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Characterisation of the magnetic shielding properties of YBaCuO thick films prepared by electrophoretic deposition on silver substrates

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Abstract. This communication reports experimental results on the superconducting properties of YBaCuO thick films prepared by electrophoretic deposition on silver substrates. The magnetic shielding properties of the coatings were characterised by various methods. First, the electrical resistance and the transport critical current density, J_C, were determined. Our coatings exhibit a superconducting transition at a temperature of 90 K. Next, shielding characterisations were carried out at 77 K for samples having either a slab or a cylindrical geometry. In both cases, the frequency of the applied magnetic field was 103 Hz; the field behind the shielding wall was measured by a pick-up coil connected to a lock-in amplifier. In the case of cylindrical samples and for an applied induction lower than 1 G, the field inside the shielding enclosure is reduced by a factor greater than 10^6 (i.e. 120 dB) with respect to the applied field.

1. Introduction

The strong diamagnetic response of high-temperature superconductors offers the possibility to design superconducting magnetic shielding systems that can operate down to very low frequencies [1,2]. Because superconducting ceramics are very brittle, it is difficult to realise large magnetic shields (on the scale of tens of centimetres) of complex shapes. A promising technique consists in depositing thick films on a metallic substrate by electrophoretic deposition (EPD technique). The purpose of this paper is to present a characterisation of the electric and magnetic properties of YBaCuO thick films that were deposited on silver substrates of planar and tubular shapes.

2. Sample preparation

A typical sample is obtained first by dispersing a ceramic powder in an organic solution (100 ml of acetone with 20 ml of iodine), and then by applying an electric field (240 V/cm) between two electrodes dipped in the mixture [3,4]. The resulting YBaCuO deposition forms on the cathode. After the deposition, a heat treatment is applied in order to optimise the superconducting properties. This treatment allows one to realise the correct stoechiometry in oxygen and to improve the grain connectivity, so as to favour intergranular superconducting shielding currents. The detailed preparation procedure is described in reference [5]. For the substrate, we used silver, which is known not to degrade the superconducting properties of YBaCuO, as opposed to other metals and alloys such as nickel or steel [6]. We characterised three samples. Sample #1 has a slab geometry and was used for electrical characterisation. Sample #2 (slab) and #3 (tube) were used to evaluate the shielding properties for different geometries. The characteristics of the samples are summarised in table 1.

Table 1. Characteristics of the different samples.

	Geometry	Coating thickness (μm)	Dimensions of the deposition
sample #1	slab	70	1 cm * 1 cm
sample #2	slab	50	4 cm * 4 cm
sample #3	tube	40	inner diameter : 2 cm ; length : 10 cm

3. Electrical characterisation

First, transport measurements were performed on sample #1 with the conventional four-probe technique. The R(T) curve shows a superconducting transition at 90 K with a width of $\Delta T \sim 3$ K. We also measured I-V curves and evaluated the critical current density using a 1 μV/cm criterion. This gives a current density $J_c \sim 500$ A/cm^2, in the absence of an applied magnetic field at T = 77 K. This value of J_c is close to those quoted in the literature for planar YBaCuO coatings of comparable thicknesses [6,7].

4. Shielding characterisation

4.1. Slab geometry (sample #2)

The shielding properties of sample #2 were measured using the experimental setup shown in figure 1. An AC magnetic field is applied by a source coil (length : 2.2 mm, diameter : 6 mm), and the magnetic induction behind the sample is measured by a sensing coil of identical geometry (#3 in figure 1). The distance between both coils is 6 mm and the sample is placed exactly in the middle. The local magnetic induction at the sensing coil is determined from its voltage drop, which is measured with a lock-in amplifier. The shielding properties are evaluated as follows: the magnetic induction at the center of the sensing coil is measured both in the absence (B_{abs}) and in the presence (B_{pres}) of the sample. We then compute the shielding factor, defined as the ratio B_{abs}/B_{pres}, which is larger than unity. The measurements are carried out in liquid nitrogen (T = 77 K) and at a frequency of 103 Hz. With such conditions the skin depth of silver, δ(77 K) ~ 2 mm, is larger than the thickness of the substrate (0.5 mm). Figure 2 shows the shielding factor as a function of the applied induction.

