# POWER DEPENDENCE OF THE RF SURFACE RESISTANCE OF $MGB_2$ SUPERCONDUCTOR*

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*Abstract*

Magnesium diboride ($MgB_2$) is a superconducting material that has a transition temperature ($T_c$) of ~40 K, which is ~30 K higher than niobium (Nb) that has been used for most superconducting RF cavities in the past decades. Last year, it was demonstrated that the RF surface resistance of $MgB_2$ can be lower than Nb at 4 K. One of the problems with other high-$T_c$ materials such as YBCO was its rapid increase in RF surface resistance with higher surface magnetic fields. Recently, we have shown that $MgB_2$ shows little increase in the surface resistance up to ~120 Oe, equivalent of an accelerating field of ~3 MV/m. The highest field tested was limited by available power. This result is encouraging and has made us consider fabrication of a cavity coated with $MgB_2$ and test it. Also, there is a potential that this material has a higher critical magnetic field that enables the cavity to run at a higher gradient than Nb cavities in addition to the possibility of operation at higher temperatures.

## INTRODUCTION

Since its discovery of superconductivity in early 2001 [1], a number of studies on $MgB_2$ have been carried out due to its near metallic nature, simplicity and lower fabrication cost compared with high $T_c$ materials such as BSCCO and YBCO.

One of the good features of $MgB_2$ is its lower losses at grain boundaries. This loss has prevented us from using high $T_c$ materials for superconducting RF (SRF) cavity applications [2-4].

This paper presents our recent results on the RF surface resistance ($R_s$) of a film coated on sapphire and niobium substrates together with a preliminary result on the power dependence test.

## $MgB_2$ FILM GROWTH

A 400-nm-thick epitaxial $MgB_2$ thin film was deposited using a reactive evaporation deposition technique developed at Superconductor Technologies, Inc. [5]. Figures 1 and 2 show a schematic and a cross-sectional view of the coating system. High-pressure Mg vapor is in a pocket heater where substrates can be exposed to the vapor at a controlled time using a rotating mechanism. This system has various advantages including a localized source of high-pressure Mg vapor, negligible MgO in the pocket, B evaporation in vacuum, no need to control Mg/B flux ratio, the ability to separate substrate temperature from that of Mg, and uniform growth on multiple large area substrates. Typical conditions for the coating are; substrate temperature 400 - 600 ◦C, vacuum <$10^{-6}$ Torr, growth rate ~6 nm/min, and film thickness 150 - 700 nm.

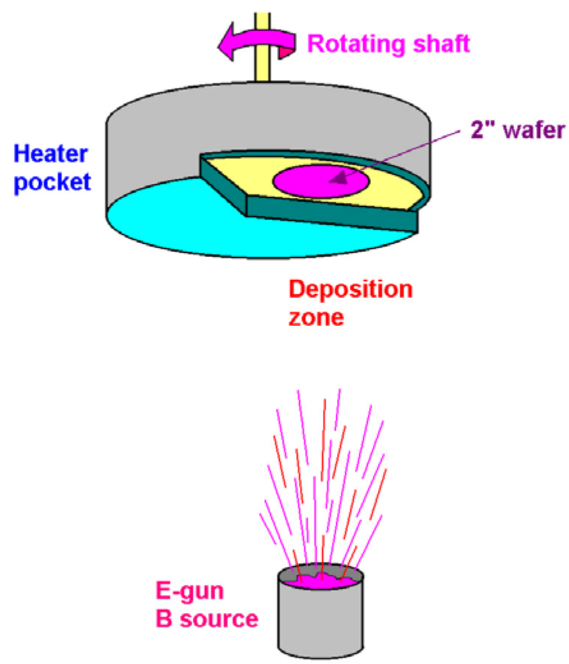


Figure 1: $MgB_2$ coating system at STI. [5]

