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Vortex states of $Bi_2Sr_2CaCu_2O_{8+y}$ with antidot array probed by *c*-axis transport measurements

Shuuichi Ooi*, Takashi Mochiku, Kazuto Hirata

National Institute for Materials Science, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan

Abstract

To study the vortex states in $Bi_2Sr_2CaCu_2O_{8+y}$ (Bi2212) high-T_c superconductor with periodic array of antidots, we have measured the *c*-axis critical current in a stack of the intrinsic Josephson junctions with a square lattice of antidots, which gives us information on the *c*-axis correlation of the pancake vortices. Without the antidot array, the *c*-axis critical current can probe the first-order vortex lattice melting transition. Additionally, a suppression of the critical current in the vicinity of zero magnetic field is found, which may be related to the instability of vortex lattice under the parallel current flow. With the square lattice of antidots, enhancements of the critical current due to the matching effect are observed in both the integer and fractional matching fields. By mapping the critical current on *H*-*T* diagram, the influence of the matching effect on the phase boundary of vortex solid and liquid is shown.

"Keywords: Matching effect; Antidot lattice; Vortex; Bi2212"

1. Introduction

While the fundamental properties on the vortex phases in high-T_c superconductors have been revealed by extensive researches in the last two decades, how to artificially control the vortex states and dynamics is an important next issue to understand the vortex matter deeply and recognize their potential for applications. Introduction of micro-fabricated pinning centers, i.e. antidots or magnetic dots, is one of the useful approaches for artificial modifications of vortex states, whose influence has been studied in films of conventional superconductors [1-3]. In the case of regular array of pinning centers like square, rectangular or triangular lattice, matching effects are normally observed as enhancements of vortex pinning in the integer multiples of H_1 in various experiments: vortex-flow resistance, critical current, magnetization and so on. Here, H_1 is the first matching field where the density of vortices coincides with that of pinning centers.

The influence of thermal fluctuation is more important in the vortex state of high-T_c superconductors. Due to the competition between vortex-vortex interaction, thermal fluctuation, and artificial pinning, we may expect new vortex behaviors which are different from those in conventional superconductors. Actually, we have studied the influence of periodic arrays of antidots in $Bi_2Sr_2CaCu_2O_{8+y}$ (Bi2212) high-T_c superconductor by applying the artificial fabrication techniques. The matching effect in the in-plane vortex-flow resistance was observed in the samples with equilateral triangular and square antidots arrays [4,5] and even with tiny surface structures [6] using Bi2212 single-crystal films,

* Corresponding author. Tel.: 81-29-859-2362; fax: +81-29-859-2301.
E-mail address: OOI.Shuuichi@nims.go.jp.

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which are prepared by a repeat of peeling to keep the quality of single crystals. Moreover, the diameter dependence of the matching effect was systematically studied in a Bi2212 sample which contains several antidot arrays of different antidot diameters [7]. Since the vortex state on periodic pinning potentials was probed only by the in-plane vortex-flow measurements in our case or the magneto-optical magnetization measurements [8] so far, we have performed the *c*-axis transport measurements using the intrinsic Josephson junction's (IJJ's) stacks, which can give us information on the correlations of the pancake vortices along the *c*-axis [9]. In this paper, we present the magnetic field dependence of the *c*-axis critical currents I_c in Bi2212 with a square lattice of antidots together with the results in the case of no antidot. While I_c is certainly able to catch the vortex lattice melting transition in the sample without antidots, it can also probe the enhancements of the *c*-axis coupling of the pancake vortices by the matching effect.

2. Experimental

High-quality single crystals of Bi2212 were grown by the traveling-solvent floating-zone technique [10]. To form the *s*-shape IJJ's stack (see the inset of Fig.1), the double-side etching process was employed [11]. First, a narrow slit was fabricated by focused ion beam (FIB) on the surface of bulk crystals. After the surface was glued on a MgO substrate using polyimide, the opposite surface of the crystal was repeatedly cleaved by adhesive tapes to make it a thin film of submicron thickness (300-500 nm). Following the deposition of thin Au layer (20 nm), the film was patterned for the 4-terminals resistance measurements by photolithography and Ar ion milling. The *s*-shape IJJ's stack is completed by the FIB milling of another slit. The antidot array was finally introduced using the FIB. The dose amount 2 nC/cm^2 of the beam used to make the through-holes corresponds to the milled thickness of 0.7 μm in our experimental condition. The main part of the fabricated sample is schematically drawn in the inset of Fig. 1. The pattern of antidot array is the square lattice of 1 μm lattice constant. The diameter of the antidot is about 200 nm. In DC resistance measurements with the current of 100 μA and the *I*-*V* measurements, the magnetic field was always applied perpendicular to the *ab*-plane.

3. Results and discussions

Temperature dependence of resistance in the sample before and after the introduction of the antidots are shown in Fig.1, indicating a typical upturn behavior of the *c*-axis resistance in Bi2212. By the fabrication of the antidot lattice, resistance at room temperatures increases by 19 %, while the inverse of cross-sectional area increases only 3 % by the perforation. Since T_c is also suppressed by 2 K after the antidot fabrication, these might be a sign of change of doping level to the underdope side and/or weak degradation during the FIB milling. However, the sharpness of the superconducting transition is a support of fine sample quality.

