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Vortex line pinning in $Bi_2Sr_2CaCu_2O_8$ single crystals with columnar defects*

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The *ac* transmittivity of heavy-ion irradiated $Bi_2Sr_2CaCu_2O_8$ single crystals shows a sharp cusp as function of the *dc* field orientation with respect to the columnar defects. This unambiguously demonstrates the connected nature of vortices in these samples. In contrast, the irreversibility line does not reveal a cusp.

1. INTRODUCTION

From the point of view of applications, one of the main drawbacks of the $Bi_2Sr_2CaCu_2O_8$ high-temperature superconductor is its layered structure and the very high ensuing effective mass anisotropy. This causes the vortex lattice in the mixed state to be extremely soft, which translates to a high sensitivity to thermal fluctuations, a low critical current j_c and high flux creep rates. In fact, it was recently inferred from neutron diffraction experiments that above $B_{2D} \approx 600$G, two-dimensional (2D) vortex segments in adjacent layers are effectively decoupled [1].

In this paper, we show that the introduction of columnar defects parallel to the sample c-axis causes the vortex tilt modulus c_{44} to increase dramatically. Angular dependent *ac*- screening measurements show that vortices remain connected at least up to the matching field B_Φ. The angular dependence of the irreversibility line is determined by the thermal depinning rate.

2. EXPERIMENTAL

The $Bi_2Sr_2CaCu_2O_8$ single-crystal was cut out of a larger piece grown using the traveling-solvent floating zone technique, and had dimensions $0.66(\mathrm{l}) \times 0.34(\mathrm{w}) \times 0.030(\mathrm{t})\mathrm{mm}^3$. It was irradiated, parallel to the sample c-axis, at a dose of $2.5 \times 10^{14}\mathrm{m}^{-2}$ 5.8GeV Pb ions, in order to produce continuous amorphous tracks traversing the entire crystal. The matching field, at which there are equally many vortices and columnar defects, was $B_\Phi \approx 5$kG. T_c after irradiation was 90.7K.

ac magnetic shielding experiments were carried out using the Local Hall Probe Magnetometer. An *ac*-field of magnitude $h_{ac} \approx 2.1$Oe and frequency $f = 7.75$Hz is applied parallel to the sample c-axis. A miniature Hall probe, placed in the centre of the sample top surface, is used to measure the screening of the *ac* field by the sample. Results are presented as the *ac* transmittivity T_H [2], $T_H = 0$ corresponding to complete screening and $T_H = 1$ to complete transmission of the *ac*-field. The third harmonic transmittivity T_{H3} is a measure of the nonlinearity of the sample $V(I)$-response. The experiment is placed in a static field H, the orientation of which can be varied with respect to the sample c-axis and the columnar defects.

3. RESULTS AND DISCUSSION

Figure 1 shows the angular dependence of the in-phase fundamental transmittivity T'_H and third harmonic amplitude $|T_{H3}|$, for $H = 5$kG and several temperatures T. Both harmonics show a sharp cusp around the angle where the field is aligned with the columnar defects ($\Theta = 90°$). Such a cusp is not expected when the angular dependence is determined by the anisotropy of the unirradiated material: the transmittivity should then be a smooth function of Θ, with a *maximum* around 90°. A cusp is, however, expected in the case of vortex line localization by the columns in the Bose-glass phase [3]. The cusp, and hence the linear nature of the vortices, persists up to the matching field, $B_\Phi = 5$kG, much higher than the 2D crossover field B_{2D} of

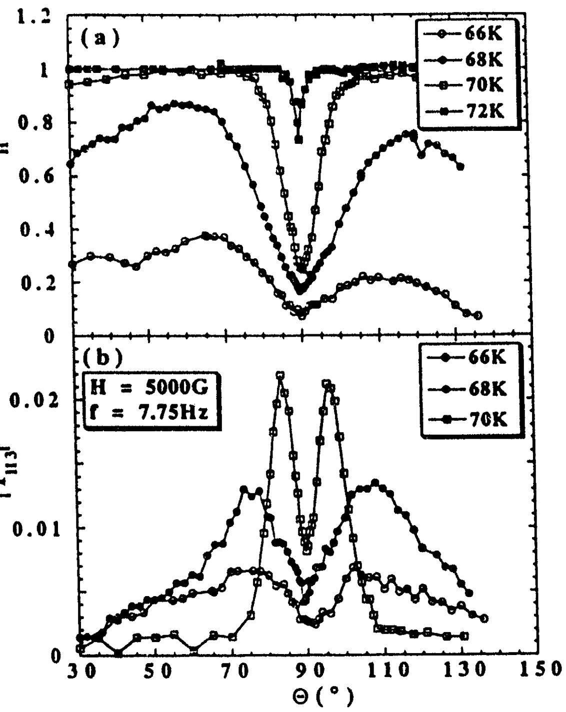

Figure 1. Angular dependence of T'_H (a) and $|T_{H3}|$(b), for $H = 5kG$ and $f = 7.75Hz$. $\Theta = 90°$ corresponds to the field being aligned with the columnar defects.

the unirradiated material. Since B_{2D} is determined by the condition that c_{44} becomes irrelevant with respect to the shear modulus c_{66}, we conclude that the introduction of columnar defects dramatically increases c_{44} in the field region $B < B_{\Phi}$.

We define the "accomodation angle" Θ_a as the angle over which the field has to be tilted away from the columns in order for $|T_{H3}|$, and hence flux pinning, to disappear. A plot of Θ_a versus T, as shown in Fig. 2, represents the angular dependence of the "irreversibility line". At low temperature, the accomodation angle is very large, $\Theta_a \approx 70°$. This may explain the apparent lack of angular dependence in previous experiments [4]. Upon increasing temperature, Θ_a shows an approximately linear decrease, followed by a sudden break at $T_1 \approx 75K$, whence Θ_a drops exponentially fast. Note that Fig. 2 does *not* reveal a cusp around $\Theta_a = 0$. Although this observation excludes the identification of the irreversibility line with the Bose–glass phase transition [3], it can be explained in terms of thermal depinning. Namely, T_1 corresponds exactly to the depinning temperature as determined from the frequency dependence of $T_{H'}$ [5]. Above T_1, the thermal wandering of the vortices causes the exponential drop with temperature of the pinning energy, which is reflected in the temperature dependence of Θ_a.

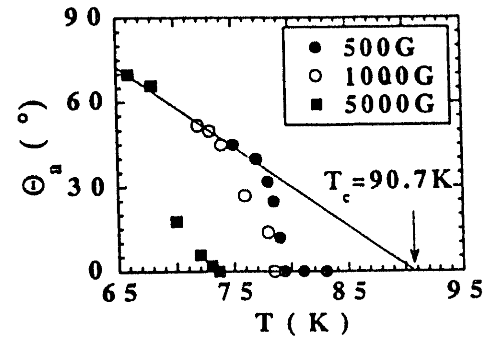

Figure 2. The accomodation angle Θ_a as function of temperature. The drawn line indicates the linear $\Theta_a \propto (T_c - T)$ dependence at low T.

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