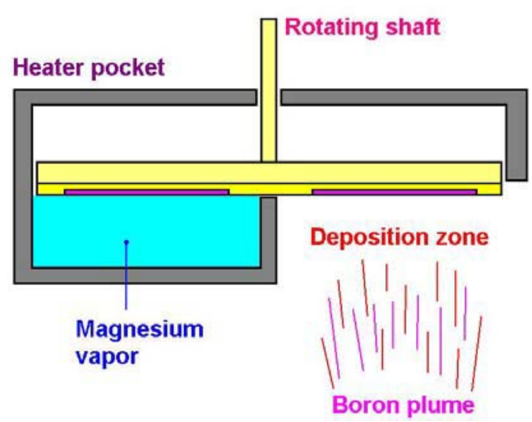


Figure 2: Cross section of the deposition chamber. [5]

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## $R_S$ AT LOW POWER

A few samples of 400-nm-thick $MgB_2$ films grown on sapphire have been tested with a parallel plate measurement method at ~10 GHz [6] Figure 3 shows the surface resistance as a function of temperature. The figure includes previous results of bulk $MgB_2$ samples that were measured at LANL [7, 8] and Nb film data for comparison.

As shown in the figure, this film showed about 30x lower $R_s$ compared to the first bulk samples data and lower than Nb at 4 K. There is still residual resistance and the $R_s$-T curve crosses with Nb data at 3.3 K, but this indicates that there is still potential for reducing the $R_s$.

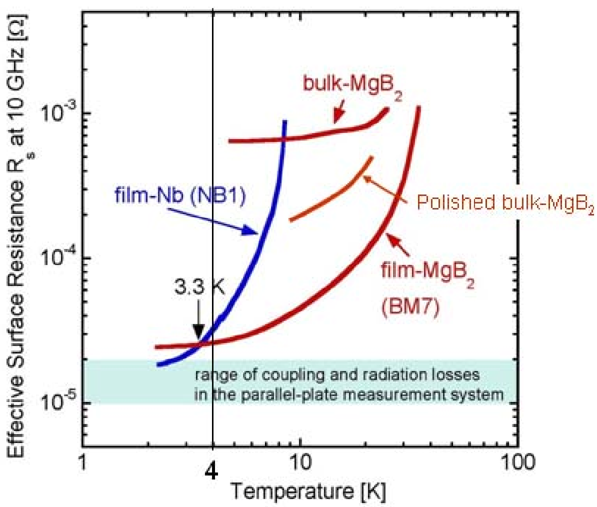


Figure 3: Surface resistance vs. temperature of a 400 nm $MgB_2$ film coated on a sapphire substrate. Bulk samples and Nb data are shown for comparison. [6]

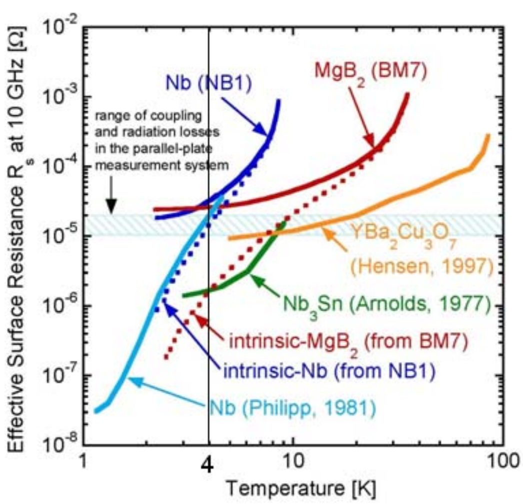


Figure 4: Prediction of intrinsic (BCS) surface resistance (dotted line) from experimental data. [6]

Figure 4 shows a prediction (dotted line) of the intrinsic $R_s$ of this $MgB_2$ film and Nb film. According to this, $R_s$ of this $MgB_2$ film is expected to be much lower than Nb, e.g., about one order of magnitude less than Nb at 4 K.

## $R_S$ AT HIGH POWER

Two Nb disks of 14.6 mm in diameter and 1.5 mm in thickness were coated with 400-nm-thick $MgB_2$ with the same method described above. Figure 5 shows the samples. The Nb substrate disks were not well prepared and had a relatively rough surface. It was the first attempt to coat $MgB_2$ on Nb and a low-power test with a parallel plate measurement showed about one order of magnitude higher $R_s$ than Nb.

