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S. Sosa-Guitron
Old Dominion University

A. Gurevich
Old Dominion University

J. Delayen
Old Dominion University

E. Chang Beom

C. Sundahl

See next page for additional authors

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MEASUREMENTS OF RF PROPERTIES OF THIN FILM NB$_3$SN SUPERCONDUCTING MULTILAYERS USING A CALORIMETRIC TECHNIQUE

S. Sosa-Guitron*, A. Gurevich, J. Delayen
Center for Accelerator Science, Old Dominion University, Norfolk, VA 23517, U.S.A.
G. Eremeev
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, U.S.A.
C. Sundhal, C.-B.Eom
University of Wisconsin, Madison, WI 53706, U.S.A.

Abstract

Results of RF tests of Nb_3Sn thin film samples related to the superconducting multilayer coating development are presented. We have investigated thin film samples of $Nb_3Sn/Al_2O_3/Nb$ with Nb_3Sn layer thicknesses of 50 nm and 100 nm using a Surface Impedance Characterization system. These samples were measured in the temperature range of 4 K - 19 K, where significant screening by Nb_3Sn layers was observed below 16-17 K, consistent with the bulk critical temperature of Nb_3Sn.

INTRODUCTION

Progress in the superconducting radio-frequency (SRF) science and technology has pushed the Nb cavities close to their theoretical limits of operation, this limitation coming mainly from the superheating magnetic field. A further enhancement of SRF breakdown fields by using superconducting multilayer coating was proposed in [1]. As part of an ongoing project towards the multilayer development, we report here the results of investigation of two Nb_3Sn thin films which were fabricated at University of Wisconsin-Madison and characterized at Jefferson Lab using the Surface Impedance Characterization (SIC) system.

SAMPLE PREPARATION

Three superconducting film samples investigated in this work were grown at the University of Wisconsin, Madison. Two of them were Nb_3Sn films deposited onto a 0.3 mm thick sapphire wafer which had the diameter of 5 cm. A thick 0.2 mm Nb film was grown on the opposite side of the wafer to fully screen the RF field applied to the thin Nb_3Sn film. The structure of both Nb_3Sn film samples is shown in Figure 1. The thicknesses of Nb_3Sn films were 50 nm and 100 nm, respectively. The third sample was a 0.2 mm thick Nb film on sapphire without Nb_3Sn. This sample was used to evaluate the contribution of dielectric losses in the sapphire wafer.

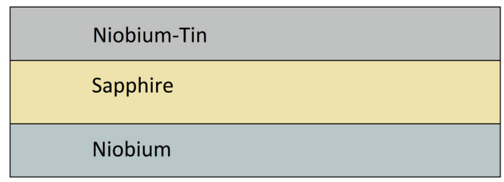

Figure 1: Sketch of the Nb_3Sn film sample. Nb_3Sn thickness is 50 nm and 100 nm, correspondingly. Sapphire substrate is 0.3 mm thick and Nb film is ~ 0.2 mm.

Nb_3Sn Film Growth

The Nb_3Sn film was grown by magnetron sputtering followed by annealing. For the 50 nm film, 6 alternating layers of Nb and 5 of Sn were grown, whereas the 100 nm film had 12 layers of Nb and 11 of Sn on the Al_2O_3 substrate. Each layer was grown under controlled Argon atmosphere pressure and the parameters summarized in Table 1, except for the first Sn layer, which was grown at 3 mTorr. Layer thickness corresponds to a growth time of 53.4 s for Nb layer and 52.4 s for Sn layer. [2] After sputtering, the structures were annealed at about 950°C for 15 mins. The 100 nm thick Nb_3Sn film attached to the SIC sample holder is shown in Figure 2.

Table 1: Nb and Sn sputtering parameters for 50 nm and 100 nm Nb_3Sn films.

	W. Pressure	Current to Target	Thickness
Nb	3 mTorr	0.1 A	5.6 nm
Sn	100 mTorr	0.07 A	3.3 nm

MEASUREMENT

SIC system has been widely used for the measurements of loaded cavity quality factor Q_L and surface resistance R_s of superconducting materials for particle accelerator applications [3] [4]. In this work the SIC system was used for the measurements of Q_L and R_s as functions of temperature. Specific details of SIC setup have been described elsewhere, for example, in [4], [5], [6] and [7]. Figure 3 shows SIC cavity with the 100 nm thick Nb_3Sn film sample loaded for the SRF measurements.

