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RF RESULTS OF Nb COATED SRF ACCELERATOR CAVITIES VIA HIPIMS*

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Abstract

Bulk Niobium (Nb) SRF (superconducting radio frequency) cavities are currently the preferred method for acceleration of charged particles at accelerator facilities around the world. However, bulk Nb cavities have poor thermal conductance and impose material and design restrictions on other components of a particle accelerator. Since the SRF phenomena occurs within a shallow depth of 40 nm (for Nb), a proposed solution to this problem has been to deposit a superconducting Nb thin film on the interior of a cavity made of a suitable alternative material such as copper or aluminum. While this approach has been attempted in the past using DC magnetron sputtering (DCMS), such cavities have never performed at the bulk Nb level. However, new energetic condensation techniques for film deposition offer the opportunity to create suitably thick Nb films with improved density, microstructure and adhesion compared to traditional DCMS. One such technique that has been developed somewhat recently is "High Power Impulse Magnetron Sputtering" (HiPIMS). Here we report early results from various thin film coatings carried out on 1.3 GHz Cu cavities, a 1.5 GHz Nb cavity, and small Cu coupon samples coated at Jefferson Lab using HiPIMS.

INTRODUCTION

Superconducting radio frequency (SRF) cavities based on bulk Nb have been used for decades in particle accelerators [1]. In order to truly engineer the active SRF surface, one can take advantage of the shallow RF penetration depth by using an alternative material for the resonant cavity structure with more favorable bulk properties, such as Cu, and coating a ~1 µm Nb thin film as the active SRF surface. One can then optimize the RF response by tuning the various coating parameters available during film growth.

Thin film SRF cavities were first implemented in the 1980's at CERN for LEP II [2], with Nb/Cu thin film cavities deposited with DC magnetron sputtering (DCMS). While these films had good low field Q-values, they exhibited a strong decreasing dependence of the Q-value on RF field, known as the "Q-slope", limiting their applications. To this day, the cause of the Q-slope has not been fully understood and has yet to be overcome.

Many causes proposed for the Q-slope [3-5] can be associated with the low energy film deposition method utilized. DCMS has been shown to yield superconducting films with properties below the bulk material. Energetic condensation methods, such as high-power impulse magnetron sputtering (HiPIMS) promise to create films with enhanced SRF properties [6]. HiPIMS is easily adaptable to coating tri-dimensional shapes and can be implemented on existing DCMS cavity coating systems.

In HiPIMS, the magnetron is pulsed to extremely high-power densities thereby increasing the plasma density by several orders of magnitude and resulting in ionization of a significantly higher fraction of the metal atoms [7, 8], allowing control of the deposition energy by applying a substrate bias. HiPIMS has been shown to yield films with much improved microstructure, density, surface roughness, adhesion and overall quality compared to the low energy DC methods [9-12]. This opens the possibility to produce higher quality films for SRF application.

In order to explore HiPIMS for SRF, a cavity deposition system was designed, built and commissioned at Thomas Jefferson National Accelerator Facility (JLab) [13]. This system offers many benefits such as the ability to mount and unmount cavities while leaving the larger system under vacuum, allowing a higher turn-around cycle and reduced risk of contamination; it also allows deposition of small coupon samples under the same pump down cycle as the cavity through a load-lock and enables conditioning of the magnetron before deposition. A custom built HiPIMS pulser, powering a cylindrical Nb cathode in a Kr atmosphere, is used to deposit Nb films. Here we present early HiPIMS coated cavity results and data from small samples carried out in the same system.

EXPERIMENT

A small sample study of Nb films on Cu substrates was performed in order to investigate the effect of peak pulse power and applied voltage bias on the resulting film properties. The Cu substrates used were polished polycrystalline OFE Cu ultrasonically cleaned in successive acetone and methanol baths. After growth, the structural and surface properties of the samples (lattice parameter, grain size, orientation, roughness…etc.) were determined via X-Ray diffraction (XRD) and Electron Backscatter Diffraction (EBSD), and atomic force microscopy (AFM).

While the ultimate goal is to deposit Nb thin films on Cu cavities, it is important to first understand the film deposition process itself, thus, a known good RF Nb cavity surface was used as first substrate. Prior to the initial baseline RF test, the 1.5 GHz C100 end cell low loss (LL) Nb cavity was exposed to a buffered chemical polish (BCP) etch followed by a high-pressure rinse (HPR). While the 1.3 GHz low surface field (LSF) Cu

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cavities were acid etched via SUBU [14] and rinsed. For all the assembly stages, for coating or RF testing, the cavities were assembled in an ISO-4 cleanroom following stringent quality procedures. Cavities were also mounted under a portable clean hood that creates an ISO-5 quality environment in order to keep particulate contamination within the deposition system and on the deposition surface minimal. The coated cavities were RF tested in JLab's Vertical Test Area (VTA). After RF testing, the Nb film was stripped from the interior cavity surface by BCP for the next coating cycle.

