Observation of local magnetic distribution in ramp-edge Josephson junctions

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Abstract

The observation of magnetic images for ramp-edge Josephson junctions (JJ) by scanning SQUID microscopy is reported. The dependence of the trapped vortex at a JJ on the external magnetic field was investigated, and it was found to be consistent with the modulation of the maximum Josephson current, showing that the vortex was not continuously changing, but that the change was quantized. A novel vortex trapped at the junction under a relatively large field is observable, which increases in quantized units as the external field is increased. Three different types of ramp-edge junctions were also investigated, showing that the difference in the magnetic penetration around the junctions reflects the junction property. These results provide us easy and useful information and an evaluation method of the junctions and the superconductivity of the films with no lead line.

1. Introduction

The ramp-edge type Josephson junction (JJ) [1, 2] finds useful applications in fundamental studies on the Josephson effect in high-Tc superconductors [3–8], as well as electronic applications such as single flux quantum (SFQ) [9]. It is very important to understand the local flux behavior in the vicinity of the junctions because the flux quantum is considered as an information unit in the SFQ circuit and also important for understanding the relation between the Josephson current and external magnetic field in high-Tc d-wave superconductors. Observations of spatial magnetic distributions and the magnitude of the flux on the superconductors measured using a scanning SQUID microscope (SSM) have provided substantial information on various problems such as the clarification of d-wave superconductivity and its fundamental properties of high Tc cuprates [3, 10–14], evaluation of the super current distribution of the strip lines [15], observation of the interlayer vortex of high Tc cuprates [16], and flux quanta on the various shapes of thin films [17, 18]. We have investigated local magnetic distributions of the artificial bicrystal and tricrystal grain boundary junctions using an SSM, which confirmed the d-wave pairing symmetry of high-Tc cuprates [11, 19]. On the other hand, the ramp-edge JJ has a better interface as it has a smooth surface compared to grain boundary junctions. Hence, it has a considerable advantage for measuring the phase sensitive properties related to the order parameter [14]. However, there are few reports on detailed flux observations on the single ramp-edge JJ. The magnetic observation of the junctions may clarify how the vortex threads through the ramp-edge area and provide us useful information to evaluate the junctions. It is considered that the comparison of magnetic distributions with different types of JJ may provide us new evaluation methods with no lead line. Furthermore, such methods are expected to be available for a large number of JJ arrays.

In this paper, we present a fundamental study on YBa2Cu3O7−δ (YBCO) ramp-edge JJs by observing the magnetic distributions at various junctions by using scanning SQUID microscopy. The relation between the external field dependence of the vortex structure and the maximum Josephson current modulation was investigated. A novel vortex trapped at the JJs was clearly observed, which increases in quantized units as the external field is increased. The observed magnetic distributions of the three types of ramp-edge JJs (typical resistively-shunted-junction (RSJ)-type JJ, flux-flow-type junction with high excess current, and broken...
junction without critical current) clarified that the difference in the magnetic penetration around the junctions reflects the junction properties, suggesting a useful method for the evaluation of JJs by SSM.

2. Experiment

The YBCO-based ramp-edge type junctions were prepared by a pulsed laser deposition method. A schematic view of the junction structure is shown in figure 1(a). Initially, CeO$_2$ (10 nm), YBCO (200 nm), and CeO$_2$ (200 nm) films were deposited on MgO substrates. The top and bottom CeO$_2$ films served as thick insulators and as a seed-layer of the YBCO thin film, respectively. Next, this trilayer film was patterned into the junction structure by using photolithography and an Ar ion milling technique. Thereafter, the PrBa$_2$Cu$_3$O$_{y}$ (PBCO, 5 nm) and YBCO (200 nm) films were subsequently deposited, and Ar ion milling was completed to define the junction line. The junction width is approximately 20 μm. The optical microscope image of the completed ramp-edge junction is shown in figure 1(b). The orientation of the bottom YBCO was rotated by 45° relative to the top YBCO film because the bottom CeO$_2$/MgO seed layer structure causes the YBCO to rotate by 45°, relative to the MgO substrate [4, 20]. The angles of the orientation of the top and bottom YBCO electrodes are shown in figures 1(a) and (b). Other details of sample fabrications are described in [4, 7, 21, 22]. The three types of junctions were prepared. One is a typical RSJ-type JJ with a critical Josephson current of $I_{Jc} \approx 0.6$ mA (type A). Others were non-ideal junctions; a junction with high excess critical current with flux-flow-type $I-V$
characteristics \( I_c = 20 \text{ mA, type B}, \) and a junction with no supercurrent, i.e., \( I_c = 0 \) (type C). Type B and C junctions were prepared for comparison with the good JJ (type A).

