Novel Angular Scaling of Vortex Phase Transitions in $Bi_2Sr_2CaCu_2O_{8+y}$

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Local magnetization measurements using micro-Hall probes in $Bi_2Sr_2CaCu_2O_{8+y}$ single crystals under various field angles θ from the c axis reveal that the angular dependence of the first-order transition (H_{FOT}) and the second peak (H_p) is clearly different from the conventional scaling law. Instead, we found a novel angular scaling, which is expressed as $H_{FOT}, H_p \propto [\cos\theta + \alpha(T)\sin\theta]^{-1}$ [$\alpha(T)$: temperature dependent parameter] in a wide angle range. Two possible origins for this novel angular dependence are discussed: (1) The effect of the electromagnetic coupling between pancake vortices and (2) the suppression of the Josephson coupling by the in-plane field. [S0031-9007(99)09180-2]

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In the mixed state of high-temperature superconductors, it has been revealed that the vortex phase diagram is more complex than that of the conventional superconductors owing to elevated critical temperature, small coherence lengths, and large anisotropy by layered structures [1,2]. Experimentally, the phase diagram has been extensively studied particularly in $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) [3] and $YBa_2Cu_3O_{7-\delta}$ (YBCO) [4,5] single crystals when the field was applied parallel to the c axis. One of the most remarkable phenomena is the first-order phase transition (FOT), which is detected as a step in the magnetization [3]. Several possibilities have been proposed as the origin of FOT: melting of the vortex lattice into a liquid of vortex lines, decoupling of liquid lines into vortex pancakes, or both transitions occurring simultaneously [6,7]. In BSCCO, the FOT line in H-T phase diagram terminates at a critical point and is followed by the line of the peak effect at lower temperatures [8]. The peak effect is interpreted as originating from 2D-3D crossover [9,10], mechanical entanglement of vortex lines [11], and a transition from a Bragg glass phase into a vortex glass or a liquid [12]. Furthermore, a more complicated phase diagram in BSCCO has been experimentally proposed by Fuchs *et al.* [13], in which two new phase boundaries, depinning and unidentified T_x lines are added.

In BSCCO, very large anisotropy is one of the key features to understand its complicated phase diagram. In this system, the angular dependence of the phase transitions can provide important information on the interlayer coupling. According to the scaling law based on the anisotropic Ginzburg-Landau (GL) theory by Blatter *et al.* [14], the angular dependence of vortex lattice melting transition is expressed by

$$H_{\mathrm{melt}}(\theta) = H_{\mathrm{melt}}(0)\,(\cos^2\theta + \gamma^{-2}\sin^2\theta)^{-1/2}. \quad (1)$$

Here, θ is the angle between the field and the c axis, and $\gamma = (m_c/m_{ab})^{1/2}$ is the anisotropy ratio. In fact, it has been reported that the angular dependence of the phase transition in YBCO ($\gamma \sim 5$) [15] is consistent with Eq. (1) [16,17]. On the other hand, in BSCCO with large anisotropy ratio $\gamma \sim 50-200$ [18,19], the discretization owing to the layered structure becomes more important. In addition, importance of the electromagnetic coupling (EMC) between pancake vortices compared with small Josephson coupling (JC) due to large γ in BSCCO has been recognized [20,21]. Inhomogeneity of magnetic field by screening cannot be neglected because the transition occurs when the vortex spacing is close to the penetration depth. EMC is predicted to change the exponent α in $H_{\mathrm{melt}}(\theta = 0) \propto (1 - T/T_c)^\alpha$ from 2 [22] to 3/2 [20], which is close to the experimentally obtained value [3]. Moreover, the temperature dependence of entropy change at FOT has been explained within this framework [21].

Since the discretization along the c axis and EMC are ignored in Eq. (1), it is unclear whether Eq. (1) also holds in BSCCO. In this Letter, we investigate the precise angular dependence of FOT field (H_{FOT}) and second peak field (H_p) in BSCCO, and find that Eq. (1) breaks down. Instead, we propose a new scaling law for the angular dependence of vortex phase transitions.