RESULTS

Small Samples

A peak power and bias series of small samples was deposited with a fixed target to substrate distance of 10 cm, the same approximate distance as to the equator region of a 1.3 GHz LSF cavity. The power series samples were deposited at a constant Kr pressure of 3.9 mTorr, substrate temperature of 350°C, bias of -100 V and constant pulse parameters, 83 Hz frequency and 110 µs pulse width, while the peak power (voltage) varied between samples. Power values were varied between 69 and 391 kW. The bias series samples were held at the same deposition parameters, except for the pressure at 4.2 mTorr and peak power around 220 kW. The bias voltage was varied between 0 and -300 V.

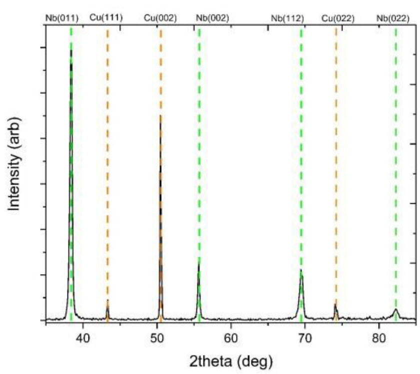

Figure 1: Representative XRD scan of Nb/Cu samples in power series

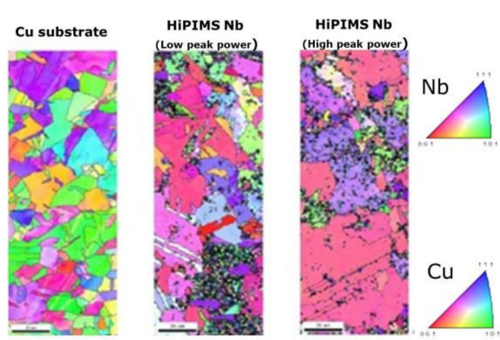

Figure 2: EBSD scans performed on Cu and Nb/Cu samples. From left to right: (a) an uncoated Cu substrate, (b) low peak-power Nb/Cu sample, and (c) high peak-power Nb/Cu sample. OIM color maps included on right for reference of crystal phases.

After deposition, the samples were analyzed using XRD to determine the resulting out-of-plane lattice parameter, grain size and mosaicity. The XRD scan in Fig. 1, shows a polycrystalline texture dominated by the Nb (011) phase. Average grain sizes were obtained using the Scherrer equation and the FWHM of the Nb (011) peak. Figure 2 shows an example of EBSD for the bare Cu substrate and two power series samples showing hetero-epitaxial growth of the film on the polycrystalline Cu. It is also noteworthy that no sharp features, detrimental to the RF performance, were observed on the surface.

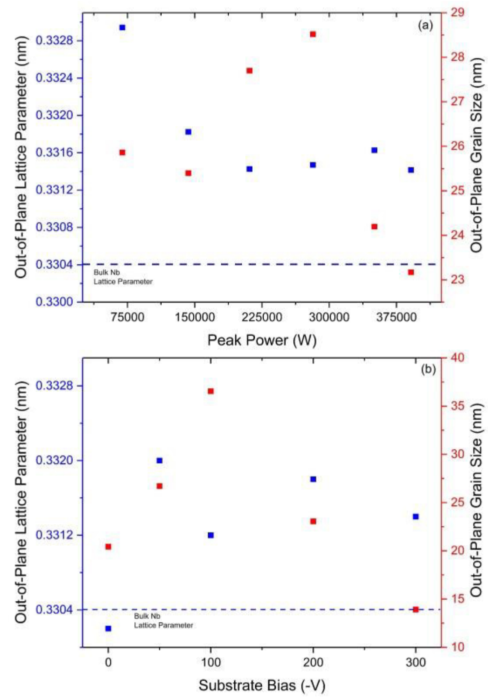

Figure 3: Plot of lattice parameter and grain size vs. (a) peak power in Nb/Cu power series and (b) applied bias in Nb/Cu bias series.

Figure 4 shows the surface roughness measured by AFM. The samples exhibited very low roughness for lower peak power and sample bias, on the order of the underlying Cu substrates. However, both show a strong increasing trend with peak power and bias, with bias much more strongly scaled, hinting at possible roughness limitation of applied bias near RF layer.

Cavity RF Results

Two Nb coatings were performed on the same Nb LL cavity. In between these two cycles, the coating system underwent a major vacuum system upgrade while keeping the overall deposition design fundamentally unchanged.

