Vortex matter in Bi$_2$Sr$_2$CaCu$_2$O$_8$ with pointlike disorder

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Abstract. We investigate the effect of point-like disorder, introduced by irradiation with 2.3 MeV electrons, on the mixed state phase diagram of Bi$_2$Sr$_2$CaCu$_2$O$_8$ single crystals. We focus on the higher irradiation doses that produce a significant depression of the critical temperature $T_c$, to as low as 2/3 of the initial value. Surprisingly, the first order phase transition (FOT) of the vortex ensemble, from a crystal to the pancake vortex liquid, persists in those highly disordered samples. The second peak in the irreversible magnetization, observed at low temperatures, is equally observed after high irradiation doses, but at much lower magnetic fields. A simple scaling of the phase diagram for samples with various degrees of disorder is not possible, indicating that several fundamental parameters of the superconductor are affected. From the analysis of the angular dependence of the FOT, we deduce that the effective anisotropy factor increases after irradiation.

1. Introduction

The phase diagram of vortex matter in the highly anisotropic, high $T_c$ superconductor Bi$_2$Sr$_2$CaCu$_2$O$_8$ is dominated by the first order phase transition (FOT) line from an ordered vortex solid to a disordered liquid (or pancake gas) phase. At high temperature, this transition is identified by the discontinuity of the reversible magnetization [1], whereas, at low temperature, it manifests itself by the second magnetization peak (SMP) [2]. While the nature of the FOT at high temperature has been understood in the framework of the analogy with conventional matter (discontinuity in the volume vs. pressure dependence), the low temperature part and the identification of the SMP as the manifestation of the phase transition has been more difficult. The effect of controlled disorder of different nature (correlated and point-like) has provided decisive arguments for the presently accepted scenario of a unique FOT between an ordered phase at low magnetic fields to a disordered solid or glass low temperature, and a liquid at high temperature. The competition between the elastic energy of the vortex solid with thermal fluctuations and pinning determines the position of the transition line [3]. A small amount of additional point disorder produces vortex flux line meandering and a strong depression of the SMP [4,5] without noticeable effect on the high temperature part of the FOT. The introduction of point-like disorder by irradiation results in excess pinning but also in the decrease of $T_c$. The latter effect was negligible in previous investigations of the vortex phase diagram, which were limited to low doses. Here we explore the evolution of the phase diagram of vortex matter of Bi$_2$Sr$_2$CaCu$_2$O$_8$ with $T_c$ tuned by disorder.
2. Experimental Results and Discussion

Selected single crystals of slightly overdoped Bi$_2$Sr$_2$CaCu$_2$O$_8$ were cut into rectangles (300 × 500 × 20 µm$^3$). Each sample was exposed to a different dose of 2.3 MeV electrons in the VINKAC facility (van de Graaff accelerator coupled to a closed-cycle hydrogen liquefier). The penetration range of the electrons exceeds the sample thickness, assuring the homogeneity of irradiation damage, which takes the guise of Frenkel pairs on all sub-lattices. In order to prevent migration and the agglomeration of defects, the samples were immersed in liquid hydrogen (20 K) during irradiation. The transfer of the samples to the Hall-array based magnetometer required warming to room temperature, resulting in the partial annihilation of defects between 120 and 140 K. The remaining stable defects at room temperature cannot be identified by transmission electron microscopy and must therefore be of atomic size. Performing electron irradiation at low $T$, below the threshold temperature for defect migration, is essential to achieve point-like disorder. Failure to do this results in a process of continuous migration and agglomeration of defects and to ill-controlled damage in the form of large clusters.

The estimated damage for the highest irradiation dose of 1.7 × 10$^{20}$ electrons/cm$^2$, expressed in displacement per atom (dpa) was 0.024, i.e., more than one atom per 50 was ejected from its initial position. As the result of this damage, $T_c$ (as deduced from AC shielding) was depressed from 87 to 58 K. The phase transition line $B_m(T)$ was identified from magnetic measurements using a Hall-array magnetometer. The position of the FOT at high temperature was obtained from the paramagnetic peak in the local AC response [5], while the sudden variation in the irreversible magnetization was used to determine the position of the vortex order-disorder transition at low temperatures.

Measurements of the dc magnetization and of the ac response were performed in the same set-up. The rectangular sample was placed on top of an 11-element array of 8 × 8 µm$^2$ 2DEG Hall sensors, with 20 µm spacing, with the short sample axis parallel to the array. First, dc magnetization loops were recorded. The data from two adjacent sensors located away from the sample center, but not too
close to the edge, were used to determine the local gradient \( \frac{dB}{dx} \) as function of the local induction \( B \), i.e., the average of the induction measured by the two sensors. At low \( T \), the abrupt change of \( \frac{dB}{dx} \) on increasing \( B \) was used to locate the transition from the low-\( B \) vortex solid to the disordered high-\( B \) phase. With higher temperature, the feature in \( \frac{dB}{dx} \) transforms to a marked decrease. This change is related to the different flux creep processes, and the correspondingly different current-voltage relations in the two vortex phases. The high field phase manifests a steeper energy barrier vs. current relation and a higher current-carrying capacity in the low-\( T \), high-current regime. At higher \( T \), the stronger magnetic irreversibility originating from the surface barrier in the low field phase predominates, leading to the slight decrease of the shielding current at the transition. The crossover from peak to step is dynamic and depends on the time scale [7]. Finally, close to \( T_c \), the transition occurs in the magnetically reversible regime and is marked by a jump in the equilibrium magnetization. In this regime, the paramagnetic peak in the ac response is a more convenient method to locate \( B_m(T) \). The signal from the sensor located near the sample center, detected by a lock-in amplifier, was used to record the ac response during cooling at constant applied field. Fig. 2 shows measurements performed on the sample irradiated to \( 8.7 \times 10^{19} \) e/cm\(^2\) (\( T_c \) reduced to 75 K). A pronounced paramagnetic peak, indicating the FOT, can clearly be observed in this highly disordered sample [8].