Single crystals of BSCCO have been grown by the floating zone method. We measured several samples with different oxygen contents, which were controlled by annealing at 300–350 °C for one day in an appropriate partial oxygen pressure. In this paper, we show results for four samples: optimally doped, slightly overdoped (as-grown), overdoped, and highly overdoped ones, whose typical dimensions are $0.5 \times 0.5 \times 0.03$ mm^3. The critical temperatures T_c are 86.7, 85.5, 80.3, and 76.8 K, respectively. The local magnetization parallel to the c axis was measured as a function of applied magnetic field (H_a) by using two micro-Hall probes (GaAs/AlGaAs two-dimensional electron gas) on the same chip. The active area of the probes is 30×30 μm^2. The configuration of the experiments is schematically shown in the inset of Fig. 1(a). A sample was directly mounted on one of the Hall probes by Apiezon grease. The small angle difference between the ab plane and Hall probe was carefully calibrated by comparing data above and below 90°. The other Hall probe was used to calibrate the angle between the c axis and the applied field.

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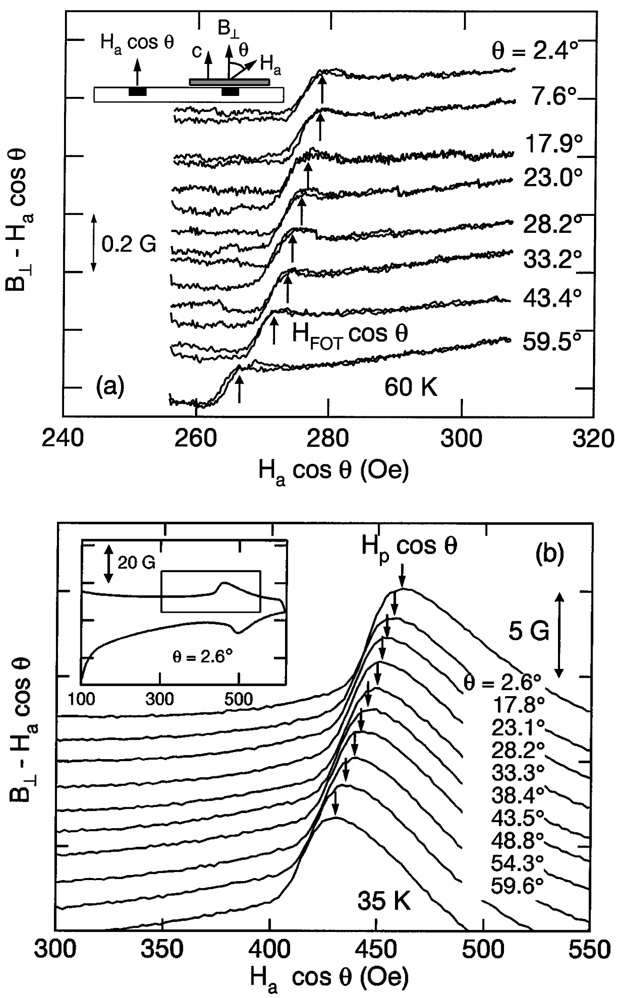

FIG. 1. Local magnetization hysteresis curves around (a) the FOT and (b) the peak effect in slightly overdoped BSCCO single crystal at various angles. In both figures, curves are shifted in the vertical direction for clarity. In (a) arrows indicate $H_{\rm FOT}\cos\theta$ and the inset shows the configuration of the Hall probes (two black rectangles) and the sample (hatched rectangle) schematically. In (b) arrows show the peak positions. The main panel is the expanded view of the rectangular flame in the inset.

