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# Defining $B_c$ , $B^*$ and $B_\phi$ for YBCO Thin Films

Petriina Paturi, Matti Irjala, Asger B. Abrahamsen, and Hannu Huhtinen

**Abstract**—The accommodation field,  $B^*$ , is generally defined to be the field at which the cross over from single vortex pinning to collective pinning occurs. It is determined from magnetization curves as the point where the  $J_c$  plateau ends and it used as a convenient way of comparing the pinning properties of superconducting films. Similarly, the characteristic field,  $B_c$ , can be obtained from magneto-optical (MO) images from when the flux fronts meet in the middle of the film. The matching field,  $B_\phi$ , at which there is one vortex line per pinning site, is sometimes thought to be the same as  $B^*$ , but in BaZrO<sub>3</sub>-doped YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> films the calculated  $B_\phi$  is much higher than the observed  $B^*$ .  $B_\phi$  can be determined from angular dependent transport measurements. All of the field values correspond to some special case in the flux pinning in the film and relate to  $J_c$ . In this work we have determined  $B_c$ ,  $B^*$  and  $B_\phi$  for different kinds of YBCO films using MO, magnetization and transport measurements to reveal the deeper meaning of the special fields.

**Index Terms**—Accommodation field, characteristic field, matching field, YBCO thin films.

## I. INTRODUCTION

**I**N high temperature superconductor research, several characteristic magnetic fields are used to specify certain points on the magnetization hysteresis loop. It seems from the literature that the terms are not definite: sometimes the matching field  $B_\phi$ , where there is one vortex per pinning site, is used to mean the accommodation field  $B^*$ , where the low field plateau ends. And in our own earlier magneto-optical measurements the full penetration field,  $B_p$ , where the flux fronts meet in the middle of the sample and which is related to the characteristic field,  $B_c$ , seemed to coincide with  $B^*$  [1] determined from the hysteresis loops. In this paper we try to make certain which field is which and how they can be measured.

The oldest of the special fields is probably the characteristic field,  $B_c$ , presented by Bean [2]. It is the magnetic field at which the flux fronts meet in the middle of the sample for slab like

samples. In thin films the characteristic field is proportional to the full penetration field,  $B_p$  [3], [4]. For thin stripes it is

$$B_p = \frac{\mu_0 J_c d}{\pi} (1 + \ln(2a/d)) = B_c (1 + \ln(2a/d)) \quad (1)$$

where  $J_c$  is the critical current density,  $d$  is the thickness of the film and  $2a$  is the width of the stripe. For field dependent  $J_c$ ,  $B_p$  can be obtained from [4], [5] to be

$$B_p \approx B_c \left(1 - \alpha \frac{B_c}{B_0}\right) \ln \left(\frac{a}{d} + \sqrt{\frac{a^2}{d^2} - 1}\right) \quad (2)$$

where  $\alpha$  and  $B_0$  are model dependent parameters, for the Kim model, where  $J_c = J_{c0}/(1 + |B|/B_0)$ ,  $\alpha = 0.51$  and for the exponential model, where  $J_c = J_{c0} \exp(-|B|/B_0)$ ,  $\alpha = 0.60$  [5].

The accommodation field,  $B^*$ , is defined as the field below which the single vortex pinning dominates and above which collective effects become important [6]. It is usually determined from the end of the low field plateau of the hysteresis loop and has been found to be proportional to the dislocation density of the films [7] and thus it has in many cases been interpreted to be equal to the matching field,  $B_\phi$ , where there is exactly one vortex per pinning site. On the other hand, in BaZrO<sub>3</sub> (BZO) doped films, there are non-superconducting rods penetrating the film, which are 5–10 nm wide [8]. These rods are natural pinning sites for vortices, but the calculated  $B_\phi$  for the films is several Tesla: for 4 wt-% doped film  $B_\phi = 5$  T [8]. For the same films the  $B^*$  is about 500 mT, which shows that the  $B^*$  and  $B_\phi$  cannot be the same field for all films. In pure films the dislocation density is about 40–100  $\mu\text{m}^{-2}$ , which leads to matching field of 80–200 mT [7].

