The critical current density and the vortex pinning in high quality $YBa_2Cu_3O_{7-\delta}$ thin films

A. Ramzi*, [1], A. Taoufik[1], A. Tirbiyine[1, 2], A. Labrag[1], A. Abaragh[1], H. Darhmaoui[3], S. Senoussi[4], L. Bougarfa[1], F. Chibane[1], M. Boujida[5], A. Bouaaddi[1] and M. Bghour[1]

[1] *Equip of Materials Superconductors at High Critical Temperature, Ibn Zohr University, Agadir, Morocco.*
[2] *Cadi Ayyad University, Poly-disciplinary Faculty, B. P. 4162, Route Sidi Bouzid 46000 Safi, Morocco.*
[3] *School of Science and Engineering, Al Akhawayn University, Ifrane, Morocco 53000*
[4] *Solids physics laboratory, Paris-Sud University, Orsay, France.*
[5] *Sidi Mohammed ben Abdellah University, sciences and technic Faculty, B. P. 2202, Route Route d'Imouzzarr Fes, Morocco.*

We have measured the critical current density J_c of high quality c-axis oriented $YBa_2Cu_3O_{7-\delta}$ thin films. Measurements were performed for various magnetic field and temperature values, and as a function of the angle θ between the c-axis and the applied magnetic field direction. A maximum of the critical current density was obtained when the flux lines are aligned along the CuO planes (θ = 90°); another maximum in J_c was also observed when the magnetic field is adjusted parallel to the c-axis. We attribute these effects to different, intrinsic and extrinsic, pinning mechanisms of vortices in the sample.

* Corresponding author : *ab_ramzi@yahoo.fr*

PACS 74.25.Fy, 74.40.+k

I. Introduction

It is very important from both viewpoints of fundamental research and practical application to understand the flux pinning mechanisms of high-T_c superconductor oxides and to get information about these mechanisms properties. On the other hand from a practical point of view the problem is to find the mechanism of strong pinning of vortices and to obtain samples with higher critical current density.

In high critical-temperature superconductors, the CuO_2 layers act as strong pinning centers for vortices which are aligned along these layers. The defects and precipitates can not work strongly as pinning centers when magnetic field is parallel to the c-axis of film with the c-axis orientation perpendicular to the film surface. This is because the coherence length along the c-axis in high critical-temperature superconductors is very short [1-6] and thus the vortex core size is very small. Consequently, interaction between the flux lines and these centers will not yield to a strong pinning. The flux lines are more stable when they are placed in the layers with the weak superconductivity and parallel to the CuO_2 planes. The pinning by *ab* planes is then more efficient than the point defects or precipitate pinning. The critical current density estimated from this pinning mechanism is very higher in the case where the applied magnetic field is parallel to the *ab* planes than when it is perpendicular.

The critical current density J_c anisotropy was studied. The $YBa_2Cu_3O_{7-\delta}$ films exhibit strongly enhanced J_c when vortices were parallel to the *ab* planes (θ = 90°) and J_c decreases when the magnetic field deviates from this planes. Tachiki and Takahachi [7] proposed an intrinsic pinning model which is based on the layer structure of high critical temperature superconductor. It has been seen that the CuO_2 layers and their vicinities are strongly superconductive and the layers with CuO and BaO and their vicinities are weakly superconductive. The weak superconducting layers work as natural pinning centers, but the model considers also the existence of extrinsic pinning centers. It has been also reported that precipitates [8], and point defects by neutron irradiation [9] or oxygen vacancies [10] act as flux lines pinning centers for $YBa_2Cu_3O_{7-\delta}$ films. Recently, Dam and Huijbregtse [11] argued that dislocations are responsible for the high critical current density in $YBa_2Cu_3O_{7-\delta}$ using a wet-chemical etching technique in combination with atomic force microscopy.In this paper, the critical current density J_c was investigated in high quality c-axis oriented $YBa_2Cu_3O_{7-\delta}$ thin films as a function of temperature and magnetic field direction with the c-axis.

