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Mechanical damping effects by flux lines in $YBa_2Cu_3O_{6.9}$ thin films

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Abstract

We present new results of internal friction (IF) measurements on epitaxial $YBa_2Cu_3O_{6.9}$ thin films in magnetic fields up to 3 T. For fields perpendicular to the *c* axis of the films we find a sharp maximum in the temperature dependence of the IF slightly below T_c. For a small tilt of the samples with respect to the magnetic field this maximum broadens and shifts to lower temperatures. It is explained within the framework of thermally assisted flux flow where the position is related to an activation energy which describes thermal diffusion of flux lines. In order to account for the width of the maximum, a distribution of activation energies has to be taken into account.

1. Introduction

The static and dynamic properties of the flux line lattice (FLL) of high temperature superconductors are still a topic of interest. Because the FLL interacts with the applied magnetic field and is pinned to the crystal lattice, internal friction (IF) is an excellent tool for studying the behaviour of the FLL. While this has been done extensively for sintered ceramics and single crystals (for a review see ref. 1), few measurements on thin films have been reported [2]. In this contribution we present new results of IF measurements on epitaxial $YBa_2Cu_3O_{6.9}$ thin films.

2. Experimental details

$YBa_2Cu_3O_{6.9}$ films were deposited by a d.c.-sputtering technique [3] on $LaAlO_3$ and $NdGaO_3$ substrates. The films grow epitaxially on these substrates with the crystallographic *c* axis perpendicular to the substrate surface. From channelling experiments one gets a minimum yield of typically 3%, indicating the high degree of epitaxy. The films had an area of 10×10 mm^2 and a thickness varying between 50 and 600 nm. The midpoint of the resistive transition yields for all samples $T_c>90$ K and the width of the transition is less than 1.3 K.

The samples were glued to the end of a low damping silicon oscillator similar to the one used by Gammel *et al.* [4]. This provides for a low background in the IF and allows the use of any substrate material, because the substrate itself is not strained and thus does not contribute to the mechanical damping.

The magnetic field *B* was applied along the length of the oscillator, perpendicular to the *c* axis of the films. The sample could be tilted with respect to the magnetic field by an angle $\theta=\pm10°$ (0.5°). Magnetic fields up to 3 T could be applied.

The mechanical oscillator was driven into resonant vibrations by an electrostatic drive system where the frequency *f* was typically near 250 Hz. The amplitude of the sample vibration was 400 nm and the IF was determined from the free decay of the oscillation.

3. Results and discussion

Figure 1 shows the IF spectra of a $YBa_2Cu_3O_{6.9}$ film 100 nm thick on $LaAlO_3$ in zero field and when cooled in a magnetic field of 200 mT. In the latter case the damping Q^{-1} shows a sharp maximum slightly below T_c and becomes essentially temperature independent at lower temperatures.

The low temperature damping is proportional to B^2 and can be explained as follows. $YBa_2Cu_3O_{6.9}$ is, like all high temperature superconductors, a type II superconductor. Therefore magnetic fields higher than the first critical field B_{c1} penetrate the films as flux lines (FLs), each containing a single flux quantum. Since B_{c1} (0 K) = 25 mT for $B\perp c$ in $YBa_2Cu_3O_7$ [5], for all fields discussed here FLs penetrate the sample. At low temperatures these FLs are rigidly pinned at their pinning sites. The IF is then due to FL segments moving freely between two pinning sites. One can consider this be-

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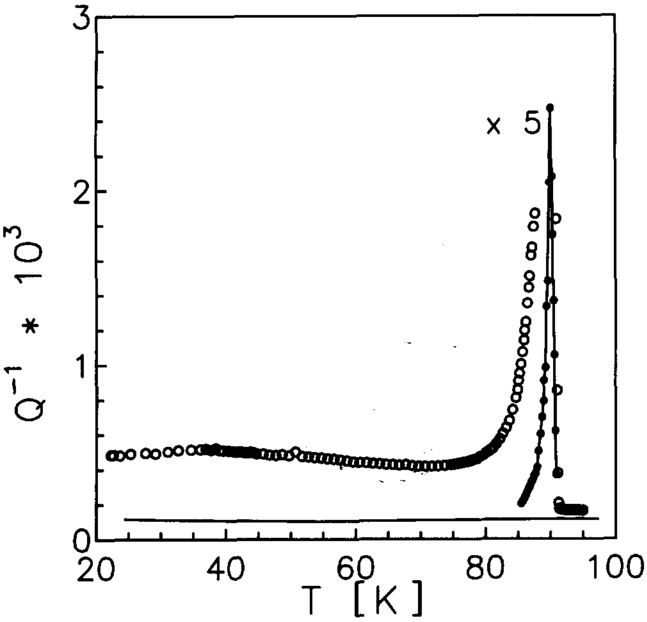

Fig. 1. Temperature dependence of the IF at $B=200$ mT (O) and zero field (——) for a $YBa_2Cu_3O_{6.9}$ film 100 nm thick.

