Frequency dependent irreversibility line and unidirectional magnetic anisotropy in thin YBa$_2$Cu$_3$O$_{7-x}$ films irradiated with heavy ions

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We study the influence of irradiation with Pb and Xe ions on the magnetic properties of thin YBa$_2$Cu$_3$O$_{7-x}$ films. Using analysis of scaled pinning force we found unidirectional magnetic anisotropy in the case of Pb irradiation. For Xe irradiated samples, such anisotropy was not found. The irreversibility lines and their frequency dependencies vary with the type of defects and the direction of the external magnetic field.

In a recent report [1] we studied the influence of irradiation with Pb$^{+53}$ (0.86 GeV) and Xe$^{+44}$ (5 GeV) ions on the irreversible magnetic properties of YBa$_2$Cu$_3$O$_{7-x}$ thin films. The total irradiation fluence was $10^{12}$ ions/cm$^2$. Four samples, thin films of thickness 300 nm, were laser ablated on [100] MgO and SrTiO$_3$ substrates. The samples are: unirradiated sample (denoted by U), two Pb irradiated samples (Pb0 and Pb45) and a Xe irradiated one (Xe45). The digits 0 and 45 refer to the angle between the direction of the ion beam and the c-axis. DC magnetic measurements were performed on an Oxford-Instrument Vibrating Sample Magnetometer, which allows rotation of a sample relative to the direction of the external magnetic field H. In the following we denote the angle between H and the c-axis in brackets after the sample name, e.g. Pb45(+45°).

Here we summarize briefly the main results of Ref. [1], focusing on the effect of irradiation on the pinning force which reflects the different pinning mechanisms. We then add new information on the effect of irradiation on the irreversibility line (IRL).

The apparent pinning force $F_p$ is obtained from the magnetization curves measured for a given time window. Isotherms of $F_p(H)$, being normalized by the irreversibility field $H_{irr}(T)$ and maximal value of the pinning force, collapse on a single curve. Fig.1. demonstrates that samples, irradiated with different ions, show different behavior of the normalized pinning force $f_p$. The two Pb irradiated samples - Pb45(+45°) and Pb0(0°) - exhibit the same $f_p$. But, if the external field is not aligned along the direction of Pb irradiation, i.e. Pb45(-45°), $f_p$ collapses on the curve for the unirradiated sample U. In contrast, Xe irradiated sample exhibits the same scaling features for either Xe45(+45°) or Xe45(-45°). The different functional dependencies of $f_p$ for the various samples imply different pinning mechanisms for samples irradiated with different ions.

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FIGURE 1. The normalized pinning force $f_p$ as a function of normalized field.
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The difference in the pinning mechanism may be related to the microscopic nature of defects: Pb ions produce continuous columnar defects in the direction of the irradiation which serve as efficient unidirectional pinning centers [2, 3]. If the external magnetic field is perpendicular to the direction of the irradiation, vortices do not "feel" the columnar defects and \( f_p \) is the same as for unirradiated sample \( U \). On the other hand, Xe ions produce cluster-like discontinuous defects [4] which apparently do not show such unidirectional anisotropy.

In the following we describe our new results on the influence of irradiation on the irreversibility line (IRL). The irreversibility temperature \( T_{irr} \) is identified as the onset of the third harmonic of the AC signal using a micro Hall probe. For details of the technique and data analysis, the reader is referred to Ref. [5].

The field dependence of \( T_{irr} \) was studied at frequency 577 Hz. At this frequency, \( T_{irr} \) is virtually field independent below 500 Oe for all (irradiated and non irradiated) samples. Such field independence is expected within a "single-vortex" pinning regime. In contrast, at low temperatures (and higher fields) the irreversibility lines are different for different samples; the irreversibility region is widest for samples with the columnar defects, for external fields parallel to these defects.

The frequency dependence of \( T_{irr} \) was measured at constant DC and AC field amplitudes. Figure 2 exhibits typical data at \( H=200 \) Oe and \( H_{ac}=0.6 \) Oe. Knowledge of \( T_{irr}(\omega) \) may yield important information on the behavior of the pinning potential \( U_p \). The pinning potential \( U_p \) vanishes at \( j=j_c \) and at some characteristic temperature \( T_0 \leq T_c \). Here we approximate \( T_0=T_c \). Near the irreversibility line:

\[
U_p = U_0(T)(1-j/j_c)^\beta \simeq U_c(1-T/T_c)(1-j/j_c)^\beta
\]

where \( \omega_0 \) is defined as a frequency at which \( T_{irr}(H)=T_c(H) \). For \( \omega > \omega_0 \) the diffusion equation is not valid and we enter the flux-flow regime. Fig.2 shows the normalized irreversibility temperature versus frequency of the AC field for DC field 200 Oe directed along the c-axis. The symbols are experimental points, and the solid lines are fits to Eq.2.

\[
T_{irr}(\omega) = T_c/\{\ln(\omega_0/\omega)T_c/U_c+1\}
\]

FIGURE 2. Normalized irreversibility temperature as a function of frequency.

From these fits we find \( \omega_0 = 15.8, 77.3, 13.1, 25.2 \) kHz and \( U_c = 0.26, 0.23, 0.07, 0.035 \) eV for samples \( U(0^\circ), Xe45(0^\circ), Pb45(0^\circ), \) and \( Pb0(0^\circ) \), respectively. Surprisingly, \( U_c \) is quite low for \( Pb \) irradiated samples. This value depends strongly also on the angle between the external magnetic field and direction of the columnar defects. Our results show that \( U_p(T) \) at high temperatures barely changes in the case of the defects induced by \( Xe \) irradiation in comparison with unirradiated sample, but smears dramatically in the case of the columnar defects.

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REFERENCES:
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