NEW MATERIAL STUDIES IN THE CORNELL SAMPLE HOST CAVITY *

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Abstract

Cornell has developed a TE mode sample host microwave cavity in order to study large, flat samples of novel SRF materials. In recent calibration tests, the cavity was shown to reach peak magnetic fields on the sample plate of >100 mT and a quality factor Q_0 greater than 10^{10}, making it a powerful system to study the performance of superconductors at high RF fields with nΩ sensitivity. In this report we present results of measurements of two samples of thin-film Nb deposited on Cu using HiPIMS at 500 °C and at 800 °C.

INTRODUCTION

The Cornell sample host cavity (Fig. 1) is a 3.9 GHz bulk niobium cavity operating in the TE_{011} mode [1,2]. It features a five-inch (12.7 cm) flat circular plate (the inner four inches (10.2 cm) of which are exposed to RF), held in place with an indium seal, which can be removed and replaced with a plate made from an alternate material in order to study its properties. Recent calibration tests have brought the cavity to reach fields in excess of 100 mT on the sample plate, with a peak quality factor of 4×10^{10} at 1.6 K [3].

The cavity is also equipped with a temperature-mapping system (T-map), which uses an array of 40 Allen Bradley resistors pressed by “pogo stick” mounts onto the outer surface of the sample plate. The system offers the ability to locate and characterize areas of heating on the order of 10 mK or greater on the plate, including heating which may lead to a quench.

METHODS

Sample Analysis

The host cavity is tested in a vertical test dewar. We take Q_0 vs. H measurements at various temperatures between 1.6 K and 2.1 K. Given the Q_0 of the cavity at a given field strength and temperature, we determine the surface resistance of the plate R_s with the following relations:

$$Q_{\mathrm{sam,calib}} = \frac{Q_{0,\mathrm{calib}}}{1-\gamma} \quad (1)$$

$$Q_{\mathrm{sam}} = \left(\frac{1}{Q_0} - \frac{\gamma}{Q_{0,\mathrm{calib}}}\right)^{-1} \quad (2)$$

* This work supported by NSF award PHY-1416318 and the DOE funded Muon Accelerator Program.
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Figure 1: Third-generation Cornell TE sample host cavity with temperature map and external temperature sensors installed.

$$R_s = \frac{G}{Q_{0,\mathrm{calib}}}\frac{Q_{\mathrm{sam,calib}}}{Q_{\mathrm{sam}}} \quad (3)$$

$$= \frac{G}{1-\gamma}\left(\frac{1}{Q_0} - \frac{\gamma}{Q_{0,\mathrm{calib}}}\right) \quad (4)$$

Here, G is the geometry factor of the cavity, $Q_{0,\mathrm{calib}}$ is the calibration quality factor of the cavity with a calibration plate manufactured from the same niobium stock, measured at the given temperature and field, $Q_{\mathrm{sam,calib}}$ is the component of the calibration quality factor corresponding to the sample plate, Q_{sam} is the component of the experimental quality factor corresponding to the new sample plate, Q_0 is the measured quality factor, and (1-γ) is the ratio of RF power incident on the plate to the power incident on the whole cavity.

Sample Preparation

Two niobium thin films were deposited using high impulse magnetron sputtering (HiPIMS) [4] using a 3-inch planar magnetron fitted with a 99.95% purity niobium target. The HiPIMS power supply was operated with constant settings for both films with pulse rates of 200 Hz, a pulse width of 100 µs, average current of 600 mA and peak currents of 40 A. The vacuum chamber was first baked for 4 days at 150 °C to reach a base pressure of 5×10^{-10} mbar. The magnetron was set at a distance of 120 mm from the sample surface at an angle of 45° from the sample plane. Krypton sputter gas was used during deposition at a pressure of 6×10^{-3} mbar and the sample was set to continuously rotate at 4 rpm. Samples were 5-inch diameter copper disks which were diamond turned with a roughness parameter, R_a, of 10 nm. Sample 1 was deposited with a substrate heated to 500 °C and with a substrate bias of -100 V. Sample 2 was deposited at 800 °C with no bias. Sample deposition lasted 10 hours. The two different deposition processes allow for the comparison of the superconducting RF properties of a niobium film deposited at high temperature to a film deposited at a reduced temperature but with increased ion energies.

