Flux Line Matching Effects in $YBa_2Cu_3O_{7-x}$ Thin Films

C. Hünnekes, H.G. Bohn, W. Schilling, and H. Schulz
Institut für Festkörperforschung, Forschungszentrum Jülich, D-52425 Jülich, Germany
(Received 1 December 1993)

We present internal friction (IF) measurements in magnetic fields up to 1.6 T of epitaxial $YBa_2Cu_3O_{7-x}$ thin films with different thicknesses. Measurements at constant temperature and varying field exhibit peaks in the IF at particular values of the field for H perpendicular to the crystallographic c axis. Assuming a rectangular flux line arrangement and taking the anisotropy of $YBa_2Cu_3O_{7-x}$ into account the positions of the peaks coincide with fields where the distance in c direction of the flux line rows becomes an integral fraction of the sample thickness. This matching effect is valid for different film thicknesses and seems to be independent of temperature.

PACS numbers: 74.60.Ge, 62.40.+i, 74.76.Bz

In $YBa_2Cu_3O_{7-x}$ the Cu-O planes, which are mainly responsible for the superconducting properties, form double layers which have a distance of around 8.3 Å from each other along the c axis. It is expected that the flux line lattice (FLL) in the mixed state will match to the crystal structure of the material as well as to the macroscopic dimensions of the investigated sample [1]. The expected matching effects are restricted to special geometric conditions, i.e., that the applied field H is parallel to the layers. Until now there has been no experimental observation of these matching effects for the high temperature superconductors. However, Brongersma *et al.* have recently shown that a series of maxima in torque measurements on Nb/Cu multilayers in a magnetic field is caused by the matching of the flux line lattice to the sample thickness [2]. In this paper we present first evidence for matching effects in $YBa_2Cu_3O_{7-x}$ which were detected by internal friction (IF) measurements on thin films. Since these matching effects can only be observed for very thin samples they remained undetected in previous experiments using thick samples only [3, 4]. A detailed study of the temperature dependence of the IF is published elsewhere [5].

$YBa_2Cu_3O_{7-x}$ films were deposited by a dc-sputtering technique [6] onto $LaAlO_3$ (sample A) and $NdGaO_3$ (sample B) substrates. The films grew epitaxially on these substrates with the crystallographic c axis perpendicular to the substrate surface. From channeling measurements a minimum yield of typical 3% was obtained indicating the high degree of epitaxy. The films covered an area of 10×10 mm^2 and had a thickness, t, of 43 nm (sample A) and 270 nm (sample B), respectively. The thickness was determined from both Rutherford backscattering spectroscopy and surface profiler measurements with an accuracy of about $\pm 10\%$. For both samples the midpoint of the resistive transition was found to be T_c=92.7 K indicating $x < 0.1$ [7] and the width of the transition was less than 0.9 K. No influence of the different substrate materials of sample A and B on the sample quality was observed.

The samples were glued to the end of a low damping Si cantilever oscillator similar to the one described by Gammel *et al.* [3]. The mechanical oscillator was driven into resonant vibrations by an electrostatic drive system. The frequency of the sample vibration was typically near 250 Hz, the amplitude was 400 nm. The IF was determined from the free decay of the oscillation after switching off the excitation. Magnetic fields up to 1.6 T were applied parallel to the cantilever, i.e., in the film plane and perpendicular to the c axis.

Whenever the flux lines (FL's) in a superconductor move energy will be dissipated. The FL's in a superconductor which is oscillating in a uniform magnetic field H try to align themselves along H. If the FL's can overcome their pinning barriers they will move relative to the superconductor. Thus the damping Q^{-1} of this oscillating superconductor is directly proportional to the energy loss due to FL movement [8] which in turn depends on the displacement of the FL's from their equilibrium position. In our experimental setup this energy loss can be measured down to approximately 3×10^{-14} J.

Figure 1 shows the damping of sample A at 20 K and 50 K as a function of the applied field H. For $\mu_0 H > \mu_0 H_{c1} \simeq 25$ mT [9] FL's penetrate into the sample and an overall increase of the damping with increasing field is observed. According to Brandt *et al.* [10] this background damping is related to the volume pinning force and follows a H^2 dependence. For our thin film samples and at fields higher than 0.4 T deviations from the predicted H^2 dependence occur. This may be due to the low sample thickness which is of the order of the penetration depth λ in the temperature range discussed here. In addition to this increase of the damping one finds, for 20 K, two distinct peaks at about 0.25 T and 0.8 T. The position of the lower peak was also checked at 50 K and found to be only slightly shifted (see inset). The same type of measurements for sample B is shown in Fig. 2. At 20 K peaks at about 0.2 T, 0.33 T, 0.38 T, 0.45 T, and 0.68 T show up. The lower three peaks were found at the same positions at 80 K (see inset). Obviously, the number and position of the peaks strongly depends on the sample thickness. While there are two peaks below

