Crossover from crossing to tilted vortex phase in Bi2Sr2CaCu2O8+δ single crystals near ab-plane

Jovan Mirkovic, Alexandre I. Buzdin, Takanari Kashiwagi, Takashi Yamamoto, Kazuo Kadowaki

Crossover from crossing to tilted vortex phase in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals near *ab*-plane

Jovan Mirkovic [a,c,*], Alexandre Buzdin [b], Takanari Kashiwagi [a], Takashi Yamamoto [a], Kazuo Kadowaki [a]

[a] *Institute of Materials Science, University of Tsukuba, 1-1-1 Tennodai, 305-8573 Tsukuba, Japan*
[b] *Institut Universitaire de France and Université Bordeaux I, LOMA, UMR 5798, F-33405 Talence, France*
[c] *Faculty of Sciences, University of Montenegro, George Washington Str., 81000 Podgorica, Montenegro*

A R T I C L E I N F O

Keywords:
Vortex phase diagram
Crossing lattices
c-Axis resistance
$Bi_2Sr_2CaCu_2O_{8+\delta}$

A B S T R A C T

In extremely anisotropic layered superconductors of $Bi_2Sr_2CaCu_2O_{8+\delta}$ the stacks of vortex pancakes (PV) and the Josephson vortex (JV) interpenetrate, and due to PV JV mutual pinning energy, weakly interact and form various tilted and crossing lattice structures including vortex chains, stripes, mixed chain + lattice phases, etc. In order to study these phenomena, it is decisive to have excellent quality of samples and the ideal experimental techniques. The vortex phases in high quality $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals were studied by in plane resistivity measurement and local ac magnetic permeability. The sharp cross over was shown by both techniques, deep in the vortex solid state separating the Abrikosov dominant 'strong pinning' phase from the Josephson dominant 'weak pinning' phase. Those two vortex states were recognized as the mixed chain + lattice vortex phase and chains (tilted) vortex phase, respectively.

1. Introduction

Owing to their layered structure, the vortex in high tempera ture superconductors cannot be considered as a classical Abrikosov tube, but rather as a stack of vortex pancakes (PVs) [1]. Therefore, in tilted magnetic fields, the PV stacks penetrate the CuO_2 plane perpendicularly, while the Josephson vortex (JV) lattice is aligned parallel to the *ab* plane. These two qualitatively different sublattic es interpenetrate, weakly interact and form various crossing struc tures, including vortex chains, a tilted vortex lattice, mixed chains + tilted lattice, etc. [2 9]. In a magnetic field applied parallel to the *ab* plane, vortices oriented along the *ab* plane are captured between CuO_2 layers [10,11], in the so called vortex lock in state, resulting in resistance oscillation phenomena [12], and possible two stage melting transition [13].

Despite a lot off efforts, it is still not quite clear how in oblique magnetic field the various vortex phases change their structure and pinning properties. In order to achieve the basic physical understanding and to study the nature of vortex matter in tilted magnetic fields, we performed a resistivity measurement in the Corbino electric contacts geometry, and local ac magnetic perme ability ($\mu = \mu' \quad i\mu''$) measurements on the exceptionally high quality $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals. The vortex lattice melting transition [14,15] phase diagram, including the various vortex states deep in the vortex solid, has been clearly obtained across the whole angular range exhibiting a peculiar step wise $H_c \quad H_{ab}$ phase diagram [16,17]. Interestingly, in addition to sharp first or der vortex lattice melting phase transition, for the first time resis tivity measurement probed very clear anomaly deep inside vortex solid phases, separating the Abrikosov dominant 'strong pinning' phase from the Josephson dominant 'weak pinning' phase. It was recognized that the combined vortex chains + vortex lattice struc ture was observed' up to $\theta = 86.6^\circ$ away from the *c* axis, while the tilted vortex chain lattice, where all PVs sit on JVs, is observed clo ser to the *ab* plane. While one may suggest the first order phase transition, the observed behavior could be explained as a crossover between two different PV JV configurations, with and without well pinned PVs lattice, which may prevent moving of JVs.

