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Vortex states in a submicron Bi2212 crystal probed by intrinsic Josephson junctions

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Abstract. To study the pancake-vortex states confined in a submicron Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ (Bi2212) crystal, we have measured the $c$-axis resistance and $I$-$V$ characteristics of a stack of intrinsic Josephson junctions with a lateral dimension less than 1 µm. Although the stack was accidentally shunted by a parallel resistance of 7.5 kΩ, the $I$-$V$ characteristics show homogeneous multiple branches after the subtraction of the component. The penetrations of single vortices into the submicron stack were clearly observed in the resistance measurements. A vortex phase diagram was constructed by mapping the $c$-axis resistance on an $H$-$T$ plane. Temperature dependence of the first-vortex penetration field is consistent with the theoretical estimation on the formation of a pancake-vortex stack in the center of a superconducting strip.

1. Introduction

With reducing the size of a small object, the increase of the surface-to-volume ratio and/or a smaller number of elements constituting the object influence their physical properties including thermodynamic ones [1]. This can be also expected in vortex matter confined in sufficiently smaller high-$T_c$ superconductors. While past extensive studies revealed very rich pancake-vortex states and phase transitions in bulk high-$T_c$ superconductors [2, 3], it has attracted interest how the vortex states and dynamical properties, such as penetrations and exits of vortices, are modified by the reduction of sample sizes. Actually, this subject was studied especially in Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ (Bi2212) in a field perpendicular to the superconducting planes [4–8]. However, these observations were limited in small Bi2212 crystals down to 10 - 20 µm, probably because of the field sensitivity and/or the spatial resolution of the measurements using magnetic detection techniques, e.g., micro-Hall-sensor, magneto-optical imaging or Bitter decoration.

On the other hand, $c$-axis electrical transport measurements using a stack of intrinsic Josephson junctions (IJJs) give us an alternative mean to detect the vortex states [9–12]. In samples with several tens micron, a melting transition of vortex lattice has been observed as a resistive jump of the $c$-axis resistance $R_c$ and as an anomaly in the $c$-axis critical current $I_c$ in stacks of IJJs [10]. Moreover, the penetrations of individual vortices were found by $R_c$ measurement in smaller stacks with an in-plane area of 1.2 to 100 µm$^2$ [11,13]. To check applicability of the vortex-detection method using IJJs for much smaller Bi2212 and to explore vortex states in such samples, we have investigated a submicron-sized stack of IJJs fabricated by a focused ion beam(FIB) in present study. In this proceeding, we report successful detection...
Figure 1. (a) Temperature dependence of $c$-axis resistance in a submicron stack (0.75×0.75 μm$^2$) of IJJs with cross-type Bi2212 electrodes. The inset schematically shows a configuration of the measured stack and the electrodes. The central part between the crossed electrodes, indicated by red, is the stack of IJJs. (b) The same data as (a) on a semi-logarithmic scale, in which a tail of resistance is manifested below $T_c$. The solid straight line is a fitting line (see text). The inset is a SIM image of the submicron stack (top view).

of the penetrations and exits of individual vortices by $R_c$ measurements and the temperature dependence of the first-vortex penetration field $H_{p1}$ in the submicron stack of Bi2212.

2. Experimental

High-quality single crystals of Bi2212 were grown by the traveling-solvent floating-zone method [14]. In present study, we employed a cross-type structure of Bi2212 containing a stack of IJJs in the center (see the inset of Fig. 1(a)). In this structure, both current and voltage electrodes are directly attached on the stack so as to only measure the $c$-axis resistance of the stack without any series in-plane resistance. Our fabrication process is similar to the method used to fabricate whiskers by Latyshev, et al. [15], in which narrow grooves were fabricated on the top and bottom surfaces by a flipping of whiskers using FIB. Only the difference from their process is that we used a thin flake of single crystal instead of the whiskers. A scanning-ion-microscope (SIM) image of a fabricated sample is shown in the inset of Fig. 1(b). The lateral dimension of the square stack is ~0.75μm and the thickness is ~30nm, estimated from the number of branches in $I$-$V$ characteristics. Transport measurements were performed using the four-probes technique with a current source (Keithley 6430) and a nanovoltmeter (Keithley 2182) in a chamber with a cryocooler. Magnetic fields were applied parallel to the $c$ axis of Bi2212. Data of the $c$-axis resistance were acquired in field-scans from negative to positive at various fixed temperatures.

3. Results and discussion

Temperature dependence of $R_c$ for the fabricated submicron stack is shown in Fig. 1(a) and (b). Upturn of $R_c$, a typical feature on the $c$-axis resistance of Bi2212, is observed above the superconducting transition temperature $T_c$. Although, even in this tiny stack, the superconducting transition accompanies rather sharp drop of the resistance as shown in Fig. 1(a),
there remains a broad resistive tail below $T_c$ which is clarified in Fig. 1(b) of a semi-logarithmic plot, where the tail is well-fitted by a line of $R_c \propto \exp(\alpha T)$. The resistance on the tail does not depend on magnetic fields unless there are no vortices in the stack. Probably, the resistive tail is related to a thermally-activated phase fluctuation, because the Josephson coupling energy $I_c \Phi_0/2\pi$ ($\Phi_0$ is the flux quantum) is comparable with the thermal energy $k_B T$ in this temperature range for this sample.

