Magneto-optical measurements of the surface step of magnetic induction in $YBa_2Cu_3O_7$ single crystals: Direct evidence of the influence of the surface barrier

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(Received 24 January 1994)

Surface steps of induction were observed at the sample edges in superconducting $YBa_2Cu_3O_7$ crystals on magneto-optically measured induction profiles. A sharp upturn was found for the temperature dependence of the step value near 35 K. Analysis of the changes of the step value and the flux distribution near the sample edge with variation of external field shows that this upturn is caused by an increase of the effect of the Bean-Livingston surface barrier at low temperatures.

INTRODUCTION

One of many unusual features of high-temperature superconductors (HTSC's) is the temperature dependence of the first critical field H_{c1}. While in conventional superconductors H_{c1} saturates with decreasing temperature at approximately $T_c/2$, in HTSC's many authors observe a low-temperature upturn of $H_{c1}(T)$; for example, see Refs. 1–4. Despite many different models trying to explain this upturn, it is not even clear whether it is a characteristic feature of high-T_c superconductors or a result of a misinterpretation of experimental data. Thus it was suggested that the upturn is a result of the incorrect determination of the penetration field H_p from magnetization curves because of not taking into account volume pinning effects. In Ref. 5, after correction of experimental H_p values using the Bean model, a conventional BCS-type $H_{c1}(T)$ dependence has been obtained. However, in Ref. 4 even after such corrections H_{c1} was found to increase exponentially with decreasing temperature. At the same time in Ref. 4 evidence was found that at low temperatures the Bean-Livingston (BL) surface barrier[6] strongly hinders the penetration of magnetic flux. As a consequence, the experimentally determined penetration field H_p is greater than H_{c1}. The exponential temperature dependence of measured H_p values was explained by the thermal activation of vortices over the surface barrier, which was shown to slow down exponentially with decreasing temperature. Evidence of the BL barrier was also obtained in Ref. 7. The authors of this work also employed it to account for the H_{c1} upturn;[8] however, their explanation is quite different from that of Ref. 4. They suppose that some weak places exist at the surface and the flux begins to penetrate the sample from such places. As in Refs. 4 and 5, they correct H_p values using the Bean model; however, this model is modified taking into account the above assumption. As a result, as opposed to Ref. 4 they obtain a conventional saturating dependence $H_{c1}(T)$; i.e., the upturn is just a result of the wrong procedure for determining H_{c1} values from magnetization curves.

There are also models regarding the true upturn of H_{c1}. It was shown that observed dependences can be caused by the layered structure of a superconductor[9,10] or by a double superconducting transition.[11,12] However, these models disagree with measurements of the temperature-dependent penetration depth λ (Refs. 13–15) giving a conventional dependence $\lambda(T)$ without anomalies.

In the present work H_{c1} is determined by surface steps of magnetic induction observed on magneto-optically measured induction profiles. Since these steps are caused by the Meissner current, this method allows one to separate its contribution to field screening from the contribution of the critical current, which flows in the sample interior and causes a gradual decrease of induction toward its center. As a result, a true value of the penetration field can be measured.

EXPERIMENTAL DETAILS

Measurements were carried out on $YBa_2Cu_3O_7$ single crystals of rectangular shape. Below, the results for a crystal with dimensions $490\times288\times89$ μm^3 are presented. The magnetic flux distribution was analyzed after application of an external field to a zero-field-cooled (ZFC) crystal. For this purpose the magneto-optic method[16] was used, which enables local measurements of the magnetic field due to the Faraday effect in the indicator film placed on the superconductor surface. The measurement scheme is shown in the inset to Fig. 1. The spatial resolution of this method was estimated by observation of fine domain patterns in magnetic materials and was found to be ~ 1 μm. This is less than the thickness of the indicator film, which is 2 μm. This means that the optical image forms mainly in the lower part of the film, which is closer to the sample, and that the gap between the indicator and sample does not exceed 1 μm.