2. Experimental details

In order to study these phenomena, it is decisive to have excellent quality of samples the as grown $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals used have a rocking angle better than 0.01° across the sample, which made it possible to probe the rich physics confined in the narrow window of the experimental conditions. To get information about the vortex melting transition and the associated vortex phases in oblique magnetic fields, we performed the resis tivity and the local ac permeability measurements ($\mu = \mu' \quad i\mu''$). Since the transport measurements basically lose the sensitivity in the vortex solid state due to zero resistance, we developed a technique to probe the vortex solid by local ac mutual inductance measurements (Fig. 1) using a simple set of two miniature coils.

* Corresponding author at: Faculty of Sciences, University of Montenegro, George Washington Str., 81000 Podgorica, Montenegro. Tel.: +382 69 491 502; fax: +382 20 244 608.

E-mail address: jovanmirkovic@t-com.me (J. Mirkovic).

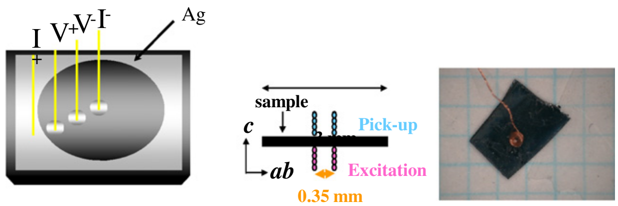

Fig. 1. A schematic of resistivity measurements in Corbino geometry (left) and magnetic permeability measurements with miniature coils (right).

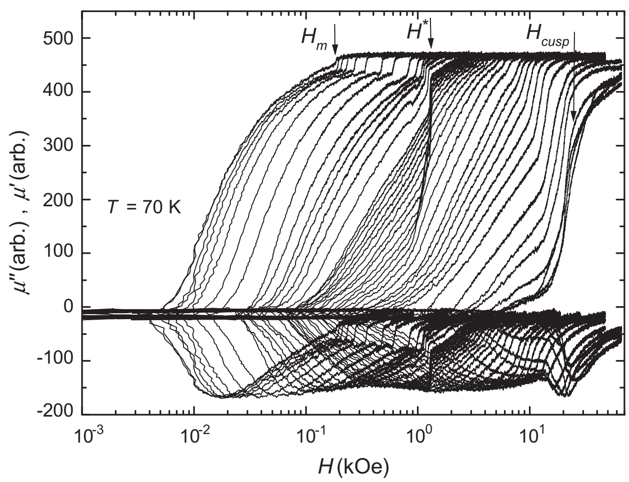

Fig. 2. The real (μ') and imaginary (μ'') part of ac-magnetic permeability as a function of H at various orientations at $T = 70$ K (#S1).

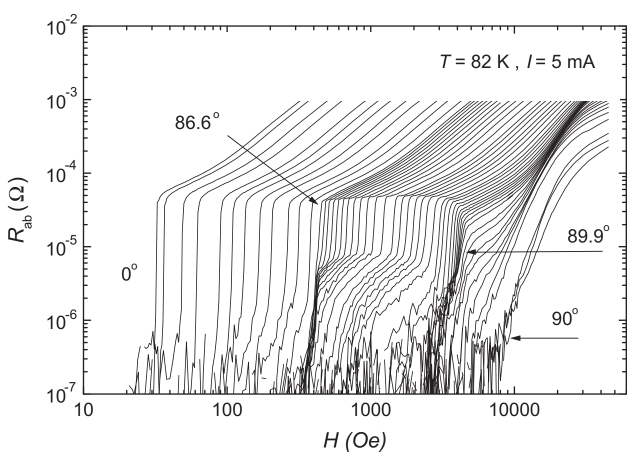

Fig. 3. The magnetic field dependence of the in-plane resistance at various orientation at $T = 82$ K (#S2), measured at a current $I = 5$ mA. At $\theta = 86.6°$ the in-plane resistivity measurements probed the sharp H^* phase line separating the mixed chains + lattice vortex phase from the chains (tilted) vortex state.

