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A comparative study of the dendritic avalanche in MgB_2 thin films synthesized by pulsed laser deposition and hybrid physical chemical vapor deposition methods

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It is known that MgB_2 thin films synthesized by using hybrid physical chemical vapor deposition (HPCVD) do not show dendritic avalanche, which is in contrast to those prepared by using pulsed laser deposition (PLD). To find the cause that makes the difference between the two cases, we studied the microscopic film structure by the scanning electron microscopy and the magnetic hysteresis by using the superconducting quantum interference device magnetometry. The critical current density (J_c), estimated from the magnetic hysteresis based on the Bean's critical-state model, shows a much higher J_c in the PLD film than in a HPCVD film. This indicates higher vortex pinning in the PLD film. We surmise that high local joule heating beyond the high J_c in the PLD film, as a vortex penetrates into the superconducting thin film, gives a path for the next vortex and induces a positive feedback effect that is absent in the HPCVD film. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3095661]

I. INTRODUCTION

It is well accepted that a vortex avalanche with a dendritic shape develops in some superconducting thin films as a result of a thermomagnetic instability.[1–10] When the magnetic diffusion is much faster than the thermal diffusion, a superconducting film becomes thermally unstable and a magnetic field penetrates it with a dendritic shape. This phenomenon has been observed in a number of superconducting thin films such as Nb, Nb alloys, and YNi_2B_2C.[11–13] The formation of the vortex avalanche is much enhanced especially in MgB_2 thin films synthesized by using pulsed laser deposition (PLD). This may be caused by its high critical current density, which in turn produces high Joule heating coupled with an induced electric field. A stable high critical current density is essential for practical applications of superconducting thin films, especially in an applied magnetic field.[14] However MgB_2 thin films show this unexpected dendritic instability below $T<10$ K and $H<2000$ Oe, which appears as a noise in the magnetic hysteresis loop and suppresses critical current density of the films.[15] Therefore, removal of the dendritic avalanche is important if a high critical current density is to be recovered. Interestingly, MgB_2 films synthesized by using hybrid physical chemical vapor deposition (HPCVD) do not show this instability.[16] Thus, it is of high interest to examine the details of the dendritic behavior between the films fabricated by the two different methods. In this study, the magnetic hysteresis was measured by using a superconducting quantum interference device (SQUID) magnetometer to understand the macroscopic vortex pinning properties. Scanning electron microscopy (SEM) was also used to examine the details of the microscopic structure that may affect a vortex pinning. The magnetic hysteresis is not a local probe. Instead, it exhibits the globally averaged pinning of vortices. Using this magnetic hysteresis curve, one can calculate the critical current density from the Bean's critical-state model. In our experiment, we obtained larger magnetic hysteresis in the PLD film than in the HPCVD film. It indicates that the critical current density is much higher in the PLD film. With SEM images, it was judged whether grain boundary can act as a defect-induced pinning center of vortices. In fact, the SEM images show clear grain boundaries of a higher density in the PLD film. This may be related to the existence of higher pinning of vortices in the PLD film. These results lead to a conclusion that once the vortex penetrates into the PLD film, Joule heating is significantly enhanced due to the high critical current density. This induces a positive-feedback effect and generates the dendritic avalanche, which is absent in the HPCVD film.

II. EXPERIMENTS AND DISCUSSION

In this study, we prepared two types of MgB_2 thin films, one synthesized by using the PLD method with postannealing and the other by using the HPCVD method. Sapphire

