Josephson lattice structure in mesoscopic intrinsic Josephson junctions by means of flux-flow resistance in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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Dynamical nature of the Josephson vortex (JV) system in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) has been investigated in the presence of the c-axis current with magnetic field alignments very close to the ab-plane. As a function of magnetic fields, the c-axis JV flux flow resistance oscillates periodically in accordance with the proposed JV triangular structure. We observe that this oscillating period becomes doubled above a certain field, indicating the structure transition from triangle to square structure. This transition field becomes lower in junctions with smaller width perpendicular to the external field. We interpret that this phenomena as the effect of the edge deformation of the JV lattice due to surface current of intrinsic Josephson junctions as pointed by Koshelev.

I. INTRODUCTION

Highly anisotropic high-$T_c$ superconductors such as Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ are well described as stacks of weakly coupled Josephson junctions, where charge coupling between CuO$_2$ double-layers is not negligible. This characteristic feature is responsible for properties of so-called intrinsic Josephson junctions (IJJ) like multiple branches in current-voltage characteristics and longitudinal Josephson plasma modes. Appearance of various vortex phases under the c-axis field indeed manifests the weak coupling between the layers.

In the magnetic field parallel to the ab plane ($\perp$ c axis), the situation becomes different because of inductive coupling between Josephson vortices generated by the parallel magnetic fields. In high fields above $\gtrsim$ 1 T, Josephson vortices occupy all block layers and form the Josephson vortex lattice which demonstrates the strong interaction between vortex arrays in the neighboring layers. This is the one of the most striking difference of Josephson vortices in IJJ from ones in isolated single Josephson junctions. Furthermore, many characteristic features of Josephson vortex state in parallel magnetic fields have been found in the I–V characteristics, the Josephson plasma resonance, and the vortex phase diagram.

Recently, Ooi et al. found periodic oscillation of the Josephson vortex flow resistance in small Bi2212 single crystal as a function of magnetic field. They claimed occurrence of the coherent flow of the triangular Josephson vortex lattice. Subsequently, Koshelev and Machida have reproduced the oscillation by calculating the flux flow resistance by taking the surface barrier effect into consideration. This means that the surface barrier is not so strong to destroy the bulk properties of the Josephson vortices, where it prefers to form the triangular lattice even in the vicinity of sample edges. This is in contrast to the vortex state in fields parallel to the c axis where vortex arrangements in the vicinity of sample edges are dominated by the surface barrier effect.

In this paper, we present experimental results of the Josephson vortex flow resistance in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ micro-structured crystals with dimensions of 1–10 $\mu$m. In the smaller samples and at higher fields, we have found periodic oscillation of the Josephson vortex flow resistance. This indicates that the square vortex lattice is realized. This experimental observation is attributed to the effect of the surface barrier, which becomes dominant in smaller samples and overcomes the bulk properties in the short stack regime.

II. RESULTS AND DISCUSSIONS

We made in-line symmetric junctions to avoid various contact problems accompanied by the transport measurements of intrinsic junctions. Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals were grown by the travelling solvent floating zone method. A cleaved thin ($\sim$ 10 $\mu$m) crystal was carefully cut into narrow strips with a width of $\sim$ 100 $\mu$m by a sharp knife. The narrow strip was put on a MgO substrate with four gold electrodes which were patterned by a vacuum deposition with a mask and the center of the strip was shaped into mesoscopic junctions as shown in the inset of Fig. 1 with the focused ion beam (FIB) machine SMI2050MS (SII NanoTechnology Inc.). We made junctions from eight different crystals from A to H and FIB processes were repeated three times in crystal H after measurements, resulting in eleven samples in total with different dimensions as listed in Table I.

By applying the c axis current between two current electrodes, the current is concentrated into small junction area only. The voltage between the voltage electrodes comes from only the small junction area because the other parts of the sample still remain in the superconducting state. The temperature dependence of resistivity of a junction is shown in Fig. 1 in which a clear superconducting transition and zero resistance below $T_c$ are obtained. External magnetic fields were applied by the split pair superconducting magnet which can generates horizontal magnetic field up to 80 kOe. Rotating magnetic field around the ab-plane with a precise rotator, the c-axis resistance suddenly increases in the vicinity of the ab-plane as shown in the inset of Fig. 1. This resistance is attributed to the Josephson vortex flow resistance and...
the lock-in state without pancake vortices is realized in this angle range. We can set the field alignment parallel to the $ab$-plane with an accuracy of 0.01 degree.