0031-9007/94/72(14)/2271(3)$06.00

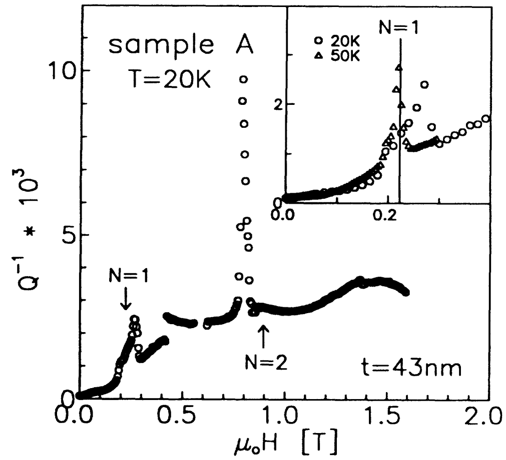

FIG. 1. Magnetic field dependence of the damping at $T = 20$ K and 50 K (inset) of a 43 nm thick $YBa_2Cu_3O_{7-x}$ film (sample A). The arrows and lines are described in the text. The step in the data at 0.41 T is an artifact of the measurement.

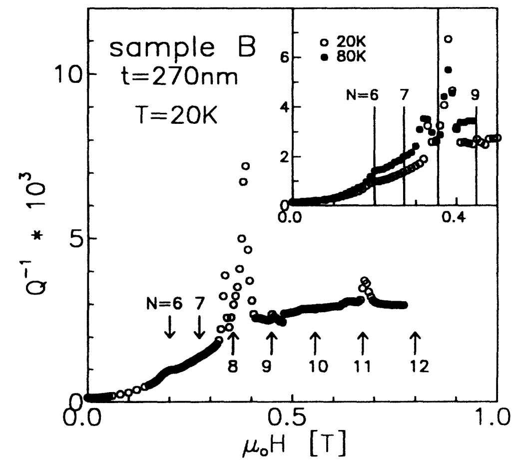

FIG. 2. Magnetic field dependence of the damping at $T = 20$ K and 80 K (inset) of a 270 nm thick $YBa_2Cu_3O_{7-x}$ film (sample B). The arrows and lines are described in the text.

1 T for sample A (43 nm, Fig. 1) one can observe five peaks for sample B (270 nm, Fig. 2) in the same field range. For both samples the peak position is the same for increasing and decreasing fields.

We believe that these peaks arise from a matching of the FLL to the sample thickness. When H is increased above H_{c1} FL's penetrate the sample forming at first a single row of FL's along the width of the sample. This row has a position at half the thickness of the sample [Fig. 3(a)] due to a repulsion from the surfaces. This repulsion arises from the periodic tilting of the sample in the uniform magnetic field which gives rise to surface screening currents and from the penetration of the external field into the superconductor [11]. With further increase of H the density of the FL's in the row increases. While the average FL distance a_y in the row decreases the repulsion between the FL's rises. Thus it becomes energetically favorable to form a second row of FL's when the repulsion from the sample surface becomes smaller than the repulsion between the FL's [Fig. 3(b)]. When forming the second row of FL's a_y doubles yielding a maximum in the H dependence of the FL distance. Near this maximum in a_y each FL becomes highly mobile and the stiffness of the FL arrangement possesses a minimum resulting in a peak in the damping Q^{-1}. This procedure will be repeated with rising H resulting in a maximum in Q^{-1} whenever N rows of FL's turn over into $N+1$ rows. The fields at which the rearrangement of the FL rows takes place can be estimated from the following simple considerations.

The total flux in the sample is related to a_y by

$$N\,\Phi_0 \simeq a_y\,t\,B, \qquad (1)$$

where $N = 1, 2, \ldots$ is the number of FL's rows in the superconductor, $\Phi_0 = 2.07 \times 10^{-15}\,\mathrm{T\,m^2}$ the flux quantum, and B the magnetic induction. We assume that whenever a_y becomes smaller than the FL distance a_{ab} (a_{ab} is the FL distance in ab direction) in an infinite sample where the FL distance is mainly influenced by the FL-FL interaction it is energetically favorable to form a new row of FL's as it is shown in Fig. 3(b).

