Interaction of vortices with different types of pinning centers in MgB$_2$ superconducting films

R. Zadorosny$^a$, W.K. Seong$^b$, W. N. Kang$^b$ and W. A. Ortiz$^a$

$^a$Grupo de Supercondutividade e Magnetismo, Departamento de Física, Universidade Federal de São Carlos, 13.565-905, CP 676, São Carlos, SP, Brazil

$^b$BK21 Division and Department of Physics, Sungkyunkwan University, Suwon 440-746, South Korea

Abstract. This contribution reports on the magnetic response of two MgB$_2$ films with 600 nm of thickness. These films were grown using the hybrid physical chemical vapor deposition (HPCVD) method under different temperatures. One of the films, grown at 580 ºC, has a microstructure with columnar grains, a rough surface and small grain size. The other, grown at 650 ºC, has a smooth surface and larger grains. A double transition is present in the columnar sample. The lower transition temperature is due to currents tunneling through the intergrain material and the higher one is associated with the transition of the grains to the normal state. Magnetic phase diagrams in tilted geometries, with the applied fields (AC and DC) forming angles in the range (0º, 90º) with the plane of the film, were determined to verify the influence of the perpendicular component of the AC field on pinned vortices. Hysteresis loops of magnetization versus applied field were also measured for both samples. The columnar sample exhibits jumps in the decreasing field branch of the magnetization, indicating that vortices pinned by the columnar microstructures leave the sample in bundles.

1. Introduction

Since the discovery of superconductivity in magnesium diboride (MgB$_2$) [1] many possible applications using this material [2, 3] have been envisaged. However, under certain circumstances, MgB$_2$ films present dendritic penetrations [4, 5]. This type of magnetic flux penetration has a thermomagnetic origin as the vortex motion heats the sample locally and, if the thermal diffusion of the superconductor is smaller than its magnetic diffusion, a flux avalanche takes place, creating a pattern of tree-like penetrated regions [5-7].

An efficient way to avoid dissipative vortex motion into the superconductor is the introduction of pinning centers (PCs). Several studies report exotic behavior when the PCs are columnar defects (CDs) inserted artificially into a superconductor film [8-12].

For granular superconductors, an alternative way to prevent the dissipative vortex motion is to trap it in the intergranular regions [13]. These grain boundaries (GBs) could contain a weaker superconductor or even an insulator material. These materials typically exhibit a double transition in AC-susceptibility measurements. Besides higher temperature (T) normal-to-superconductor phase
transformation, another transition occurs at lower Ts, below which supercurrents begin to tunnel through the GB region. This behavior is followed by a second peak in the imaginary part of AC-susceptibility, $\chi''$.

This work presents the initial study of two MgB$_2$ films grown by the same technique [14, 15]. One of them has a smooth surface and the other has columnar grains and a rough surface.

2. Experimental Procedures
Two MgB$_2$ films with thickness of 600 nm were used in this study. Both were grown using the hybrid physical chemical vapor deposition (HPCVD) technique [14, 15] under different temperatures. One of the films, grown at 580 ºC, has a structure with columnar grains, rough surface and small grains, this film was labeled CS (columnar sample). The other one, grown at 650 ºC, has a smooth surface and larger grains and was labeled SS (smooth sample).

The magnetic phase diagram was determined applying an AC-field, h, of 15 Oe with a frequency of 1 kHz under different DC-fields. For CS, the study was repeated for three relative orientations ($\theta$) between the applied fields (AC and DC) and the plane of the film. Magnetization versus applied field curves, M(H), were determined for both samples too. All these measurements were carried out in a Quantum Design PPMS model 6000.

3. Results and discussion
We started our study measuring the AC-susceptibility for both samples. As shown in figure 1, SS does not present a double transition and its response, in modulus, is greater than the CS equivalent. We associated this behavior as an indication that the sample is a continuous film, as can be seen in the lower right panel of figure 1.

Also in figure 1, the double transition of CS is shown where, as already discussed, for T above the second peak of $\chi''$, $T_p$, there are no currents tunneling through the GB.

Figure 1. AC-susceptibility response of CS (squares) and SS (circles). The main panel shows the real part of AC-susceptibility, $\chi'$, and the inset shows the imaginary part, $\chi''$. Panels on the right hand side are SEM micrographs of both samples.

