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Josephson Vortex Lattice Melting in Bi-2212 Probed by Commensurate Oscillations of Josephson Flux-Flow[¶]

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We studied the commensurate semifluxon oscillations of Josephson flux-flow in Bi-2212 stacked structures near T_c as a probe of melting of a Josephson vortex lattice. We found that oscillations exist above 0.5 T. The amplitude of the oscillations is found to decrease gradually with the temperature and to turn to zero without any jump at $T = T_0$ (3.5 K below the resistive transition temperature T_c), thus, indicating a phase transition of the second order. This characteristic temperature T_0 is identified as the Berezinskii–Kosterlitz–Thouless (BKT) transition temperature, T_{BKT}, in the elementary superconducting layers of Bi-2212 at zero magnetic field. On the basis of these facts, we infer that melting of a triangular Josephson vortex lattice occurs via the BKT phase with formation of characteristic flux loops containing pancake vortices and antivortices. The *B*–*T* phase diagram of the BKT phase found from our experiment is consistent with theoretical predictions. © *2005 Pleiades Publishing, Inc.*

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The vortex phase diagram in layered high-T_c materials in parallel magnetic fields is significantly less studied than for perpendicular fields. This is related to the great difficulty in visualization of Josephson vortices [1] and the Josephson vortex lattice (JVL) [2]. Recently, a method of identification of triangular JVL has been found [3]. It was demonstrated as oscillations of Josephson flux-flow resistance in narrow Bi-2212 mesa structures in a parallel field with a periodicity of $\frac{1}{2}\Phi_0$ per elementary Josephson junction. The effect has been interpreted as a result of commensurability of a triangular JVL period with mesa width. In this paper (see also [4]) we develop an idea to use the effect of Josephson flux-flow (JFF) commensurate oscillations for probing of JVL melting. In a triangular lattice, the periodic rows of JVs in adjacent layers are shifted by π. Therefore, JFF oscillations with semifluxon periodicity reflect the transverse coherence of a triangular lattice. The melting of a triangular lattice should be accompanied by a loss of transverse coherence and, as a result, by disappearance of semifluxon oscillations. Different scenarios of melting can occur: melting into the liquid phase or melting into the Berezinskii–Kosterlitz–Thouless (BKT) phase [5–7]. For the latter case, the possibility of second order transition has been considered [7, 8]. The influence of BKT transition on a JVL phase at high fields and high temperatures has been widely debated [5–9]. However, until recently, there were no systematic experimental studies of JVL melting.

The experiment was carried out on stacked structures of slightly overdoped Bi-2212 with lateral sizes of $L_a \times L_b$ = 15–30 μm × 3–5 μm containing about 100 elementary junctions (Fig. 1). The structures were fabricated by double sided processing of Bi-2212 whiskers by a focused ion beam (FIB) [10]. The field was ori-

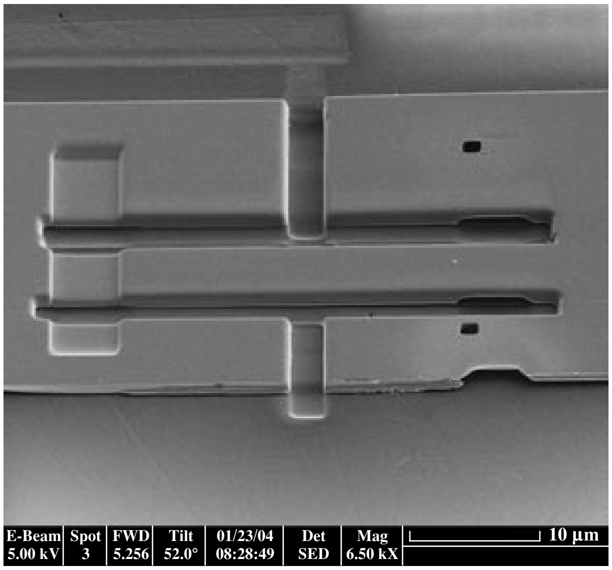

Fig. 1. SEM picture of the stacked structure fabricated by double sided FIB etching of a Bi-2212 single crystal whisker.

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ented strictly parallel to the *ab*-plane and perpendicular to the *a*-axis. The parallelity of the field orientation was adjusted within 0.01° by fixing that at the sharp maximum of the JFF magnetoresistance with field rotation around the *a*-axis. For that purpose, along with a main coil providing a magnetic field up to 1T, an additional perpendicular coil was used. The data were collected by a computer controlled current source and a nanovoltmeter.

