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Crystal growth of BiSrCaCuo thin films on submicron-sized step structures

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Abstract

In order to fabricate intrinsic Josephson junctions (IJJs) on a submicron-scale, crystal growth of $Bi_2Sr_2CaCu_2O_x$ (BiSrCaCuO) at step edge structures has been investigated. In this paper, we report on a crystal growth of BiSrCaCuO at step edges structures fabricated on $SrTiO_3$ substrates. Line patterns with a line width of 0.3 μm are prepared at a lower part of the step edge structures along [1 1 0] and [1 0 0] azimuth of $SrTiO_3$. The BiSrCaCuO crystals have successfully been grown on the step edge structures. The step edge structures consist of a stack of plate-shaped crystals surrounded by (0 0 1), (1 1 0), (0 1 0) and (1 0 0) facets. A 0.7-μm-wide bridge structure of BiSrCaCuO fabricated by the same technique shows a superconductivity and has a critical current density of $4.8 \times 10^6\,A/cm^2$ at 37 K. These results indicate that this technique is promising for device fabrications in submicron- or nano-scale. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The process for superconducting devices in submicron- and nano-scale is not established to date. Although high-resolution patterns less than 1 μm can be obtained by the lithography technique such as electron beam lithography technique, etching processes such as chemical etching, Ar^+ ion etching, etc., deteriorate transport properties and crystal qualities of the materials. In order to obtain high-quality submicron structures, we have proposed a fabrication technique by using facet growth in the case of $Bi_2Sr_2CaCu_2O_x$ (BiSrCaCuO) [1]. By using that technique, a line structure with a line width of 0.3 μm and a mesa structure with a size of $0.5 \times 0.5\,\mu m^2$ have been successfully grown.

It is considered that our fabrication technique is suitable for a fabrication of intrinsic Josephson junctions (IJJs). It is known that IJJs, in which layered structures in the crystal of high-T_c superconductors act as a stacked superconductor/insulator/superconductor (SNS) junctions, is the only junction which shows ideal Josephson effect in high-T_c superconductor devices [2]. However, IJJs have not been used for application in the superconducting electronics until now. The reason is that BiSrCaCuO thin films which have enough quality for IJJs cannot be obtained, although thin films are better than single crystals for the

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applications. In the case of IJJs prepared on the BiSrCaCuO single crystals, top electrode was made of normal metal. Considering superconducting electronics, all the electrodes should be made of superconductors. Kim et al. have fabricated IJJ in BiSrCaCuO single-crystal whisker by focused ion beam (FIB) method [3]. This technique is promising to obtain high-quality junctions in submicron-scale. However, it is difficult to fabricate many number of junctions, such as integrated circuits, by that technique. In order to solve these problems, we propose a novel submicron-sized fabrication for IJJs using thin films by using patterned substrates. In this paper, we report on the crystal growth of step edge structures of BiSrCaCuO crystal grown by utilizing the facet growth. Transport properties of the bridge structure are also reported to manifest transport properties of the submicron structures fabricated by our technique.

2. Experimental details

The *c*-axis-oriented BiSrCaCuO thin films with a thickness of 200 nm were grown on the patterned $SrTiO_3$ (0 0 1) substrates by the molecular beam epitaxy (MBE) method [4]. A substrate temperature of 740°C, and a growth rate of 2.5 nm/min were maintained during the growth of the BiSrCaCuO thin film. An oxygen and an ozone mixture with ozone content of 10% or NO_2 gas was introduced into the MBE chamber at 1–2×10^{-5} Torr. The typical critical temperature of the as-grown BSCCO film is between 60 and 70 K.

The submicron BiSrCaCuO structures were prepared on the patterned $SrTiO_3$ (0 0 1) substrates processed by the focused ion beam (FIB) apparatus (SMI9200, Seiko Instruments Ltd.). The step edge structures and the line patterns were directly drawn on the substrates by the Ga ion beam accelerated at 30 kV. The spot size of the Ga ion beam used in this experiment was about 50 nm at an 80 pA beam current. A thickness of 1 μm can be etched with an ion dose of 4.8×10^{18} ions/cm^2 for the $SrTiO_3$ crystal. The step height was 100–500 nm, and the line width was 300 nm.

