

Vortex matter transition in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+y}$ under tilted fields

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Vortex phase diagram under tilted fields from the c axis in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+y}$ is studied by local magnetization hysteresis measurements using Hall probes. When the field is applied at large angles from the c axis, an anomaly (H_p^*) other than the well-known peak effect (H_p) is found at fields below H_p . The angular dependence of the field H_p^* is nonmonotonic and clearly different from that of H_p and depends on the oxygen content of the crystal. The results suggest existence of a vortex matter transition under tilted fields. Possible mechanisms of the transition are discussed.

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It has been made clear that the vortex state in high- T_c superconductors has various interesting features.¹ Important parameters which control these features are large thermal fluctuations due to high critical temperature T_c and the anisotropy of these materials. Although the anisotropy parameter $\gamma(\equiv\lambda_c/\lambda_{ab})$ is very different in two typical high- T_c superconductors, $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) $\gamma\sim 5$ (Ref. 2) and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+y}$ (BSCCO) $\gamma\sim 200$ (Ref. 3), similar phenomena such as the first-order phase transition (FOT)⁴⁻⁶ and the (second) peak effect^{7,8} are commonly observed. The difference of anisotropy is reflected in the fact that these transitions in BSCCO occur in a much lower-field range than those in YBCO. An interesting question one may ask is whether the difference of anisotropy induces a qualitative difference in the vortex states or not.

When the field is inclined from the c axis, a drastic change in the vortex order is expected due to large anisotropy. A vortex chain state in which all vortices form arrays in the tilt plane has been observed under tilted fields in YBCO by the Bitter decoration method.⁹ The existence of such a vortex chain in anisotropic superconductors has been predicted within the framework of the anisotropic London model.¹⁰ The motive force of the chain formation originates from the attractive magnetic interaction between inclined vortices. On the other hand, vortices form more complicated arrangements in BSCCO. Vortex chains embedded in approximately triangular vortex lattices have been observed.^{11,12} This vortex ordering has attracted theoretical attention and the coexistence of two vortex species has been suggested.¹³⁻¹⁵ Experimentally, Grigorieva *et al.* concluded that vortex chains embedded in the vortex lattice consist of two inclined vortex species which have different angles from the c axis.¹² These results suggest that the difference of anisotropy between YBCO and BSCCO causes different vortex arrangements under tilted fields.

Such observations of vortex states under tilted fields, however, have been limited to very low fields (<200 Oe). Our purpose is to clarify the vortex phase diagram in BSCCO single crystals under tilted applied fields in a wide field range (<10 kOe). In this paper, we report on an anomaly in the local magnetization in BSCCO which is observed only under tilted fields. This anomaly suggests the existence of vortex matter transition under tilted fields.

Based on the angular, temperature, and doping-level dependence of the anomaly, we discuss the origin of the transition.

Single crystals of BSCCO have been grown by the floating-zone method.¹⁶ We measured several samples with different oxygen contents, which were controlled by annealing at 300–500 °C for one day in appropriate partial oxygen pressure. In this paper, we show results for four samples; optimally doped (OPT), overdoped (OV1, OV2), and highly overdoped (HOV) crystals. The critical temperatures T_c are 86.7, 80.3, 83.5, and 76.8 K, respectively. The configuration of the measurement by using micro-Hall probes is schematically shown in the inset of Fig. 1. The details of the measurement are described in the previous paper.¹⁷

A typical local magnetization curve at 35 K under a tilted field from the c axis is shown with a curve in the field parallel to the c axis in Fig. 1. In addition to the well-known peak effect (H_p),⁷ an anomaly, indicated by H_p^* , is observed below H_p . This anomaly is observed only under tilted fields. We confirmed the presence of this anomaly in more than ten single crystals and Pb-doped BSCCO crystals.¹⁸

Figures 2(a) and 2(b) show the first quadrant part of the local magnetization hysteresis curves at 35 K in the OV1

