Vortex-matter phase transitions in $Bi_2Sr_2CaCu_2O_8$: Effects of weak disorder

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The vortex matter phase diagram in $Bi_2Sr_2CaCu_2O_8$ crystals is investigated by introducing very low doses of point and correlated disorder. We conclude that at least three distinct phases are present. The ordered low-field quasilattice phase has a finite shear modulus which vanishes at the first-order melting or sublimation transition at elevated temperatures. At lower temperatures the quasilattice transforms into a disordered solid as field is increased above the second magnetization peak. This disorder-driven transition shifts to lower fields with increased point disorder. The first-order transition displays corresponding downward curvature in the vicinity of the critical point. [S0163-1829(97)51526-8]

The behavior of vortices in type-II superconductors is determined by complex repulsive interactions between each other and by attractive interactions with the material defects. Thus the vortex matter structure is a complicated function of temperature, magnetic field, and material disorder.[1] This results in a rich phase diagram which is divided by numerous phase transitions and crossovers, the exact natures of which are still not resolved. Over the last few years it has become apparent that in high-temperature superconductors thermal fluctuations cause melting of the vortex lattice, thus forming two distinct phases, the vortex solid and the vortex liquid.[1,2] However, in highly anisotropic superconductors like $Bi_2Sr_2CaCu_2O_8$ (BSCCO) an unexpected additional phase boundary, the so called second magnetization peak, appears to exist within the region that is assumed to be the vortex solid.[3–6] The second peak transition forms an almost horizontal line in the low field and low temperature region of the B-T phase diagram (Fig. 1). Another fascinating feature of the vortex matter is the experimentally observed first-order phase transition (FOT).[7–12] The position of the FOT line on the phase diagram of BSCCO is shown in Fig. 1. This transition is expected, and indeed observed to occur only in very clean systems, whereas continuous transition or crossover is anticipated in the presence of strong disorder.[1] The exact nature of the observed FOT is still unclear. The three prevailing theoretical descriptions of the FOT can be classified as melting, evaporation, or sublimation.[1] The more commonly accepted scenario is melting of an ordered *solid* vortex lattice into a *liquid* of vortex lines.[1,2] In the evaporation (decoupling) transition the vortex-line *liquid* dissociates into a *gas* of uncorrelated vortex pancakes in the individual CuO planes.[13] Recently a sublimation transition (simultaneous melting and decoupling) was proposed in which the *solid* vortex lattice undergoes a direct transition into the pancake *gas*.[14] Figure 1 also shows a third experimentally observed boundary line, the depinning line, where the bulk pinning of the vortices drops below a detectable level.[15]

The emerging experimental picture of Fig. 1 is that the vortex matter seems to display at least *three* distinct phases with three phase boundary lines, rather than *two* main phases (solid and liquid) with only one transition line between them. In this paper we elucidate the structure of the different vortex phases (indicated as A, B, and C in Fig. 1) and the nature of the transitions between them. Our approach is based on controlled introduction of very low doses of point and correlated disorder as a weakly perturbative tool to investigate the underlying physical phenomena. Until now most experimental and theoretical efforts have focused on the rather extreme cases of clean[1,2,5–14] and highly disordered systems,[1,16] respectively. In contrast, the general knowledge of the effects of *weak* disorder is very limited.[3,17] We find that by exposing

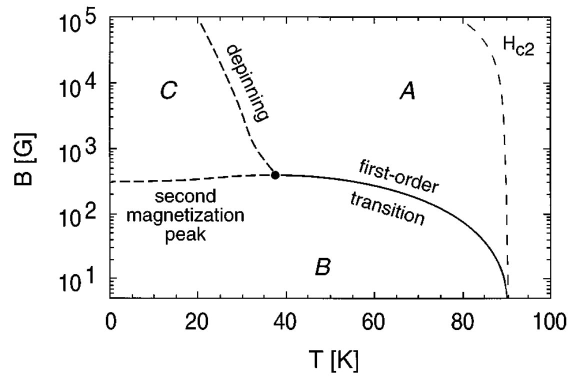

FIG. 1. Schematic vortex matter phase diagram in BSCCO (on a logarithmic scale). The major part of the diagram is occupied by phase A which is a vortex liquid (or a gas of vortex pancakes). Phase B is a rather ordered solid quasilattice, whereas phase C is a highly disordered vortex solid. At elevated temperatures the quasilattice is destroyed by thermally-induced melting (or sublimation) at the FOT. At low temperatures a disorder-driven solid-solid transition occurs at the anomalous second magnetization peak. The disordered solid, C, melts continuously at the depinning line.