The SSM system based on the commercially distributed system (SII SQM-2000) contains a dc-SQUID magnetometer made of Nb/Al–AlO\(_x\)/Nb tunnel JJs. The magnetometer had a one-turn pickup coil having an effective diameter of 10 \( \mu \text{m} \) and detects the \( z \)-axis component of the magnetic field \( B_z(x, y) \). The sample-coil distance was approximately 3–5 \( \mu \text{m} \); hence, the spatial resolution of the magnetic image was estimated \( \sim 5 \mu \text{m} \). The magnetic flux sensitivity was better than \( 5\mu\Phi_0/\text{Hz}^{1/2} \). The sample temperature was controllable between 3 and 100 K by a dc current heater and control of the He gas flow. However, the temperature of the observations was fixed at \( T = 3.0 \text{ K} \). A Cu wire coil was wound around the sample holder to generate a magnetic field. The details of this system are described elsewhere [23, 24].

3. Results and discussion

3.1. Magnetic properties and distributions at single JJs

Figure 1(c) shows the external magnetic field \( H \) dependence of the maximum Josephson current \( I_{c0} \) \( (I_{c0} = \mu_0 \mu H) \) in the ramp-edge JJ (type A). Because the current value was continuously measured at a fixed constant voltage of \( (40 \mu \text{V}) \), the current was slightly higher than the exact critical current, but almost at same as (within 10\%) the critical current. (See \( I-V \) curve (insertion) of figure 1(c).) The magnetic field was applied normal to the sample surface (\( c \)-axis direction of the YBCO films), the same as the SSM measurement. Basically, \( I_{c0} \) was periodically modulated in approximately a few tens of \( \mu \text{T} \). However, it was not simple one such as the so called Fraunhofer pattern of \( J \) of the conventional superconductors. It is considered mainly to be due to the \( d \)-wave symmetry, a four-leaf clover shaped lobe of order parameters of cuprate superconductors. Therefore, we should take the \( d \)-wave symmetry of the order parameter into account for a fitting of \( I_{c0} = \mu_0 H \) relation. In this case, the relative angle between the lobes of the two YBCO electrodes (\( \alpha_{0} \)) is \( 45^\circ \), and the angle between the direction normal to the junction boundary interface and the \( a \)-axis of the bottom YBCO is \( \beta = 20^\circ \) (see the schematic view of figures 1(a) and 1(b)). The red-dashed lines in figure 1(c) show the fitting curve of the \( I_{c0} = \mu_0 H \), based on the theoretical calculation from the [4] of figure 5, the external field dependence of the \( d \)-wave based Josephson current with \( \alpha_{0} = 45^\circ \) and \( \beta = 20^\circ \). For comparison, we also show the conventional magnetic field dependence of the maximum Josephson current (Fraunhofer pattern) as the blue-dotted lines in figure 1(c). The \( d \)-wave based fitting curve reproduces qualitatively better modulation periodicity than that of the conventional one, which shows the \( \Phi_0/2 \) periodic behaviors. Nevertheless, in detail, there were still some discrepancies between the fitting curve and the experimental results. It may due to the inhomogeneous interface of the junction such as zigzag structures and the mixture of the various angles of the interfaces, which may generate the complex configurations of the Josephson current.

From the \( d \)-wave based fitting curve, the period of the magnetic field \( \mu_0 H_0 = 17.5 \mu \text{T} \) is estimated, that corresponds to the effective Josephson penetration depth \( \lambda_{pen} \) of several hundreds of \( \mu \text{m} \), assuming the typical value of the London penetration depth of YBCO \( \lambda_{pen} \sim 0.25 \mu \text{m} \). The estimated \( \lambda_{pen} \) is about ten times larger than the widely recognized Josephson penetration depth of \( \sim 10 \mu \text{m} \). It is considered to be due to the above mentioned inhomogeneous interface of the junctions. The results also predicted that the Josephson vortex began to be trapped at approximately with the order of \( \sim 10 \mu \text{T} \) and periodically of several tens \( \mu \text{T} \). It is also noted that the \( \Phi_0/2 \) periodic behavior is suggestive of the existence of the half integer vortices at the corresponding external magnetic fields.

