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Angular dependence of magnetoresistance and critical current density of sputtered $YBa_2Cu_3O_{7-\delta}$ films

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Abstract

Superconducting $YBa_2Cu_3O_{7-\delta}$ films were prepared by DC-sputtering on single crystal $SrTiO_3$ substrates. The angular dependence of the magnetoresistance and the critical current density of these films were measured for different magnetic fields and temperatures. The anisotropy of the dissipation was investigated in high as well as in low magnetic fields. The results show the measured properties of the $YBa_2Cu_3O_{7-\delta}$ films strongly dependent on the tilt angle θ between the magnetic field and the ab-plane of the film due to the anisotropy of the layered superconductor in the mixed state. Furthermore the ϕ-dependence is discussed with ϕ being the angle between the current direction and the θ-rotation plane.

1 Introduction

Since high-T_c superconductors (HTSC) become more and more important for various applications much effort was spent to understand the mechanism of dissipation in the mixed state of HTSC's. An important contribution to enlighten the behaviour of the HTSC's could be to investigate the angular dependence of the magnetoresistance ρ and the critical current density j_c [1-4]. The values of ρ and j_c, which are correlated to the strength of the intrinsic pinning, depend on the angles between the magnetic field and the films. So the quality of the HTSC thin films can be investigated by measuring the angular dependence of ρ and j_c. The angular dependence of the dissipation mechanism could be a criterion to characterize the HTSC thin films.

2 Experimental

The thickness of the $YBa_2Cu_3O_{7-\delta}$ films on single crystal $SrTiO_3$ ranged from 100 to 200 nm. X-ray diffraction pattern show the films highly oriented with the c-axis perpendicular to the substrate surface. Paths of 20 μm and 40 μm width and 2 mm length were structured by wet chemical etching. The electric contacts were attached by bonding gold wires on the contact areas of the film. To avoid warming up of the contacts a pulsed current method was used with the possibility to change form, duration and period of the current pulses. To study the angular dependence of the magnetoresistance and the critical current density in magnetic fields a sample holder was used, which allows to change the angle between the magnetic field and the ab-plane of the film (angle θ) as well as the angle between the current direction and the plane determined by the magnetic field and the c-axis (angle ϕ). The angle resolution was better than 0.05°, but an offset of 1° could occur due to an inaccurate adjustment. The θ-dependence was measured for different angles ϕ between the current direction and the θ-rotation plane. Magnetic fields between 10 mT and 6 T were used.

The inductively determined T_c^{onset} by measuring the complex AC-susceptibility of the sputtered $YBa_2Cu_3O_{7-\delta}$ films were between 85 K to 88 K with transition widths of 1 to 4 K. The critical current density j_c was measured as a function of temperature. Depending on the quality of the superconducting films j_c achieved values of about $2 \times 10^5\,A/cm^2$ to $3 \times 10^6\,A/cm^2$ at 77 K. Current-voltage curves were taken and hysteresis measurements were made for various angles and magnetic fields.

3 Results and Discussion

3.1 High magnetic fields

In this section some typical results of the measurements in high magnetic fields are discussed. Figure 1 shows the dependence of the magnetoresistance ρ on the angle θ between the magnetic field and the ab-plane. The measurements were made for various fields between 0.5 T and 6 T and a high current density of $1.4 \times 10^6\,A/cm^2$. At $\theta = 0°$ and $\theta = 180°$, when the magnetic field is parallel to the ab-plane of