Superconducting samples were attached to SIC calorimeter under clean room conditions, using cryogenic-rated, N-

* salvaisg@jlab.org

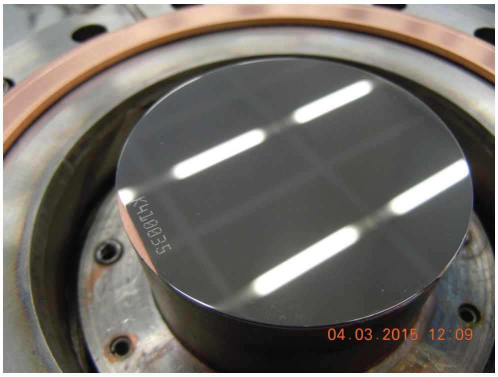

Figure 2: The 100 nm Nb_3Sn film sample attached to SIC calorimeter.

type Apiezon grease, which improves thermal contact between the sample heater and the superconducting sample. A stainless steel sample holder was then attached to the calorimeter on top and around the sample, and tightened at a constant torque. SIC was then vacuum-sealed and transported to the Vertical Test Area of Jefferson lab, where it was cooled down to 2 K for the Q_L and R_s measurements.

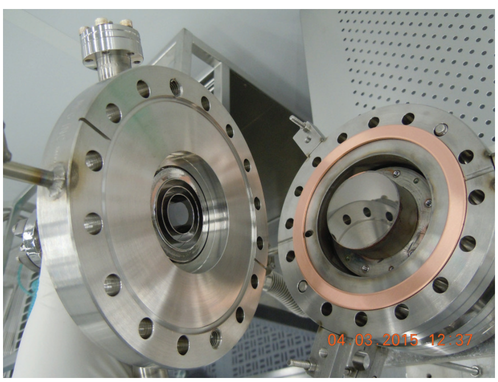

Figure 3: The 100 nm thick Nb_3Sn sample, center right, attached to the calorimeter of SIC before vacuum sealing for the measurements. Sapphire loaded cavity with choke joints is shown on the left.

Q_L Measurement

Loaded quality factor Q_L was determined by measuring a signal transmission coefficient s_{21} in a narrow bandwidth around the TE_{011} frequency of 7.4 GHz:

$$Q_L = \frac{f_0}{|f^{+(-3dB)} - f^{-(-3dB)}|}, \quad (1)$$

where f_0 is the resonant frequency and $f^{(-3dB)}$ is the frequency corresponding to half transmitted power. Figure 4 shows the measured Q_L values for all three samples as functions of temperature. The superconducting critical temperatures T_c were determined from the temperature dependence of the signal transmission coefficient $s_{21}(T)$ recorded during the Q_L measurement [4]. The measurements gave:

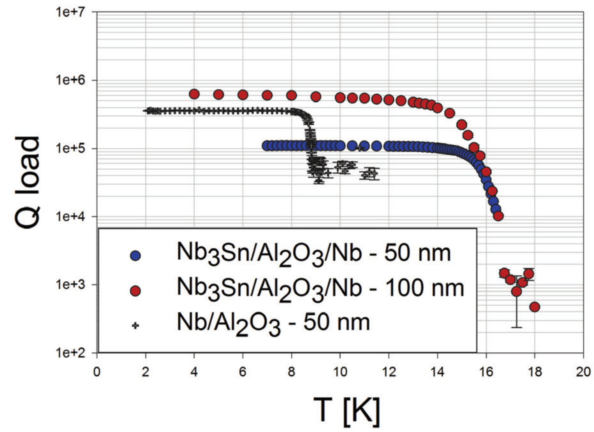

Figure 4: Q_L measurement results for Nb (black), 50 nm thick Nb_3Sn (blue) and 100 nm thick Nb_3Sn (red).

$T_c \simeq 8.88$ K for Nb sample, $T_c \simeq 17.4$ K for the 50 nm thick Nb_3Sn, and $T_c \simeq 16.75$ K for the 100 nm thick Nb_3Sn. The temperature dependencies of s_{21} are shown in Figure 5.

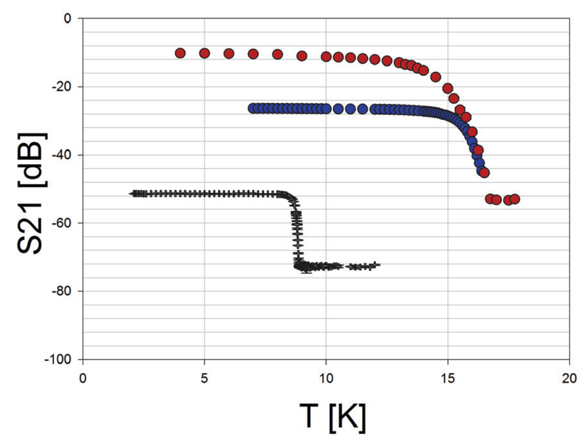

Figure 5: Signal transmission coefficient s_{21} vs T for critical temperature determination. Nb (black), Nb_3Sn - 50 nm (blue) and Nb_3Sn - 100 nm (red).

