Thickness Dependence of Critical Current Density in Thick MgB_2 Films

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***Abstract* - A study was performed to examine the J_c behavior as a function of thickness in MgB_2 films fabricated by *ex situ* annealing at 840°C of boron films, grown by chemical vapor deposition, in Mg vapor. The film thicknesses range between 300 nm and 10 µm. The values of J_c range from 1.2×10^7 A/cm^2 for 300 nm to 1.9×10^5 A/cm^2 for 10 µm film thickness at 20 K and self-field. The study shows that critical current density (J_c) in MgB_2 films decrease with increasing film thickness, similar to that observed in YBCO coated conductors. The results were interpreted.**

I. INTRODUCTION

For coated-conductor applications, it is necessary to deposit thick films in order to maximize the critical current in the wire or tape and enhance the engineering critical current density. However, the main obstacle to higher current in thicker films is that the critical current density (J_c) in the superconductor drops dramatically as the coating thickness is increased [1-7]. This limitation was first observed over 18 years ago in YBCO coated-conductors, yet only recently it became one of the most important remaining challenges in the coated conductors field as they are approaching the commercialization stage [5]. As MgB_2 coated conductors started hitting the road since the discovery of superconductivity in MgB_2 seven years ago [8], a study on J_c thickness dependence in MgB_2 films is deemed to be necessary.

II. EXPERIMENTS

The films used in the study were fabricated by *ex situ* annealing of boron films in Mg vapor. Boron films were deposited on (0001) 6H-SiC substrates by CVD using a precursor gas of 5% B_2H_6 in H_2. The B film was then wrapped with a Nb foil and sealed in a low-carbon steel tube with high purity Mg pellets wrapped in a separate Nb foil and the tube was sealed in Ar atmosphere and sintered. The normal sintering procedure included a fast heating to a constant temperature of 840°C for all films in 30 min, followed by holding at that temperature for 2 to 6 h depending on the boron film thickness, and then quench cooling to room temperature in 10 min. The films experience a volume expansion of about 200% when changing from B to MgB_2. For example, a ~2.5 µm thick B film results into a ~5 µm thick MgB_2 film after the reaction. Critical current densities were obtained using magnetization measurements and determined from hysteresis loops using the Bean critical state model.

III. RESULTS

Table 1 shows a list of films used in this study and their corresponding thicknesses as well as critical current density and critical current values at self field at temperatures of 5 K and 20 K. These values are higher than values previously reported in the literature for MgB_2 films fabricated by the *ex situ* annealing method [9-19]. The high J_c values reported here show the efficiency of the *ex situ* annealing method in the fabrication of MgB_2 films; and achieving them at such a low annealing temperature of 840°C is promising for low temperature industrial fabrication of resonance frequency (RF) MgB_2 cavities.

TABLE I
MgB_2 FILMS STUDIED AND THEIR CORRESPONDING CRITICAL CURRENT DENSITY AND CRITICAL CURRENT VALUES

MgB_2 Film Thickness (µm)	**J_c (A/cm^2) @ 0T,5K**	**J_c (A/cm^2) @ 0T,20K**	**I_c (A/cm-w) @ 0T,5K**	**I_c (A/cm-w) @ 0T,20K**
0.3	1.97×10^7	1.2×10^7	591	360
0.5	1.41×10^7	7.42×10^6	705	371
1	1.36×10^7	7.28×10^6	1360	728
2	2.1×10^6	1.14×10^6	420	228
3	1.79×10^6	9.94×10^5	537	298
5	1.03×10^6	5.41×10^5	515	270
10	3×10^5	1.9×10^5	387	190

Figure 1 shows the MgB_2 films J_c thickness dependence curve at self field. It shows a clear decrease of J_c with increasing film thickness. This behavior of J_c decreasing with increasing MgB_2 film thickness is similar to the J_c thickness dependence behavior in YBCO coated conductors [1-7].

In an effort to understand the dependence of J_c on film thickness in MgB_2, we used a model developed by Foltyn et al. which they used to understand the same behavior in YBCO. In their model, the value of j_c in YBCO is a function of the slice's distance from the substrate (z), and $j_c(z)$ is related to the average J_c for a film of thickness t by

$$J_c(t) = (1/t)\int_0^t j_c(z)dz.$$

The model suggests that there are two main values for J_c, the highest one near the film-substrate interface (j_{ci}), which also corresponds to the one in very thin films, and the lowest one near the bulk value (j_{cb}), which also corresponds to the one in thick films. Thus the model assumes that J_c decreases linearly from j_{ci} to j_{cb} over a range z_r, and then remains constant throughout the rest of the film, leaving z_r as the only adjustable parameter. By using that model, both calculated and measured J_c values were in excellent agreement for experimental results, where the best fit was obtained for a z_r of 0.65 μm in YBCO. Applying the same model to MgB_2 films show the same agreement. Figure 2 shows the experimental MgB_2 confirmation of the conceptual incremental function $j_c(z)$. The continuous line in the figure is the incremental critical current density model used for the fit. The best fit is obtained when z_r is adjusted to 2 μm. The distance from substrate (z) in figure 2 corresponds directly to the MgB_2 film thickness, where each thickness represents a new MgB_2 film. The reasons for the J_c decrease with increasing film thickness can be the high density of flux pinning defects and dislocations near the film-substrate interface, the presence of vortices in the film, and/or the degradation of microstructure at higher thickness.

