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Bean–Livingston surface barriers for flux penetration in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals near the transition temperature

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ABSTRACT

The first field for magnetic flux penetration H_p in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) single crystals near the critical temperature T_c was investigated from the local magnetic hysteresis loops registered for different magnetic field H sweeping rates by using a scanning Hall probe microscope (SHPM) with ∼1 μm effective spatial resolution. Evidences for a significant role of the surface barrier were obtained: the asymmetric shape of the magnetization loops and an anomalous change in the slope of $H_p(T)$ close to T_c.

1. Introduction

Surface barriers represent one of the important sources of magnetic irreversibility (directly related to the critical current density J_c) in high-temperature superconductors (HTS) at elevated temperatures T. Bean–Livingston (BL) surface barriers [1] affect the magnetic flux penetration or exit from a superconductor due to the competition between flux attraction by its "mirror" image at the edge and repulsion, caused by the interaction with the screening currents. Surface barriers control the first field for flux penetration [1] $H_p > H_{c1}$, where H_{c1} is the first critical magnetic field. For a perfect edge surface, $H_p \approx H_c \approx \kappa H_{c1}/\ln k$, where H_c is the thermodynamic critical field and the ratio κ between the magnetic penetration depth λ and the coherence length ξ is the Ginzburg–Landau parameter. For HTS, $\kappa \approx 100$ and $H_c/H_{c1} \approx \kappa/\ln \kappa \approx 20$, which means that strong surface effects may be present. In real samples the barriers are influenced by edge imperfections and $H_{c1} < H_p < H_c$ [2]. H_p can exceed significantly H_{c1}. This circumstance is responsible for some conflicting experimental results on HTS.

The effects of surface barriers in HTS where investigated both theoretically [1–6] and experimentally [2,7–12]. They were intensively studied mainly for $T \leqslant T_c/2$, and preferentially on $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystals [2,9,10]. Until now, there are no systematic studies regarding the creep through surface barriers at T close to T_c for Bi-2212 single crystals. The influence of the field sweeping rate dH/dt on H_p was investigated in details only for $T < 61$ K [11]. Moreover, the key technical point of many measurement methods was the use of a Hall sensor with tens and/or hundreds μm active size. At present, the "local" induction measurements benefit of Hall sensors with micron or submicron dimensions, and the measured signal (which is always an average over a certain area) is closer to the local one. This aspect becomes essential if the sample is not homogeneous, where the use of large area Hall sensors can make some effects unobservable, such as the sudden drop in the magnetization related to vortex lattice melting, or the sharp cusp in the magnetic behavior near T_c.

In this work, local induction measurements were performed on Bi-2212 single crystals using a scanning Hall probe microscope (SHPM) with an outstanding field sensitivity of $\sim 3 \times 10^{-7}$ $\mathrm{THz}^{-1/2}$ and an active aria of ∼1 μm². The $H_p(T)$ dependence at $T > T_c/2$, as well as the variation of H_p with the field sweeping rate are discussed in the framework of the theory from Ref. [3].

2. Experimental

The design of scanning Hall probe microscope (SHPM) with an effective spatial resolution of ∼1 μm has described in detail elsewhere [13]. The local DC magnetization measurements were performed in zero-field-cooling conditions in the T range from 66 K to 84.7 K, and for an external magnetic field H up to 100 Oe oriented perpendicular to the flat surface of the crystal. The magnetic field sweeping rate dH/dt was between 1 and 392 Oe/s.

The high quality as-grown Bi-2212 single crystal investigated here was prepared by the traveling solvent floating zone technique. The $\sim 2 \times 2 \times 0.08$ mm³ single crystal was cut from a larger plate.

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The investigated face was cleaved in the aim to remove the surface inhomogeneities caused by sample preparation. The crystal has T_c = 85.5 K (slightly underdoped). The scheme of Hall probe position with respect to the crystal edges is shown in the inset of Fig. 1.

3. Results and discussions

Typical 'local' magnetization curves can be seen in Fig. 1, which shows the magnetization curves registered with dH/dt = 392 Oe/s, for different T values.

The magnetization is defined as the difference between the magnetic induction and H. A strong evidence for the presence of BL surface barriers is given by the asymmetric shape of the magnetization loop. A sudden drop in the magnetization above the first flux penetration at H_p on the ascending branch (increasing H) is present, whereas the magnetization of the descending branch (decreasing H) is almost zero, which indicates that the bulk pinning is very weak.

