RF SURFACE IMPEDANCE OF MgB_2 THIN FILMS AT 7.5 GHz *

B. P. Xiao[1,2#], H. L. Phillips[1], C. E. Reece[1], T. Tajima[3], M. J. Kelley[1,2]
[1]Jefferson Lab, Newport News, VA 23606
[2]College of William and Mary, Williamsburg, VA 23187
[3]Los Alamos National Lab, Los Alamos, NM 87545

Abstract

The Surface Impedance Characterization (SIC) system at Jefferson Lab [1] can presently make direct calorimetric RF surface impedance measurements on the central 80 mm^2 area of 50 mm diameter disk samples from 2 to 40 K exposed to RF magnetic fields up to 14 mT at 7.5 GHz. MgB_2 thin films from STI/LANL were deposited on 50 mm diameter Nb disks using reactive evaporation technique. We will report the results of measurement on one of these samples using the SIC system. The data is interpreted based on BCS theory as the temperature-dependant properties suggest evaluation of the T_c, energy gap, penetration depth, mean free path and coherence length.

INTRODUCTION

The accelerating gradient of superconducting radiofrequency (SRF) Nb cavities has been pushed to 52 MV/m for single-cell cavity [2] with quality factor higher than 10^{10}, approaching the theoretical limit of Nb. It is still not quite clear that whether RF critical field of SRF cavities are limited by superconductor's superheating critical field or not, the efforts on Nb cavities already showed that RF critical field could be higher than Nb's lower critical field. Thus, superconductors with surface resistance lower than, and superheating critical field higher than those of Nb are of great interest for SRF application. Magnesium diboride (MgB_2), discovered to be a superconductor by Nagamatsu et al, in 2001 [3], could potentially be one of the substitute materials for SRF applications.

MgB_2 is a simple binary compound that contains graphite-type boron (B) layers separated by hexagonal close-packed magnesium (Mg) layers, with a high critical temperature at 39~40 K [4], twice as high as the second highest T_c (Nb_3Ge at 23K) in binary superconductors. It has two energy gaps, with π-band at 2.3 meV and σ-band at 7.1 meV [5]. At temperatures much lower than its critical temperature, the BCS surface resistance $Rs \sim (A\omega^2/T)\exp(-\Delta/k_bT)$ is dominated by the π-band. Comparing with Nb's energy gap at 1.5 meV, the BCS surface resistance of MgB_2 could be much lower than that of Nb. The superheating critical field for MgB_2 can be calculated from $H_{sh} = 0.75\sqrt{H_{c1}H_{c2}}$ [6], which is about 170~1000 mT [4] depending on the field's direction. In case the RF performance is limited by its lower critical field, MgB_2 is still an attractive choice for multilayer thin film coating, which is proposed by Gurevich [7], that the structure of alternating insulating layers and thin superconducting layers of thickness smaller than the London penetration depth could be adopted to overcome the RF critical field of either superconducting layer or superconducting substrate, and at the same time to get benefit from the low surface resistance of the superconducting layer.

In this paper, we report the use of the SIC system developed at Thomas Jefferson National Accelerator Facility (JLab) to measure the surface impedance of MgB_2 under different temperatures.

DESCRIPTION OF APPARATUS

In the SIC system a sample is placed at the open end of a TE_{011} cylindrical Nb cavity with a sapphire rod inside, shown in Figure 1. The whole system works at 7.5 GHz. The sample is thermally isolated from the cavity body. Heat can be conducted from the sample only via the thermal insulator. The surface impedance of the sample can be derived by directly substituting heater heat for RF heat (heat substitution method) under controlled RF field and temperature conditions. A detailed description has been given in [1].

The calorimetry of the SIC system has been recently upgraded to accommodate different substrates such as aluminium, copper, sapphire, magnesium oxide, Nb, silicon, etc. Two versions of calorimetry system are currently using in SIC system: high precision version and high power version. The only difference between them is that the high precision version adopts stainless steel as the thermal insulator while the high power version adopts copper. Samples are clamped onto the sample holder using a stainless steel cap with 6 aluminium bolts and 15 lb-in torque on each of them. The thermal contraction $(L_{293}-L_0)/L_{239}$ of aluminium is 0.00415, larger than those of copper (0.00326) and stainless steel (0.00296), which would make the thermal contact between sample and sample holder even better while cooling down from room temperature to 2 K. G-10 washers are used to thermally separate aluminium bolts from the stainless steel cap so that thermal leak from the stainless steel cap to the bath could be minimized. Thermal radiation of the sample is in μW range; the ratio between thermal leak from electric wires for heaters/sensors and the designed thermal pass is less than 1%. Sample temperature is measured from sensor N in Figure 1, which is mounted on a spring and could directly measure the temperature on the back of the

* This manuscript has been authored in part by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes. #bpx@jlab.org

sample. Calibration has been done using a 50 mm diameter, 3 mm thick Nb disk with heater and sensor attached on top. Power has been separately applied to the heater on sample and heater L in Figure 1, temperature of the sample holder has been measured from sensor O in Figure 1. The results for high power version are shown in Figure 2, from where the error of heat replacement measurement has been ensured to be within 3%. Similar test has been done for high precision version under different range of power and temperature response, with an error within 2%.

