

FABRICATION OF ARRAY OF MESAS ON SUPERCONDUCTING $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ SINGLE CRYSTALS

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The superconducting properties of multi-layered high temperature superconductors (HTS) result mainly from the CuO_2 planes, while the other structural components behave simply as charge reservoirs. Using these perfect-layered structures of HTS, arrays of mesas have been fabricated on the surfaces of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi2212) single crystals using photolithography and argon ion beam etching techniques. These arrays have current-voltage (I-V) characteristics that consist of some branches corresponding to different intrinsic Josephson junctions in the mesas. The surface topography and heights of the mesas were examined with atomic force microscopy. Due to the small mesa area, conventional wire bonding techniques are not applicable. A novel method, point contact tunneling apparatus with a sharp Au tip, was used to obtain the I-V characteristics of the fabricated intrinsic Josephson junctions, below the critical temperature of Bi2212. Since the ultimate goal was to obtain an ordered group of mesas with small lateral dimensions, to eliminate heating effects during I-V measurements, we showed that submicron-sized mesas could be characterized by the new technique.

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1. Introduction

The layered crystal structure of high temperature superconductors (HTS) gives them novel anisotropic electrical properties. For example, $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi2212) single crystals consist of superconducting CuO_2 planes separated by non-superconducting Bi-O and Sr-O layers along the c-axis, which causes that electrical conductivity along the a-b plane to be three orders of magnitude larger than that along the c-axis. Since all HTS contain CuO_2 layers, it is important to study c-axis transport, not only in terms of the fundamental physics but also the potential new applications such as terahertz sources. While artificial Josephson junctions based on Nb have been studied by Ustinov *et al.* [1], in 1992 Kleiner *et al.* [2] observed SISISI (S: superconductor, I: insulator) characteristics in HTS, and named them as intrinsic Josephson junctions (IJJ). A single junction with a metal electrode (SIN, N: normal metal) and a single Josephson junction (SIS) can be obtained by point contact tunneling spectroscopy [3], and the results are in good agreement with Scanning Tunneling Microscopy/Spectroscopy (STM/S) measurements [4-6], which exhibit similar spectral tunneling density of states characteristics. In contrast, IJJs with even a small number of junctions were not able to produce robust spectral features [7]. Heating and non-equilibrium effects are usually suggested by various groups [8,9]. One of the ways to eliminating heating is to use a short pulse of current [10], and this has recently exhibited dip and hump features as seen by STM/S and point contact tunneling (PCT) [4-6]. It is shown that these features are related to the fundamental pairing mechanism of HTS [11]. An alternative way is to intercalate the Bi2212 with HgBr_2 , HgI_2 or I_2 to reduce the coupling between CuO_2 layers. The intrinsic Josephson junctions prepared by HgBr_2 intercalated Bi2212 also showed dip and hump features [12], which is an indication of less heating.

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In this study, we fabricated mesa structures on Bi2212, with small lateral sizes. Since it is difficult to obtain a contact from the top of the mesa because of the small size, we used the Au tip of a PCT probe as an electrode to obtain the low temperature characteristics of the IJJ. The IJJ I-V and dI/dV -V characteristics were compared to those of a single Josephson junction.

2. Mesa preparation and characterization

Single crystals of Bi2212 with $T_c = 93$ K were grown by self-flux technique, as described elsewhere [13]. A small amount of yttrium was substituted, for phase stabilization. For mesa fabrication, a single crystal having a smooth surface (the a-b plane) was first glued onto an alumina substrate by an epoxy. In order to get a fresh surface, the crystal was then cleaved with the aid of adhesive tape and was immediately placed in the vacuum chamber. A thin film of Au was deposited onto the cleaved crystal, to protect the surface from chemicals during photolithography and to get electrical contacts for characterization. Photolithography was then applied to replicate different sized mask patterns, such as squares with edge dimensions of 10 and 20 μm , on the crystals. Finally, Ar-ion beam etching was used to obtain proper mesa structures consisting of many intrinsic Josephson junctions. We could observe more than 1000 mesas over the $300 \times 300 \mu\text{m}^2$ area. Since the height of the Bi2212 unit cell, consisting of two SIS junctions, is known, the number of intrinsic Josephson junctions in each mesa could be obtained by measuring the height of the mesa by Atomic Force Microscopy (AFM). The surface topography of the single crystals was also investigated by AFM. Fig. 1 shows an optical micrograph of a sample containing $10 \times 10 \mu\text{m}^2$ mesas on a Bi2212 single crystal. The distance is 5 μm between two mesas in the photomask. Since the mesa area is very small, a novel method using point contact tunneling (PCT) apparatus was used to get contacts from the top of a mesa for electrical characterization. The temperature dependence of the I-V characteristics was performed using an experimental system described elsewhere [14]. Single Josephson junctions were also obtained, by a break junction method [3] with a blunt Au tip on the same batch of crystals, for comparison with IJJ.