In this paper we measure these special fields for several YBCO films with different types and densities of pinning sites and different thicknesses to find out what is the actual dependence of the special fields on film geometry and pinning site density.

## II. EXPERIMENTAL DETAILS

The YBCO films were deposited on single crystal SrTiO<sub>3</sub> (100) with pulsed laser ablation from targets with nano- and micronsized grains (n- and  $\mu$ -films) and a target with 4% BZO added to the nanograined target (BZO+n-film). Detailed description of the deposition process can be found in [9]. The  $\mu$ - and BZO+n-films were 150 nm thick and the n-films had thicknesses of 50, 150, and 500 nm as measured by atomic force microscopy over an etched stripe in the films. For magneto-optical (MO) and transport measurements, the films were patterned to 50–1000  $\mu\text{m}$  wide microbridges.

The magneto-optical measurements were done in the normal Faraday geometry and the images were enhanced by dividing

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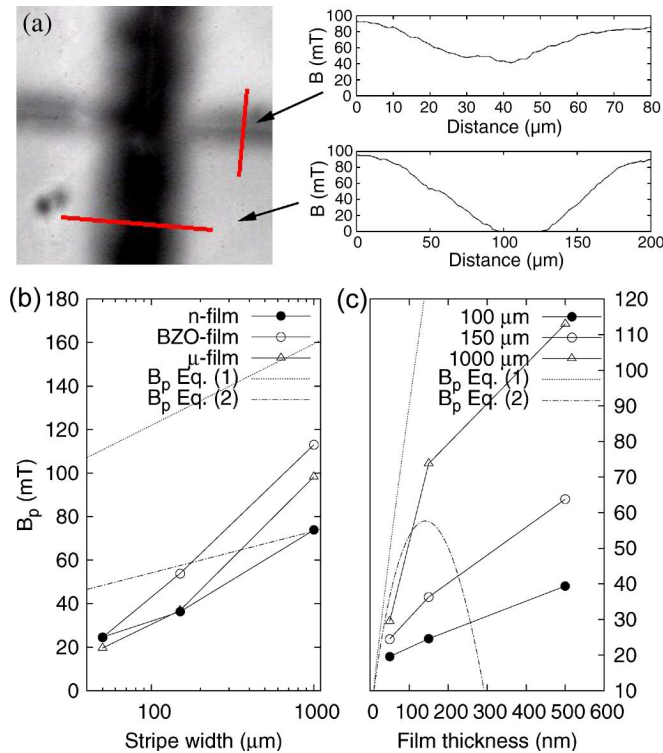


Fig. 1. (a) A MO-image of the 500 nm thick n-film at 90 mT and profiles over the 50  $\mu\text{m}$  and 150  $\mu\text{m}$  stripes. (b) The  $B_p$  measured from MO-images as a function of the stripe width for three different 150 nm thick films. The  $B_p$  line from (1) is with  $J_c = 2.7 \cdot 10^{11} \text{ A/m}^2$  for 150 nm thick films. The  $B_p$  from (2) has additional parameters of  $\alpha = 0.6$  and  $B_0 = 0.02 \text{ T}$  corresponding to the exponential critical state model. (c)  $B_p$  as function of film thickness for three different stripe widths on n-films. The  $B_p$  lines are calculated from (1) and (2) for 150  $\mu\text{m}$  wide stripe with the same parameters as in (b).

the scaled background images as described in [10]. All MO-images were taken at the base temperature of 12 K and in fields up to 120 mT. The hysteresis loops were measured using a Quantum Design PPMS with the ACMS option at 10 K and between  $-8$ – $8 \text{ T}$ . The film shape was rectangular. The critical current densities from transport measurements were determined with the same PPMS using the ACT option with horizontal rotator at 10 K and 70 K and in fields of 0–8 T. The critical current was determined from the voltage criterion of  $10 \mu\text{V/cm}$ . For magnetic and transport measurements 150 nm thick films were used.