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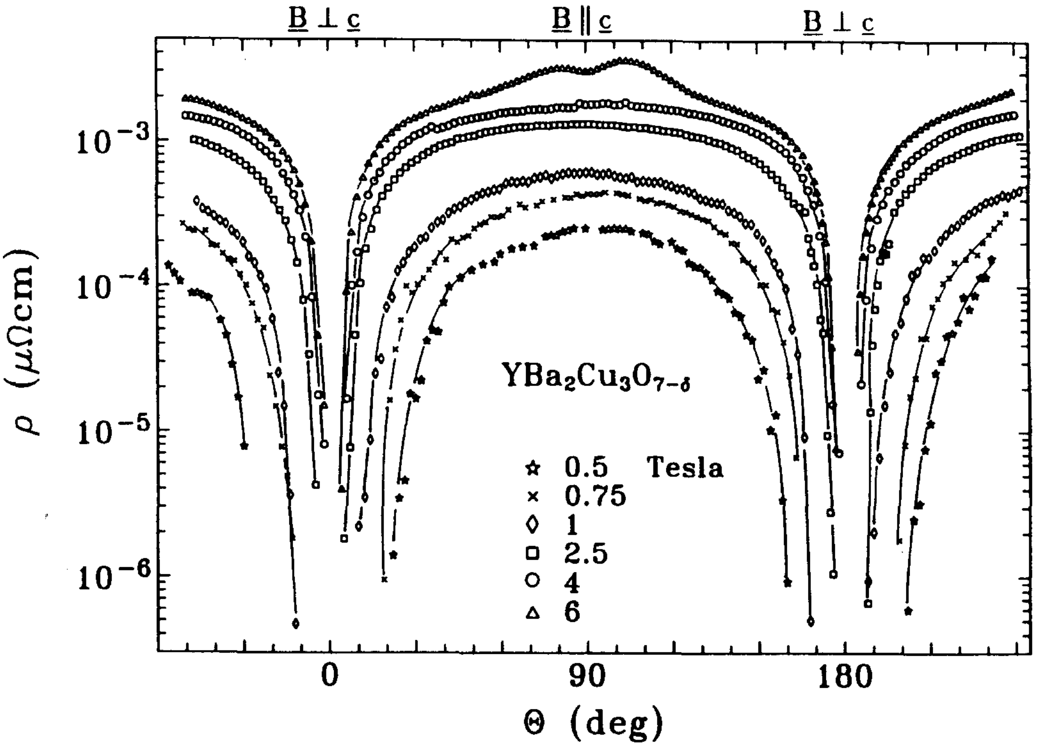

Figure 1: Magnetoresistance ρ as a function of the angle θ between the magnetic field and the ab-plane of the film. The angle ϕ between the current direction and the θ-rotation plane is 0°. At a measuring temperature of 4.2 K the current density is $j = 1.4 \times 10^6$ A/cm^2 (The lines between the measuring points are only an eye-guide).

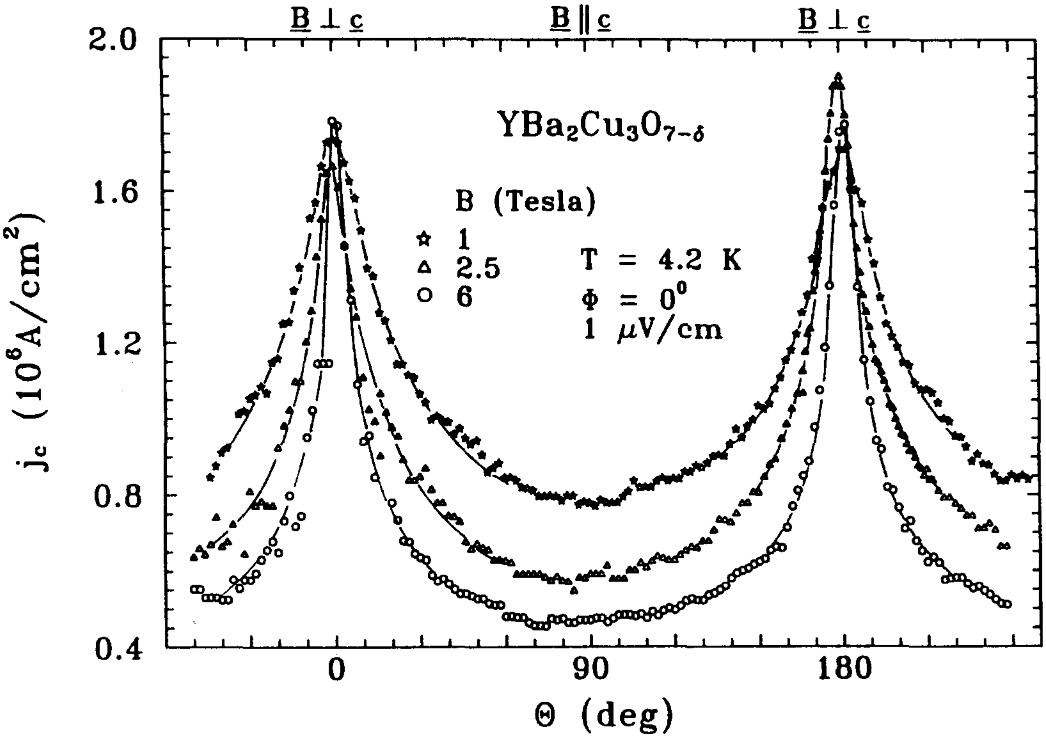

Figure 2: Critical current density j_c as a function of the angle θ between the magnetic field and the ab-plane of the film.

