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PERFORMANCE OF SAMPLES WITH NOVEL SRF MATERIALS AND GROWTH TECHNIQUES*

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Abstract

Novel materials are currently being studied in an attempt to push accelerating superconducting RF cavities to support higher accelerating fields and to operate with lower power loss. Growing layers of these materials of the quality necessary has proven to be difficult. In this work, we present the SRF performance of planar samples of the promising materials, NbN and Nb_3Sn, grown using atomic layer deposition (ALD) and chemical vapor deposition (CVD) respectively. Results are promising.

INTRODUCTION

SRF technology for accelerator applications over the last four or five decades has focused almost exclusively on niobium (Nb). Despite its success, resulting from Nb's natural superconducting properties and enormous research efforts, there will come a time when intrinsic limits of Nb will not be able to provide cavities that can meet the requirements of future accelerators. Different superconductors must therefore be investigated. Candidate materials are those that, relative to Nb, can support larger RF fields in the Meissner state, operate with lower losses, and are (reasonably) easy and cheap to produce on a scale relevant to accelerator needs while maintaining extremely conformal and pure film depositions.

The behavior of superconductors exposed to microwave radiation with high field strengths between its lower critical field, H_{c1} and its superheating field H_{sh} is not fully understood, with current studies limited essentially only to Nb and Nb_3Sn. Obtaining data on the behavior of other superconductors exposed to fields at or approaching its critical levels would illuminate new faces of the superconducting state through showing how superconductors with different parameters behave. The study and RF characterization of non-Nb superconductors is therefore important not only to accelerators, but to improving the understanding of superconductors as a whole.

In addition to material studies, it is essential to investigate different growth techniques. Obtaining a uniform layer is highly important to SRF applications due to the tendency of cavities to quench (go normal conducting) at defects in the surface rather than from intrinsic material limitations. Further, non-ideal regions of surfaces can lead to greater losses and therefore increase the power requirements of an accelerator.

With the above in mind, the goal of this work is to study the microwave response of candidate SRF materials and growth techniques. Specifically flat 5" diameter samples of chemical vapor deposition (CVD) Nb_3Sn and atomic layer deposition (ALD) NbN, prepared respectively by Ultramet and Veeco-CNT, are exposed to non-uniform 4 GHz fields ranging from 1 – 35 mT at temperatures ranging from 1.6 – 4.2 K.

Nb_3Sn and NbN are of interest to accelerators because, grown correctly, they can reach critical temperatures (T_c) of 18 K and 16 K respectively (Nb $T_c = 9.2$ K) and BCS gap parameters (Δ) of 3.1 meV and 2.6 meV respectively (Nb $\Delta = 1.5$ meV) [1] [2]. The higher T_c and Δ theoretically reduce the surface resistance and could be used to significantly decrease refrigeration cost by enabling cryomodule operation at higher temperatures or potentially operation with a cryocooler-like mechanism. The superheating field of Nb_3Sn is almost twice that of Nb [3] and could theoretically allow for stronger accelerating fields.

The initial results presented here are promising. The surface resistance is extracted at 4.2 K with the Nb_3Sn and NbN, reaching surface resistances of 20 $\mu\Omega$ and 10 $\mu\Omega$ respectively. There have been more successful RF tests of both materials (Nb_3Sn (on bulk Nb - not copper as discussed in this work) [4]) (NbN - better surface resistance but at a very low field [5]) but these are, to the authors' knowledge, the best results obtained for these particular deposition technologies. Both of which should allow for significant improvement if the companies continue to refine their recipes to produce more perfect materials. Note that this is the best performance of Nb_3Sn on copper, as opposed to the much more expensive bulk Nb referenced above.

SAMPLES

RF test results for three sample plates are presented here.