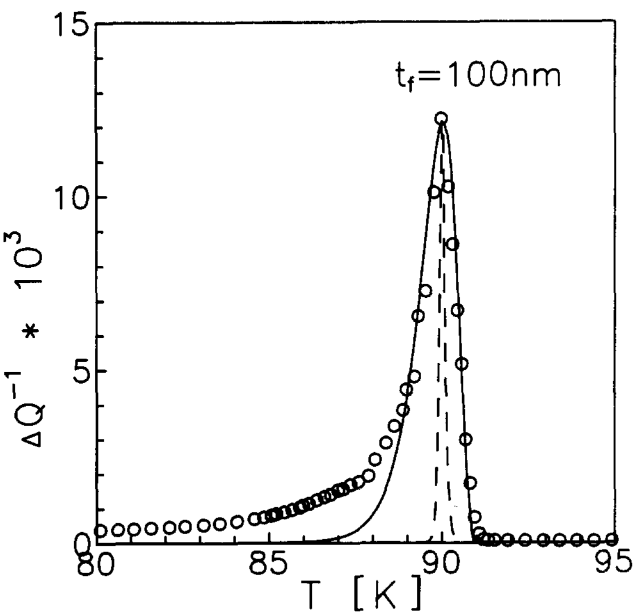

Fig. 2. IF of a $YBa_2Cu_3O_{6.9}$ film near T_c: O, difference between measurements at 200 mT and zero field (see Fig. 1); - - -, calculation using a single activation energy; ——, calculation using a log–normal distribution of activation energies.

haviour of the FL segments as swinging strings. The damping is independent of temperature owing to the rigid pinning.

In the following we would like to focus on the maximum in the IF just below T_c. Figure 2 shows the difference between the two data sets of Fig. 1. The maximum in the damping can be explained within the model of thermally assisted flux flow (TAFF). In this model one assumes thermally activated diffusion of the FLs, which is a phenomenon specific to the high temperature superconductors. Because of their high T_c, thermal energies can become comparable with the pinning energy. The diffusion of the FLs is described by a field- and temperature-dependent relaxation time

$$\tau(B, T) = \tau_0 \exp\left(\frac{U(B, T)}{kT}\right) \tag{1}$$

with the pre-exponential factor τ_0 depending only on the sample geometry [6]. The activation energy $U(B, T)$ can be written as [7]

$$U(B, T) = U_0(B)\left(1 - \frac{T}{T_c}\right)^{3/2} \tag{2}$$

Maximum energy dissipation is found for $2\pi f\tau = \omega\tau = 1$ [6]. Assuming a Debye law for the damping,

$$Q^{-1} = \Delta \frac{\omega\tau}{1 + (\omega\tau)^2} \tag{3}$$

where Δ is the relaxation strength, the temperature dependence of the IF can be calculated using eqns. (1)–(3). The result is shown in Fig. 2 as the dashed curve when U_0 (200 mT) = 63 eV and $\Delta = 2.44 \times 10^{-2}$ is chosen. Obviously the measured maximum is much broader than the calculated one. One has, however, to take into account that there exist different types of pinning sites (*e.g.* point defects, twin boundaries, stacking faults, etc.) for the FLs in the film. These different pinning sites correspond to a distribution of activation energies. Assuming a log–normal distribution [8] with the mean value at U_{0m} and a width σ, one can fit the measured data reasonably well as shown by the solid curve in Fig. 2.