We traced the oscillating dependence of the JFF resistance on a parallel magnetic field at fixed temperatures with temperature variation by small steps (Fig. 2). The period of the oscillations exactly corresponds to 1/2 fluxon per elementary junction, $\Delta B = 0.5\Phi_0/Ls$, with L (the stack size) being perpendicular to the magnetic field and s being the inter-layer spacing. The amplitude of the oscillations decreases with temperature and turns to zero at some temperature T_0, which is 3.5 K below T_c (Fig. 3). Figure 2 shows that, at a fixed temperature, oscillations exist within some field interval. The boundaries of that interval, which are marked in the picture, define the lower and upper boundaries of the triangular JVL state at the B–T diagram (Fig. 4a).

Let us discuss the main features observed. The characteristic point at the phase diagram corresponds to B = 0.6–0.7 T, where the upper and lower boundaries meet each other at $T = T_0$. There are no JFF oscillations above this temperature. We can then conclude that there is no triangular JVL state above that temperature. The value of T_0 lies 3.5 K below the transition temperature. That is very close to the bare BKT transition temperature observed at zero magnetic field on similar Bi-2212 single crystals [11]. The BKT transition is characterized by spontaneous formation of free pairs of pancake vortices and antivortices within elementary superconducting layers. Below T_{BKT}, the vortex–antivortex pairs can be unbound by the in-plane current and the I–V characteristics have the power law $V = I^{a(T)+1}$, where the exponent $a = \Phi_0^2 d/(4\pi\lambda)^2$ (with d being the thickness of the layer and λ the London penetration depth) is proportional to the unbinding energy. At the BKT transition, this exponent undergoes a universal jump from 2 to 0, which is known as the Nelson–Kosterlitz jump, which is a characteristic feature of the BKT transition. By observation this jump, the BKT transition has been identified in the elementary conducting layers of Bi-2212 single crystals [12] with $T_{\mathrm{BKT}} - T_{co} = 3.5$ K.

The BKT transition in a parallel magnetic field [5, 9] was considered in connection with melting of JVL [7, 8] and with the observation of independent Lorentz force dissipation when both the transport current and magnetic field lie in the *ab*-plane [13]. The elementary process accompanying JVL melting has been considered by Blatter *et al.* [6]; that is, the hopping of a segment of Josephson vortex into the neighboring junction with formation of a loop that includes a pancake vortex and antivortex (Fig. 5).

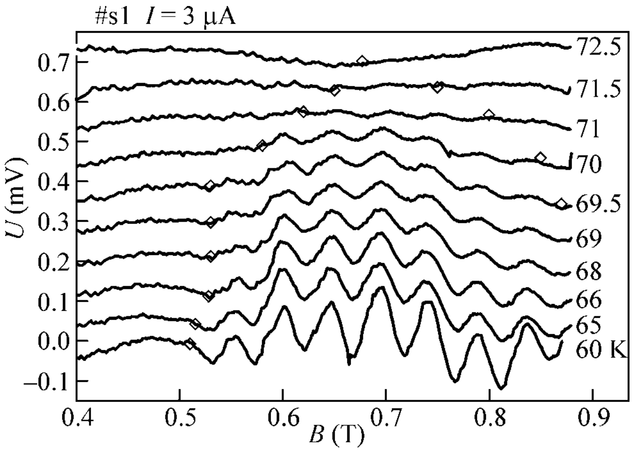

Fig. 2. Semifluxon oscillations of Josephson flux-flow voltage of Bi-2212 mesa with lateral sizes of $L_a \times L_b$ = 15 μm × 5 μm in the parallel field $B \parallel b$. The linear part is subtracted. The curves are shifted for clarity. The markers (rhombuses) indicate the lower and upper boundaries of the existence of oscillations.

