# Suppression of Surface Barriers in Single Crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ 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 $Bi_2Sr_2CaCu_2O_{8+\delta}$ 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, $Bi_2Sr_2CaCu_2O_{8+\delta}$, resistivity, vortex dynamics

The first-order vortex lattice melting phase transition (hereafter VLMT) [1] in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals occurs at low resistivity level $R_{\rm melt}$ [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 $Bi_2Sr_2CaCu_2O_{8+\delta}$ exhibited, surprisingly, the non-Ohmic behavior [3,4] well above the VLMT, in strong contrast to $YBa_2Cu_3O_{7-\delta}$. 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 $Bi_2Sr_2CaCu_2O_{8+\delta}$ 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 $Bi_2Sr_2CaCu_2O_{8+\delta}$ [10] in magnetic fields titled away from the $c$-axis. The sample #S1 ($T_{c1}$ = 83.5 K)was cut into typical platelet shape ($0.9 \times 3.4 \times 0.022$ mm$^3$) with electric contacts set close to the edges, which is favorable for the surface barrier effect. In the second crystal #S2 ($T_{c2}$ = 89.5 K, $2.6 \times 3.4 \times 0.022$ 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 ($T_{c3}$ = 89.6 K) was the Corbino disc (diameter D = 1.9 mm and thickness t = 20 $\mu$m), 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 iduced using a split superconducting coil, was rotated with angular resolution of 0.01°.

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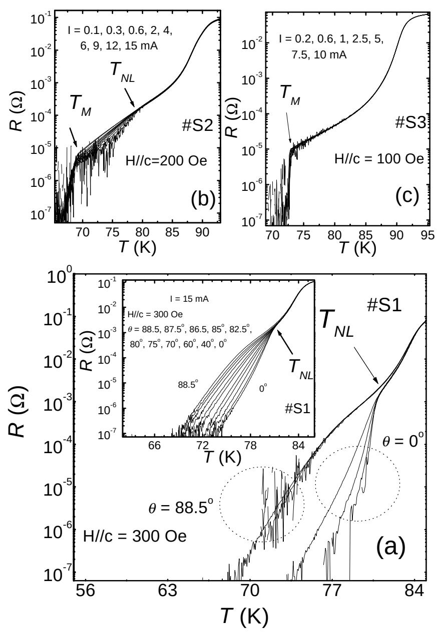


Fig. 1. (a) Temperature dependence of resistivity obtained at field orientation of $\theta = 0°$ ($c$-axis) and 88.5° on the sample #S1 with the constant out-of-plane field of 300 Oe was measured at current levels of 0.1, 0.3, 0.6, 3, 15 mA. Inset: $R$ versus $T$ at different angles with H $\parallel$ c = 300 Oe, with current of 15 mA. (b) and (c) show the $R(T)$ curves obtained for H $\parallel$ c on the samples #S2 and #S3 respectively. $T_M$ denotes the melting transition temperature, whereas $T_{NL}$ marks the non-linear resistance onset.

The main plot of Fig. 1(a) shows the set of resistance versus temperature curves measured on the sample #S1, with different current levels. At quite high levels of resistance, the curves obtained in the field parallel to the $c$-axis, demonstrate a clear resistance kink anomaly, followed by the non-linear response of the resistivity. The sharpness and intensity of the anomaly become weaker as the current is increased. On the other hand, the temperature where the resistivity kink occurs is surprisingly weakly affected by the driving force. It was found that the non-linear behavior of resistance becomes slightly less pronounced in high magnetic fields, but still quite strong in perpendicular magnetic fields higher than 10 kOe.

The resistance kink, associated with VLMT, vanished in the experimental noise in the sample #S1, while the samples #S2 and #S3, with suppressed surface barriers, exhibited the clear resistivity kink attributed to the VLMT (see Fig. 1b and c).

In the next stage, the resistance was measured in a magnetic field tilted away from the $c$-axis, at $\theta = 88.5°$ but with the same out-of-plane field component $H_c = 300$. It is clearly seen that the nonlinear behavior of resistance is suppressed by applying the higher in-plane 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 nonlinear 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 $|\theta - 90°| < 0.04°$ [11].

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.

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