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Uniformity of $YBa_2Cu_3O_7$ Step-edge Josephson Junctions

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$YBa_2Cu_3O_7$ 모서리 죠셉슨 접합의 균일성

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Abstract

Uniformity of critical currents of $YBa_2Cu_3O_7$ step-edge Josephson junctions on $SrTiO_3(100)$ substrates have been studied at various step-line angles. 15 identical junctions were made in series on each substrate that has a long straight step-edge line. Step-line angles studied were 0°, 15°, 30°, and 45° with respect to the crystal major axes of the substrate. Scattering of junction critical currents among the junctions on the same substrate increased with the step-line angle. Current-voltage curves showed standard resistively-shunted-junction (RSJ) characteristics in most of the 0° junctions. However, the number of junctions showing RSJ behavior decreased with increasing step-line angle. Variations of detailed microstructure of the step-edge among junctions, which are coupled with the d-wave symmetry of $YBa_2Cu_3O_7$, are believed to be the main cause for the nonuniformity in the critical current.

Keywords : Josephson junction, critical current, step-edge junction, $YBa_2Cu_3O_7$

I. Introduction

Among the various types of high T_c Josephson junctions developed up to the present, bicrystal [1], step-edge [2], and ramp-edge [3] types have been most successful. Bicrystal junctions have the advantages of easy fabrication, reproducibility, and excellent noise property. But expensive substrate and restricted topological freedom limit their application to a-few-junction devices. On the other hand, ramp-edge junctions have large topological freedom, but the fabrication technology of reliable high quality junctions has not been established yet. Step-edge junctions can be a compromise of the two and thus can play a major role in future superconductive electronic applications. One of the major obstacles for electronics application using high temperature superconductors is nonuniformity in critical current among junctions not only on different substrates but also on the same substrate.

Step-edge junctions are cost effective and easy to

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fabricate. In addition they have relatively large topological freedom. However, uniformity of the junction critical current is yet to be improved. Critical properties of the step-edge Josephson junction are affected by several factors, among which are crystallinity of the film, microstructure of the step-edge, patterning procedure, and so on. Among those, microstructure of the step-edge is known to be the most important factor. Others, such as film fabrication technology and patterning procedure are well established.

A step-edge junction has two grain boundaries, one at the top edge and the other at the bottom edge, each of which has both in-plane and out-of-plane misorientations in general [4]. The local orientation of the grain boundaries varies depending on the local state of the step-edge and so does the local misfit angle between the grains of the superconductor film. These variations in local misfit angle coupled with *d*-wave symmetry of $YBa_2Cu_3O_7$ superconductor [5],[6] result in local variation in the junction critical current [7],[8]. Therefore, the uniformity of junction critical current will be sensitive to the microstructure of the step-edge. To find out how the uniformity of the critical current is affected, the information of which is crucial to maximize the topological freedom of the step-edge junction, the critical properties of the step-edge junction as a function of the step-line angle need to be studied systematically.

In this work, we have investigated fabrication procedures of the step-edge on single crystal $SrTiO_3(100)$ substrates and obtained optimum conditions. We also have studied critical properties of the $YBa_2Cu_3O_7$ step-edge junctions for various step-line angles with respect to the major axes of the substrate. We measured current-voltage characteristics and critical currents of the junctions as a function of the step-line angle and analyzed how the uniformity of junction critical properties changes with the angle.

II. Experiments

We used single crystal $SrTiO_3(100)$ substrates because they have been most extensively studied for high T_c superconductor films and would be one of the most widely used substrates for high T_c electronic applications. We used AZ5214 photoresist as the milling mask and Ar ion milling system for etching the substrate. Firstly, 40 nm thick gold film was deposited on the substrate by rf sputtering and then 1.5 μm thick resist was spin-coated, and exposed and developed to form a step-edge mask. The purpose

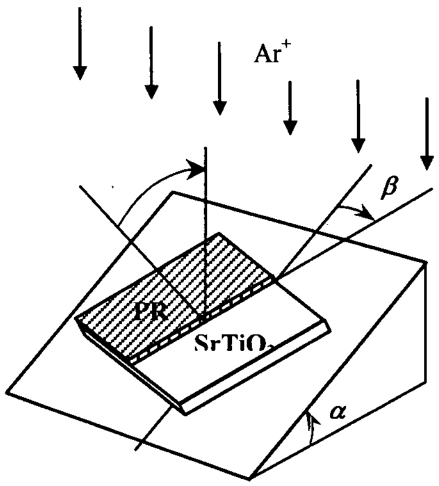

Fig. 1. Schematic of argon ion milling conditions. α is the tilt angle and β is the rotation angle of the substrate. Note that β is defined positive when the mask edge faces away from the incident beam.

