Electrical properties of Bi 2Sr 2CaCu 2O x submicron structures grown on patterned substrates

Article *in* Physica C Superconductivity · February 2002

DOI: 10.1016/S0921-4534(01)01043-7

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Physica C 367 (2002) 414–418

PHYSICA C

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Electrical properties of $Bi_2Sr_2CaCu_2O_x$ submicron structures grown on patterned substrates

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Abstract

In order to investigate the electrical properties of submicron-size $Bi_2Sr_2CaCu_2O_x$ (BSCCO) structures grown on patterned substrates, submicron-size bridge structures of BSCCO have been studied. BSCCO bridge structures 0.7–3.0 μm in width and 1.0 μm in length were grown on patterned $SrTiO_3$ (STO) substrates by a molecular beam epitaxy technique. Patterned STO substrates were fabricated by a focused ion beam (FIB) technique. The BSCCO bridge structure has well-defined facets of {1 0 0} and {1 1 0} planes. In the current (I) voltage (V) characteristics of these bridges, a large critical current density (J_c) of the order of 10^6 A/cm^2 was obtained. © 2002 Published by Elsevier Science B.V.

PACS: 74.60.Jg; 74.76.Bz; 81.15.Hi
Keywords: $Bi_2Sr_2CaCu_2O_x$; Submicron size structure; Molecular beam epitaxy; Critical current density

1. Introduction

Patterning processes for high-T_c superconductors have been considerably behind those of the semiconductors. To attain an integration and a size reduction of Josephson junctions, high resolution patterning process should be established, although most of researchers have concentrated on developing the Josephson junction itself. In the conventional patterning process, a lithography technique and a etching process have been used. In that case, the size of the patterning is limited to a micron order, because the patterned high-T_c superconductors are given damages by the etching process.

Recently, Kim et al. have successfully fabricated intrinsic Josephson junctions on whisker crystals of $Bi_2Sr_2CaCu_2O_x$ (BSCCO) and single crystals of $YBa_2Cu_3O_y$ by using a focused ion beam (FIB) technique [1–3]. However, that technique is not suitable for a process in a large area >100 μm.

In order to solve these problems, we have proposed a novel technique using a selective growth of high-T_c superconductors on patterned substrates. Advantages of our technique are follows; (i) A facet growth of the high-T_c superconductor is utilized. (ii) No etching process is used for high-T_c superconductors. (iii) Only two processes are used to prepare submicron-size structures. These advantages allow us to fabricate high quality submicron structures.

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0921-4534/02/$ - see front matter © 2002 Published by Elsevier Science B.V.
PII: S0921-4534(01)01043-7

Furthermore, this technique can be developed for a pattering process for a large area with a nanometer size, if high resolution technique, such as electron beam lithography, is applied for the process of patterned substrates.

In order to study electrical properties of submicron structures fabricated by our technique, submicron-size BSCCO structures have been fabricated. In this paper, we report on the preparation and the electrical properties those bridge structures.

2. Preparation of bridge structure

BSCCO bridge structures were grown on patterned $SrTiO_3$ (STO) substrates by using a selective growth technique [4]. A schematic illustration of this process is shown in Fig. 1. At first, a Bi thin film with 100 nm in thickness was deposited on the STO substrate in molecular beam epitaxy (MBE) chamber as in Fig. 1(a). The bridge structure was drawn directly on the Bi covered substrate by a focused Ga ion beam with the acceleration voltage of 30 kV by using an FIB apparatus (Seiko Instruments SMI9200). This Bi film prevent a charging up of the sample during the etching by the Ga ion beam, which leads to a decrease in the resolution making edges of fabricated structures round. A diameter of the Ga ion beam was 50 nm. A 1 μm thick STO substrate can be etched with an ion irradiation of 4.8×10^8 ions/cm^2. The bridges were fabricated along one of the STO $\langle 110 \rangle$ directions. The depth of the etched area was 0.5 μm and the width of the bridge was 0.7–3.0 μm.

BSCCO thin films were epitaxially grown on the patterned substrates by MBE technique as illustrated in Fig. 1(c). The substrate temperature was 740 °C and the growth rate was 4.2 nm/s. Thickness of the thin film was 150 nm. The detail of the preparation of BSCCO thin films have been described elsewhere [5]. For oxidization of the BSCCO, NO_2 gas with a pressure of 3×10^{-6} Torr was introduced into the MBE chamber. Fig. 2 shows a reflection high-energy electron diffraction (RHEED) pattern of BSCCO observed with an electron beam incident along [1 0 0] azimuth of the STO substrate. This result indicates that a c-axis oriented BSCCO thin film was grown epitaxially with a flat surface, and it has a twin structure as reported in Ref. [6]. XRD pattern of the BSCCO thin film indicates that single phase of 2212 phase with c-axis length of 3.06 nm was grown, as shown in Fig. 3. The chemical composition of these films was determined by using an energy dispersive X-ray microanalyzer (EMAX-5782XI) to be 2.1:2.0:1.4:2.0 for the BSCCO thin films on MgO substrates prepared. at the same condition.