- 1 – 3 μm CVD Nb_3Sn from Ultramet deposited on a 5" diameter copper substrate. XRD studies indicate portions of the surface have different atomic Sn concentrations ranging from 16% to 19%.
- 15 μm CVD Nb_3Sn from Ultramet deposited on a 5" diameter copper substrate. XRD studies indicate portions of the surface have different atomic Sn concentrations ranging from 19% to 21%.
- 100 nm ALD NbN from Veeco-CNT deposited on a 5" diameter Nb substrate.

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Table 1: Material Parameters (from literature) [2] [1] [6] [7]

	Clean Nb	19% Sn Nb_3Sn	22% Sn Nb_3Sn	T_c = 11 K NbN
T_c (K)	9.2	6	12	11
$\frac{\Delta}{k_b T_c}$	1.89	1.5	1.5	2
λ (nm)	39	89	89	450
ξ (nm)	38	7	7	4
l (nm)	1000	2	2	6

METHODS

RF testing is performed with Cornell's sample test cavity shown in Fig. 1. This cavity consists of a Nb body over which a 5" diameter plate is clamped. The RF surface of the plate can be coated with arbitrary material. A TE_{011}-like mode is excited at 3.96 GHz through a loop coupler. Peak fields up to ~ 100 mT have been observed on the sample plate.

The average surface resistance of the sample plate can be extracted by exciting the resonant mode, turning off the power, and then measuring the decay time of the energy stored in the cavity to obtain the average quality factor of the joint sample plate + Nb body cavity. Next, the cavity is simulated using microwave studios to obtain the fields present on the Nb body and the sample plate and a calibration test is performed using a Nb plate that is ideally similar in performance to the body. Combining this simulation and measurement can be used to find the amount of power dissipated on the cavity body - which is independent of sample plate. Thus the surface resistance is extracted by searching for the amount of extra dissipation not accounted for by the Nb body.

The system is currently suffering from an unknown source of residual resistance limiting the achievable surface resistance resolution to ~ 150 nΩ which limits what can be observed at low temperatures. At 4.2 K, where the resistances are significantly larger than this, measurements can be made with sufficient accuracy to extract information about the sample.

Trapped magnetic flux can lead to significant losses. To minimize this effect the test is performed in a magnetically shielded dewar to minimize ambient flux. Due to the bi-metallic structure of the plates, thermal gradients parallel to the interface (Nb-NbN or Cu-Nb_3Sn) can lead to current loops generating flux inside the material that can then be trapped. To minimize this, the helium transfer is performed slowly, allowing the contents of the dewar to equilibrate and thus reducing the thermal gradient. In this experiment the gradient from the center of the plate to its edge (measured by two Lakeshore Cernox sensors) was kept below 100 mK during the transfer.

Nb_3Sn RESULTS

The critical temperature was roughly measured through observations of flux expulsion during cool-down and the

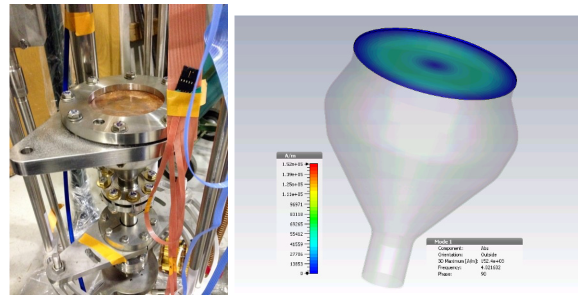

Figure 1: (Left) The realized cavity with the Ultramet Nb_3Sn-on-copper plate clamped on. (Right) Microwave Studios simulation of magnetic field strength on the sample plate. The Nb body is shown in gray and the sample plate is color coded blue-green depending on the field strength at a particular point. Note that the displayed field values correspond to the cavity storing 1 J of energy.

change of the position and shape of the reflected power resonance on a network analyzer during warm-up. These observed critical temperatures were consistent with XRD data showing a range of atomic tin concentrations from 19% to 21% which correspond to critical temperatures of 6 – 10 K. These measurements also suggest that atomic Sn concentration could be as high as 23% on some portions of the plate, corresponding to T_c = 14 K [7].