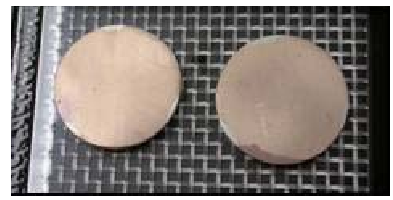

Figure 5: $MgB_2$ coated Nb disks of 14.6 mm in diameter.

The power dependence was measured with a 6 GHz $TE_{011}$ mode cavity at Cornell that was used for measuring YBCO samples in 1988. A detailed description of the equipment can be seen in Ref. [9]. The sample was put on a sapphire rod located at the center of the bottom plate.

Figure 6 shows the $R_s$ of the cavity as a function of the peak magnetic field on the sample at 4.2 K. The Nb BCS resistance is shown for comparison. As one can see, the measured $R_s$ was about one order of magnitude higher than that of Nb, which is consistent with the parallel-plate measurement result. This indicates that the $R_s$ is dominated by the $R_s$ of $MgB_2$ sample.

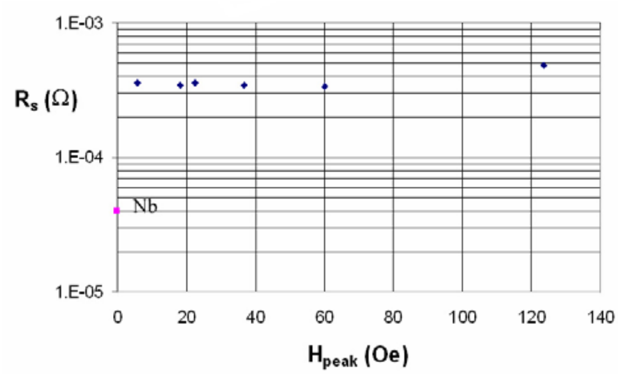


Figure 6: $R_s$ of the Nb $TE_{011}$ mode cavity with a $MgB_2$ sample at the center of the bottom plate, as a function of the peak magnetic field on the sample. The data was converted to 10 GHz using an $f^2$ law.

Regarding the dependence of $R_s$ on the surface magnetic field, the data show no increase up to 60 Oe and slight increase at ~120 Oe. Although this is still preliminary in the sense that there has been only one test and that the $R_s$ of the $MgB_2$ film is not as good as the samples shown in Fig. 3, this result is encouraging since the $R_s$ does not increase up to some practical level, i.e., 120 Oe, which is ~3 MV/m in accelerating gradient for electron accelerators.

These data also indicate that some published data that showed an onset of nonlinearity at ~10 Oe [10] are not from the intrinsic nature of $MgB_2$ and that $R_s$ could stay low at much higher power if extrinsic source of weak links in the grain boundaries can be eliminated.

The maximum tested field was limited by available power and results with higher power will be investigated in the near future in addition to some attempts to improve the $MgB_2$ film quality.

## SOME IDEAS OF COATING A CAVITY

In parallel with the proof-of-principle tests such as the power-dependence test and critical RF-magnetic-field tests [11], we started looking into ways of coating $MgB_2$ onto an RF cavity.

Currently, there are some methods that could be used for this, e.g., magnetron sputtering, cathodic arc deposition, electroplating [12] and pulsed laser deposition [13].

Figure 7 is a conceptual drawing of a system using a pulsed-laser deposition technique. Conditions such as laser power density and target angle are optimized with separate experiments, and the positions/angles of the $MgB_2$ target and laser irradiation control can be automated to coat all the cavity surfaces under optimum conditions.