As was shown by decoration experiments on $YBa_2Cu_3O_{7-x}$ with $H \perp c$ the FL's (which are Josephson FL's in this geometry) form a rectangular FLL [12]. The ratio of the FL distances a_{ab}/a_c (a_c is the FL distance in c direction) equals the anisotropy $\Gamma \simeq 5$ in $YBa_2Cu_3O_{7-x}$ [13]. Thus one obtains

$$a_{ab} \simeq (\Gamma \Phi_0/B)^{1/2}. \qquad (2)$$

A new row of FL's is therefore created at fields $H(N)$

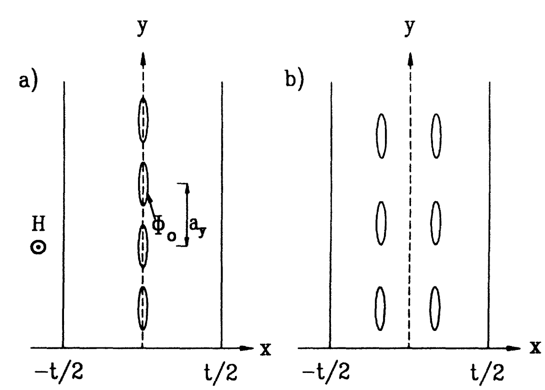

FIG. 3. Schematic drawing of the flux line arrangement in a superconducting film with a thickness t. At low applied fields H first a single row of flux lines is formed (a) which turns over into two rows when the field is raised (b).

where $a_{ab} = a_y$:

$$H(N) \simeq \frac{\Phi_0}{\mu_0 \Gamma} \left[\frac{N}{t}\right]^2 . \tag{3}$$

This simple formula only contains as sample dependent parameters the sample thickness and the anisotropy and is similar to the one derived by Brongersma *et al.* in explaining the maxima in torque measurements on Nb/Cu multilayers [14].

In Figs. 1 and 2 the values of $H(N)$ calculated from Eq. (3) are marked by arrows or lines. One can see that all measured peaks coincide or are close to a selected value $H(N)$. For the thicker sample not at all possible fields peaks were found indicating that there must exist additional selection rules which are not incorporated into our simple model given above. While the influence of the sample thickness on the peak position is well explained by Eq. (3) the height of the peaks is not yet understood. Also Eq. (3) does not contain any temperature dependence. This is basically in accordance with our experimental observations which show only a slight (if any) shift of the peak position. Detailed calculations of the FL arrangement in thin films similar to those performed in Ref. [2] may help to get a better understanding of these effects.

IF measurements of two epitaxial $YBa_2Cu_3O_{7-x}$ films with thicknesses of 43 nm and 270 nm have been performed. The measurements were carried out at constant temperature and in magnetic fields up to 1.6 T. The field was oriented perpendicular to the crystallographic c axis. The IF as a function of the field exhibits peaks at particular values of the field. We believe that for the HT_c superconductors these peaks indicate the first observation of a matching of the FLL to the sample geometry, i.e., the sample thickness. The weak (if any) temperature dependence and the influence of the sample thickness on the peak position support our hypothesis. However, less peaks than expected are observed in the 270 nm sample and also the height of the peaks is not yet understood. Nevertheless, our simple model describes the observed peaks in a sufficient way.

We acknowledge helpful discussions with R. Wördenweber.

[1] D. Feinberg and C. Villard, Phys. Rev. Lett. **65**, 919 (1990).

[2] S.H. Brongersma, J.J.M. Pothuizen, E. Verweij, N.J. Koeman, D.G. de Groot, and R. Griessen, Phys. Rev. Lett. **71**, 2319 (1993).

[3] P.L. Gammel, L.F. Schneemeyer, J.V. Waszczak, and D.J. Bishop, Phys. Rev. Lett. **61**, 1666 (1988).

[4] A. Gupta, P. Esquinazi, and H.F. Braun, Physica (Amsterdam) **165B&166**, 1443 (1990).

[5] C. Hünnekes, H.G. Bohn, W. Schilling, and H. Schulz, Proceedings of ICIFUAS-10, Rome, 1993 [J. Alloys Compd. (to be published)].

[6] U. Poppe, N. Klein, U. Dähne, H. Soltner, C.L. Jia, B. Kabius, K. Urban, A. Lubig, K. Schmidy, S. Hensen, S. Orbach, G. Müller, and H. Piel, J. Appl. Phys. **71**, 5572 (1992).

[7] H. Theuss and H. Kronmüller, Physica (Amsterdam) **177C**, 253 (1991).

[8] P. Esquinazi, J. Low Temp. Phys. **85**, 139 (1991).

[9] Y. Yeshurun, A.P. Malozemoff, F. Holtzberg, and T.R Dinger, Phys. Rev. B **38**, 11 828 (1988).

[10] E.H. Brandt, P. Esquinazi, and H. Neckel, J. Low Temp. Phys. **63**, 187 (1986).

[11] C.P. Bean and J.D. Livingston, Phys. Rev. Lett. **12**, 14 (1964).

[12] G.J. Dolan, F. Holtzberg, C. Field, and T.R. Dinger, Phys. Rev. Lett. **62**, 2184 (1989).

[13] G. Burns, *High Temperature Superconductivity* (Academic Press, New York, 1992), p. 156 ff.

[14] S.H. Brongersma, J.J.M. Pothuizen, E. Verweij, N.J. Koeman, D.G. de Groot, and R. Griessen, J. Alloys Compd. **195**, 443 (1993).