At 4.2 K the BCS resistance dominates. The 4.2 K surface resistance of the Ultramet Nb_3Sn plates at 3.96 GHz is shown in Fig. 2 (top). Along with the measured results, BCS predictions [8] for Nb_3Sn parameters corresponding to the observed T_c and atomic Sn content are shown for comparison. Parameters used are given in Table 1. The average surface resistance of the plate is all that can be obtained in this measurement, and thus the observed value for the thick-coated Nb_3Sn is between the two lines corresponding to 19% and 22% atomic Sn content. The surface resistance predicted for 16% and 19% is similar, so the thin coated plate is near the line corresponding to 19%. The BCS resistance can be improved by orders of magnitude by obtaining 24% or 25% Nb_3Sn films. This will be the focus of future work.

The residual resistance-dominated quality factor is shown in Fig. 2 (bottom) as a function of peak field on the sample. Due to problems with the test system it is difficult to make quantitative statements about the residual resistance of the plates. However, the low temperature performance of the thicker coated layer was comparable to the clean Nb calibration plate, which is promising.

The plate was subject to thermal quenching due to the thick coating, poor thermal conductivity of Nb_3Sn and the regions of the plate having a T_c of only 6 K. The highest field observed on the plate was roughly 25 mT prior to thermal quenching at 2.1 K

NbN RESULTS

The 4.2 K surface resistance of Veeco-CNT NbN plate at 3.96 GHz is shown in Fig. 3 (top). Material parameters for

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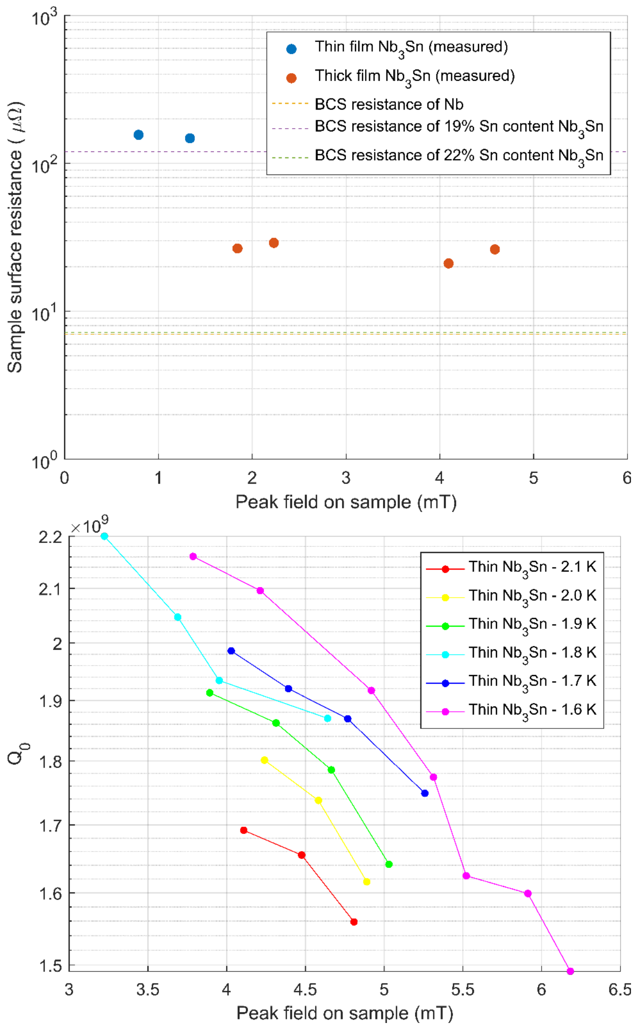

Figure 2: (Top) Measured surface resistance of the 15 μm Ultramet Nb_3Sn plate at 4.2 K and 4 GHz as a function of the peak field reached on the sample plate. BCS predictions for relevant parameters (displayed in Table 1) are shown as dashed lines along with the BCS prediction of clean Nb. (Bottom) Measured quality factor of the Nb body + Nb_3Sn plate system at 4 GHz as a function of the peak field reached on the sample plate.

