Supercooling of the high field vortex phase in single crystalline BSCCO

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Time resolved magneto-optical images show hysteresis associated with the transition at the so-called “second magnetization peak” at \(B_{sp}\) in single-crystalline Bi\(_{2}\)Sr\(_{2}\)CaCu\(_{2}\)O\(_{8+\delta}\). By rapid quenching of the high–field phase, it can be made to persist metastably in the sample down to fields that are nearly half \(B_{sp}\).

Field–tuned pinning–induced order–disorder transitions \[1\] in the vortex lattice in type II superconductors have received much attention \[2–5\], for the insight they bring to the statistical mechanics of elastic manifolds in a random potential, but also because the plastically deformed disordered state is that which is most frequently encountered in practice, and which determines the high critical currents in technological superconductors. The transition to the disordered vortex state is particularly pronounced in layered materials such as Bi\(_{2}\)Sr\(_{2}\)CaCu\(_{2}\)O\(_{8+\delta}\) (BSCCO), in which the very small vortex line tension allows an optimal adaptation of the disordered vortex lattice to the local “pinscape”; hence, the transition is accompanied by a sharp and spectacular increase of the screening current \(j\) related to pinning, leading to the so-called “second magnetization peak” (SMP) \[6,4\]. This very marked feature has lead to speculations that the SMP represents a transition that is peculiar to layered superconductors. Here, we show that the transition at the SMP in BSCCO is accompanied by hysteresis and the persistence of the metastable high-field (disordered) vortex state at inductions \(B\) much smaller than \(B_{sp}\), at which the transition occurs when the system is near thermodynamic equilibrium.

The presence of the low–field (ordered) and high–field (disordered) vortex states in the sample is detected by direct imaging of the flux density distribution on the sample surface using the magneto-optical technique. The different vortex states can then be identified from the different critical current density which is related to the local induction gradient \(\partial B/\partial x\). For the experiments, we choose an optimally doped BSCCO single crystal of size 630 \(\times\) 250 \(\times\) 35 \(\mu\)m\(^3\), grown by the travelling solvent floating zone technique. The sample was covered by a magnetic garnet indicator film with in-plane anisotropy and cooled using a continuous flow cryostat. Magnetic fields \(H_a\) of up to 600 G could be applied using a split-coil electromagnet surrounding the cryostat. The magnet power supply and simultaneous data acquisition were controlled using a two-channel synthesized wave-generator.

Several types of experiment were performed: (i) rapid field sweeps (with different periods < 10 s) with synchronized acquisition of magneto-optical images at fixed phase (ii) relaxation of the flux distribution after a rapid drop of \(H_a\) from a

Figure 1. Magneto-optical image of the flux density distribution on the surface of the BSCCO crystal at \(T = 25\) K, after the magnetic field was rapidly decreased (rise time < 100 \(\mu\)s) from 600 G to 56 G. The image was taken 0.24 s after the target field was reached.
value above or close to $B_{sp}$. An example of the latter is depicted in Fig. 1, which shows the flux distribution 0.24 s after the target field of 56 G was reached following a quench from $H_a = 600$ G (the larger intensity corresponds to the greater flux density). Figure 1 shows a bright area of nearly constant $B$ in the crystal center, separated from the peripheral low $B$, low $\partial B/\partial x$ area by a belt of high flux density gradient. Analysis of the image shows that this high gradient is equal in magnitude to that measured during a slow field ramp for $B > B_{sp}$, even though here the local induction during the relaxation is (up to 160 G) smaller than $B_{sp}$. The same is found when the field is continuously swept at a sufficiently large rate. Fig. 2 shows profiles measured during the first and second quarter cycles after the application of a triangular waveform AC field of amplitude 600 G and frequency 0.1 Hz. The profiles are characterized by a jump in $B$ at the crystal edge due to the presence of the edge barrier current \footnote{6}, followed by the gradual decrease of $B$ in the interior, resulting from the bulk pinning current. From the break in the profiles and the appearance of a second Bean–like flux front above $B_{sp}$ in panel (a), we determine $B_{sp} = 360$ G for $T = 26$ K. Panel (b) shows that when $H_a$ is rapidly decreased, the relatively large gradient present at $B > B_{sp}$ is maintained around a gradually shrinking region in the crystal center, while, again, the local induction is smaller than $B_{sp}$.

We interpret these observations as being the result of the persistence of the metastable high–field vortex state at fields below the equilibrium phase boundary. While the appearance of the higher $\partial B/\partial x$ at a constant induction $B = B_{sp}$ during upward field ramps (Fig. 2(a)), independent of sweep rate, indicates that the order-disorder transition at the SMP is a thermodynamic phase transition, the observation of a persistent metastable state suggests that it is first order. The consequences are multiple. First, the phenomenology of the SMP in BSCCO is entirely equivalent to that in moderately anisotropic \footnote{3,5} or even isotropic superconductors \footnote{2}, i.e., one is dealing with a similar transition in each case. Second, a first order transition at the SMP implies that there is no critical point in the phase diagram, as previously suggested \footnote{7}. Finally, the presence of the quenched disordered vortex state at $B < B_{sp}$ will critically affect the outcome of dynamical creep and transport measurements at fields near the transition.

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