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<tr>
<td><strong>Citation</strong></td>
<td>Physica C: Superconductivity, 357-360 : 1473 - 1477</td>
</tr>
<tr>
<td><strong>Issue Date</strong></td>
<td>2001-08</td>
</tr>
<tr>
<td><strong>DOI</strong></td>
<td>10.1016/S0921-4534(01)00590-1</td>
</tr>
<tr>
<td><strong>Self DOI</strong></td>
<td></td>
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<tr>
<td><strong>URL</strong></td>
<td><a href="http://ir.lib.hiroshima-u.ac.jp/00046734">http://ir.lib.hiroshima-u.ac.jp/00046734</a></td>
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Evaluation of supercurrent distribution in High-$T_C$ superconductor by Scanning SQUID Microscopy (SSM)

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Abstract

Scanning SQUID Microscope (SSM) is a powerful tool for observing small magnetic flux. It measures the z-component signal of flux density, but it is also available for observation of current distribution by inverting the Biot-Savart law. We report the two dimensional (2D) vector mapping of current distributions in high-$T_C$ superconducting YBa$_2$Cu$_3$O$_{7-y}$ (YBCO) thin films obtained by converting magnetic-field data measured by SSM. The current distribution contains those from both transport supercurrent and vortex current. The transport supercurrent is found to flow mainly along the edge of a stripline. The results are in good qualitative agreement with the calculated results based on simple London model. The YBCO films with an artificial grain boundary, i.e. Josephson boundary are also observed. The transport current seems to flows with avoiding the vortices, and an irregular vortex is observed at a point of grain boundary.

PACS Codes.: 74.50.+r; 74.60.Jg; 74.76.Bz; 85.25.D

Keywords: Scanning SQUID Microscope; Current Distribution; Vortex; HTSC

Introduction

Recently, the scanning SQUID microscope has been found to have very profitable application of superconductor for various purpose.[1][2] It has been pointed out that SQM2000) is almost similar to that of Ref. [7]. It contains the SSM can also probe a current distribution by use of the a dc-SQUID magnetometer made of Nb/Al-AlO$_x$/Nb tun-inverted Biot-Savart’s law, and the current distribution of nel Josephson junctions combined with a one-turn pickup a semiconductor chip at room temperature was reported coil of 10 $\mu$m diameter. The sample-coil distance was less by measuring the spatial distribution of magnetic field us- than 10 $\mu$m. A Cu wire coil was wound around the sample ing an SSM.[2] The SSM has much advantage to compare holder to generate a small magnetic field.

The films with a grain boundary were deposited on the MgO bicrystal substrates (12 $\times$ 12 $\mu$m) by PLD Method. The SSM has much advantage to compare holder to generate a small magnetic field.

To obtain the current the two-dimensional vector distrib- able for the investigation of superconductors. The current distribution map from magnetic field data, we use the inverted and magnetic distributions of Josephson junction is inter- Biot-Savart law. By assuming that the supercurrent in vested subjects for application of Josephson devices and for the specimen is limited to the sheet of film thickness d and basic understanding of superconductors because the vor- tex is much larger in a Josephson junction is strongly conected with the than d ($z_0 \gg d$), the following formula can be applied. phase of order parameter in the junction. We report the According to the work by Wikswo et al.[8], the inverted supercurrent distributions of YBCO thin films with and Biot-Savart’s law in Fourier space in this case is given by without an artificial grain boundary. The observed mag- netic signal was converted into the current distribution by the inverted Biot-Savart law and compared with the the-oretical model.

\[
\begin{align*}
  j_x(k_x, k_y) &= -\frac{2i e^{k z_0}}{\mu_0 d} k_y b_z(k_x, k_y) \\
  j_y(k_x, k_y) &= \frac{2i e^{k z_0}}{\mu_0 d} k_x b_z(k_x, k_y).
\end{align*}
\]

Experimental and calculations

YBCO thin films were deposited by a pulsed laser de- position (PLD) method. The film thickness was about 100 nm. All samples were patterned by conventional photolithography technique and the Ar ion milling technique. The width of a YBCO stripline was about 100 $\mu$m. The critical temperature ($T_C$) was around 88 K and the critical current density ($J_C$) was about $10^7$ $A/cm^2$ at 10 K.

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In practice, at first, the two-dimensional z-component of the magnetic field data from SSM are transformed into discrete FFT form, then $j_x$ and $j_y$ are calculated using Eqs. (1) and (2) in k-space, and finally, $J_x(x, y)$ and $J_y(x, y)$ are obtained by inverse FFT of $j_x(k_x, k_y)$ and $j_y(k_x, k_y)$.

