Angular Dependence of Critical Current Density and Magnetoresistance of Sputtered High-T_c-Films

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Abstract

The angular dependence of the critical current density and the magnetoresistance of high-T_c-films in high and low magnetic fields and for different temperatures were measured to investigate the flux pinning and the superconducting properties. A comparison of the results for the different superconductors shows their inrcreasing dependence on the angle Θ between the magnetic field and the *c*-axis of the film due to the anisotropy of the chosen superconductor. Furthermore the influence of the current direction to the Θ-rotation plane is discussed.

1. INTRODUCTION

Although the high-T_c-superconductors (HTSC) are used in many various applications, the mechanisms of many effects these materials show are not very well understood until now. To study the flux line lattice by the intrinsic pinning the magnetoresistance and the critical current density are measured as a function of the angle between the magnetic field and the HTSC thin film. Besides other criterions of characterization the quality of the HTSC films can be determined by measuring the angular dependence of the dissipation mechanism.

2. EXPERIMENTAL

The DC-sputtered films with a thickness between 70 nm and 250 nm are highly oriented with the *c*-axis perpendicular to the surface of the $SrTiO_3$ single crystal substrate. SEM pictures show that the films are without any outgrowths larger 1 µm. Especially the $YBa_2Cu_3O_{7-\delta}$ films with a T_c up to 90 K and a transition width of 1-2 K determined by measuring the AC-susceptibility reach critical current densities about 9×10^6 A/cm^2 at 77 K. The as grown $Bi_2Sr_2CaCu_2O_{8+x}$ films show a T_c about 75 K. The critical current densities yield values about 5×10^5 A/cm^2 at 50 K.

The angular dependence of the critical current density and the magnetoresistance were measured with a pulsed current method to avoid warming up of the bonded gold wire contacts on the structured film. Conduction paths of 20 μm width and 2 mm length were prepared by wet chemical etching.

The used sample holder allows to vary the angle between the magnetic field and the *c*-axis of the film (angle Θ) as well as the angle between the current direction and the Θ–rotation plane. The accuracy of the tilt angle is better than 0.05^o. An offset of 1^o can occur due to inaccurate adjustment. The temperature was varied between 4.2 K and 77 K and magnetic fields between 10 mT and 8 T were used.

3. RESULTS AND DISCUSSION

To study the pinning of the HTSC films they were investigated by measuring the critical current density and the magnetoresistance dependent on the temperature and the strength and the angle of the magnetic field. Furthermore current-voltage-curves were taken. The results for $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_{8+x}$ films are compared due to the anisotropy of the chosen superconductor.