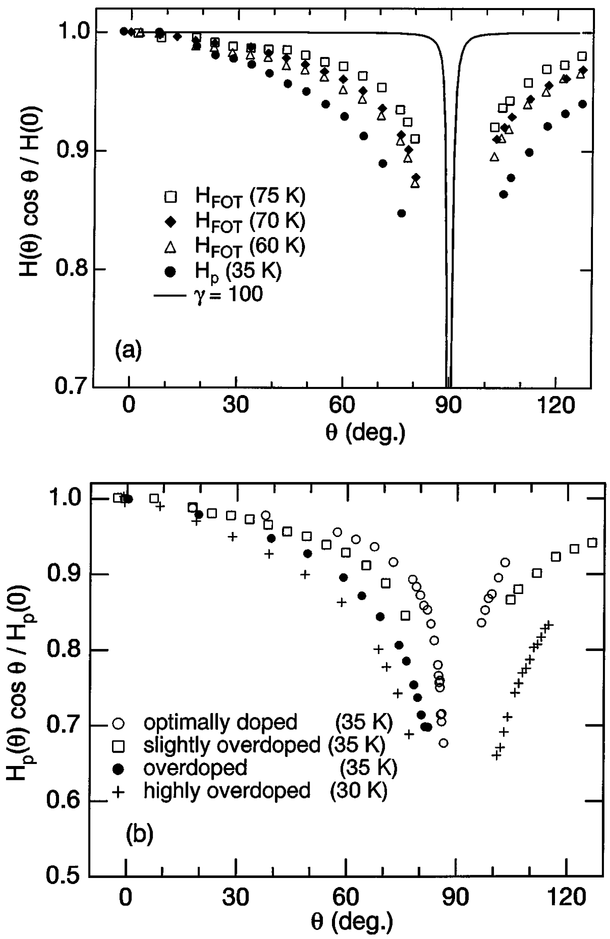

FIG. 2. Angular dependence of (a) $H_{\rm FOT}\cos\theta$ and $H_p\cos\theta$ in slightly overdoped sample and (b) $H_p\cos\theta$ in the samples with different oxygen contents. The horizontal values are normalized by the value at $\theta = 0°$ of each data. In (a) the solid line shows the curve of Eq. (1) with $\gamma = 100$.

Hall probes detect the local induction perpendicular to the plane ($B_\perp$). Therefore, we can measure the local magnetization perpendicular to the *ab* plane ($B_\perp - H_a\cos\theta$).

Figure 1(a) shows the field dependence of local magnetization around FOT at various field angles at 60 K in the slightly overdoped BSCCO. If the angular dependence of $H_{\rm FOT}$ is represented by Eq. (1), $H_{\rm FOT}(\theta)\cos\theta$ should be almost constant, $H_{\rm FOT}(0)$, except for a narrow angle range near $\theta = 90°$ ($H_a \parallel ab$) because of the large anisotropy in BSCCO. However, $H_{\rm FOT}(\theta)\cos\theta$ decreases gradually with increasing θ as shown in Fig. 1(a). A similar angular dependence is also observed for $H_p(\theta)\cos\theta$ as shown in Fig. 1(b). The angular dependence of $H_{\rm FOT}$ and H_p at several temperatures is plotted in Fig. 2(a) together with the curve of Eq. (1) with $\gamma = 100$. A clear difference is observed between the data and the curve of Eq. (1). For the peak effect, the deviation clearly starts from small angles ($<10°$). Similar deviations from the scaling at large angles ($\theta > 60°-70°$) have been reported in other experiments [23,24]. The deviation from Eq. (1) becomes larger with decreasing temperature. Figure 2(b) shows the angular dependence of H_p in samples with different oxygen contents [25]. Deviations of $H_p(\theta)$ from Eq. (1) are observed in all samples. The deviation becomes larger when the doping level is increased.

One might think that the angular dependence of $H_{\rm FOT}$ is different from that of $B_{\rm FOT}$ because of the angular dependence of the reversible magnetization ($M_{\rm rev}$). An angular dependence study of the magnetization by using the SQUID magnetometer [23] shows that the absolute value of $M_{\rm rev}$ parallel to the *c* axis gradually increases by approximately 10% for $\theta = 76°$ around $H_{\rm FOT}$ at 70 K in an overdoped BSCCO. Since the local reversible magnetization is less than 5 G and the $H_{\rm FOT}$ is $\sim$150 Oe in our slightly overdoped sample at 70 K, the influence due to the angular dependence of $M_{\rm rev}$ is small enough ($<0.4\%$) compared with the deviation from Eq. (1). Therefore, the deviation for the angular dependence is intrinsic to the FOT and the peak effect.

To check whether Eq. (1) can be fitted to the experimental data qualitatively, the data are plotted in Fig. 3, whose horizontal and vertical axes are $[H(\theta)\sin\theta/H(0)]^2$ and $[H(\theta)\cos\theta/H(0)]^2$, respectively. Although Eq. (1) must be shown by a straight line in this plot, the experimental results are clearly different from that. To understand this deviation, we need to consider effects which were ignored in the derivation of the scaling law [14].

One possible origin is the influence of screening [24,26]. In the derivation of the scaling law [Eq. (1)], it is assumed that the field is large enough and the screening of the magnetic field is ignored. This assumption corresponds to ignoring EMC term in the tilt modulus [26]. In BSCCO, however, the FOT and the peak effect occur near H_{c1}. In this situation, EMC is important as is JC.

The observed deviation from Eq. (1) can be qualitatively explained as follows. The contribution of EMC to the tilt modulus does not depend on γ, while the contribution of JC decreases to zero with increasing γ to infinity [20]. In the condition of $\gamma = \infty$ without EMC, the angular dependence of the transition field is determined by the out-of-plane component of the field. However, if there is a finite EMC between pancake vortices, this contribution makes the system more isotropic and weakens the angular dependence over that given by Eq. (1). Therefore, it is expected that EMC makes vortex transitions occur at lower fields than that by Eq. (1) in tilted fields. Experimentally, the deviation from Eq. (1) is more remarkable at lower temperatures. This behavior is consistent with the fact that EMC becomes more important than JC at low temperatures [21].

