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Effects of irradiation on magnetization curves in high temperature superconductors

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Abstract

Irradiation of high temperature superconductors yields effects that reveal significant information concerning the pinning mechanism. After electron irradiation highly mobile defects migrate to the surface and cause a significant reduction in the irreversible magnetization and thus demonstrates the importance of surface barriers. The realization of the role of the surface barriers resolve some of the most bothering puzzles in the magnetic behavior of high temperature superconductors. Irradiation with heavy ions which produces columnar defects induces "flux-flop" in the low field limit, from a direction determined by the field towards the defect direction. This phenomenon enables an experimental evaluation of the energy of a fluxon trapped by a columnar defect.

Magnetization curves have been always an important source of information concerning the nature of type II superconductors (SC). In this work we review some of the unusual magnetization curves which have been observed for high temperature superconductors. In particular, we describe results for crystals irradiated with 2.3 MeV electrons[1] or with 5.3 GeV Pb ions[2]. These results, for Y-Ba-Cu-O (YBCO) crystals were first published in references 1 and 2. We add here new experimental data, mostly for a thin YBCO film and for Bi-Sr-Ca-Cu-O (BSCCO) crystal irradiated with Pb ions.

The magnetization curves for a pure, ideal type II SC are described by the equations for an equilibrium, thermodynamic state. In this description, the magnetization curves are, of course, reversible, independent of the thermal and magnetic history of the sample. In practice, such pure samples are not superconductors because the fluxons move and cause dissipation whenever a finite current will pass through the sample. Therefore, for practical applications, efforts have been made to produce SC samples with pinning centers for the fluxons, thus allowing for larger currents to pass through the sample without any dissipation. In such samples, the magnetization is irreversible and it exhibits an hysteresis loop. The width of the hysteresis is proportional to the critical current in the material. The details of this loop is usually described by the Bean model[3] and its derivatives.

High temperature superconductors are known to have relatively weak pinning centers, especially at high temperatures. Yet, the Bean model is extensively applied, though some important modifications are essential. We find, however, that YBCO films, with their intrinsic pinning centers, follow the prediction of the model. In Fig. 1 we show new magnetization M versus field H data for a 600Å YBCO film prepared by laser ablation deposition. The figure shows a 'classic' Bean loop at quite an elevated temperature of 80 K. This data is even more impressive when compared with M(H) results for an YBCO crystal at similar temperatures, see Fig. 2. Data for these crystals show some puzzling results which can not be explained in the framework of the Bean model. In particular: (i) The temperature dependence of the first field for flux penetration $H_p(T)$ do not follow the expected BCS behavior. (ii) The loops show a very unusual feature, namely that when the field is reduced

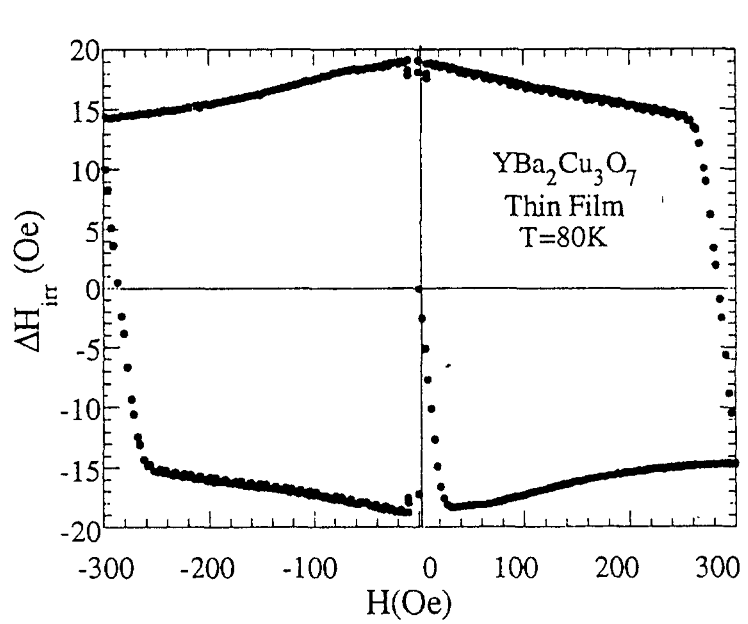

Figure 1. The magnetization curve of an YBCO film at T = 80 K.

