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Interlayer Phase Coherence in the Vortex Matter Phases of $Bi_2Sr_2CaCu_2O_{8+y}$

T. Shibauchi,[a,b] T. Nakano,[b] M. Sato,[b] T. Kisu,[b] N. Kameda,[b] N. Okuda,[b] S. Ooi,[b]* and T. Tamegai[b]

[a]IBM T. J. Watson Research Center, P. O. Box 218, Yorktown Heights, NY 10598, USA
and MST-STC, Los Alamos National Laboratory, MS-K763, Los Alamos, NM 87545, USA

[b]Department of Applied Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

The vortex matter phase diagram in $Bi_2Sr_2CaCu_2O_{8+y}$ is studied by the magnetization measurements and by Josephson plasma resonance. Above the first-order transition (FOT), sample-moving magnetization measurements show an anomaly suggesting the surface-barrier related transition (T_x line). We find a strong change in the interlayer phase coherence at the FOT and the second peak lines, indicating the decoupling nature of these lines. However, we find no anomaly in the interlayer phase coherence at the T_x line. These results rule out the existence of the vortex line liquid state.

1. INTRODUCTION

The vortex phase diagram in high-T_c superconductors is rich and complex. In $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO), there is a first-order transition (FOT) line well below the mean-field T_c, which terminates at the critical point and is followed by the second peak line (H_{sp}). In addition, a possible new phase boundary (T_x line) above the FOT was suggested by Fuchs *et al.* [1]. The nature of each vortex matter phase can be clarified by investigating the coherence between the layers. The interlayer phase coherence $\langle\cos\phi_{n,n+1}\rangle$ can be determined experimentally by the Josephson plasma resonance (JPR) [2], since the Josephson plasma frequency ω_p is given by

$$\omega_p^2(H,T) = \omega_p^2(0,T)\langle\cos\phi_{n,n+1}\rangle(H,T), \qquad (1)$$

where $\phi_{n,n+1}$ is the gauge-invariant phase difference between the layers n and $n+1$, and $\langle\cdots\rangle$ denotes thermal and disorder averaging [3].

2. EXPERIMENTS

Single crystals of BSCCO were grown by the floating zone method [4]. In this paper, we focus on the results in an underdoped crystal with $T_c = 84.6$ K. We determined vortex phase boundaries by global and local magnetization measurements using a commercial SQUID magnetometer and a micro-Hall probe [5]. The JPR at 11 frequencies was investigated by using the cavity perturbation technique with the microwave electric field E_ω parallel to the c axis [6]. The resonance field (H_p), where the measurement frequency coincides with the plasma frequency, is determined by the peak in the field dependence of the microwave absorption.

3. RESULTS AND DISCUSSION

Figure 1 shows the vortex phase diagram in the BSCCO crystal. The FOT temperature (T_{FOT}) was determined by a step in the temperature dependence of the magnetization $M(T)$ and the second peak field (H_{sp}) was determined by a peak in the field dependence of the magnetization $M(H)$ at temperatures below the critical point. At higher fields, sample-moving magnetization measurements show a distinct step in reversible $M(T)$ [7]. The positions of the steps in H-T plane (T_x in Fig. 1) are quite consistent with the surface-barrier related transition proposed by Fuchs *et al.* [1]. The step height at T_x depends on the scan length while the position remains unchanged. Thus, we interpret this anomaly as a

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*Present address: National Research Institute for Metals, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan

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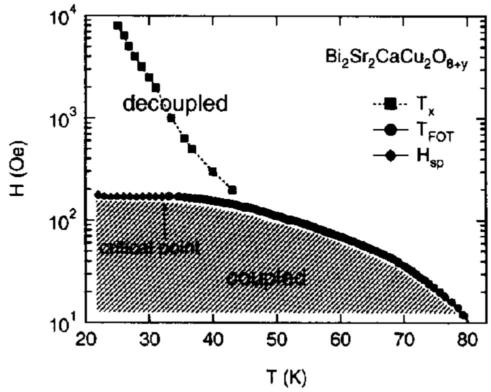

Figure 1. Vortex phase diagram of an underdoped BSCCO crystal.

