Statistical Studies of the Anisotropy of the Pinning Mechanism in YBaCuO Films Deposited on Polycrystalline YSZ Substrates

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Abstract. We have studied the I-V characteristics and the behaviour of the critical current density of $YBa_2Cu_3O_{7-x}$ films, prepared by sputtering, at different values of applied magnetic field and of temperature. The superconductor was deposited onto polycrystalline ZrO_2 (8 mol % Y_2O_3). The I-V characteristics were obtained by using a short current pulse measurement technique in order to avoid heating phenomena. We have used a theoretical model to describe the I-V characteristics, based on a statistical treatment of the motion of vortices in an arbitrary pinning potential. Besides the determination of the critical current density J_c, this model allows to characterise the pinning sites by a function giving their energetic distribution. In this way we have been able to make a clear distinction between intrinsic and extrinsic pinning in sputtered $YBa_2Cu_3O_{7-x}$ films.

1. INTRODUCTION

A common characteristic of high-Tc superconductors is to exhibit highly anisotropic superconducting properties due to their layered structure. Tachiki and Takahashi proposed a theoretical model for the intrinsic pinning and derived the dependence of the critical current density J_c as a function of the direction of the magnetic field respective to crystallographic axes [1]. This model is based on the modulation of the superconducting order parameter due to the commonly admitted alternance of strong superconducting layers such as CuO_2 planes and weak superconducting layers such as CuO chains and BaO planes, in $YBa_2Cu_3O_{7-x}$. Most of the reported experimental results agree rather well with those expected for this intrinsic pinning model [2]. It is known that the good quality single-crystalline samples provide detailed investigations of the anisotropy. Therefore a huge number of studies have already been performed on single-crystalline films [3, 4] but there has only been relatively few investigations on the anisotropy in polycrystalline films [5].
The aim of this paper is to present detailed investigations of the I-V characteristics and transport critical current density J_c in thin $YBa_2Cu_3O_{7-x}$ films deposited on polycrystalline ZrO_2 substrate. The results are described by a statistical model which provides a qualitative study of the anisotropy of the pinning mechanism in granular media for which it is sometimes hard to conduct an elemental description of the involved phenomena.

2. EXPERIMENTAL PROCEDURE

For the determination of the critical current, conventional d.c. four terminal measurements are often complicated by ohmic heating at the resistive contacts between the superconductor and the current leads. Indeed heat can diffuse into the sample causing a significant thermal instability and leading to a measured value of the critical current density much smaller than the actual one. In order to circumvent such problems, a pulsed current system was developed, which enables reliable measurement of the critical current density.

The apparatus used for the determination of the critical current and I-V characteristics is shown in figure 1. To insure a good electrical contact quality, 50 μm diameter gold wires were ultrasonically bonded to Au contacts evaporated onto the film. The current was delivered by a programmable current source (Keithely Inst., model 220), in the form of single pulses of maximum amplitude I_m and duration $\delta\tau$ (10 to 20 ms). The voltage appearing between the voltage contacts was measured by a programmable digital oscilloscope after being amplified by a high gain (100 dB) low noise voltage amplifier.
If heating effects constitute a major problem in conventional d.c. measurements, the single pulse method is very sensitive to the electrical noise because of the large bandwidth of the oscilloscope. Therefore in order to reduce these noise effects, we have applied the usual techniques allowing to get an acceptable noise level. In particular, we have shielded and twisted all voltage leads and grounded this shielding to the platform of the cryostat. The low noise preamplifier was placed as near to the sample as possible to reduce the induced voltage on the amplifier input. We have also interposed a lowpass filter between the amplifier and the oscilloscope in order to minimise the high frequency noise. As the detected noise was essentially random, the pulse rate was fixed at 0.5 Hz and the measurements were averaged over more than 30 identical current pulses at the same fixed J, T and H values. The resulting voltage noise level for the measurements reported later in this paper was about 30 nV.
Typical voltage pulse waveforms are shown in figure 2. An initial transient of about 0.5 ms in duration is generally observed, which can be either positive or negative. Such a transient arises probably from the self inductance of the loop formed by the sample and the voltage sensing leads. Then the voltage increases up to its normal value with a rise time resulting from the filter. In order to rule out these filtering effects, the measured voltage value was defined as the average over about 50 points between arrows as shown in figure 2.
The granular film studied here was sputtered on a ZrO_2 polycrystalline substrate of surface 10×3 mm^2 [6]. The film thickness as determined by means of a profilometer was 6000 Å. The transition temperature obtained from the resistive transition in zero magnetic field is Tc=85 K. The X-ray diffraction diagram shows that this film has highly predominant c-axis orientation parallel to the normal of the film.