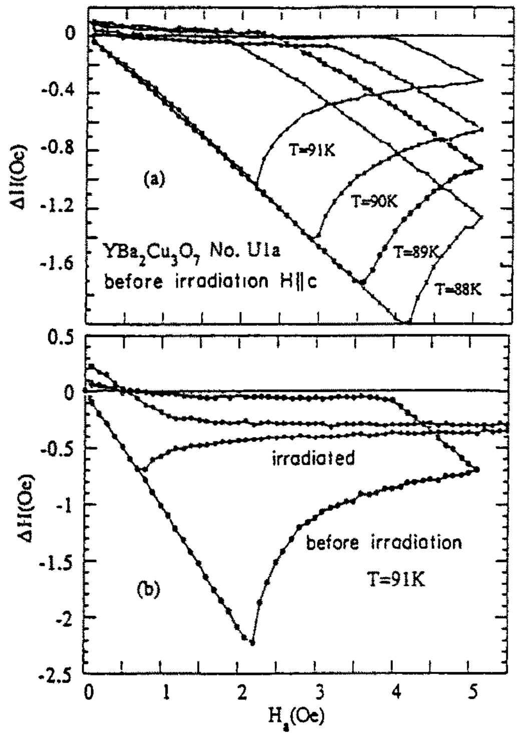

Figure 2. (a) The magnetization curves of an YBCO crystal before irradiation. Note that M=0 in the descending branch. (b) The magnetization curves of YBCO crystals before and after irradiation. Note the decrease in the width of the loop after irradiation. (After ref. 1)

from its maximum value the magnetization is virtually zero and not positive as predicted by the Bean model. This feature is observed for all temperatures above 70K. (iii) Irradiation with electrons caused a **reduction** of the irreversible magnetization which implies a reduction in J_c. This is contrary to what one would have anticipated knowing that irradiation causes damages which may serve as pinning centers. (iv) There is a significant decrease in H_p after irradiation. This last point demonstrates that H_p is not the thermodynamic first field for flux penetration. Indeed, all the above features are due to the Bean-Livingston surface barriers which are significant in crystals with smooth surface and reduced when the surface becomes rougher after irradiation. For details, the reader is referred to Ref. 1. Here we just emphasize that the irreversibility which is shown in Fig. 2 implies that surface barriers may have a significant contribution to flux pinning. We return to this point at the end of the article. We also note that the realization of surface barriers in high temperature SC explains the diversity of the reported results for $H_{c1}(T)$, the lower critical field; apparently the measured value is $H_p > H_{c1}$ and it is sample dependent.[4]

We describe now results for YBCO crystals irradiated with 5.3 GeV Pb ions. The crystals were irradiated either along the **c** direction or at 45 degrees with respect to it. This type of irradiation produces continuous amorphous tracks with a diameter of 5-7 nm.[5] As was expected,[6] a unidirectional pinning enhancement was observed for fields along the defect. However, in the low field limit, we observed a novel phenomenon, namely, flux-flop from a direction determined by the field towards the defect. This reorientation leads to a sudden increase in the pinning energy which is manifested in an upturn in the magnetization curves. At high enough temperatures the magnetization curves for applied fields at various angles relative to the **c** direction also converge near H=0. In figure 3 we show magnetization curves of an YBCO crystal which was irradiated at 45 degrees with respect to the **c** direction with the applied field at various directions. We can clearly observe the sudden upturn in the magnetization curves when the field is not along the defect and we also notice the convergence of all magnetization curves near H=0. This is further demonstrated