### III. RESULTS AND DISCUSSION

#### A. Characteristic Field

According to the Bean theory the characteristic field,  $B_c$  should depend only on the width of the superconductor slab, which is in parallel field, and  $J_c$ , but the full penetration field film samples,  $B_p$  depends also on the thickness of the sample as seen from (1) and (2). To determine if this simple way can be used to evaluate  $J_c$ , we measured  $B_p$  for samples of different widths and thicknesses. In Fig. 1(a) is shown a MO-image of a 500 nm thick n-film at 90 mT along with the line profiles over the stripes. It is clear that the 50  $\mu\text{m}$  stripe is already fully penetrated, while the 150  $\mu\text{m}$  stripe is not. In Fig. 1(b) are

shown the  $B_p$  of the different kinds of 150 nm thick YBCO films as a function of the stripe width determined from the MO-images by increasing the external field with 2 mT steps and identifying the full penetration field from the image series. Along with the experimental data Fig. 1(b) shows the lines calculated from (1) and (2) with  $J_c = 2.7 \cdot 10^{11} \text{ A/m}^2$  obtained for the 150 nm thick n-film by inverting the MO-image using the procedure in [13], and  $\alpha = 0.6$  and  $B_0 = 0.02 \text{ T}$  for (2). It is clearly seen that all the width dependence of  $B_p$  observed in the films cannot be explained with the simple Bean model, the field dependent exponential model works much better, but has extra fitting parameters, which complicate the  $J_c$  determination from  $B_p$ . Fig. 1(c) shows the  $B_p$  as a function of film thickness for different widths of n-YBCO films. Also shown is the line calculated from (1) and (2) with  $J_c = 2.7 \cdot 10^{11} \text{ A/m}^2$ ,  $\alpha = 0.6$  and  $B_0 = 0.02 \text{ T}$  for 150  $\mu\text{m}$  wide line. It can be seen that neither model explains the thickness dependency of  $B_p$  and the field dependent model reaches its approximation limits leading to decreasing  $B_p$  of thick films. It is well known that  $J_c$  depends on film thickness [11] because of different pinning properties close to the substrate surface, in the bulk and on the surface and also the surface degradation of thick films. This can explain the non-linear dependence of  $B_p$  on film thickness.

Thus, we can say that the  $B_p$  depends on thickness of the films and on the width of the stripe, but all the dependence observed experimentally is not explained by the Bean model. The field dependent models work much better, although the two extra fitting parameters make determination of  $J_c$  this way extremely uncertain. Also with thin films one should take into account the curvature of the vortices near the edges of the stripe [12] leading to variation of the  $J_c$  through the thickness of the film. This means that the  $B_c$  should not be used on determination of absolute  $J_c$ , instead the  $J_c$  values should be determined with a more sophisticated method [13], [14], which are based on inverting the MO-image using the Biot-Savart law. Furthermore, we can conclude that the earlier observation of similar values for  $B_p$  and the accommodation field was purely coincidental, since the samples used for measuring  $B^*$  are several mm wide and thus their  $B_p$  would be well over hundred mT, whereas the observed  $B^*$  for undoped films was usually less than 100 mT [1]. The BZO-doped film on the other hand has  $B_p$  approximately the same as undoped films, whereas the  $B^*$  is found to be much higher.

#### B. Accommodation Field

The accommodation field,  $B^*$ , is usually defined as the end of the low field plateau of  $J_c$ , in practice  $B^*$  is defined as the magnetic field where  $J_c$  has dropped to 90% of its zero field value [8], [15]. Most often it is defined from the  $J_c$  values calculated from the opening of the hysteresis loop with the Bean model.  $B^*$  has been used as a simple way to characterize the differences between different films. At low temperature, it is generally found to be less than 150 mT for undoped YBCO films [7], [16] and up to 500 mT for BZO-doped films [8].

The inset of Fig. 2 shows the  $J_c$  of  $\mu$ -, n-, and BZO+n-films calculated from magnetic hysteresis loops. The determined  $B^*$  at 10 K are 30, 130, and 500 mT, respectively. These are in good agreement with previously published data [7], [8], [16]. The

