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MgB_2 for Application to RF Cavities for Accelerators

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***Abstract*—Magnesium diboride (MgB_2) has a transition temperature (T_c) of ∼40 K, i.e., about 4 times as high as that of niobium (Nb). We have been evaluating MgB_2 as a candidate material for radio-frequency (RF) cavities for future particle accelerators. Studies in the last 3 years have shown that it could have about one order of magnitude less RF surface resistance (R_s) than Nb at 4 K. A power dependence test using a 6 GHz TE_{011} mode cavity has shown little power dependence up to ∼12 mT (120 Oe), limited by available power, compared to other high-T_c materials such as YBCO. A recent study showed, however, that the power dependence of R_s is dependent on the coating method. A film made with on-axis pulsed laser deposition (PLD) has showed rapid increase in R_s compared to the film deposited by reactive evaporation method. This paper shows these results as well as future plans.**

***Index Terms*—Co-evaporation, MgB_2, particle accelerators, PLD, superconducting RF cavities.**

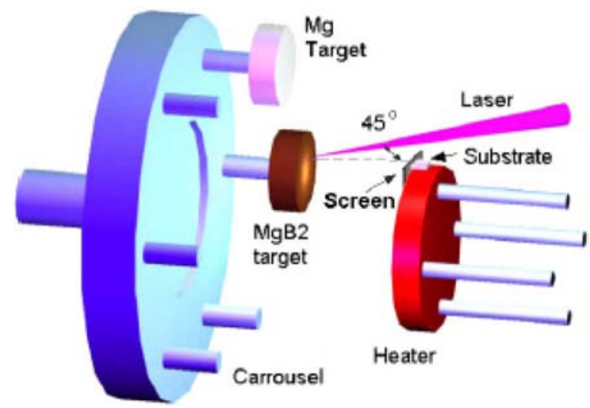

Fig. 1. An illustration of off-axis PLD [4].

I. Introduction

A number of studies on MgB_2 have been carried out due to its near-metallic nature, simplicity and lower fabrication cost compared to high T_c materials such as BSCCO and YBCO.

In the particle accelerator world, Nb has been successfully used for superconducting radio-frequency (SRF) cavities in the last few decades.

The Nb SRF cavity technology has reached a point where, in principle, cavities can achieve very close to theoretical limit of ∼200 mT, i.e., equivalent of ∼50 MV/m in accelerating gradient for typical electron accelerators.

While Nb SRF cavities have successfully reduced the high running cost of many particle accelerators for high energy and nuclear physics, new materials that could exceed the benefits of Nb cavities will be necessary to further reduce the cost of still expensive accelerators.

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One of well known good features of MgB_2 for RF applications is the absence of “weak links” between grains, although there have been few tests that confirm it with SRF cavities. The losses at grain boundaries of present high-T_c materials rapidly increase with higher surface magnetic fields, which has prevented us from using them for SRF cavity applications [1]–[3].

Although the $T_c(\sim 40\ K)$ of MgB_2 is not as high as YBCO, it is about 4 times that of Nb (9.2 K), this is still a significant benefit in terms of the reduction in cryogenic costs compared to running Nb cavities at 2 K. Also, if the RF critical magnetic field is higher than Nb, there is a potential of cavities that can be run at higher gradients than Nb cavities.

II. MgB_2 Coating Techniques

To the best of our knowledge, the coating techniques that have been studied for MgB_2 are physical vapor deposition (PVD) such as pulsed laser deposition (PLD) [4], molecular beam epitaxy (MBE) [5], coaxial energetic arc deposition [6] and magnetron sputtering [7] as well as chemical vapor deposition (CVD) [8], electrochemical plating [9], hybrid physical CVD (HPCVD) [10] and reactive evaporation [11]. Among these, HPCVD and reactive evaporation methods seem to give highest quality films for the cavity application. Very encouraging results with the films prepared by reactive evaporation have been reported [11]–[14].

In [13], we proposed to use PLD to coat a cavity. To check the feasibility of this technique, we coated some substrates made of Nb and Al_2O_3.