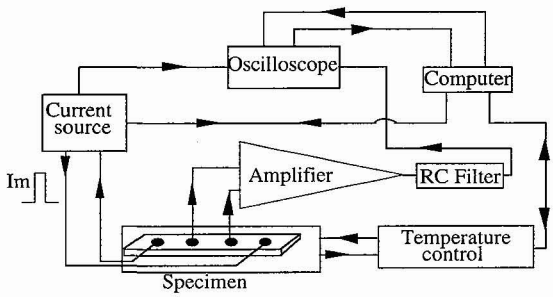

Figure 1: Schematic representation of the pulsed current system for the determination of the I-V characteristics.

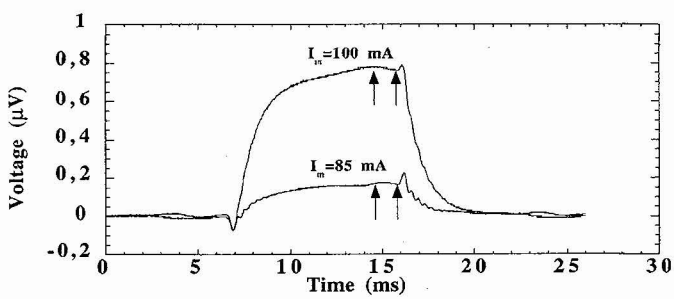

Figure 2: Typical shape of the voltage pulse across a sample as a response to the current pulse. Time interval between arrows indicates the actual measurement duration.

3. STATISTICAL MODEL

Our model [7] allows the analysis of the flux flow regime in a superconductor containing structural defects whatever their nature. For this purpose we carry out a statistical treatment of the motion of the vortices interacting with these defects. We consider the case in which the magnetic field is always perpendicular to the transport current but can be either parallel or perpendicular to the c-axis.
For a particular pinning centre, as soon as the local current density exceeds the critical current density, the vortex which is initially pinned, can move freely. In the course of its motion, the vortex can meet other defects and, depending on the depth of the potential well, it can (or cannot) be pinned until the local current density reaches the corresponding critical current density.
This behaviour can be described easily by defining the local critical current densities $\vec{J}_c(\vec{r}_i)$ corresponding to the different pinning forces. These critical current densities must be compared to the local transport current density $\vec{J}(\vec{r}_i)$ in order to know if the vortex is pinned or is moving with the velocity $\vec{V}_L$; so one gets :

$$\left|\vec{V}_L(\vec{r}_i)\right| = 0 \qquad \text{if } \left|\vec{J}(\vec{r}_i)\right| < \left|\vec{J}_c(\vec{r}_i)\right| \tag{1}$$

and

$$\left|\vec{V}_L(\vec{r}_i)\right| > 0 \qquad \text{if } \left|\vec{J}(\vec{r}_i)\right| > \left|\vec{J}_c(\vec{r}_i)\right| \tag{2}$$

Thus after leaving the pinning centre, situated at $\vec{r}_i$ and satisfying the relation (2), the vortex will move until it finds a pinning centre satisfying the relation (1). In other words, because of the diversity of the potential wells, some vortices can be moving while others are staying pinned. It is to be emphasized that the motions of vortices are correlated by the electromagnetic interactions.
For the simple geometry considered here (the current is perpendicular to the magnetic field) and assuming that the transport current density J is uniform inside the sample, the Eq. describing the motion of a vortex "i" can be written as :

$$\eta V_{Li} = J\Phi_0 - F_{pi} = (J - J_{ci})\Phi_0, \text{ with } J > J_{ci} \tag{3}$$

Here F_{pi} is the pinning force exerted on the vortex "i", which can be associated with a critical current density J_{ci}. V_{Li} is the velocity of the vortex and η is the viscosity coefficient assumed to be the same for all vortices.
The magnetic induction in the superconductor is $B = n\Phi_0$ where n is the density of the vortices per unit area perpendicular to the magnetic field ; for a transport current density J, only a fraction n_1 of the total density n of vortices move, so that the expression of the power dissipated per unit volume can be written as :

$$P = J\Phi_0 \sum_{i=1}^{n_1} V_{Li} = \frac{J\Phi_0^2}{\eta} \sum_{i=1}^{n_1} (J - J_{ci}) \tag{4}$$

Further, the electrical field in the sample generated by this dissipation is :

$$E = \frac{\Phi_0^2}{\eta} \sum_{i=1}^{n_1} (J - J_{ci}) \tag{5}$$

In order to characterise the statistical spreading of pinning forces, one can introduce a distribution function of the critical current densities $f(J_{ci})$ so that :

$$\int_0^\infty f(J_{ci})\, dJ_{ci} = 1 \tag{6}$$

therefore the electrical field can be expressed as :

$$E = \frac{n\Phi_0^2}{\eta}\int_0^J (J - J_{ci}) f(J_{ci}) dJ_{ci} = \frac{B\Phi_0}{\eta}\int_0^J (J - J_{ci}) f(J_{ci}) dJ_{ci} \tag{7}$$

