

The dependence of resistively measured B_{c2} and B_{irr} on $BaZrO_3$ concentration in $YBa_2Cu_3O_{6+x}$ thin films

M Malmivirta¹, H Palonen^{1,2}, H Huhtinen¹ and P Paturi¹

¹ Wihuri Physical Laboratory, Department of Physics and Astronomy, FI-20014 University of Turku, Finland

² The National Doctoral Programme in Nanoscience (NGS-NANO), Turku, Finland

E-mail: mika.malmivirta@utu.fi

Abstract. The effect of $BaZrO_3$ (BZO) concentration on B_{irr} and B_{c2} in $YBa_2Cu_3O_{6+x}$ (YBCO) thin films was investigated with resistive measurements. It was found that in field out-of-plane configuration both B_{irr} and B_{c2} decrease with the highest BZO concentration of 9 wt% whereas the other samples show no significant change. The angular dependence of B_{irr} of the highest BZO concentration sample has a pronounced c -axis peak that is typical for BZO-doped YBCO but the others do not exhibit that clear peak. On the other hand, B_{c2} obeys the Blatter scaling law and the Blatter scaling parameter γ levels off to 3 – 3.5 above few wt% of BZO.

1. Introduction

In the applications of high-temperature superconductors isotropic high critical current is a preferred property. $YBa_2Cu_3O_{6+x}$ (YBCO), however, has intrinsically anisotropic properties. Doping YBCO with non-superconducting second phase, *e.g.* $BaZrO_3$ (BZO), improves flux pinning and reduces its anisotropic properties [1]. The pinning properties affect extrinsic properties like critical current densities and the irreversibility field B_{irr} . The upper critical field B_{c2} , on the contrary, is an intrinsic property. It should not be affected by the second phase unless doping changes some intrinsic properties. However, it has been seen that BZO increases B_{c2} [2,3]. Another intrinsic property, anisotropy, is quantified with the Blatter scaling parameter γ [4] and it can be determined from the measurements of B_{c2} with a straightforward process. The larger γ is, the larger is the anisotropy. Due to the high values of B_{c2} , usually a pulsed magnetic field system is needed to determine the anisotropy parameter.

In this paper B_{irr} and B_{c2} have been determined by resistive measurements of YBCO thin films doped with different concentrations of BZO. The angular dependence of B_{c2} is interpreted in terms of Blatter scaling.

2. Experimental details

Thin films doped with BZO between 0 – 9 wt% were grown with a pulsed laser deposition (PLD) XeCl excimer laser ($\lambda = 308$ nm) system on 5×5 mm² $SrTiO_3$ (100) substrates. The process is the same as for the BZO-doped films in [2].

The films were first characterized with Quantum Designs Physical Property Measurement System (PPMS) by determining the critical temperature from the AC magnetization. The critical temperature was defined to be the temperature at which magnetization is 10 % of its



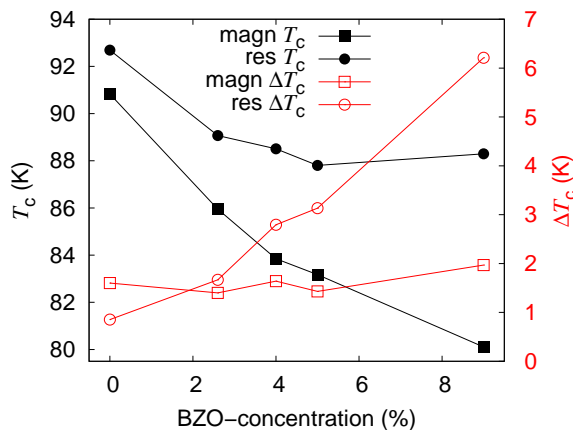


Figure 1. The critical temperatures and the widths of the transitions determined by magnetic and resistive measurements.