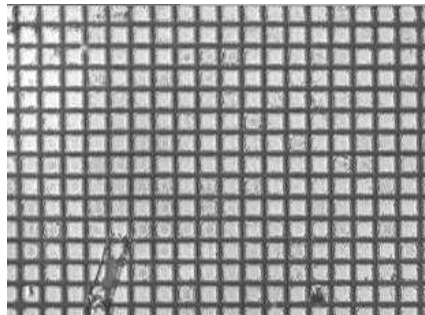


Fig. 1. $10 \times 10 \mu\text{m}^2$ array of mesas on Bi2212.

3. Results and discussion

Fig. 2 shows the single break junction I-V and dI/dV -V characteristics of Bi2212 at 4.2 K. The junction was fabricated by an Au tip, which breaks the crystal to obtain the SIS spectra. Since the SIS dI/dV -V is a convolution of two tunneling density of states of Bi2212, we can obtain the energy gap, Δ . In the SIS junction geometry, the peak to peak separation corresponds to 4Δ . For this particular junction, an energy gap of 30 meV is seen. This is on the lower side for optimally doped Bi2212, because of the inhomogeneity of the crystal structure due to yttrium addition. Energy gaps of 30 to 40 meV are found from the SIS measurements. Enhanced dip and hump features are seen in the dI/dV -V characteristics (Fig. 2). For this spectrum, the maximum power loss is 6.0 μW , which can be easily dissipated in LHe through the Bi2212 crystal. Since the effective tunneling area is unknown, we cannot estimate the heat generated per unit area. It is well known that Bi2212 single crystals have a comparatively low thermal conductivity (roughly 3 orders less than metals at liquid He temperatures) like all HTS, which causes local overheating. In early studies of IJJ, it was realized

that decreasing the area of the mesa minimized the local overheating. We have fabricated array of mesas as small as $5 \times 5 \mu\text{m}^2$, to overcome heating effects. The results are described elsewhere [15].

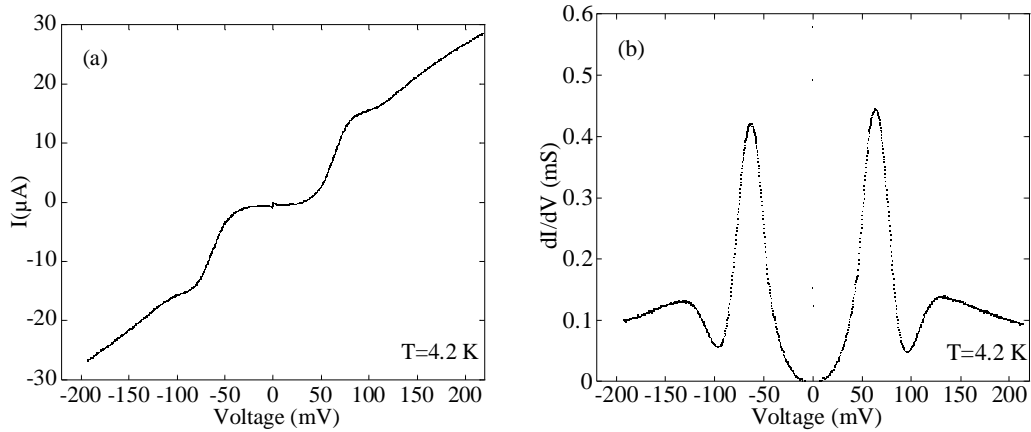


Fig. 2. (a) Current-voltage and (b) tunneling conductance-voltage characteristics of a SIS break junction of Bi2212, at 4.2 K

