Bean-Livingston barriers and first field for flux penetration in high-$T_c$ crystals

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We present evidence for the importance of Bean-Livingston (BL) barriers for field penetration into high-$T_c$ crystals. The magnetization curves $M(H)$ and the first field $H_c$ for flux penetration were measured near the transition temperature $T_c$ of untwinned Y-Ba-Cu-O crystal by using a miniature Hall probe. There are three observations that serve as evidence for the efficiency of BL barriers: (1) the magnetization was found to be almost zero on the descending branch of the magnetization loop; (2) The slope of $H_c(T)$ exhibits a clear change close to $T_c$, being largest at $T_c$; (3) after introducing damage by irradiating the sample, both the field $H_c$ and the width of the $M(H)$ loops reduce significantly, showing almost reversible behavior for the sample. We explain these observations in terms of BL barriers which are shown to be especially important in high-$T_c$ superconductors, and these could be responsible for the controversy of the $H_c$ values reported previously in the literature.

The observation of Bean-Livingston (BL) surface barriers$^1$ for flux penetration into a bulk superconductor is considered to be a rather delicate experimental task. The source of the barrier is the attraction of the Abrikosov vortex to its "mirror image" near the surface. It prevents flux penetration at $H = H_{cl}$, until at $H = H_c$ ($H_c$ is the thermodynamic critical field). At this field the shielding currents become large enough to tear a vortex off its "mirror image" and push it inside the sample.$^2$ However, in most cases the suppression of the superconducting properties at the surface (because of oxidation, etc.), roughness of the surface or presence of defects (like twins) remove the BL barrier, so special preparation and polishing of the surface is required for the barrier to be observed in ordinary (e.g., Nb type) superconductors (see, for instance, Ref. 3).

The goal of our article is to show that high-$T_c$ materials provide a unique opportunity to observe the BL barriers$^3$ because of the very large value of $\kappa - \lambda/\xi \approx 100$, where $\lambda$ is the penetration depth and $\xi$ is the coherence length. In this case $H_{cl}/H_c \approx \kappa/\ln(\kappa) \approx 10$. Therefore, even in the case of some suppression of the barrier by surface defects, one can expect that the first field for flux penetration, $H_p (H_{cl} < H_p < H_c)$ should exceed $H_{cl}$ noticeably. This makes more difficult the determination of the $H_{cl}$ field itself and can be responsible for the wide range of conflicting experimental data for $H_{cl}$ in high-$T_c$ crystals available so far.

We investigated the magnetization of several twinned and untwinned YBa$_2$Cu$_3$O$_{7-x}$ samples. In this article we present data for two untwinned YBa$_2$Cu$_3$O$_{7-x}$ samples, which we denote nos. 1 and 2, with $T_c = 92.4$ K. The samples 1 and 2 were plates with dimensions $1090 \times 460 \times 4$ and $1700 \times 1400 \times 23$ $\mu$m$^3$ and demagnetization factor $N$ close to 1. The method of crystal growth uses an off-stoichiometric composition rich in BaCuO$_2$ and CuO. Details concerning preparation and properties of the samples and the method of measurement (which is based on the use of a miniature InSb Hall probe with $80 \times 100$ $\mu$m$^2$ active area for direct determination of the induction $B$ at the surface of the sample) were presented in Ref. 5. The resolution of the probe is $0.004$ G corresponding to approximately one flux line on the probe surface. All measurements were carried out with the external field $H[\parallel c]$.

A typical magnetization curve $M(H)$ is presented in Fig. 1 (for the as grown sample no. 1). The magnetization $M$ is denoted in Fig. 1 as $\Delta H = B - H$ ($B$ is the induction inside the sample and $H$ is the external field) in order to emphasize that $B$ was measured directly by the Hall probe. The linear Meissner part is followed by a sharp drop of magnetization at $H = H_{tp}$ unlike the situation in most twinned samples which show a slow deviation from linearity.$^6$ The shape of the magnetization curves and very small remanent magnetization $M_{rem}$ (when the field is removed after field cooling) suggest that bulk pinning does not play an important role in these samples.