First, we investigated the vortex states by the *c*-axis critical current I_c measurements before the introduction of antidots for comparison. Figure 2(a) shows I_c as a function of magnetic field H at 65 K. Two characteristic features are found: an reduction of I_c above 65 Oe, and a dip structure in 10-20 Oe. The reduction of I_c is corresponding to the first

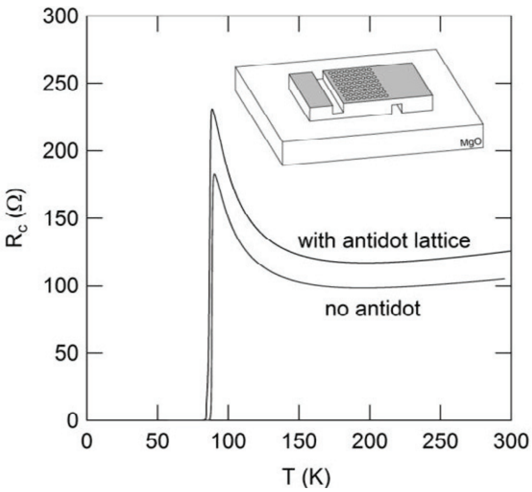

Fig. 1. Temperature dependence of *c*-axis resistance before and after the introduction of antidot lattice. The inset is a schematic drawing of a fabricated sample with a square lattice of antidots for *c*-axis transport measurements.

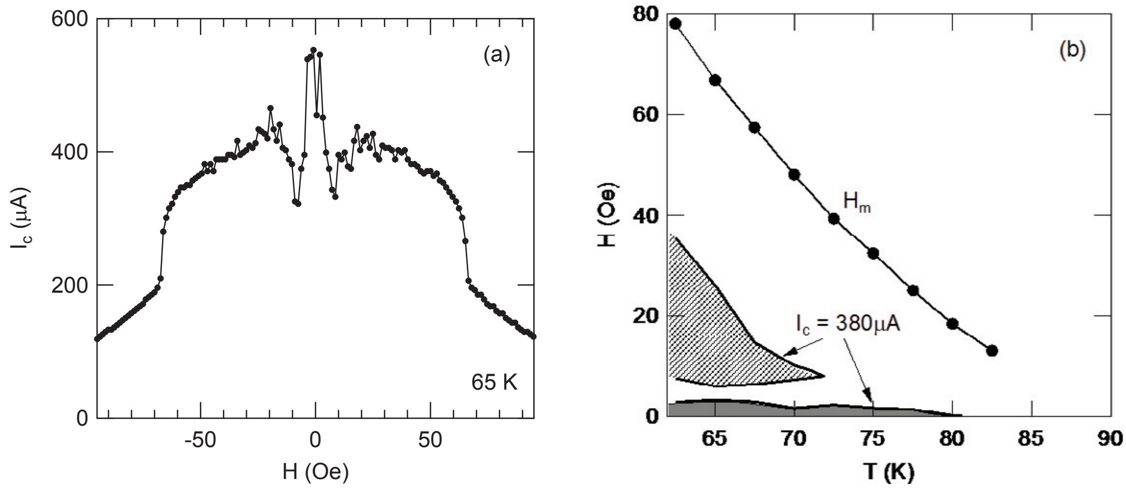

Fig. 2. (a) Magnetic field dependence of the critical current in the sample before antidot introduction at 65 K. The voltage criterion for the determination of I_c is 200 μV. (b) *H-T* diagram constructed form the results of I_c-*H*. The solid circles show the field of sharp enhancements of I_c, indicating the vortex lattice melting transition. The hatched and shadow areas mean higher I_c area than 380 μA. The shadow area lying on the zero-field line is corresponding to the central peak in I_c-*H*. There is a gap between the two areas, where I_c is relatively suppressed.

order melting transition of the vortex lattice, which reproduces the our previous results [9]. This indicates the ability of *c*-axis transport measurements as a sensitive probe of vortex states. On the other hand, the dip structure has not been reported explicitly, but is often observed in our experiments. Actually, the similar feature can be also seen in our reported data [9]. To demonstrate the vortex phase diagram of Bi2212 without the antidot array, the melting transition field $H_m(T)$ and the contour lines for I_c=380 μA are plotted in Fig.2(b). The dip structures are observed in a gap region between the hatched and shadow area in the phase diagram. As discussed in our paper [9], the vortex state under the current parallel to the direction of vortex line is modified because of the enhancement of fluctuation. Savel'ev *et al*. has theoretically predicted a reentrance of the melting transition in the vicinity of the zero field for the vortex state in Bi2212 [12]. In the proposed vortex phase, the region of the low-field vortex liquid locates at very similar position to the low-I_c gap of Fig.2(b). The observed dip structures of I_c might have a relation with the enhancement of vortex fluctuation by the parallel current.