Table I: List of samples which we measured. Numbers following capital letters refer to sizes of junctions perpendicular to the magnetic field and the $c$-axis.

| $w$ [$\mu$m] | $l$ [$\mu$m] | $t$ [$\mu$m] | $T_c$ [K] |
|--------------|--------------|-------------|-----------|
| A94          | 9.4          | 10.3        | 0.3       | 86.6      |
| B19          | 1.9          | 11.7        | 0.5       | 90.0      |
| C22          | 2.2          | 8.9         | 0.14      | 83.6      |
| D49          | 4.9          | 17.8        | 0.08      | 88.2      |
| E44          | 4.4          | 9.5         | 0.15      | 84.7      |
| F18          | 1.8          | 9.9         | 1.14      | 87.2      |
| G20          | 2.0          | 10.2        | 0.9       | 84.3      |
| H41          | 4.1          | 5.5         | 2.0       | 86.9      |
| H55          | 5.5          | 4.1         | 2.0       | 86.9      |
| H38          | 3.8          | 5.5         | 2.0       | 86.9      |
| H30          | 3.0          | 5.5         | 2.0       | 86.9      |
| H23          | 2.3          | 5.5         | 2.0       | 86.9      |

Figure 2(a) represents field dependence of the $c$-axis resistance $R_c$ at 60 K in H55. External field was applied parallel to the $ab$-plane and swept up to 50 kOe with a constant $c$-axis current (1 $\mu$A) at a constant temperature. With increasing field from zero, the resistance smoothly increases up to 8 kOe, then begins to oscillate with oscillation center being monotonically increasing. The oscillation period $H_p$ is constant up to 30 kOe, $H_p = 1.25$ kOe, and the amplitude is maximized around 25 kOe, above which the oscillation gradually diminishes with increasing field. However above 35 kOe, the other oscillation in resistivity with different $H_p$ develops and the oscillation of $H_p = 1.25$ kOe seems to disappear above 40 kOe.

$H_p$ below 30 kOe is very close to the field, which corresponds to add a half flux quantum $\phi_0/2$ to a JY array in a Bi2212 block layer as $H_0/2 = \phi_0/2ws = 1.25$ kOe for H55, where $s = 15$Å is the periodicity of CuO$_2$ double layers of Bi2212. This oscillation is quite similar to the previous results observed by Ooi et al. where they argued that this is due to surface barrier effect for JVs forming the triangular lattice. The surface barrier for the triangular JV lattice is considered to be enhanced when the number of JVs in a layer ($H/H_0$) corresponds either an integer or a half odd integer because the periodicity of the JV lattice matches with the junction width for both two cases. These two matching result in the oscillation having period of $H_0/2$ and the bottom at $H/H_0$ being half integers.

$H_p$ above 40 kOe was found to be 2.49 kOe, which is twice as the period below 30 kOe and very close to the $H_0$ value of 2.50 kOe. With increasing field in transient region from the $H_0/2$ oscillation to the $H_0$ oscillation, the amplitude of $H_0/2$ oscillation diminishes and the amplitude of the $H_0$ oscillation develops, resulting in the oscillation amplitude is larger than one of the $H_0/2$ oscillation. The $H_0$ oscillation starts at lower fields in samples with smaller width as shown in Fig. 2(b) where $H_0/2$ oscillation is hardly seen even at the lowest field, while in the largest sample A94 $H_0/2$ oscillation was observed up to the maximum field range. We now understand that the $H_0/2$ oscillating behavior observed by the previous measurement by OOi et al. is due to the large sample width of more than 20 microns.