The first critical field was determined by surface steps of induction. The step value in the external field $H>H_{c1}$ can be written as[17]

$$\Delta H_s = H - B_{eq}(H) = m(H) H_{c1} , \tag{1}$$

where $B_{eq}(H)$ is the thermodynamical equilibrium induction value and $m(H)$ is a dimensionless factor. In materials with high Ginzburg-Landau parameter κ, the approxi-

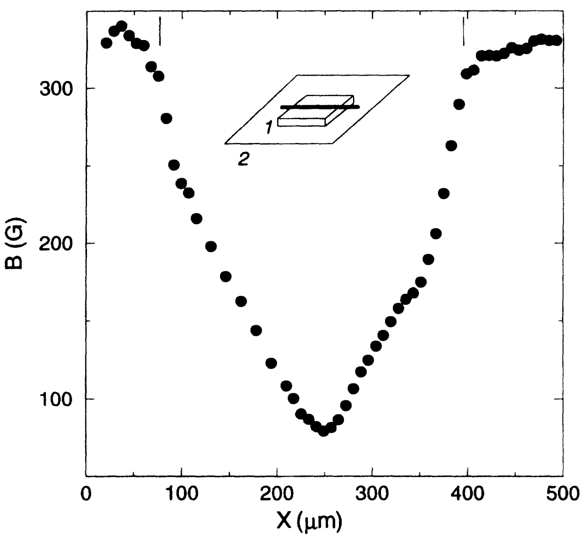

FIG. 1. Magnetic induction profile in a zero-field-cooled crystal at 60 K. The external field of 330 Oe is directed along the c axis. Surface steps of induction are seen at the sample edges (which are marked with short vertical lines). The inset shows the scheme of measurements: 1, sample; 2, indicator film. The profile was measured along the bold line.

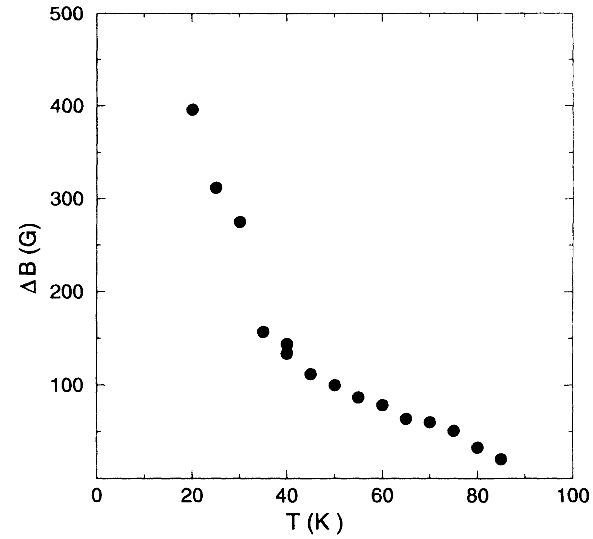

FIG. 2. Temperature dependence of the surface induction step. An upturn is clearly seen at 35 K.

mation,[17] in which $m(H)$=const at $H_{c1} < H \ll H_{c2}$, works well. Hence the surface step value is directly proportional to H_{c1}.

RESULTS AND DISCUSSIONS

A profile of magnetic induction in a zero-field-cooled sample at 60 K is shown in Fig. 1. The external field of 330 Oe is normal to the ab crystal plane. Right at the sample edges there are sharp drops of induction due to the Meissner current flowing on the edge surface. Further inside the sample the induction falls smoothly due to screening by the critical current. Since the field distribution was measured in the indicator film, which was placed above the sample (see the inset to Fig. 1), the experimentally observed field drops are not sharp, but have a width of ~20 μm. Also, the value of the induction step ΔB at this height is less than exact at the crystal edge. Both of these effects are determined only by the crystal shape and the film thickness and are temperature independent. In order to estimate the value of the step right at the sample edge, a spatial distribution of the field produced by a surface current flowing on the edge surface was calculated for the height of 1 μm (half thickness of the film) above the sample. This calculation showed that the measured ΔB should be multiplied by a factor about 5 in order to obtain the true value, which would have been obtained if it was possible to measure the field right at the sample edge. The temperature dependence of the surface step is shown in Fig. 2. The curve turns up at approximately 35 K. As mentioned above, the surface step value is determined by the Meissner current and is not affected by the critical current. Hence the upturn of the penetration field really exists and is not a result of a misinterpretation of experimental data as was suggested in Refs. 5, 7, and 8.