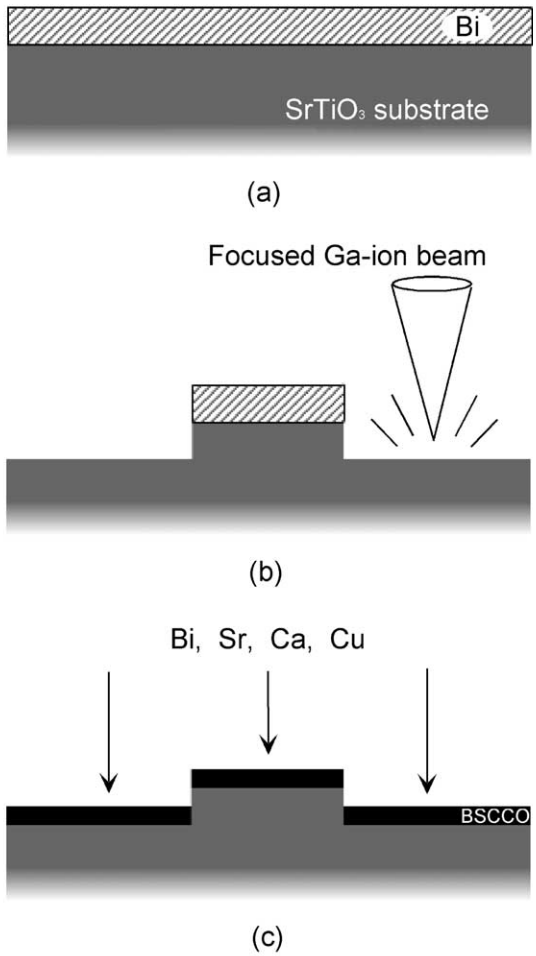

Fig. 1. A schematic drawing of the process: (a) STO substrate is covered with Bi thin films. (b) Patterns are fabricated by FIB. (c) BSCCO is grown on the patterned $SrTiO_3$.

The Bi films on the substrate evaporate before the growth of the BSCCO film, because the substrate temperature of 740 °C is higher than the

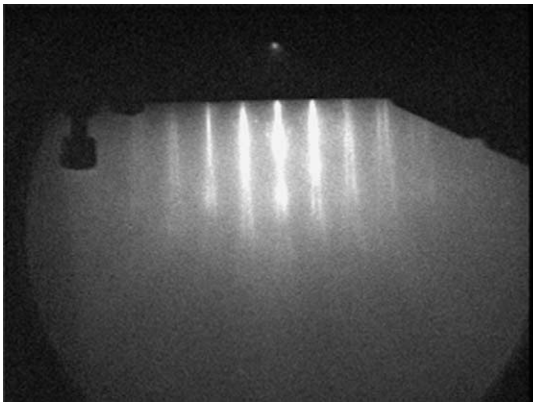

Fig. 2. A RHEED pattern of the BSCCO thin film during the growth.

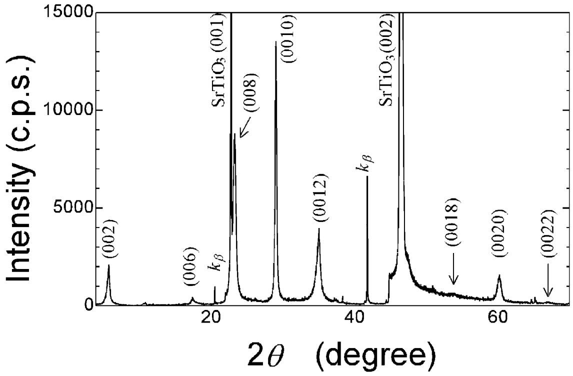

Fig. 3. XRD pattern of the BSCCO thin film. The *c*-axis oriented thin film with 2212 phase is obtained.

