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# Angular dependence of isothermal remanent magnetization of sputtered YBCO thin films (*)

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**Summary.** — Because of their intrinsic layered structure, high temperature superconductors are suitable systems for studying the strong anisotropy of their superconducting properties. In fact, the response of a sample to an external magnetic field H depends generally not only on the magnitude but also on the orientation of **H**. Since remanent magnetization is a measurement of the effective flux-pinning strength in superconductors, it depends upon both the temperature and the applied field, as well as on the history of processing and the angle between the applied magnetic field and the crystallographic axis directions. In this framework we report the studies of the angular dependence of remanent isothermal magnetization $M_{\mathrm{rem}}$ in YBCO sputtered films. The projections of the remanent magnetization on the direction of the magnetometer axis were measured for each of the films. The results show the orientational preference for flux trapping, related to intrinsic features. Moreover, an angular dependence of the remanent magnetization can be calculated in good agreement with the experimental data.

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## 1. – Introduction

It is well known that remanent magnetization (*i.e.* the residual magnetization after the applied field has been turned off) is an interesting manifestation of the irreversible magnetic properties in hard superconductors, since it is a measurement of the effective flux-pinning strength. Therefore, it has proven useful for obtaining information about the behaviour of the vortex lattice, its interaction with pinning centers [1-8], and for determining the critical current density [9,10].

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These are the reasons why many groups have measured remanent magnetization and studied its angular dependence. Regarding these analyses, Felner *et al.* [8] performed field-cooling experiments on single crystals of YBCO and BSCCO. For rotations around an axis parallel to $a$ remanent magnetization results revealed uniaxial anisotropy for flux trapping with the $c$-axis as anisotropy axis and the amount of trapped flux determined by the component of the field **H** along $c$, while for flux trapping with **H** in the $a$-$b$ plane they showed unidirectional anisotropy defined by **H** during the cooling process.

Liu *et al.* [3] performed magnetization-vector measurements on small crystallites of YBCO in an epoxy matrix and obtained information on the penetrating vortex flux component of the sample magnetization and on the remanent trapped-flux magnetization. They showed the preference of the initial penetration for the $a$-$b$ plane, and of the trapped-flux magnetization toward the $c$-axis. However the autors showed that "this contrast in behaviour is not conflicting but represents two different manifestations of the stronger pinning for the vortex lines along $c$ than for those along $a$-$b$" [3].

Yi Song *et al.* [5] studied the three components of the low-field ($H_{\text{appl}} = 10$ Oe) remanent magnetization in YBCO single crystals, showing a larger remanent magnetization in the $a$-$b$ plane than along the $c$-axis. They discussed their experimental data in terms of relevant vortex-flux penetration and flux pinning models, suggesting that at low internal fields the remanent magnetization is oriented preferably parallel to the $a$-$b$ plane. The authors showed [6] that, for higher fields, as in ref. [3], the remanent magnetization switches over to the $c$-axis.

The main purpose of this paper is to show the magnetic anisotropy of flux trapping in sputtered $YBa_2Cu_3O_{7-\delta}$ thin films. Because of the extremely anisotropic trapping in the measured samples, the results indicate that isothermal remanent magnetization scales as $\cos\theta$ ($\theta$ is the angle between the applied magnetic field and the crystallographic $c$-axis direction of the films), showing a preferred flux trapping for magnetic fields applied parallel to the $c$-axis.

## 2. – Experimental details

Superconducting films of $YBa_2Cu_3O_{7-\delta}$ were deposited on $LaAlO_3$ (100) substrates using a planar magnetron sputter gun in a commercial K. J. Lesker deposition system. The stoichiometric target was prepared from citrate pyrolysis reported elsewhere [11]. The sputter gun was mounted in a cryopump vacuum chamber; the base pressure was $3 \times 10^{-8}$ Torr. The sputtering atmosphere varied between 40 and 60 mTorr $O_2$ and 160 and 240 mTorr Ar. An RF power of 100 W generates a cathode self-bias of $-70$ mV and gives a deposition rate for the off-axis geometry of about 0.1 Å/s, which depends on the total pressure and $Ar/O_2$ ratio (200 mTorr with 20% $O_2$ and 80% Ar in this case). The substrate was fixed on the holder by silver paste. During film growth the substrate temperature was held constant at $T_{\text{sub}} = 780$ °C. After deposition, the chamber was immediately vented to 20 Torr of pure oxygen and the substrate is allowed to cool slowly to room temperature. A detailed structural and magnetic characterization of the produced films is reported elsewhere [12].

The films (FY0495 and FY0995) have a thickness of $\sim 0.2\,\mu$m. The critical temperature, $T_c^{\text{ons}}$, (taken as the onset of the diamagnetism, $H_{\text{appl}} = 50$ Oe and parallel to the $c$-axis) is 88 K (FY0495) and 89 K (FY0995).