A. Pulsed Laser Deposition (PLD)

The coating has been done at University of Wollongong [4]. Fig. 1 shows a schematic of the equipment. We tried the deposition in two modes, on-axis, i.e., the substrate surface is facing the MgB_2 target, and off-axis, i.e., the substrate surface is normal to the MgB2 target with a screen as shown in Fig. 1.

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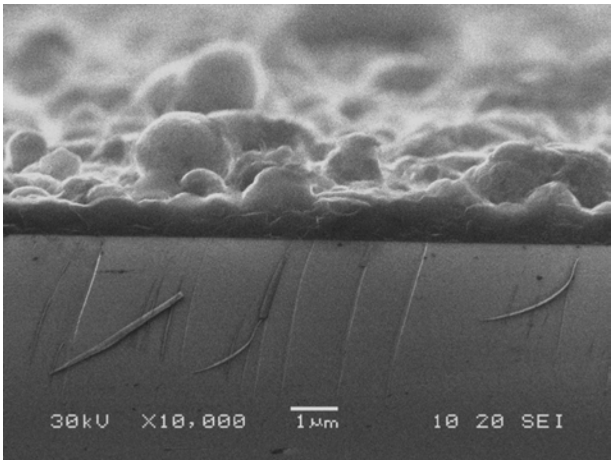

Fig. 2. A SEM image of the cross section of on-axis deposited MgB_2 film (ID: 250705) on Al_2O_3. The film has a thickness of 400–500 nm and many droplets are present on top of the film.

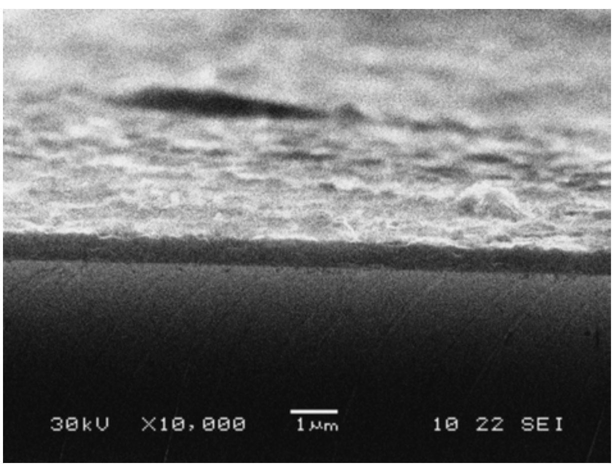

Fig. 3. A SEM image of the cross section of off-axis PLD MgB_2 film (ID: 300705 v) on $Al_2O_3 - C$ substrate. The film thickness is 500–700 nm.

A KrF laser ($\lambda = 248$ nm, 25 ns) was used in 120 mTorr Ar atmosphere, then an *in-situ* annealing was carried out at 680°C for 2 min in a 760 Torr Ar atmosphere [4]. Figs. 2 and 3 show cross sections of on-axis and off-axis depositions on Al_2O_3 substrates, respectively.

Apparently, the off-axis PLD gives better surface than on-axis, but still has defects spread over the surface as seen in Fig. 4.

Fig. 5 shows a result of magnetic moment measurements for on-axis PLD samples. T_c was measured to be ~27 K. In our experience, transport measurements usually show much narrower ΔT_c than magnetic moment measurements. The first two substrates (Al_2O_3 and Nb) were placed side by side, but the third one (Al_2O_3) was measured separately. From the fact that the two curves for the Al_2O_3 and Nb substrates are very close, we can conclude that the MgB_2 film deposited on Nb with a 680°C *in-situ* annealing for 2 min does not react with Nb substrate, and thus it is possible to develop MgB_2 coating on Nb with PLD.