3.1. Critical Current Density

3.1.1. $YBa_2Cu_3O_{7-\delta}$

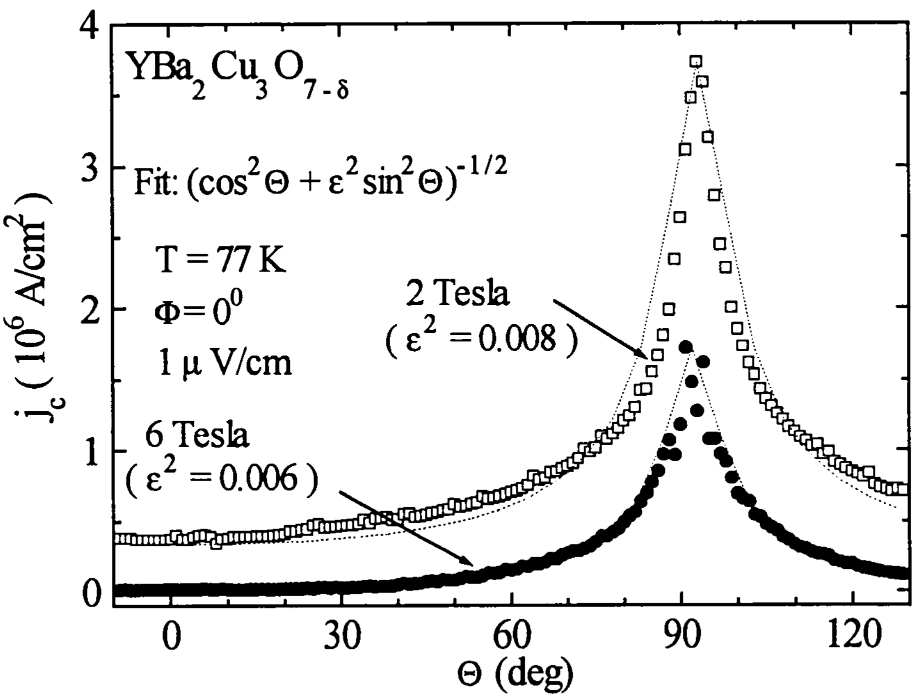

Figure 1. Critical current density $j_c(\Theta)$ in high magnetic fields.

Figure 1 shows some typical results of an investigated $YBa_2Cu_3O_{7-\delta}$ film. These measurements of the angular dependence of the critical current density were made in high magnetic fields and at a temperature of 77 K. As criterion for the critical current density a voltage of 1 μV/cm was chosen. At $\Theta = 0^o$ the *c*-axis of the $YBa_2Cu_3O_{7-\delta}$ film is parallel to the magnetic field *B* and at $\Theta = 90^o$ the *c*-axis is perpendicular to the magnetic field. Due to the layered structure of this superconductor the critical current density $j_c(\Theta)$ reaches its maximum at $\Theta = 90^o$ when the magnetic field is parallel to the CuO_2 planes [1]. This indicates the strong pinning at this angle where the flux lines are located by extrinsic pinning centers. The minimum of $j_c(\Theta)$ appears for the magnetic field being parallel to the *c*-axis of the film ($\Theta = 0^o$).

The fits of the data were made using the function $j_c(\Theta) \sim (\cos^2\Theta + \varepsilon^2\sin^2\Theta\ )^{-1/2}$. For this fit the effective magnetic field is reduced to $B_{eff} = B(0^o)(\cos^2\Theta + \varepsilon^2\sin^2\Theta)^{1/2}$ with ε being the anisotropy parameter [2]. For $\varepsilon^2 = 0.008$ at two Tesla and $\varepsilon^2 = 0.006$ at six Tesla this function fits the data quite well. The small value for ε, which decreases with increasing the magnetic field, shows the very anisotropic behaviour of the $YBa_2Cu_3O_{7-\delta}$ film in high magnetic fields.

In Figure 2 the corresponding results of $j_c(\Theta)$ in low magnetic fields are presented. In low magnetic fields the same function as used for the high fields fits the results, but the dependence on the angle Θ is less pronounced, which can be observed in the higher values of the anisotropy parameter between $\varepsilon^2 = 0.14$ and $\varepsilon^2 = 0.25$.