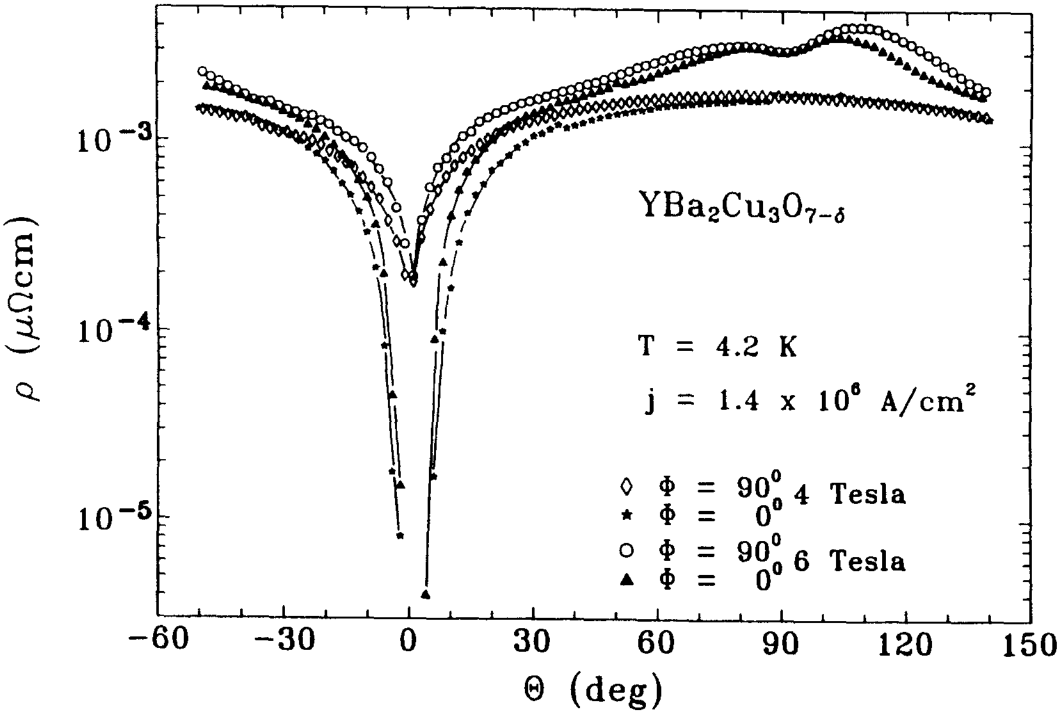

Figure 3: Magnetoresistance $\rho(\theta)$ for different angles ϕ between the current direction and the cB-plane.

the thin film, the magnetoresistance drops [1]. The θ-dependence of the critical current density j_c in high magnetic fields is shown in figure 2. The current density j_c reaches its maxima at $\theta = 0°$ and $\theta = 180°$. The minimum is located at $\theta = 90°$, where the magnetic field is perpendicular to the ab-plane [2].

The magnetoresistance increases with increasing magnetic field. Because of the sample being in the mixed state all the resistance is connected with the motion of the vortices. The angular dependence of ρ and j_c is due to the anisotropy of $YBa_2Cu_3O_{7-\delta}$ [5]. The anisotropy with respect to the angle θ is caused by the value of the projection of the magnetic field on the c-direction. From $\theta = 45°$ to $\theta = 90°$ the value of the factor of the projection changes only about 0.3 ($\sin\theta$ varies from $\sqrt{2}/2$ to 1), but from $\theta = 0°$ to $\theta = 45°$ the change of the factor is 0.7. So this could explain the strong θ-dependence of $\rho(\theta)$ and $j_c(\theta)$ near $\theta = 0°$ and $\theta = 180°$.

Beside the measurements described above it is also interesting to investigate the dissipation for different angles between current direction and magnetic field. So $\rho(\theta)$ and $j_c(\theta)$ were measured for different angles ϕ between the current direction and the θ-rotation plane. At $\theta = 0°$ and $\phi = 0°$ the current is parallel to the magnetic field and at $\theta = 0°$ and $\phi = 90°$ the current is perpendicular to the magnetic field. In figure 3 $\rho(\theta)$ curves for different angles ϕ are compared. The measuring temperature was 4.2 K.

The different results for the current direction parallel or perpendicular to the θ-rotation plane may indicate that a strong Lorentz force acts on a segment of the flux lines parallel to the layers and causes the ϕ-dependent part of the dissipation [3]. But with the intrinsic pinning getting stronger the ϕ-dependence should decrease [4]. So this could be a criterion for the quality of the $YBa_2Cu_3O_{7-\delta}$ films. If at 4.2 K the difference between $\phi = 0°$ and $\phi = 90°$ disappears, the intrinsic pinning is very strong and so the quality of the films should be high.

It should be pointed out that in high magnetic fields there is actually no difference between the values of the external magnetic field and the internal field, which influences the motion of the current carriers. The situation is different at relatively weak magnetic fields, which are discussed in the next section.