The submicron BiSrCaCuO structures were observed using Hitachi S-4500 field-emission scanning electron microscope (FE-SEM). In order to measure transport properties of the submicron BiSrCaCuO structures, the *I–V* characteristics of the bridge structures with a line width of 0.7 μm were measured.

3. Results and discussion

In order to understand the facet growth of the BiSrCaCuO crystal, BiSrCaCuO thin films were prepared on the columnar structures fabricated on the $SrTiO_3$ substrates. Fig. 1 shows a BiSrCaCuO crystal grown on a columnar $SrTiO_3$ with a diameter of 1 μm. An octagonal BiSrCaCuO single crystal was grown on top of the columnar $SrTiO_3$. This crystal is surrounded by (0 0 1), (1 0 0), (0 1 0), (1 1 0) and (1 $\bar{1}$ 0) facets. The [1 0 0] azimuth of BiSrCaCuO is parallel to [1 1 0] or [1 $\bar{1}$ 0] of $SrTiO_3$, and [0 0 1] of BiSrCaCuO is parallel to [0 0 1] of $SrTiO_3$. This result indicates that fine structures of lines, bridges, step edges, etc., should be fabricated along those planes. We have succeeded in fabricating a 300-nm-wide line

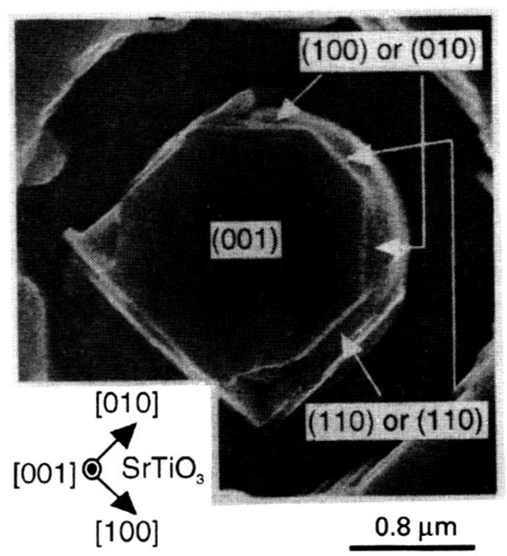

Fig. 1. An SEM image of the BiSrCaCuO crystal grown on the columnar $SrTiO_3$.

structure along [1 1 0] and [1 0 0] azimuth of $SrTiO_3$ [1]. In this experiment, therefore, the step edges have been fabricated along those directions.

The transport properties of submicron BiSrCaCuO structure were measured by using the bridge structure. Fig. 2 shows FE-SEM image of a BiSrCaCuO bridge structure with a line width of 1 μm and a length of 1 μm. The BiSrCaCuO has been successfully grown on the bridge structure fabricated on the substrate, where the bridge is parallel to the [1 1 0] azimuth of $SrTiO_3$. The edge of the bridge consists of the (1 0 0) or the (0 1 0) facets of BiSrCaCuO as observed in Fig. 2. Superconductivity of this bridge has been confirmed by the I–V characteristics. In this case, BiSrCaCuO crystals grown at bottom of the etched region cannot affect the I–V measurement of the bridge structure, because the depth of this trench is sufficient to isolate the bottom region from the bridge. The BiSrCaCuO crystal grown on the side wall also cannot affect the measurement, because the crystal growth on the side wall strongly depends on the angle of Bi flux and the growth can be prevented as we have reported previously [1]. Fig. 3 shows an I–V curve of the 0.7-μm-wide bridge, which was measured at 37 K. Superconducting current and hysteresis are observed in the I–V curve. It is considered that the hysteresis is due to a thermal effect induced by the current. It is surprising that the critical current density (J_c) of the bridge is determined to be $4.8 \times 10^6\,A/cm^2$. This value is comparable with those of thin films without any processing, or higher than those [5]. J_c of an order of $10^6\,A/cm^2$ has been reproducible for the bridge structures with the line width between 0.7 and 3 μm. The reasons why those submicron structures have such high J_c, even smaller than 1 μm, are as follows. The bridge structures consist of the single crystal, because the size of the bridge is smaller than the grain size of the BiSrCaCuO thin film. The bridge structure is not fabricated by the etching process which causes a deterioration of the properties, but formed by the self-organized crystal growth. These results indicate that the step edge structures must have good transport properties.