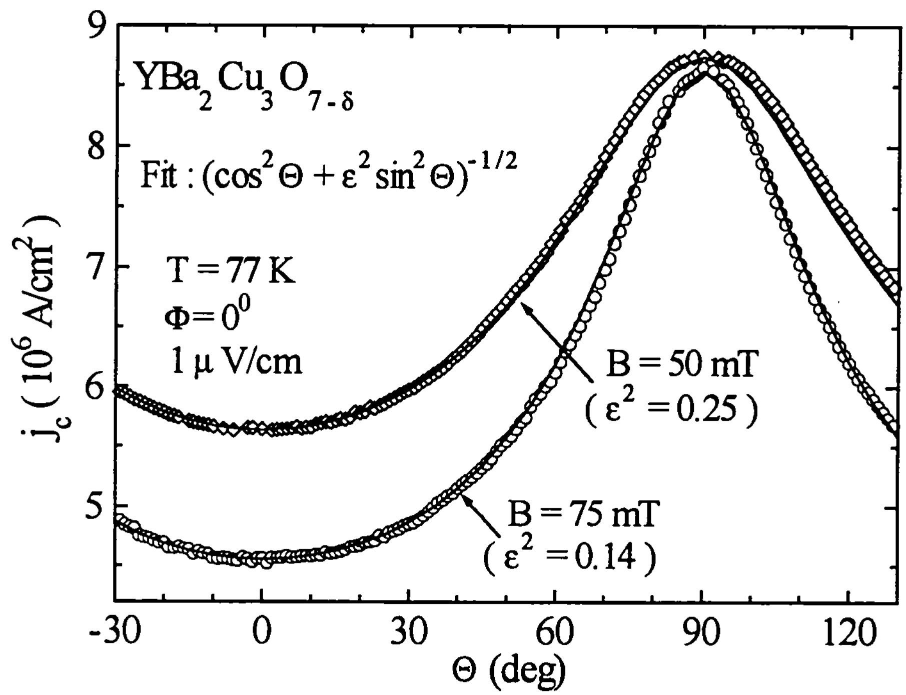

Figure 2. Critical current density $j_c(\Theta)$ in low magnetic fields.

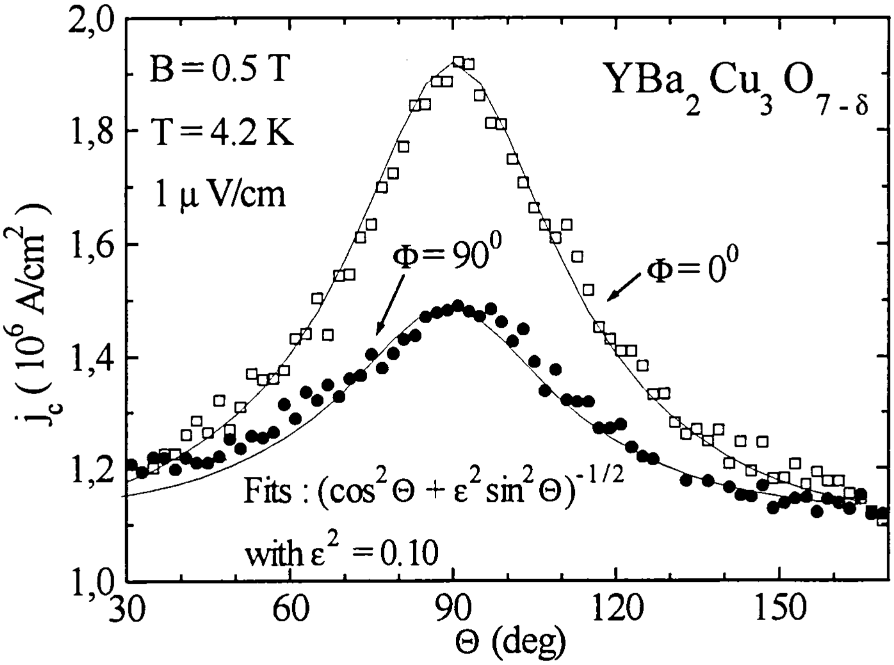

Figure 3. Critical current density $j_c(\Theta)$ for different angles Φ.

In Figure 3 a typical example of the different results of $j_c(\Theta)$ for the current direction parallel ($\Phi = 0^o$) or perpendicular ($\Phi = 90^o$) to the Θ-rotation plane (*cB*-plane of the film) is presented. Although both curves fit the theory quite well with the same anisotropy parameter, the curves differ from each other, especially for the tilt angle Θ near 90^o. For $\Phi = 90^o$ the difference between the maximum and the minimum of the critical current density is only half as big as for $\Phi = 0^o$. For the angles $\Theta = 90^o$ and $\Phi = 90^o$ the *c*-axis of the film is perpendicular to the external magnetic field *B* and the current flows perpendicular to *B*. So this effect may be caused by a strong Lorentz force acting on a segment of the flux lines parallel to the layers [3]. This would also explain that the curves for angles Θ near 0^o or 180^o lie one upon another because for the *c*-axis parallel to the magnetic field there is no difference in the measuring geometry wether the angle Φ is 0^o or 90^o. This difference between $\Phi = 0^o$ and $\Phi = 90^o$ disappears for high quality films with high critical current densities, for which the intrinsic pinning is strong enough to cover the Φ-dependent part of the dissipation. So these measurements could be used as a criterion of film quality.

