Vortex Phases in Single Crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ Near ab-plane Studied by c-axis and In-plane Resistivity Measurements

Jovan Mirković [a,1], Sergey Savel'ev [b], Shin Hayama [a] Emiko Sugahara [a] Kazuo Kadowaki [a]

[a] *Institute of Materials Science, University of Tsukuba, Tsukuba 305-8573, Japan*

[b] *Frontier Research System, The Institute of Physical and Chemical Research (RIKEN), Saitama, Wako-shi 351-0198, Japan*

Abstract

The in-plane and out-of-plane resistivity measurements have probed the vortex lattice melting transition in the single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ indicating the crossing vortex lattice structure in the magnetic fields tilted away from the c-axis. In contrast to the in-plane resistivity measurements, the c-axis driving current strongly suppressed the melting transition accros the wide angular range. However, both the c-axis and the in-plane resistivity measurements demonstrated a clear distinct anomaly at $\theta \approx 89.8°$, suggesting the complex two-stage melting phase transition in parallel magnetic fields.

Key words: vortex melting transition, $Bi_2Sr_2CaCu_2O_{8+\delta}$, c-axis and in-plane resistivity, vortex dynamics

The vortex lattice melting transition (hereafter VLMT) in strongly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ superconductors has been studied intensively in the oblique magnetic fields recently [1–5], but the nature of phase transitions and the vortex phases near ab-plane remains controversial. According to the theory [6], the strong intrinsic pinning [7] captures vortices oriented along the ab-plane in-between CuO_2 layers, resulting in melting of the vortex-lattice into the vortex-smectic phase, which, in the second stage, melts into the vortex-liquid. Contrary, from the recent simulations [8], the only single phase transition in parallel magnetic fields is proposed - the second or the first-order phase transition in high or low magnetic fields respectively. Interestingly, it was found that the in-plane resistivity kink attributed to the VLMT in the $YBa_2Cu_3O_{7-\delta}$ crystals, [9] vanishes near the ab-plane, which was interpreted as the second-order vortex-lattice–vortex-smectic phase transition, while the out-of-plane resistivity measurements performed on $YBa_2Cu_3O_{7-\delta}$ [10] and $YBa_2Cu_4O_8$ [11], showed the VLMT kink even in the parallel magnetic fields.

In this paper, we report how different driving currents may probe and affect the melting transition in the magnetic fields, aligned very close to the ab-plane. The in-plane measurements were carried out on the as-grown single crystal of $Bi_2Sr_2CaCu_2O_{8+\delta}$(the sample #S1) which was the Corbino disc ($T_c = 89.3$ K, diameter D = 1.9 mm, thickness t = 20 μm), where the vortices flow in the concentric circles without crossing the edge i.e., avoiding the surface barriers [12] (see inset in Fig. 1a). The c-axis resistivity measurements were performed on the $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal with $T_c = 86.6$ K, diameter of disc $D = 1.6$ mm, and thickness $t \approx 30\mu$m (the sample #S2). The measuremente were caried out by using the ac lock-in technique at 37 Hz. The magnetic field was rotated with fine angular resolution of $0.01°$.

The typical field dependence of the in-plane resistance, obtained at different field orientations with respect to the c-axis, is presented in Fig. 1a). The clear resistivity kink anomaly, attributed to the VLMT, has been detected across a wide angular range $\theta < 89.8°$, as reported previously [1]. The out-of-plane resistivity

[1] Corresponding author. Present address: Faculty of Sciences, University of Montenegro, PO Box 211, 81000 Podgorica, Serbia and Montenegro, E-mail: mjovan@cg.ac.yu

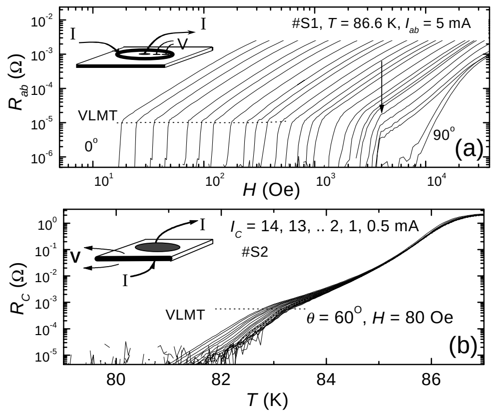

Fig. 1. (a) H-dependence of the in-plane resistance obtained at various orientations on the sample #S1 measured by current of 5 mA at $T = 86.5$ K. The dotted line corresponds to the vortex lattice melting transition, while the vertical arrow marks the sharp anomaly at $\theta = 89.8^\circ$. Inset: the sketch of the electric contacts in the Corbino geometry. (b) Temperature dependence of the c-axis resistance in magnetic field of 80 Oe at $\theta = 60^\circ$ measured by various c-axis driving currents on the sample #S2.

