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SUPERCONDUCTIVITY

Josephson Vortex Lattice Melting in Bi-2212

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Abstract—The B–T diagram of Josephson vortex lattice melting in Bi-2212 is analyzed (B is magnetic induction parallel to the layers, T is temperature). It is shown that the Josephson vortex lattice melting at $B > B^* =$ 0.6–0.7 T is associated with Berezinsky–Kosterlitz–Thouless transition in individual Bi-2212 superconducting layers and is a second-order phase transition.

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In a recent study [1], a method was found for identifying a triangular lattice of Josephson vortices from observation of Josephson vortex flow resistance oscillations due to commensurability between the period of a moving vortex lattice and the size of the underlying layered structure. We used this phenomenon to examine Josephson vortex lattice melting [2], assuming that the vortex flow resistance oscillations vanish with increasing temperature because of breakdown of long-range order in a Josephson vortex system.

The experiment was conducted on overdoped Bi-2212 layered structures (mesas) (see Fig. 1). The structures were stacks of size $L_a \times L_b$ = (15–30) × (3–5) μm^2 consisting of approximately 100 junctions (see Fig. 1). The structures were fabricated from Bi-2212 whiskers by double-sided focused-ion-beam etching [3]. The samples were aligned so that the applied magnetic field was parallel to the *ab* planes and perpendicular to the *a* axis (the long side of the sample). Parallel alignment to an accuracy of approximately 0.01° was achieved by precise adjustment of the angle of sample rotation about the *a* axis to a sharp peak of the Josephson vortex flow resistance with the use of an additional coil generating a perpendicular field. Data acquisition was performed by means of a current source and a nanovoltmeter, which were controlled by a computer.

We measured the oscillating Josephson vortex flow resistance of the mesa as a function of the parallel magnetic field at several constant temperatures, with a small temperature step (see Fig. 2). The oscillation period was exactly corresponding to half a flux quantum per junction, $\Delta B = 0.5\Phi_0/Ls$, where L is the structure size in the direction perpendicular to the applied magnetic field and the separation between neighboring layers, s = 1.5 nm, corresponds to a triangular lattice of Josephson vortices. The oscillation amplitude decreased with increasing temperature and vanished at a temperature T_0 that was 3.5 K below T_c. It is clear from Fig. 2 that oscillations are observed at constant temperature over a certain interval of magnetic induction. The endpoints of the intervals, marked in the figure, determine the upper and lower boundaries of the triangular-lattice state in the B–T diagram of Fig. 3.

The point in the diagram where the upper and lower boundaries meet at $T = T_0$ corresponds to B = 0.6–0.7 T. Since no oscillation is observed at higher temperatures, we conclude that the triangular lattice of Josephson vortices does not exist at these temperatures. The temperature T_0 is lower than the transition temperature by 3.5 K. This value is close to the temperature of the Berezinsky–Kosterlitz–Thouless (BKT) transition, which is observed at zero field in measurements of the in-plane I–V characteristics of analogous Bi-2212 single crystals [4]. The BKT transition is characterized by spontaneous vortex–antivortex pair formation in individual superconducting layers. The BKT temperature

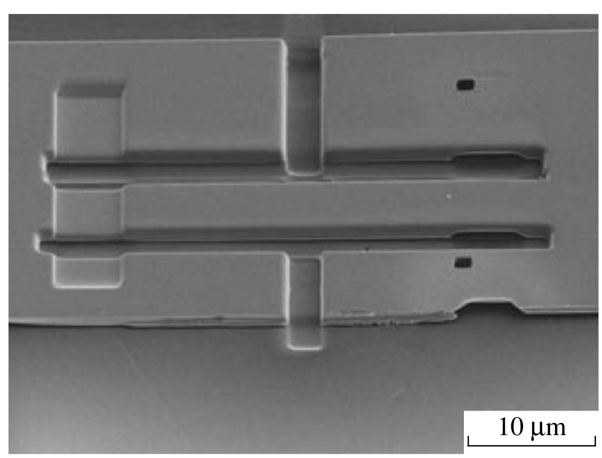

Fig. 1. Image of a layered structure obtained by double-sided focused-ion-beam etching of a Bi-2212 single-crystal whisker.