In order to find a reason for the observed upturn, the existence of the surface barrier was checked at different temperatures above and below the upturn point. This was done using measurements of the flux distribution in a ZFC crystal in a decreasing external field. In the case of equilibrium magnetization, the flux should escape from the sample with decreasing field, but the value of the surface step should not change strongly while $H > H_{c1}$. This case, corresponding to the Bean model, is shown in Fig. 3(a) (see Ref. 18). In the opposite case the BL barrier should prevent flux escape at initial stages of field lowering. As a result, the surface induction step will decrease and finally completely vanish; i.e., the screening surface current caused by the BL barrier will compensate completely the Meissner current.[19,20] This situation is shown in Fig. 3(b).

Experimental profiles of magnetic induction in a subsequently decreasing field (after reaching the maximum value) are shown in Fig. 4 for two different temperatures: 60 K [Fig. 4(a)] and 30 K [Fig. 4(b)]. In both cases the upper curves correspond to the maximum field applied to the ZFC sample. At 60 K the flux begins to escape from the sample with decreasing the field and the front of its motion advances into the crystal. This behavior corresponds to the case illustrated in Fig. 3(a). However, some weak evidence of the surface barrier is revealed: In the very beginning of field lowering, the flux does not leave the sample and the surface induction step decreases [the curve denoted by crosses in Fig. 4(a)]. The influence of the surface barrier can also explain the initial increase of the normal induction component in the sample, seen on the same curve. This increase may occur due to a straightening of the vortices, which were bent during flux penetration into a thin sample[21] and which could not escape from it because of the BL barrier. Despite these effects, the influence of the barrier at 60 K is weak. As is seen from the figure, it cannot compensate the Meissner current and the surface induction step does not vanish even in low field. At 30 K, in contrast to the previous case, the flux does not exit from the sample until the surface step becomes zero. Appropriate flux profiles, shown

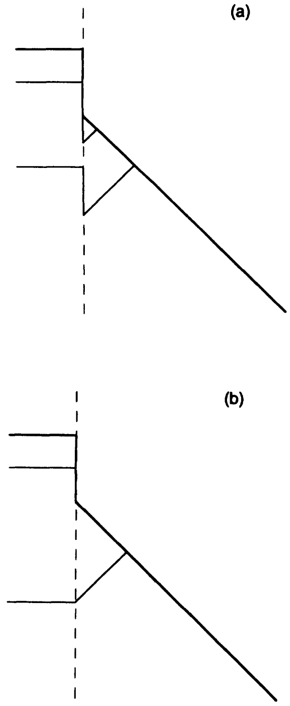

FIG. 3. Schematic representation of changes of the flux distribution in a ZFC sample with decreasing field. The bold lines show flux profiles in the maximum field. (a) Equilibrium case; the surface step is weakly dependent on the field. (b) The influence of the surface barrier; the surface step decreases and vanishes with decreasing field. The dashed line denotes the sample edge.