The magnetic induction on the abscissa of the graph in figure 2 is the applied induction at the center of the sample, where there is only a component perpendicular to the plane of the sample. Below 0.05 mT and for a decreasing applied induction, the shielding factor increases rapidly and reaches values of ~ 230 at 0.01 mT. For lower applied inductions, it is actually not possible to measure the magnetic induction in the presence of the sample with our setup. For magnetic inductions larger than 0.05 mT, the shielding factor falls to unity, indicating that the sample ceases to shield. The value of the maximum field that can be shielded is relatively low (compared to bulks) and is related to the low critical current density as well as to the thickness of the sample.

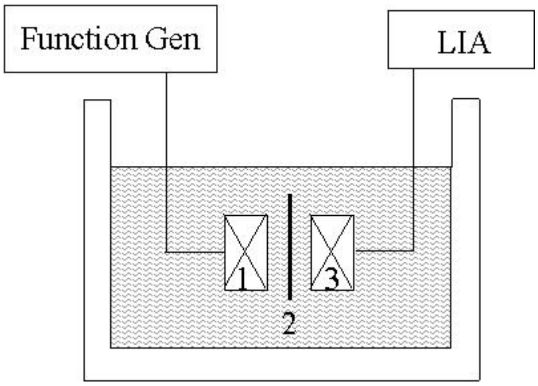

Figure 1. Experimental setup for the shielding characterisation of planar samples at 77 K. The coil #1 (resp. #3) is the source coil (resp. the sensing coil). The sample is in position #2.

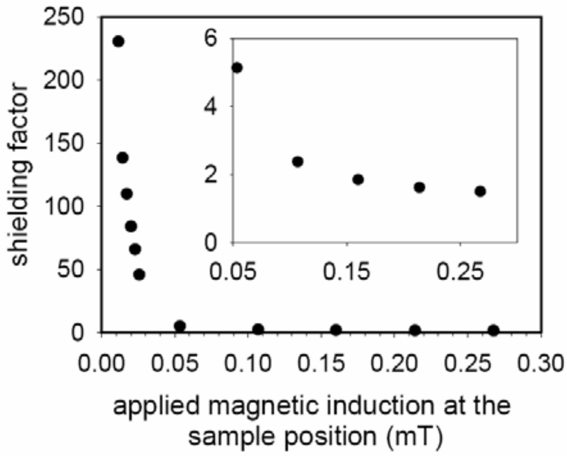

Figure 2. Shielding factor of sample #2 with respect to the applied magnetic induction at the sample position (#2 in figure 1). The frequency is 103 Hz.

4.2. Tubular geometry (sample #3)

We now turn to the tubular sample. The sample is subjected to an AC magnetic field, applied parallel to the axis of revolution, as depicted in figure 3. The magnetic induction inside the cylinder is measured via a sensing coil of 800 turns and a height of 5 mm. The voltage drop across the sensing coil is measured by a lock-in amplifier. The source coil, the sample, and the sensing coil are immersed in liquid nitrogen (77 K). The frequency of the applied field is again 103 Hz. The minimum detectable induction at 103 Hz is of the order of 1 nT.

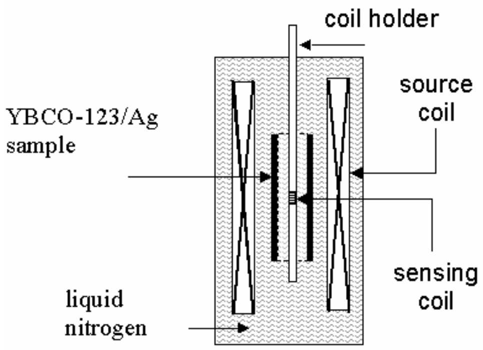

Figure 3. Experimental setup for the shielding characterisation of tubular samples at 77 K. The sensing coil is connected to a lock-in amplifier.

