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A New Technique for the Determination of the Critical Current Density in Superconducting Films and Flat Samples

Conor McLoughlin · Pierre Bernstein ·
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Abstract The determination of their critical current density in the whole range of the temperature below T_c is of first importance to understand the physical processes occurring in superconducting films. We describe here a technique suitable for square films based on the measurement of the magnetic moment due to the currents persisting in the superconductor after the application of a perpendicular high magnetic field. Typically, with a 1 K interval between two measurements, using a SQUID magnetometer the measurement time is of 2 hours only by this technique. An intriguing aspect of the obtained results is that they are much more accurate if the current lines are supposed to be circular than if we suppose, as suggested by theoretical considerations and magnetooptical observations that they have the sample symmetry.

Keywords Critical current density measurement technique · Persistent current lines

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1 Introduction

The classical techniques employed for determining the critical current density of thin films superconductors are current–voltage measurements and the Bean method [1] that requires to record hysteretic magnetic loops. Both techniques are time consuming. As a result, the measurements are carried out either in a restricted range of temperatures or at large intervals of temperature. This is especially detrimental in the case of the coated conductors, whose characterization is seldom carried out far below 77 K, while their very large critical current density at low temperature is interesting for many applications. We have proposed for some time a technique suitable for square films [2, 3], based on the measurement of the magnetic moment generated by the current lines persisting in the sample after the application of a magnetic field. Typically with this technique, using a SQUID magnetometer, the measurements time in the whole range of the temperatures below T_c with a 1 K interval is of 2 hours. In this contribution, we will describe the measurements technique and we will compare some of the results obtained with those resulting from the use of other techniques. We will discuss an intriguing aspect of the results, that is, that they are much more accurate if the current lines are supposed to be circular than if we suppose, as suggested by theoretical considerations and magneto-optical observations that they have the sample symmetry.

Section 2 is devoted to the description of the measurements technique. We compare results obtained by this technique to those gained by other methods in Sect. 3. In Sect. 4, the possible reasons that the circular symmetry and not that of the sample is relevant for the current lines in this type of measurements are discussed.

2 Measurements Technique

The technique presented here is based on the measurement in self field, as a function of the temperature, of the magnetic moment **m** due to the currents persisting in a superconducting thin film after the application of a strong perpendicular magnetic field. In this section, we describe the measurements procedure and we give the relations permitting one to calculate the sheet critical current density of the sample, $J_{\mathrm{cr}}^{\mathrm{S}}$, (i) if we suppose that the symmetry of the current lines is that of the sample, and (ii) if we suppose that they are circular.

The samples with a square shape are zero field cooled to the lowest measurements temperature. A high magnetic field, B_{a}, is applied perpendicular to the sample plane and subsequently switched off. The same process is carried out with a reverse field. This procedure aims at establishing the same magnetic state in all the investigated samples and to generate screening currents. Then the magnetic moment resulting from the currents persisting in the sample is measured via a SQUID magnetometer or another technique, while increasing the temperature up to T_{c}. From classical electromagnetism, the magnetic moment due to the currents circulating in a film with surface S takes the form:

$$m = \frac{1}{2}\iint_S r \times J^{\mathrm{S}}\, dS \tag{1}$$

where J^{S} is the sheet current density. For a an applied field larger than the field of complete penetration, B_{T}, the sheet density of the screening current can be regarded as equal to the critical value everywhere in the film and we can write [4]:

$$J^{\mathrm{S}} = J_{\mathrm{cr}}^{\mathrm{S}} \tag{2}$$

in Eq. (1). In the case of a 90 nm thick $\mathrm{YBa_2Cu_3O_{7-\delta}}$ film cooled at 20 K, Fig. 1 shows that this condition is fulfilled if $B_{\mathrm{a}} \geq 0.05T$, because $\mathbf{m}(T)$ does not depend on the amplitude of the applied field if B_{a} is larger than this value. To ensure that it is always the case, we have routinely applied a $5T$ field. Considering that the current lines keep the sample symmetry, as suggested by theory [5] and magneto-optical observations [6], Eq. (1) results in:

$$m = -J_{\mathrm{cr}}^{\mathrm{S}}\frac{w^3}{12} \tag{3}$$

and $J_{\mathrm{cr}}^{\mathrm{S}}(T)$ can be determined from $\mathbf{m}(T)$ and w. We have also investigated the possibility that the current lines have the circular shape shown in Fig. 2. Then Eq. (1) takes the form:

$$J_{\mathrm{cr}}^{\mathrm{S}} = -\frac{24m}{\pi w^3[1 + \frac{(\sqrt{2}-1)}{2}]} \tag{4}$$