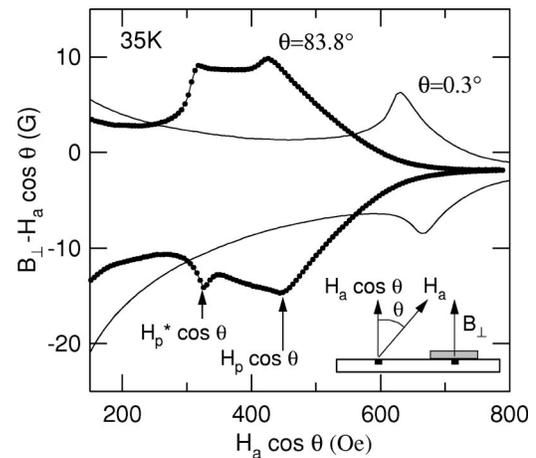


FIG. 1. Local magnetization hysteresis curves at $\theta=0.3^\circ$ and $\theta=83.8^\circ$ in the OV1 sample. Arrows indicate the positions of two characteristic anomalies. The horizontal axis shows the field parallel to the c axis, $H_a \cos \theta$. The inset shows the configuration of a sample and micro-Hall probes schematically.

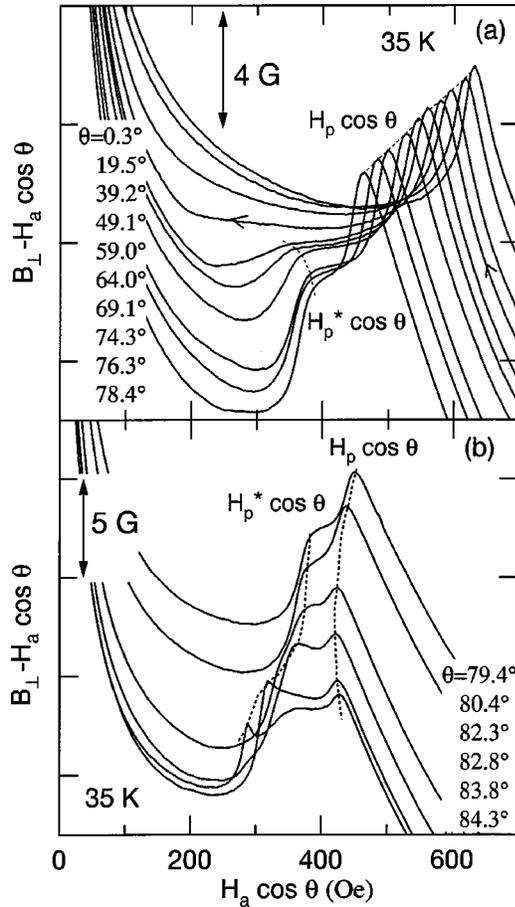


FIG. 2. First quadrant part of hysteresis curves at 35 K in the OV1 sample at angles (a) below θ^* and (b) around θ^* . Dashed lines indicate peak positions $H_p \cos \theta$ and $H_p^* \cos \theta$. The definition of θ^* is described in Fig. 3. Each curve is properly shifted along the vertical axis for clarity.

sample at various angles from 0° to 84° . When the field is nearly parallel to the c axis, only the peak effect (H_p) is observed at 630 Oe. On the other hand, the magnetization anomaly H_p^* starts to be observed below H_p at angles above about 60° in this crystal. Since the anomalies have a broad steplike forms at lower angles, the field H_p^* is picked up as the position of the shoulder of magnetization, which is shown by the dashed line in Fig. 2. At larger angles, the anomaly has sharper shape and the definition of H_p^* is not ambiguous.