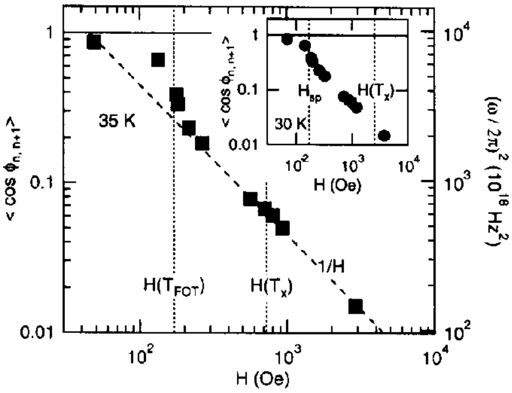

Figure 2. Field dependence of the interlayer phase coherence above (main panel) and below the critical point (inset).

sign of a change in the vortex penetration owing to the small change of the applied field during the scan in an inhomogeneous field distribution. The sample-stationary measurements show no such step within our resolution (< 0.1 G). This is also consistent with the previous reports [1,4].

The field dependence of the interlayer phase coherence at 35 K is plotted in Fig. 2. Here $\langle\cos\phi_{n,n+1}\rangle$ was determined by using Eq. (1). At the FOT field, the interlayer phase coherence changes drastically, indicating the decoupling nature of the FOT. Above the FOT field, the $\langle\cos\phi_{n,n+1}\rangle$ changes smoothly as $1/H$, which is consistent with a theoretical calculation [8] assuming the decoupled pancake liquid state. No anomaly in the interlayer phase coherence is found at the T_x line. This result indicates that the decoupling occurs at the FOT, not at the T_x line. Thus, we can rule out the line liquid state in BSCCO. We note that similar first-order decoupling transition has been found in a layered organic superconductor [9].

Below the critical point, the interlayer phase coherence also shows a strong change around the second peak line, as demonstrated in the inset of Fig. 2. Such a loss of interlayer coherence at H_{sp} is strong experimental evidence for disorder-induced decoupling [10] or entanglement [11] scenarios for the second peak.

In summary, we clarified the nature of each vortex matter phase in terms of interlayer phase coherence, which is summarized in Fig. 1. Vortices in BSCCO are decoupled just above the FOT and the second peak lines, and no anomaly in the interlayer phase coherence was found at the T_x line.

REFERENCES

1. D. T. Fuchs *et al.*, Phys. Rev. Lett. **80** (1998) 4971.
2. Y. Matsuda *et al.*, Phys. Rev. Lett. **75** (1995) 4512; Phys. Rev. Lett. **78** (1997) 1972.
3. L. N. Bulaevskii *et al.*, Phys. Rev. Lett. **74** (1995) 801.
4. S. Ooi *et al.*, Physica C **302**(1998) 339 .
5. T. Tamegai *et al.*, Phys. Rev. B **45** (1992) 2589.
6. T. Shibauchi *et al.*, Phys. Rev. B **55** (1997) R11977.
7. T. Shibauchi *et al.*, Phys. Rev. Lett. **83** (1999) 1010.
8. A. E. Koshelev, Phys. Rev. Lett. **77** (1996) 3901.
9. T. Shibauchi *et al.*, Phys. Rev. B **57** (1998) R5622.
10. B. Horovitz and T. R. Goldin, Phys. Rev. Lett. **80** (1998) 1734; B. Horovitz, Phys. Rev. B **60** (1999) R9939.
11. D. Ertas and D. R. Nelson, Physica C **272** (1996) 79; T. Giamarchi and P. Le Doussal, Phys. Rev. B**55** (1997) 6577.