The spatial magnetic distributions by SSM under the lower external magnetic field (0 \( \mu \text{T} \leq \mu_0 H \leq 10 \mu \text{T} \)) at the type-A JJ are shown in figures 2(a)–(d). The junction position is indicated by the dashed arrow in figure 2(a). Before the SSM observations, the sample was cooled from room temperature under the low environmental magnetic field \( \mu_0 H \sim +0.5 \mu \text{T} \) with the upper direction. Then, during the observations, the counter directions of the external magnetic fields of (a) \( \mu_0 H = 0 \mu \text{T} \), (b) \( \mu_0 H = -1 \mu \text{T} \), (c) \( -5 \mu \text{T} \) and (d) \( -10 \mu \text{T} \) were applied. In figures 2(a)–(c), the apparent vortex was not observed at the junction positions under the lower applied magnetic fields of \( |\mu_0 H| \leq 5 \mu \text{T} \). On the other hand, as shown in figure 2(d), the penetrated magnetic field at the junction position was seen with different directions to the bulk vortex under the applied magnetic field of \( \mu_0 H = -10 \mu \text{T} \), while the trapped vortex was in the upper direction (red peak at the bottom right in each figure). Figure 2(e) shows the magnetic distribution under the external magnetic field of 0 \( \mu \text{T} \) after the observation of figure 2(d). The trapped vortex with a magnetic height of \( B \sim -11 \mu \text{T} \) was clearly observed at the junction position, demonstrating that the stable vortex was certainly trapped at \( \mu_0 H \sim -10 \mu \text{T} \). Therefore, at the junction position, the magnetic field did not penetrate the junction under the lower field (figures 2(a)–(c)), but gradually penetrated the junction under the external field of \( \sim 10 \mu \text{T} \) (figure 2(d)). These results were almost consistent with the observed magnetic field dependence of \( I_{c0} = \mu_0 H \) in figure 1(c) \( |\mu_0 H| = 10 \sim 20 \mu \text{T} \). It is noted that the magnetic field easily penetrated through the YBCO film just above the ramp surface,
although the ramp-edge surface was covered with the top superconducting YBCO film, indicating that superconductivity above the ramp surface may weaken. The possibility that the flux could escape from the top YBCO film and leak through each side may arise. However, within our experimental spatial resolution (\( \sim 5 \mu m \)), the peak was not split side by side and the position of the peak was not changing, suggesting that the flux penetrated the weakened-superconducting electrode above the ramp-edge surface.

The effects of much higher magnetic fields were also examined. Figure 3(a) shows the magnetic distribution at the type-A JJ after inducing a downward direction of the higher external field, \( \mu_0 H = -80 \mu T \). The measurement was performed after cutting the magnetic coil current as the high external field interrupts stable measurements. This situation ensures clear distinction between the trapped vortices at the junction and enlarged external field affected by the edge shape of the superconductor. The vortex peak at the JJ is indicated by the black arrow, and this vortex was considerably larger than the bulk vortex at the bottom right of this frame, indicating that the vortex was a different kind of bulk vortex, the ‘Josephson’ vortex. Figure 3(b) shows the cross-sectional data of the trapped Josephson vortex in different external fields. The value of the external field was from \( \mu_0 H \sim -10 \mu T \) up to \( -80 \mu T \). At \( \mu_0 H = -25 \mu T \), the vortex shape was almost same as that of \( \mu_0 H = -10 \mu T \), corresponding to a 1\( \Phi_0 \) vortex. It suggested the vortex was not continuously changing but that the change was quantized. At higher fields of \( \mu_0 H = -50, -80 \mu T \), the vortex peaks were enlarged, corresponding to \( 2\Phi_0 \) and \( 4\Phi_0 \) respectively, from the comparison of the peak magnitudes. It is uncertain this vortex intrinsically contains a large amount of flux or a bundle of vortices so that the spatial resolution is about \( 5 \mu m \). However, this behavior was quite different from that of a bulk vortex, such as similar to the vortex at the bottom right of the frame in figure 3(a), which has no change at the magnetic field as long as the film is in the superconducting state. The period of the penetrated-quantized Josephson vortex (\( 4\Phi_0 \) for \( -80 \mu T \)) by SSM was slightly larger but almost in good agreement with the estimated period of \( \sim 17 \mu T \) by \( I_c = \mu_0 H \) relation in figure 1(c). The complicated changes in \( I_c \) around \( |\mu_0 H| \geq 30 \mu T \) in figure 1(c) indicates that the higher field properties of the JJ did not follow the simple relation. We must also note that the possibility of the half integer and/or fractional quantized vortex [19] in such \( d \)-wave JJ with inhomogeneous interfaces. We consider that such unconventional vortex is possibly observed. However, within our SSM observation of the ramp-edge JJ\( s \), such fractional vortices have not been observed yet. As one of the reasons, it may due to that the ramp-edge JJ possesses smoother interface than grain boundary (bicrystal) JJ\( s \). From these results, it was confirmed that the external field significantly influences the Josephson vortex compared to a conventional vortex, indicating that slight changes of the environment fields generate the extra amount of flux and is not good for the working of a Josephson device.
3.2. Magnetic distributions at various types of ramp-edge junctions

