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Frequency dependent irreversibility line and unidirectional magnetic anisotropy in thin $YBa_2Cu_3O_{7-x}$ 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 $YBa_2Cu_3O_{7-x}$ 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 $YBa_2Cu_3O_{7-x}$ 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 $F_{p,app}$ is obtained from the magnetization curves measured for a given time window. Isotherms of $F_{p,app}(H)$, 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.

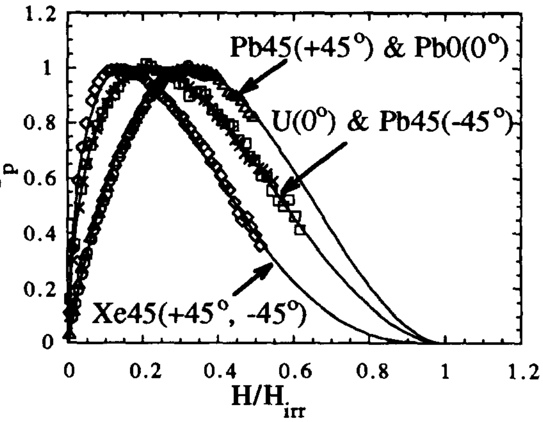

FIGURE 1. The normalized pinning force f_p as a function of normalized field.

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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 $T_0 \le T_c$. Here we approximate $T_0=T_c$. Near the irreversibility line:

$$U_p=U_0(T)(1-j/j_c)^{\beta} \approx U_c(1-T/T_c)(1-j/j_c)^{\beta} \qquad (1)$$

It is important to note that the value of U_c is linear extrapolation of $U_0(T)$ to T=0. We maintain that the actual pinning potential $U_p(T)$ is a nonlinear function of T, and probably saturates at low temperatures. At the same time parameter U_c gives an estimation of the pinning strength at high temperatures and its temperature dependence near IRL. Using the standard diffusion equation for flux creep we get:

$$T_{irr}(\omega)=T_c/\{\ln(\omega_0/\omega)T_c/U_c+1\} \qquad (2)$$

where ω_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

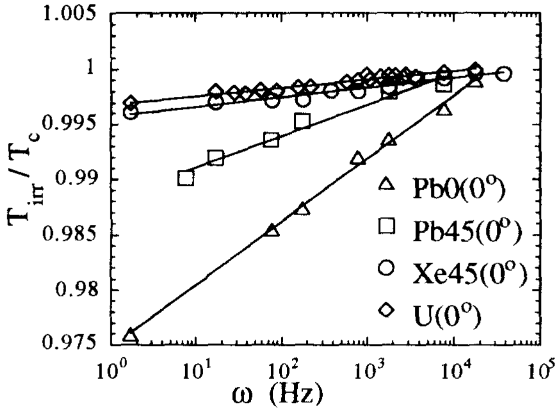

FIGURE 2. Normalized irreversibility temperature as a function of frequency.

From these fits we find ω_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°), Xe45(0°), Pb45(0°), and Pb0(0°), 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 $U_0(T)$ 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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