Figures 4 and 5 show the shielding factor as a function of the applied magnetic induction, for different positions of the sensing coil along the axis. Figure 4 (resp. figure 5) corresponds to positions in the lower (resp. upper) half of the cylinder. It can be seen that both halves behave differently, suggesting that the superconducting properties of the film are not uniform along the cylinder axis. For instance, for the lower part (figure 4), the shielding factor is maximum at the center of the cylinder. For the upper part (figure 5), however, the maximum lies at 18 mm from the center at low applied fields and migrates off the center as the field increases. For this part, the shielding factor reaches 10^6 (120 dB) at 1 G. The behaviour of the position corresponding to the maximal shielding factor as a function of the applied field is not yet fully understood but is probably also related to the lack of uniformity of the film.

Keeping now the position fixed and increasing the applied field, the shielding factor rapidly decreases and remains appreciably larger than unity in a relatively low range of amplitudes, $B < B_{lim}$. Arbitrarily taking the limiting shielding factor to be 100, we find B_{lim} ~ 0.2 mT. Such a result is related to the low values of the film thickness and of the critical current density. The limiting field, B_{lim}, is of the order of the penetration field estimated from the Bean model. For a cylindrical superconducting shell of thickness t, the field of penetration, H_P, is given as $H_P = J_C{*}t$, where J_C is the critical current density. Taking $J_C = 500$ A/cm^2 and t = 40 μm, we obtain $B_{lim} \sim \mu_0 H_P = 0.25$ mT.

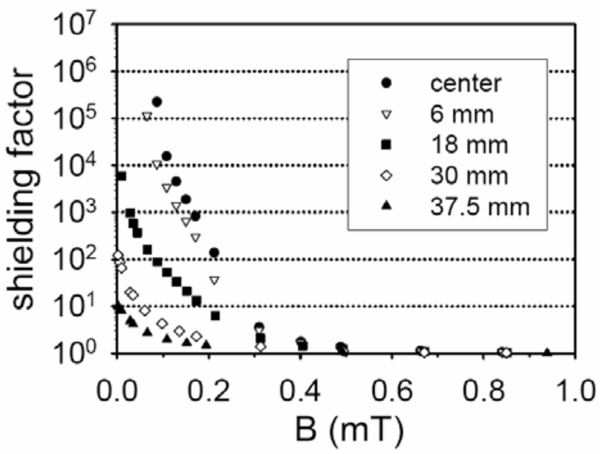

Figure 4. The shielding factor as a function of the applied magnetic induction at different positions along the axis of the lower half of the tubular sample.

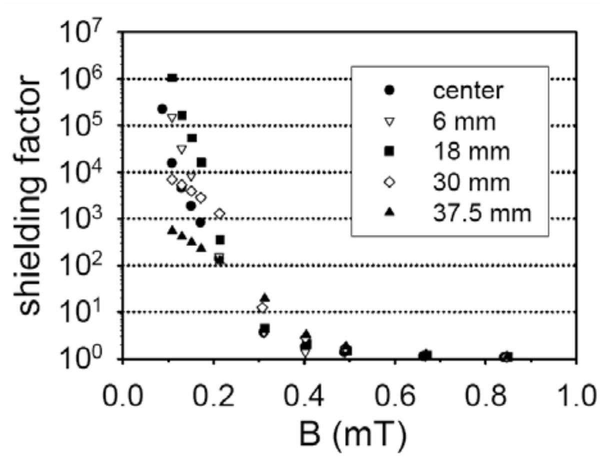

Figure 5. The shielding factor as a function of the applied magnetic induction at different positions along the axis of the upper half of the tubular sample.

5. Conclusions

The electrophoretic deposition is a convenient technique that allows one to obtain large HTS magnetic shields of complex shapes. We have built a setup allowing us to measure the shielding factor at different positions along the axis of tubular samples with a high sensitivity. The YBaCuO coatings exhibit high magnetic shielding capabilities (up to 120 dB) at 77 K for quite large samples (10 cm high tube). We have however measured a low limiting field, $B_{lim} \sim 0.2$ mT for sample #3 and a lack of uniformity of the superconducting properties of the films. It will be interesting to investigate how improvements of the EPD technique, leading to a higher Jc, affect both B_{lim} and the uniformity of the film magnetic response.

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