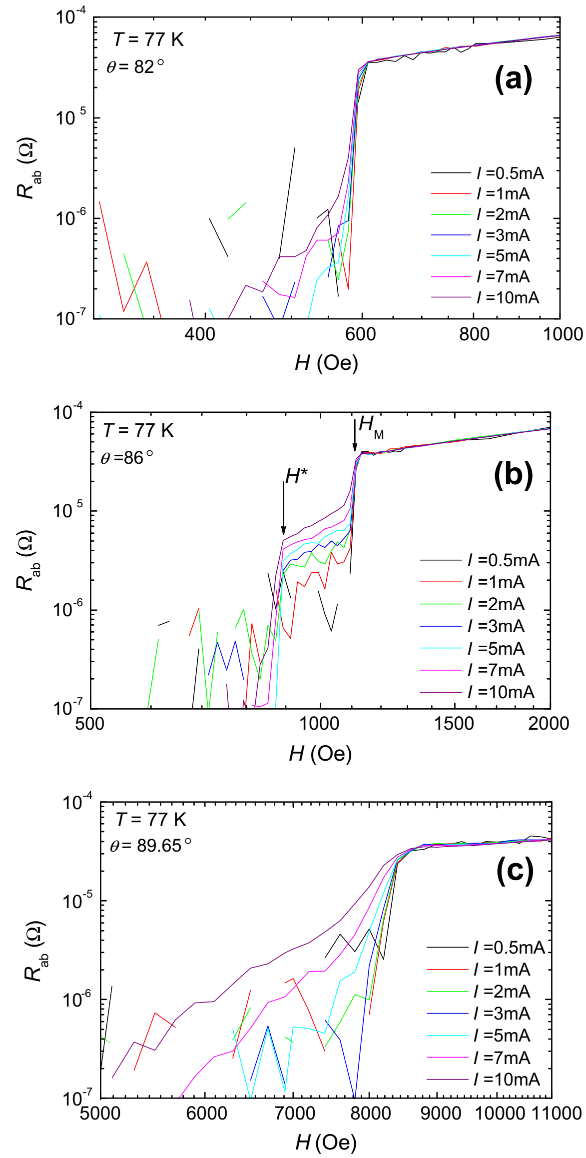

Fig. 4. The magnetic field dependence of in-plane resistance at $T = 77$ K (#S2), measured by different currents at $\theta = 82°$ (a); $\theta = 86°$ (b) and $\theta = 89.65°$ (c).

The size of coils was 0.35 mm, sufficiently smaller than the size of sample #S1 (3×3 mm^2, $T_c = 84$ K), which means that the edge and surface barrier effects could be ignored. Since the coils were fixed for the sample, the sensitivity in all directions was kept constant even in the case of the exact parallel magnetic fields, in contrast to the widely used Hall probe technique. The in plane resistivity was measured in Corbino electric contact geometry on the single crystal #S2 with the diameter of 1.9 mm, thickness of 20 µm, and transition temperature of $T_c = 84.1$ K. Corbino resistivity measurements are a unique technique used to avoid the surface pinning effects since the vortices flow in the concentric circles without crossing the edge of the sample, i.e. avoiding the surface barriers [18]. The resistance was measured using the standard lock in technique at 37 Hz as a function of magnetic field and temperature at the various field orientations with respect to the c axis. Magnetic field, generated by a 60 kOe split s/c coil magnet, was rotated with a fine angular resolution of $\delta\theta = 0.01°$.

3. Results

Fig. 2 shows the magnetic field dependence of local magnetic ac permeability measured on the sample #S1 at $T = 70$ K at the various field orientations with a local magnetic field of 1.3 G at frequency of $\nu = 2$ kHz. The local ac magnetic response showed a maximum value for μ' (the real part) at H_m where the first order vortex lattice melting transition occurs. By varying the magnetic field angle, the melting transition field H_m could be traced, demonstrating the unusual linear dependence of the c axis melting field component $H_c(H_{ab})$ firstly observed around the c axis by Ooi et al. [19] and explained [4] as an indication of the crossing lattice