II. Experiment

The studied sample was a high quality single crystal $YBa_2Cu_3O_{7-\delta}$ thin film deposited by the laser ablation method on the surface (100) of a $SrTiO_3$ substrate. In zero magnetic field, the resistance vanished at T_c = 90 K. The c-axis was perpendicular to the surface of the film. Electrodes of measurements were in gold and deposited on the surface of the sample by in situ evaporation. The film thickness and width were 400 nm and 7.53 µm,

respectively. The distance between electrodes of measurements was 135 µm. Contact resistances were less than 1 Ω . Measurements were realized by using the DC four–probe method. J_c was defined as the critical current density where an electric field of 1µV/cm appears. The films were oriented with respect to the magnetic field direction from 0° to 180°. The current was reversed to simulate the range from 180° to 360°.

The signal was passed through a low-noise transformer with a ratio n = 100, then it was amplified with a preamplifier and finally in a RC filter. The signal was visualized on a programmable oscilloscope, recorded and analyzed by computer as in [12]. In order to rule out distortions of the *E-J* curves by extensive heating that could be induced by the very high dissipation levels employed here, a pulsed current power supply was used with a time duration $\tau \approx$ 10 ms, a waveform repeat time ~ 2 s and an average over 64 pulses at the same fixed *J*, *T*, and *H*. Transmission electron microscopy (T. E. M) observations performed on our sample revealed not only the presence of the usual twin boundaries as the major visible defect but also, a set of columnar-like defects. In addition, the sample certainly contains also point defects, in particular oxygen vacancies.

III. Results and discussion

The typical $J_c(T)$ behavior for the configurations where the applied magnetic field is parallel to the *c*-axis (θ = 0°) and perpendicular (θ = 90°), is plotted in figure 1. The magnetic field value is 0.6 Tesla.

For all temperatures, the critical current density is greater when the magnetic field is applied parallel to the CuO_2 planes than when it is perpendicular to these planes.

The critical current density $J_c(\theta)$ behavior is shown in detail in figure 2 for two temperature values at fixed *H*. We observe that high critical-current density values are obtained when the applied magnetic field is perpendicular to the *c*-axis. As can be seen in figure 2, J_c peak occurs at 90° (*H* parallel to the CuO_2 planes). The higher values of J_c are obtained if the Lorentz strength $F_L = J_c \wedge H$ is directed to the film substrate interface. In this case the flux lines are aligned parallel to the *ab* planes and are driven across these planes by the Lorentz strength towards the film-substrate interface, the strong pinning is then produced. When the temperature increases the $J_c(\theta)$ peak at 0.3 T and θ = 90° becomes less intense, an other maximum appears at 0° and 180° (*H* parallel to the *c*-axis).

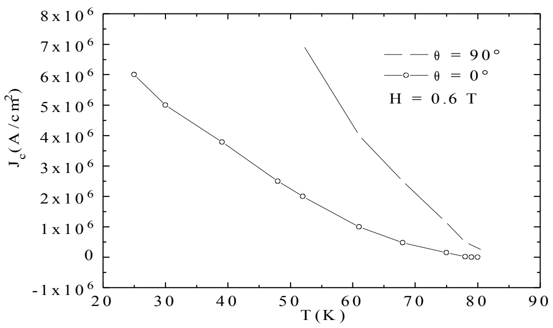

Figure 1. Critical current density as a function of the temperature for *H* parallel to the *c*-axis (open circles) and parallel to the *ab* planes (solid squares).

For *H* parallel to the *ab* planes (θ = 90°), the flux lines are aligned along this planes: in this case the mechanism responsible for the strong pinning is an intrinsic pinning between the superconducting planes. The CuO planes distance is comparable to the coherence length ξ_c which is very short [1-5] and thus the vortex core size is very small. Therefore, the point defects, impurities and precipitates cannot act as strong pinning centers. This imply that the *ab* planes apply the strong pinning force on the vortices in the $YBa_2Cu_3O_{7-\delta}$ films. The high critical current density at 90° is due to the maximal pinning strength which is present if the flux lines are aligned exactly parallel to the film planes interacting with the weakly superconducting layers between the CuO planes along the whole flux lines length.