3.2 Low magnetic fields

In low magnetic fields phenomena are seen, which seem to be related with penetration and trapping of flux. Figure 4 shows $\rho(\theta)$ at a magnetic field of 10 mT. The measuring temperature was 4.2 K. Depending on the direction of the tilt angle θ the minima of the magnetoresistance are shifted from the $\theta = 0°$ and

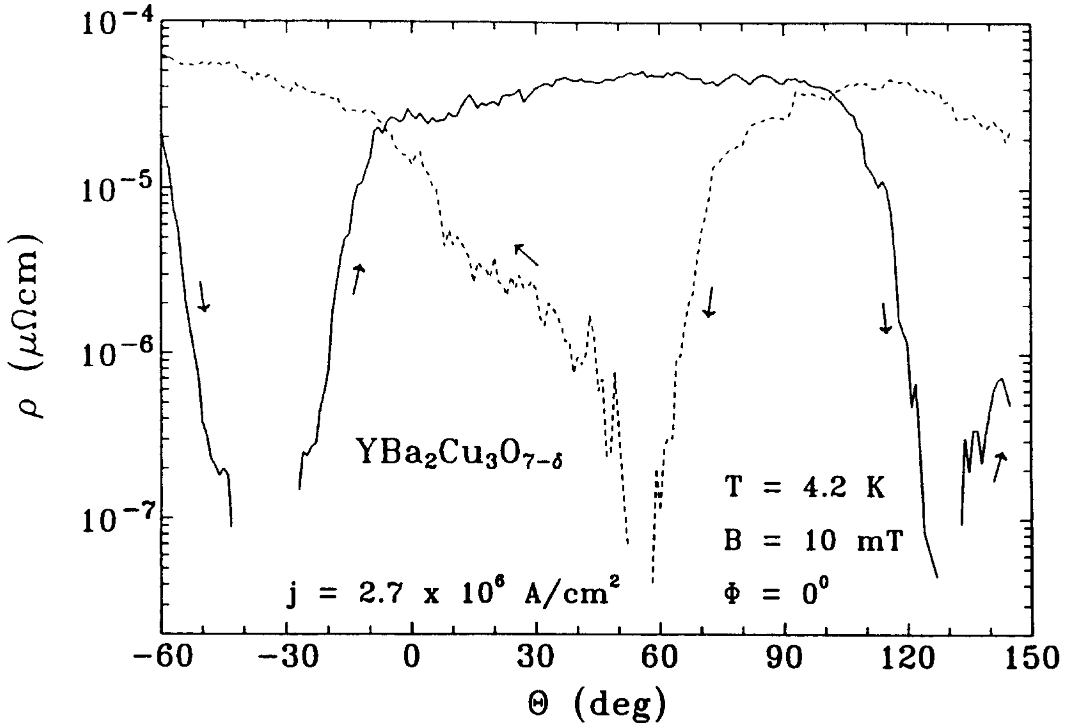

Figure 4: Magnetoresistance $\rho(\theta)$. The θ-steps are moved from opposite directions.

$\theta = 180°$ positions. If the magnetic field is switched off before every θ-step, the minima of the magnetoresistance recover at $\theta = 0°$ and $\theta = 180°$ again as in the case of high magnetic fields. At higher temperatures (above the irreversibility line) the magnetoresistance reaches its minima at $\theta = 0°$ and $\theta = 180°$, too. We got corresponding results for the critical current density in low magnetic fields.

The dependence of the internal magnetic field, which means the magnetization, on the value of the external magnetic field has an irreversible character as hysteresis measurements show also. There is a difference between increase and decrease of the external magnetic field. In the first situation the dependence of the magnetization on the external field B_o is in equilibrium, whereas in the latter case it is not. The induction B (the field in the sample) depends on the external field as a result of the changes in the density of vortices. When B is changed, the motion of the vortices takes place. This motion is pinned due to the macroscopic inhomogeneity of the pinning potentials in the sample [6]. While the flux seems to penetrate and to be trapped if the magnetic field stays constant [7], the flux is expelled from the sample if the magnetic field is switched off between the θ-steps. To explain these interesting phenomena more detailed and further investigations are necessary.

4 Remarks

For high magnetic fields measurements two fits of the data for the relevant magnetic field were tried due to the proposal of the referee: The first fit $H(\theta) = H(90°)\sin\theta$ seems to be quite good for low temperatures, but also the second fit $H(\theta) = H(90°)(\sin^2\theta + \gamma^2\cos^2\theta)^{1/2}$, with γ being the anisotropy paramter, works not so bad. But none of them fit sufficiently especially for higher temperatures, so investigations on more films are necessary.

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