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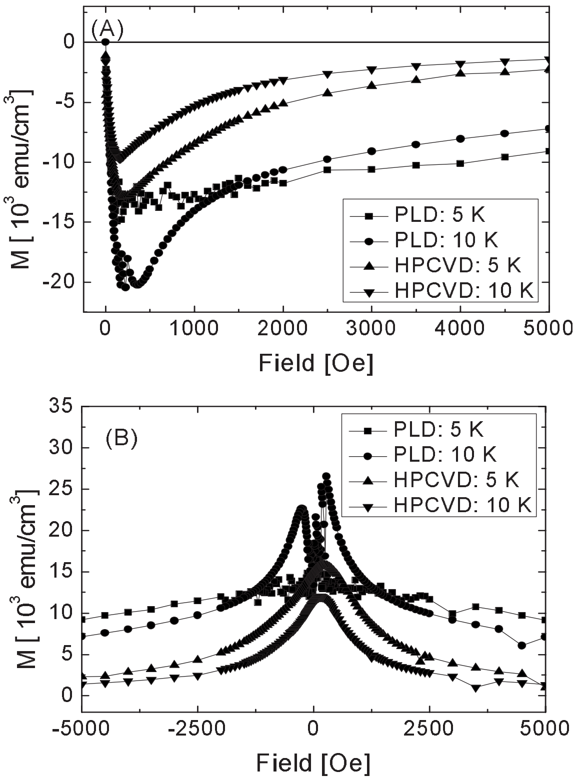

FIG. 1. Magnetic hysteresis loops of the (a) initial part and the (b) remnant part of each film.

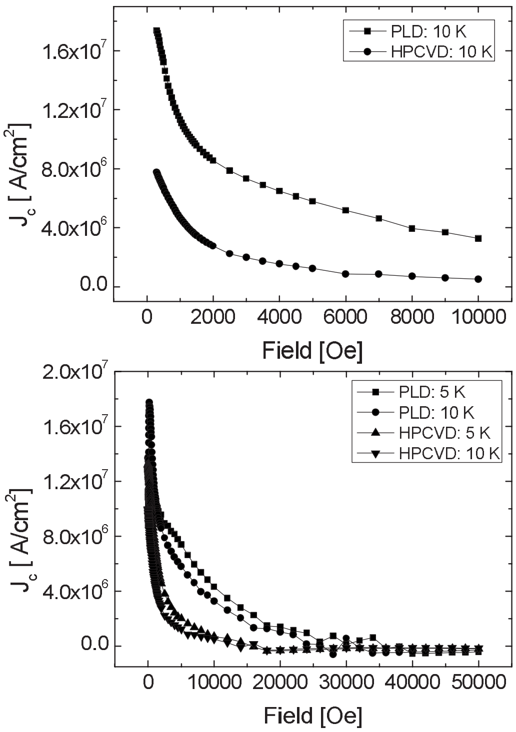

FIG. 2. Estimated critical current density in the PLD and the HPCVD films. (b) presents the data for the range from 0 to 5 T.

(silicon carbide) substrates were used for the PLD (HPCVD) film. The details of synthesizing these thin films can be found in Refs. 16 and 17. Both samples were rectangular in shapes with dimensions of $2.4\times 2.1\ \mathrm{mm}^2$ (PLD film) and $2.0\times 2.3\ \mathrm{mm}^2$ (HPCVD film). The magnetization was taken by using SQUID (Quantum Design, MPMSXL) magnetometers. The flux-noise region and the critical current density were obtained by measuring the magnetic hysteresis loops (M-H) at 5 and 10 K in the field range of −5–5 T. The temperature dependence of the magnetization (M-T) shows the onset of the superconducting transition at 38 K in the PLD film and 41 K in the HPCVD film. Microscopic images of the thin films were taken by the SEM. The critical current density was estimated from the magnetic hysteresis loop (M-H loop). The result in Fig. 1(a) is the initial portion and that in Fig. 1(b) is the remnant portion of M-H loop. As described above, in contrast to the HPCVD film, the PLD film exhibits a larger magnetic hysteresis.[18] Even in the flux-noise region (−500–700 Oe at 5 K and −250–250 Oe at 10 K), the PLD film has a larger magnetic hysteresis with higher vortex pinning than the HPCVD film.

Since the dendritic avalanche is closely related to the J_c of the films, we estimate the value of J_c for both of the films by using the Bean's critical-state model: $J_c=20\Delta M/[a(1-b/3a)]$.[19] In this formula, ab is the area of our rectangular films perpendicular to magnetic field and ΔM is the height of the hysteresis loop. Figure 2(a) shows the critical current densities of the PLD and the HPCVD films at 10 K. A direct comparison between the two samples was made in the region above 300 Oe, excluding the flux noise region in the PLD film. Figure 2 shows the full range of J_c at temperatures of 5 and 10 K. The J_c of the PLD film is significantly higher (about 2–3 times) than that of the HPCVD film.