The angular dependence of $H_p^* \cos \theta$ is plotted in Fig. 3 together with the normal peak effect. The difference of peak positions between increasing and decreasing field process is due to the self-trapped field in the crystal. The angular dependence of H_p follows the scaling relation, $H_p \propto (\cos \theta + \alpha \sin \theta)^{-1}$, as reported previously.¹⁷ At angles higher than a characteristic angle θ^* , $H_p \cos \theta$ deviates from the scaling and starts to increase. On the other hand, $H_p^* \cos \theta$ slightly increases with increasing angle up to θ^* , and it decreases rapidly above θ^* . At around θ^* both $H_p \cos \theta$ and $H_p^* \cos \theta$ approach closely to each other. Since the angular dependence of H_p^* is quite different from that of H_p , the origins for these

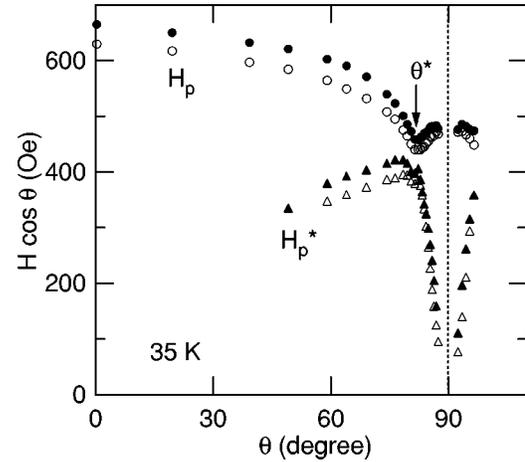


FIG. 3. Angular dependence of $H_p^* \cos \theta$ (triangles) and $H_p \cos \theta$ (circles) in the OV1 sample at 35 K. Closed and open markers show the peak fields in field-increasing and -decreasing processes, respectively. At θ^* , the angular dependence of $H_p \cos \theta$ has a minimum.

two anomalies should be different.

Figure 4(a) shows the hysteresis curves at 45 and 55 K at a constant angle of 83.7° which is larger than θ^* . The normal peak effect observed at 45 K and 630 Oe changes into the magnetization step at 55 K which is a sign of the FOT. In addition, a steplike structure is observed at a field lower than H_p . This anomaly can be traced to the anomaly H_p^* observed at lower temperatures as shown in Fig. 1. We could not observe an anomaly within our experimental resolution ~ 10 mG when the irreversible magnetization disappears at

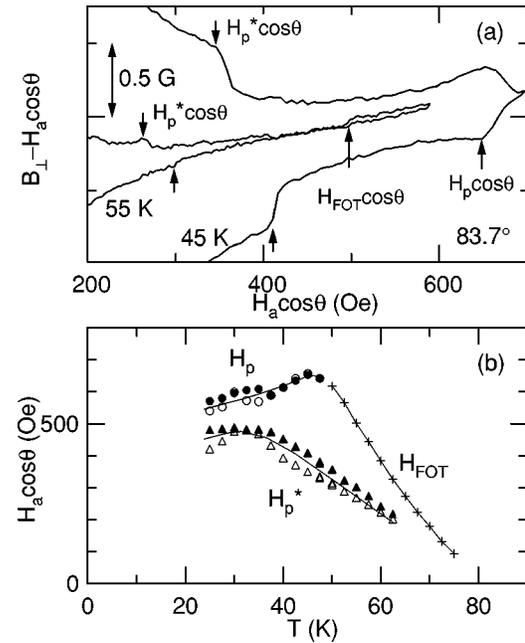


FIG. 4. (a) Hysteresis curves at 45 and 55 K at a constant angle of 83.7° in the OV2 sample. Arrows indicate positions of the anomalies. (b) Temperature dependence of the c -axis component of H_{FOT} , H_p , and H_p^* . Closed and open markers indicate the field increasing and decreasing processes, respectively.

high temperatures. The temperature dependence of H_{FOT} , H_p , and H_p^* at 83.7° is shown in Fig. 4(b). One can see that the $H_p^*(T)$ line is always below the normal transition lines (H_{FOT}, H_p) even above θ^* , which rules out a possibility that $H_p(\theta)$ crosses $H_p^*(\theta)$ at θ^* (see Fig. 3). Thus this H_p^* line divides the vortex lattice phase into two parts under an oblique field.