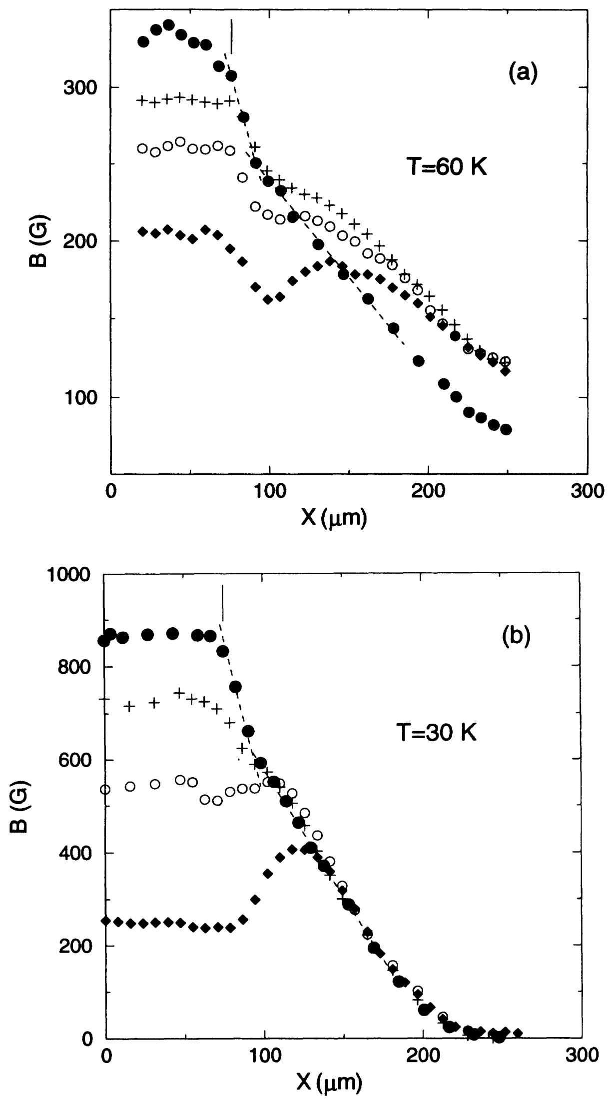

FIG. 4. Evolution of flux profiles in the sample with field lowering at different temperatures. (a) $T=60$ K; the surface step preserves until H is greater than H_{c1}. This corresponds to Fig. 3(a). (b) $T=30$ K; this case corresponds to Fig. 3(b). The dashed lines are drawn to highlight the surface steps of induction; the sample edge is marked with a short vertical line.

in Fig. 4(b), correspond to the case of a strong surface barrier illustrated in Fig. 3(b). Thus the obtained data show that the BL surface barrier weakly affects the sample magnetization at higher temperatures, but its influence becomes strong in the low-temperature region. This explains the sharp increase of the penetration field at low temperatures.

To check this conclusion the magnetic flux distribution was studied in a broken crystal (dimensions of this sample are $1940\times670\times45$ μm^3). An induction profile in this crystal is shown in Fig. 5. The left-hand induction step on the profile takes place at the as-grown edge surface and the right-hand one at the fresh surface. The surface step value is less at the broken edge than at the as-grown one. And its temperature dependence at this edge was found to be closer to the conventional saturating curve (see the inset to Fig. 5). This obviously demonstrates that at the broken edge the surface step is closer to H_{c1}; i.e., the surface barrier is weaker there. The reason for that may be defects at the broken surface. Thus comparison of absolute values and temperature dependences of the surface step at the broken and as-grown edges of the same crystal supports the idea that the upturn in the temperature dependence of the penetration field is caused by an increase of the influence of the surface barrier at low temperatures.

In the profile of Fig. 5, there is an interesting feature—an induction minimum near the intact edge of the crystal. Such a minimum is absent in the Bean model for a long superconducting cylinder or a slab in a parallel field and is probably connected with the shape of the sample. In the case of an infinite cylinder or a slab, the superconducting current flows over an infinite surface and produces a homogeneous screening field. For a thin superconducting crystal in a normal field, the current flowing over its edge surface cannot produce a homogeneous field. The spatial field change for such a current is shown in Fig. 6. The shielding field is maximum at some distance from the sample edge, and hence the magnetic induction should have a minimum there. (The curve of Fig. 1 was measured on a sample with larger thickness-to-width ratio, which is closer to an infinite cylinder. This is the reason for absence of such a minimum on that curve.) However, in order to reach

