In situ comparison of the critical current density in $YBa_2Cu_3O_{7-\delta}$ thin films measured by the screening technique under two criteria

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Abstract. In this investigation we report the determination of the critical current density J_c flowing in a $YBa_2Cu_3O_{7-\delta}$ superconducting thin film. Estimation of J_c was carried out by an inductive technique, the so-called screening technique, in which both the imaginary part of the fundamental harmonic of susceptibility χ_1'' and third harmonic voltage V_3 criteria were considered for the determination of the full penetration field. In order to verify the reliability of this technique under two criteria, we investigated the homogeneity of J_c via transport measurements conducted on four microbridges patterned in the same film. Based on the transport method we found that both techniques yield similar results in the determination of J_c for temperatures close to critical temperature T_c. However, at temperatures relatively far from T_c, the V_3 criterion showed a better agreement with the transport data. Furthermore, using both criteria, we propose a methodology to estimate in situ the coil factor associated with the V_3 criterion, avoiding in this way the need of implementing an additional technique.

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1. Introduction

The application of high-temperature superconductors (HTSC) in the electronics industry is a promising enterprise, which goes from SQUID's to integrated circuits to superconducting computers. Therefore, it is of prime importance to understand the superconducting properties of these materials not only of bulk samples but of thin films as well. In recent years, a great deal of attention has been put in studying properties of superconducting thin films. To determine the superconducting properties such as the critical current density J_c of either a bulk or a thin film superconductor, researches often use the traditional four-probe technique. Although this technique is quite satisfactory for bulk samples, it is highly intrusive for thin films and, as a consequence, most of the times they can no longer be used in further tests. To overcome this problem, several non-invasive techniques have been proposed. So far, two inductive techniques of this kind are widely used. In one of these cases known as the conventional ac susceptibility technique[1, 2], the sample is embedded in a pick-up coil, which in turn is coaxially mounted inside a driving coil. The experimental arrangement is sensitive to the overall magnetic response of the sample when it is subjected to the influence of an ac magnetic field of the form $H(t) = H_0 \cos(\omega t)$, where H_0 is the amplitude, ω the frequency and t the time. The induced voltage in the pick-up coil is zero when the sample is in its normal state but as the superconducting transition occurs an unbalanced voltage sets in [1]. Due to the nonlinear magnetization of the sample, harmonics of the voltage will emerge. It has been shown that harmonics of the magnetic susceptibility are proportional to the harmonics of the voltage. With the help of this technique and based on analysis of the imaginary part of the fundamental complex magnetic susceptibility as a function of the temperature $\chi_1''(T)$, Xing *et al* [3] proposed a method to determine the J_c in superconducting thin films.

The other alternative, the mutual inductive technique or screening technique[4, 5], offers a practical approach not only to determine the J_c[5, 7, 6, 8] but also to measure the harmonics of the magnetic susceptibility[9, 10]. In this experimental setup the film is placed between two small coils forming a sandwich arrangement, and as in the conventional ac susceptibility technique, the induced voltage is measured through the pick-up coil. The reliability of the technique can be guaranteed if the size of the sample is at least twice larger than the outer radius of the coils [4]. Previous experiments[7, 6, 8] have shown that the amplitude of the third harmonic voltage V_3 emerges when the amplitude I_0 of the driving current reaches a threshold current I_{th} which can be related to the J_c of the film.

Therefore, there are two criteria to estimate the J_c independent of the technique used. For brevity we will call them: the $\chi_1''(T)$ criterion and the $V_3(I_0)$ criterion. Although both criteria are widely used there is not consensus in their convergence and no fundamental theory to single out one or the other.

In this investigation, we realized measurements of J_c in $YBa_2Cu_3O_{7-\delta}$ superconducting thin films using both criteria as measured with the screening technique only. Then, we compare our results with the conventional four-probe method. We found that both criteria yield similar results for the temperatures close to T_c, however for temperatures relatively far from T_c the corresponding curves begin to diverge. Moreover, the analysis of these criteria sheds light on the determination of the coil factor k from the $V_3(I_0)$ criterion and therefore, its dependence on other experimental techniques is not necessary.