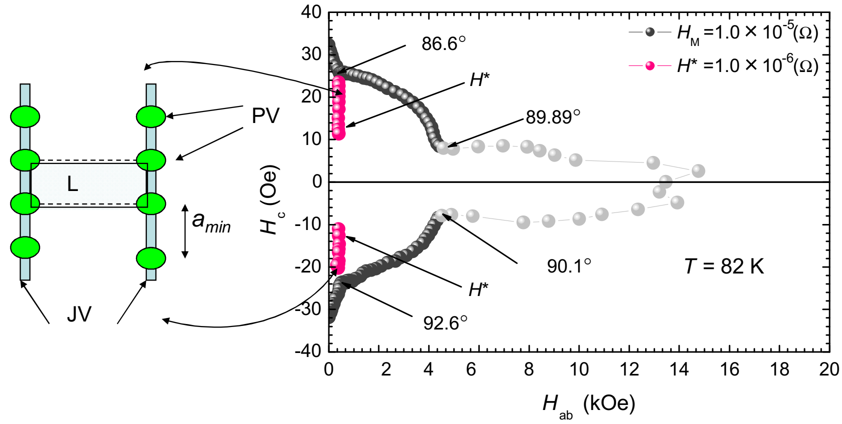

Fig. 5. The illustration of the PV–JV configuration at the crossover (left); the H_c–H_{ab} vortex phase diagram obtained from resistivity data shown in Fig. 3 at T = 82 K, measured at a single current I = 5 mA (right).

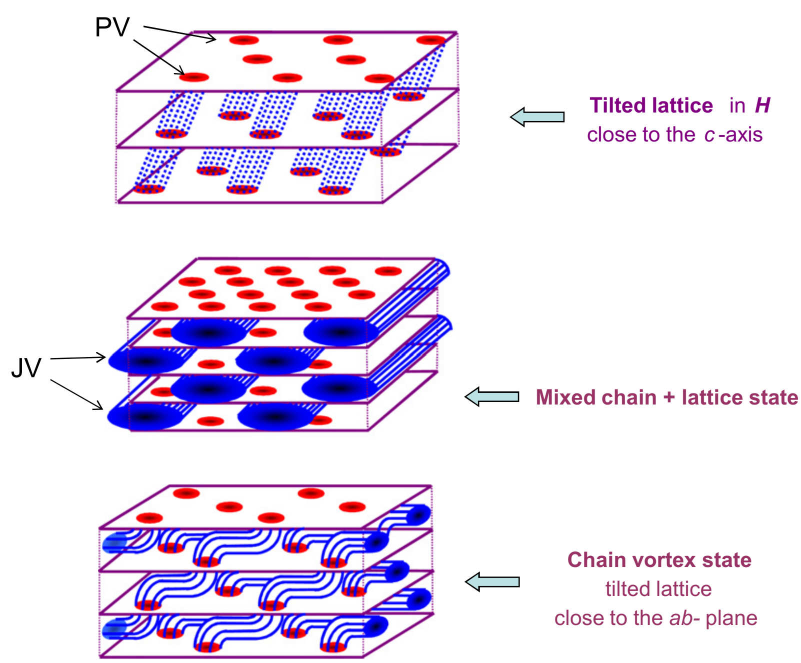

Fig. 6. A sketch of the vortex structures in titled magnetic fields: a tilted lattice near the c-axis [5] (top); mixed vortex chains + lattice vortex state (middle); chain vortex state (bottom).

of the PVs and the JVs. As reported earlier [16], by further tilting the magnetic field toward the ab plane, the linear behavior of the $H_c(H_{ab})$ changes the slope and becomes an almost flat plateau, exhibiting the step wise behavior [17]. In addition to transition H_m, an another characteristic field, H^*, was recognized by the ac response deeply inside the vortex solid state, marking an almost the vertical transition phase line on the H_c H_{ab} phase diagram [20]. While the melting transition H_m has been well studied [21,22] (identified here up to 89.8° off the c axis, in the magnetic field denoted as H_{cusp}), this work is focused more on the anomaly marked as H^*, using the resistivity measurements and probing the pinning properties of the different vortex phases.