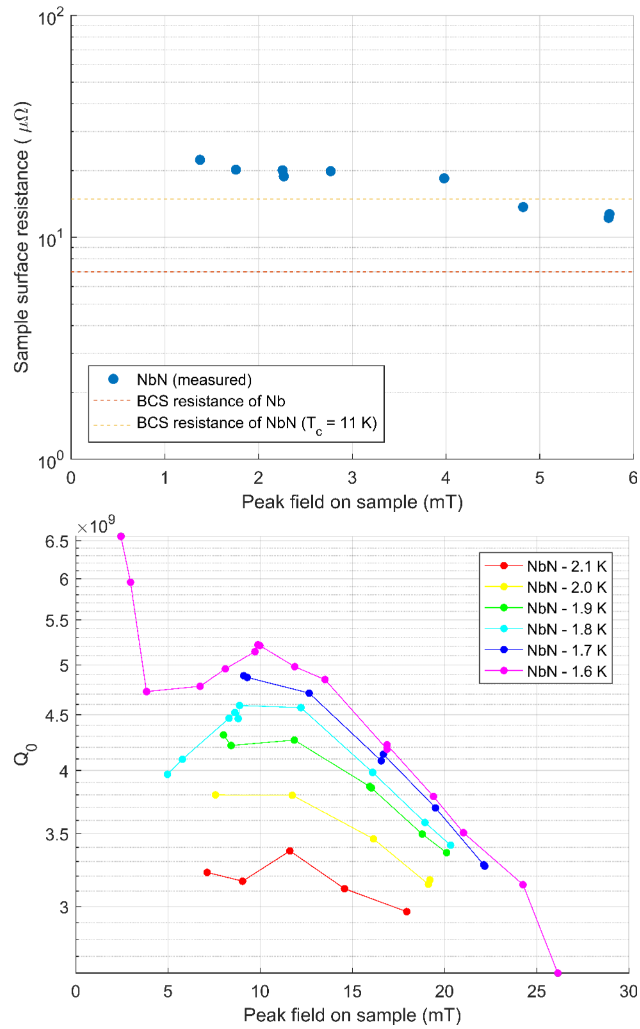

Figure 3: (Top) Measured surface resistance of the Veeco-CNT NbN plate at 4.2 K and 4 GHz as a function of the peak field reached on the sample plate. BCS predictions for relevant parameters (displayed in Table 1) are shown as dashed lines along with the BCS prediction of clean Nb. (Bottom) Measured quality factor of the Nb body + NbN plate system at 4 GHz as a function of the peak field reached on the sample plate.

this sample are not yet known, but by estimating their values from NbN literature it is possible to roughly estimate the T_c by seeing how BCS predictions [8] for various parameters compare to the measurements. A close agreement is found for $T_c = 11$ K as can be seen in Fig. 3. Parameters used for this calculation are shown in Table 1.

The residual resistance-dominated quality factor is shown in Fig. 3 (bottom). Again, the residual resistance cannot be found quantitatively. However, the low temperature quality factors were comparable (or perhaps even higher) than those of the Nb calibration plate. This is very promising for a first trial. Fields as high as ~ 30 mT were observed without quench.

CONCLUSION

Promising results are shown for Ultramet's CVD Nb_3Sn and Veeco-CNT's ALD NbN, reaching surface resistances of 20 $\mu\Omega$ and 10 $\mu\Omega$ respectively at 4 GHz and 4.2 K. Producing superconducting films is an accomplishment alone, but because the surface resistances of NbN and Nb_3Sn depend strongly on the ratios of the elements present in the crystal structures, it should be possible for Ultramet and Veeco-CNT to make small adjustments to their already successful recipes to produce truly revolutionary materials.

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