The integration has to be performed over the vortices which are in movement i.e. for $0<J_{ci}<J$. According to Eq. (7), the behaviour of the E-J curves results from the shape of the distribution function of the pinning forces $f(J_{ci})$. It also follows from Eq. (7) that $f(J_{ci})$ can be determined from the experimental E-J characteristics but this method is often laborious, so we have determined a general form of $f(J_{ci})$ from simple considerations [7]. Therefore the final expressions for $f(J_{ci})$ and for the electrical field are :

$$f(J_{ci}) = \begin{cases} 0 \text{ for } J_{ci} < J_c \\ \frac{1}{J_0}\exp\left(-\frac{J_{ci} - J_c}{J_0}\right) \text{ for } J_{ci} \geq J_c \end{cases} \tag{8}$$

$$\boxed{E = \frac{B\Phi_0}{\eta}\left[J - J_c - J_0\left(1 - \exp\left(-\frac{J - J_c}{J_0}\right)\right)\right]} \tag{9}$$

where J_0 is a physical parameter characterising the width of the distribution function $f(J_{ci})$, and J_c represents the smallest pinning force acting on the assembly of vortices.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 displays a typical resistive transition curve E-J for the film at 75 K for two values of the magnetic field. The agreement between the experimental data and the theoretical curve resulting from Eq (9) shows that the general form of the distribution function given by Eq. (8) fits well our data.

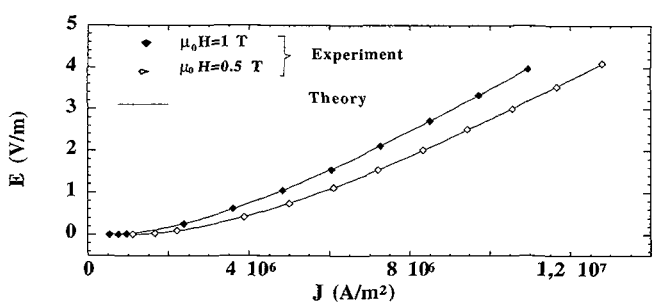

Figure 3: E-J curves for the film at 75 K. The lines are the theoretical curves given by Eq. (9) and the dots represent the experimental results.

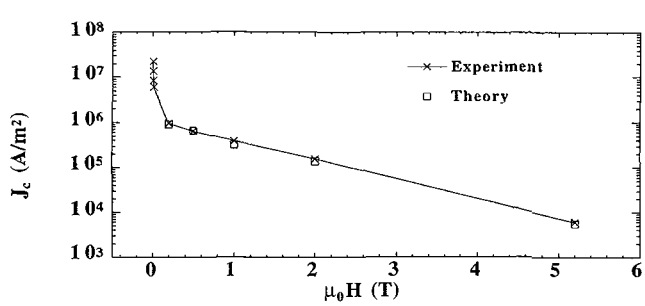

Figure 4: Comparison of the calculated (□) and the measured (-✕-) critical current densities of the YBaCuO film at 75 K. The curve is only a guide for the eye.

The critical current density can be deduced either directly from the experimental data or from the calculated E-J curve using a fitting method. For the experimental determination we have used an electrical field criterion of 10 μV/cm. Figure 4 represents the comparison between the calculated and the measured critical current densities. Again, from this figure, we note the good agreement between the experimental results and the values obtained from our model.
The description of our experimental results in the framework of the statistical model allows us to determine the fraction p(J) of the vortices in motion due to the Lorentz force $J\Phi_0$ as well as the average F(J) of the pinning forces exerted on the moving vortices. According to this model, p(J) is given by :

$$p(J) = \int_0^J f(J_{ci})dJ_{ci} = \frac{\eta}{\Phi_0 B}\frac{dE}{dJ} \tag{10}$$

In order to obtain F(J), one only has to take the tangent to the E-J curve at the point of coordinates (J, E(J)) ; it intersects the J-axis at J_{tg} given by

$$J_{tg} = \frac{\int_0^J J_{ci} f(J_{ci})dJ_{ci}}{p(J)} \tag{11}$$

and one gets $F(J)=J_{tg}\Phi_0$.
It is worth noting that when J tends to infinity J_{tg} tends to J_0+J_c ; therefore J_0+J_c appears to be the mean pinning force for the whole assembly of vortices.
Seeing that our model fits well the experimental data, we have used it in order to obtain some qualitative information about the pinning mechanisms in the film under investigation. For this purpose we have plotted in figure 5 the ratio (J_0/J_0+J_c), which characterises the spreading of the pinning forces, as a function of the magnetic applied field for T=70K. In the same way we present in figure 6 the corresponding plot for the critical current density versus magnetic field.
In the high field region ($\mu_0 H \geq 0.5$ T), the critical current density J_c shows a small decrease with increasing field. In this region the dissipation results from both vortex creep and flow inside the grains. Furthermore, the behaviour of the critical current density for H//ab ($J_c^{H//ab}$) is different from that corresponding to H//c ($J_c^{H//c}$). The difference between the values of these two critical current densities has a tendency to increase when the magnetic field and temperature increase as is shown in figure 6. This behaviour results from the anisotropy of the pinning forces in high-Tc superconductors.