RESULTS AND ANALYSIS

500 °C HiPIMS Sample

The 500 °C sample plate exhibited a surface resistance that increased with applied field. At 1.6 K, we found the surface resistance to be 205±55 nΩ at low fields, rising linearly to 715±190 nΩ until reaching quench at a peak sample plate field of approximately 90 mT. At the higher temperature of 1.8 K, the plate quenched at a lower field, approximately 50 mT. Here the surface resistance was found to be 150±150 nΩ at low fields, increasing linearly to 240±170 nΩ. Figure 2 shows these results. The resistance at the higher temperature was indeed found to be lower than that at the lower temperature; however, the measurements are within each other's intervals of uncertainty, so it is likely that this was the result of a systematic error. In particular, the calibration surface resistance of the cavity was significantly higher than the optimal BCS resistance (see Fig. 2); further investigation is needed to determine the cause of this increase and to reduce uncertainty in the cavity's resistance in order to increase accuracy of R_{sam} measurements at temperatures above 1.6 K.

This linear increase in surface resistance with RF field is consistent with results that have been seen previously on sputtered films [5, 6]. Figure 2 shows previous thin film results, scaled to 3.9 GHz by the relation $R_s \propto \omega$ for residual resistance [7], alongside the results of the 500 °C HiPIMS plate. Results are consistent with early sputtered films, shown in green, but the performance does not match more recent results, shown in maroon. From this we see that this new method of Nb film deposition is promising, but there is much room for improvement.

We performed T-map measurements of the 500 °C plate as well, the results of which are shown in Figs. 3 and 4. We found an area of localized heating near the peak field region, a ring of radius 2.5 cm concentric with the sample plate. When investigating the resistor that detected this heating, we found that the heating ΔT increased with increasing field strength, with heating strongly exceeding an H^2 relation with a set-in region at around 2500 mT^2. These observations together make a strong suggestion that the sample plate was limited by a defect quench, perhaps caused by flux entry above a threshold field or thermal feedback occurring with a strong nonlinearity in the surface resistance.

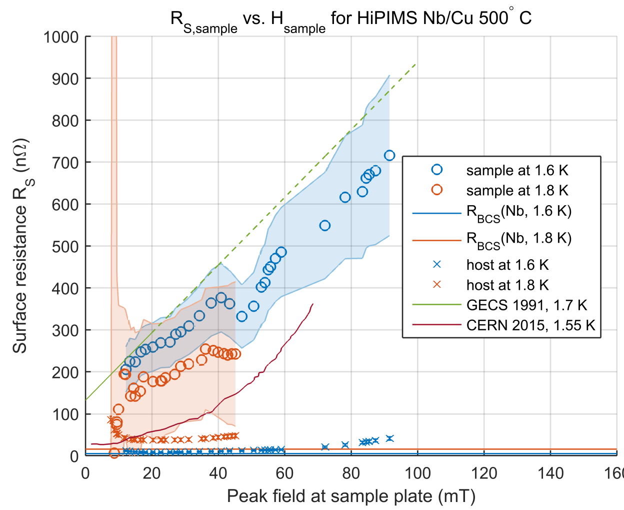

Figure 2: Surface resistance of the 500 °C sample at 1.6 K and 1.8 K, compared with the surface resistance of the body of the cavity as well as the BCS prediction of R_s for niobium at 3.9 GHz. Also included are previous results of sputtered films, scaled to 3.9 GHz. Results in green from LEP2 cavities measured for GECS and presented in [5]; more recent HIPIMS results in maroon presented in [6].

Unfortunately, T-maps were unavailable at 1.8 K due to a failure in the T-map system; future tests will reinvestigate in order to determine why the quench field reduced with increasing temperature.

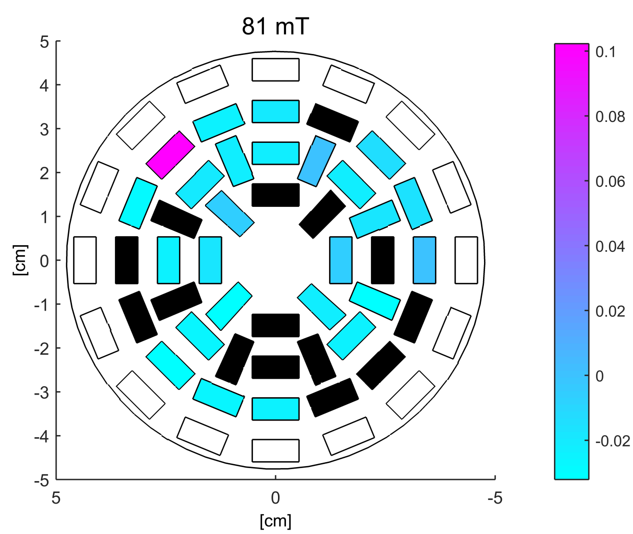

Figure 3: Example temperature map of the 500 °C sample at 1.6 K and a peak sample plate field of 81 mT. This localized heating, near the peak field ring 2.5 cm from the center, is indicative of a defect quench.