Magnetic measurements were performed on a Vibrating Sample Magnetometer ($20\text{ K} < T < 300$ K; $H_{\max} = 10$ kOe): the external field was applied along the magnetometer axis, and the magnetometer was equipped with a rotary sample holder, whose axis of rotation was perpendicular to the magnetometer axis and parallel to the *a*-*b* planes of the films.

The experimental procedure was the following: the sample was cooled from room temperature to the measurement temperature ($< T_c$) in a zero nominal field at an angle $\theta$ between the direction of the *c*-axis and that of the magnetometer axis. The field orientation with respect to the *c*-axis of the films was carefully controlled, and the uncertainty was about one degree. The magnetic field was swept at a constant rate ($H_{max} = 10\,\mathrm{kOe}$) and the magnetic moment was continuously measured. Isothermal remanent magnetization $M_{rem}$ was measured as the applied field was turned off.

## 3. – Results and discussion

Figure 1 shows the hysteresis cycles for the FY0495 sample ($T = 15$ K, $dB/dt = 2.5\,\mathrm{kOe/min}$) for two orientations of the applied magnetic field with respect to the *c*-axis direction of the sample. The data indicate that the maximum applied field (10 kOe) is greater than the full penetration field $H_p$, defined as the merging of the first and the fifth branches of the hysteresis cycles. As a consequence, with the experimental procedure followed in this work, the sample is first fully penetrated, and then its remanent magnetization is measured. As has been shown [13, 14], while the applied field is in this region, the remanent magnetization does not vary with the applied field and only depends upon sample size, geometry, and material parameters or temperature. Moreover, it can be argued that this procedure allows to neglect the

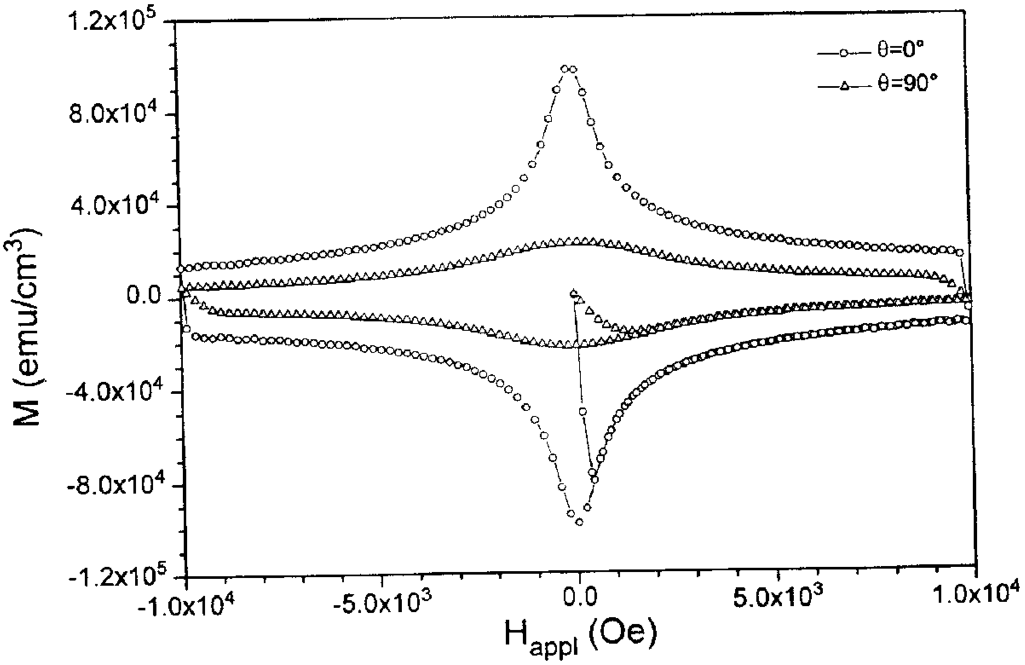

Fig. 1. – Hysteresis cycles (FY0495 sample) for the indicated zero-field cooling angles at 15K.

