Josephson vortex flow and pinning probed by c-axis transport measurements

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Abstract

Measurements on current-voltage ($I-V$) characteristics along the c-axis of $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals have been performed as functions of temperature and magnetic field parallel to the ab-plane in order to investigate dynamics of the Josephson vortex (JV) system. Two JV states, one in which JVs are pinned and the other in which JVs are flowing parallel to the ab-plane, were found in $I-V$ characteristics. The threshold current between the pinned and the flowing states shows a peak effect slightly below T_c. This phenomenon cannot be explained with random pinning of JVs.

Key words: Josephson vortex; Intrinsic Josephson junctions; Flux flow resistance; Peak effect

Nature of the Josephson vortex (JV) system which is realized under magnetic fields parallel to the superconducting layers of intrinsic Josephson junctions (IJJ) such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) has been attracting much attention very recently [1,2]. The c-axis transport properties of BSCCO single crystals are determined by dynamics of the JV system because JVs are considered to move along the layers by DC currents parallel to the c-axis. When the JVs flow coherently over the stacking layers and its velocity matches the Josephson plasma (JP) wave velocity, strong emission of an electromagnetic wave is expected [3]. This is very important not only for high-frequency applications of IJJ but also for understanding non-linear dynamics of Josephson junctions.

We have investigated the JP resonance of BSCCO in the presence of JV lattices. As a result, two collective modes were found: one at higher frequency is clearly explained by the transverse JP mode the other would be attributed to the vortex oscillation mode [4]. The vortex mode is considerably higher than theories based on the ideal single junction model, where the gapless excitation is expected [5]. This discrepancy can be interpreted due to stacking effects of IJJ and pinning effects of JVs. In order to study the interaction between JVs and JP and the emission of millimeter-wavelength electromagnetic waves, it is important to reveal features of JV pinning and flowing. Moving JVs create voltage along the junction proportional to magnetic field and velocity of vortices [6]. Since the JV flow voltage is inversely proportional to the viscously of JV system, the temperature and field dependence of the JV flow resistance can be a powerful probe to investigate the JV phase diagram.

For current-voltage ($I-V$) measurements we prepared BSCCO mesas with dimension of $100 \times 100\ \mu m^2$ across and 0.1 μm height fabricated on the ab-surface of BSCCO single crystal by a focused ion beam (FIB) etching. $I-V$ characteristics were measured in a two-terminal configuration with a spring contact of 25 μm Au/Ni wire touching to a gold pad evaporated onto the freshly cleaved surface in advance of the FIB etching. The external magnetic field alignment parallel to the ab-plane was decided from the symmetry of angular dependence of the c-axis resistance at given field intensities. The experimental details will be described

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elsewhere.

Figure 1 represents $I-V$ curves at 40 K for various fields up to 3 T. In zero magnetic field, the $I-V$ curve shows large hysteresis and multi-branch structure, in which n-th branch means $n-1$ junctions are switched to the gap state. Many branches were found in the experiment by carefully sweeping current up and down with changing the maximum value. The magnetic field decreases the slope of the lowest branch where all junctions are superconducting, and the hysteresis is almost vanished at 3 T. This resistivity increase is explained by flux flow resistance of JVs, which is thought to be proportional to the number of JVs. In angular dependence of the resistance at a constant c-axis current, mesa-like JV flow resistance profile similar to Fig. 3 in Ref. [7] was obtained.

In the $I-V$ characteristics at finite fields, four current regions corresponding to the voltage behaviors were found: I) zero resistance, II) single branch with finite resistance III) multiple voltage branch, and IV) normal regions. At 1.2 T for instance, I, II, and III correspond to ranges up to 0.5, 4, and 7 mA, respectively. In an ideal JV system, region I may not be realized in finite fields because the JV sliding mode is gapless. Therefore it is natural to be interpreted that JVs are pinned by some reasons in region I then dragged by the c-axis current in regions II and III.

To investigate the origin of the pinning of JVs, we measured temperature dependence of the flux flow resistance for various fields. 3D and contour plots of the flux flow resistance at 0.5 T are shown in Fig. 2. Dark and light blue regions correspond to regions I and II, respectively. The flux flow resistance does not depend on the c-axis current in each region, suggesting that the JV pinning in region I and JV flow with a constant viscosity in region II are realized. Moreover, temperature expands region I between 40 and 75 K then rapidly reduces towards $T_c = 88$ K. In other words, the JV pinning shows a peak effect with the maximum at 75 K at $H = 0.5$ T. If the pinning is attributed to either crystalline dislocations or defects, the pinning is reduced monotonically as a function of temperature as well as the irreversibility line in the c-axis fields. Another pinning mechanisms such as the crossed lattice [1] are required to solve this peak effect.

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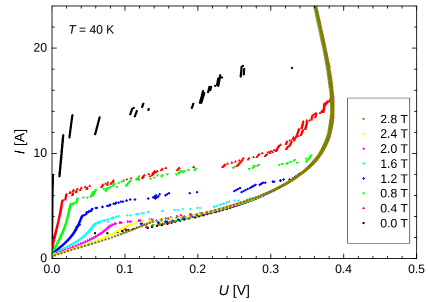

Fig. 1. $I-V$ characteristics at various magnetic fields parallel to the ab-plane at 40 K. Contact resistance is subtracted.

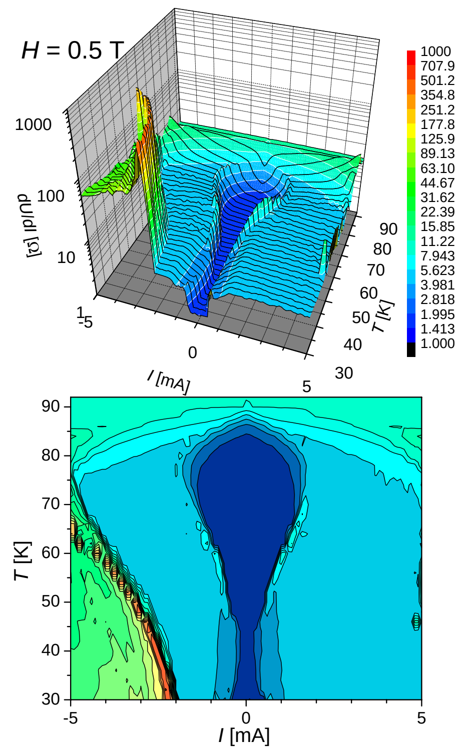

Fig. 2. 3D (upper panel) and contour (lower panel) plots of differential resistivity as functions of current and temperature. The boundary between the pinned (dark blue) and the flowing (light blue) states shows peak effect at 75 K.

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