BSCCO crystals to very low doses of electron or heavy-ion irradiation the basic structure of the vortex matter phase diagram is preserved, while the position of the transition lines is slightly shifted and the pinning properties are modified. A comparative study of these variations provides new insight into the underlying mechanisms governing the second peak, the first-order transition, and the structure of the related phases.

The BSCCO crystals, with $T_c \simeq 90$ K, were grown by the traveling solvent zone method.[18] Several small crystals with typical dimensions of $500\times300\times10$ μm^3 were cut from one large single crystal of very high quality and uniformity and irradiated by 2.5 MeV electrons or 5.8 GeV Pb ions. Electron irradiation (performed at École Polytechnique, France at 20 K) results in a random spread of point defects and small clusters with total damage of the order of 5×10^{-4} and 10^{-3} displacements per atom for our two irradiation doses.[3] Heavy-ion irradiation (GANIL, France), produces columnar defects extending through the crystal parallel to the c axis. We have investigated very low irradiation doses corresponding to matching fields B_ϕ of 5, 10, 20, 50, and 100 G ($B_\phi = n\phi_0$, where n is the density of columns and ϕ_0 is the flux quantum. For $B_\phi=5$ G, for example, the average distance between the columns is about 2 μm). Local magnetization measurements were made using arrays of microscopic GaAs/AlGaAs Hall-sensors[8] in external fields applied parallel to the c axis.

We first analyze the nature of the FOT and of phases A and B in Fig. 1 by studying the effects of columnar defects. In particular, we would like to know whether phase B is a solid or a liquid. Solids have a finite shear modulus and as a result can be pinned much more efficiently by material disorder. Thermal fluctuations, however, cause significant smearing of the point disorder pinning potential. As a result we find that bulk vortex pinning due to intrinsic disorder in as-grown BSCCO crystals is unobservably low at elevated temperatures both in phase A and in phase B,[15,19,20] and hence their structure cannot be readily established. Columnar defects, on the other hand, create very efficient trapping sites. We find that for $B_\phi \lesssim 20$ G the basic phase diagram of Fig. 1 is preserved: the transition lines are unshifted and the equilibrium magnetization step of the FOT at high temperatures is still observed. However, the pinning properties are changed appreciably as follows.

Figure 2 shows the local magnetization of as-grown BSCCO crystal in the vicinity of the FOT at 60 K, along with a crystal irradiated at a very low dose of $B_\phi=5$ G. The unirradiated crystal shows practically reversible magnetization below the FOT with unobservably low critical current. A small density of columns results in a pronounced hysteresis due to bulk pinning. Figure 3 displays this effect more clearly where the apparent critical current derived from the hysteretic magnetization is shown at $T=52$ K. The critical current is finite at low fields and it drops abruptly to zero at the location of the FOT indicated by B_m. Columnar defects corresponding to $B_\phi=5$ G trap only one in sixty vortices at fields of about 300 G in the vicinity of the FOT in Fig. 3, as indicated schematically in the inset. This situation is similar to trying to tack a carpet with just a few nails. In a liquid phase the untrapped 59 vortices can flow around one trapped vortex and the critical current remains zero. However in a solid phase all the vortices become effectively pinned through a finite shear modulus and the critical current is finite. Figures 2 and 3 are therefore a direct demonstration that phase B below the FOT is a vortex solid with a finite shear modulus which drops sharply to zero at $B_m(T)$. Phase A above the transition has no shear modulus and therefore is either a liquid of lines or a gas of pancakes. These conclusions are consistent with recent resistive measurements on BSCCO crystals with irradiated channels[21] as well as on unirradiated samples.[22,23] Since phase B is a vortex *solid*, the FOT cannot be an evaporation (decoupling) transition of a vortex line *liquid*. Hence the observed FOT is either vortex lattice melting, or rather a sublimation transition as concluded from recent multiterminal resistive measurements.[23]