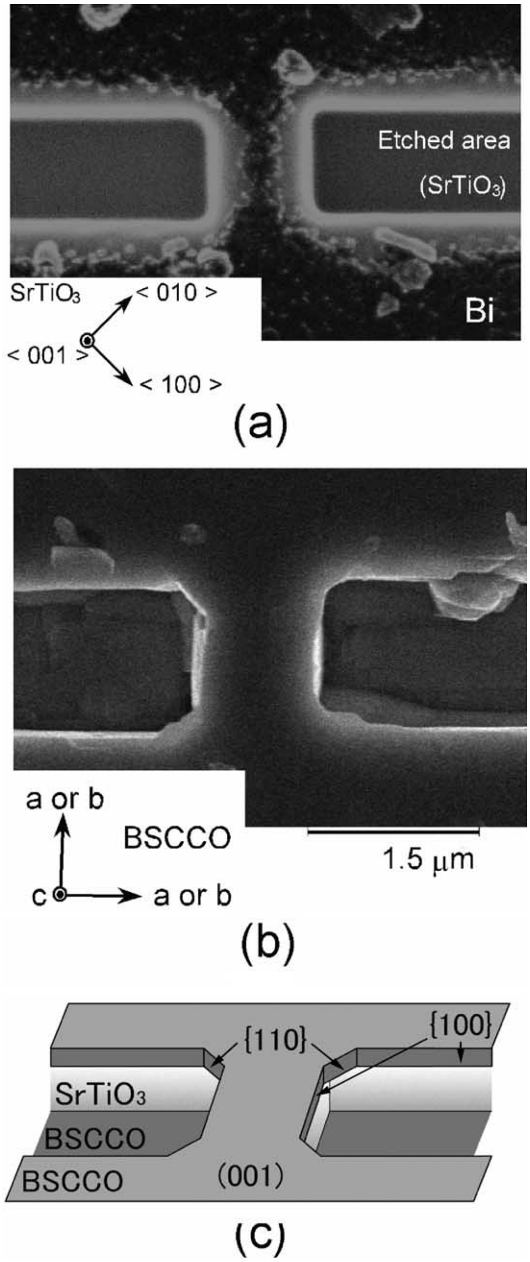

Fig. 4. (a) A SIM image of the bridge structure of STO fabricated by FIB process. (b) A SEM image of the bridge structure of epitaxial BSCCO crystals. {1 0 0} and {1 1 0} facets of BSCCO are observed. (c) A schematic illustration of the bridge structure.

boiling temperature of Bi. Therefore, no additional process for removing the Bi is necessary as compared with a usual BSCCO growth.

3. Structural characterization of bridge

Fig. 4(a) shows a scanning ion microscope (SIM) image of the bridge structure fabricated on the STO substrate. The width of the bridge is 1 μm, the length is 1 μm and the depth of grooves is 0.5 μm. The Bi film near the edge of the structure was etched out by the Ga-ion irradiation, and the edge of the STO was rounded because of the spread of the Ga-ion beam.

Fig. 4(b) shows a SEM image of a surface of the epitaxial BSCCO thin film grown on the bridge pattern of STO. The growth of BSCCO crystals is observed both on the bridge structure and the bottom of the etched area. The bottom part does not influence the electrical measurement described below, since the depth of 0.5 mm is sufficient to isolate the crystal grown at the bottom area from the BSCCO bridge structure. The BSCCO bridge structure shows the same crystalline habit with well-developed facets as reported previously [4]. Fig. 4(c) shows a schematic illustration of the bridge structure. Crystal planes of these facets are indexed as {1 0 0} and {1 1 0}, taking into account an epitaxial relationship between the BSCCO and the STO. In other word, the bridge is parallel to the *a*- or *b*-axis of the BSCCO.

4. Electrical properties of submicron size bridge

For the measurement of electrical characteristics, the conventional photolithography technique was employed combined with a wet-etching process to remove an unnecessary region. The etching process was carried out using a mixed solution of nitric acid (0.25%) to deionized water (99.75%) for 4 s. The photo-resist was removed by an acetone after etching, and the acetone remaining on the surface of the sample was substituted by an ethyl alcohol. Au electrodes with thickness of 100 nm were vacuum-evaporated at base pressure of 3×10^{-6} Torr. Electrical characteristics were measured by the four-probe method using a current source (Keithley 2400) and a voltmeter (Keithley 182). Temperature of the sample was changed from 15 to 55 K in a He-refrigerator-type cryostat.

Electrical characteristics were measured in two BSCCO bridge structures A_1 and A_2. The width of the bridge A_1 and A_2 are 0.9 and 3.0 μm, respectively. The obtained *I*–*V* characteristics of BSCCO bridge structures A_1 and A_2 measured at 15–51 K with 3 K step are shown in Fig. 5(a) and (b), respectively. These two bridges can be compared with each other, because these two bridges were fabricated on the same substrate with a spacing of 10 μm. Both *I*–*V* curves show characteristics typical to the superconducting current. Critical current of the bridges A_1 and A_2 at 15 K was determined as 4.75 and 5.75 mA, respectively.