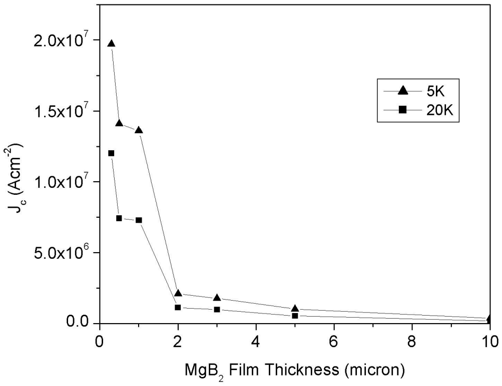

Fig. 1. MgB_2 films J_c thickness dependence at self field.

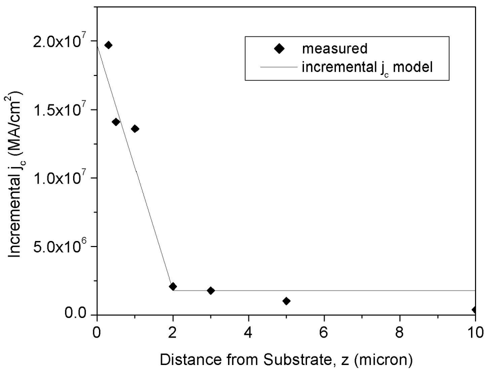

Fig. 2. Experimental confirmation of the conceptual incremental function $j_c(z)$. The best fit is obtained when z_r is adjusted to 2 μm MgB_2 film thickness.

Figure 3 shows the I_c thickness dependence of MgB_2 films at self field. The figure displays that, similar to YBCO coated conductors, critical current in MgB_2 films drops beyond ~1 μm thickness, which is probably due to impurity diffusion during annealing and microstructural degradation for thicker films. This indicates that 1 μm MgB_2 films can carry critical current that is higher than thicker MgB_2 films, which is economical for industrial applications such as the fabrication of MgB_2 superconducting cavities and coated-conductor wires and tapes.

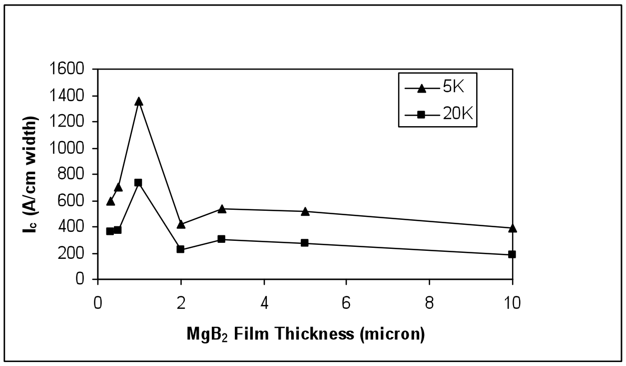

Fig. 3. MgB_2 films I_c thickness dependence at self field.

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REFERENCES

[1] Foltyn S R *et al* 1999 *Appl. Phys. Lett.* **75** 3692
[2] Foltyn S R *et al* 2003 *Appl. Phys. Lett.* **82** 4519
[3] Arendt P N *et al* 2004 *Physica C* **412-414** 795
[4] Civale L *et al* 2004 *Journal of Low Temperature Physics* **135** 87
[5] Foltyn S R *et al* 2005 *Appl. Phys. Lett.* **87** 162505
[6] Wang H *et al* 2005 *Physica C* **433** 43
[7] Ijaduola A O *et al* 2006 *Phys. Rev. B.* **73** 134502
[8] Nagamatsu J *et al* 2001 *Nature* **410** 63
[9] Hanna M *et al* 2008 *Supercond. Sci. Technol***.** **21** 045005
[10] Vaglio R, Maglione M G and Di Capua R 2002 *Supercond. Sci. Technol.* **15** 1236
[11] K¨uhberger M, Gritzner G, Sch¨oppl K R, Weber H W, Olsen A A F and Johansen T H 2004 *Supercond. Sci. Technol.* **17** 764
[12] Wang S F, Zhou Y L, Zhu Y B, Liu Z, Zhang Q, Chen Z H, Lu H B, Dai S Y and Yang G Z 2003 *Supercond. Sci. Technol.* **16** 748
[13] Ferdeghini C *et al* 2001 *Supercond. Sci. Technol.* **14** 952
[14] Eom C B *et al* 2001 *Nature* **411** 558
[15] Kang W N, Kim H-J, Choi E-M, Jung C U and Lee S I 2001 *Science* **292** 1521
[16] Moon S H, Yun J H, Lee H N, Kye J I, Kim H G, ChungW and Oh B 2001 *Appl. Phys. Lett.* **79** 2429
[17] ParanthamanM *et al* 2001 *Appl. Phys. Lett.* **78** 3669
[18] Plecenik A, Satrapinsky L, Kus P, Gazi S, Benacka S, Vavra I and Kostic I 2001 *Physica* C **363** 224
[19] Bu S D *et al* 2002 *Appl. Phys. Lett.* **81** 1852