Another possible origin is the effect of the in-plane field on JC, which is averaged over in the anisotropic GL model ignoring layered structure. The fields where vortex lattice melting transition [22], decoupling transition [27], and 2D-3D crossover [28] occur are expected to be proportional to γ^{-2} at $\theta = 0°$. Assuming that the in-plane field suppresses JC and the apparent anisotropy increases at constant out-of-plane field, $H_{\mathrm{FOT}}\cos\theta$ and $H_p\cos\theta$ are expected to become smaller with increasing the in-plane field.

To see the influence of the in-plane field, the out-of-plane component $[H_\perp = H(\theta)\cos\theta]$ of the transition field is plotted in Fig. 4(a) as a function of the in-plane field $[H_\parallel = H(\theta)\sin\theta]$ in the slightly overdoped crystal. Interestingly, the transition field follows a straight line in this plot for all temperatures. Therefore, we obtain a unique relation as an experimental result,

$$H(\theta) = H(0)[\cos\theta + \alpha(T)\sin\theta]^{-1}. \qquad (2)$$

Here, $\alpha(T)$ is the only one fitting parameter. As shown in the inset of Fig. 4(a), $\alpha(T)$ becomes large at lower temperatures. This new relation also holds with good accuracy for the peak effect in samples with different oxygen contents as shown in Fig. 4(b). In the inset of Fig. 4(b), α is plotted as a function of $H_p(0)$ which is roughly proportional to γ^{-2}.

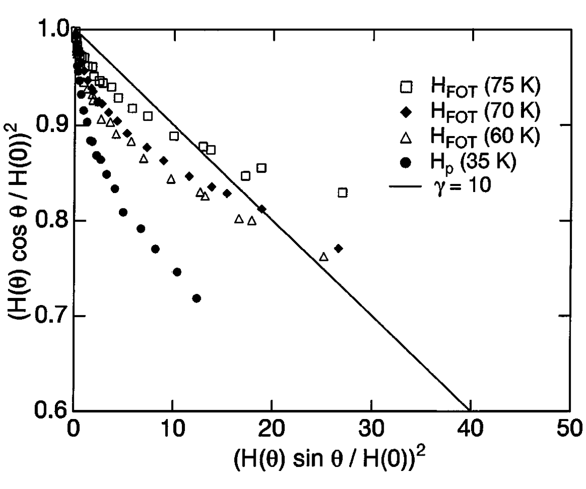

FIG. 3. $[H(\theta)\cos\theta/H(0)]^2$ as a function of $[H(\theta)\sin\theta/H(0)]^2$ in the slightly overdoped BSCCO. The solid straight line represents the conventional scaling [Eq. (1)] with $\gamma = 10$.