2. Theory

The experimental geometry used in this work is shown in Fig. 1. An ac magnetic field $H = H_0 \cos(\omega t)$ has been applied along the c axis of the film. The field is generated just above of the film by a current $I = I_0 \cos(\omega t)$ passing through the drive coil. Then, the superconducting response is registered through the pick-up coil placed on the rear of the film. The induced voltage depends on the coupling between the coils and is strongly influenced by the superconducting behavior of the film.

2.1. The $\chi_1''(T)$ criterion

Xing et al.[3] used the imaginary part of fundamental harmonic of susceptibility $\chi_1''(T)$ to estimate J_c. He found that the magnetic moment or the shielding current in the hysteresis cycle saturates when the amplitude H_0 reaches the penetration field H^*, which is related to J_c by

$$H^* = \frac{J_c d}{3} \tag{1}$$

where d is the film thickness. Based on the Sun model[11] the imaginary part of the fundamental harmonic for a thin film is found to be

$$\chi_1'' \propto \frac{e^{-h}}{h}[h \cosh(h) - \sinh(h)] \tag{2}$$

where $h = H_0/H^*$ is the reduced field. A plot of χ_1'' versus h shows a peak at $h = 1.344$ or $H_0 = 1.344H^*$. If χ_1'' is plotted as a function of the temperature, a peak appears at a temperature T_p where the above relation is satisfied, i.e., $H_0 = 1.344H^*(T_p)$. From the last relation and Equation (1), the following formula is obtained[3]:

$$J_c(T_p) = 3.157\frac{H_0}{d}. \tag{3}$$

Here d is given in meters and H_0 is the rms value in A/m. Since $V_1''(T) \propto \omega H_0 \chi_1''$ [9] one can obtain J_c by plotting $V_1''(T)$ as a function of the temperature for distinct magnetic field amplitudes. So, for each curve a peak appears at a temperature T_p, and using the previous relation (3), we can obtain the temperature dependence of J_c.

2.2. The $V_3(I_0)$ criterion

Consider that the sample is held at a constant temperature T ($T < T_c$) and a small field H has been applied to the film. If the value of I_0 is smaller than a certain threshold value I_{th} ($I_0 < I_{th}$), the magnetic field under the film is screened by a superficial superconducting current K_s (sheet current) that flows in the film. The magnetic field amplitudes at the upper and lower surfaces of the film are, $H_1 = 2H_0$ and $H_2 = 0$, respectively[4, 5]. In this case, the film is regarded as an image coil reflected through

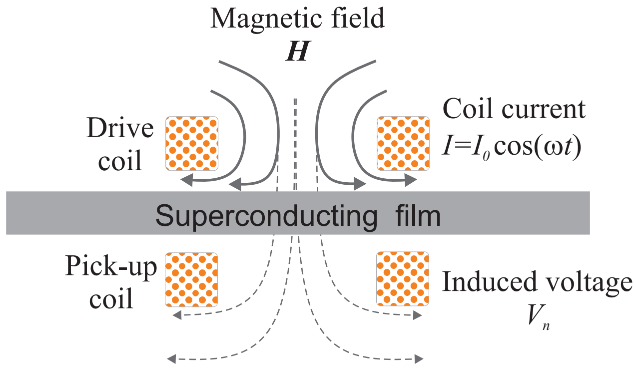

Figure 1. The screening technique: transversal section. A pair of small and coaxial coils with the film of interest interposed between them. The magnetic field is generated by the driving current $I_0 \cos\omega t$ that flows through of the drive coil mounted just above a superconducting thin film. The pick-up coil detects the magnetic response at the rear region of the film (dotted lines represent the lines of the magnetic field when the film is in the normal state).

the upper surface of the film, carrying the same current but in the opposite direction. The magnetic response of the film is linear, and no harmonics of the voltage are induced in the pick-up coil. When $I_0 = I_{th}$, the magnetic field achieves the full penetration and the film response is no longer lineal. As a result, the third-harmonic voltage V_3 in the pick-up coil starts to emerge. At this point, the amplitude of the ac magnetic field near the surface of the film is $H_1 = 2H_0 = J_c d$[4, 5]. Then, I_{th} can be expressed as $I_{th} = (d/k)J_c$, where k is a coil factor and J_c can be determined by measuring the occurrence of V_3 with increasing I_0. The coil factor depends on the shape and the location of the experimental coils. Then, to determine its value it is necessary to measure the J_c by implementing an additional technique.