Fig. 3 shows the I-V characteristics of a $10 \times 10 \mu\text{m}^2$ mesa, measured at 4.2 K. This is representative of data taken for 20 mesas. AFM gave the Au thickness as 55 nm and the total intrinsic Josephson junction height as 65 nm corresponding to about 45 IJJs. The bias voltage was continuously swept positively and negatively, to obtain different quasiparticle branches, giving an independent measurement of the mesa height. If there is a small contact resistance between the Au and the Bi2212, Cooper pairs tunnel at zero bias and a Josephson current is seen. There is no Josephson current at zero bias in Fig. 3a, which reflects the comparatively high resistance between the Au and the Bi2212 relative to the resistance of the mesa. This indicates that the first junction is SIN. There are 26 quasiparticle branches in the I-V curve, which is well below the AFM estimate. The reason is presumably local heating at high bias, so that the local temperature might be higher than critical temperature of Bi2212.

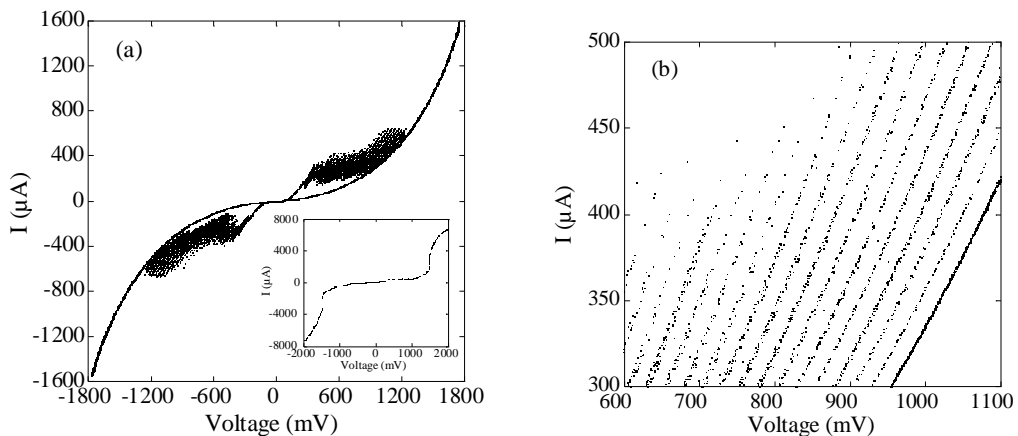


Fig. 3. (a) Current-Voltage characteristics of $10 \times 10 \mu\text{m}^2$ IJJ at 4.2 K. Inset shows extended bias range; (b) high resolution presentation of quasiparticle branches given in (a).

The inset in Fig. 3a shows the I-V characteristics of the same mesa in the extended bias range. The backbending can be seen as an indication of non-equilibrium or heating effects [8]. The total dissipated power was around 2.4 mW when we observed backbending. Note that this is 400 times larger than for the single Josephson junction in Fig. 2. Since the total junction area was

1.0×10^{-6} cm², the power per unit area was 2.4 kW/cm², which indicates why there was substantial heating. The normal state resistance of the junction cannot be estimated from the inset in Fig. 3a.

The best way to find the normal state resistance is to obtain the temperature dependence of the I-V characteristics, since there is a smaller heating contribution with increasing sample temperature. The $d_{x^2-y^2}$ fit to the resulting I-V curve with SIS convolution gives a rough estimate of when heating starts to affect the sample [15]. In the inset of Fig. 3a, the dip and hump observed in single Josephson junctions (i.e. Fig. 2) cannot be seen, because the heating is more effective at high bias. The Bi2212 is in a normal state, where there is no dip and hump associated with superconductivity.

In Fig. 3b, the quasiparticle branches can be seen in detail. If there are no heating or non-equilibrium effects, the separation between branches must be about 2Δ , i.e. 60-80 meV for this particular Bi2212. However, it was found to be 25 meV, which is less than half the energy gap found in single Josephson junctions for the same crystal. In the literature, a reduction in the gap as large as 85% has been found, and explained by the collective contribution of heating and a non-equilibrium effect (quasiparticle injection) [8].

In conclusion, we have fabricated mesa arrays, allowing us to study intrinsic Josephson junctions of Bi2212. Since the mesa features were too small for conventional wire bonding techniques, we used a novel technique to get contact and obtain the I-V characteristics of the mesa structures. We produced and analyzed the I-V characteristics that are compatible with those in the literature. This preliminary study shows that the characterization of small mesas with submicron sizes is possible. Such mesas will have small critical currents and they will be less affected by heating and non-equilibrium effects.

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