Fig. 4 shows the FE-SEM images of the BiSrCaCuO grown on the step edge structures fabricated on $SrTiO_3$ substrate. The line patterns with a line width of 0.3 μm were prepared at the lower part of the step. The step height is 150 nm. The step edge is parallel to the [1 1 0] and [1 0 0] azimuth of $SrTiO_3$ in Fig. 2(a) and (b), respectively. It can be seen that the BiSrCaCuO crystals at the step edges consist of a stack of plate-shaped crystals in both Fig. 4(a) and (b). A schematic

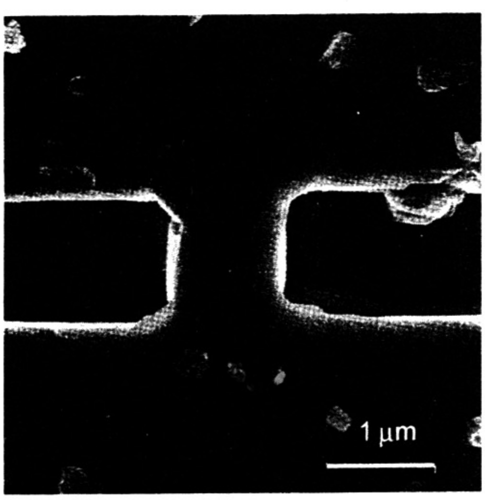

Fig. 2. SEM images of the step edge structures along (a) [1 1 0] and (b) [1 0 0] of $SrTiO_3$.

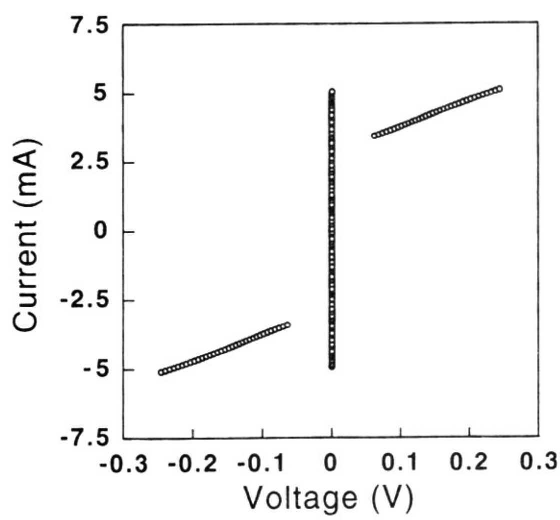

Fig. 3. An SEM image of the bridge structures with a width of 1 μm.