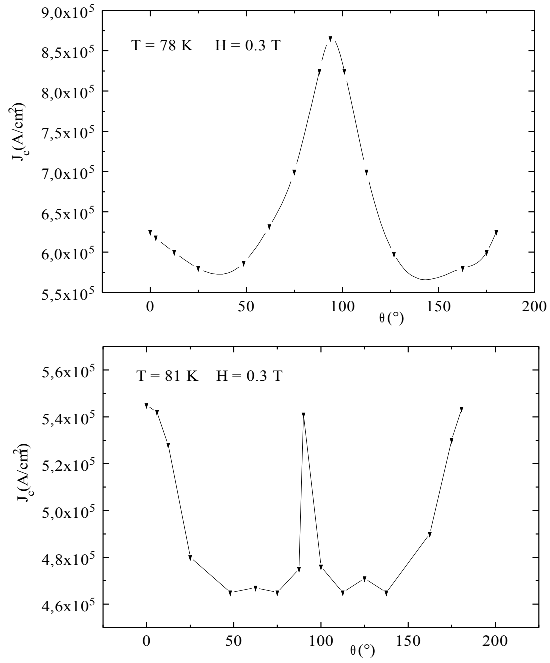

Figure 2. The angular dependence of the critical current density $J_c(\theta)$ at 78 K and 81 K.

A second maximum was found for H parallel to the *c*-axis (θ = 0° and 180°) where the flux lines are perpendicular to the *ab* planes. In that case the point defects parallel to the *c*-axis work as pinning sites, the flux lines are not pinned along the whole of the length but only at the intersection points.

Extended two-dimensional defects in line with the *c*-axis, like twin or stacking faults, act as pinning centers in that case [13]. In CVD- YBaCuO film (Chemical Vapor Deposition), there is not any other peak except the angle θ = 90° [14]. That means, the laser ablation processes in our case introduce clear twin planes which trapped the flux lines parallel to the crystallographic c-axis. The twin planes work as pinning centers most effectively when the magnetic field is parallel to the c-axis [7]. The critical current density becomes then intense at 0° and 180°.

In conclusion, intrinsic pinning between the CuO planes due to the layered structure of the superconductor and extrinsic one by point defects affect strongly the critical current density in high quality $YBa_2Cu_3O_{7-\delta}$ thin films.

References

[1] T.K. Worthington, W.J. Gallagher, D. L.Kaiser, F.H. Holtzberg and T.R. Dinger, *Physica C* **153-155** (1988) 32.
[2] Y. Tajima, M. Hikita, T. Ishii, H. Fuke, K. Sugiyama, M. Date, A. Yamagishi, A. Katsui, Y. Hidaka, T. Iwata and S. Tsurmi, *Phys. Rev. B* **37** (1988) 7956.
[3] T.T.M. Palstra, B. Batlogg, L.F. Schneemeyer, R.B.Van. Dover and J.V. Waszczak, *Phys. Rev. B* **38** (1988) 5102.
[4] G. Deutscher, *Physica C* **153-155** (1988) 15.
[5] Y. Yeshurun and A. P. Malozemoff, *Phys. Rev. Lett.* **60** (1988) 2202.
[6] A. Ramzi, A. Taoufik, S. Senoussi, A. Tirbiyine and A. Abaragh, *Physica A* **358** (2005) 119
[7] M. Tachiki and S.Takahashi, *Solid State Commun.* **70** (1989) 291.
[8] K. Watanabe, T. Matsushita, N. Kobayashi, H. Kawab, E.Aoyagi, K. Hiraga, H. Yamane, H. Kurosawa, T. Hirai and Y. Muto, *Appl. Phys. Lett*. **56** (1990) 1490.
[9] H. Küpfer, I. Apfelsted, R. Flükiger, C. Keller, R. Meier-Hirmer, B. Runtsh, A. Turowski, U. Wiech and T. Wolf, *Cryogenics* **29** (1989) 268.
[10] M. Daeumling, J.M. Seuntjens and D.C. Larbalestier, *Nature* **346** (1990) 332.
[11] B. Dam, J. M. Huijbregtse, F.C. Klaassen, R.C.F. Van deer Geest, G. Doornbos, J.H. Rector, A.M. Testa, S. Freisem, J.C. Martinez, B. Stäuble-Pümpin and R. Griessen, *Nature* **399** (1999) 439.
[12] A. Ramzi, A. Taoufik, S. Senoussi and A. Labrag, *Phys. Stat. Sol. (c)* **1, N° 7** (2004) 1908
[13] B. Roas, L. Schultz, G. Saemann-Ischenko, *Phys. Rev. Lett.,* **64** (1990) 479.
[14] K. Watanabe, S. Awaji, N. Kobayashi, H. Yamane, T. Hirai, and Y. Muto, *J. Appl. Phys.,* **69** (1991) 1543