Suppression of Surface Barriers in Single Crystals of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ by In-plane Magnetic Fields

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Abstract

The non-linear behavior of the in-plane resistivity in the vortex liquid phase is observed in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals, in magnetic fields applied along the c-axis, for samples which favor surface barriers. However, in tilted magnetic fields, it was found that in-plane magnetic field component strongly suppresses the non-Ohmic behavior of resistivity, which may indicate the suppression of the surface barrier effect.

Key words: surface barriers, Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$, resistivity, vortex dynamics

The first-order vortex lattice melting phase transition (hereafter VLMT) [1] in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals occurs at low resistivity level $R_{\text{melt}}$ [2], several orders of magnitude below the resistivity in the normal state $R_N$, and may be considered the boundary line of the true superconducting phase. However, the in-plane resistivity measured in the vortex-liquid phase in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ exhibited, surprisingly, the non-Ohmic behavior [3,4] well above the VLMT, in strong contrast to YBa$_2$Cu$_3$O$_{7-\delta}$. Tsuboi et al. [5] attributed the observed non-linear behavior of resistivity to the plastic deformation and viscosity effects in the vortex liquid phase [6]. However, some other groups [3,7] considered the non-linear c-axis resistivity as an indication that VLMT is the two-stage, melting-decoupling transition. On the other hand, Fuchs et al. [8] claimed that the transport properties in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals are governed mainly by the surface barriers. Indeed, we found previously [9] that in magnetic fields applied along the c-axis, the nonlinear behavior persists well above the VLMT in the platelet samples, while the Ohmic response of resistance is observed as soon as the surface barriers are avoided.

In order to understand more clearly the role of the surface barrier effect on transport properties in the vortex liquid phase, we performed the in-plane resistivity measurements on three as grown single crystals of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ [10] in magnetic fields titled away from the c-axis. The sample #S1 ($T_c = 83.5$ K) was cut into typical platelet shape (0.9 × 3.4 × 0.022 mm$^3$) with electric contacts set close to the edges, which is favorable for the surface barrier effect. In the second crystal #S2 ($T_c = 89.5$ K, 2.6 × 3.4 × 0.022 mm$^3$) the electric contacts were positioned in the center of samples, so far from the edges (partly suppressed surface barriers). The third sample #S3 ($T_c = 89.6$ K) was the Corbino disc (diameter D = 1.9 mm and thickness t = 20 µm), where the Lorentz force is azimuthal and the vortices flow in concentric circles without crossing the edge i.e., so avoiding the surface barriers.

The resistance was measured by the conventional four probe ac method with lock-in technique at low frequency of 37 Hz. At a constant magnetic field, the temperature sweeps were carried out at a rate of 0.2 K/min. The magnetic field, of up to 60 kOe induced using a split superconducting coil, was rotated with angular resolution of 0.01°.
magnetic field. The inset in Fig. 1a demonstrates how the kink anomaly, associated with the onset of the non-linear behavior of resistivity, also quickly diminishes in the oblique magnetic field, while the resistance below the non-linear onset gradually increases with the in-plane magnetic field.

The similar behavior was observed in the platelet sample #S2, while the sample #S3 (Corbino disc) exhibited only the Ohmic response in the vortex liquid phase across practically the whole angular range $|\theta - 90^\circ| < 0.04^\circ$.

Some theoretical works [12,13] suggest that the vortex liquid phase is characterized by the finite line tension, and may transform into the zero-line tension vortex liquid well above the VLMT via the first or second-order phase transition in low or high magnetic fields, respectively. However, the in-plane magnetic field may also suppress the coupling of the three dimensional (3D) stack of vortices, changing its tension and transforming into the two dimensional (2D) vortex-pancakes phase. In such a scenario, where the surface barriers might be sensitive on the dimensionality of the probed vortex phases, i.e., it could be expected that surface barriers are more effective if the 3D vortex stack are probed than the decoupled vortex-pancakes.

In summary, it is found that the non-linear behavior of resistance in the vortex liquid phase, as well as the surface barriers, are strongly suppressed by the in-plane magnetic fields.

References