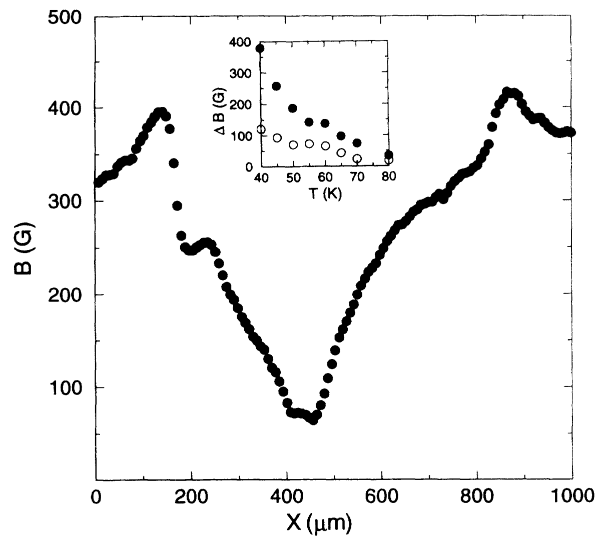

FIG. 5. Magnetic induction profile in a broken crystal, $T=55$ K, $H=290$ Oe. The left-hand induction step takes place at the as-grown crystal grain and the right-hand one at the fresh surface. A local minimum of induction near the as-grown edge is caused by inhomogeneous screening field of the surface current. The inset shows the temperature dependences of the surface steps at the as-grown (●) and broken (○) edges.

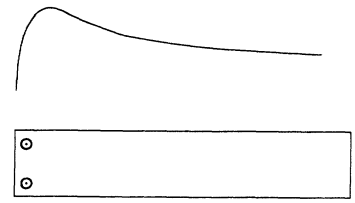

FIG. 6. Spatial distribution of the shielding field produced by the surfaced current, flowing along the crystal edge.

such an induction configuration, vortices should move against the flux gradient. This could occur due to flux creep, although it seems doubtful since the energy barrier is too wide—about 100 μm. There is also the possibility that the flux enters the superconductor at separate weak places where the screening current is suppressed. In this case vortices can approach the surface from inside the specimen not moving against the flux gradient. Some defect places, where the flux enters from, were really observed at the edge surface of the crystal at high temperatures. At the broken surface the concentration of such defects was very high, which could result in a strong suppression of the surface current, as already mentioned. At temperatures below ~40 K, the surface defects were not revealed; that is, the screening current could flow undisturbed and this might be the reason why the surface barrier becomes important only at low temperatures.

Another explanation of the low-temperature increase of the effect of the BL barrier was suggested in Ref. 4. It takes into account the flux creep over the barrier. The creep rate was found to decrease exponentially with temperature lowering. Thus at high temperatures the creep is very fast and the equilibrium flux distribution in the sample can be reached during the time of experiment even if a strong BL barrier exist at the surface. At lower temperatures the time of measurement is not long enough to reach the equilibrium state, and hence the sample magnetization is affected by the surface barrier. To check this assumption the time evolution of the flux profiles was studied after application of the field to the sample at different temperatures. At 65 K no changes were revealed during a period of 100 min. At the same time, at 30 K the flux was observed to advance into the sample in 30 min. This means that the creep through the surface exists and at 65 K it is so fast that during the time of measurement of one profile (~30 sec) the surface barrier is completely surmounted. Thus the obtained results support the model of creep over the sample surface. It seems likely that this creep is faster at weak places on the surface, described above. Hence both effects (the change of the creep rate and the disappearance of weak places) can lead to a low-temperature increase of the effect of the surface barrier.

CONCLUSIONS

In the present work a method of measurement of the temperature dependence of the first critical field by the surface step of magnetic induction is suggested. The obtained temperature dependence of the penetration field turns up at 35 K. It is shown that the reason for this upturn is an increase of the effect of the Bean-Livingston surface barrier at low temperatures, which is caused by the disappearance of weak places on the surface and a decrease of the rate of flux creep over the barrier.

ACKNOWLEDGMENT

The authors are thankful to Dr. V. K. Vlasko-Vlasov for a very helpful discussion of the results of this work.

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