3.1.2. $Bi_2Sr_2CaCu_2O_{8+x}$

Besides measurements on $YBa_2Cu_3O_{7-\delta}$ thin films sputtered $Bi_2Sr_2CaCu_2O_{8+x}$ films were investigated, too.

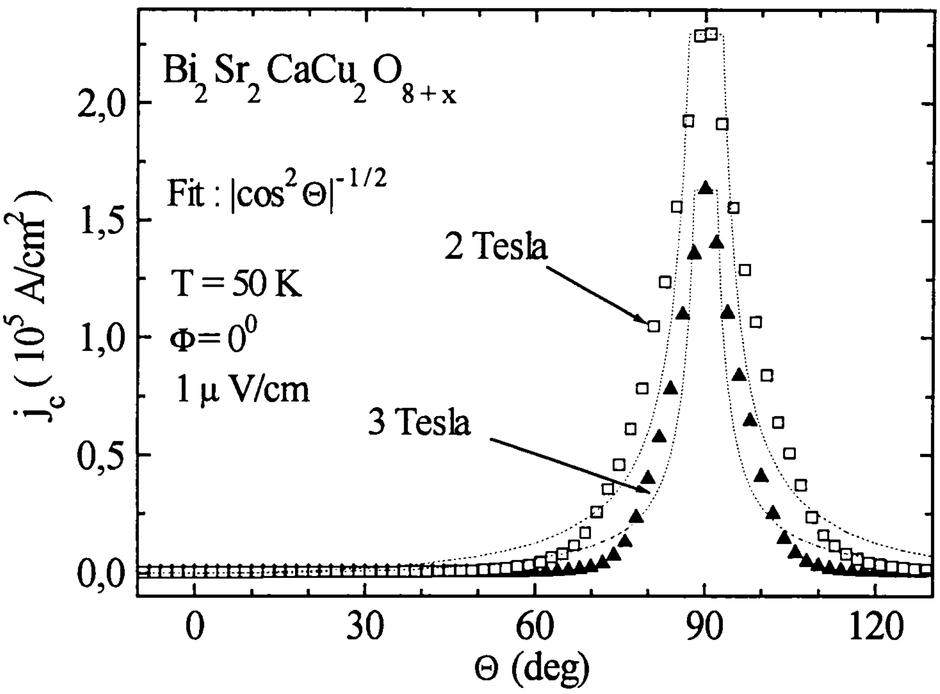

Figure 4. Critical current density $j_c(\Theta)$ in high magnetic fields.

In Figure 4 the results of the angular dependence of the critical current density $j_c(\Theta)$ for a $Bi_2Sr_2CaCu_2O_{8+x}$ film in high magnetic fields are presented. The sharpened maxima of the critical current densities compared to the results for $YBa_2Cu_3O_{7-\delta}$ films seem to be related to the stronger anistropy of the layered structure of these films. For the nearly two dimensional behaviour of this superconductor in high magnetic fields the function $j_c(\Theta) \sim |\cos^2\Theta|^{-1/2}$ is best fitting [3]. But also the function used for the $YBa_2Cu_3O_{7-\delta}$ results with a very small anisotropy parameter fits the $Bi_2Sr_2CaCu_2O_{8+x}$ measurements quite well.

A typical result for $j_c(\Theta)$ in a low magnetic field is shown in Figure 5. Corresponding to the measurements on the $YBa_2Cu_3O_{7-\delta}$ films the anisotropic behaviour of the film decreases with decreasing the magnetic field. For an external magnetic field of 50 mT the function $j_c(\Theta) \sim (\cos^2\Theta + \varepsilon^2\sin^2\Theta)^{-1/2}$ is best fitting. But whereas the anisotropy parameter ε for the $YBa_2Cu_3O_{7-\delta}$ film for this magnetic field is around $\varepsilon^2 = 0.25$, this parameter is for the $Bi_2Sr_2CaCu_2O_{8+x}$ film with $\varepsilon^2 = 0.08$ only about 1/3 of this value due to the stronger anisotropy of the $Bi_2Sr_2CaCu_2O_{8+x}$ superconductor.