3. Experimental

Figure 2 shows the measurements regions patterned on the 15 mm × 15 mm $YBa_2Cu_3O_{7-\delta}$ thin film (Theva Co.) used in this work. The film of thickness d = 200 nm, was deposited on a CeO_2-buffered R-cut Al_2O_3 substrate by the so-called thermal co-evaporation method and was coated in situ with a 200 nm layer of Au. The growth and patterned details were reported elsewhere[12]. For comparison and with the purpose of evaluating the precision of both criteria, J_c was also determined from transport measurements by the conventional four-probe method. The film has two measuring sections. A section for inductive measurements and a section for transport measurements where four microbridges of 1 mm length and 40 μm width can be found. In the inductive region the pair of coils were placed at the center, as scketched in the Fig. 1. Each coil had 360 turns, an outer diameter of 5 mm, inner diameter of 1 mm, and height of 1 mm.

The block diagram of the experimental setup for inductive measurements is shown

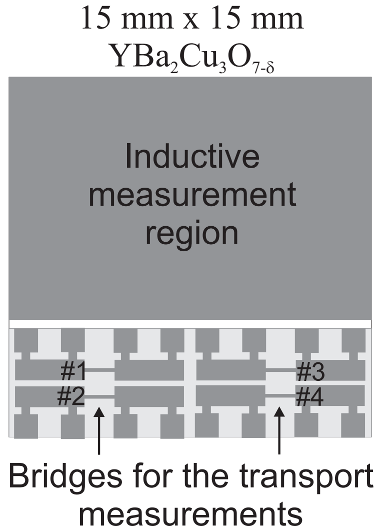

Figure 2. The 15 mm x 15 mm $YBa_2Cu_3O_{7-\delta}$ thin film used in this work (Theva Co.). Upper zone for inductive measurements and lower zone with four patterned bridges (etched)

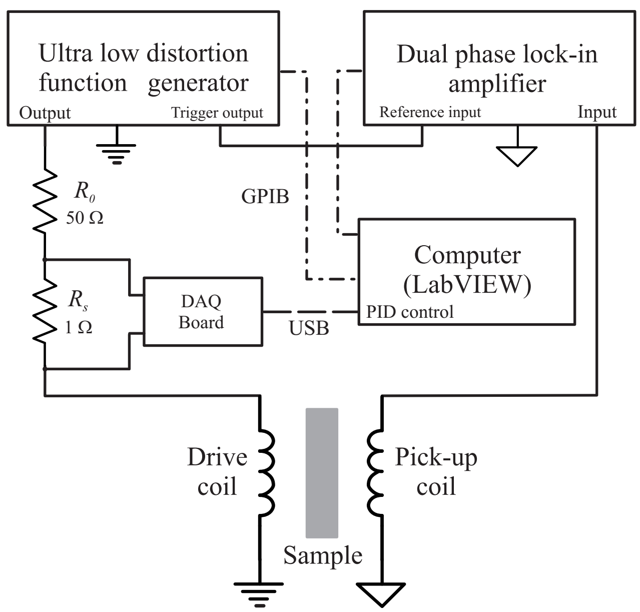

Figure 3. Block diagram of the experimental setup for the inductive measurements.

in Fig. 3. The sinusoidal voltage was supplied from a low distortion generator (SRS-DS360) to the drive coil. For the V_3 criterion, the current was determined measuring the drop voltage in the resistor R_s in series with the drive coil by means of a data acquisition board (NI-USB6216). For the case of the $\chi_1''(T)$ criterion, we wish to maintain a constant magnetic field as the temperature is changed, so the current in R_s was controlled by means of a Proportional-Integral-Derivative (PID) control implemented in a computer program. In both criteria, a phase-sensitive lock-in amplifier (SRS-SR830) was used to

Table 1. T_c and J_c measurements for the bridges at positions #1 − #4. J_c values defined at $E = 1\times10^{-3}$ V/m.