No off-axis coating was tried on the Nb substrate since the substrate (14.6 mm-diameter disk) was too large for the equipment. Also, no SEM image of the film coated on the Nb sub-

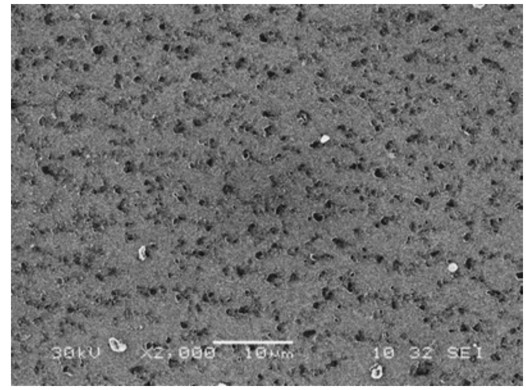

Fig. 4. Surface of off-axis PLD MgB_2 film (ID:300705 v) on $Al_2O_3 - C$ substrate.

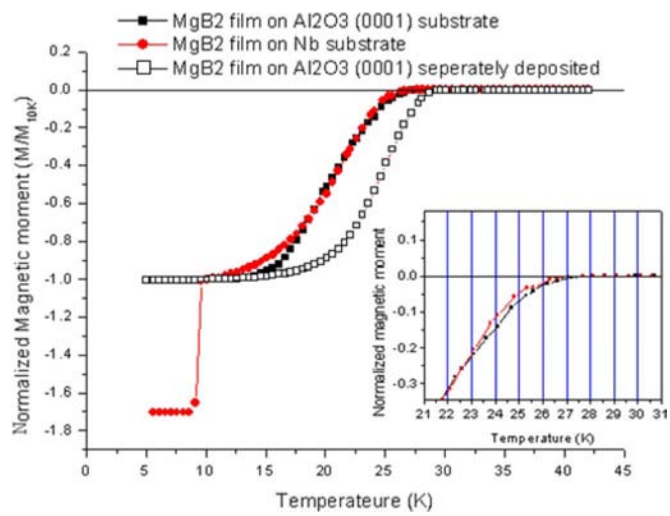

Fig. 5. Normalized magnetic moment as a function of temperature for on-axis PLD MgB_2 films deposited on Nb and Al_2O_3.

strate was taken since it was difficult to cut the sample and show a clear cross section. Its surface was as rough as the sample shown in Fig. 2. In addition, the substrate itself was quite rough ($R_a \sim 400$ nm) as well.

B. Reactive Evaporation

One of the most promising deposition methods has been developed at STI [11]. The key of this technique is that it uses a heater pocket in which sufficiently dense magnesium vapor is contained. A disk with substrates rotates to make the substrates be exposed to boron plume and magnesium vapor repeatedly as shown in Fig. 6.

As shown in Fig. 7, very smooth and dense film can be grown with this technique.

III. Power Dependence of RF Surface Resistance

The measurement was carried out at Cornell University using a 6 GHz TE_{011}-mode cavity made of Nb. The detail of the equipment is described in [15] and [16]. A schematic of the cavity cross section is shown in Fig. 8.

For this measurement, samples of MgB_2 films coated on Nb substrate were prepared by both PLD and reactive evaporation methods. Fig. 9 shows the surface of the films deposited by the

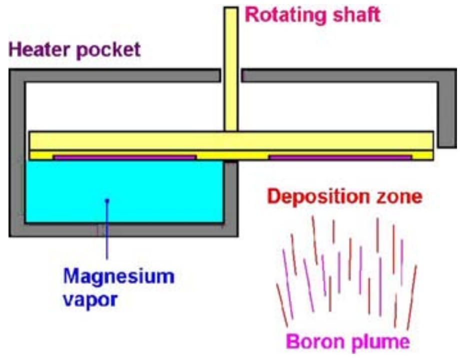

Fig. 6. A schematic showing the principle of reactive coating technique developed at STI [11].