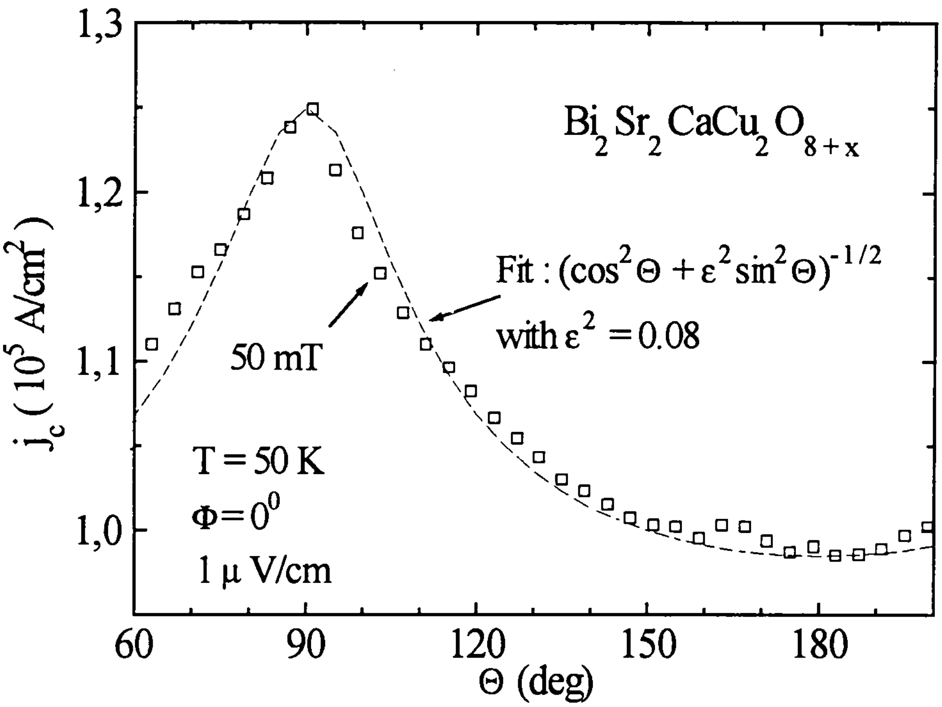

Figure 5. Critical current density $j_c(\Theta)$ in a low magnetic field.

3.2. Magnetoresistance

Besides investigations of the angular dependence of the critical current density $j_c(\Theta)$, the magnetoresistance $\rho(\Theta)$ was measured in high and low magnetic fields.

3.2.1. High magnetic fields

Figure 6 shows a typical result of the angular dependence of the magnetoresistance $\rho(\Theta)$ in high magnetic fields at a temperature of 4.2 K for a $YBa_2Cu_3O_{7-\delta}$ film. The measurements were made for high current densities due to the superconductor being in the mixed state. As expected the magnetoresistance reaches its minimum at $\Theta = 90^\circ$, which means that the *c*-axis of the film is perpendicular to the magnetic field *B*. The maximum of $\rho(\Theta)$ appears at $\Theta = 0^\circ$ where the *c*-axis is parallel to *B*. As in the corresponding measurements of the critical current density the magnetoresistance in high magnetic fields reveals the strong anisotropy of these superconductors because of the layered structure of these films [4]. The function $\rho(\Theta) \sim |\cos^2\Theta|^{1/2}$ for nearly two dimensional behaviour of the film fits as well as $\rho(\Theta) \sim (\cos^2\Theta + \varepsilon^2\sin^2\Theta)^{1/2}$ with $\varepsilon^2 \leq 0.01$. So this also supports the assumption that for the magnetic field parallel to the CuO_2 planes the pinning is very strong and the flux lines are located by extrinsic pinning centers.