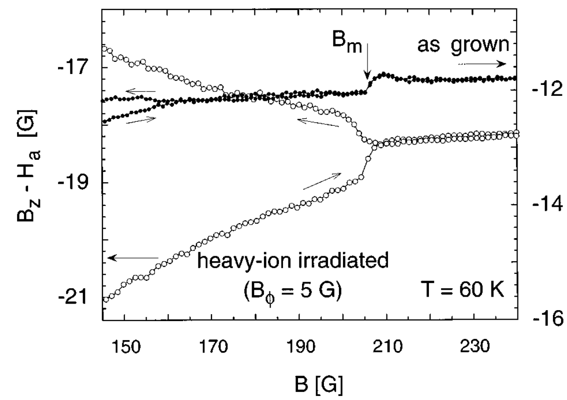

FIG. 2. Local magnetization loops $B_z - H_a$ vs the local field B_z ($T=60$ K) in BSCCO crystals before and after a very low dose of heavy-ion irradiation ($B_\phi=5$ G). B_m indicates the position of the equilibrium magnetization step at the FOT in the unirradiated crystal. Large hysteresis due to bulk pinning is observed after irradiation in the quasilattice phase below $B_m(T)$.

Next we turn to the question of the nature of the second peak transition. Phase C displays strong bulk pinning even in as-grown crystals, and hence is generally accepted to be a vortex solid. The second peak transition $B_{sp}(T)$ must therefore be a transition between two solid phases. Local magnetization measurements show that the transition is very sharp and that the apparent critical current, which is insignificant *below* $B_{sp}(T)$, appears abruptly as the field is raised above

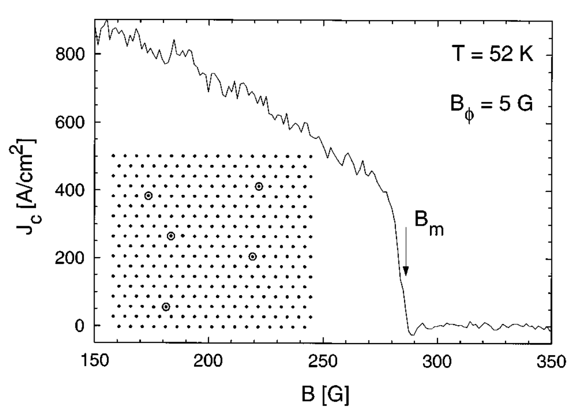

FIG. 3. Magnetically measured critical current in irradiated BSCCO crystal with $B_\phi=5$ G. The finite critical current in the solid quasilattice phase disappears suddenly at B_m due to an abrupt loss of the shear modulus at the FOT. Inset: a simplified corresponding schematic picture of a lattice of vortex lines (dots) in the presence of a low density of columnar defects (circles) for $B/B_\phi=60$.