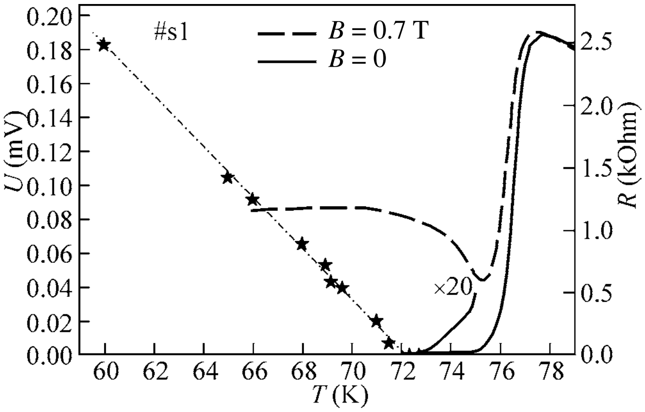

Fig. 3. Temperature dependence of the amplitude of semifluxon JFF oscillations on a parallel magnetic field measured near the field of 0.7 T for the Bi-2212 stacked junction and the superconducting transition for the same junction at zero field and at B = 0.7 T.

The BKT transition facilitates the hopping providing the free vortices and antivortices necessary for formation of a loop. The unbinding of vortex–antivortex pairs by the in-plane component of the current circulating around the Josephson vortex happens even at temperatures considerably lower than T_{BKT}. The hopping becomes preferable at higher temperatures, because of an increase of the thermal fluctuations, and also at a high enough magnetic field with an increase of the vortex concentration and, correspondingly, with an increase of the intervortex repulsive interaction in one junction. The critical field for JVL melting into the

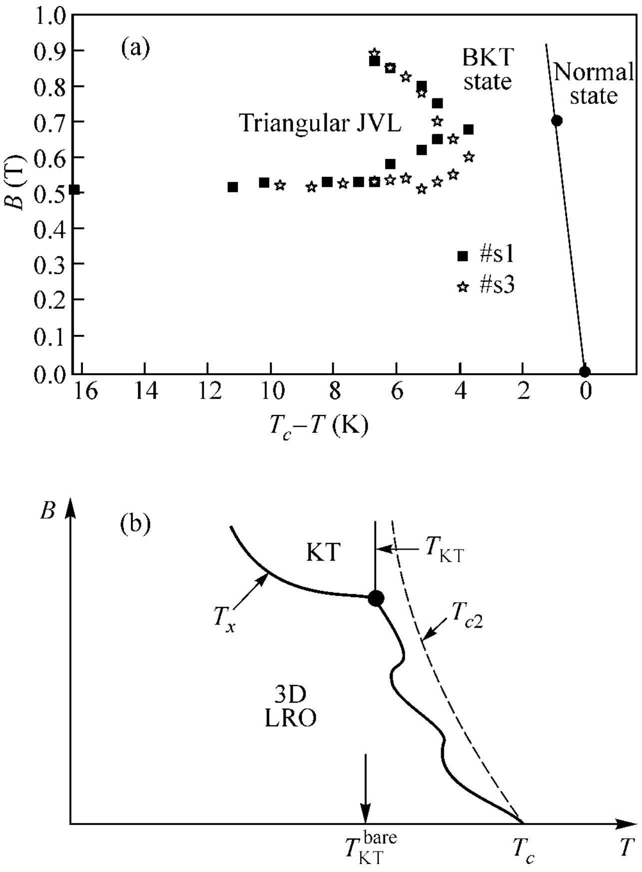

Fig. 4. Phase diagram of the JVL state restored from the data on semifluxon oscillations of the JFF voltage on a parallel magnetic field for two Bi-2212 mesas (a) and the schematic picture of the phase diagram considered in [7] (b).

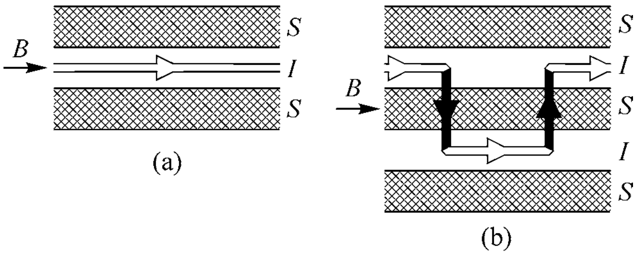

Fig. 5. Schematic illustration of hopping of a Josephson vortex segment with formation of a flux loop containing a pancake vortex and antivortex pair: (a) Josephson vortex before hopping, (b) after hopping.

BKT phase B^* has been calculated by Hu and Tachiki [7, 8] $B^* = \Phi_0/(2\sqrt{3}\gamma s^2)$ with γ being the anisotropy of the London penetration depths $\gamma = \lambda_c/\lambda_{ab}$, and s being the spacing between the elementary conducting layers. They also considered the B–T phase diagram of the JVL melting schematically shown in Fig. 4b.