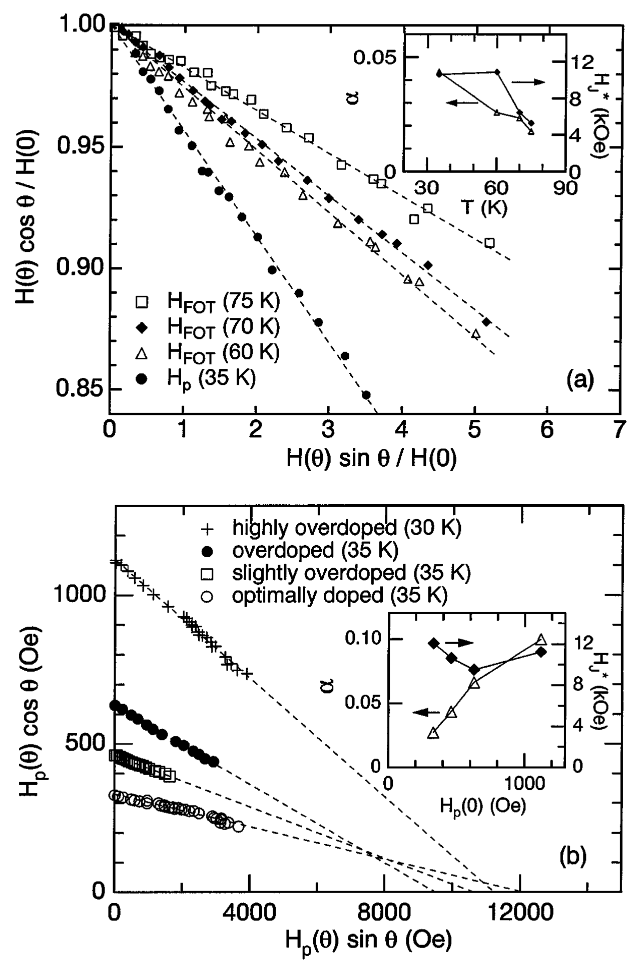

FIG. 4. Angular dependence of $H_{\mathrm{FOT}}\cos\theta$ and $H_p\cos\theta$ plotted as a function of the in-plane field ($H\sin\theta$) for (a) the slightly overdoped sample and (b) the samples with different oxygen contents. In both figures, the broken lines show the results of fitting by Eq. (2). The insets are (a) temperature and (b) H_p dependence of α and H_J^*.

We try to interpret this angular dependence as the change of anisotropy by the in-plane field. From Eq. (1), $H(\theta)$ is approximately equal to $H(0)/\cos\theta$ at large γ except near $\theta = 90°$. The angular dependence, therefore, can be written as

$$H(\theta)\cos\theta \simeq H(0) \equiv H_0/\gamma^2. \tag{3}$$

Here, the anisotropy dependence of $H(0)$ is assumed to be proportional to γ^{-2} and H_0 is a constant. When the field is tilted, however, the results show that the angular dependence gradually deviates from $(\cos\theta)^{-1}$. If the deviation is caused by the change of the anisotropy by $H_\parallel$, the anisotropy depends on $H_\parallel$ as

$$1/\gamma^2 = 1/\gamma_0^2(1 - H_\parallel/H_J^*) \tag{4}$$

in order to reproduce the experimental relation Eq. (2). Here, γ_0 is γ at $H_\parallel = 0$ and H_J^* is a characteristic in-plane field. By substituting Eq. (4) into Eq. (3), we can obtain Eq. (2) with $\alpha(T)$ represented by $H(0)/H_J^*$.

Equation (4) implies that when $H_\parallel$ reaches H_J^*, the anisotropy γ diverges to infinity, i.e., the correlation of pancake vortices between the layers disappears. H_J^* is estimated as about 10 kOe at 30 K [Fig. 4(b)] and has a tendency to decrease with increasing temperature [see inset of Fig. 4(a)]. The decoupling by the in-plane field is expected to occur at $H_J = \Phi_0/\gamma s^2$, when the phase cores of Josephson vortices start to overlap [1]. If H_J is the same value as H_J^*, the anisotropy is estimated to be approximately 1000 for $s = 15$ Å which is larger than reported values. Moreover, H_J^* hardly depends on the oxygen contents. Thus, H_J^* is independent of anisotropy which depends strongly on the oxygen content in BSCCO. By contrast, H_J does depend on oxygen content and cannot be simply related to H_J^*. A plausible explanation is that the linear relation Eq. (2) holds well when $H_\parallel$ is not so large, while near $\theta = 90°$ some higher order terms of $H_\parallel$ might be important.

Recently, Koshelev showed that a linear dependence of the melting field on the in-plane field is expected in the case where the ground state is represented by a sparse lattice of Josephson vortices coexisting with a dense lattice of pancake vortices [29]. In layered superconductors with very weak JC such ground state may be realized when EMC predominates.

Finally let us comment on the relation between our results and previous studies on angular dependence in BSCCO. There are several studies which show that the in-plane field does not influence JC. For instance, the angular dependence of magnetoresistance [30] was interpreted as evidence that BSCCO is transparent for the in-plane field [31]. Josephson plasma resonance, which reflects the strength of JC, is reported to be almost determined by the out-of-plane field at $\theta < 85°$ [32]. These experiments, however, were carried out in *the vortex liquid phase.* Since JC in *the vortex lattice phase* is rather important for the angular dependence of H_{FOT} and H_p, they cannot be compared with results in the vortex liquid state.

In conclusion, the angular dependence of H_{FOT}, H_p cannot be fitted by the conventional angular scaling based on the anisotropic GL model. Instead, we found an unique relation $H(\theta) \propto [\cos\theta + \alpha(T)\sin\theta]^{-1}$. We propose two scenarios for this novel angular scaling: (1) The contribution of the electromagnetic coupling and (2) the effect of the in-plane field on the Josephson coupling. For the former, a quantitative theoretical calculation is needed. On the other hand, in the latter scenario our experimental result implies that the Josephson coupling is strongly suppressed by the in-plane field in vortex lattice phase.

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