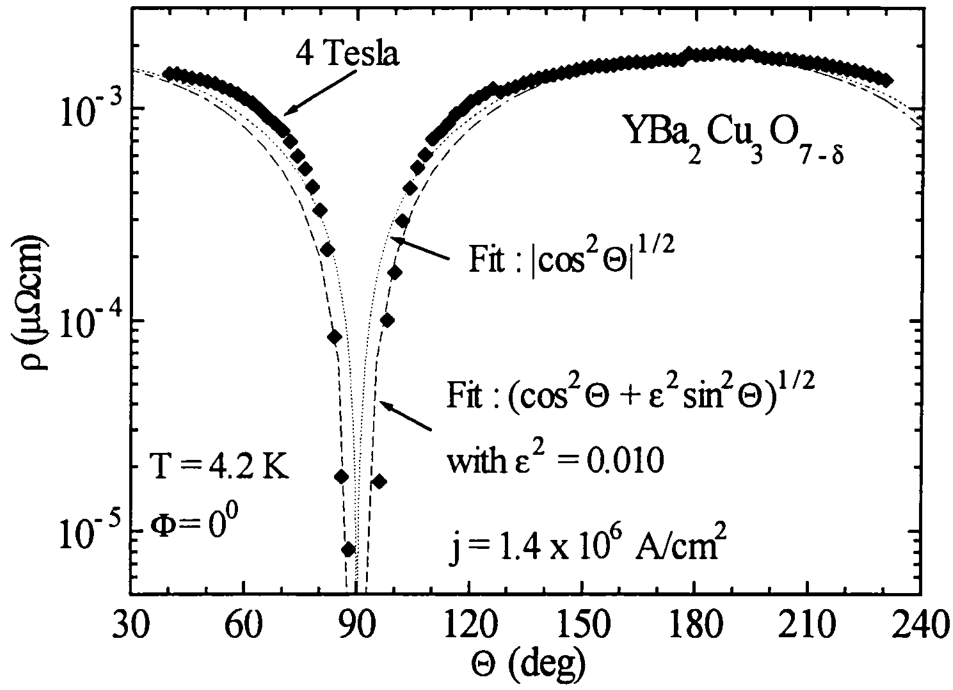

Figure 6. Magnetoresistance $\rho(\Theta)$ in a high magnetic field.

For the measurements of the magnetoresistance $\rho(\Theta)$, as presented in Figure 7, the angle Φ between the current direction and the cB-plane (Θ-rotation plane) of the film was 90^o, which means that for $\Theta = 90^o$ the current direction was perpendicular to the magnetic field B. The amplitude of the magnetoresistance is smaller for $\Phi = 90^o$, but the minima are sharpened. These results correspond to the measurements of the angular dependence of the critical current density $j_c(\Theta)$ as far as for $\rho(\Theta)$ there is a Φ-dependent part of the dissipation probably caused by the Lorentz force acting on the flux lines, too. The logarithmical $\rho(\Theta)$ curves are similar to the inverted $j_c(\Theta)$ curves.

At six Tesla there is a local minimum for $\Theta = 0^o$ or 180^o independent of the angle Φ. This form of the curves appears only in high magnetic fields and not all measured films show this effect. We attribute these extra pinning of the flux lines to the pinning at twin boundaries [5,6].

In high magnetic fields and at $\Phi = 90^o$ the function $\rho(\Theta) \sim |\cos^2\Theta|^{1/2}$ is best fitting due to the nearly two dimensional behaviour of the $YBa_2Cu_3O_{7-\delta}$ film. For the results obtained in a magnetic field of 0.5 Tesla the function $\rho(\Theta) \sim (\cos^2\Theta + \varepsilon^2\sin^2\Theta)^{1/2}$ is used because of the decreasing anisotropy with decreasing the magnetic field.