Fig. 3. shows the set of the typical in plane resistance curves measured as a function of magnetic field on sample #S2 at various orientations with respect to the c axis, at a temperatures of 82 K. The first order vortex lattice melting transition is clearly indicated by a distinct resistivity anomaly at low resistance level, which sharply separates the vortex lattice and the vortex liquid across a wide angular range (0° < θ < 89.86°). But, in addition to the vortex lattice melting transition, the different vortex solid phases were probed for the first time, through resistivity measurements, far below the melting transition, in a sample of exceptional high quality. Namely, a strong anomaly was identified by both techniques, deep in the vortex state, at θ = 86°. Above that angle, the resistance jump changed into two distinct steps with a tail in between, characterized by a non linear current dependence. Fig. 4 shows a magnetic field dependence of resistivity measured at temperature T = 77 K, at the various current levels, I = 0.5, 1, 2, 3, 5, 7 and 10 mA, and at three field orientations θ = 82°, 86° and 89.62°. While the resistance curves obtained at θ = 82° (Fig. 4a) demonstrate a single sharp drop at the vortex lattice melting transition, probing the strong pinning vortex solid phase, at θ = 86° (Fig. 4b) all of the resistance curves show two clearly distinguished steps separating the vortex liquid ($H > H_m$), weak pinning state ($H^* > H > H_m$) and vortex solid phase ($H < H^*$). Resistance values probed in the weak pinning state increases with current level. It is important to note

that this two step behavior occurs exactly where the linear dependence $H_c(H_{ab})$ is sharply transformed into a plateau [16]. In strong contrast to resistance behavior at $\theta = 82°$ the curves obtained very near *ab* plane, at $\theta = 89.65°$, exhibit nonlinear behavior, with a long tail that increases by the higher current level (Fig. 4c).

4. Discussion

One may suppose that the matching of PVs and JVs lattices may activate the crossing lattice pinning responsible for such a sharp change at H^* [17]. On the other hand, Konczykowski et al. claim from local dc magnetization measurements [23], that it is the first order phase transition intersecting the melting line in a tri critical point. However, what we see is a strong difference in the pinning properties of the two phases. In the first, Abrikosov dominant phase, the vortex pancakes are pinned well and it seems that the PVs are easily pinned to the native pinning centers and the flow of JVs is prevented. In the second, Josephson dominant weak pinning phase, the vortex pancakes are highly mobile, as are the JVs. On the other hand, from the calculation [6] the minimal distance between PVs on JV (due to attraction) may be estimated as $a_{min} = 2\lambda$ where λ is penetration depth. Thus, the question is above which in plane magnetic field, all PVs would sit on JV, without PVs lattice between JVs. A simple calculation shows that for the experimental conditions obtained (Fig. 3 and the corresponding H_c H_{ab} phase diagram at Fig. 5), $T = 82$ K, $H_{ab} > H^* = 0.5$ kOe ($\theta > 86.6°$), all PVs sit on the JVs, when the condition:

$$H_c \cdot L \cdot a_{min} = \Phi_o$$

is fulfilled, where L is the distance between JVs, and Φ_o is the quantum of the magnetic flux. For the given experimental conditions, $T = 82$ K, $H_c = 25$ Oe, $a_{min} = 2\lambda = 4 \times 10^3$ Å, we obtain $L = 2 \times 10^4$ Å. On the other hand, the distance between JVs, L, could be estimated also from relation, $H_{ab} = \Phi_o/(dL)$, where d is the distance between the nearest JVs along c axis, while $L = \gamma\, d$, where γ is anisotropy parameter. Taking the experimental value $H_{ab} = H^* = 0.5$ kOe and assuming $\gamma = 200$, it gives $L = 3 \times 10^4$ Å, that is quite close to the value as obtained above. Therefore, it could be believed that we experimentally probed a sharp crossover from the *mixed chains + lattice vortex phase* to *chains (tilted) vortex state*. The schematic sketch of the vortex structures in tilted magnetic fields, including both PVs and JVs could be described as shown in Fig. 6.