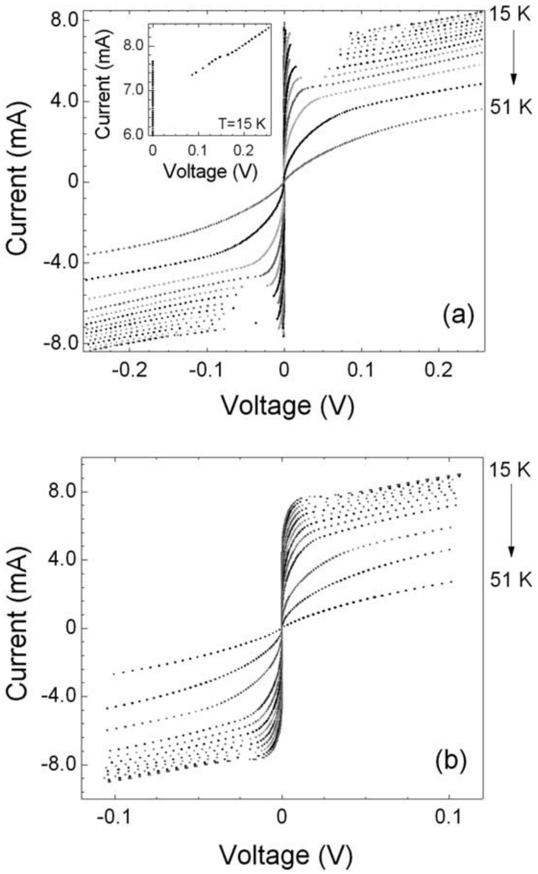

Fig. 5. *I*–*V* curves of bridge (a) A_1 ($d = 0.9$ μm) and (b) A_2 ($d = 3$ μm) measured at 15–51 K with 3 K step.

Clear hysteresis is observed in *I*–*V* curve at low temperature, for bridge A_1. In the *I*–*V* curve measured at 15 K for the bridge A_1, the voltage jumps up to 189 mV from the zero-voltage state at 7.9 mA, and recovers from 109 mV to the zero-voltage state. This hysteresis of the bridge A_1 is more pronounced than that of the wider bridge A_2. The hysteresis decreases and disappears as temperature increases. These hysteresis behaviors are due to thermal effect induced by the Joule heating at the normal state.

Bridges broken by an over-current during the *I*–*V* measurement were analyzed by SEM. Cracks were observed in the bridges. This indicates that superconducting current flow only through the bridge region in the electrical measurements.

Table 1
Critical currents I_c and critical current densities J_c of four junctions

Bridge	d (μm)	I_c (mA)	J_c (A/cm^2)
A_1	0.9	4.75	3.52×10^6
A_2	3	5.75	1.28×10^6
B_1	0.7	4.99	4.75×10^6
B_2	2.2	7.2	2.18×10^6

Width of bridges d, critical current I_c, and critical current density J_c of bridge A_1 and A_2 are shown in Table 1 with those of bridge B_1 and B_2 which were fabricated at the same time. These four bridges have large current densities J_c of an order of 10^6 A/cm^2. These values are comparable to or even higher than those of thin films without any processing. The J_c of an order of 10^6 A/cm^2 has been reproduced for all the bridge structures with line width between 0.7 and 3 μm. We attribute the huge J_c observed in the bridge structures grown on the patterned substrates to the grain-free crystallinity of the bridges, because the size of bridge is shorter than the grain size commonly observed in the BSCCO film.

It is found from comparison of the d–J_c relationship in both pairs of A_1A_2 or B_1B_2, that narrower bridges have larger J_c than wider bridges. This result indicates that a crystal quality of smaller structures is better than that of larger structures, while the electrical properties of high-T_c superconductors are degraded by the conventional processes. This means our technique is suitable for the submicron-size fabrication of high-T_c superconductors.

5. Summary

Submicron-size bridge structures of BSCCO were successfully fabricated on the patterned STO substrates etched by the FIB process. These fine stuructures of the BSCCO were grown by the MBE method taking account of the facet growth of the BSCCO crystal without any etching processes for BSCCO. These bridges showed critical current of an order of 10^6 A/cm^2 at low temperature. These results indicate that this technique is suitable for the submicron-size fabrication of the high-T_c superconductors.

Acknowledgements

This work has been supported by the joint Research Project between Japan and Korea by Japan Society of the Promotion of Science.

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