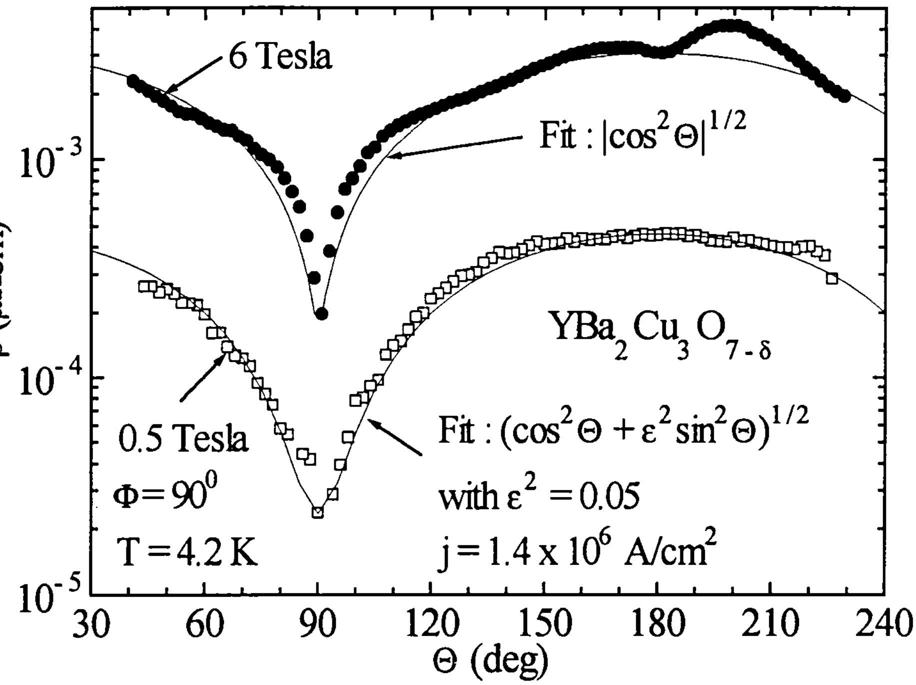

Figure 7. Magnetoresistance $\rho(\Theta)$ for $\Phi = 90^o$.

3.2.2. Low magnetic fields

While for high magnetic fields the value of the external magnetic field is the same as for the internal field, the external field may differ from the field in the sample in very low magnetic fields. Probably because of this in low magnetic fields phenomena are seen, which are related to some hysteretical effects.

In Figure 8 the magnetoresistance $\rho(\Theta)$ in a magnetic field of 25 mT at a temperature of 4.2 K is presented. Whereas the dashed curve was measured with a constant magnetic field between the angle Θ–steps, the solid line shows the $\rho(\Theta)$ curve with no magnetic field between the Θ-steps. If the external magnetic field is switched off before every Θ-step, the minimum of the magnetoresistance appears at $\Theta = 90^o$ as expected. But if it is continously operated during the angle Θ movement from 30^o to 240^o, the minima of $\rho(\Theta)$ are shifted and asymmetrical. The drop of the magnetoresistance is sharpened, whereas the increase of $\rho(\Theta)$ is broadened. If the angle Θ is tilt in the opposite direction, the shift changes its direction, too [7].

This hysteretical effect is not seen for high quality films or at higher temperatures above the irreversibility line. It seems to be related with penetrating and trapping of flux, if the sputtered HTSC film consists of several granular parts. The change of the effective external field, which depends on the tilt angle Θ, influences the internal field in the sample due to a motion of vortices. Therefore the flux seems to penetrate and to be trapped for a constantly applied magnetic field [8], which means that the vortices are pinned due to the macroscopic inhomogeneity of the pinning potentials in the sample [9]. If the magnetic field is switched off before every Θ-step, the flux is expelled from the sample. For corresponding critical current measurements on these films we got similar results. The appearance of this effect could be a further criterion of the quality for the HTSC films.