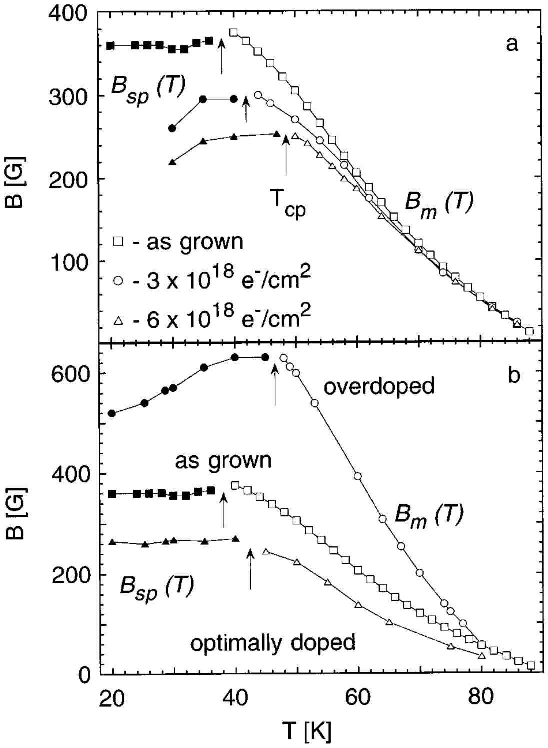

FIG. 4. (a) FOT lines $B_m(T)$ (open symbols) together with the second peak transition lines $B_{sp}(T)$ (filled symbols) for BSCCO crystals irradiated with different indicated doses of 2.5 MeV electrons. Enhanced point disorder destabilizes the quasilattice and causes a downward shift of the $B_{sp}(T)$ transition line. (b) Comparison of $B_m(T)$ and $B_{sp}(T)$ lines for different oxygen stoichiometry. Note the relative change in slope of the $B_m(T)$ lines at high temperature in contrast to the behavior in (a).

this line.[6] Several scenarios have been suggested to explain the second magnetization peak, including field dependent pinning,[24] dynamic effects,[25] and dimensional crossover B_{2D}.[4] However none of these mechanisms can explain the sharpness of the observed transition.[6] Figure 4(a) shows the FOT line $B_m(T)$ together with the second peak line $B_{sp}(T)$ in the as-grown crystal. These two lines merge at a critical point T_{cp}, where the FOT manifested by the equilibrium magnetization step terminates. Figure 4(a) also shows the position of these lines, both after a low dose of electron irradiation and after a second repeated irradiation of the same crystal, thereby doubling the dose. The selected low doses produce sufficiently weak point disorder that the FOT step is preserved and the position of the FOT line is unaffected at high temperatures. It also results in some increase of bulk pinning at very low temperatures. The main effect of this weak point disorder is, however, a significant shift of the $B_{sp}(T)$ line toward smaller fields as reported previously.[3] Further, the FOT line shows downward curvature at intermediate temperatures and an associated shift which matches that of the B_{sp} line. This remarkable behavior (the irreversibility or depinning line is generally expected to shift upwards with disorder in contrast to a downward shift here) was confirmed on a second different batch of crystals.

We argue that these findings demonstrate that (i) phase B is a well ordered vortex lattice, which we will refer to as the *quasilattice* state, (ii) phase C is a highly disordered vortex solid, and (iii) $B_{sp}(T)$ is a *disorder-driven* solid-solid transition. These conclusions are consistent with other experimental findings; small angle neutron diffraction measurements in phase B show clear Bragg peaks which are associated with an ordered state.[5] The ordered structure of phase B is also supported by μSR[5] and decoration[26] experiments. Figure 4(a) confirms this conclusion by demonstrating that phase B is *unstable* with respect to weak point disorder, as expected for an ordered state, and its stability region on the B-T phase diagram shrinks with increased point disorder. The existence of a finite long-range order and a lattice symmetry in phase B is also strongly supported by the fact that this phase melts through a FOT at elevated temperatures. Furthermore, we find that a low dose of columnar defects does not destabilize the quasilattice. This implies that the vortices in this phase are rather straight linelike objects. Point disorder, in contrast to the columnar defects, induces distortions or wiggling of the lines and leads to the destruction of the ordered lattice. Phase C, unlike phase B, is a highly disordered state according to the neutron diffraction and μSR measurements.[5] Figure 4(a) further emphasizes this conclusion by demonstrating that phase C is in fact *stabilized* by point disorder and its range on the B-T diagram expands when disorder is increased. This disordered state melts through a continuous transition where it becomes mobile at the depinning line of Fig. 1.[15,27]