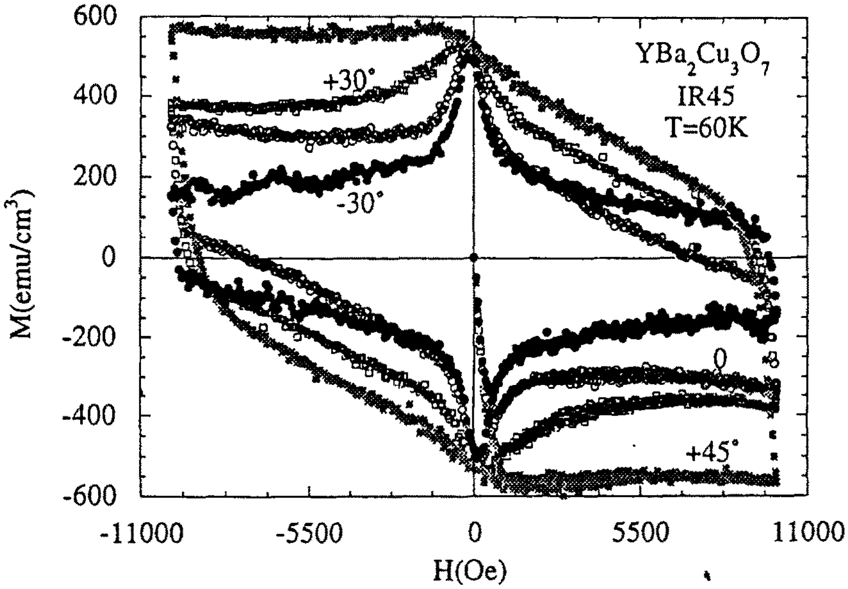

Figure 3. The magnetization curves of an YBCO crystal irradiated at 45 degrees with respect to the c direction. The field is applied at the indicated angles with respect to the c direction.

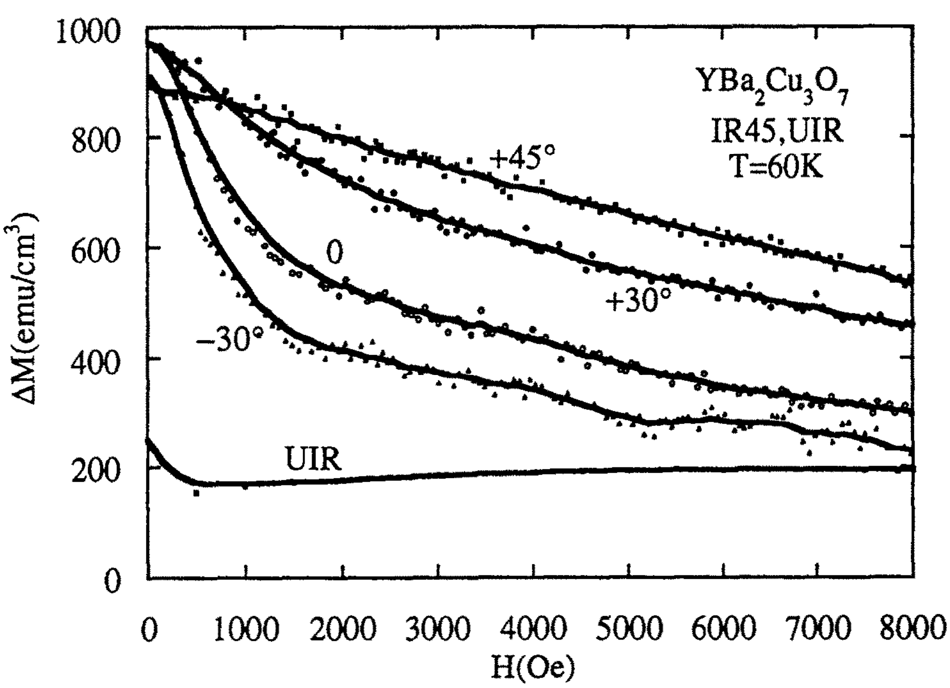

Figure 4. The widths of the magnetization curves of figure 3. The width for an unirradiated sample is given for reference.