R_s Measurement

Surface resistance R_s was measures by a power compensation technique. Here, RF power P_{RF} dissipated on the sample was inferred from the difference between the heater power required to maintain the sample at a fixed temperature with and without an applied RF field. The surface resistance of the sample is obtained from:

$$R_{RF}(H_p, T_s) = \frac{P_{RF}(H_p, T_s)}{k \cdot H_p^2}, \quad (2)$$

where $k = 3.7 \cdot 10^7$ W/ΩT^2 is a geometry-dependent factor for a given frequency [4] [6]. It is also possible to determine

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R_s from the Q_L data using $R_s = G/Q_L$, where $G = 300\ \Omega$ is the cavity geometrical factor. The latter method is less accurate because it includes extra contributions from the cavity couplers. Figure 6 shows the results of R_s measurement

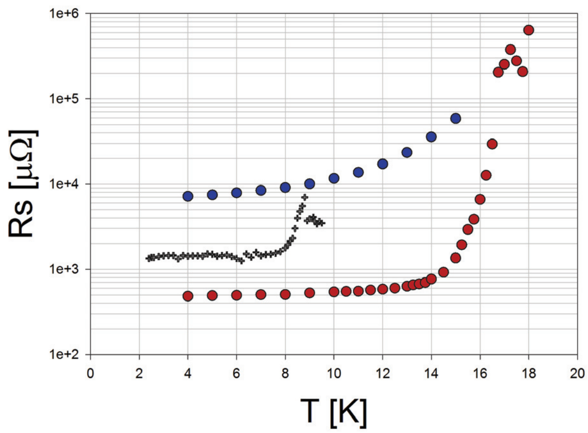

Figure 6: R_s measurement results for Nb (black), Nb_3Sn - 50 nm (blue) and Nb_3Sn - 100 nm (red). Nb and 50 nm thick Nb_3Sn samples were characterized using heater power compensation technique, 100 nm thick sample was derived from Q_L measurement.

for the three superconducting samples. Here Nb and 50 nm thick Nb_3Sn films were measured using the power compensation technique. For the 100 nm thick Nb_3Sn sample, R_s was inferred from the Q_L data.

DISCUSSION

Figure 6 shows that the 50 nm thick Nb_3Sn sample had the largest surface resistance. This can be attributed to the RF fields partly penetrating through the thin Nb_3Sn film into the substrate and causing dielectric losses in the sapphire. To corroborate this, a 100 nm thick Nb_3Sn sample was made for SIC characterization. The power compensation measurement was not available at that time so R_s of this sample was extracted from the Q_L measurements. We found that the residual resistance of this sample, even though it was not measured by the calorimetric technique, was indeed about an order of magnitude lower than R_{res} measured on the 50 nm film.

To analyze our data, we used the standard expression for the surface resistance at low temperature $T < T_c/2$:

$$R_s(T) = \frac{A\omega^2}{T} \exp\left(-\frac{\Delta}{k_B T}\right) + R_{res}. \quad (3)$$

Here the first exponential term describes the BCS contribution $R_{BCS}(T)$, where ω is the cavity angular frequency, Δ is the superconducting energy gap, A is a material related constant, and R_{res} is a temperature-independent residual resistance. The analysis of our data has revealed a large residual resistance which dominates over $R_{BCS}(T)$. For instance, for the 50 nm Nb_3Sn film and the Nb sample, which were both measured by the calorimetric method, R_{res} dominates over $R_{BCS}(T)$ from 4 K to 8 K. We obtained $R_{res} \simeq 1.3$ mΩ for the Nb sample and $R_s \sim 5.1$ mΩ for the 50 nm thick Nb_3Sn film sample. On the other hand, surface resistance of the 100 nm thick Nb_3Sn saturates at $R_{res} \simeq 0.5$ mΩ. The large residual resistances observed in our experiments can come from both material-related and the SIC-related sources which are subjects of the ongoing investigation.

CONCLUSION

We investigated two thin film Nb_3Sn samples measured using SIC system. Both the 50 nm and 100 nm films exhibit good superconducting properties and the respective critical temperatures of 17.4 K and 16.75 K close to T_c of stoichiometric Nb_3Sn. We observed a significant enhancement (by more than an order of magnitude) in the quality factor Q_L below T_c, which indicates good SRF properties of these Nb_3Sn films as well. However, the surface resistance of our films measured at temperatures $T < T_c/2$, is dominated by a large residual resistance. The work on reducing the residual resistance and optimizing the thin film growth conditions is ongoing.

ACKNOWLEDGMENTS

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