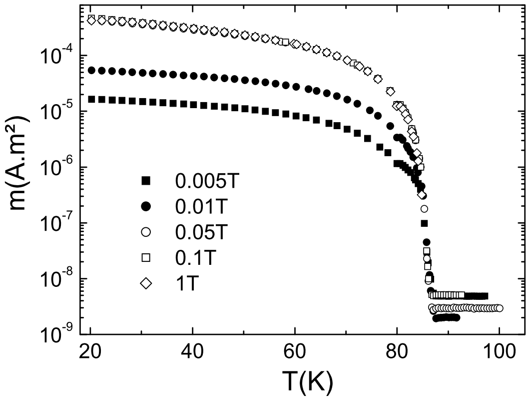

Fig. 1 Magnetic moment of a 90 nm thick YBCO film deposited on a $\mathrm{SrTiO_3}$ substrate measured as a function of the temperature for various values of B_{a}

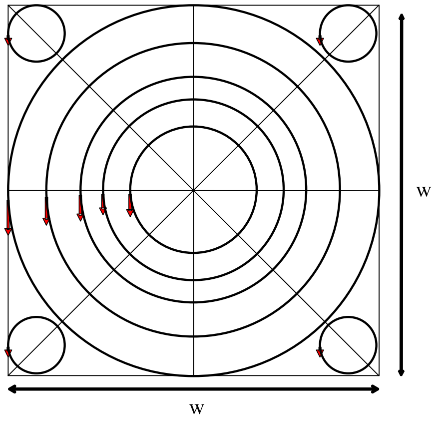

Fig. 2 The circular current lines considered for deriving Eq. (4)

In Sect. 3, we compare the $J_{\mathrm{cr}}^{\mathrm{S}}(T)$ obtained for some samples with Eq. (3) and Eq. (4) to those obtained with other techniques.

3 Results

Th. Lécrevisse et al. [7] have carried out current–voltage measurements on a Superpower SCS4050AP coated conductor at various temperatures. Figure 3 shows the sheet critical current density corresponding to these measurements as well as the $J_{\mathrm{cr}}^{\mathrm{S}}(T)$ curves obtained from $\mathbf{m}(T)$ measurements on the same sample using Eq. (3) and Eq. (4). Clearly, Eq. (4) gives results in better agreement with the transport measurements than Eq. (3). Table 1 compares the critical current densities of various THEVA films, calculated with Eq. (3) and Eq. (4) from measurements carried out at 77 K, to data provided by the manufacturer. We stress that, for some films, an additional step consisting in etching the edges of the films was added to the fabrication process. Table 1 shows that for all the samples the critical current

Table 1 Comparison of the critical current density of THEVA films calculated with Eq. (3) and Eq. (4) to the values provided by the manufacturer

SAMPLE	Theva M 700 nm [140708]	Theva E 200 nm [280305 B]	Theva M 700 nm [071010 A]	Theva E 700 nm [161110 A]	Theva E 200 nm [151110 B]	Theva S 200 nm [081010 A]
j_{cr} (A/m^2) square symmetry	3.59×10^{10}	3.38×10^{10}	5.49×10^{10}	2.35×10^{10}	2.26×10^{10}	4.60×10^{10}
j_{cr} (A/m^2) circular symmetry	2.2×10^{10}	2.1×10^{10}	3.4×10^{10}	1.5×10^{10}	1.4×10^{10}	2.85×10^{10}
j_{cr} (A/m^2) THEVA	2.5×10^{10}	2.8×10^{10}	3.3×10^{10}	1.6×10^{10}	1.5×10^{10}	2.6×10^{10}
etched edges	no	no	yes	yes	yes	yes

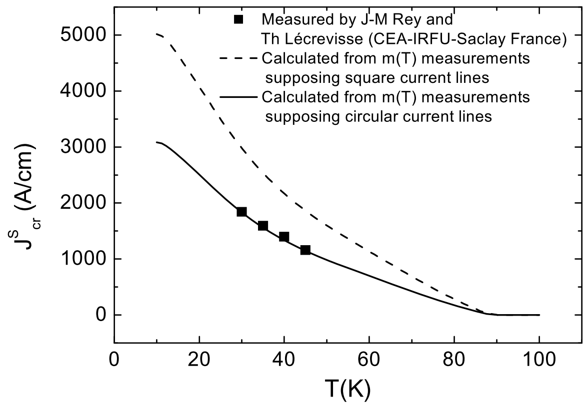

Fig. 3 Comparison between the sheet critical current density obtained from current–voltage measurements carried out on a Super-Power SCS4050AP coated conductor and the values obtained from $\mathbf{m}(T)$ measurements using Eq. (3) and Eq. (4)

density calculated with Eq. (4) is a better approximation to the data provided by THEVA than the j_{cr} calculated with Eq. (3). The agreement is very good for all the etched films, but only fair for the nonetched samples. The reason is probably that the defects along the edges of the nonetched films have some effect on the shape of the persisting current lines.

As a conclusion for this section, the comparison between our measurements and experimental results obtained by other techniques indicate that we can reliably calculate the sheet critical density of square thin films from the measurement of their magnetic moment in zero field, supposing that the persisting current lines are circular.

