Bean–Livingston surface barriers for flux penetration in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals near the transition temperature

V. Mihalache $^{a, *}$, M. Dede $^b$, A. Oral $^b$, L. Miu $^a$

$^a$National Institute for Materials Physics, P.O. Box MG-7, RO-077125 Bucharest-Magurele, Romania
$^b$Bilkent University, Department of Physics, Ankara, Turkey

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, $H_p \approx H_{c1} \approx \kappa H_{c1}/\ln k$, where $H_{c1}$ is the thermodynamic critical field and the ratio $\kappa$ between the magnetic penetration depth $\lambda$ and the coherence length $\xi$ is the Ginzburg–Landau parameter. For HTS, $\kappa \approx 100$ and $H_{c1}/H_{c2} \approx \kappa/\ln \kappa \approx 20$, which means that strong surface effects may be present. In real samples the barriers are influenced by edge imperfections and $H_{c1} < H_p < H_{c2}$ [2]. $H_p$ can exceed significantly $H_{c1}$. This circumstance is responsible for some conflicting experimental results on HTS.

2. Experimental

The design of scanning Hall probe microscope (SHPM) with an effective spatial resolution of $\sim 1 \mu m$ 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 $\sim 2 \times 0.08 \text{ mm}^2$ single crystal was cut from a larger plate.
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 \( \frac{dH}{dt} = 392 \) 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 \( H_p(T) \) and \( H_p(T) \) were estimated from the equations:

\[
H_{11} = \left( \frac{\Phi_0}{4\pi \xi^2} \right) \ln(\kappa), \\
H_{12} \approx \kappa H_{11} / \ln(\kappa),
\]

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

The demagnetization factor was estimated as \( 1 - N = (d/d\omega)^{1/2} = 0.2 \) (see [3] and references therein) where \( d \) is the thickness and \( \omega \) the lateral size of the crystal. It can be seen in Fig. 2 that \( H_p(T) \) changes at a certain \( T^* \approx 82.3 \) 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 \( \xi \) and the surface roughness. The small defects [9,14] of the order of \( \xi(0) - \xi(0) \) 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 \( H_{11} \) and \( H_{12} \). By increasing \( T \) in the vicinity of \( T_c \), where \( \xi \) and \( \kappa \) diverge as \( \tau \), these defects become ineffective, and \( H_p(T) \) will approach the thermodynamic \( H_{12}(T) \) curve. Thus, the crossover between these regimes is expected at

\[
\tau \approx \frac{\xi(T)^2 a^2}{\Phi_0}, \quad \text{[9], where} \ a \ \text{is the size of the defect (the depth of the cavity, for example) on the surface.}
\]

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

\[
U(j) \sim \ln^2 \left( j_w/j_0 \right) / 2\Phi_0, \quad \text{[3]}
\]

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

\[
U(j) \approx T \ln(t_w/t_0), \quad \text{[4]}
\]

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
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 $H_p \sim 1/\ln(t/t_0)$. This dependence for half-loop penetration can be written as [3]:

$$
(H_p/H_p)_0 \ln^2 \left( \frac{H_p}{H_p} \right) = c \ln(t/t_0) = c \ln \left( \frac{1}{dH/dt} - \ln t_0 \right). 
$$

In the inset of Fig. 3 we plotted $$(H_p/H_p)_0 \ln^2 \left( \frac{H_p}{H_p} \right)$$ vs. $\ln(1/(dH/dt))$. The fit with the equation $$(H_p/H_p)_0 \ln^2 \left( \frac{H_p}{H_p} \right) = c \ln \left( \frac{1}{dH/dt} - \ln t_0 \right)$$ (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 $T < T_c$ by the relation $H_p - H_p(T_c^*) \propto [(T_c - T)^{3/2}]/T$. 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 $\sim 1 \times 10^3$ Oe/s) reflects the thermal activation over BL barriers (increasing at low current densities).

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References