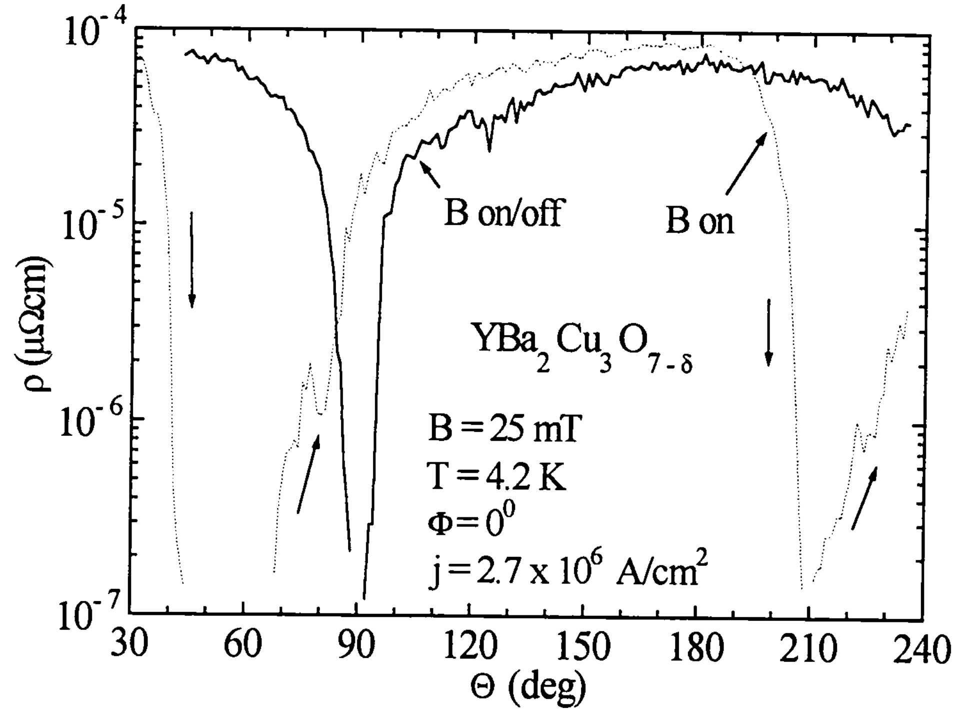

Figure 8. Magnetoresistance ρ(Θ) in a low magnetic field.

The dependence of the magnetoresistance on the strength of the external magnetic field B for low magnetic fields at a constant angle $\Theta = 0^{o}$ is shown in Figure 9. The results reveal a $\rho(B) \sim B^{1/2}$ dependence, which indicates a more three dimensional behaviour of the $YBa_2Cu_3O_{7-\delta}$ films for low magnetic fields due to the theory [10,11]. For measurements of the critical current density dependent on the strength of the magnetic field B, we got a $j_c(B) \sim 1/B$ dependence for very low magnetic fields, which also indicates the small anisotropy of these films for low magnetic fields. This is in agreement with our other results, which show the anisotropic character of the investigated $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_{8+x}$ films increasing with increasing the magnetic field.

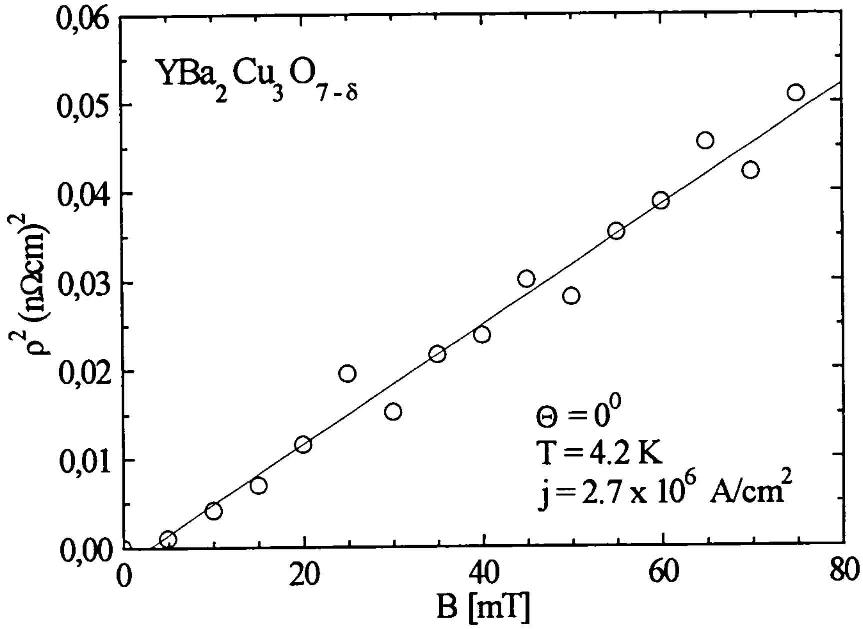

Figure 9. $\rho^2(B)$ curve for low magnetic fields.

Acknowledgement

This work was supported by the BMFT (FKZ : 13N5487/5).

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