In Fig. 2 the dependence of $H_p$ on temperature is plotted for both samples and appears to be strongly nonlinear. This circumstance can be described in terms of the BL barrier. If the surface of the sample is perfectly smooth then $H_p = H_c$ should grow linearly with $T$ (see Fig. 2). Suppose, however, that there is a small defect [a cavity of depth $\delta = \xi(0)$] in the surface (Fig. 3). It plays the role of a "gate" for easier flux penetration, because a vortex now
FIG. 1. Magnetization curves $\Delta H$ vs $H$ for untwinned YBaCuO, sample no. 1, as grown, and after irradiation. The dashed line is obtained theoretically on the assumption that penetration of vortices is governed by the Bean-Livingston barrier only.

FIG. 2. Temperature dependence of $H_p$ for untwinned sample no. 1 (Δ - as grown, ▲ - after irradiation) and for no. 2: ◊ (as grown). Solid curves represent theoretical fit to $H_p$ in terms of BL barriers, $H_{cl}$ and $H_p$ correspond to $0 = 1700$ Å and $\xi = 20$ Å. Note that the scale of fields depends on demagnetization factor $N$.

FIG. 3. Shape of surface defect used for theoretical calculations of $H_p$. Shaded and dashed circles show the size of the vortex core well below and in the very vicinity of $T_c$, respectively. Circles at the surface represent the auxiliary vortices used in theoretical analysis.

(where $r_0$ is the position of the vortex) with the boundary condition $B = H_p$ at the surface of the sample, where $H_p$ is the external field. In the case of a smooth surface this problem can be solved by introducing a “mirror image” of the vortex with the opposite sign (see, for instance, Ref. 7).

To confirm these qualitative arguments for nonlinearity in $H_p(T)$ we performed a numerical analysis of the interaction between the vortex and non-smooth surface in the London approximation which is suitable in this case because of the very large value of the parameter $\kappa = \lambda / \xi = 100$ in YBaCuO. We have to solve the London equation

$$B + \lambda^2 \nabla \times \nabla \times B = \psi r (r - r_0)$$

(1)

To fit $H_p(T)$ curves within the approach outlined above, we consider a surface with a cavity of the Gaussian form: $z = a \exp(-x^2/p^2)$, where $p = 34$ Å and $a = 300$ and $166$ Å for samples 1 and 2, respectively; $\lambda = (0) = 1700$ Å and $\xi = 20$ Å were used. One can see that this approach gives a reasonable fit to the nonlinear $H_p(T)$ dependence.

Another fingerprint of BL barriers is given by the form of the $M(H)$ magnetization curve (Fig. 1), namely in the descending branch the magnetization $M = 0$. As was mentioned by Campbell and Evetts, this kind of behavior results from the fact that at $H = H_c$ the shielding current vanishes, the BL barrier for vortex escape from the sample disappears, and fluxons can leave the sample freely. This also proves that in our case no critical models (like Bean or Kim models) based on pinning can be applied because in the latter case $M$ should inevitably change sign at the descending branch. The theoretical analysis of the magnetization curve $M(H)$ due to the BL barrier (in the absence

of any bulk pinning) predicts \( H^2 = (H_p^2 + B^2) \) for the ascending branch (see the dashed line in Fig. 1).

The final evidence of the importance of the BL barrier for the vortex penetration into untwinned high-\( T_c \) crystals is borne out by low-temperature (20 K) irradiation of sample no. 1 by a low dose of 2.5 MeV electrons. The damage is estimated to be of order \( 10^{-4} \) displacements per atom. Irradiation decreases \( H_p \) significantly (see Figs. 1 and 2) making the magnetization curve \( M(H) \) practically reversible. This can be understood in terms of producing surface damage by defects that are created in the bulk during irradiation and that then migrate to the surface during room-temperature annealing.\(^\text{11} \) Thus new “gates” for flux penetration appear and the role of BL barriers is suppressed. It is worth noting that if pinning and not surface barriers governs the flux penetration then irradiation, which creates new defects, can by no means reduce the penetration field \( H_p \).

To conclude, we showed that in YBaCuO crystal the first field for flux penetration \( H_p \) exceeds significantly the field \( H_{cl} \) because of the importance of the Bean–Livingston barrier in these compounds. This circumstance could be responsible for the ongoing controversial values of \( H_{cl} \) in high-\( T_c \) crystals.

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\(^7\) P. G. de Gennes, \textit{Superconductivity of Metals and Alloys} (W. A. Benjamin, New York, 1966), Chap. 3.