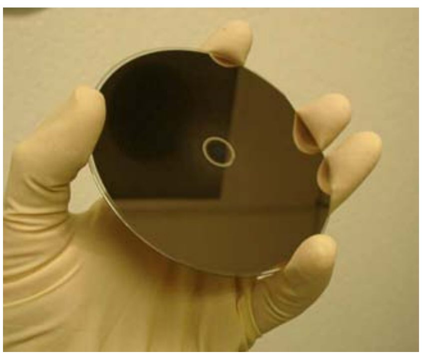

Fig. 7. A 550 nm MgB_2 film grown with reactive evaporation method on r-plane sapphire substrate [14]. The rms surface roughness is 4.4 nm.

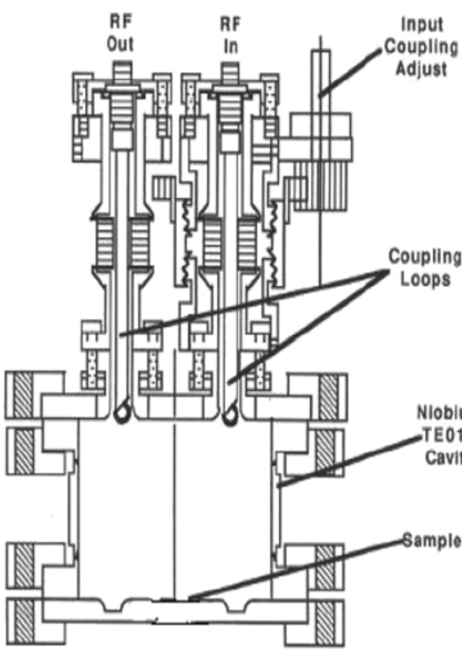

Fig. 8. A vertical cross section of the Cornell 6 GHz TE_{011} cavity [16].

reactive evaporation method at STI. The surface finish does not look as good as that coated on sapphire because the Nb substrates had a very rough surface of ∼400 nm in rms roughness. This could have contributed to the higher surface resistance compared to the samples coated on smooth sapphire substrates [12], [13].

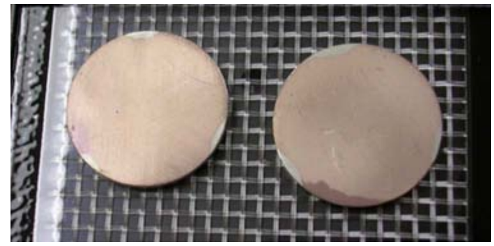

Fig. 9. Two samples of 400 nm MgB_2 films coated with reactive evaporation on Nb disks of 14.6 mm in diameter and 1 mm in thickness.

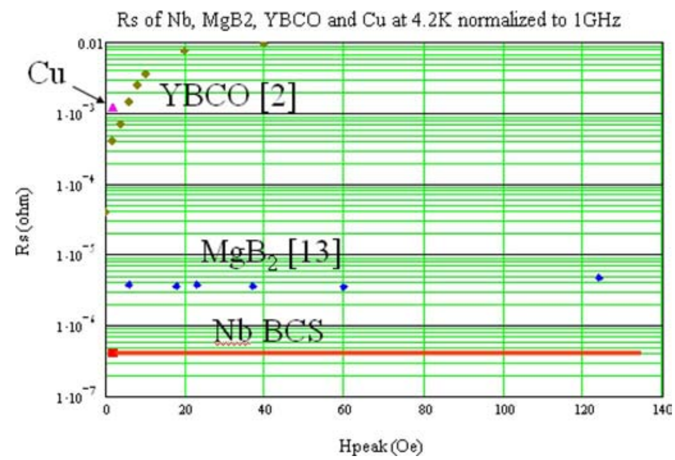

Fig. 10. Surface resistance at 1 GHz as a function of surface magnetic field. The data were scaled from 6 GHz data using f^2 law.

Fig. 10 shows the RF surface resistance $(\mathrm{R_s})$ dependence on surface magnetic fields. In the Figure also shown are data for YBCO and copper.

It was found that, although the surface resistance at low field is similar for both films with PLD and reactive evaporation techniques, the power dependence is very different. Whereas the film deposited with reactive evaporation method showed little increase with magnetic fields, the on-axis PLD film showed a rapid increase.