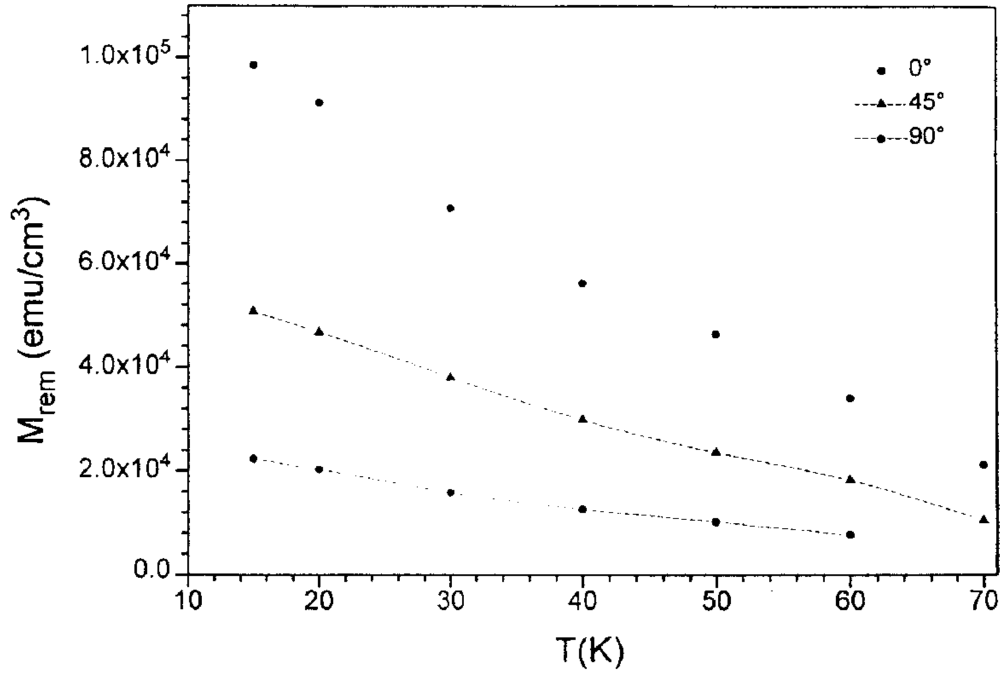

Fig. 2. – The isothermal remanent magnetization $M_{rem}$ (FY0495 sample) as a function of the temperature for the indicated zero-field cooling angles (lines are only a guide for the eye).

demagnetizing field correction because measurements are performed in zero applied magnetic field.

Remanent magnetization data for the FY0495 sample as a function of the temperature for $\theta = 0°$, 45° and 90° are presented in fig. 2 showing that, according to the critical-state model, the trapped flux is rapidly excluded with the increasing temperature. It can be seen that the magnitude of $M_{rem}$ decreases with increasing the angle between the applied magnetic field and the $c$-axis direction.

The data of fig. 3 , showing $M_{rem}$ *vs.* $T$ for FY0495 and FY0995 ($T = 20$ K, $dB/dt =$ 2.5 kOe/min), give some information on the similar quality of the two samples.

Figure 4 exhibit the angular dependence of the remanent magnetization as a function of the rotation angle $\theta$ for the film FY0995, $T = 20$ K, $dB/dt = 5$ kOe/min. The data can be reasonably approximated by the formula

$$M_{rem}(\theta) = A\cos^2(\theta - \theta_0) + B\,. \tag{3.1}$$

The dotted line in fig. 4 is the best fit of formula (3.1) to the experimental points, with $A \sim 8.0 \times 10^4$ emu/cm$^3$; $B \sim 1.2 \times 10^4$ emu/cm$^3$.

These results point to a strong intrinsic anisotropy in the measured YBCO sputtered thin films, because, as told before, they are not significantly affected by an angular dependence of the demagnetizing factor. Moreover, in a reply [15] to a comment [16], Felner *et al.* showed in fact that the effect of geometry for low fields, though strong, does not mask the intrinsic anisotropy.