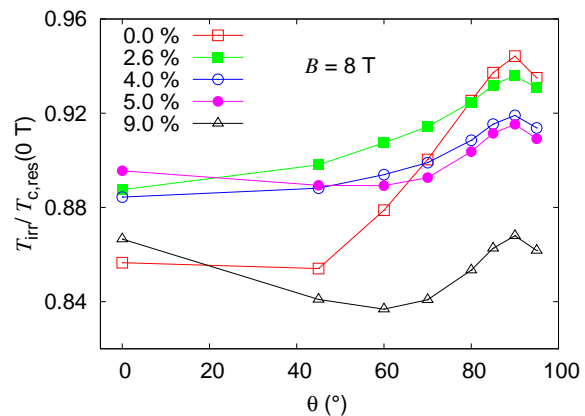


Figure 2. T_{irr} scaled with the resistive critical temperature as a function of the angle between sample and magnetic field, measured at 8 T.

saturation value. The width of the transition was defined to be the temperature difference between 10 % and 90 % of the superconductive state. On resistive measurements, however, the width was between 80 % and 10 % due to the definition used for B_{c2} . Also the DC magnetization was measured at 10 K and magnetic field was varied between -8 and 8 T to determine the critical current of the films using the Bean model. For the resistive measurements of B_{c2} and B_{irr} , the films were etched with photolithography. A standard four probe configuration with a $50 \mu\text{m}$ wide current stripe was used.

The resistances of the films were measured as a function of temperature between 120 and 40 K with $10 \mu\text{A}$ probing current. Several scans were taken for one sample. Magnetic field was varied between 8 and 0 T with smaller step size at small fields. Also, angle θ was changed from 0° to 95° focusing on larger θ values. The value $\theta = 0^\circ$ corresponds to the case $B \parallel c$ -axis of YBCO.

The temperature T_{irr} corresponding to the irreversibility field at a certain scan was defined to be the the temperature at which the electric field was $1 \mu\text{V}/\text{cm}$. B_{c2} was defined from scaled data: At first the data was divided with a line which was fitted on the normal state resistivity. Then the temperature corresponding to B_{c2} at certain field was taken to be the point where resistance was 80 % of its normal state value. This has been noted to be approximately the same as finding the intersection of two line fits to steepest transition and normal state [5]. Also, other ways to determine B_{c2} were used, but this was found most reliable for all the samples, fields and angles. It is very close to the method used in [5].

3. Results and discussion

The critical temperature decreases as BZO concentration increases (figure 1), which is typical for BZO-doped films [6]. Magnetic T_c decreases much more (from 92 to 84 K) than resistive T_c (from 93 K to 88 K). On the other hand, the width of the magnetic transition stays at 1 – 2 K whereas resistive widths increase from 1 K up to 6 K. A two-step transition was observed in samples with higher BZO concentration. The second phase got more pronounced with increasing BZO concentration. The same phase has also been noted before as the peak the in magnetic absorption in AC magnetization during the transition had split into two [6]. In resistive measurements a small current is able to choose a route using only the best path, whereas in magnetic measurements the signal comes from the whole sample. However, as the