![Figure 3](image3.png)

Figure 3. Phase diagram of vortex matter in a set of samples cut from the same Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_8\) crystal, and irradiated with different doses of 2.3 MeV electrons at 20 K. Full symbols represent dc mode data, open circles identify the FOT obtained from the paramagnetic peak in ac mode. Note the small misfit arising from the difference between the applied field recorded in ac mode and the local induction measured in dc mode.

![Figure 4](image4.png)

Figure 4. Field-angle dependence of the FOT, determined from the position of the paramagnetic peak on pristine (full circles) and electron irradiated samples (open circles) at the same reduced temperature \( T/T_c \). Here, \( H_{ab} \) is the field component parallel to the CuO\(_2\) planes, and \( H_z \) is the perpendicular field component. The triangles represent the transition from a combined lattice to a tilted lattice configuration. The lines are a fit of the FOT in the tilted vortex lattice regime to the anisotropic Ginzburg-Landau model.

A complete set of data, illustrating the evolution of the phase diagram of vortex matter in Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_8\) with various degrees of disorder is presented in Fig. 3. The full circles indicate the local induction at the transition as identified from the jump in the reversible dc magnetization (high T), and from the discontinuity in the dc irreversible magnetization (low T). The open circles represent the applied field at which the paramagnetic peak in the ac response is observed. Obviously, there is a mismatch between the applied field and the local induction at the transition. The influence of the in-
plane field on the position of FOT has been investigated following the procedure used in Ref. [10]. The polar (two field-component) phase diagrams measured on pristine and irradiated Bi$_2$Sr$_2$CaCu$_2$O$_8$ (8.7 $10^{19}$ e/cm$^2$, $T_c = 75$ K) at the same reduced temperature $T/T_c$ are presented in Fig. 4.

3. Discussion

The hysteresis loops measured on highly disordered Bi$_2$Sr$_2$CaCu$_2$O$_8$ crystals do not manifest any noticeable increase of $dB/dx$ with electron dose. Contrary to common belief, excess point-like disorder does not provide a noticeable increase in pinning. Either the preexisting disorder is strong enough to mask the effect of that introduced by irradiation, or an increase in the in-plane penetration depth $\lambda_{ab}$, accompanying the strong depression of $T_c$ [9] and accounting for the downward shift of the SMP compensates the extra point defect density. In contrast, irradiation with $10^9$ cm$^{-2}$ swift heavy ions amounting to an equivalent damage of 0.024 dpa, produces a drastic enhancement of magnetic irreversibility, without change of $T_c$.

Close to $T_c$, the slope $dB_m(T)/dT$ decreases with disorder. However, this decrease does not scale with the much stronger depression of the SMP, consistent with earlier observations [4,5]. More insight can be earned from the analysis of the field-angle dependence of the FOT, shown in Fig. 4. This shows the recently identified transition from a combined lattice to a tilted vortex lattice at high in-plane field, where $B_m$ in the tilted vortex regime follows the prediction of the anisotropic London model [10]. The quadratic dependence of $B_m$ on the field component parallel to the CuO$_2$ planes, $H_{ab}$, allows for the determination of the effective anisotropy coefficient $\gamma$. The intercept of the high $H_{ab}$ dependence with $H_{ab}=0$ yields the position of the FOT in the absence of magnetic coupling between pancake vortices. The difference between the observed $B_m$ at $H_{ab}=0$ and this intercept, represents the contribution of the magnetic interaction to the melting field, $\Delta B_m = C_m \Phi_0/4\pi \lambda_{ab}^2$, and is an indirect measurement of $\lambda_{ab}$ ($C_m \approx 5.5$ for a Lindemann number $c_L^2 = 0.07$). Fig. 4 shows that $\Delta B_m$ Oe, at the same reduced temperature, decreases from 23 to 14 Oe after the introduction of point disorder). This means that $\lambda_{ab}$ has increased and that the superfluid density has decreased. Simultaneously, the apparent anisotropy factor $\gamma$ increases from 140 to 190, indicating that interlayer coupling is depressed by point disorder.

4. Conclusion

We demonstrate the complex effect of point disorder on the fundamental parameters of the layered superconductor Bi$_2$Sr$_2$CaCu$_2$O$_8$ leads to a non-trivial evolution of the vortex phase diagram. Most surprisingly, the first order vortex solid-to-liquid transition is robust to substantial amounts of point disorder introduced by electron irradiation.

References

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