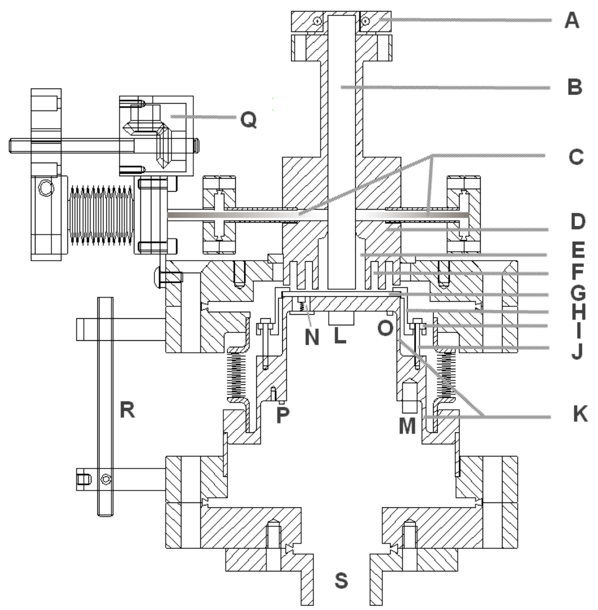

Figure 1: SIC system overview. A. Cap for sapphire rod, B. Sapphire rod, C. RF coupler, D. Nb cavity body, E. TE_{011} cavity, F. Double choke joints, G. Sample on copper support plate, H. Stainless steel sample clamp, I. G-10 washer (x6), J. Aluminium bolt (x6), K. Stainless steel (or copper) thermal insulator, L&M. Heater, N. Thermal sensor mounted on spring, O&P. Thermal sensor, Q. Coupler tuning mechanism, R. Distance tuning mechanism (x3), S. Port for vacuum and wires. (Vacuum port of the cavity is not shown).

The surface impedance can be calculated from formula (1):

$$Z_s = \frac{P_{rf}}{kH_{pk}^2} + i\omega\mu_0\left(\lambda_{ref} + \frac{f - f_{ref}}{M}\right) \qquad (1)$$

The real part is the surface resistance and imaginary part is the surface reactance. P_{rf} is the RF induced heat, k and M are geometry dependent coefficients and ω is the resonant circular frequency. The RF induced heat is calculated from the difference between the power from the heater required to keep a constant sample temperature without RF fields in the cavity and the power from the heater required to keep the sample's equilibrium temperature unchanged when RF fields are present, so called thermal substitution technique. The change of surface reactance is proportional to the change of penetration depth. It can be derived from changes of the resonant frequency of the TE_{011} mode versus sample temperature.

Figure 2: Temperature versus power for heater "L" (upper line) and for heater on sample surface (lower line).

EXPERIMENT

Sample Preparation

A single crystal Nb disk 50 mm in diameter was adopted as the substrate. It was mechanically polished to a root mean square average surface roughness of 0.65 nm before coating. MgB_2 thin film was deposited using reactive evaporation technique at Superconductor Technologies, Inc. (STI) [8]. A 300 nm Al_2O_3 layer had been deposited on top of Nb, following with a 200 nm MgB_2. The sample was mounted on the SIC sample holder using the method mentioned above. For all measurements, the SIC assembly was immersed in 2 K liquid helium. The sample temperature was controlled by adjusting the power supplied to heater L in Figure 1, while the other portion of the cavity remains at 2 K.

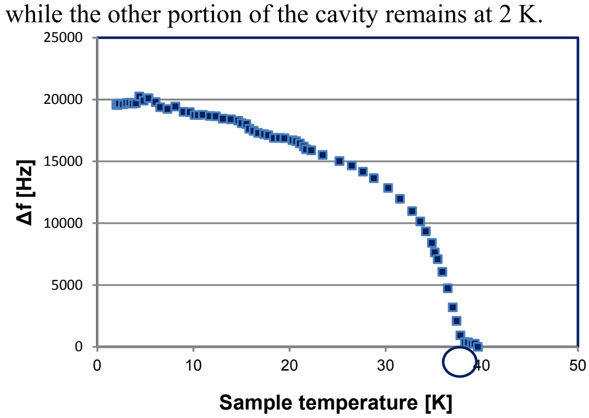

Figure 3: Frequency shift versus sample temperature.

Transition Temperature

The transition temperature could be measured from the frequency shift while changing the sample temperature. This sample shows a result at 38.2±0.2 K, see Figure 3. One should also notice there is no sharp transition of frequency nearby 9.2 K, the critical temperature of Nb, which indicates that the RF field did not penetrate significantly into superconducting Nb.

Penetration Depth

The penetration depth change $\Delta\lambda$ versus sample temperature could be derived from the above frequency shift measurement. $\Delta\lambda$ versus $1/\mathrm{sqrt}(1-(T/T_c)^4)$ has been plotted in Figure 4, a linear fit with suggested value of $\lambda(2K) = 208$ nm and $\lambda_L\sqrt{1+\xi/l} = 437$ nm is also plotted.