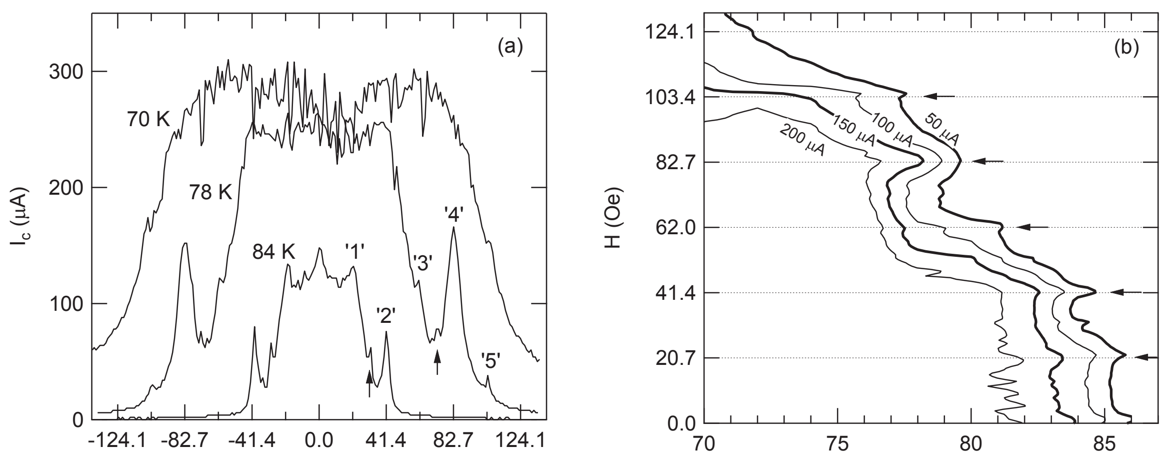

Fig.3. (a) Magnetic field dependence of the critical current in the sample after the antidot introduction at 70, 78, and 84 K. The voltage criterion for the determination of I_c is 200 μV. Labels on the peaks mean the number n of the integer matching field $n{\cdot}H_1$. Arrows indicate the peaks of I_c by the fractional matching effect of 3/2 and 7/2. (b) *H-T* diagram constructed form the results of I_c-*H*. The contour lines for the *c*-axis critical currents of 50, 100, 150, and 200 μA are drawn, where the bold lines are of 50 and 150 μA. The arrows indicate the peaks by the integer matching effect.

Next, we evaluated I_c using the same sample after the introduction of the square array of antidots. The magnetic field dependence at 70, 78, and 84 K is shown in Fig.3 (a). The peaks of I_c appear in the integer and fractional matching fields as indicated in the figure. These peaks mean that the *c*-axis coupling of the pancake vortices are strengthened in the matching field, suggesting that more vortices tend to align along the *c*-axis direction. As there is no clear step or jump of I_c like that observed in no antidot sample, it is difficult to determine the phase boundary of the pinned vortex solid and liquid phases surely. Another point which makes harder to probe the vortex states is existence of a plateau around the zero field in contrast to Fig.2(a) of the no antidot sample. In the plateau region, there is almost no structure depending on the magnetic field. The *c*-axis transport properties may not reflect the vortex alignments in this region anymore, probably caused by the suppression of the maximum I_c inherent to the junctions during the introduction of the antidot lattice.

However, it is possible to roughly know the behavior of the phase boundary between the vortex solid and liquid by drawing the contour map of I_c in *H-T* diagram using some current levels which enable to detect the melting transition. In no antidot case, the current level of 200 to 300 μA separates the two phases as shown in Fig.2(a). Figure 3(b) is the contour lines from 50 to 200 μA plotted in *H-T* diagram. There are peak structures in the contour lines pointed by the arrows, indicating the stabilization of the solid phase by the integer matching effect. Interestingly, the appearance of the peaks is different in each matching number. For instance, the temperatures at the peaks irregularly drop from second to third one, especially in the high I_c contour lines. This irregularity of the matching effect probably relates to the antidot diameter, which has been observed in our previous experiment used the in-plane vortex-flow resistance [7]. Further improvement of sample fabrications toward less damage enables us to approach the detail structure of vortex phases in the Bi2212 with antidot lattices.

In conclusion, we have measured the *c*-axis critical current in a stack of the intrinsic Josephson junctions with a square lattice of antidots to study the *c*-axis correlation of the pancake vortices and the phase boundary in Bi2212 high-T_c superconductor with periodic pinning potentials. Without the antidot array, the *c*-axis critical current fairly probes the first-order vortex lattice melting transition and additionally shows a suppression of the critical current in the vicinity of zero magnetic field, which may be related to the instability of vortex lattice under the parallel current flow. With the antidot array, enhancements of the critical current due to the matching effect are observed in both the integer and fractional matching fields. There is an irregularity in the appearance of the matching effects in *H-T* diagram, roughly constructed by mapping of the *c*-axis critical current.

Acknowledgements

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