The experimentally found phase diagram of JVL melting is quite similar to the theoretical picture. The maximum temperature of existence of the BKT phase T_0, as it was mentioned, corresponds well to the bare BKT transition. The critical magnetic field B^* estimated for our samples with $\gamma = 500$ [14] corresponds to 0.5 T, which is close to the experimental value 0.6–0.7 T. The upper boundary of JVL existence is also in qualitative agreement with the theoretical $B(T)$ dependence for the melting line: B grows with a decrease in T. The crossing of the BKT melting line by moving from the JVL state either by increasing the temperature or field corresponds to a continuous decrease of the amplitude of the oscillations to zero without any jump expected for the first order transition. That is a signature of the JVL melting into the BKT phase since, as it was argued in [7] for $\gamma > 9$ and $B > B^*$, it should be a phase transition of the second order. Note that the experimental picture corresponds to the sliding JVL, while the theoretical picture relates to the static case. However, due to the small dc currents used in the experiment, the JVL velocity was relatively small, about 3% of the Swihart velocity.

In contrast, the lower boundary is characterized by much sharper variation of the oscillation amplitude with a decrease of the field. The origin of the low boundary is still not quite clear. The JFF voltage is known to have a threshold as a function of the magnetic field [15] that corresponds to a flux density of $0.7\Phi_0$ per junction. The oscillations appear starting with a field of about 0.5 T and are nearly independent of the temperature. That field corresponds to 5–7 periods of triangular JVL, which appears to be the threshold value for the commensurability effect corresponding to the minimal number of periods for the lattice to start to behave as a solid piece.

We found that the Josephson flux-flow branch still exists on the I–V characteristics above T_{BKT}; however, the JFF voltage drops rapidly at $T > T_{\text{BKT}}$ (Fig. 3). The study of the JFF state above T_{BKT} is of great interest for future research. Another interesting point is to study the influence of the c-axis field component on the JVL melting temperature.

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REFERENCES

1. J. Clem and M. Coffey, Phys. Rev. B **42**, 6209 (1990).
2. L. N. Bulaevskii and J. Clem, Phys. Rev. B **44**, 10234 (1991).

3. S. Ooi, T. Mochiku, and K. Hirata, Phys. Rev. Lett. **89**, 247002 (2002).
4. Yu. I. Latyshev, A. E. Koshelev, M. Gaifullin, *et al.*, in *Proceedings of 4th International Symposium on Intrinsic Josephson Effect and Plasma Oscillations in High-T_e Superconductors* (Tsukuba, Ibaraki, Japan, 2004), p. II-85-87.
5. S. E. Korshunov and A. I. Larkin, Phys. Rev. B **46**, 6395 (1992).
6. G. Blatter, B. I. Ivlev, and J. Rhyner, Phys. Rev. Lett. **66**, 2392 (1991).
7. X. Hu and M. Tachiki, Phys. Rev. B **70**, 064 506 (2004).
8. X. Hu and M. Tachiki, Phys. Rev. Lett. **85**, 2577 (2000).
9. B. Horovitz, Phys. Rev. B **47**, 5947 (1993); Phys. Rev. B **47**, 5964 (1993).
10. Yu. I. Latyshev, S.-J. Kim, and T. Yamashita, IEEE Trans. Appl. Supercond. **9**, 4312 (1999).
11. S. N. Artemenko, I. G. Gorlova, and Yu. I. Latyshev, Phys. Lett. A **138**, 428 (1989); S. N. Artemenko and Yu. I. Latyshev, Mod. Phys. Lett. B **6**, 367 (1992).
12. S. N. Artemenko, I. G. Gorlova, and Yu. I. Latyshev, Pis'ma Zh. Éksp. Teor. Fiz. **49**, 566 (1989) [JETP Lett. **49**, 654 (1989)].
13. Y. Iye, S. Nakamura, and S. Tamegai, Physica C (Amsterdam) **169**, 433 (1989).
14. Yu. I. Latyshev, A. E. Koshelev, and L. N. Bulaevskii, Phys. Rev. B **68**, 134504 (2003).
15. Yu. I. Latyshev, A. E. Koshelev, V. N. Pavlenko, *et al.*, Physica C (Amsterdam) **367**, 365 (2002).