Bridge	T_c (K) $\pm$ 0.1 K	J_c ($\times10^6$A/cm^2) at 77.3 K
#1	88.0	3.545 (−0.12%)
#2	88.0	3.549 (+1.31%)
#3	88.0	3.547 (+0.12%)
#4	88.0	3.548 (−1.28%)
Average	88.0	3.542

analyze the signal coming from the pick-up coil. The superconducting sample was cooled down by means of a He cold finger coupled to a cryostat (Cryotech-ST15) compressor and the temperature was controlled via a temperature controller (SI-9600) and monitored by a diode (SI-410A) placed near the sample.

4. Experimental results and discussion

We first characterized the bridges as of J_c and T_c. Table 1 shows a summary of the results for the four bridges. The transport measurements were carried out in a liquid nitrogen bath with the conventional four-probe method and a criterion of electric field $E = 1\times10^{-3}$ V/m was applied. We could verify that both T_c and J_c for the four bridges are quite homogeneous along the sample.

The next step was to estimate J_c by the screening method according to the two criteria outlined above. The curves of the imaginary part of fundamental harmonic V_1'' as a function of the temperature for several magnetic field amplitudes H_0, are shown in the Fig. 4. Amplitudes of ac magnetic field ranging from 0.4 to 4.4×10^3 A/m were applied to the film at a cooling rate of 2 K/min. From these curves we obtained the value of the temperature at the maximum (T_p) of each curve and use Equation (3) to estimate $J_c(T_p)$ for a temperature range between 84.6 K and 87.6 K. We can see that as the amplitude increases the peak shifts towards lower temperatures and at the same time, the width of the curve increases. It is well known that these effects are due to the field and temperature dependence of J_c[3, 10, 11]. Then, we estimated J_c by the V_3 criterion for a similar temperature range. The curves for the third harmonic of the voltage V_3 as a function of the driving current amplitude I_0 are shown in the Fig. 5. Note that as the temperature decreases the curve of V_3 rises smoother than at temperatures close to T_c. From these results, the $I_{th}(T)$ curve was obtained. I_{th} was estimated at the current I_0 when V_3 reached 1 μV. In order to obtain the $J_c(T)$ with this criterion, the coil factor k was determined by fitting the $I_{th}(T)$ data with the J_c curve obtained by means of the transport measurements. Then, a coil factor k =139$\pm$23 cm^{-1} was obtained. The temperature dependence of J_c for the four bridges obtained by transport and inductive measurements is shown in Fig. 6, for temperatures ranging from 83.7 K to 87.7 K. The values of the transport measurements reported represent an average of the data

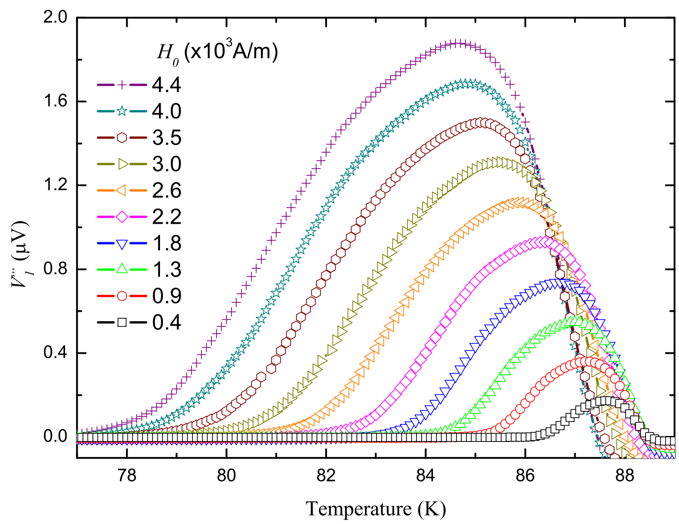

Figure 4. Temperature dependence of the V_1'' for several magnetic field amplitudes H_0. Both V_1'' and H_0 are given in rms values.