To analyze the dynamic of vortex penetration into CS, a diagram of the applied field versus $T_p$ was built. References [11, 16] show that the application of an AC-field (shaking field) induces depinning that is more efficient when h is parallel to the plane of the film. In order to study the influence of h on vortex depinning, we made measurements with the sample tilted by an angle $\theta$ relative to the horizontal. The angles used were 0º, 15º and 26º. For higher angles, the sample signal becomes too noisy and it is difficult to determine $T_p$. However, as shown in figure 2, the field-temperature, H(T),
diagram for the second peak is the same for all angles employed. This is an indication that the PCs are 
quite strong and do not allow depinning of the trapped flux, even under the influence of a shaking 
field.

![Diagram showing magnetic phase transitions](image)

**Figure 2.** CS magnetic phase diagram. The plotted field was obtained projecting the applied field on 
the direction perpendicular to the surface of the film.

Although the magnetization versus field curves of MgB$_2$ films may present fluctuations due to 
thermomagnetic instabilities, the samples studied here do not present this feature. However, in the 
decreasing field branch, SS has a smooth behavior for a large range of temperatures, indicating that 
flux leave the sample continuously. On the other hand, CS presents some jumps in the temperature 
range for which currents are already tunneling through GBs. Above 20 K, the curve becomes smooth, 
as shown in figure 3. Contrarily, SS has a smooth response for all temperatures.

We relate each magnetization jump to the exit of a bundle of vortices, a feature that will be 
discussed elsewhere.

![Magnetization vs. field curve](image)

**Figure 3.** M(H) curve for both samples. The magnetization jumps for CS (closed symbols) indicates 
the exit of bundles of vortices.
4. Final Remarks
We studied two MgB$_2$ films with different structures of pinning centers. One of them has a smooth surface (SS) and the other has columnar grains (CS). A double transition is seen in CS, but not in SS which is a continuous film. Comparing M(H) curves for both samples, we ascribe the magnetization jumps in CS with the exit of bundles of vortices.

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References
[1] J. Nagamatsu, N. Nakagawa, T. Muranaka, Y. Zenitani and J. Akimitsu, Nature 410, 63A (2001)
[2] Scanlan R M, Malozemoff A P and Larbalestier D C Proc. IEEE 92, 1639 (2004)
[3] H.J.M. ter Brake et al., Physica C 439, 1 (2006)
[4] Johansen T H, Baziljevich M, Shantsev D V, Goa P E, Galperin Y M, Kang W N, Kim H J, Choi E M, Kim M S and Lee S I, Europhys. Lett. 59, 599 (2002)
[5] F. Colauto, E. M. Choi, J. Y. Lee, S. I. Lee, V. V. Yurchenko, T. H. Johansen and W. A. Ortiz, Supercond. Sci. Technol. 20, L48 (2007)
[6] Denisov D V, Rakhmanov A L, Shantsev D V, Galperin Y M and Johansen T H, Phys. Rev. B 73, 014512 (2006)
[7] E. Altshuler e T. H. Johansen, Rev. Mod. Phys. 76, 471 (2004)
[8] M. V. Milosevic e F. M. Peeters, Phys. Rev. Lett. 93, 267006 (2004)
[9] K. Harada, O. Kamimura, H. Kasai, T. Matsuda, A. Tonomura e V. V. Moshchalkov, Science 274, 1167 (1996)
[10] A. V. Silhanek, L. Van Look, R. Jonckheere, B. Y. Zhu, S. Raedts, V. V. Moshchalkov, Phys. Rev. B 72, 014507 (2005)
[11] J. S. Nunes et al., Jour. Mag. Mag. Mat. 320, e516 (2008); idem ibidem, Physica C 468, 820 (2008)
[12] R. Zadorosny et al., Jour. Phys.: Conf. Ser. 97, 012301 (2008); W.A. Ortiz et. al., Physica C 437, 254 (2006)
[13] W.A.C. Passos, P. N. Lisboa-Filho, R. Caparroz, C. C. de Faria, P. C. Venturini, F. M. Araujo-Moreira, S. Sergeenko and W. A. Ortiz, Physica C 354, 189 (2001)
[14] W.K. Seong, J. Y. Huh, S. G. Jung, W. N. Kang, H. S. Lee, E. M. Choi and S. I. Lee, Joun. Kor. Phys. Soc. 51, 174 (2007)
[15] [2] J. Y. Huh, W.K. Seong, H. S. Lee, W. N. Kang, N. K. Yang and J. G. Park, Joun. Kor. Phys. Soc. 51, 174 (2007)
[16] E. H. Brandt and G. P. Mikitik, Supercond. Sci. Technol. 20, S111 (2007)