Since the magnetic hysteresis loops show differences in the hysteretic characteristics, the thin films are supposed to have different microstructures from each other. Images of both samples are taken by using the scanning electron microscope (Fig. 3). Side views of the PLD film and the HPCVD film are shown in Figs. 3(a) and 3(b), respectively. The pictures in Figs. 3(c) and 3(d) are top views of the PLD and the HPCVD films, respectively. The thickness of the PLD (HPCVD) film is ~500 nm (~200 nm). In the PLD film, we may distinguish a larger number of grain boundaries, although grains also exist in the HPCVD film but the boundary

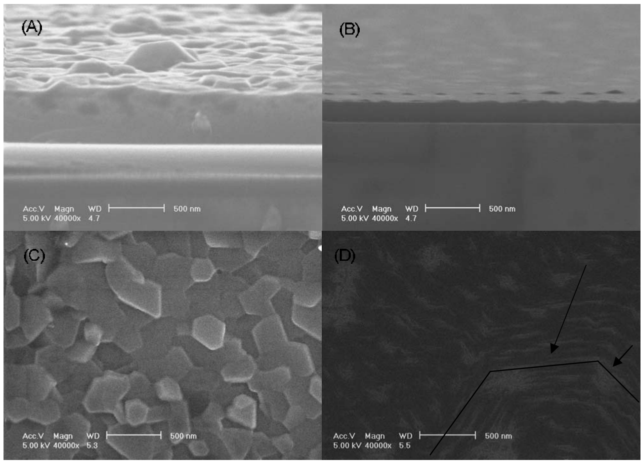

FIG. 3. SEM images of the (a) PLD and the (b) HPCVD films. In comparison with the HPCVD film in (d), the PLD film in (c) shows a rough surface, clear grain, and grain boundaries. Black arrows in (d) indicate growth directions of the grain.

cannot be clearly recognized within the resolution of our measurement. In the top view of Fig. 3(d), the white line indicates a grain boundary with a hexagonal shape. In the HPCVD film grains grow along the *c*-axis direction from the seed grains at the bottom similar in Ref. 18. The size of seed grain is about 1500 nm, which is about 3–10 times larger than for the PLD film. It implies that more grains are supposed to be present with larger grain-boundary vortex pinning in the PLD film. This is consistent with the result of magnetic hysteresis. The grain-boundary vortex pinning is one of the major pinning sources in a superconductor, which induces the high-critical current density and leads to the vortex glass state.[14,20] Now, let us analyze the details of the dendritic propagation in our experimental results. Theoretically, the dendritic growth occurs when the magnetic diffusion is much faster than the thermal diffusion. It is known that the ratio τ between the thermal and the magnetic diffusion time is proportional to the flux flow resistivity ρ_f. Since the value of ρ_f for the PLD film is 17 times higher than that for the HPCVD film, as mentioned in Ref. 21, the value of τ for PLD film is much smaller than the HPCVD film, which triggers a dendritic instability in the PLD film. The enhancement of ρ_f of the PLD film indicates higher pinning impurities. Another reason for such a pronounced dendritic avalanche in the PLD film is its high critical-current density. Since the generation of Joule heating is directly related to the critical-current density of the thin film, Joule heating is significantly enhanced when vortices penetrate into the PLD film. In this case, the first vortex penetrating into the superconducting thin film gives a way for the penetration of the next vortex. It induces a positive feedback effect, which is absent in the HPCVD film. This high thermal instability of the PLD film results in the dendritic growth.

III. CONCLUSIONS

In summary, we studied the dendritic avalanche in the MgB_2 thin films by comparing the vortex-pinning properties of the thin films prepared by using two different film-growth techniques, the PLD and the HPCVD. Critical current densities were compared by using the magnetic hysteresis loops while microstructures were compared by using SEM. The enhanced J_c and ρ_f, along with the large vortex-glass region, imply that vortex pinning is much stronger in the PLD film than in the HPCVD film. It induces a magnetic thermal instability that leads to a dendritic avalanche in the PLD film.

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