800 °C HiPIMS Sample

The 800 °C sample plate exhibited a much higher surface resistance than the 500 °C plate. Here, the resistance was found to be invariant with field strength, with a value of 3985±735 nΩ, much higher than the 500 °C plate. The plate

ISBN 978-3-95450-147-2

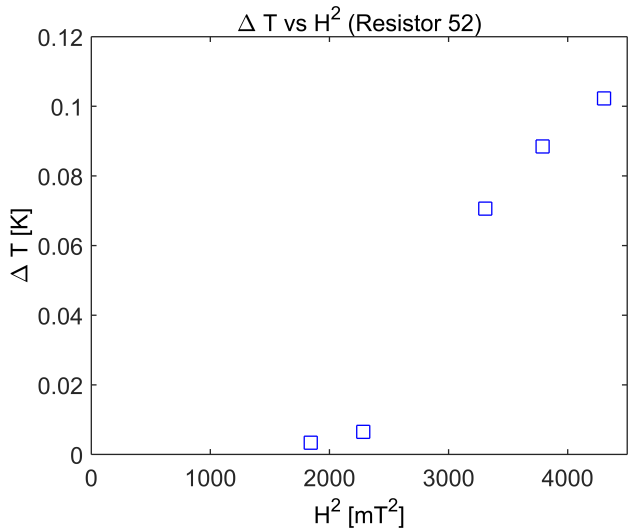

Figure 4: Heating in resistor near suspected quench area ΔT plotted against the square of the magnetic field, H^2.

also quenched at a significantly lower field, at 25 mT at a temperature of 1.6 K. Figure 5 shows these results.

The poor performance of this plate may have been due to the higher temperature used for deposition, 800 °C. Due to the material similarities between niobium and copper, we can approximate the diffusion of copper into niobium as the self-diffusion of copper. At this temperature, the self-diffusion coefficient of copper is approximately 5×10^{-11} cm^{2}s^{-1}, corresponding with a diffusion length for one hour of approximately 8.5 μm [8]. It is likely that a large amount of copper diffused into the RF penetration layer, creating normal-conducting regions and causing high RF losses.

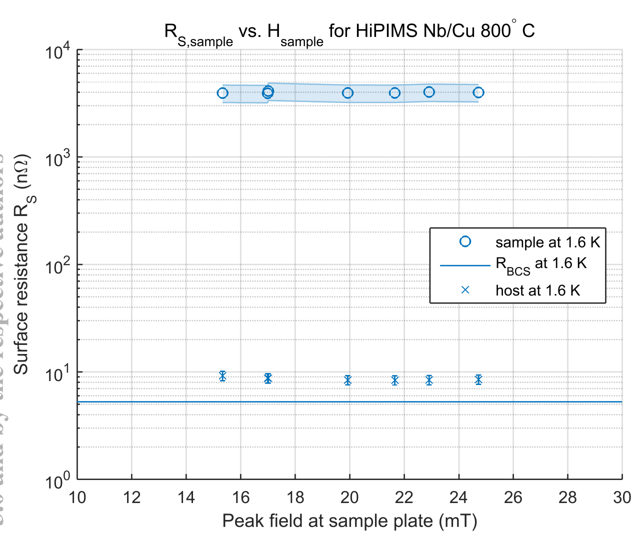

Figure 5: Surface resistance of the 800 °C sample at 1.6 K, compared with the surface resistance of the body of the cavity as well as the BCS prediction of R_s for niobium.

FORTHCOMING WORK

We plan to continue the testing of HiPIMS sample plates in the coming months, including samples deposited at room temperature with a voltage bias on the plate to increase binding energy. We also expect to perform surface analysis of the plates tested in this report, to investigate more closely what caused the quenches of each.

In addition, we plan to test plates coated with Nb_3Sn in the near future, both standard films produced at Cornell using vapor diffusion and multilayer samples produced at Jefferson Lab using magnetron sputtering.

CONCLUSIONS

We have tested two thin-film Nb/Cu plates using the Cornell sample host cavity. The plates were produced using HiPIMS, one at 500 °C and the other at 800 °C. The 500 °C plate showed a linear dependence of the surface resistance on applied field, ranging from 205±55 nΩ at low fields to 715±190 nΩ at 90 mT. These results are consistent with previously-measured Nb-on-Cu films such as the LEP2 cavities [5], but do not match the state of the art of HIPIMS [6]. Using T-map measurements, we determined that the quench was most likely caused by a surface defect. The 800 °C plate showed a constant surface resistance of 3985±735 nΩ, quenching at 25 mT. It is likely that this plate suffered from normal-conducting regions of copper in the RF penetration depth due to diffusion at the higher processing temperature.

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