CRYOGEN-FREE RF SYSTEM STUDIES USING CRYOCOOLER-COOLED MAGNESIUM DIBORIDE-COATED COPPER RF CAVITIES*

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Abstract

Studies on the application of magnesium diboride (MgB_2) high-Tc superconducting films have shown promise for use with rf cavities. Studies are directed towards applying the films to niobium cavities with the goal to increase accelerating gradients to greater than 50 MeV/m. Our current research is directed towards depositing MgB_2 films onto copper, or other high thermal conductivity metal, substrates which would allow future cavities to be fabricated as film-coated copper structures. We have started atomic layer deposition studies as well as coating of thin films of MgB_2 on 2-inch copper coupons using a hybrid physical-chemical vapor deposition (HPCVD) technique [1].

INTRODUCTION

Over the last few years there has been research on the application of MgB_2 films to niobium (Nb) cavities to enhance performance because of the higher T_c available with MgB_2 compared to niobium [2-4]. Most of the current interest in the accelerator community is directed towards increasing the accelerating gradient beyond the 50-MV/m limit imposed by the quench field of niobium. However, there are properties of MgB_2 that might make it possible to design and build helium-free superconducting systems for storage-ring-based light sources, x-ray free electron lasers, and possible industrial and medical linear accelerators. Measurements reported by Oates et al. [5] suggest that a cavity coated with MgB_2 film can achieve the same surface resistance R_s at 8-12 K that is achieved with Nb at 4 K. The goal of this study is to investigate the feasibility of designing helium-free superconducting rf cavity systems using cryocoolers operating in the 8-12 K range.

CAVITY AND CRYOMODULE DESIGN

Typically superconducting cw cavity designs require about 20 to 60 watts at 4 K if the superconducting material is Nb. If MgB_2 films can achieve similar surface resistances at 8-12 K as those of Nb, then the heat removal demand on a cavity cooled with cryocoolers would be in the same range. The typical load map for an RDK-415 Sumitomo cryocooler is shown in Fig. 1. As can be seen, the cooling capacity on the second stage of the cryocooler over the range of 8 K to 12 K is between 10 and 20 watts, and is almost independent of the first-stage temperature over the range of 30 K to 70 K. The second-stage cooling capacity is up to 80 watts at 90 K and over 40 watts at 60 K.

RDK-415D Typical Load Map (60 Hz)

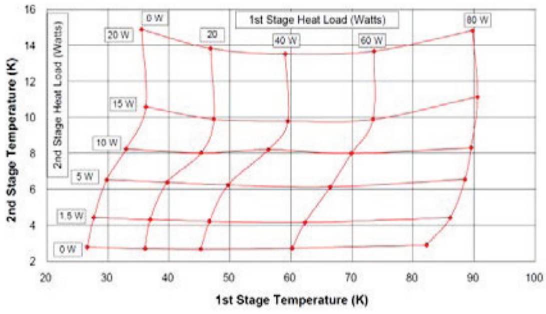

Figure 1: Load lines for a Sumitomo RDK-415 cryocooler at 60 Hz.

The cavity cell geometry is, of course, independent of the cryogenic cooling system. The cryomodule without liquid cryogens is considerably simplified. No liquid filling ports or internal piping, liquid reservoirs, or internal gas piping is required. An artist's simplified sketch showing a cutaway of a typical 500-MHz, 5-cell cavity with the cryocooler connections is found in Fig. 2. The second stage is connected to the cavities through commercially available thermal links that are fabricated with many thin high-conductivity copper foils capable of flexing and absorbing motion and differences in thermal contraction. The first stages are connected to heat shields and other heat intercept points from the room temperature flanges. Four cryocoolers are mounted on the cavity providing 80 watts of cooling at just over 12 K and 60 watts at 8 K. The first stages provide 320 watts of cooling at 70 K. Less cooling power required by the second stage would result in the shield operating at a lower temperature.

Ideally, a high-thermal-conductivity material like copper would be best for the cavity. Thermal conductivities above 100 W/mK provide enough heat removal for temperature differences across the cavity to be less than 0.2 K. Copper with an RRR value of 100 has a thermal conductivity greater than 1000 W/mK, so the temperature variation across the cavity would be reduced to the milli-Kelvin range. The thermal conductivity of Nb is about 200 W/mK, so even Nb would be usable as a substrate if MgB_2 cannot be deposited on copper. The temperature gradient would be a bit higher across the cavity with Nb, but within an acceptable range. The thermal links might well provide the largest temperature difference between the cavity surface and the second stage of the cryocooler. Thermal conductance per link can be as high as 13.5 to 15.5 watts/link. The temperature difference between the cold head and the cavity would be

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about 0.5 K. A more complete analysis using a 3-D heat analysis computer code is needed to see if any extra elements or added thermal link connections are needed to keep the total temperature difference to 0.5 K, or less.

