Status of MgB$_2$ Coating Studies for SRF Applications

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• KEK provided copper surrogate cavities.
• JLAB provided a Nb surrogate cavity.
• Cornell and FNAL provided their Nb disks and cavities, respectively, and FNAL offered to test MgB\textsubscript{2} coated cavities with diagnostics.
• Dan Oates of MIT for the email today!
Outline

• Background and motivation to use MgB$_2$.

• Brief summary of the characteristics of MgB$_2$ thin films comparing to Nb bulk and films

• Coating system at LANL

• Conclusions
Background and motivation
Background

• Nb technology has become close to its full capacity on gradient ($E_{acc} \sim 50$ MV/m for electron accelerator) due to its well known critical fields ($B_{c1} \sim 170$ mT and $B_c \sim 200$ mT).

• New materials with Gurevich’s multi-layer idea could produce cavities that exceed the performance of Nb cavities and open up more opportunities to use SRF cavities.
Motivation to use MgB$_2$

- MgB$_2$ has quite high $T_c \sim 40$ K compared to other conventional s-wave superconductors ($<20$ K), leading to lower BCS resistance and higher thermal tolerance.
- Absence of weak links (low dependence of $Q_0$ on H)
- Simple chemical composition
- Can be coated at a large range or temperatures ($>\sim 250$ °C)
In equilibrium

\[ P = 10^{\frac{-7561}{T} + 8.673} \]

(Lower boundary)
78 mTorr  ↓
(2.8 x 10^{-5} Torr)
2.7 mTorr
(3.1 x 10^{-7} Torr)
3.0 x 10^{-5} Torr
(7.3 x 10^{-10} Torr)

\[ P = 10^{\frac{-10142}{T} + 8.562} \]

[from Liu et al., APL 78 (2001) 3678.]
A brief summary of the characteristics of MgB$_2$ thin films compared to bulk and film Nb.

Figure 2. Resistivity versus temperature for an MgB$_2$ film deposited on polycrystalline alumina. This film was grown at 550 °C to a thickness of 550 nm and has a zero-resistance $T_c$ value of 39.1 K. The inset shows a photograph of an MgB$_2$ film grown on a 4 inch diameter $r$-plane sapphire substrate.
Summary of $B_{vp}$ for STI films (200, 300 and 500 nm) compared with cavity-grade bulk Nb and sputtered Nb films. MgB$_2$ thin films show remarkably high $B_{vp}$ !!

MgB$_2$ thin films show remarkably high $B_{vp}$ !!

Assume $B_{peak}/E_{acc} = 4$ mT/(MV/m)

[Tajima et al. SRF2011] modified
Comparison with theoretical curve of $B_{c1}$ for thin films assuming $\lambda = 110$ nm and $\xi = 6$ nm.

$$B_{c1} \ (d \ll \lambda) \approx \frac{2\Phi_0}{\pi d^2} \ln \frac{d}{\xi}$$  
Gurevich, APL 88 (2006) 012511

L. Civale et al., PRB 48 (1993) 7576

[**Tajima et al. SRF2011**] modified
Temple University (Xiaoxing Xi’s group) samples prepared with hybrid physical chemical vapor deposition (HPCVD) showed the highest $B_{vp}$ at the same thickness.
Our plan to overcome the difficulty of measuring ultra-thin (<200 nm) films and realize cavity-like configuration

Magnetic moment $m$ 
$\propto$ volume of film (very small) 

$m \propto$ volume of the football shape (very large)
Low-power $R_s (T)$ test results at MIT

$R_s$ extrapolated to 2.2 GHz by $f^2$

-- [Oates et al., SRFTF workshop, JLAB, 2012]
$R_s (T)$ measured at JLAB

[B.P. Xiao et al., SUST 25 (2012) 095006]
$R_s (H)$ measured at MIT

![Graph showing the relationship between surface resistance ($\mu\Omega$) and peak magnetic field (Oe). The graph includes data points for different materials and conditions, such as 500 nm stripline on sapphire from STI, 500 nm on niobium from STI, HPCVD on sapphire from X.X.Xi, and Nb on sapphire 4 K. The graph plots $T = 5$ K and is scaled to 2.2 GHz.]

[Oates et al., SRFTF workshop, JLAB, 2012]
More recent data from MIT

No quench
Power limited

60 mT

[Dan Oates, email today]
Coating system at LANL
HPCVD was selected because

- Showed highest $T_c$
- Showed highest $B_{vp}$
- No UHV is required

Need to be very careful about diborane ($B_2H_6$) gas due to its toxicity and flammability!
MgB$_2$ CVD reactor located at Technical Area 35 at LANL (unfortunately only US citizens allowed)

12” diameter, 67” long furnace in large walk-in hood with separate building exhaust and H$_2$ / B$_2$H$_6$ gas monitors room pressure negative with respect to the building
Furnace is big enough for a 1.3 GHz 9-cell cavity
Currently a 1-cell Cu surrogate cavity is used with 6 mm × 6 mm (sapphire and Nb) samples attached in the holes on the surface.

Mg pellets in this

B₂H₆

Local heater (not shown)
Schematic of present coating system (Looking from Top)

- Mg pellets with heater
- $\text{H}_2$ + 0.3% $\text{B}_2\text{H}_6$
- Total pressure 28 Torr
- 2.8 L/min

Left:
- SST
- Samples
- Pump

Right:
- Pump

Top:
- Pump
Learned facts after 10 runs at different furnace T (300-600 °C) and Mg source T (400-840 °C)

• Boron was not coated on the cavity surface at ≥500 °C (B₂H₆ gas was likely to be decomposed and consumed on the long inlet line before reaching the cavity)

• Insufficient Mg vapor pressure on the cavity surface. Even heating Mg pellets to ~840 °C with a local heater (Mg melting temperature is 650 °C) did not form MgB₂ on the 400 °C cavity surface, while B₂H₆ was flowing.
Boron growth rate vs. Temperature

- Our data on inlet BP >11.7 nm/min@400°C
- 0.2 nm/s =12 nm/min
- Our data on cell L (1.3 nm/min = 0.22 Å/s)

[from D.R. Lamborn, PhD thesis, August 2007]
B thickness profile

Sample position

Inlet BP  Cell  Outlet BP

Boron thickness (nm)

880
435
570

@360 °C for 2 hours
Future options

- Move the location of Mg source into the SST pipe attached to the cavity so that sufficient Mg vapor reaches cavity surface and maintain the coating temperature at 550 °C or lower.
- 2-stage coating (coat B then react with Mg) at a high temperature (≥700 °C, although <800 °C is preferable to avoid Nb re-crystallization when coated on Nb) (Mg diffused into B only about 20 nm at 600 °C.)
Conclusions

- MgB$_2$ thin film samples especially prepared by HPCVD have shown excellent properties relevant to SRF applications, which warrants the coating of practical-size cavities and study the performance as a cavity.

- LANL as well as other institutes and companies are trying to develop a suitable technique to coat cavities and hope to produce a lot of cavity results by the next SRF conference.