Critical current density $J_c$ as a function of $H ||$ of H41 is shown in Fig. 3 which is extracted from $I - V$ characteristics at various $H ||$ with a criterion of $V = 1$ mV. One finds that $J_c(H)$ below 35 kOe oscillates with period of $H_0/2$ and has a local maxima at $H/H_0$ being half integers, whereas $J_c(H)$ above 42 kOe shows oscillation with the period being $H_0$ and local maxima at $H/H_0$ being half odd integers. Magnetic field dependence of $J_c$ similar to our results in low fields has been expected theoretically by taking boundary deformation of JV lattice into consideration. Also, $J_c(H)$ in high fields is similar to magnetic field dependence of $J_p$ in single Josephson junctions in a sense that the points where the magnetic flux inside the junction equals to the half odd integer flux quanta corresponds to the local maxima of the critical current. The Fraunhofer-like oscillation of $J_c(H)$ is interpreted that the Josephson vortices form a square
lattice where all layers are identical to edges.

Such a Fraunhofer oscillation in $J_c(H)$ of multilayered system like Bi2212 has been expected when the condition $w \ll \lambda_J \equiv \gamma s$ is satisfied. However, $\lambda_J$ is estimated to be in a range from 0.075 to 1.5 $\mu$m for slightly over-doped Bi2212, which is much smaller than $w$ of this sample. This discrepancy seems to occur due to inhomogeneity of the current, which is more realistic in the real specimens of high-$T_c$ superconductors. It is known that the Bean-Livingstone surface barrier is pronounced in high-$T_c$ superconductors, so that vortices prefer to stay at the edge of the sample. This boundary effect can also explain $H_0/2$ oscillation in $J_c(H)$ as discussed by Koshelev.

The boundary effect for the JV lattice should be more pronounced in smaller junctions because the number of vortices at both ends of vortex arrays inside a layer (usually two), which are most seriously affected by the boundary effect in smaller junctions has a greater ratio to the number of total vortices of the array than in the case of larger samples at constant fields. Consider a Josephson junction with two JVs as an extreme case. In $\rho - H$ curve as shown in Figs. 2(a) and (b), we define threshold field $H_{th}$ above which local minima in the vicinity of $H/H_0$ being an integer cannot be resolved (indicated by arrows in the figure). It was found that $H_{th}$ is lower in samples with smaller $w$ from $\rho - H$ curves in samples with various $w$ as plotted in Fig. 2(c). These results suggest that the square JV lattice is more favorable for smaller junctions and higher fields.

Now, let us consider how vortices inside the junctions interact with edges and each other in transition from triangular lattice to square lattice. At low fields (although high enough to form dense lattice), the JV system is dominated by the interaction between vortices in adjacent layers because the separation between JVs inside a layer is too far to convey the boundary deformation to all vortices in the layer. With increasing magnetic field, vortices inside the layer become closer and closer while the separation between layers does not change and the boundary effect becomes stronger and stronger because JVs are more closely packed in the layer. The JV system is finally dominated by the boundary effect and turns to the square lattice in high field region at the cost of inductive coupling between layers. The inductive coupling is weaker in a smaller junction because the total number of vortices in a layer is fewer, resulting in the transition from triangle to square at lower fields.
According to theoretical calculation by Koshelev, JVs with their center being closer to both edges than the lattice deformation length \( l_B = \gamma s (\pi \gamma s^2 B/\sqrt{2} \phi_0) \) deviate from positions extrapolated from the bulk region assuming an undeformed lattice. Here \( \gamma \) and \( B \) are the anisotropy parameter and induced flux density in the sample, respectively. This means Josephson vortices inside samples with \( w < 2l_B \) may not form the triangular lattice, so that the surface barrier effect dominates the system is written as a function of \( w \),

\[
H_{th} = \frac{w \phi_0}{\gamma s 2 \pi \gamma s^2}.
\]

Equation (1)

A thick line in Fig. 2 (c) corresponds to Eq. (1) with \( \gamma = 110 \). The agreement is rather good and the value of the obtained \( \gamma \) is reasonable for slightly over-doped Bi2212.

III. CONCLUSION

We have investigated Josephson vortex lattice structure in mesoscopic (~ µm) intrinsic junctions with the probe of the JV flow resistance along the c axis. For the small \( (w < 6 \mu m) \) mesas, the JV lattice is found to change the structure from triangular to square lattice with increasing fields in low current limits. Transition field from the triangular to square lattice monotonically increases with \( w \). This is attributed to the interplay between the surface barrier effect and the inductive coupling between Josephson vortex arrays in intrinsic Josephson junctions.

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