5. Conclusion

In summary, the H_c H_{ab} vortex phase diagram for $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals was studied near the *ab* plane through both resistivity and magnetic permeability measurements on high quality single crystals. A clear anomaly, detected by both techniques, separated sharply the Josephson dominant weak pinning phase and the Abrikosov dominant strong phase, indicating a crossover from the *mixed chains + lattice vortex phase* to *chains (tilted) vortex state*.

Acknowledgements

We appreciate our stimulating discussions with S.E. Savel'ev, I. Kakeya and F. Nori. This work was partially supported by CREST JST, WPI MANA, and the Strategic Initiative category (A) at the University of Tsukuba. J. Mirkovic also acknowledges support from the Ministry of Science of Montenegro (Project *Physics of Nanostructures*).

References

[1] A.I. Buzdin, D. Feinberg, J. Phys. (Paris) 51 (1990) 1971;
J.R. Clem, Phys. Rev. B 43 (1991) 7837;
S.N. Artemenko, A.N. Kruglov, Phys. Lett. A 143 (1990) 485.
[2] L.N. Bulaevskii, M. Ledvij, V.G. Kogan, Phys. Rev. B 46 (1992) 366.
[3] R. Kleiner, F. Steinmeyer, G. Kunkel, P. Müller, Phys. Rev. Lett. 68 (1992) 2394.
[4] A.E. Koshelev, Phys. Rev. Lett. 83 (1999) 187.
[5] S.E. Savel'ev, J. Mirkovic, K. Kadowaki, Phys. Rev. B 64 (09) (2001) 4521.
[6] A. Buzdin, I. Baladie, Phys. Rev. Lett. 88 (2002) 147002.
[7] A.N. Grigorenko, S. Bending, T. Tamegai, S. Ooi, M. Henini, Nature (London) 414 (2001) 728.
[8] V.K. Vlasko-Vlasov, A. Koshelev, U. Welp, G.W. Crabtree, K. Kadowaki, Phys. Rev. B 66 (2002) 014523.
[9] J. Mirkovic, S.E. Savel'ev, H. Sato, F. Nori, K. Kadowaki, New J. Phys. 8 (2006) 226.
[10] D. Feinberg, C. Villard, Phys. Rev. Lett. 65 (1990) 919.
[11] M. Tachiki, S. Takahashi, Solid State Commun. 70 (1989) 291.
[12] S. Ooi, T. Mochiku, K. Hirata, Phys. Rev. Lett. 89 (2002) 247002.
[13] L. Balents, D.R. Nelson, Phys. Rev. B 52 (1995) 12951.
[14] G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, V.M. Vinokur, Rev. Mod. Phys. 66 (1994) 1125.
[15] E. Zeldov, D. Mayer, M. Konczykowski, V.G. Gashkenbein, V.M. Vinokur, H. Strikhman, Nature (London) 375 (1995) 373.
[16] J. Mirković, E. Sugahara, K. Kadowaki, Physica B 284–288 (2000) 733.
[17] J. Mirkovic, S.E. Savel'ev, E. Sugahara, K. Kadowaki, Phys. Rev. Lett. 86 (2001) 886.
[18] D.T. Fuchs, E. Zeldov, M. Rappaport, T. Tamegai, S. Ooi, H. Shtrikman, Nature (London) 391 (1998) 373.
[19] S. Ooi, T. Shibauchi, N. Okuda, T. Tamegai, Phys. Rev. Lett. 82 (1999) 4308.
[20] M. Tokunaga, M. Kishi, N. Kameda, K. Itaka, T. Tamegai, Phys. Rev. B 66 (2002) 220501.
[21] J. Mirkovic, S. Savel'ev, E. Sugahara, K. Kadowaki, Physica C 364–365 (2001) 515;
J. Mirkovic, S. Savel'ev, E. Sugahara, K. Kadowaki, Physica C 357–360 (2001) 450.
[22] J. Mirkovic, S. Savel'ev, E. Sugahara, K. Kadowaki, Phys. Rev. B 66 (2002) 132505.
[23] M. Konczykowski, C.J. van der Beek, A.E. Koshelev, V. Mosser, M. Dodgson, P.H. Kes, Phys. Rev. Lett. 97 (2006) 237005.