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Critical currents of $YBa_2Cu_3O_7$ step-edge Josephson junctions on $SrTiO_3$ (100) substrates.

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Abstract

We have studied critical currents of $YBa_2Cu_3O_7$ step-edge junctions with different step orientations with respect to the major axes of $SrTiO_3$ (100) substrates. The junctions were prepared by pulsed laser deposition and argon ion milling with photoresist mask. We investigated current-voltage characteristics and critical current of the junctions as a function of the angle. The junction critical current showed an angle dependent modulation with maxima near 0 or 90 degree and minima near 45 and 135 degrees. The experimental results were analyzed based on the microstructure of the junction along the step and the *d*-wave symmetry of $YBa_2Cu_3O_7$ superconductor.

Keywords : Josephson junction, d-wave symmetry, critical current

I. Introduction

Since the discovery of high temperature superconductors, various types of high T_c Josephson junctions were developed for electronic applications. Among them bicrystal junctions [1], step-edge junctions [2], and ramp-edge junctions [3] are most widely used. Bicrystal junctions are easy to fabricate, reproducible, and excellent in noise property. However, high cost of the substrate and restricted topological freedom are major obstacles to applications that require many junctions. On the other hand, ramp-edge junctions have large topological freedom, but the fabrication technology of reliable high quality junctions is yet to be developed. Step-edge junctions can be viewed as a compromise of the two.

Step-edge junctions are cost effective and easy to fabricate. In addition, they have good noise properties comparable to bicrystal junctions and relatively large topological freedom. For those reasons, the step-edge junction can be the major junction type for the future high T_c electronics. However, uniformity of the junction critical current is yet to be improved. To maximize the topological freedom of step-edge junctions and also to find out the cause of the relatively poor uniformity of the critical current, junction properties need to be investigated systematically for various step-line orientations with respective to the axes of the substrate.

Usually it is recommended that the step-line is oriented parallel to one of the substrate axes to get good step-edge junction properties. Different step-line orientation will induce different microscopic structure and thus affect the critical junction properties. However, how it affects the junction properties is not known clearly, nor has it been studied systematically. In addition, the effects of symmetry of the high T_c superconductor have not

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been studied in step-edge junctions.

In this work, we fabricated $YBa_2Cu_3O_7$ (YBCO) step-edge junctions with various tilt angles of the step-line with respect to the $SrTiO_3$ (STO) substrate axes, and investigated current-voltage characteristics and critical current of the junctions. The results were analyzed based on the junction microstructure and the *d*-wave symmetry.

II. Experiments and Results

Junctions were made on a 1 cm × 1 cm $SrTiO_3$ (100) substrate and each junction had a different step-line angle, $\phi = 0° \sim 165°$ with a 15° interval. The tilt angle ϕ is defined as in Figure 1. Substrate steps were formed on $SrTiO_3$ (100) by ion milling with photoresist mask. We deposited about 20-nm-thick Au film on the substrate prior to photolithography. The usage of Au film is known to reduce scattering of ultraviolet under the Cr mask during exposure [4], and the step-line was much better defined according to scanning-electron-microscopic study. To make the ramp-angle of the steps uniform, the substrate was rotated at a few rpm's during milling with the substrate's normal tilted from the beam. incidence direction by 20°. The ramp angle of the step was about 60°..

YBCO film was deposited by pulsed laser deposition method and patterned by Ar ion milling with a photoresist mask. Step height (h) was 220 nm – 270 nm and the film thickness (t) was 140 nm – 160 nm with $t/h \approx 2/3$. During film deposition oxygen pressure was 400 m torr and the substrate temperature was 810 °C. After deposition the film was annealed

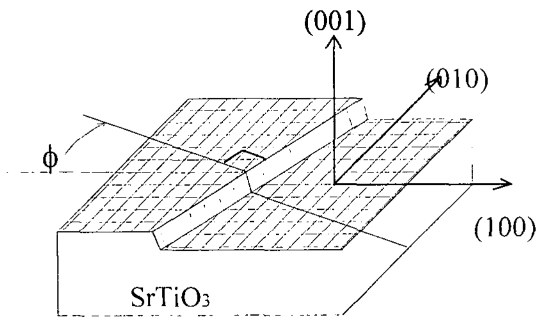

Fig. 1. Schematic of the step-edge formed on the SrTiO substrate. ϕ is the tilt-angle of the step line.

for 1 hour at 500 °C in 1 atmospheric pressure of oxygen. Details of the fabrication conditions are described in the reference [5].