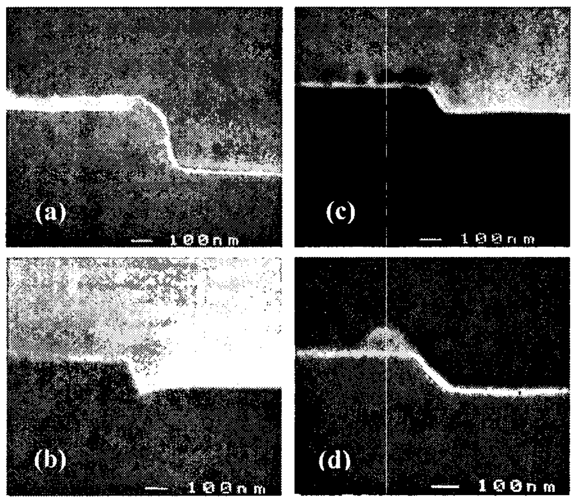

Fig. 2. Scanning electron micrographs of cross sections of substrate step-edges prepared with α=30°, and (a) β=0°, (b) β=30°, (c) β=60°, (d) β=90°.

of the Au film deposition prior to resist-coating was to obtain a well-defined mask-edge by minimizing smearing of the mask edge due to multiple reflections of ultraviolet light in the substrate.

In order to get step-edges with a 60°~70° slope which is optimum for step-edge junctions, we investigated various conditions of argon ion mill. As shown in Fig. 1, we controlled two parameters, which are the tilt angle (α) and the rotation angle (β) of the substrate with respect to the incident ion beam. The results for α=30° are shown in Fig. 2. As the substrate rotation angle β increases from 0° to 90°, the ramp angle of the step-edge decreases. To get a steep slope low angles are favorable. However, as shown in the figure, 0° step-edge has substantial redeposition of the etched substrate material. The bulge due to redeposition causes disconnection of the junctions. For negative angles, i.e., when the mask edge faces the incident beam, redeposition and hardening of the resist were always observed. The best result without redeposition is obtained at β=30°, where the slope angle is a 70°. We repeated the investigation for α=15° and obtained similar results. Taking redeposition into account, the optimum angles obtained to get a steep slope of the step-edge were α=15°~30° β=20°~30°. For all our samples of Josephson junctions studied in this work, we used α=20° and β=20°.

We made 15 junctions, all with the same angle of step-line on the same substrate. Junction width was 3 μm. To minimize any deviation in fabrication conditions among junctions, all of the junctions were designed within 150 μm range. Step-line angle was controlled by twisting the substrate under the same e-beam mask during exposure. $YBa_2Cu_3O_7$ film was deposited by KrF pulsed laser deposition method and patterned into junctions by argon ion milling with a photoresist mask. The laser energy was 1.2 J/pulse energy at 3 pulses/s, substrate temperature was 810 ℃, and the oxygen pressure was 400 mtorr. The photoresist mask for junction patterning was prepared using the same recipe as that for step-edge formation but without Au layer and the normal beam incidence angle was used for argon ion etch. Au contact pads were prepared using rf sputter -deposition and lift-off method

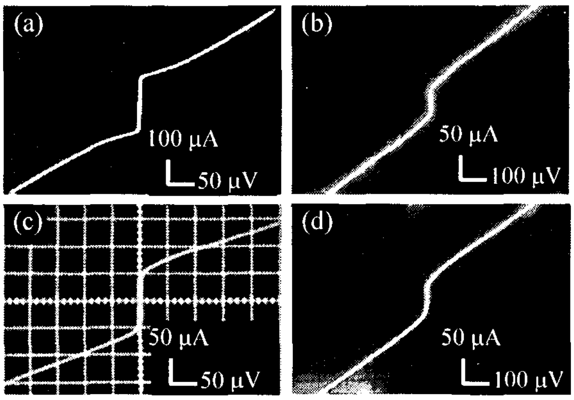

Fig. 3. Current-voltage curves of junctions with step-line angles of (a) 0°, (b) 15°, (c) 30°, and (d) 45°. T=77 K.