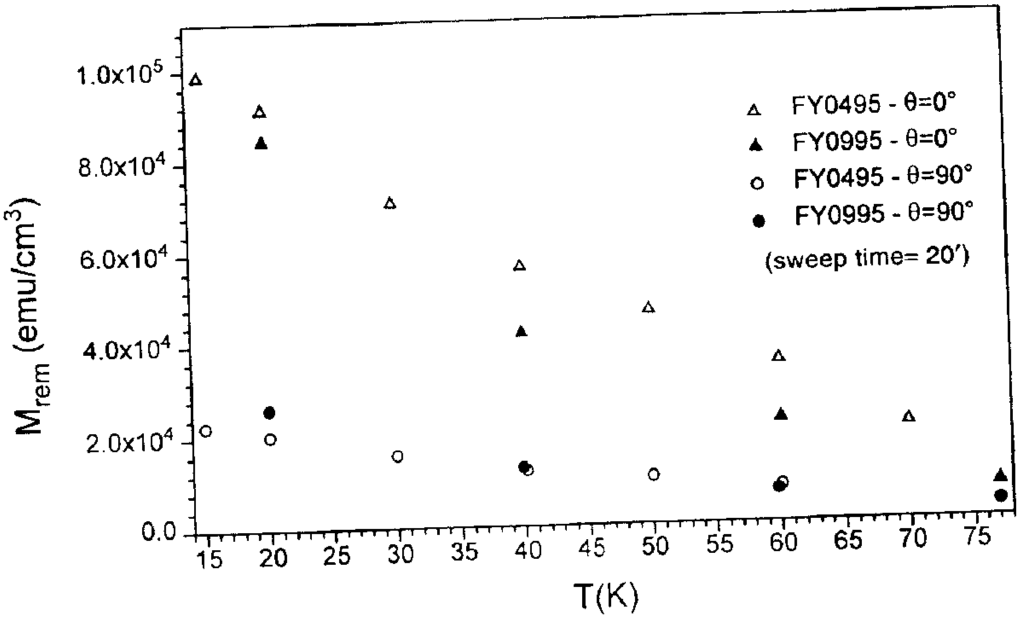

Fig. 3. – The isothermal remanent magnetization $M_{\rm rem}$ (FY0495 and FY0995 samples) as a function of the temperature for the indicated zero-field cooling angles.

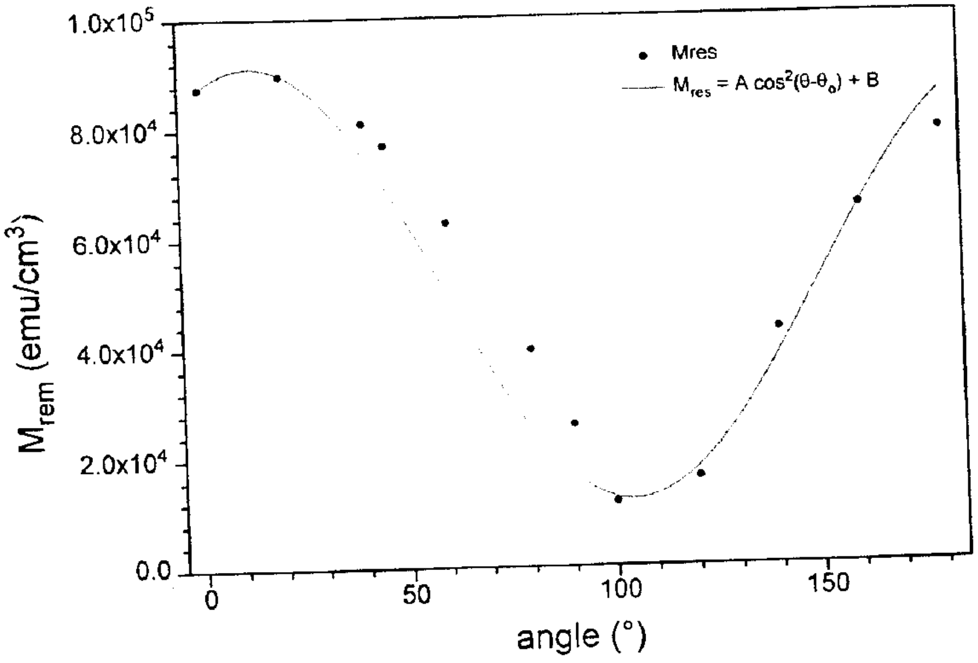

Fig. 4. – Angular dependence of the isothermal remanent magnetization $M_{\rm rem}$ for the FY0995 sample at $T = 20$ K. The dotted line is the best fit to eq. (3.1), see text.

The results presented in fig. 4 show that angular dependence of isothermal remanent magnetization of the samples here analysed is almost identical to the so-called *initial remanent magnetization* $M^{\mathrm{i}}_{\mathrm{rem}}(\phi)$ [1, 4] obtained cooling the sample in a field **H** at an angle $\phi$ between **H** and the $c$-axis and then switching off the field.

For a better understanding of these results, it is necessary first to recall that conventional magnetometers, such as SQUID or VSM, only give the component of the magnetization **M** parallel to the applied field (equal to $\mathbf{M}\cdot\mathbf{H}/H$) [17, 18]. As a consequence, according to ref. [1], it is apparent that isothermal remanent magnetization scales as $\cos\theta$, as $M^{\mathrm{i}}_{\mathrm{rem}}$ does. The constant term in expression (3.1) ($B \sim 1.2 \times 10^4$ emu/cm$^3$) represents the flux trapped in the $a$-$b$ plane. To sum up, it can be argued that after zero-field cooling, when submitted to applied magnetic fields greater than the full penetration field, vortex lines align themselves parallel to the field. As the field is removed, only the components $\cos\theta$ of the total flux are trapped [1], related to current loops in the $ab$-planes.

## 4. – Conclusions

The results for the trapped flux magnetization $M_{\mathrm{rem}}$ in $YBa_2Cu_3O_7$ sputtered thin films show a preference of $M_{\mathrm{rem}}$ for the crystallographic $c$-axis. Moreover we have found experimentally that the angular dependence of the measured isothermal magnetization $M_{\mathrm{rem}}$ is almost identical to the *initial field-cooled remanent magnetization* reported in the literature on YBCO single crystals.

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