Figure 2(a) shows $I$-$V$ characteristics of the submicron stack at 5.5 K in a zero field. Although it seems that $I_c$ of IJJs is inhomogeneous, this is because of a shunt resistance $R_{\text{shunt}}$ which may be accidentally introduced during the fabrication. After the correction on the current axis to subtract the contribution of $R_{\text{shunt}}$, i.e., $I - V/R_{\text{shunt}}$, we obtain $I$-$V$ characteristics with quite uniform multiple branches as shown in Fig. 2(b). The number of the branches is 21 and the branches have uniform value of $I_c \sim 30 \mu\text{A}$, corresponding to a critical current density $J_c \sim 4700 \text{ A/cm}^2$, indicating this stack is in the overdoped regime. This high value of $J_c$ prevents the suppression of $J_c$ itself from the thermal fluctuation even in the tiny submicron stack of IJJs. More increase of the doping level of Bi2212, i.e., increase of $I_c$, is a route to realize much smaller stacks of IJJs without the suppression of $J_c$, which would be useful to study vortex state confined in a Bi2212 crystal of 100-nm or less size.

Vortex states in the submicron Bi2212 are studied by magnetic field dependence of $R_c$ at a fixed temperature. A representative example of $R$-$H$ curve is shown in Fig. 3(a). Around the zero field there is a small offset resistance which is equivalent to the resistance tail observed in $R$-$T$. The periodic peaks appeared above 100 Oe indicate the vorticity change, i.e., the penetration or exit of an individual vortex [12, 13]. For instance, the field interval of the neighboring third and fourth peaks from the zero field is 43 Oe, corresponding to the magnetic field to add $\Phi_0$ in an area of 0.69 $\mu\text{m}^2$. Although this is a little smaller value than the fabricated sample dimension, estimated sizes of samples are usually smaller than actual ones, probably because of the existence of a screening current and a thin region around the edges damaged by FIB [13]. To unveil the whole features of the vortex phase diagram, we map log $R_c$ on a $H$-$T$ plane as shown in Fig. 3(b). The regions with a different vorticity are well separated, so that it is easy to distinguish
Figure 3. (a) c-axis resistance of the submicron stack as a function of magnetic field at 79.4 K with an applied current of 100 nA. Sharp resistance peaks emerge when an individual vortex penetrates or exits from the stack. (b) Mapping of $\log R_c$ on a $H$-$T$ plane, indicating a vortex phase diagram in the submicron squared Bi2212. The fields of the resistance peak corresponding to the first-vortex penetration fields $H_{p1}$ are marked by the red circles. The red curve shows a fitting curve of Eq. (1) for the field where fast pancake-vortex stack formation starts in the center of a superconducting strip.

the number of vortex at a certain point on the map, especially at higher temperatures than 60 K. Below ~60 K, appearance of the $\log R_c$ map is asymmetric with respect to the $H = 0$ line, which means hysteretic and irreversible behavior regarding the vortex penetrations and exits at the low temperatures. This is caused by the Bean-Livingston surface barrier and/or the pinning by quenched disorder whose influence becomes stronger at lower temperatures [2].

In the reversible region, the first-vortex penetration fields $H_{p1}$ are well-defined in the map, which are marked by red circles. $H_{p1}$ rapidly drops in the vicinity of $T_c$ with increasing temperature. This temperature dependence is consistent with the theoretical analysis for the stability of pancake vortices. The field where a stack of pancake vortices is formed in the center of a strip-shaped layered superconductor with a width $w$ has been evaluated as

$$H_{s1} \approx \frac{\Phi_0}{4\pi\lambda^2} \left[ \ln \left( \frac{w}{\pi\xi} \right) + 0.5 \right] \frac{\cosh(w/2\lambda)}{\cosh(w/2\lambda) - 1}, \quad (1)$$

here $\lambda$ and $\xi$ are the penetration depth and the superconducting coherence length, respectively [16]. As shown in Fig. 3(b), the temperature dependence of $H_{p1}$ is nicely fitted by Eq. (1) with fixed parameters of $T_c = 88.0$ K and $\lambda/\xi = 100$, and a temperature dependence $(1 - T/T_c)^{-1/2}$ for $\lambda$ and $\xi$. Obtained fitting parameters are $w = 0.65 \mu$m and $\lambda = 0.23 \mu$m, both of which are quite reasonable values in spite of the difference of sample shapes (square and strip).
4. Summary
We have studied the pancake-vortex states confined in a submicron-sized Bi2212 single crystal by the \(c\)-axis electrical transport measurements using a square stack of IJJs with a lateral dimension of 0.75 \(\mu m\). After the correction of the contribution from the parallel resistance, which was accidentally introduced during the fabrication, the \(I-V\) characteristics shows homogeneous multiple branches. The penetrations(exits) of individual vortices into(from) the submicron stack were clearly observed in \(R_c-H\) measurements. The vortex phase diagram constructed by a mapping log\(R_c\) on an \(H-T\) plane shows a reversible feature for the penetrations of vortices above 60-70 K. The temperature dependence of the first-vortex penetration field is consistent with the theoretical estimation on the formation of a pancake-vortex stack in the center of a superconducting strip.

Acknowledgements
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