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Effects of correlated disorder on vortex-lattice melting in BSCCO

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The vortex-lattice phase transitions in $Bi_2Sr_2CaCu_2O_8$ crystals with very low doses of artificially induced correlated disorder are studied using local magnetization measurements. A low density of columnar defects shifts the first-order transition to higher fields, apparently transforming it into a continuous transition.

The first-order vortex-lattice melting transition (FOT) manifests itself in magnetic measurements as a sharp step in equilibrium magnetization vs. temperature or applied field [1]. We study how this transition is changed in the presence of correlated disorder (columnar defects) in the crystal structure of $Bi_2Sr_2CaCu_2O_8$ (BSCCO). The FOT occurs only in very clean systems, whereas in the presence of strong disorder only continuous phase transitions or crossovers are anticipated [2,3]. Artificially induced disorder has a profound effect on the mixed state B - T phase diagram, substantially modifying the structure, dimensionality, and pinning behavior of the various vortex phases, and shifting the boundaries between the phases [2]. Until now most of the experimental efforts have focused on high densities of columnar defects [2]. Here we investigate the vortex-lattice phase transitions in BSCCO crystals in the presence of very low density of correlated disorder.

The experiments were carried out on several BSCCO crystals [4] with typical dimensions of $700 \times 300 \times 10\ \mu m^3$. The crystals were irradiated by 1 GeV Xe or 0.9 GeV Pb ions, which produced uniform columnar defects parallel to the crystalline c-axis. We have investigated very low irradiation doses corresponding to matching fields B_ϕ of 20, 50, and 100 G ($B_\phi = n\phi_0$, where n is the density of the columnar tracks and ϕ_0 is the magnetic flux quantum). The local magnetization measurements were performed in applied field $H_a||z||c$-axis using arrays of $10 \times 10 \mu m^2$ GaAs/AlGaAs Hall sensors [1].

Figure 1 shows magnetization curves in the vicinity of the melting transition $B_m(T)$ before and after irradiation with the lowest dose of $B_\phi =$ 20 G. At high temperatures we can still resolve the FOT magnetization step as indicated for the $T = 85$ K data in Fig. 1. At lower temperatures the step is not resolved, either due to possible masking by the strong pinning or due to the transformation of the FOT into a second-order transition [3]. The analysis of the field gradient dB/dx across the sample following the procedure of the Ref. [5] indicates that in the as-grown samples at high temperatures the bulk critical current is vanishingly small, and hence the hysteresis is due to surface and geometrical barriers, rather then due to bulk pinning. A small density of columnar defects causes very pronounced onset of strong bulk pinning even for $B \gg B_\phi$, which terminates abruptly at the bulk irreversibility field $B_{IB}(T)$. This $B_{IB}(T)$ is located at the original FOT line $B_m(T)$ for $B_\phi = 20$ G, when at higher irradiation doses, $B_\phi = 50$ G and 100 G, corresponding $B_{IB}(T)$ is now significantly shifted toward higher fields as shown in Fig. 2.

The bulk irreversibility line $B_{IB}(T)$ at $B_\phi = 50$ G displays a very interesting phenomenon. Figure 2 shows that at low fields $B_{IB}(T) \simeq B_m(T)$, at higher fields B_{IB} rises significantly and reaches a maximum relative deviation in the range of 100 to 150 G, and then approaches again the original $B_m(T)$ line at higher fields. This remark-

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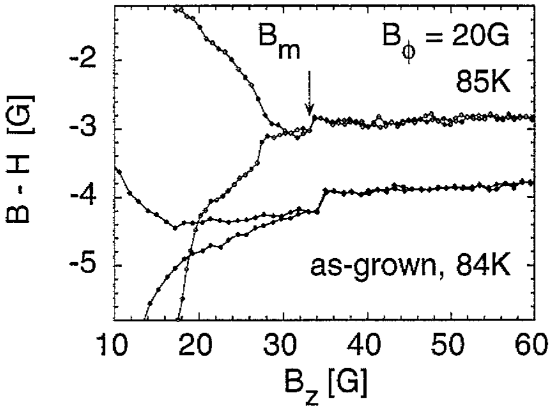

Figure 1: The magnetization step at B_m in as-grown crystal (84 K) and $B_\phi = 20$ G irradiated crystal (85 K).

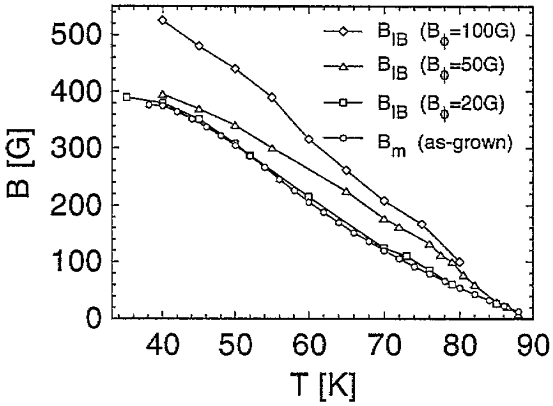

Figure 2: Bulk irreversibility line $B_{IB}(T)$ for BSCCO crystals after heavy-ion irradiation with various doses. The FOT line $B_m(T)$ for as-grown crystal is shown for reference.

able behavior can be interpreted as follows. At fields comparable to B_ϕ each vortex is effectively pinned by a columnar defect and the pinning interaction outweighs the vortex-vortex interactions. As a result, the pinned vortex lattice remains intact at the original $B_m(T)$ and the melting occurs only at higher temperatures. At fields significantly higher than B_ϕ the interaction between vortices outweighs the pinning potential, whereas at very low fields the original $B_m(T)$ probably occurs above the depinning temperature of columnar defects so that vortex-vortex interactions are dominant again. Therefore the relative shift of the transition for the $B_\phi = 50$ G sample is non-monotonic (see Fig. 2). On the other hand, $B_\phi = 100$ G is large enough to result in a substantial shift of the transition over almost the entire field range. The effects of columnar defects in the regime discussed above were recently analyzed theoretically within the Bose-glass description [3]. The Bose-glass transition $B_{BG}(T)$ in irradiated samples is in very good qualitative agreement with the data in Fig. 2. It is thus very tempting to interpret our $B_{IB}(T)$ as the Bose-glass transition.

In conclusion, we find that the FOT persists in the presence of sufficiently low doses of correlated disorder. Higher doses of columnar defects transform the first-order melting into probably second order Bose-glass transition, *stabilize* the solid phase with respect to the vortex liquid, thereby shifting the solid-liquid transition to higher fields.

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