These fits yield a width of the distribution $\sigma = 0.75$, which within experimental error is the same for all samples and corresponds to an energy range $U_{FWHM}/U_{0m} = 1.13$. Thus the only varying fit parameter is U_{0m}, which is plotted in Fig. 3 *vs.* the magnetic field on a double-logarithmic scale for all samples measured. U_{0m} follows approximately a $1/B$ law, which results in the following form of the activation energy:

$$U(T, B) = \frac{A_0}{B}\left(1 - \frac{T}{T_c}\right)^{3/2} \tag{4}$$

At T_m, the temperature position of the peak, the activation energy $U(T, B)$ is basically the same for all applied fields B. Therefore one gets the field dependence of T_m as $1 - T_m/T_c \propto B^{2/3}$, which is the form of the often found irreversibility or depinning line in magnetization measurements [9]. Moreover, one can derive from the slope of the $1/B$ law shown in Fig. 3. $A_0 \approx 10$ eV T ($B \perp c$), while for $B \parallel c$ lower values ranging from 2.9 to 6.2 eV T have been reported [10]. It is reasonable to expect an enhanced activation energy for $B \perp c$ be-

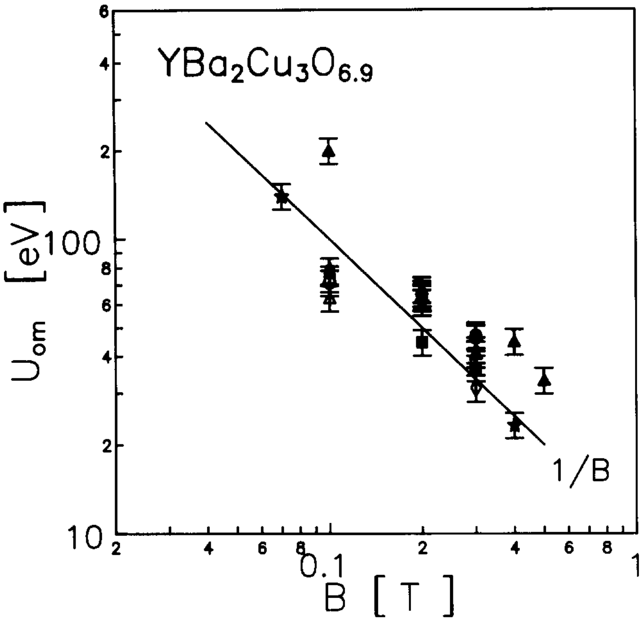

Fig. 3. Field dependence of the activation energy U_{0m}. Each symbol corresponds to a different sample. The line represents a $1/B$ dependence.

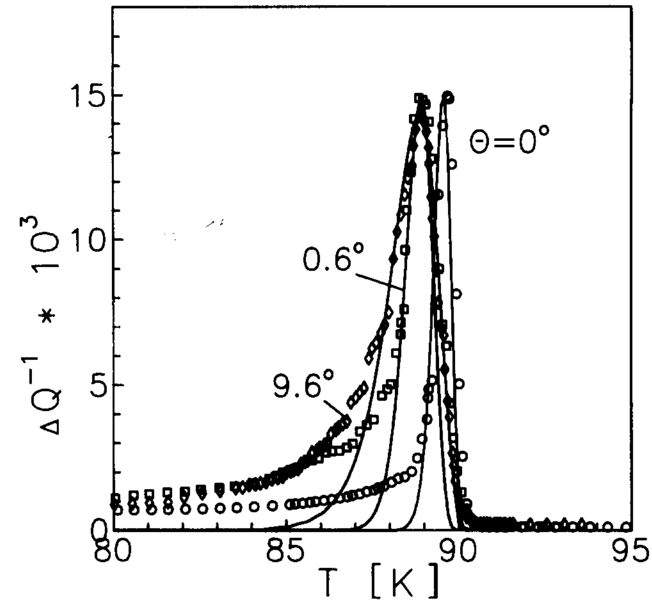

Fig. 4. Temperature dependence of the IF for three different tilt angles θ with respect to the magnetic field (200 mT) for a $YBa_2Cu_3O_{6.9}$ film 275 nm thick. The curves represent best fits as described in the text.

cause of the more effective pinning of FLs lying between the superconducting *ab* planes of the film. This pinning mechanism is often called intrinsic pinning.

The relaxation strength Δ turned out to be proportional to B^2 and independent of the film thickness t_f. For seven films with t_f varying between 50 and 600 nm a value of $\Delta/B^2 = 3.0 \pm 0.9$ T^{-2} was obtained. The relaxation strength can also be calculated within the framework of the TAFF model [6]. This theory predicts Δ proportional to B^2, independent of t_f and a value of $\Delta/B^2 = 2.34$ T^{-2} for the geometry used in our experiments. Thus the experimental results are in very good agreement with theory.