As can be seen in Fig. 1, the shape of the magnetization curves is T dependent. The width of the magnetization loop and H_p increase as T decreases. The magnetization curves at constant T for different dH/dt (not shown here) indicate that the width of the magnetization loop and H_p increase as the sweeping rate increases.

The $H_p(T)$ dependence at different dH/dt is plotted in Fig. 2, where $H_{c1}(T)$ and $H_c(T)$ were estimated from the equations:

$$H_{c1} = (\Phi_0/4\pi\lambda^2)\ln(\kappa), \quad (1)$$

$$H_c \approx \kappa H_{c1}/\ln(\kappa), \quad (2)$$

where a standard T variation of the (in-plane) magnetic penetration depth λ was used for T close to T_c, with $\lambda(0)$ = 170 nm. Here we also considered κ = 100 and the demagnetization factor N = 0.8.

The demagnetization factor was estimated as $1 - N = (d/w)^{1/2} = 0.2$ (see [3] and references therein) where d is the thickness and w the lateral size of the crystal. It can be seen in Fig. 2 that $H_p(T)$ changes at a certain $T^* \sim 82.3$ K. Burlachkov et al. [9] observed a similar phenomenon in the case of YBCO single crystals. They discussed the change in the apparent slope dH_p/dT in the vicinity of T_c in terms of BL surface barriers, based on the interplay between λ and the surface roughness. The small defects [9,14] [of the order of $\xi(0) - \lambda(0)$] on the surface serve as a gate for easier flux penetration and the first flux entering occurs at a smaller H_p, which lies between H_{c1} and H_c. By increasing T in the vicinity of T_c, where ξ and λ diverge as $\tau = (1 - T/T_c)^{-1/2}$, these defects become ineffective, and $H_p(T)$ will approach the thermodynamic $H_c(T)$ curve. Thus, the crossover between these regimes is expected at $\tau \approx [\xi(T)/a]^2$ [9], where a is size of the defect (the depth of the cavity, for example) on the surface.

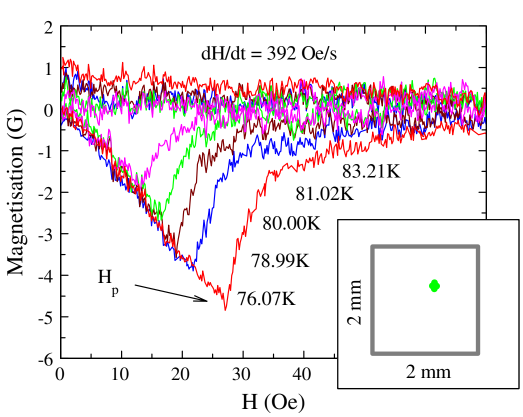

Fig. 1. Local magnetization loops measured at different temperature T values and dH/dt = 392 Oe/s. Inset: the hall probe position with respect to the crystal edges.

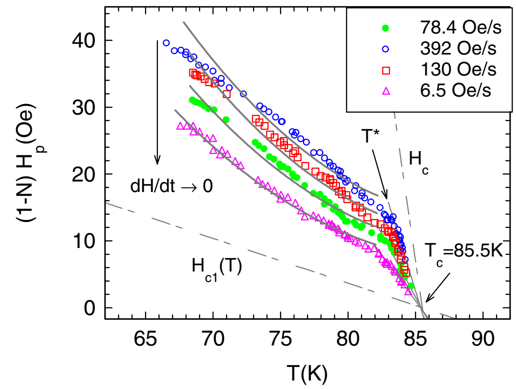

Fig. 2. T dependence of the first field for magnetic flux penetration H_p for different field sweep rates. The fit of $H_p(T)$ curves with the relation H_p-$H_p(T^*)\propto([(T_c$-$T)^{3/2}]/T$ is also illustrated.

Fig. 3 illustrates the variation of H_p with dH/dt. Here we plotted H_p vs. $1/(dH/dt)$. It can be seen that for the values dH/dt used by us, H_p increases continuously with increasing dH/dt. This behavior is related to vortex creep over the surface barriers, as shown below.