Figure 5 shows RF results for both coatings done on the LL Nb cavity with their respective baseline RF test results. Both cavities were tested without high pressure water rinsing. The first Nb coating showed a low-field Q equivalent to the underlying bulk Nb and maintained a reasonably flat Q up to 10 MV/m. The performance was limited by field emission beyond 10 MV/m. The second

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coating showed a good low-field Q but exhibited a thermal switch.

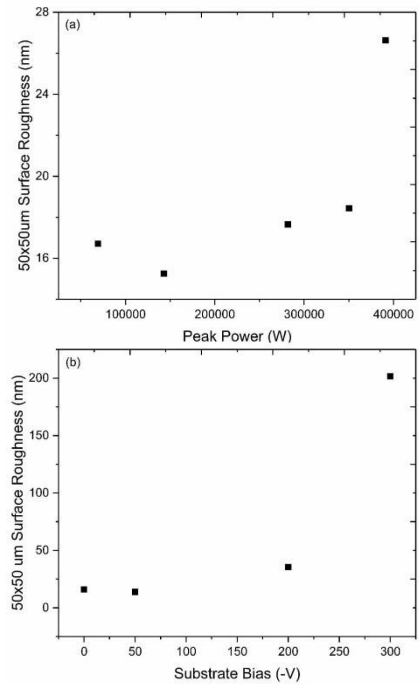

Figure 4: Plot of RMS roughness, on 50×50 µm scale, vs (a) peak power for Nb/Cu power series samples, and (b) applied bias for Nb/Cu bias series samples. Note the roughness scale difference compared to the power series results above.

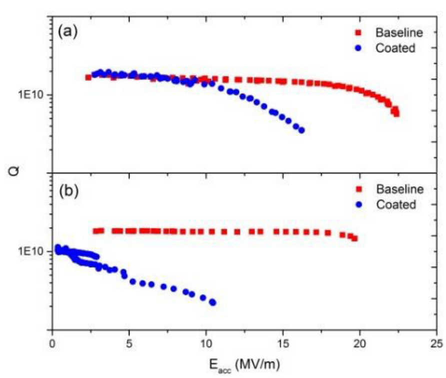

Figure 5: Quality Factor of Nb/Nb coatings (B_{peak}/E_{acc}=4.19) before (red) and after (blue) coating for (a) the first and (b) the second coating done at JLab.

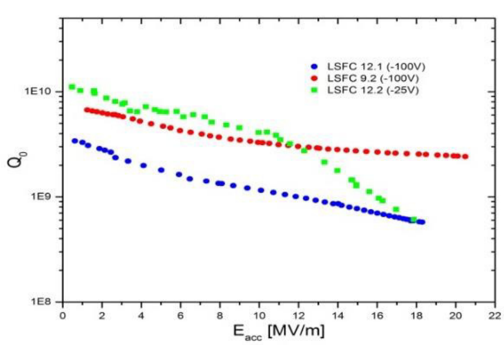

Figure 6: Quality Factor of HiPIMS Nb/Cu LSF cavities (B_{peak}/E_{acc}=3.68). No field emission was detected.

Nb/Cu RF results are shown in Fig. 6, where the cavities exhibit low field Q values in the mid to high 10^9 range and performing up to ~21 MV/m. After high pressure water rinsing, the Nb/Cu cavities had no detectable field emission. The first Nb/Cu coating (LSFC12.1) was hindered by a misalignment of the Nb cathode during coating, i.e. a non-uniformity in coating thickness. After cathode alignment corrections, the same coating parameters were applied to LSFC9.2 which showed a net improvement. However the film had a T_c of 9.5 K suggesting significant intrinsic stress in the film. In an effort to reduce the stress in the film, the next coating was performed at a lower bias (-25 V). The cavity (LSFC12.2) exhibited a slight improvement at low field but had a mid-range Q-slope that seems to be substrate related. These results show a gradual increase in performance of films deposited in this system and hold promise for future film manipulation for RF performance improvement.

CONCLUSION

The results presented here have shown that HiPIMS has great promise for high quality SRF thin films. Small coupon samples were produced with bulk-like lattice parameters and low roughness with implications for future surface engineering. The preliminary results on cavities have also shown great promise. We have achieved a Nb thin film cavity with a Q value equal to that of its bulk Nb counterpart at low field and remaining relatively flat up to 10 MV/m. Also, we have deposited Nb/Cu cavities that exhibit performance in line or better than previously reported results at similar deposition parameters. These give a starting point to begin pursuing control over the flaws observed in the technology over the last 40 years.

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