Influence of misorientation angle on third harmonic voltages $V_3$ induced by YBCO thin films on bi-crystal substrates

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Abstract

YBa$_2$Cu$_3$O$_y$ thin films have been deposited on SrTiO$_3$ bi-crystal substrates with various misorientation angles and a STO single-crystal substrate by a pulsed laser deposition method. The magnetic field dependence of third harmonic voltage $V_3$ vs. coil current $I_0$ was measured by the third harmonic voltage method when the coils were mounted on the crystal grain boundary. The $V_3$ increases monotonically with increasing $I_0$ in the single-crystal substrate. However, the $V_3$ increases strangely with increasing $I_0$ in the bi-crystal substrate with low-angle grain boundary in low-magnetic fields. On the other hand, the $V_3$ increases monotonically in the bi-crystal substrates with high-angle grain boundary.

1. Introduction

High critical current density $J_c$ and its high uniformity are required for the development of long-length YBa$_2$Cu$_3$O$_y$ (YBCO) coated conductors [1]. Then, it is important to investigate the local distribution of $J_c$ in YBCO coated conductors to detect crystal grain boundary, crystal defects, etc. As the typical measurement technique for nondestructive measurement of $J_c$, there are the third harmonic voltage method [2] and the permanent magnet method [3].

The third harmonic voltage method is very useful to nondestructively estimate the $J_c$ distribution of a superconducting film without contact. In this method, an ac magnetic field is applied by a small coil placed just above the superconducting film. The harmonic voltages are generated due to the nonlinear magnetic response of the superconducting film and $J_c$ is determined by detecting the largest harmonic voltage: the third harmonic voltage $V_3$. The validity of this method was clarified by some research groups theoretically and experimentally [4-9]. Recently, we have presented an interesting measurement result of a YBCO thin film on a SrTiO$_3$ (STO) bi-crystal substrate using the third harmonic voltage method [10].

In this study, we measured the third harmonic voltage $V_3$ as a function of the coil current $I_0$ in YBCO thin films deposited on STO bi-crystal substrates with various misorientation angles and a STO single-crystal substrate. The influence of the misorientation angle on $V_3$ and the magnetic field dependence of $V_3$ were investigated.
2. Experimental

The YBCO thin films were deposited on STO bi-crystal substrates with nominally symmetric [100] tilt boundaries and a STO single-crystal substrate by a pulsed laser deposition method. The detail of the sample preparation has been published elsewhere [11]. The size and thickness of the YBCO thin films are 10 mm × 10 mm and about 280 nm, respectively. Table 1 shows the misorientation angle for STO bi-crystal substrates. We prepared the sample E which has an artificial defect in surface of YBCO thin film for comparison. The artificial defect was made by hand-scratched using cut-knife, and the width of ditch is about 20 μm. Fig. 1 shows the X-ray φ scans of the (102) peak of the YBCO thin films on STO bi-crystal substrates and STO single-crystal substrate. We confirmed that the peak appears whenever φ shifts by the misorientation angle.

In the third harmonic voltage method, we used the two kinds of small coils, the drive and pick-up coils. The internal pick-up coil (1.0 mm in inner diameter, 2.4 mm in outer diameter, 1.0 mm in height and 200 turns winding) and the external drive coil (2.4 mm in inner diameter, 5.0 mm in outer diameter, 1.0 mm in height and 400 turns winding) were wound and the coils were made of the enamel wire 50 μm in diameter. Fig. 2 shows the block diagram of an electronic system for measuring a $V_3/I_0$ curve by the third harmonic voltage method. The frequency $f$ of the coil current was changed in the range of 0.5 ~ 10 kHz. The ac current $I_0 \cos 2\pi ft$ was supplied from a signal generator to the drive coil, and the third harmonic voltage induced in the pick-up coil was measured with a lock-in amplifier. The voltage of a shunt resistance was measured with a digital multimeter to monitor the current through the drive coil. The coils were placed so that these axes were parallel to the c-axis of the YBCO thin film and were mounted about 0.2 mm above the YBCO thin film.

The YBCO thin film protected by a kapton sheet was fixed on the sample holder of the measurement system and cooled by liquid N2. A magnetic field was applied by a neodymium magnet and was measured by two Hall devices put on the corners of the sample holder.