When both magnetic induction $\vec{B}$ and transport current density $\vec{J}$ are parallel to the ab planes, the Lorentz force is perpendicular to these planes and the vortices have to move in the c-direction and thus must overcome the energy well to cross the CuO_2 planes, thus experiencing an intrinsic pinning force. The corresponding critical current density $J_c^{H//ab}$ is then expected to be higher than in any other configuration. This kind of pinning is only slightly sensitive to the variation of the magnetic field i.e. to the fluxoid spacing, so that the spreading of the pinning forces (J_0/J_0+J_c) is relatively constant (figure 5) and, as it can be seen in figure 6, $J_c^{H//ab}$ is almost magnetic field independent. Nevertheless as

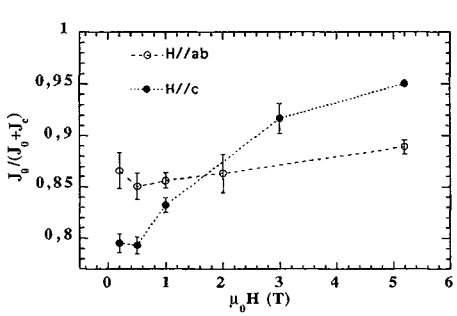

Figure 5: Spreading of the pinning forces in the YBaCuO film as a function of magnetic field at T=70 K.

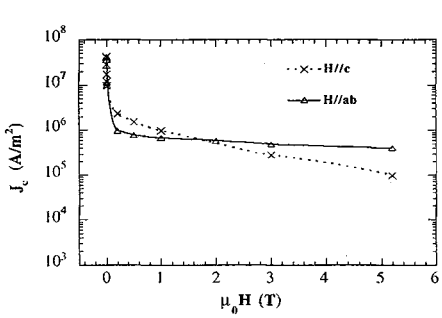

Figure 6: Variation of J_c of the YBaCuO film with magnetic field at T=70 K.

the magnetic field increases, (J_0/J_0+J_c) increases slightly showing probably that extrinsic pinning due to defects in the sample is added to the intrinsic one. As a consequence, the pinning forces spread out over a large number of values because of the increasing of the vortex density and thereby the resulting $J_c^{H//ab}$ becomes more sensitive to the magnetic field.

In contrast, when the magnetic induction $\vec{B}$ is parallel to the c-axis and the transport current $\vec{J}$ is parallel to the ab planes, the Lorentz force is also parallel to these planes. In this situation, the vortices interact principally with defects. Therefore the pinning is essentially extrinsic and the resulting critical current density $J_c^{H//c}$ depends on the efficiency of the pinning centres for which the energetic distribution is still given by (J_0/J_0+J_c). At low field (around 0.2 T), we notice that $J_c^{H//c}$ is high and (J_0/J_0+J_c) is low, giving the impression that the vortices are pinned firstly by the pinning centres for which the efficiencies are almost the same and roughly act individually on the few vortices which are far from each other. When the vortex density increases their magnetic interaction cannot be neglected compared to the pinning forces, on the other hand, the number of occupied pinning centres increase more and more. Consequently, the range of values over which the pinning forces are distributed is very large. This situation evolves towards the melting vortex state characterised by an increase of (J_0/J_0+J_c) and a noticeable decrease of $J_c^{H//c}$.

Moreover we observe that the transport critical current density drops sharply ($\sim 1/H^{0.5}$) by more than two orders of magnitude between 0 and 8 mT. This behaviour can be interpreted as follows : at low magnetic field the transport critical current in polycrystalline YBaCuO is mainly determined by weak-link regions separating high-J_C regions in the material [8]. In favour of this assumption we can note that the critical current density does not depend on the field direction in the low field region in agreement with an intergrain Josephson behaviour.

5. CONCLUSION

The study of the distribution functions of the pinning forces permits to make a clear distinction between intrinsic and extrinsic pinning. The intrinsic pinning, exerted on vortices lying between superconducting layers, is characterised by the narrowing of the distribution function and by its magnetic field independence. On the contrary, the extrinsic pinning, exerted on vortices by defects like grain boundaries or non-superconducting precipitates, is characterised by distribution functions which widen with increasing field. Our statistical model does not take into account the low magnetic field region (≤ 10 mT) where the critical current is controlled by the Josephson nature of the intergranular coupling between grains.

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