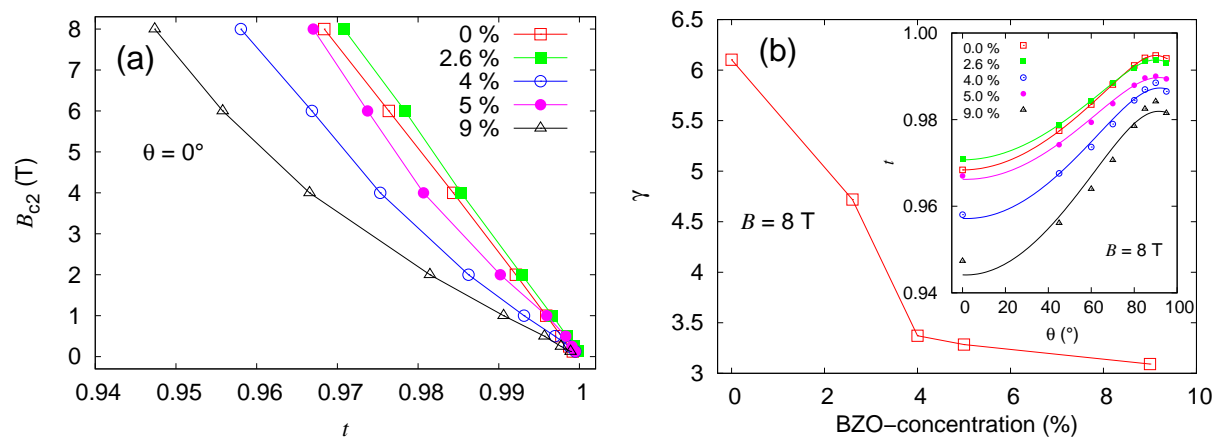


Figure 3. (a) The dependence of B_{c2} on reduced temperature in samples with different BZO concentrations. (b) Inset: The dependence of the reduced temperature t corresponding to B_{c2} at 8 T on the angle between sample and magnetic field. Solid lines are fits to equation (1). The main figure shows that the Blatter scaling γ decreases and levels off as the BZO concentration is increased.

BZO concentration increases, the amount of good quality areas in the film decreases and the transition broadens. The high- T_c phase is so small that it can barely be seen in magnetic measurements. The magnetically determined critical current densities are in the range 25 – 35 MA/cm² at 0 T, only the 9 % sample has smaller J_c . This is similar to what has been found before [6]. More details on J_c can be found in [7].

The irreversibility field as a function of the angle between the magnetic field and the sample for different concentrations shows rather different shapes for the various concentrations (figure 2). The change is best seen at the highest measured field 8 T. BZO doping increases the irreversibility temperature in middle concentrations. With the highest concentration of 9 wt% measured here, the irreversibility temperature decreases. Probably the most important reason for this is that the width of the transition is largest. The ab -peak, on the other hand, drops monotonically as the BZO concentration increases. The c -axis peak seen in higher concentrations is due to correlated columnar nanorods typical for BZO [1].

The order of the curves at $\theta = 0^\circ$ is not monotonic with respect to concentration. However, at fields of a few teslas, the undoped film has the smallest T_{irr} and the others have larger T_{irr} with the exception of the 9 % sample. The undoped sample has been noted to give the smallest B_{irr} in measurements in pulsed magnetic field [8]. However, at fields smaller than 2 T the undoped film has the largest T_{irr} and T_{irr} decreases monotonically with increasing BZO concentration. The same kind of difference between doped and undoped films has been found in magnetic measurements [7]. The optimal BZO concentration increases with increasing field, as has been noted before [8].

The dependence of B_{c2} on reduced temperature t ($t = T/T_{c,res}(0\text{ T})$) varies with BZO concentration (figure 3 (a)). The sample with the largest BZO concentration has so many defects that it decreases the B_{c2} significantly compared to the other samples. The other small differences originate possibly from the small distinctions in the high- T_c phases and uncertainties in the determination of B_{c2} . Recently it has been found that, in contrast to this result, doping improves B_{c2} in samples measured both with pulsed magnetic field setup [2] and with magnetic measurements [3, 7]. The films used in this work are the same as in [7] and quite similar to samples in [2], so the reason for different behaviour is probably the small probing current used

here. For the same reason, the measured properties of B_{c2} are quite strongly affected by the small amount of high- T_c phase where the current percolates.

The angular dependence of B_{c2} (figure 3 (b) inset) exhibits no c -peak in contrast to $B_{irr}(\theta)$ -data. The 9 % sample has on the whole angle range the smallest values of the reduced temperature corresponding to B_{c2} . The strain caused by BZO results in degradation of the crystal structure and thus the drop of T_c . In addition, the distorted crystal structure also affects the coherence length ξ which in turn affects the values of the upper critical field.

