CVD Nb_3Sn-ON-COPPER SRF ACCELERATOR CAVITIES [*]

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Abstract

Nb_3Sn is the most promising alternative material for achieving superior performance in Superconducting Radio-Frequency (SRF) cavities, compared to conventional bulk Nb cavities now used in accelerators. Chemical vapor deposition (CVD) is an alternative to the vapor diffusion-based Nb_3Sn growth technique predominantly used on bulk niobium cavities now and may enable reaching superior RF performance at reduced cost. In collaboration with Cornell, Ultramet has developed CVD process capabilities and reactor designs to coat copper SRF cavities with thick and thin films of Nb and Nb_3Sn. In this paper, we present our latest research efforts on CVD Nb_3Sn-on-copper SRF cavities, including RF performance test results from two 1.3 GHz SRF cavities coated by Ultramet.

INTRODUCTION

Nb_3Sn is the most promising material for next-generation SRF cavities, as it can reach a T_c as high as 18 K and has the potential to double the gradients achieved by Nb [1]. Achieving higher operating gradients would decrease overall length and cost, while a high T_c would lead to an important reduction in cryogenic costs.

A vapor diffusion-based growth process for Nb_3Sn has given the best RF results from current growth methods [2], but it still performs well below the ultimate predicted limit of this material. Defects and surface roughness are limiting factors of these films so exploring alternative Nb_3Sn growth methods is important for improving performance beyond current limits.

The SRF Group at Cornell tested two 1.3 GHz single-cell SRF cavities. They are comprised of copper substrates with thin-film interior surface coatings of niobium interlayer/CTE(coefficient thermal expansion)-bridge and Nb_3Sn formed via chemical vapor deposition (CVD). The coating was performed by industry partner Ultramet using unique CVD precursor materials developed by researchers at Florida State University.

The copper cavity substrates were fabricated by Niowave (welded) and Bailey Tool (seamless). The high thermal conducting copper substrates were used to promote efficient heat dissipation for added thermal stability [3] and reduce per-cavity Nb requirements. Detailed RF performance test results are presented for the two cavities identified as SN 38-39 (welded) and SN 4 (seamless).

OBSERVATIONS FOR THE CVD COATING

Ultramet was able to achieve Nb_3Sn coatings on coupons ($\approx .75\,''\times .75\,''$) with a Sn content of $24-25\%$ using the processing developed during this project. However, scaling up the Nb_3Sn CVD process to obtain coatings with a consistent $24-25\%$ Sn content over large surface areas (e.g.: ILC cavities) has been found to be challenging. This is reflected in the RF test results presented below.

Both cavities had some degree of substrate surface texture/terrain issues/distress that might explain the low quality factors discussed below. This also encourages further copper cavity substrate manufacturing process and conditioning process development. Annealing at high temperatures might improve the surface structure, but the low melting point of copper makes that difficult. The Nb_3Sn coating had a crack in the beam tube section of SN 38-39. When Ultramet performed Nb_3Sn coatings directly on bare copper cavities (no CVD Nb interlayer) early in the project, there were no cracks in the Nb_3Sn coating. This might be explained by a much thicker coating of Nb_3Sn of $\approx$ 50-100 μm initially, versus the current thickness, 13-25 μm of Nb_3Sn on the surface. This crack might suggest the CVD Nb interlayer was too thin in the latest coating in that particular section, which is an issue that can be fixed with more process development. The CVD Nb interlayer was intended to function as a CTE-bridge to relieve stress between coating and substrate.

An optimized copper-Nb_3Sn ILC cavity (even with a thin CVD Nb interlayer) would reduce the per-cavity Nb raw material requirements by over 90% as compared to bulk Nb cavities.

Figure 1: SN 38-39 cavity on the RF testing insert under vacuum.

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[*] This work was supported by the DOE SBIR award DE-SC0017902 to Ultramet and by U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams

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SN 38-39 CAVITY TEST

Figure 1 shows an image of the cavity on the RF test insert. The mean free path, the critical temperature T_c, the energy gap Δ and the residual resistance determine the characteristics of the Nb_3Sn film on the surface. These all give information about the quality of the superconducting film. The Q versus E curve at 4.2 K and at temperatures below 4.2 K give information on the overall performance of the cavity and can be correlated with the other measurements.

The critical temperature for SN 38-39 is determined to be $T_c \approx 16.5$ K, by measuring flux expulsion when the Nb_3Sn film transitions from the normal conducting to the superconducting state.