in Fig. 4 which describes the width of the hysteresis loop (which is proportional to J_c) as a function of the applied field, before irradiation and in various orientations after irradiation. We also show here, for the first time, similar data for a BSCCO sample,[7] see Fig. 5. The origin of this phenomenon is the fact that the energy gain due to the columnar defect is obtained only when the fluxons are exactly aligned along the defect and there is no gain in a gradual inclination towards the defects. Therefore, when the gain in the pinning energy exceeds the cost of the Gibbs energy due to misorientation along the defect, a flux-flop occurs. The importance of the flux-flop is in the ability to evaluate directly the pinning energy from measuring the field at which the flux-flop occurs. Our results seems consistent with the theoretical estimation of the (electromagnetic) energy of a fluxon in an insulating columnar defect with a diameter d ($\lambda >> d > \xi$) which is $\varepsilon_P=(\Phi_0/4\pi\lambda)^2\ln(\lambda/d) < \varepsilon_0=(\Phi_0/4\pi\lambda)^2\ln(\lambda/\xi)$ where ε_0 is the energy of an Abrikosov vortex.[8] Substituting reasonable values for d (70 Å), ξ (13 Å) and λ (1400 Å) we find $u_P=(\varepsilon_0-\varepsilon_P)/\varepsilon_0=0.4$. Thus the relative energy gain for a fluxon along the columnar defect is of order ε_0, much larger than the usual gain in the core condensation energy $\varepsilon_c=H_c^2\xi^2/8\pi$ for point defects which is only a few percents of ε_0 when $\lambda>>\xi$.

In spite of the large pinning energy which have been verified experimentally, the activation energy is still low enough to allow significant relaxations. A way to increase the activation energy is to further increase the pinning energy by increasing the diameter of the columnar defect. However, we should

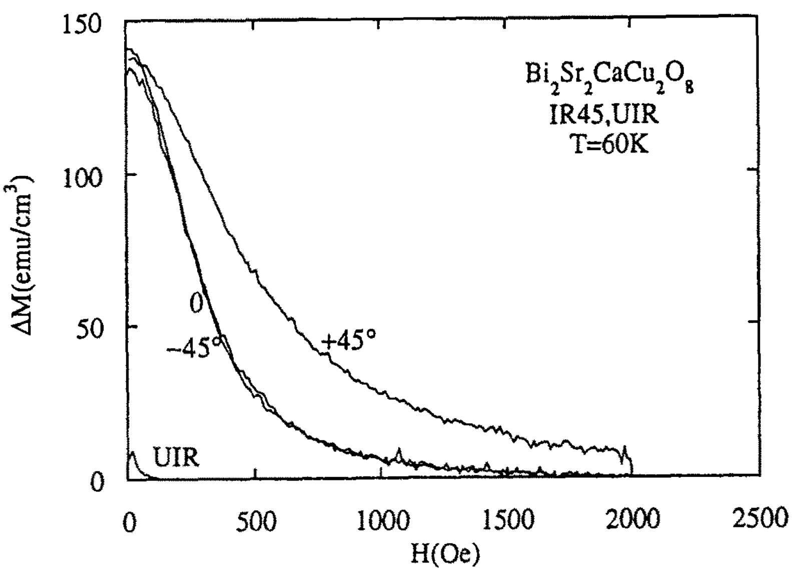

Figure 5. The widths of the magnetization curves at T = 60 K of BSSCO crystal irradiated at 45 degrees with respect to the c direction. The width of the unirradiated (UIR) sample is given as a reference.

notice that this energy depends only logarithmically on the diameter of the defect. Therefore, a significant enhancement of pinning energy will be obtained only when the diameter of the defect will be large enough so that surface barriers on the surface of the columnar defect will act as pinning centers. This will happen only when the diameter will be of order of the penetration depth.

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