**Results and discussion**

Figure 1 shows that the observed magnetic field images ((a) and (b)) and current distribution images ((A) and (B)) of YBCO thin film of 100 µm wide (y-direction) under different transport currents (1.0 mA in (a) and (A), 10 mA in (b) and (B)). The x-direction length of measured stripline was about 60 µm (A) and 25 µm (B), respectively. The current flows along the x-direction. In Fig. 1(a), the magnetic-field data contain a single trapped vortex, hence the current distribution consists of the sum of transport current and vortex shielding current. The transport current flows mainly along the edge of the stripline, and small circular current that generates the vortex is also seen in the center part of this image. By considering the spread of a magnetic field at the detecting position (about 10 µm height above the sample surface) and the pick-up coil of 10 µmφ, the real vortex and transport currents would be localized in small area. Figures 2(a) and 2(b) show the magnetic-field data and the calculated current distribution across the film of Fig. 1(b) and 1(B) (at $x = 635$ µm), together with numerical results based on the simple London model, respectively. Since the transport current was only 1 % of film critical current (~1A), we assume the most ideal and classical model\[9\]\[10\], $J(y) = I(a^2 - y^2)^{-1/2}/\pi$ in all but the extreme edge regions, where $a$ is the half-width of stripline. The magnetic field is given by $B(y) = 0$ ($|y| < a$), $B(y) = \frac{\mu_0I}{2\pi}y/\sqrt{y^2 - a^2}$ ($|y| > a$). The calculated $B(y)$ and $J(y)$ profiles correspond to the dashed lines in Fig. 2(a) and 2(b), respectively. The solid line in Fig. 2(a) is the calculated result of a magnetic-field distribution at the detector position by assuming that the surface ($z = 0$) distribution given by this equation, $B(y)$ and $J(y)$ . The open circle dots are experimental data. The agreement between the experimental data and the calculated result is qualitatively good. The solid line in Fig. 2(b) is the calculated current distribution based on $B(x, y, z_0)$. Open square dots are obtained from the experimental magnetic-field data in Fig. 2(a), and the dashed line is the current distribution model on the surface. The experimental current distribution almost agrees with the calculated result by taking the detection area of the SQUID loop into account. For 100 µm $< y < 200$ µm, the discrepancy occurred due to the slight tilt of SQUID pickup coil to y-direction. Although the 2D mapping of current distribution does not exactly correspond to that of real surface ($z = 0$) itself, it essentially reflects the true nature of transport current or vortex current.

The current and magnetic distributions on the thin film with an artificial grain boundary are shown in Fig. 3. Fig. 3(a)-(3d) are the magnetic-field maps and 3(A)-3(D) are the calculated current maps with current vectors. This specimen was cooled down under a magnetic field of a few µT, then was measured at 3 K. Fig. 3(A), depicts...
the initial state without transport current. Fig. 3(b) and 3(B) are under the presence of the transport current of 100 µA, Fig. 3(c) and 3(C) corresponds to 500 µA. The vertical dashed line of each figure corresponds to the artificial grain boundary in a bicrystal substrate. In Fig. 3(A), some circular vortex currents were seen. One downward direction vortex was clearly observed at the grain boundary interface. It is considered that the current might be perturbed by grains or some defects, hence irregular different direction vortex was generated. Such vortices were also seen in some YBCO thin films without artificial grain boundaries, however, they were more frequently observable in Josephson boundaries. In Fig. 3(B) and 3(C),

with that of Fig. 3(a). while the position of other vortices didn’t change. It is explained that the current (higher than $I_{JC}$ and lower than $I_C$ (film itself)) makes super to normal transition only at the junction area. In this situation, the magnetic field induced by transport current was frozen in a moment when the current is reduced below $I_C$.

**Summary**

The 2D current distributions in YBCO thin films including an artificial grain boundary were obtained by SSM. In the 100 µm wide stripline of YBCO thin film, the transport current flows mainly at the edge of the stripline, and the agreement between the experimental data and the calculated results based on simple London model is qualitatively good. In the samples with the bicrystal Josephson junctions, one downward direction vortex was observed at the point of interface boundary. The transport current was found to flow with avoiding the vortices. The positions of vortices did not change for the transport current below the Josephson critical current, $I_{JC}$, but the generation of a new vortex accompanying the enhancement of downward vortex component occurred above the transport current of $I_{JC}$. It is considered that they might be caused by magnetic field induced by transport current at the interface boundary. These results demonstrate that the SSM system provides a useful tool for studying the current distribution in a superconductor.

**References**