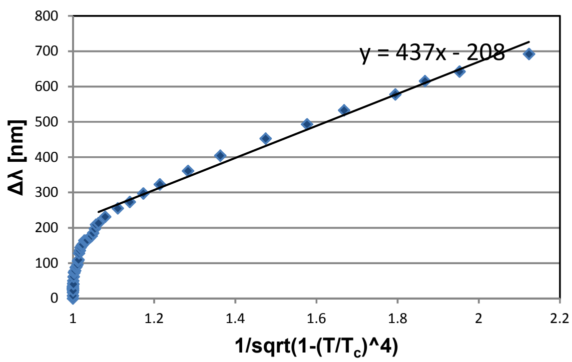

Figure 4: Penetration depth versus sample temperature in $1/\mathrm{sqrt}(1-(T/T_c)\hat{}4)$ form.

Surface Resistance

The surface resistance of this sample has been measured using thermal substitution technique with sample temperature lower than 15 K. Between 30 K and critical temperature, the surface resistance has been extrapolated from the quality factor change of the SIC system while changing the sample temperature, shown in Figure 5. The parameters calculated from least square fitting with $\Delta/kT_c = 2.14$, $T_c = 38.2$ K, London penetration depth = 357 nm, Coherence length = 5 nm, Mean free path = 10 nm and Residual Resistance = 181 µΩ are also given in Figure 5.

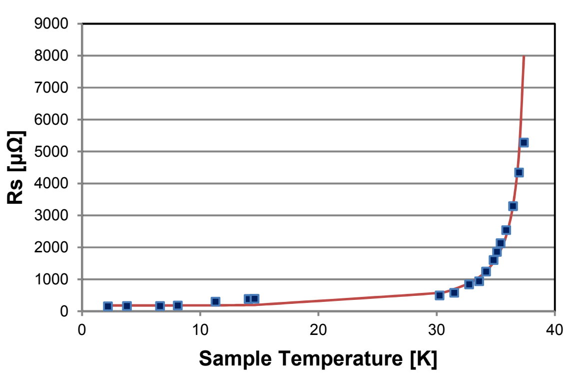

Figure 5: Surface resistance versus sample temperature. ■ Measured data. — Theoretical fitting with parameters mentioned above.

Next Steps

The evidence of no sharp transition at around 9.2 K is consistent with J. Guo's measurement result on the same sample [9]. The measurement on a MgB_2 100 nm/B 10 nm/Nb substrate thin film, however, showed a sharp transition at 9.2 K [10], the surface impedance of this sample will also be measured in the new future. MgB_2 thin film on Al_2O_3 substrate is suggested to be investigated to compare with this result.

SUMMARY

The surface impedance characterization (SIC) system in Jefferson Lab has been modified to accommodate thin films on top of a variety of substrate materials. Two calorimetry systems have been adapted to either precisely measure µW power dissipated on sample or measure watts of power with less accuracy. A thermal substitution technique has been qualified in both calorimetry systems within 3% error.

The RF properties of a sample with 200 nm MgB_2 on top of 300 nm Al_2O_3 with Nb substrate S-I-S structure thin film has been measured using the SIC system. The surface resistance at 2.2 K is 156 µΩ and critical temperature is 38.2±0.2 K. No sharp transition nearby Nb's critical temperature has been found in the surface impedance. Fitting the surface impedance data suggests parameters with london penetration depth = 357 nm, coherence length = 5 nm, mean free path = 10 nm. The surface resistance is dominated by the larger energy gap at $\Delta/kT_c = 2.14$.

REFERENCES

[1] Xiao B P, Reece C E, Phillips H L, Geng R L, Wang H, Marhauser F and Kelley M J *Rev. Sci. Instrum.* **82** 056104 (2011).

[2] Geng R L, Eremeev G V, Padamsee H, Shemelin V D *Proceedings of 2007 Particle Accelerator Conference* 2337 (2007).

[3] Nagamatsu J, Nakagawa N, Muranaka T, Zenitani Y and Akimitsu J *Nature* **410** 63 (2001).

[4] Buzea C and Yamashita T *Supercond. Sci. Technol.* **14** 115 (2001).

[5] Iavarone M, Karapetrov G, Koshelev A E, Kwok W K, Crabtree G W and Hinks D G *Phys. Rev. Lett.* **89** 187002 (2002).

[6] Padamsee H, Knobloch J and Hays T *John Wiley & Sons* (1998).

[7] Gurevich A *Appl. Phys. Lett.* **88**, 012511 (2006).

[8] Moeckly B H and Ruby W S *Supercond. Sci. Technol.* **19** 21 (2006).

[9] Guo J, Tantawi S, Yoneda C, Martin D, Tajima T *Thin Films and New Idea for SRF Workshop 2010* (2010).

[10] Tajima T, Eremeev G, Zou G, Dolgashev V, Martin D, Nantista C, Tantawi S, Yoneda C, Moeckly B H , Campisi I *9th European Conference on Applied Superconductivity* and *Journal of Physics: Conference Series* **234** 012043 (2010).