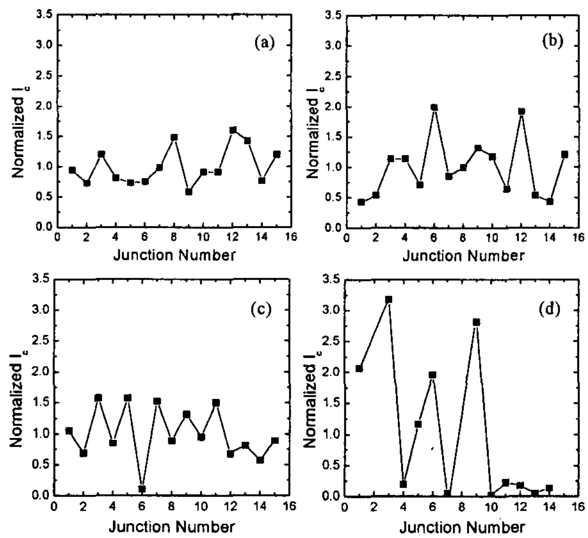

Fig. 4. Normalized critical currents of junctions on 4 different substrates with step-line angles of 0°, 15°, 30°, and 45°. For comparison, critical currents were normalized with respect to the average value of junctions on each substrate. T=77 K.

We measured current-voltage (I-V) curves and obtained junction critical currents from those I-V curves. To minimize external measurement noise, we performed all the measurements using Ithaco low noise preamplifiers in battery mode and Tektronix oscilloscopes. Data acquisition using PC with an ADC board often affected the I-V curves, which might be due to either power line or digital noise.

Figure 3 shows some of the measured current-voltage curves of junctions with different step-line angles. Although all the current-voltage curves showed relatively well-defined resistive transition, notable difference was observed in the detailed structure of the curves between low angle junctions and high angle junctions as shown in Fig. 3. I-V curves of most of the 0^{o} junctions showed standard resistively-shunted-junction (RSJ) characteristics. However, majority of high angle junctions showed non-RSJ behavior. Those non-RSJ junctions showed rounded transitions or abrupt transitions to the nonzero voltage states at the critical current.

Figure 4 shows the normalized critical currents of junctions made on 4 different substrates, each of which has one of the step-line angles of 0^{o}, 15^{o}, 30^{o}, and 45^{o}, respectively. To compare the degree of nonuniformity in critical current among junctions on different substrates, data for each substrate were normalized independently. In the figure, one can notice that the nonuniformity tends to increase as the step-line angle increases, and reaches the maximum data at 45^{o}.

III. Discussion

We believe that the increase of nonuniformity in critical current with increasing step-line angle is related to the microstructure of the step-edge in coupling with d-wave symmetry of $YBa_2Cu_3O_7$ superconductor. Figure 5 shows schematic of the step-edge junction with the step-line twisted by ϕ from the crystal axes of the substrate. A step-edge junction has two grain boundaries and each grain boundary has both twist angle and tilt angle [4].

According to the theory of d-wave superconductivity [9]-[10], energy gap has the angular dependence of $\cos(2\phi)$, where ϕ is the angle from the major axes of the superconductor film. As shown in Fig. 7, since the misfit angle on the planar sides is ϕ and that on the ramp is zero, the critical current of each boundary of the step-edge junction, which is proportional to the product of the gap energies of both sides, is $\sim\cos(2\phi)$. Since one step-edge junction contains two grain boundaries and the misfit angles are the same, the critical current of a

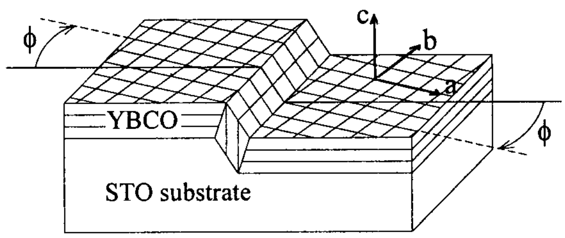

Fig. 5. Crystal orientations of the step-edge junction on the $SrTiO_3(100)$ substrate. Step-line angle is the same as the twist angle ϕ in the figure.

step-edge junction is proportional to $\cos^2(2\phi)$. Junction critical current is sensitive small deviations at large misfit angles.

Mannhart et al. have studied scanning tunneling microscopic study of local critical current distribution of bicrystal grain junctions [8]. They found that random distribution of local facet angles of the grain boundary of $YBa_2Cu_3O_7$ superconductor induced an irregular distribution of local critical current. Since a step-edge junction has two grain-boundaries and each boundary has both twist and tilt angles, the irregularity will be muh larger. Assuming that deviations in both twist angle and tilt angle have the same effect on the scattering in critical current, the scattering will be doubled compared with that of a bicrystal junction. For the same distribution of deviations of local misfit angles from the average for all ϕ values, nonuniformity of local critical current within a junction will increase as ϕ increases because critical current is proportional to $\cos^2(2\phi)$. Accordingly, the nonuniformity of critical current among junctions will increase with increasing misorientation angle, which is in qualitative agreement with the results described in Fig. 6. Resistive transition in I-V curves will be more smeared at high angles due to wider distribution of local critical current within a junction.

Acknowledgments

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