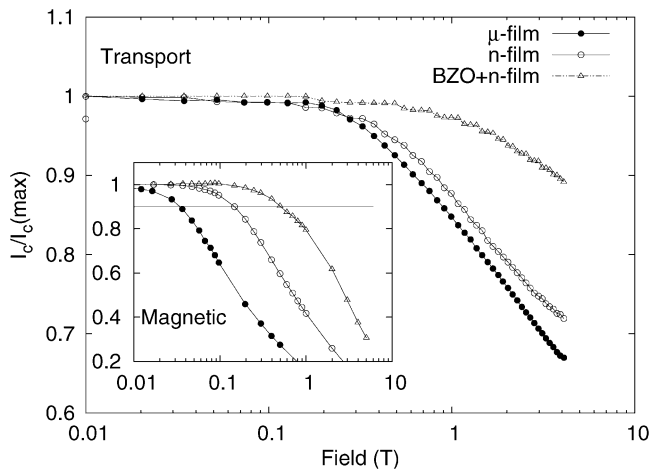


Fig. 2. The normalized  $J_c(B||c)$  of the different kinds of 150 nm thick YBCO films as a function of the magnetic field at 10 K with transport measurements (main figure). In magnetic measurements (the inset) the  $B^*$  is usually defined at 90% limit marked with a line. It is clear from the figure that the same definition cannot be used for transport measurements.

main Fig. 2 shows the  $J_c$  of similar films determined from transport measurements. Here the obtained  $B^*$  with the 90% rule are 0.62, 0.84, and 3.66 T for the  $\mu$ -,  $n$ -, and BZO+n-films, respectively. It is clear that the same 90% limit cannot be used for both transport and magnetic measurements, at least the values cannot be compared to each other. In transport measurements the  $I_c$  voltage limit (here  $10 \mu\text{V}/\text{cm}$ , on longer samples usually  $1 \mu\text{V}/\text{cm}$ ) increases the actual  $B^*$  value from the one observed from the stricter criteria of magnetic measurements. On the other hand, the order of  $B^*$  for the films and the approximate relations stay the same.

The strong pinning theories predict the  $J_c$  plateau at low fields [11], [17], [18], whereas weak pinning theories do not have the plateau, although it can be seen as an artefact in the magnetization measurements [19]. Since the YBCO thin films are very strongly pinned and the plateau is observed also in transport measurements, in the present case we consider the plateau to be real and not an artefact of the measurement. Theoretically [17], the accommodation field depends on the matching field so that at low temperatures  $B^*$  is higher than the matching field and at high temperatures  $B^* < B_\phi$ . This in approximate accordance with the observed temperature dependence of  $B^*$  [16], where it has been seen that  $B^*$  decreases with increasing temperature. Assuming that this relation between  $B^*$  and  $B_\phi$  stays the same for all the films (measured in the same way),  $B^*$  is extremely convenient way of comparing the pinning site densities of pure YBCO films.

### C. Matching Field

The matching field,  $B_\phi$ , is sometimes used as a synonym for the accommodation field,  $B^*$ , but here we mean the field where there is exactly one vortex per pinning site. The confusion arises from the undoped films where the accommodation field (end of plateau) might even coincide with the matching field [7]. In BZO-doped films, though, it is perfectly clear that the matching field is much higher than the magnetically measured accommodation field. For example, the matching field calculated from

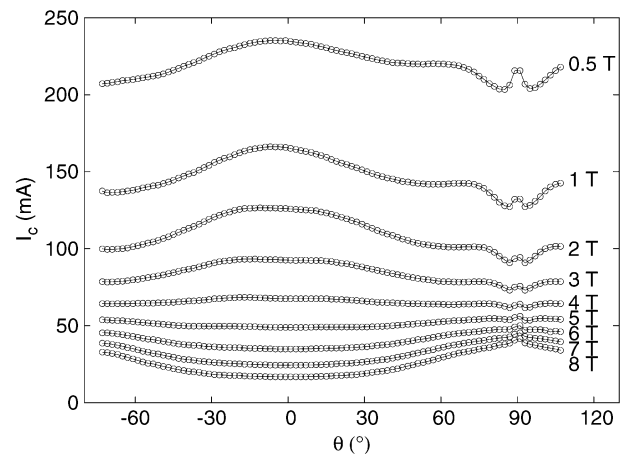


Fig. 3. The  $I_c$  of the 4%-BZO doped of YBCO film as a function of the angle between the  $c$ -axis and the magnetic field at 70 K.  $B_\phi$  can be determined as the field where the curve turns from concave to convex.