We measured current-voltage (I-V) curves and critical current of the junctions. Junction I-V curves of one of the samples studied are shown in Figure 2. All curves show a sharp transition above the critical currents. According to the thermal fluctuation theory [6], $\gamma = \hbar I_c / e k_B T > 10^3$, and thus thermal rounding at the transition is negligible, as observed in the figure. Above the critical current, the curves show downward curvature instead of the typical upward curvature of the standard resistively-shunted-junction

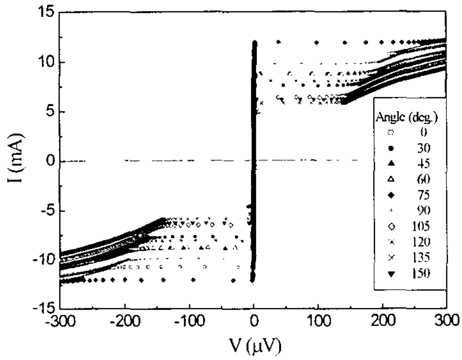

Fig. 2. Current-voltage curves of 10 junctions with different tilt-angles made on the same $SrTiO_3$ substrate. Junction width was 5 μm.

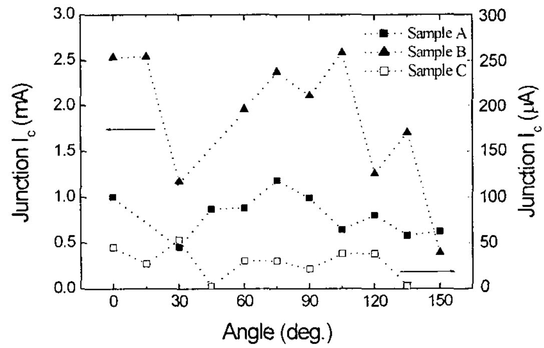

Fig. 3. Critical current as a function of the tilt-angle for three different samples. Sample A and B were measured at 77 K and C at 70 K. All the junctions were 5 μm wide

model [7]. The reason for downward curvature could be flux flow which was self-induced by the junction current.

In Figure 3 critical currents of the junctions obtained from the I-V curves for 3 different samples are plotted as a function of the step-line angle. Lines connecting data points are drawn as a guide to the eye. As shown in the figure, the critical current, I_c is maximum near 0° and 75°-90°, and minimum around 30°-45° and 135°. In other words, when the step-line is parallel to the crystal axis of the substrate, critical current is maximum, and when the step is tilted by 45° from the axis, I_c is minimum. Even though some of the data points show slight deviation, the general trend as mentioned above can be easily recognized.

However, some of our samples showed almost no correlation between the critical current and the tilt angle. They were mostly non-RSJ-like in I-V characteristics and showed structural defects under a scanning electron microscope. But the more profound cause is ascribed to the nonuniformity of the critical current density associated with the d-wave symmetry and the microstructural nonuniformity along the junctions.

III. Discussion

The modulation of the junction critical current in angle is believed to originate from the following two possibilities. One possibility is microscopic structure along the step line. The atomic arrangement along the step is jagged and the jag period depends on the tilt angle. Growth of $YBa_2Cu_3O_7$ (YBCO) film on the jagged edge will be different from that on the edge without jag, and thus geometry of the grain boundary might be different. Scanning electron microscopic study supported this interpretation [5]. Equally spaced small bumps were also observed along the step line and the period of the bump occurrence was dependent on the tilt-angle of the step line. Quantitative analyses are yet to be done.

A more persuading possibility is *d*-wave symmetry. Epitaxial growth of $YBa_2Cu_3O_7$ film on the $SrTiO_3$ substrate induces two grain boundary junctions at the step-edge with the tilt-angle of the grain boundary equal to the step-line angle. According to the theory of the *d*-wave symmetry, the critical current of the grain boundary junction is proportional to the cosine of the twice of the tilt angle, ϕ, i.e., $\cos(2\phi)$ [9]. The critical current is maximum for $\phi = 0°, 90°$, and minimum for $\phi = 45°, 135°$. Our experimental results are in qualitative agreement with the *d*-wave theory. However, the quantitative comparison of the experimental results with the theory needs some explanation.

According to Mannhart et al [8] the bicrystal grain boundary is zigzagged and the distribution of the current density is strongly affected by the orientation of the boundary due to *d*-wave symmetry. Step- edge junctions will be also zigzagged for the same reason as the bicrystal junction and the critical current is the integral of the complicated current distribution. The random nature of zigzagging will lower the uniformity of the critical current among junctions. In addition, a step-edge junction contains two grain-boundaries and thus the critical current nonuniformity will be larger than that of the bicrystal junction. Therefore, one can conclude that the cause of the deviation of some of the data points in Figure 3 is *d*-wave symmetry in association the microstructure of the junction. For the same reason, we couldn't observe the modulation in certain samples.

IV. Conclusion

The current-voltage characteristics and critical current of the $YBa_2Cu_3O_7$ step-edge junction on the $SrTiO_3$ (100) substrate were studied as a function of the tilt-angle of the step-line with respect to the major axes of the substrate. Junction critical current showed a modulation with maxima near 0° or 90° and minima around 45° or 135°. The I_c modulation observed in the measurement is believed due mainly to the microstructure of the epitaxially grown $YBa_2Cu_3O_7$ film at the step in coupling with the *d*-wave symmetry of the energy gap.

Acknowledgments

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