4 Discussion and Conclusion

In this section, we discuss the reasons why $J^{\mathrm{S}}_{\mathrm{cr}}(T)$ can be calculated with accuracy if we suppose that the persisting current lines in square films are circular, while theory and magneto-optical observations suggest that they have the sample symmetry.

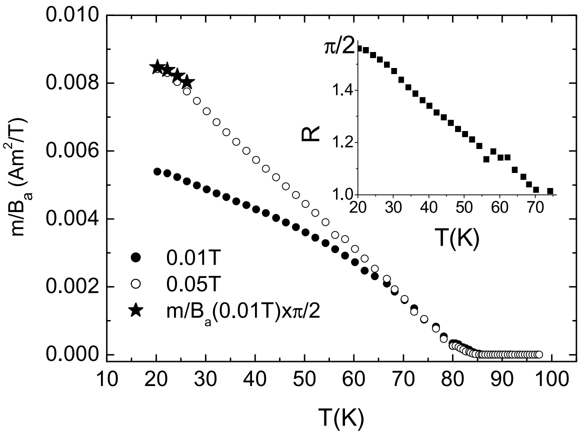

Fig. 4 $m/B_{\mathrm{a}}(T)$ curves calculated from the measurements carried out at (i) $B_{\mathrm{a}} = 0.01T$ and (ii) $B_{\mathrm{a}} = 0.05T$ reported in Fig. 1. The *inset* shows the ratio R of m/B_{a} at $0.05T$ to m/B_{a} at $0.01T$. The stars at low temperatures are the m/B_{a} values at $B_{\mathrm{a}} = 0.01T$ multiplied by $\pi/2$

The model we have used is very naïve, since we have supposed that for a large enough applied field, the sheet current density of the persisting current lines was equal to $J^{\mathrm{S}}_{\mathrm{cr}}$ everywhere in the superconducting film. As the applied field decreases from its maximal amplitude to zero, the flux distribution changes in the film, generating current lines that can have a direction opposite to that of the currents resulting from the previously applied field [8]. Due to this complicated current distribution, the calculation of $J^{\mathrm{S}}_{\mathrm{cr}}$ with circular current lines could accidentally result in a good approximation of the current density in the film, while the actual current lines have the square symmetry. However, Eqs. (3) and (4) show that for the same $J^{\mathrm{S}}_{\mathrm{cr}}$, circular current lines generate a larger $\mathbf{m}$ than square ones, while one expects that the existence of currents loops with opposite directions results in a lower magnetic moment. Another possibility arises from the comparison between measurements carried out with $B_{\mathrm{a}} > B_{\mathrm{T}}$ and $B_{\mathrm{a}} < B_{\mathrm{T}}$. Figure 4 shows the quantity m/B_{a} calculated with the measurements reported in Fig. 1, for $B_{\mathrm{a}} = 0.01T$ and $B_{\mathrm{a}} = 0.05T$. Above 67 K, m/B_{a} takes identical values for both curves. It has been established that in the parts of a film penetrated by the flux and the screening currents Eq. (2) is satisfied, although penetration is not complete [4], as it is the case when applying $B_\mathrm{a} = 0.01T$. Assuming that $B_\mathrm{T} = 0.05T$, the similarity of the curves above 67 K in Fig. 4 suggests that (i) the penetrated area does not change with the temperature and (ii) that the modulation of m/B_a is independent of the surface of this area and is due to that of J_cr^S only. We stress that, of course, this is valid only for $B_\mathrm{a} \leq B_\mathrm{T}$. Below 67 K, the m/B_a curves have shapes that are different from one another. If we suppose that the symmetry of the current lines is circular for $B_\mathrm{a} = 0.05T$ in the whole temperature range, this suggests that it is the case above 67 K only if the applied field is equal to $0.01T$. For a completely penetrated square sample, from Eqs. (3) and (4), we have:

$$\frac{m_\mathrm{c}}{m_\mathrm{r}} \approx \frac{\pi}{2} \tag{5}$$

where m_c and m_r are the magnetic moments resulting, for the same J_cr^S, from circular and square current lines, respectively. The same relation should hold for m/B_a, if this quantity depends on J_cr^S only. The inset in Fig. 4 shows the ratio of m/B_a for $B_\mathrm{a} = 0.05T$ to m/B_a for $B_\mathrm{a} = 0.01T$. This ratio increases from 1 above 67 K to $\pi/2$ in the 20 K–25 K range. This result suggests strongly that, while the current lines are rectangular at low temperatures when the applied field is equal to $0.01T$, a transition toward circular current lines occurs in the 25 K–67 K domain. More generally, one can suspect that the shape of the current lines is rectangular for $B_\mathrm{a} < B_\mathrm{T}$, at least at low temperature, while it is circular in the whole temperature range for $B_\mathrm{a} > B_\mathrm{T}$. The probable reason for these changes in the current lines symmetry is that circular current lines yields a reduction in the vortex density and, as a result, in the intervortex repulsive energy since they generate a larger $\mathbf{m}$. Work is in progress to make these aspects clear.

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