This clearly shows that, while MgB_2 film is intrinsically absent from weak links, depending on how you deposit or grow the film, the weak link behavior can appear.

Another thing that we might be able to deduce from the fact that the low-field $\mathrm{R_s}$ for both films with PLD and reactive evaporation techniques are almost the same is that the low-field $\mathrm{R_s}$ might not have been significantly affected by the substrate roughness.

An independent measurement of low-field $\mathrm{R_s}$ of the film coated with reactive evaporation method on r-plane sapphire having a surface roughness $\mathrm{R_a} < 0.2\,\mathrm{nm}$ showed an $\mathrm{R_s}$ slightly lower than Nb at 4 K [12], [13], whereas the films deposited on a rough surface of $\mathrm{R_a} \sim 400\,\mathrm{nm}$ have shown about one order of magnitude higher $\mathrm{R_s}$ than Nb as shown in Fig. 10.

IV. Future Plan

The following will be carried out in the future.

- Measurement of RF critical magnetic field at ∼11 GHz using a TE_{013}-like mode mushroom cavity at SLAC [17]

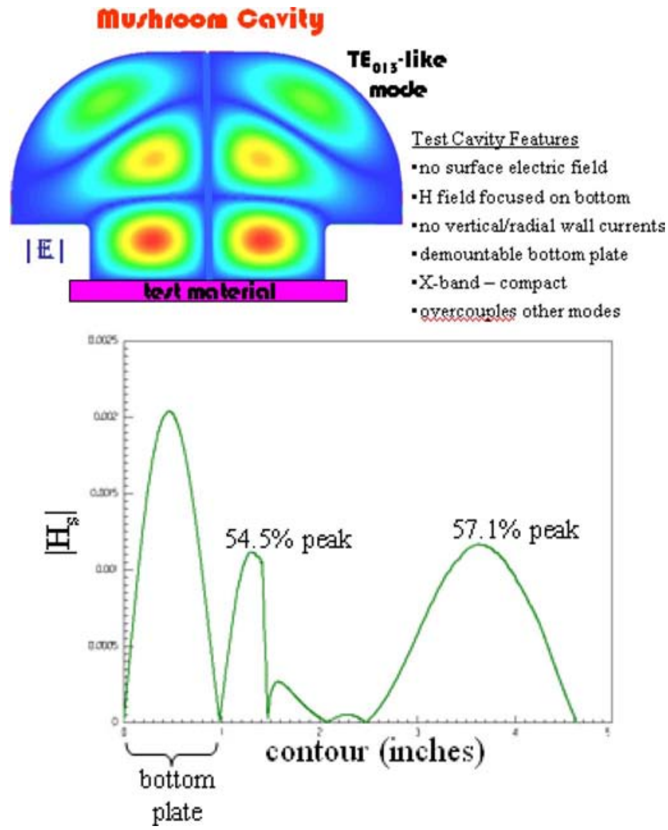

Fig. 11. A SLAC cavity for testing superconducting materials and its surface magnetic field profile along the contour in the radial direction on the bottom plate and side wall. The highest magnetic field is located on the bottom sample plate at ∼50% in the radial direction [17].

Fig. 11 shows a cross sectional view with a sample located at the bottom and its surface magnetic field profile on the sample and side wall surfaces. As one can see, the highest field is located about half way in the radial direction on the sample. The RF critical magnetic field will be measured by detecting the change of $\mathrm{Q_0}$ at the transition from superconducting to normal conducting states.

Recently, we successfully tested Nb as a reference. A MgB_2 bulk sample of 2 inches in diameter and 0.25 inches in thickness will be tested soon.

- Measurement of $\mathrm{R_s}$ dependence on surface magnetic fields at higher power using a $\mathrm{TE_{011}}$ cavity with a calorimetric method at JLab [18].
- Investigation of the effect of substrate surface roughness on the $\mathrm{R_s}$
- Investigation of the source of residual resistance and development of the way to reduce it
- Development of the technique to apply reactive evaporation method to coat the inner surface of an RF cavity
- Improvement of the quality of the film deposited with PLD

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