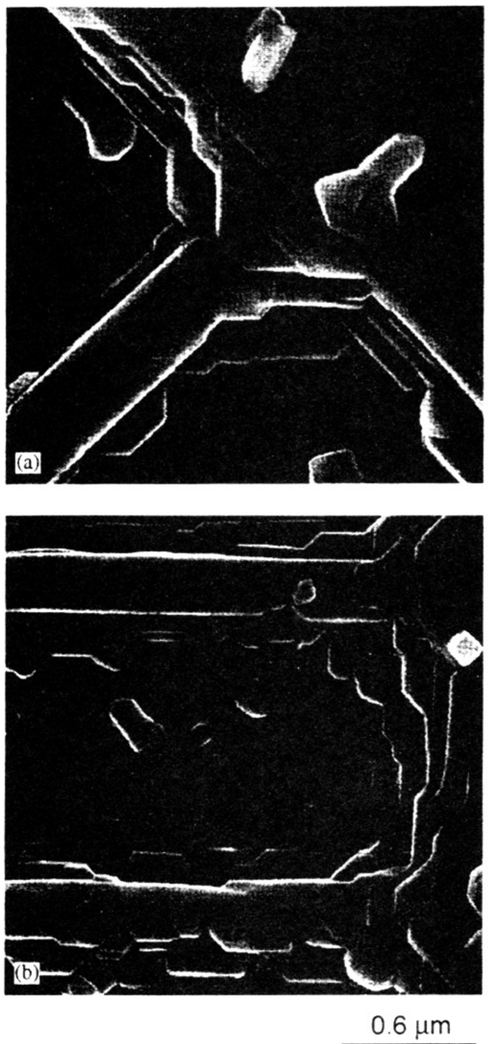

Fig. 4. *I–V* curve of the 0.7-µm-wide brige of BiSrCaCuO measured at 37 K.

drawing of these structures is shown in Fig. 5. We consider that these plate-shaped crystals show good electrical properties, and these structures must show the intrinsic Josephson effect. The IJJs should be of high quality, in other words, crystal structures without defects are required. However, most of the thin films of high-T_c superconductors have not satisfied this requirement. For example, the usual junctions fabricated by conventional

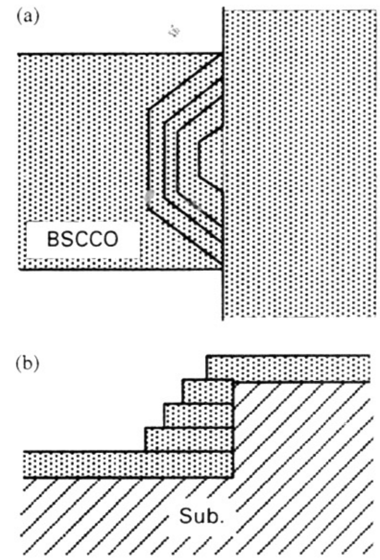

Fig. 5. Schematic drawing of the step edge structures; (a) top view and (b) cross section.

technique should include several grains in the junctions, because the size of the grains is smaller than the size of the junctions. A typical size of the grain is of several micrometers. In our case, the BiSrCaCuO crystals grown at the bridges and the step structures are single crystalline structures, since these structures are smaller than the size of the grains in the thin films and are grown by utilizing facet growth technique. We believe that our technique is promising as the superconducting device fabrications in submicron- or nano-scale, and this kind of technique should be required, because the junction size and the patterning resolution should be developed in the future for the superconductiong application such as the RSFQ circuit, SQUID, X-ray detector, microwave devices, etc.

4. Conclusions

The crystal growth of BiSrCaCuO on step edge structures has been done and been investigated. Submicron BiSrCaCuO structures were successfully grown by using facet growth technique. The transport properties of the submicron BiSrCaCuO structures were measured for the bridge structures, and the critical current density was determined to be $4.8 \times 10^6\,A/cm^2$ at 37 K for 0.7-μm-wide bridge. The step structure consisting of plate-shaped crystals were obtained along the [1 1 0] and [1 0 0] azimuth of $SrTiO_3$. We consider that these structures are ideal structures for the IJJs.

References

[1] T. Ishibashi, T. Kawahara, H. Kaneko, K. Sato, Jpn. J. Appl. Phys. 37 (1998) L863.

[2] R. Kleiner, P. Müller, Phys. Rev. B 49 (1994) 1327.

[3] S.-J. Kim Yu, I. Latyshev, T. Yamashita, Appl. Phys. Lett. 74 (1999) 1156.

[4] T. Ishibashi, K.H. Song, Y. Okada, M. Kawabe, Jpn. J. Appl. Phys. 31 (1992) L406.

[5] P. Schmitt, P. Kummeth, L. Schultz, G. Saemann-Ischenko, Phys. Rev. Lett. 67 (1991) 267.