It was pointed out [11] that the behavior of H_p at high sweeping rates is determined at low T by creep of pancake vortices, whereas at high T this is due to half-loop vortex excitations over the surface barriers. Briefly, as deduced theoretically by Burlachkov et al. [3], the thermal activation of half-loops over the surface barriers involves the energy

$$U(j) \propto \ln^2(j_0/j)/2\Phi_0 J, \quad (3)$$

where j is the density of the macroscopic currents induced in the sample, and j_0 is the depairing critical current density. At the same time, using the general vortex-creep relation, $U(j)$ from Eq. (3) is approximated by:

$$U(j) \approx T\ln(t_w/t_0), \quad (4)$$

where $t_w \sim 1/(dH/dt)$ is the relaxation time window and t_0 is a macroscopic time scale for creep [15]. Since H_p is proportional to the magnetization at H_p (see Fig. 1), and the latter is directly related

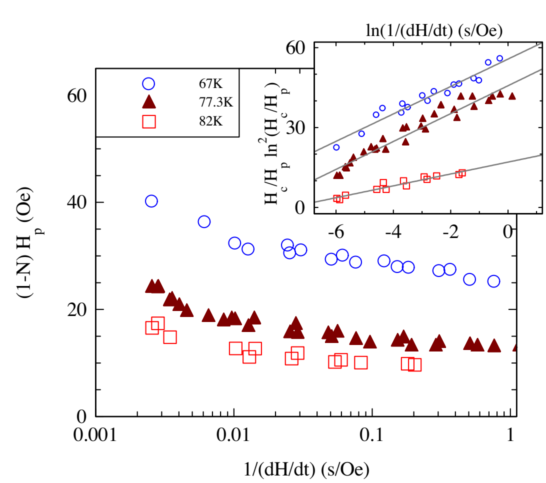

Fig. 3. The first field for magnetic flux penetration H_p vs. $1/(dH/dt)$ for different T values. Inset: $(H_c/H_p)\ln^2(H_c/H_p)$ vs. $\ln(1/dH/dt)$ and the fit with the equation $(H_c/H_p)\ln^2(H_c/H_p) = c(\ln(1/(dH/dt)) - \ln t_0)$.

to $j(t_w)$, Eq. (3) and the general vortex-creep relation can explain the increase of H_p at high field sweeping rates from Fig. 3.

On the other hand, using Eqs. (3) and (4) the results of Ref. [3] predict that at high temperatures H_p is expected to depend on the sweep rate as $H_p \sim 1/\ln(t/t0)$. This dependence for half-loop penetration can be written as [3]:

$$(H_c/H_p)\ln^2(H_c/H_p) = c\ln(t/t_0) = c(\ln(1/dH/dt) - \ln t_0), \quad (5)$$

In the inset of Fig. 3 we plotted $(H_c/H_p)\ln^2(H_c/H_p)$ vs. $\ln(1/dH/dt)$. The fit with the equation $(H_c/H_p)\ln^2(H_c/H_p) = c(\ln(1/(dH/dt) - \ln t_0)$ (shown in the inset of Fig. 3) gives $t_0 \sim 10^{-10}$, 10^{-9}, and 10^{-8} s for 67, 77.3, and 83 K, respectively. (The values for H_c were taken from the calculated curve $H_c(T)$ shown in Fig. 2). The obtained values for t_0 are very close to those reported in literature for the low-H range. The successful fits with theoretical predictions demonstrate that the behavior of H_p in the investigated T range (near T_c) is in good agreement with the theory of the creep of vortex lines over BL surface barriers. This creep is believed to occur by excitation of vortex half-loops with $H_p \propto [(T_c - T)^{3/2}]/T$ (see [3]). The H_p (T) curves in Fig. 2 were satisfactorily fitted at $T < T^*$ by the relation $H_p - H_p(T^*) \propto [(T_c - T)^{3/2}]/T$. The curves at lowre sweep rates in Fig. 2 are clearly more consistent with this functional form.

4. Conclusions

In summary, by applying the scanning Hall probe microscopy we found evidences for the presence of effective BL barriers in Bi-2212 single crystals even in close vicinity of T_c. The $H_p(T)$ dependence obtained by us is in good agreement with the theory from Ref. [3], whereas the variation of H_p with the field sweeping rate (in the range $\sim$1–10^3 Oe/s) reflects the thermal activation over BL barriers (increasing at low current densities).

Acknowledgments

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