The mean free path of the superconductor is determined by measuring the frequency of the cavity versus temperature. In practice the measurement is performed by warming the cavity from 4.2 K to the critical temperature T_c of the superconductor. The change in frequency is related to the change of penetration length of the RF fields in the superconductor, and that change in penetration length can be used to calculate the mean free path.

The measurement of the quality factor versus temperature can be directly related to the resistance of the superconductor versus temperature using the geometry factor of the cavity [4]. The resistance versus temperature data can be used to extract the energy gap and the residual surface resistance. In practice the cavity is cooled down below 4.2 K and measurements of the quality factor versus temperature are performed at a constant accelerating field.

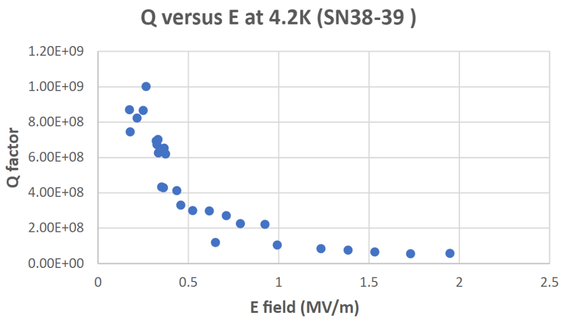

Figure 2: Q versus E at $T = 4.2$ K for SN 38-39.

Figure 2 shows the Q versus E plot at 4.2 K for the cavity SN 38-39. There is a strong initial Q drop at low fields with an overall low quality factor. The curve is relatively flat after a strong initial Q drop.

For comparison, vapor diffusion Nb_3Sn cavities formed on bulk niobium cavities routinely reach $T_c \approx 18$ K and $Q_0 \approx 2 \times 10^{10}$ at T= 4.2 K.

At $T = 1.9$ K, the Q versus E curve drops quickly and becomes flat at higher fields, as seen in Figure 3. At both 1.9 K and 4.2 K, the cavity did not quench, but the field was limited by maximum RF power. Also, the value of the quality factor is similar to the quality factor at T = 4.2 K.

Results from Q versus T testing for SN 38-39 are shown in Figure 4. The residual resistance was determined to be around a few μ Ohms, too high to determine the BCS resistance and energy gap Δ. The high residual resistance is likely due to surface contamination due to surface contamination at the end of the CVD process. A similar behaviour of low Q_0 was seen initially on the CVD Nb cavities. After a brief electropolishing, Q_0 improved significantly, as detailed in [3], proving that surface contamination was the cause of bad performance. As a final note, it is an artifact of the measurement that the resistance seems a little lower at higher temperatures. At higher temperatures the fields at which the measurements were taken were systematically smaller.

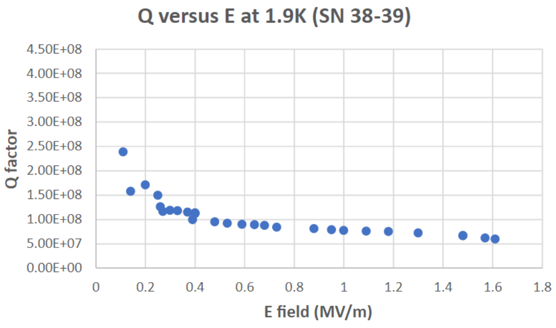

Figure 3: Q versus E, SN 38-39, at T = 1.9 K. The curve is relatively flat after a strong initial Q drop.

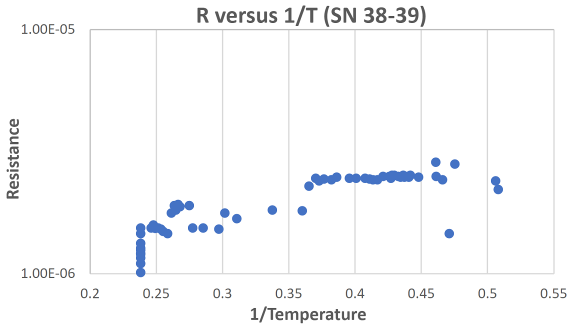

Figure 4: R (Ohm) vs 1/T (1/K)) for SN 38-39.

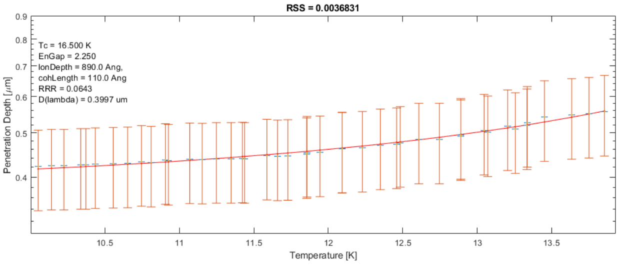

Figure 5: Frequency versus temperature fitting for SN 38-39.