When all elements in the respective cooling systems are included, the electrical utility installation should be comparable for both cryocoolers and liquid helium systems. The cryocoolers operating at 9-12 K require 7.5 kW to deliver 20 watts of cooling. This number is comparable to the electrical requirements for a large liquid helium system that achieves 500 W/W for a 100 watt system and 250 W/W for a 1 kW system at 4 K [6].

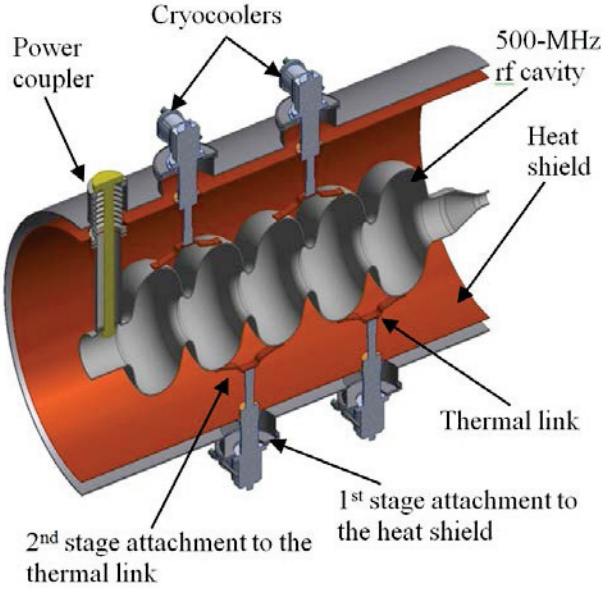

Figure 2: A simplified sketch shows a cutaway of a typical 500-MHz, 5-cell cavity with the cryocooler connections.

DEPOSITION, COATING AND FILM GROWTH CHALLENGES

Magnesium is volatile and MgB_2 decomposes at high temperature when not under sufficient Mg vapor pressure. The most serious challenge in growing MgB_2 films is to provide a very high Mg vapor pressure at the growth temperature [7]. For growing clean MgB_2 films, it is also critically important to prevent contamination from oxygen and carbon. The hybrid physical-chemical vapor deposition (HPCVD) technique [1] effectively satisfies these requirements. It provides a high Mg vapor pressure by thermally evaporating bulk Mg pieces. Diborane precursor gas is the boron source. The ultra-high purity of Diborane and hydrogen carrier gas keeps the process free from oxygen and carbon contamination. It is also compatible to coating curved surfaces.

Large-Area MgB_2 Films by HPCVD

The original HPCVD system was modified for 2"-diameter films. In this system, a resistive heater and a 3" Mo susceptor were used. To ensure sufficient Mg vapor pressure across the 2" substrate, the center of the susceptor was slightly cooler than the edge to create a temperature gradient that drives the Mg vapor from the edge of the susceptor, where it is generated, to the center of the substrate. This was achieved by adjusting the radial density of the resistive heating element [8]. During the deposition a hydrogen carrier gas of 40 Torr with a flow rate of 400 sccm was used. The boron source was 5% Diborane in hydrogen and a flow rate of 40 sccm was used during the growth. The substrate temperature was about 720°C.

Figure 3 is a photograph of a 2"-diameter MgB_2 film on sapphire substrate. The film was cut into five pieces along a diameter, and the properties of these films were measured to test the uniformity of the 2" film. The thickness variation across the film is about 10%, shown in Fig. 4. The zero-resistance T_c of the film is almost independent of the location at 39.5 K, whereas the residual resistivity changes between 0.5 μΩcm and 1.3 μΩcm (see Fig 5). Figure 6 is the resistivity versus temperature curve for one of the five films cut from the 2" film.

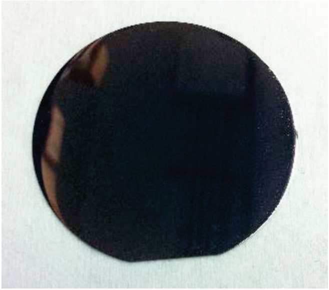

Figure 3: A photograph of a 2"-diameter MgB_2 film on sapphire substrate.