Figures 4(a)–(c) show three-dimensional magnetic field images with the different properties of the junctions ((a) type-A, (b) type-B, (c) type-C) under the same conditions of the external magnetic field 10 μT. In figure 4(a), as mentioned above, the normal type-A JJ allows a small amount of penetration of the magnetic field at the junction position. On the other hand, in figure 4(b) of type-B, the magnetic field did not penetrate and strongly maintained the Meissner state even at the junction position. It is quite reasonable considering the junction was strongly coupled and behaved as a normal strip-line film with the flux-flow type $I-V$ characteristics. In contrast, in the case of the junction with no superconducting coupling (broken junction) of type-C as shown in figure 4(c), the flux freely penetrated at the junction position just like the cutoff strip line.

From these results, the observations of flux, including the junctions by SSM, would be a useful method for the evaluation of junctions with no lead line. Figures 4(d)–(f) show the cross-sectional magnetic field data of each type of junction along the junction positions (indicated by the black lines of the insets). In the case of the type-A junction of the normal JJ, the penetrated magnetic field in the junction position was slightly below the outside field level (about $\sim -10 \mu$T below) while that of type-B (leaky junction) far below the outside field level (about $\sim -40 \mu$T below) that nearly corresponds to the back ground (Meissner) level. On the other hand, that of type-C (broken junction) exceeds the outside field level with upper directions that correspond to the applied magnetic field direction. Therefore, we can suggest one of the simple evaluation methods of the junctions by SSM observations as follows. Initially, the samples are cooled below $T_c$ under the nearly zero-magnetic field. Then, the external magnetic field is applied about one flux $\Phi_0$ level (about $\sim 10 \mu$T in this case) in the superconducting state. Next, the SSM observations are done at the junction positions, and one evaluates the magnetic field at the junctions. If the observed magnetic field level is in excess of the applied field level, then such junction is broken.
just like a cut off strip line. On the contrary, if the observed field is near the background (Meissner) level, such a junction is leaky (flux-flow type) as a normal strip line film. The good JJ shows the magnetic distribution of the slightly penetrated magnetic field at the junction position above the Meissner level, but below the applied field level. Thus, the magnetic images under the condition of external fields yield valuable information of the junction conditions and how much superconductive coupling of junctions exists.

4. Summary

We have reported the observation of magnetic distributions around the ramp-edge JJs using SSM. The external magnetic field dependence of the trapped vortex at the JJ was investigated and was almost consistent with the modulation of the maximum Josephson current. A novel vortex trapped at the junction under a relatively large field is observable, which increases in quantized units as the external field is increased. It was also confirmed that the external field significantly influenced the Josephson vortex compared to a conventional vortex, indicating that slight changes of the environment magnetic fields generate the extra flux and is not good for the working of a Josephson device. At the typical RSJ-type JJs, slight penetrations of the flux were allowed, but did not completely penetrate like the cut off superconducting line, whereas magnetic distributions around the leaky junctions behaved like strip line, and broken junctions with no critical current behave as a cut off line under the same external field condition of ~10 µT. All results show that the magnetic field image reasonably reflects the properties of the superconducting junctions and provide us easy and useful information on the evaluation method of junctions and superconductivity of films with no lead line.
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