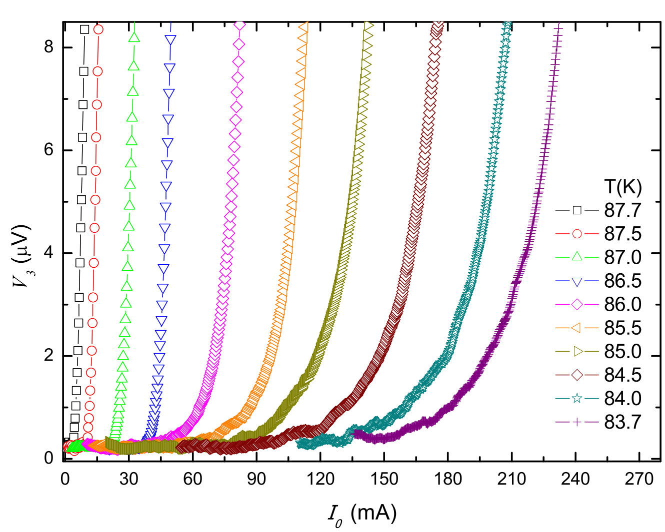

Figure 5. Driving current dependence of V_3 for several temperatures. Both I_0 and V_3 are given in rms values.

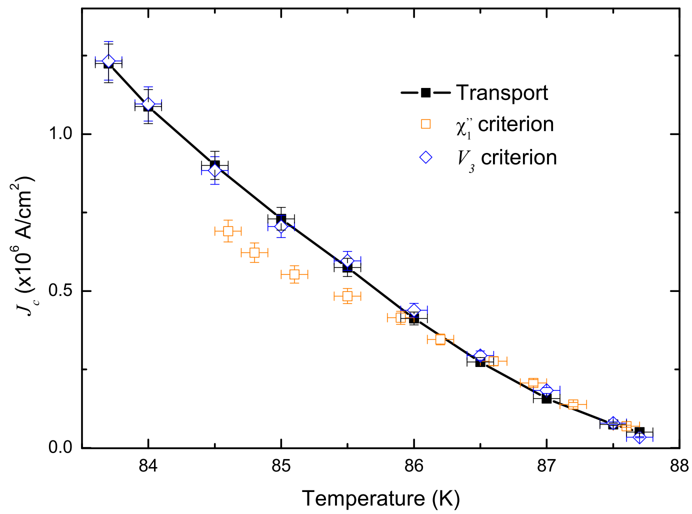

Figure 6. Dependence of the J_c obtained by the transport technique and the screening technique for temperatures varying from 83.7 to 87.7 K. For the screening technique, the J_c under the V_3 and χ_1'' criteria are presented.

corresponding to the different values obtained for each bridge. These curves are in good agreement among the different approaches. However, if the $I_{th}(T)$ is fitted with the curve of J_c from χ_1'' criterion, then we get $k = 127{\pm}19$ cm^{-1}, the same value found previously. Convergency of both inductive criteria near T_c have been previously reported by Acosta *et al* [13]. However, their measurements reached a wider temperature range (possibly due to a lower J_c of their sample), but their resolution near T_c was poor and therefore a useful comparison with our results was not feasible. In addition, they determined the J_c with the V_3 approach but taking the value of the driving current as the voltage starts to emerge and applying the Equation (1). For the J_c curves based on the χ_1'' criterion they determined the H^* considering the value of the temperature at the peak of the curve of the fundamental harmonic of voltage. Experimentally we found that both voltages start to emerge at the same amplitude of the magnetic field (proportional to the drive coil current), leading to an overestimation of J_c according to the χ_1'' criterion, as finally they conclude.

On the other hand, we noted that for lower temperatures, deviations from the χ_1'' criterion are observed. Because the determination of J_c depends on the specific selection of the full penetration field H^*, then we are observing the behavior of the H^* from each criterion. It follows that both criteria converge near T_c and they start to deviate as the temperature moves away from T_c. Similar behavior of the fields has been reported by Shaulov[14] in sintered YBCO samples that were studied with conventional ac susceptibility technique.

5. Summary

In this research the V_3 and χ_1'' inductive approaches were confronted with the conventional transport method. We found that both criteria yield similar results for temperatures close to T_c and agree with that transport measurements. However, for lower temperatures the J_c curves based on the χ_1'' criterion diverge considerably whereas the V_3 criterion agree pretty well along the whole temperature treated in this work.
Our investigation also provided a methodology to estimate in situ the k coil factor associated with the V_3 criterion. This is achieved by using the χ_1'' criterion without the need of any additional technique.

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