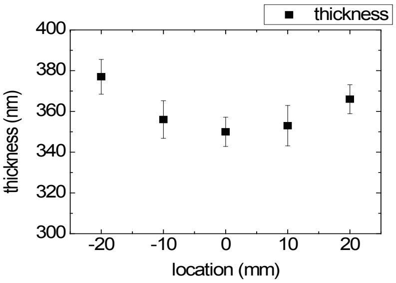

Figure 4: Coating thickness variation across the 2" MgB_2 film.

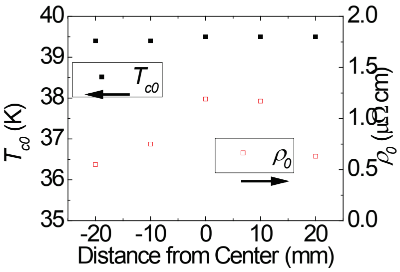

Figure 5: Variation of T_C and residual resistivity across the 2" MgB_2 film.

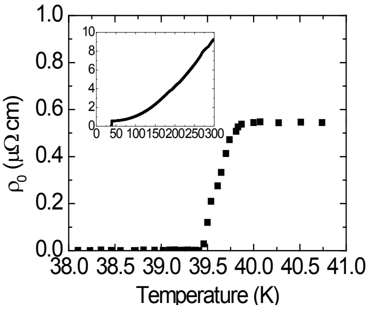

Figure 6: Superconducting transition of a small MgB_2 cut from the 2" film.

Atomic Layer Deposition of MgB_2

Atomic layer deposition (ALD) is a highly conformal deposition technique that enables a very high-precision level of thickness and composition control on arbitrarily shaped surfaces. The ability to synthesize by ALD high Tc materials [9] such as MgB_2 at low temperature would represent a breakthrough not only for the synthesis community but also for a wide range of applications from SRF cavities to magnets and sensors. Traditional synthesis or deposition techniques usually require very high temperature (>600°C) in very reactive environments such as Mg and B vapor. As such, growing high-quality superconducting MgB_2 at low temperature (<450°C) is a real challenge. We have conducted the ALD experiments in a homemade ALD system, with *in situ* monitoring (RGA and QCM). After modifying the ALD system to be able to handle safely Diborane gas (B_2H_6), we attempted to use $Mg(Cp)_2$ and B_2H_6 below the decomposition point of Diborane (<250°C) without success. Our chemist collaborators at IIT suggested using TriEthylBorane $(B(Et))_3$ or $(B(C_5H_5))_3$ as a more reactive source of Boron and stable to higher temperature (350°C), relying on the combination of both precursor's organic ligands at high temperature to form volatile compounds, as seen previously in the literature with other precursors. However this attempt did not succeed with $Mg(Cp)_2$.

Changing the approach, we decided to synthesize a more reactive Mg precursor. Previous experience of our chemist collaborator showed great success in synthesizing highly reactive Open Cp compounds of Fe that enabled much lower growth temperature by ALD. The synthesis of an Open Cp compound of Mg is a challenge in itself; the crucial synthetic step that is now ongoing is to be able to isolate the Open Cp and to check its melting point. We are expecting this new precursor very soon and will resume the ALD growth study of MgB_2.

In parallel to the synthesis effort we have also investigated the growth of epitaxial MgO as a potential tunnel barrier or nucleation layer for the growth of epitaxial MgB_2 (001). We found that at a moderate temperature of 300°C, as compared to the usual deposition techniques (sputtering) that require temperature >600°C, we can grow epitaxial MgO (111) on C axis-sapphire.

SUMMARY

Development of MgB_2 and other possible thin film technologies makes it possible to operate SRF cavities at 8-12 K with efficient cryocoolers that provide significant benefit with reduced cost. It will eliminate all liquids (He and N_2), liquid transfer and gas lines, storage tanks, and gas compressors. There will not be a need for conventional facilities to house this equipment.

CONCLUSION

We have started feasibility studies using MgB_2 as a thin film superconducting layer on copper using HPCVD and ALD techniques. A successful demonstration of MgB_2 coating and deposition on copper coupons and follow-up rf tests and measurements will potentially pave the way to apply these techniques to an accelerating cavity with the goal of designing helium-free superconducting rf cavity systems using cryocoolers operating in the 8-12 K range.

ACKNOWLEDGMENT

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