Let us discuss possible origins of the observed anomaly at H_p^* . Dynamical scenario may also be applied in this case as in the case of the fish-tail effect in YBCO.¹⁹ However, in such a case, changes in the irreversible magnetization are smoother compare with the present case at H_p^* . The situation is rather similar to the case of the peak effect in BSCCO,⁷ where the irreversible magnetization shows a step-like change. The peak effect is believed to be a transition in the vortex solid phase, and is accompanied by a drastic change in the vortex configuration.^{20,21} A disorder-induced transition^{20,21} and a dimensional crossover of the vortex system⁷ are proposed as possible origins of the peak effect. Since the critical current is related to the collective pinning force determined by the configuration of vortices and the pinning potential, a change in the vortex configuration induce a steplike change of the critical current at the characteristic field. As a result, the irreversible magnetization show a distinct anomaly, as in the present case at H_p^* . Although magnetization step is not observed in the reversible regime, the height of the step might be simply too small to be observed. Since the transition occurs within the vortex solid state, it is reasonable that the entropy change, which is proportional to the magnetization step, is much smaller than the case of the vortex lattice melting transition.

Several theories predict an existence of a transition of the vortex arrangements in highly anisotropic layered superconductors under tilted fields. A recent theoretical work by Koshelev²² showed that the ground state under the tilted fields except for $\theta \sim 0^\circ$ is the crossing lattice state consisting of almost independent units of pancake and Josephson vortices in such superconductors. The interesting Bitter decoration pattern of vortex chains embedded in vortex lattices observed in BSCCO single crystals¹¹ is explained by the mechanism that Josephson vortices attract additional pancake vortices. In the same framework, experimentally observed linear dependence of $H_{FOT} \cos \theta$ on the in-plane component of field¹⁷ is also understood. In this theory, a transition from the mixed chains-lattice state to the distorted lattice is suggested in the crossing lattice state. This transition is a good candidate for the origin of the anomaly at H_p^* . Experimental data below θ^* can be fitted by the estimated transition field (Eq. 11 of Ref. 22) as shown in Fig. 5(a). Although we have a reasonable fitting to the data in $\theta < \theta^*$ and the reasonable values of γ (600, 240, 200, 140 for the OPT, OV1, OV2, HOV samples, respectively), the obtained penetration depth $\lambda = 400 \text{ \AA}$ is too short compared with generally accepted value of about 2000 \AA in BSCCO. Strictly speaking, the formula is valid when pancake-lattice spacing $a \gg \lambda$ and $\gamma \gg \lambda/s$, which do not hold at H_p^* . However, general trend is believed to be valid beyond this range. This might be the reason why we get unexpectedly short λ from the fitting.