Figure 5 contains the frequency versus temperature fit. The mean free path obtained from the analysis of f versus T is 0.385 nm. This is much smaller than Nb_3Sn mean free path obtained for state-of-the-art vapor diffusion Nb_3Sn-niobium cavities, which is ≈ 2 nm [5]. The small mean free path suggests that there is an abundance of defects in the surface layer, or significant impurities present.

SN 4 CAVITY TEST

An image of the cavity on the testing insert is shown in Figure 6. The measured performance of this cavity is similar to that of SN 38-39. The critical temperature is $T_c \approx 16.5$ K. The Q versus E curve is shown in Fig. 7 and, as before, there is a strong initial Q_0 drop and the fields are limited by maximum RF power, not by a quench. Q versus T was not measured as the residual resistance was too high to get information on BCS resistance and the energy gap. Figure 8 shows the analysis of frequency versus temperature for SN 4, and the mean free path (mfp) is determined to be 0.083 nm. This mpf is again much smaller than the mean free path for state-of-the-art vapor diffusion Nb_3Sn cavities on Nb substrates.

Figure 6: SN 4 cavity on the testing insert under vacuum.

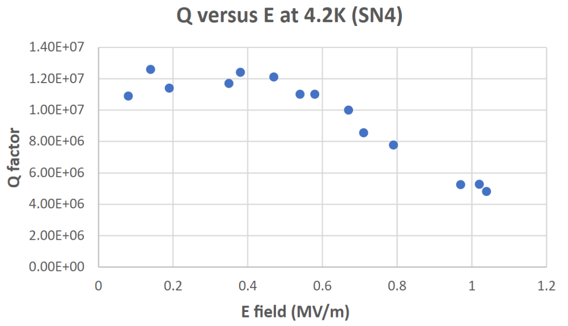

Figure 7: Q versus E for SN 4 at 4.2 K.

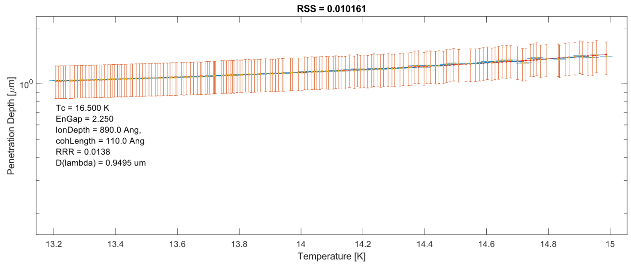

Figure 8: Frequency versus temperature fitting for SN 4.

Figure 9 is an image of the Nb_3Sn coating on the inside of seamless cavity SN 4. Upon removing the cavity off the insert following the RF test, Cornell researchers noticed "dust" of unknown composition from inside of the cavity. It was speculated that the change in temperature caused some of the Nb_3Sn coating to dislodge off from the cavity interior.

Figure 9: Image of the Nb_3Sn coating at the inner surface of RF test cavity SN 4 and location where dust residue was noticed upon removal of the RF test insert.

CONCLUSIONS

These cavities are the first-ever fabricated CVD Nb_3Sn-on-copper SRF cavities, and they were successfully tested at Cornell. Uniform and robust CVD Nb, and CVD Nb_3Sn coatings in the A15 phase were formed on copper cavity substrates of the 1.3 GHz single-cell ILC design.

The measured quality factors of the two Ultramet CVD Nb_3Sn cavities are low in comparison to those of state-of-the-art vapor diffusion Nb_3Sn-Nb cavities. This is thought to be in part due to a very high residual surface resistance, observed to be in the μ Ohm range. The critical temperature is around $T_c = 16.5$ K, which suggests that there are non-ideal relative concentrations of Nb and Sn present on the surface of the cavity. For comparison, vapor diffusion Nb_3Sn-Nb cavities reach $T_c \approx 18$ K and $Q_0 \approx 2 \times 10^{10}$ at $T = 4.2$ K. The mean free paths for SN 4 and SN 38-39 are quite small compared to that seen in high performing vapor diffused Nb_3Sn-Nb cavities ($mfp \approx 2$ nm), discussed in [5]. The small mean free path for both cavities suggests that there are significant defects in the surface layer, and/or that there are impurities.

These are promising initial results and future work is needed for CVD process scaling to optimize Sn-to-Nb ratio consistency, increase mean free path, reduce residual surface resistance, and continue copper cavity fabrication process development.

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