### Table 1 Specification of the samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Material</th>
<th>Substrate</th>
<th>Misorientation angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>YBCO</td>
<td>STO single-crystal</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>YBCO</td>
<td>STO bi-crystal</td>
<td>$2\theta = 10.0^\circ$</td>
</tr>
<tr>
<td>C</td>
<td>YBCO</td>
<td>STO bi-crystal</td>
<td>$2\theta = 22.6^\circ$</td>
</tr>
<tr>
<td>D</td>
<td>YBCO</td>
<td>STO bi-crystal</td>
<td>$2\theta = 36.8^\circ$</td>
</tr>
<tr>
<td>E</td>
<td>YBCO</td>
<td>STO single-crystal</td>
<td>scratch defect</td>
</tr>
</tbody>
</table>

3. Results and discussion

Fig. 3 (a) and (b) show the dependence of $V_3$ and $V_3/I_0$ on $I_0$ for Sample A and Sample B in the self-magnetic field, respectively. The coils were mounted at the center of the YBCO thin films. This area is just above the crystal grain.
boundary as shown in Fig. 3 (b). In Fig. 3 (a), the typical third harmonic voltage curves induced by the YBCO thin film on STO single-crystal substrate for various frequency (0.5 ~ 10kHz). The $V_3$ increases monotonically with increasing $I_0$ over a certain threshold value. Fig. 3 (b) shows the $V_3$-$I_0$ curves of Sample B in which the misorientation angle of the substrate is $2\theta = 10.0^\circ$. Unlike the behavior of $V_3$ in Sample A, the $V_3$ of Sample B decreases once after having increased, and then increases again with increasing $I_0$. In Sample B, after the shielding current flowing across the crystal grain boundary (inter-grain current) reaches the critical value, the main part of the shielding current flows along the crystal grain boundary [12], because the inter-grain critical current is much smaller than the intra-grain critical current [13]. This complicated behavior of the shielding current affects the generation of $V_3$. We must also consider the edge effect [14, 15] by the crystal grain boundary.

Fig. 4 (a) and (b) show the $V_3$-$I_0$ curves of Sample D in which the misorientation angle of the substrate is $2\theta = 36.8^\circ$ and Sample E with the artificial defect at the center, respectively. Unlike the behavior of $V_3$ in Sample B, the $V_3$ of Sample D increase monotonically with increasing $I_0$. The monotonic increase of $V_3$ with increasing $I_0$ is also observed in Sample E. However, the amplitude of $V_3$ in Sample D is smaller than that of Sample E in high frequency region. The shielding current cannot flow across the artificial defect in Sample E, the schematic illustration of the shielding current flowing in Sample E is shown in the Fig. 4 (b) [15]. On the other hand, a few shielding current flows across the crystal grain boundary in Sample D. Therefore, the behavior of $V_3$ depends on the amount of the inter-grain current strongly.
Fig. 5 (a) and (b) show the magnetic field dependence of $V_3-I_0$ curves in 10 kHz for Sample B and Sample C, respectively. In Sample B, the $V_3$ in low-magnetic field shows the two-step increase behavior. When the magnetic field increased, the behavior of $V_3$ has changed from a two-step increase into a monotonic one. The shielding current in high-magnetic field is composed mainly of the intra-grain current flowing along the grain boundary, because the inter-grain critical current reduces drastically with increasing magnetic field [10]. In Sample C, the $V_3$ increases from zero point in all the magnetic field, because the magnetic flux which generated from the drive coil was not completely shielded by the YBCO thin film. The $V_3$ shows a little two-step increase behavior. It is considered that only a few shielding current flows across the crystal grain boundary, because the misorientation angle of Sample C is larger than that of Sample B.

![Graphs](image)

**Fig. 5.** The magnetic field dependence of $V_3-I_0$ curves in 10 kHz.

4. Conclusion

In this study, we measured the $V_3-I_0$ curves in YBCO thin films on STO bi-crystal substrates with various misorientation angles using the third harmonic voltage method. In the YBCO thin films on STO bi-crystal substrates with $2\theta = 10.0^\circ$ and $22.6^\circ$, the $V_3$ exhibits the two-step increase. In the case of $2\theta = 36.8^\circ$, however, the $V_3$ increases monotonically. From measuring result of the YBCO thin film with the artificial defect, we can confirm that the inter-grain current hardly flows across the crystal grain boundary in the case of high-angle grain boundary.

References