It would be very surprising if the B_{sp} transition did not share a common mechanism with the FOT, since these two lines always form one continuous transition line across which the quasilattice state is destroyed. We argue that this is indeed the case; there are two sources for destruction of long range correlations in the vortex lattice. These are thermally induced vortex deformations and point disorder induced distortions respectively. As field or temperature are increased the elastic stiffness of the lattice becomes softer and the quasilattice becomes more susceptible to destruction. At high temperatures thermally induced deformations are large, while the effects of weak point disorder are strongly suppressed by thermal smearing. As a result at high temperatures the quasilattice is destroyed through *thermal melting*, and the position of the transition line is practically *independent of disorder* [see Fig. 4(a)]. At low temperatures the situation is just the opposite since thermal deformations are very weak. Here the quasilattice is destroyed at some characteristic field through *disorder-induced transition*, and the position of the transition line is practically *independent of temperature*. With increased point disorder this transition is shifted downwards. At intermediate temperatures, the two mechanisms add up and tail smoothly into one another, forming one continuous quasilattice phase boundary. The critical point T_{cp} marks where the transition changes from predominantly disorder induced to thermally induced character, and thus shifts to higher temperatures with increased disorder [Fig. 4(a)]. At temperatures slightly above T_{cp} disorder still contributes weakly by assisting the thermal destruction of the quasilattice, thereby resulting in the peculiar downward curvature of the FOT line towards T_{cp}. At the highest temperatures the point disorder is completely smeared out by thermal fluctuations and hence no effect on the FOT line is observed.

In the above discussion we have neglected the possibility that point disorder induced by electron irradiation can modify the penetration depth λ, anisotropy γ, and T_c, and thus cause an artifactual shift of the transition lines. Numerical estimates suggest that at our low doses these modifications are very small. More importantly, however, is the following direct *experimental* evidence against such possible artifact. Figure 4(b) shows both the $B_m(T)$ and $B_{sp}(T)$ transition lines in the as-grown crystal along with two oxygen doped crystals.[6] This doping is known to change the values of γ and λ (see Ref. 6 for details), and as a result, a significant shift in the transition lines is induced.[6,28] Both γ and λ enter as scaling parameters in the vortex melting expressions. When these parameters are changed the entire transition line is proportionally rescaled. For example, in the optimally doped crystal of Fig. 4(b) B_{sp} is shifted down to about 260 G as compared to about 360 G in the as-grown sample. This shift is accompanied by a uniform rescaling of the FOT line at all temperatures as expected. The effects of disorder in Fig. 4(a), however, are markedly different. At our highest irradiation dose, the shift of B_{sp} is comparable to the shift for the optimally-doped crystal of Fig. 4(b). However, in the case of irradiation, $B_m(T)$ is practically unchanged at high temperatures, and only the flattening of $B_m(T)$ at intermediate temperatures is affected. This strongly supports our interpretation that the changes in Fig. 4(a) are due to disorder which is effective only at low and intermediate temperatures. The fact that the FOT line at high temperatures did not change its slope and its position indicates that the microscopic parameters did not change within our experimental resolution.

Finally, we address the agreement between our findings and a number of recent theoretical studies[29,30] and numerical simulations[31] on this topical issue. We emphasize, however, that there is currently no explicit theoretical basis for the observed enhanced pinning above $B_{sp}(T)$. On the other hand, significant progress has been made recently in the description of the various transition lines in agreement with our experimental findings.[29–31] In particular, the quasilattice (or Bragg glass) is predicted to melt through a FOT at high temperatures, and to transform into a disordered state with a high density of dislocations as field is increased at low temperatures. The two transitions are predicted to form a single transition line that shifts downwards with increased point disorder[29–31] in accordance with our experimental observations. We find that the FOT persists even in the presence of a very low dose of columnar defects, whereas higher doses ($B_\phi > 20$ G) seem to transform it into a continuous transition. In conclusion, we have demonstrated experimentally that the quasilattice is a solid phase with a finite shear modulus, and that the downward curvature of the FOT, its termination at a critical point, and the continuation as the second peak transition at lower temperatures are all driven by quenched point disorder in BSCCO crystals.

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