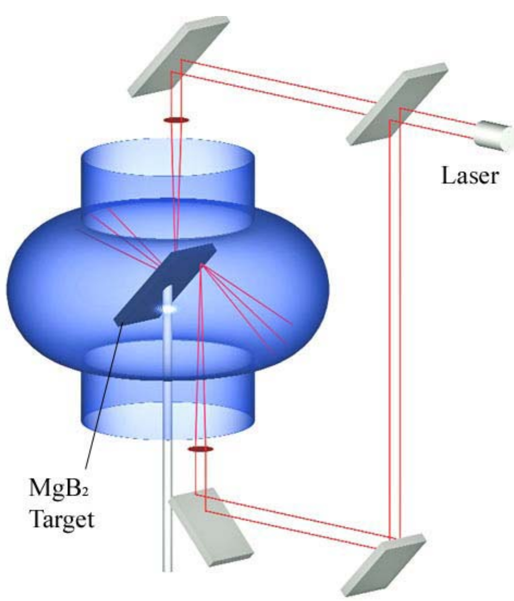


Figure 7: An idea for coating a cavity using a $MgB_2$ target and a KrF excimer laser.

## FUTURE PLAN

We have informal collaborations with the following institutes on various coating techniques:

- National Institute for Materials Science (NIMS), Japan: Electroplating.
- University of Wollongong, Australia: Pulsed laser deposition.

Each institute will coat $MgB_2$ on the Nb substrates that were sent from LANL using their own technique and send the samples back to LANL for evaluation of the film.

We have also started to discuss collaborations with JLab and the University of California, San Diego, on the sputtering of $MgB_2$ on the cavity.

In addition, we plan to test the RF critical magnetic field of $MgB_2$ at SLAC using an X-band cavity and a very short pulse in collaboration with SNS and SLAC [11].

## ACKNOWLEDGMENTS

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## REFERENCES

[1] J. Nagamatsu, et al., "Superconductivity at 39 K in Magnesium Diboride," Nature 410 (2001) 63.

[2] A.T. Findikoglu et al., "Power-dependent microwave properties of superconducting $YBa_2Cu_3O_{7-x}$ films on buffered polycrystalline substrates," Appl. Phys. Lett. 70 (1997) 3293.

[3] J.R. Delayen and C.L. Bohn, "Temperature, frequency, and rf field dependence of the surface resistance of polycrystalline $YBa_2Cu_3O_{7-x}$," Phy. Rev. B40 (1989) 5151.

[4] J. Liu et al., "RF Field Dependence of Surface Resistance for a-b Plane Textured $YBa_2Cu_3O_{7-\delta}$ Films Deposited on Copper Substrate," J. Supercond. 14 (2001) 3.

[5] B.H. Moeckly, MRS Fall Meeting, Boston, MA, Dec. 1-5, 2003, and "Microwave properties of $MgB_2$ thin films grown by reactive evaporation," ASC2004, Jacksonville, FL, Oct. 3-8, 2004.

[6] A.T. Findikoglu et al., NSF/DOE Workshop on RF Superconductivity, Bethesda, MD, Aug. 29, 2003.

[7] A.T. Findikoglu et al., "Microwave performance of high-density bulk $MgB_2$" Appl. Phys. Lett. 83 (2003) 1.

[8] T. Tajima et al., ""RF Surface Resistance of a HIPped $MgB_2$ sample at 21 GHz," 6$^{th}$ European Conference on Applied Superconductivity, Sorrento, Italy, September 14-18, 2003.

[9] D.L. Rubin et al., "Observation of a narrow superconducting transition at 6 GHz in crystals of $YBa_2Cu_3O_7$," Phys. Rev. B38 (1988) 6538.

[10] A.J. Purnell et al., "Nonlinear microwave response of an $MgB_2$ thin film," Supercond. Sci. Technol. 17 (2004) 681.

[11] I.E. Campisi et al, "Limiting RF fields in Superconductors at X band," Pushing the Limit of RF Superconductivity Workshop, ANL, Sept. 22-24, 2004, http://www.aps.anl.gov/conferences/RFSC-Limits/presentations/Day1/Campisi.pdf.

[12] H. Abe et al., "Superconducting properties of $MgB_2$ films electroplated to stainless steel substrates," Appl. Phys. Lett. 85 (2004) 6197.

[13] Y. Zhao et al., "Off-axis $MgB_2$ films using an *in situ* annealing pulsed laser deposition method," Supercond. Sci. Technol. 18 (2005) 395.



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