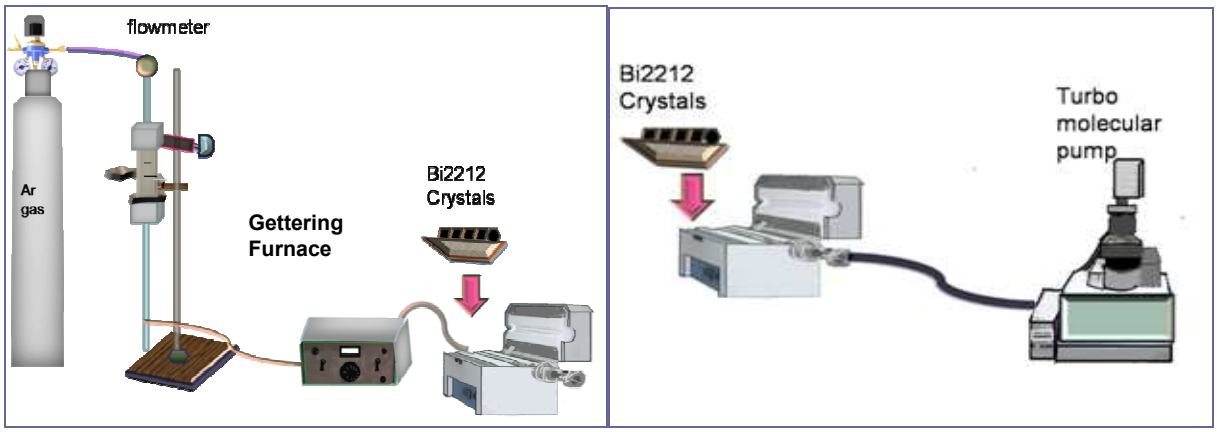


Fig. 2 Two different annealing procedure.

## 3. Results

After the mesa fabrication, the exact dimensions of the mesas were obtained using surface profilometer and atomic force microscope. We have taken SEM images and optical photos of the samples. Figure 3 is optical photo of a one of the double mesas. The number of Josephson junctions were determined which gives emission voltage. The electrical characterization of the mesas was obtained room temperature through low temperatures. In order to characterize the Bi2212 mesas, by three probe contact *c*-axis resistance versus temperature (*R–T*), and current–voltage behavior (*I –V)* were measured in a He flow cryostat. During *I–V* characterization, we used a Si composite bolometer to detect the THz emission. The c-axis R-T measurements of the mesas exhibit near underdoped behavior of Bi2212 single crystal. Some of the hysteretic quasiparticle branches are seen in the I–V characteristics of Bi2212 crystals. The magnitude of Josephson critical current of one of the underdoped Bi2212 single crystal is 18 mA for a 50x300 $\mu m^2$ mesa. At high bias backbending due to the heating effect is observed.

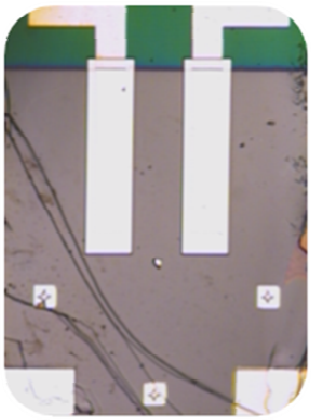

Fig. 3 Optical photograph of double mesas.

To conclude up, in order to generate continuous and monochromatic THz radiation, the possible optimum doping level is searched. The measurements revealed distinct features of intrinsic Josephson junctions and the mesas exhibit underdoped behavior. Quite different from the process of photolithography, e-beam lithography requires higher efficiency for the fabrication of mesa structures. We observed hysteretic quasiparticle branches in the performed I-V measurements are all in agreement with the mechanism of terahertz emission. Our results show a strong feasibility of developing terahertz wave radiated devices. Most importantly electromagnetic emission in THz range may find many applications in near future.

## 4. Acknowledgments

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