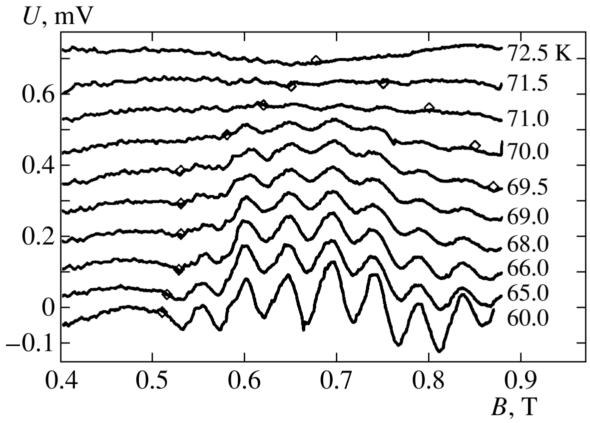

Fig. 2. Voltage oscillations caused by Josephson vortex motion in a Bi-2212 structure of size $L_a \times L_b = 15 \times 5\ \mu m^2$ in a magnetic field parallel to the b axis for $I = 3\ \mu A$. The linear contribution is subtracted out. The curves are shifted along the voltage axis. Diamonds denote the upper and lower boundaries of the oscillating state.

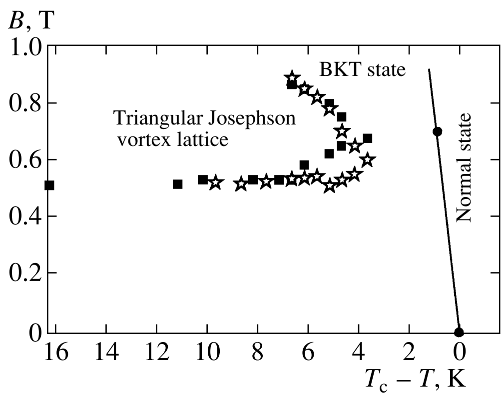

Fig. 3. Phase diagram of Josephson vortex lattice obtained by setting to zero amplitude of Josephson vortex flow resistance oscillations with a period of $\Phi_0/2$ for two Bi-2212 samples (denoted by squares and stars, respectively).

for Bi-2212 single crystals corresponds to $T_{BKT} - T_c = 3.5$ K [5].

The BKT transition in a parallel magnetic field [6, 7] has been analyzed in relation to Josephson vortex lattice melting [8, 9], which involves generation of flux loops including pancake vortex–antivortex pairs by the hopping of Josephson vortex segments between neighboring junctions [10].

The BKT transition leads to a higher hopping rate via generation of free vortex–antivortex pairs required to form flux loops. The unbinding of vortex–antivortex pairs induced by in-plane currents circulating around Josephson vortices occurs even at temperatures much lower than T_{BKT}. The hopping rate increases with temperature because of thermal fluctuations and with magnetic field because of the stronger vortex–vortex repulsion due to a higher vortex concentration. The critical field B^* for BKT transition in a Josephson vortex lattice is estimated as [8, 9]

$$B^* = \frac{\Phi_0}{2\sqrt{3}\gamma s^2},$$

where the anisotropy γ of London penetration depth is defined as $\gamma = \lambda_c/\lambda_{ab}$.

The experimentally determined Josephson vortex lattice melting diagram is consistent with the theoretical model. The maximum temperature T_0 at which the BKT phase exists corresponds to zero-field BKT transition. The critical field B^* estimated for our samples with $\gamma = 500$ [11] is 0.5 T, which is close to the measured 0.6–0.7 T. The upper boundary of the triangular-lattice state is also in qualitative agreement with the theoretically predicted melting line $B(T)$: the field B increases with decreasing T. The continuous decrease to zero in oscillation amplitude with increasing temperature or magnetic field suggests that the boundary corresponds to a second-order phase transition. This points to a melting transition to a BKT state, because the melting transition from Josephson-lattice to BKT state must be a second-order transition at $\gamma > 9$ and $B > B^*$ [8]. Note that the experimental results are obtained for a moving Josephson vortex lattice, whereas the theoretical analysis has been restricted to the static case. However, the measurements were performed at low currents, which correspond to slow Josephson vortex-lattice motion.

In contrast to the upper boundary, the lower boundary is characterized by rapid decrease in oscillation amplitude with applied field. Currently, the mechanism underlying the lower boundary is not well understood. The oscillations occur at $B > 0.5$ T and are almost independent of temperature. This corresponds to the minimum of 5–7 triangular-lattice periods required for the commensuration. We believe that the lower boundary of triangular lattice states is associated with formation of a dense lattice.

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