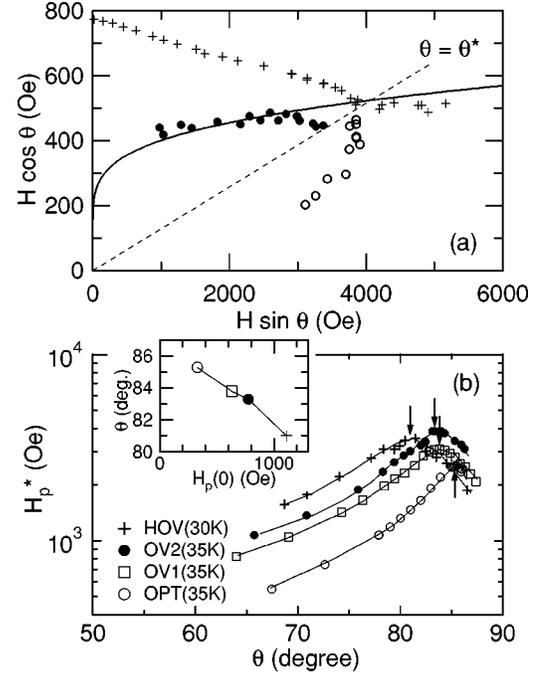


FIG. 5. (a) Dependence of $H_p^* \cos \theta$ on the in-plane component of the field for the OV2 sample below (closed circles) and above (open circles) θ^* . Additionally, $H_p \cos \theta$ (pluses) is also plotted. Solid curve shows a fit to the transition line for the mixed chains lattice state to the distorted lattice with $\gamma=200$, $\lambda=400 \text{ \AA}$ and the distance between neighboring superconducting layers $s=15 \text{ \AA}$. (b) Angular dependence of H_p^* in decreasing-field branch for four samples with different doping levels. Solid lines are guides to the eye. Arrows indicate the angle where $H_p^*(\theta)$ shows a maximum. This angle is plotted as a function of $H_p(0)$ in the inset.

In this scenario, deviation from the above behavior at angles larger than θ^* might reflect the presence of additional transition in the vortex lattice structure. Particularly, it is interesting to point out that the transition in this angle range occurs at an almost constant in-plane field value as shown in Fig. 5(a), suggesting the contribution from the Josephson vortex lattice. The deviation from the scaling law of H_p above θ^* may also be understood as reflecting a change in Josephson vortex lattice, such as the overlap of Josephson vortices.

Another possible transition is the one from the mixed chains lattice state to uniformly tilted lattice state. Bitter decoration pattern observed by Bolle *et al.*¹¹ implies that the uniformly tilted lattice is not an equilibrium phase in low and oblique fields in superconductors with large anisotropy. Besides Koshelev's theory, the instability of uniformly tilted vortex lattice has been predicted by several theories.²³⁻²⁵ Particularly, Thompson and Moore²⁵ have suggested that uniformly tilted vortex lattice state including vortex chain state observed in YBCO is not stable in low and tilted fields, when the superconductor has larger anisotropy ratio than a threshold. According to their calculation, the threshold is $\gamma \sim 12$ for $\kappa=50$, which is much smaller than γ of BSCCO.

To compare the anomaly with the instability of the vortex lattice, the angular dependence of H_p^* in four samples with different oxygen contents is plotted in Fig. 5(b). The charac-

teristic features that $H_p^*(\theta)$ reaches maximum at about 80° and decreases at higher angles are consistent with the expectation of the instability field for $\gamma=60$ and $\kappa=50$ by Thompson and Moore.²⁵ The angle where the instability field has a maximum is predicted to shift to lower angle at smaller anisotropy γ . This is actually observed in our experiments. As shown in the inset of Fig. 5(b), this angle decreases with decreasing anisotropy, which is known to be inversely correlated to the peak field $H_p(0)$ when $H\parallel c$.²⁶ Another point is that the temperature dependence of the instability field is expected to be proportional to the mean-field upper critical field $B_{c2}(T)$, which may explain the observed linear temperature dependence above $0.5T_c$ [Fig. 4(b)]. As shown above, qualitative features of the magnetization anomaly H_p^* are consistent with the calculation of Thompson and Moore.

In summary, we measured the local magnetization hysteresis curves under tilted fields from the c axis in BSCCO single crystals. We found a magnetization anomaly in the

vortex lattice phase, which is not present when the field is parallel to the c axis. Observed sharp change of magnetization at the anomaly (H_p^*) suggests the change of the vortex ordering as a possible origin of the anomaly. Transition from the mixed chains lattice state to the distorted lattice state as suggested recently by Koshelev may explain this anomaly. Alternatively, the angular, temperature, and oxygen doping dependence of H_p^* are qualitatively similar to the theoretical calculation for the instability of the uniformly tilted vortex lattice. Direct observations of vortex lattice ordering under tilted fields in the field range of interest are highly desirable.

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