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_p 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 $H_p(T)$ 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_p 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_{c1} 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 $H = H_{c1}$, 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[4] because of the very large value of $\kappa = \lambda/\xi \simeq 100$, where λ is the penetration depth and ξ is the coherence length. In this case $H_c/H_{c1} \simeq \kappa/\ln(\kappa) \simeq 20$. 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 ($H_{c1} < H_p < H_c$) should exceed H_{c1} noticeably. This makes more difficult the determination of the H_{c1} field itself and can be responsible for the wide range of conflicting experimental data for H_{c1} in high-T_c crystals available so far.

We investigated the magnetization of several twinned and untwinned $YBa_2Cu_3O_{7-x}$ samples. In this article we present data for two *untwinned* $YBa_2Cu_3O_{7-x}$ 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 $1700 \times 1400 \times 23$ μm^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 80×100 μm^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 $H \| c$.

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 $H = H_p$, 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 $a \simeq \xi(0)$] in the surface (Fig. 3). It plays the role of a "gate" for easier flux penetration, because a vortex now

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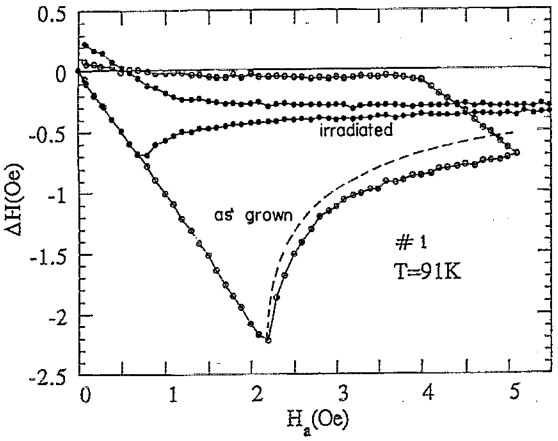

FIG. 1. Magnetization curves ΔH vs H for untwinned YBaCuO, sample no. 1, as grown, and after irradiation. The dashed line is obtained theoretically on the assumption that penetration of vortices is governed by the Bean–Livingston barrier only.

can, in zero approximation, start penetration from the depth $z = a$ where the force of the "mirror image" is reduced [it falls at short distances $z \simeq \xi(0)$ as $1/z$]. Thus, in turn, H_p reduces from $H_p = H_c$ to some intermediate value $H_{c1} < H_p < H_c$. But as $T \rightarrow T_c$ the size of the vortex (both ξ and λ) diverges as $\tau^{-1/2}$, where $\tau = (T_c - T)/T_c$, so in the very vicinity of T_c this defect should play no role at all, and $H_p \simeq H_c$. The crossover between these two regimes should be expected at $\tau \simeq [\xi(0)/a]^2$.

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 $\kappa = \lambda/\xi \cong 100$ in YBaCuO. We have to solve the London equation

$$B + \lambda^2 \text{ curl curl } B = \phi_0 \delta(r - r_0) \qquad (1)$$

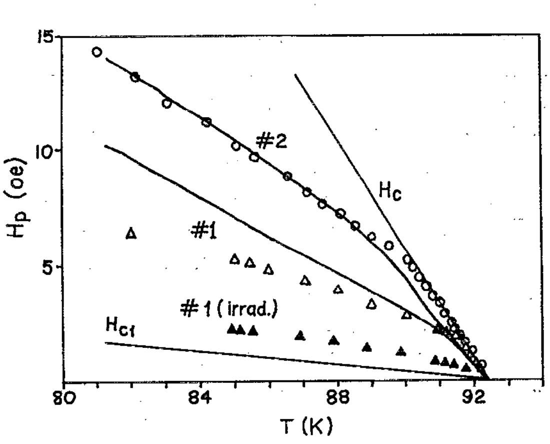

FIG. 2. Temperature dependence of H_p for untwinned sample no. 1 (△ - as grown, ▲ - after irradiation) and for no. 2: ○ (as grown). Solid curves represent theoretical fit to H_p in terms of BL barriers, H_{c1} and H_c correspond to $\lambda_0 = 1700$ Å and $\xi_0 = 20$ Å. Note that the scale of fields depends on demagnetization factor N.

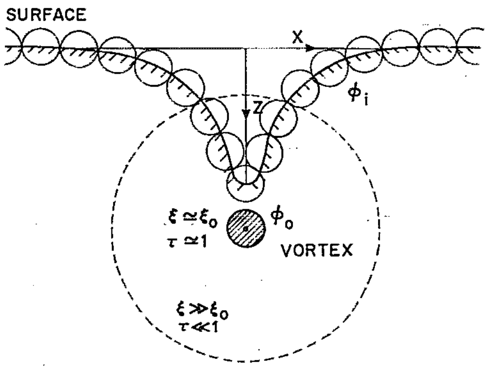

FIG. 3. Shape of surface defect used for theoretical calculations of H_p. Shaded and dashed circles show the size of the vortex core well below and in the very vicinity of T_c, respectively. Circles at the surface represent the auxiliary vortices used in theoretical analysis.

(where r_0 is the position of the vortex) with the boundary condition $B = H_e$ at the surface of the sample, where H_e 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). We used a more general procedure, namely, covering of the surface with auxiliary vortices with fractional flux ϕ_i (see Fig. 3). Then the field inside the superconductor can be calculated as

$$B = B_0 + \sum B_i, \qquad (2)$$

where B_0 and B_i are the fields of the vortex itself and auxiliary vortices, respectively. This expression certainly satisfies the London equation. The values of fractional flux ϕ_i should be found numerically to satisfy the boundary condition $B = H_e$. This method enables the calculation of the interaction between the vortex and the surface in the case of the arbitrary form of the surface (if the surface is smooth, it just restores the classical result, see Ref. 7). More details concerning this method are to be published elsewhere.

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; $\lambda_{ab}(0) = 1700$ Å and $\xi_{ab}(0) = 20$ Å were used.[9] 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 $M \simeq 0$. As was mentioned by Campbell and Evetts,[10] this kind of behavior results from the fact that at $H = B$ 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[8] 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.[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_{c1} because of the importance of the Bean–Livingston barrier in these compounds. This circumstance could be responsible for the ongoing controversial values of H_{c1} in high-T_c crystals.

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