Figure 4 shows the influence of a slight tilt of the *c* axis with respect to the applied field. The IF spectra of a $YBa_2Cu_3O_{6.9}$ film 275 nm thick on $NdGaO_3$ in a magnetic field of 200 mT are plotted for three different tilt angles θ. One can see that with increasing θ the maximum in the damping shifts to lower temperatures and broadens while its height remains basically unchanged. Analysing the data as described before, one obtains both the relaxation strengths and the activation energies as a function of tilt angle. The result is shown in Fig. 5, where $\Delta(\theta)$ and $U_{0m}(\theta)$ normalized to their values at zero tilt are plotted *vs.* θ. For a tilt angle smaller than 1° U_{0m} is reduced by 30% and does not change further up to 10°, which was the largest angle available in the experiments. The relaxation strength Δ, which is a measure of the dissipated energy, is increased by 50% for tilt angles higher than about 2°.

The tilt of the sample causes FL segments to align parallel to the *c* axis. For this direction the activation

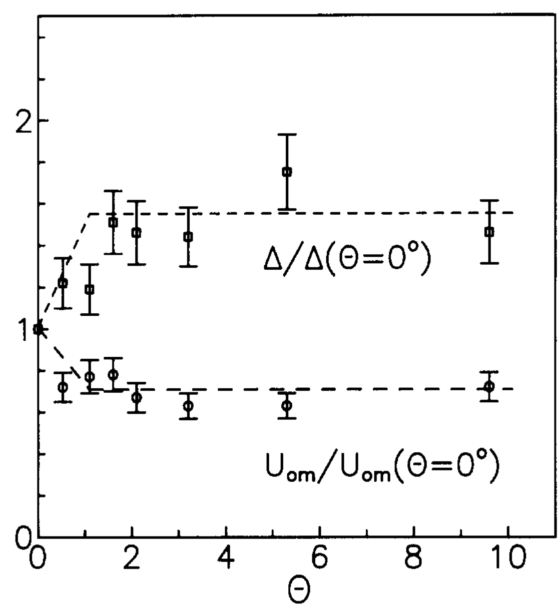

Fig. 5. Relaxation strength Δ and activation energy U_{0m} normalized to values at $\theta = 0°$ as a function of the tilt angle θ for a $YBa_2Cu_3O_{6.9}$ film 275 nm thick. The applied field was 200 mT. The lines are only a guide to the eye.

energy is known to be reduced [10]. Whenever a segment of the FLs is parallel to the *c* axis, this component will move within the *ab* planes. In the high temperature superconductors the Cu–O planes, which are parallel to the *ab* planes, mainly contain the superconducting carriers. Therefore the energy dissipation of FLs moving in the *ab* plane is higher than for FLs oriented parallel to the planes. Thus the damping Q^{-1} is dominated by those FL segments which are parallel to the c axis. A change in both the relaxation strength and activation energy is found for an angle $\theta > 1°$, which indicates that intrinsic pinning mainly occurs for angles smaller than 1°.

4. Summary and conclusions

IF measurements on epitaxial $YBa_2Cu_3O_{6.9}$ thin films with thicknesses varying between 50 and 600 nm have been performed. The measurements were performed in magnetic fields up to 0.5 T where the field was oriented parallel to the crystallographic c axis. A sharp maximum in the IF was found slightly below T_c. It can be explained quantitatively by the TAFF model. A relaxation strength of $\Delta/B^2 = 3.0 \pm 0.9$ T^{-2} was found which is in good agreement with $\Delta/B^2 = 2.34$ T^{-2} derived from theory. The field dependence of the position of the maxima follows the well-known $B^{2/3} \alpha\, 1 - T_m/T_c$ law of the irreversibility line. The activation energy of about 10 eV for $B = 1$ T is reasonable for $B \perp c$ as compared with 2.9–6.2 eV found for $B \| c$ [10]. To the best of our knowledge the measurements presented here are the first to give information about the activation energy of moving FLs for $B \perp c$.

Upon tilting the sample with respect to the applied field, a lower activation energy and an enhanced relaxation strength due to FL movement within the superconducting planes are found. Intrinsic pinning is observed for tilt angles smaller than approximately 1°.

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