TEM-images for 4% BZO-doped YBCO film is about 5 T [8], whereas the end of the low field plateau occurs at 500 mT. With this ten fold difference, we were motivated to look for a way to define the actual matching field.

The BZO-nanorods show up as a broad peak in field parallel to crystallographic  $c$ -axis ( $B||c$ ) in the angular dependency of the critical current [20]. According to the theory [21] above the matching field the vortices in between the pinning sites form a porous vortex solid at low temperatures, which at high temperature melts to a nanoliquid phase where the vortices are weakly pinned between the columnar pinning sites. This melting changes the angular dependency of  $J_c$  to more isotropic, i.e. without the  $c$ -axis peak at high temperature and above  $B_\phi$ . In Fig. 3 are shown the angular dependencies of  $J_c$  for a 4% BZO-doped YBCO film in external magnetic fields up to 8 T at 70 K. For this doping the BZO-rod areal density,  $n = 2500 \mu\text{m}^{-2}$  and therefore the expected matching field is  $B_\phi = n\Phi_0 \approx 5 \text{ T}$  [8]. As can be seen from Fig. 3 this perfectly coincides with the field where the  $J_c(\theta)$  changes from convex to concave, which at high temperature should lead to isotropic behavior according to the porous vortex solid theory. At lower temperatures the  $c$ -axis peak persists to higher fields than  $B_\phi$  (see e.g. [20]) since the vortices are pinned to the porous solid, therefore  $B_\phi$  can be determined using this method only at temperatures close to  $T_c$ .

It is clear by comparison to angular dependencies of the undoped films that the same criteria of disappearance of the  $c$ -axis peak will lead to the conclusion that the accommodation field equals or is higher than the matching field, since these films do not show the  $c$ -axis peak if deposited on single crystalline substrates, except for the  $n$ -films at low field and high temperature [20], for which a small peak appears. This can be expected from the same theory [21] assuming that the main pinning site in  $n$ -films is dislocation cores or twin planes. Therefore, the thing we need to explain is why  $B^*$  is so much lower than  $B_\phi$  for the BZO-doped samples. One plausible explanation would be that in the doped films the BZO-rods are so close to each other that the vortex-vortex interaction has to be taken into account. This interaction effectively lowers the potential wells created by the

pinning sites and thus lowers also the observed  $J_c$  even in the single vortex pinning regime. Conveniently, this thought experiment also explains the observed lower  $J_c$  decay rates with field,  $J_c \propto B^{-\alpha}$ , ( $\alpha \approx 0.2$  instead of  $\alpha \approx 0.6$  as is observed for undoped films [8]), since the vortex-vortex interaction only lowers the potential wells of the pinning sites in contrast to the vortices being pinned in between the pinning sites, as happens above the matching field and which leads to  $\alpha \approx 0.6$ . It is further supported by the fact that in the doped YBCO films the  $J_c(B)$  does not have a sharp edge at the end of the plateau as in undoped films, instead it smoothly decreases making it hard to define the end of the plateau (see Fig. 2).

#### IV. CONCLUSIONS

We have studied the characteristic field,  $B_c$ , accommodation field,  $B^*$  and the matching field  $B_\phi$  in different kinds of YBCO films on SrTiO<sub>3</sub> single crystal substrates. We found that the full penetration field,  $B_p$ , which depends on  $B_c$ , depends on the width and thickness of the sample, but the simple Bean theory does not explain it fully. Therefore, it is important not to use  $B_c$  or  $B_p$  for calculation of  $J_c$  but instead use some more sophisticated method [13], [14] based on the inversion of the Biot–Savart law.

The  $B^*$  and  $B_\phi$  were found to depend on each other for undoped films and they can be determined from the end of the  $J_c$  low field plateau as long as the same measurement method is used for all the films that are compared. With doped films it is concluded that the matching field and thus the dislocation density of the film cannot be defined from the end of the plateau (or the 90% limit), instead it should be determined from the point where the  $c$ -axis peak disappears from the angular dependency of  $J_c$  at high temperature. The matching field obtained this way coincides perfectly with the one calculated from the amount of BZO-rods seen in TEM-images.

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