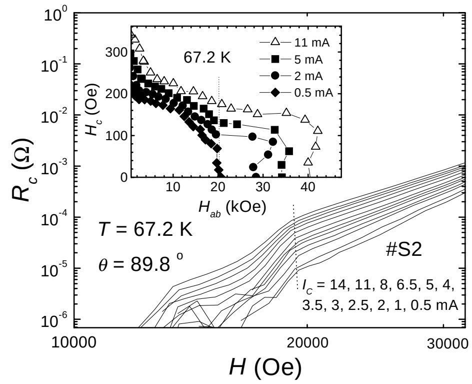

Fig. 2. Field dependence of the c-axis resistance obtained at $\theta = 89.8^\circ$ measured by various current levels at $T = 67.2$ K. Inset: The $H_c - H_{ab}$ vortex solid phase diagram obtained from the $R(H)$ measured by different currents at $T = 67.2$ K by using the criterion of $R = 2 \times 10^{-5}\Omega$. The vertical dotted line marks the sharp resistivity anomaly which occurs at $\theta \approx 89.8^\circ$.

kink associated with the VLMT in the sample #S2 was also detectable, but somewhat suppressed due to the disorder in that particular sample. Contrary to the in-plane resistance, which exhibits the non-Ohmic behavior in the vortex liquid only within the interval of $\Delta\theta \approx 0.2^\circ$ from the ab-plane [1], the c-axis resistance showed the nonlinear behavior across the whole angular range. Figure 1b) displays the $R(T)$ data which exhibit the non-Ohmic behavior above the VLMT in the magnetic field of 80 Oe at $\theta = 60^\circ$. The next experimental finding is that the non-linear behavior of the out-of-plane resistance is more pronounced as the magnetic field is applied closer to the ab-plane, accompanied with a strong suppression of the VLMT by the c-axis driving currents (see Fig.1b). This is also in a contrast to the in-plane resistivity behavior, since the VLMT practically does not depend on the in-plane driving force [13]. On the other hand, the $H_c - H_{ab}$ vortex solid phase diagram, determined by the arbitrary low enough resistance level of $2 \times 10^{-5}\Omega$ is different for the different currents used on the sample #S2 at 67.2 K, but still with the typical step-wise shape [1](see inset in Fig. 2), indicating the crossing vortex lattice structure [4,5].

However, as the magnetic field further approaches the ab-plane, both the in-plane and c-axis resistivity curves show the distinct anomaly (see the main plot in Fig. 2) at about $\Delta\theta \approx 0.2^\circ$ from the ab-plane, followed by the continuous resistivity transition and the cusp in the $H_c - H_{ab}$ phase plane for H $\parallel$ ab. The observed behavior could indicate the two-stage melting transition such as vortex-lattice – vortex smectic – vortex liquid phase transition [6] or, alternatively, crossing lattice - tilted lattice - vortex liquid phase transition[5].

In summary, the onsets of both the in-plane and out-of-plane resistivities in tilted magnetic fields provided the stepwise $H_c - H_{ab}$ melting transition phase diagram, dependent on the c-axis driving current. The peculiar behavior of $R_{ab}(H)$ and $R_c(H)$ was observed very near the ab-plane, indicating the complex two-stage melting transition in parallel magnetic fields.

References

[1] J. Mirković, S. E. Savel'ev, E. Sugahara, and K. Kadowaki, Phys. Rev. Lett. **86** (2001) 886.

[2] J. Mirković, S. Savel'ev, E. Sugahara, and K. Kadowaki, Physica C **357-360** (2001) 450.

[3] A. Grigorenko *et al.*, Nature **414**(2001) 728.

[4] A.E. Koshelev, Phys. Rev. Lett. **83** (1999) 187.

[5] S. E. Savel'ev, J. Mirković, and K. Kadowaki, Phys. Rev. B **64** (2001) 94521.

[6] L. Balents and D. R. Nelson, Phys. Rev. B **52** (1995) 12951.

[7] M. Tachiki and S. Takahashi, Solid State Commun. **70** (1989) 291.

[8] X. Hu and M. Tachiki, Phys. Rev. Lett. **85** (2000) 2577.

[9] W. K. Kwok *et al.*, Phys. Rev. Lett. **72** (1994) 1088.

[10] M. Charalambous, J. Chaussy, and P. Lejay , Phys. Rev. B **45** (1992) 5091.

[11] N.E. Hussey *et al.*, Phys. Rev. B **59** (1999) 11668.

[12] D. T. Fuchs *et al.*, Nature **391** (1998) 373.

[13] J. Mirković, K. Kimura, K. Kadowaki, Phys. Rev. Lett. **82** (1999) 2374.