Using the dependence of B_{c2} near T_c from the Ginzburg-Landau equations [9, p. 53], solving it for $\frac{T}{T_c}$ and applying Blatter scaling [4] for B_{c2} at 0 K, we get

$$\frac{T}{T_c}(\theta) = 1 - \frac{B_{c2}}{2B_0} \left(\frac{\sin^2(\theta)}{\gamma^2} + \cos^2(\theta) \right)^{1/2}, \quad (1)$$

where θ is the angle between sample normal and magnetic field, B_0 is B_{c2} at 0 K with $\theta = 0^\circ$ and γ is the Blatter anisotropy parameter. Fits to equation (1) are solid lines in figure 3 (b) inset and they fit best to the data of low BZO concentration, probably due to uncertainties caused by the small high- T_c phases in higher BZO concentrations. The values of γ obtained from these fits (figure 3 (b)) is 6 for undoped, which is near to what has been found before [10]. For doped YBCO the value levels off to 3 – 3.5 which has also been seen before [2]. However, no change in γ was seen in the case of isotropic BZO nanodots [11].

4. Conclusions

B_{irr} and B_{c2} were determined by resistive measurements of PLD YBCO thin films doped with different concentrations of BZO. It was found that both B_{irr} and B_{c2} decreased when the doping concentration was high enough. However, the results are inconsistent with magnetic measurements and pulsed magnetic field data. This probably results from the small probing current. From the angular dependence of B_{c2} it was found that the value for Blatter scaling γ is 3 – 3.5 for doped samples.

Acknowledgments

Jenny and Antti Wihuri foundation, Finnish Foundation for Technology Promotion and Finnish Cultural Foundation are acknowledged for financial support.

References

- [1] MacManus-Driscoll J L, Foltyn S R, Jia Q X, Wang H, Serquis A, Civale L, Maiorov B, Hawley M E, Maley M P and Peterson D E 2004 *Nat. Mater.* **3** 439
- [2] Palonen H, Huhtinen H, Shakhov M A and Paturi P 2013 *Supercond. Sci. Technol.* **26** 045003
- [3] Matsushita T, Nagamizu H, Tanabe K, Kiuchi M, Otabe E S, Tobita H, Yoshizumi M, Izumi T, Shiohara Y, Yokoe D, Kato T and Hirayama T 2012 *Supercond. Sci. Technol.* **25** 125003
- [4] Blatter G, Feigel'man M V, Geshkenbein V B, Larkin A I and Vinokur V M 1994 *Reviews of Modern Physics* **66** 1125
- [5] Ando Y, Boebinger G S, Passner A, Schneemeyer L F, Kimura T, Okuya M, Watauchi S, Shimoyama J, Kishio K, Tamasaku K, Ichikawa N and Uchida S 1999 *Phys. Rev. B* **60** 12475
- [6] Peurla M, Paturi P, Stepanov Y P, Huhtinen H, Tse Y Y, Bódi A C, Raittila J and Laiho R 2006 *Supercond. Sci. Technol.* **19** 767
- [7] Paturi P, Malmivirta M, Palonen H and Huhtinen H 2013 *Journal of Physics: Conference Series* **submitted**
- [8] Huhtinen H, Irjala M, Paturi P, Shakhov M A and Laiho R 2010 *J. Appl. Phys.* **107** 053906
- [9] Poole Jr C P, Farach H A, Creswick R J and Prozorov R 2007 *Superconductivity, Second Edition* (Academic Press)
- [10] Civale L, Maiorov B, Serquis A, Willis J O, Coulter J Y, Wang H, Jia Q X, Arendt P N, MacManus-Driscoll J L, Maley M P and Foltyn S R 2004 *Appl. Phys. Lett.* **84** 2121
- [11] Llordés A, Palau A, Gázquez J, Coll M, Vlad R, Pomar A, Arbiol J, Guzmán R, Ye S, Rouco V, Sandiumenge F, Ricart S, Puig T, Varela M, Chateigner D, Vanacken J, Gutiérrez J, Moshchalkov V, Deutscher G, Magen C and Obradors X 2012 *Nat. Mater.* **11** 329