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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 at surfaces within a shallow depth of ~ 1 mm, 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 a 1.5GHz Nb cavity and small coupon samples coated at Jefferson Lab using HiPIMS.

INTRODUCTION

Superconducting radio frequency (SRF) cavities have been used for decades in particle accelerators around the world. SRF allows a particle accelerator to operate in a high duty cycle, or CW mode, due to the significantly reduced heat generation in the superconducting material, as well as low beam impedance and high efficiency of RF power transfer to the beam [1]. Throughout the history of SRF, cavities have been made from bulk Nb shaped and welded into adequate resonant cavity designs. However, bulk Nb imposes several drawbacks. First, Nb can exhibit significantly varied RF properties based upon how the Nb material was originally processed, pertaining the cavity construction and conditioning. In particular, due to its refractory metal nature, Nb can be notoriously difficult to machine and weld into the required resonant cavity shapes. Second, since some heat is still generated by a superconductor in the RF mode and the system must be operated at 2K, the poor thermal conductance of Nb can lead to high cryogenic cooling costs. Lastly, niobium itself is a costly material compared to copper or aluminum. As mentioned earlier, one alternative proposed is to take advantage of the shallow, ~1µm, depth of the SRF phenomena by using an alternative suitable material for the resonant cavity shape and coating the interior active surface with an appropriate superconducting thin film, such as Nb. Thin films offer many advantages over bulk materials due to the possibility of engineering the resulting film, and thereby surface, properties using the various processing parameters available during the film growth and coating the interior of materials with more favorable bulk properties, such as Cu, thereby reducing the production as well as operating costs of SRF accelerating structures.

Thin film SRF cavities have been attempted in the past with limited success. The first time thin film Nb cavities were attempted in earnest was in the 1980’s at CERN for the LEP accelerator [2]. CERN deposited Nb thin films on the interior of Cu cavities using DC magnetron sputtering (DCMS) and DC biased diode sputtering. While the CERN films exhibited good low field Q-values, they had a major downside, which was the observed strong dependence of the Q-value on RF field. That is, as the accelerator was driven to higher power the efficiency of the cavity strongly decreased. This behavior was termed the “Q-slope”. Even with this problem, CERN used Nb/Cu cavities in the LEP and LHC facilities since the cavities still met the operating criteria and exhibited enhanced magnetic properties allowing reduction of shielding in the system. To this day, the cause of the Q-slope has not been fully understood and no Nb thin film cavities have overcome this defect. Many explanations have been proposed as the cause of the Q-slope such as poor film-substrate interface, poor Nb thin film quality and even microscopic film delamination leading to a feedback system of heating; but none have been unequivocally demonstrated [3,4,5].

Of the many causes proposed for the Q-slope, many can be associated with the film deposition methods utilized. DC sputtering is a low energy deposition method and, even though it is still quite good for many other applications, it has been shown to yield films with properties below their bulk counterparts for the case of superconducting materials. Therefore, one proposed solution is to explore more energetic condensation methods, such as: high power impulse magnetron sputtering (HiPIMS) or electron-cyclotron resonance (ECR), to create films with enhanced properties more suitable for SRF application [6]. However, due to the geometric challenges of coating the interior of SRF cavities some techniques are more easily adapted than others. HiPIMS is one such technique which offers the ability to coat the interior of an SRF accelerating cavity using existing DCMS systems. HiPIMS works on the principle of pulsing the magnetron to extremely high power densities thereby increasing the plasma density by several orders of magnitude over DCMS plasma resulting

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Table 1: Properties of the Nb Samples Deposited Using Different Peak Powers

Sample	Peak Voltage (-V)	Peak Current (-A)	Peak Power (kW)	Lattice Parameter (nm)	Grain Size (nm)	RMS Roughness (nm)
A	360	115	41.4	0.3318	26.75	20.44
B	390	185	72.15	0.3326	26.62	27.86
C	411	232	95.35	0.3325	24.17	NA
D	360	304	109.44	0.3309	30.56	19.41
E	435	312	135.72	0.3318	26.67	20.75

in a superior ability to ionize a significant fraction of the sputtered metal atoms [7,8]. Having a large ion fraction enables control of the deposition energy by applying a bias to the substrate. 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 for some materials [9,10,11,12]. This opens the possibility of being able to coat the interior of an SRF cavity with a high quality Nb film and possibly overcome the Q-slope.

In order to explore HiPIMS created films, 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 actual deposition system under vacuum; it also allows deposition of small coupon sample tests under the same pump down cycle as the cavity through a load-lock and enables conditioning of the magnetron cathode before deposition of the actual cavity. Recently, this system has been used to deposit Nb thin films using a custom built HiPIMS pulser on small samples and the interior of a 1.5GHz Nb cavity. While the ultimate goal is to deposit Nb thin films on the interior of cavities made of materials other than Nb, it is important to first understand the film deposition process itself, thus, a known good RF cavity surface was used. Here we present early HiPIMS coated cavity results from the JLab cavity deposition system and data from small samples carried out in the same system.

EXPERIMENT

Small coupon samples and cavities were coated using the Jefferson Lab cavity deposition system. This system contains features designed to allow deposition of small samples via a load-lock port and an isolatable cavity attachment section in order prevent venting the entire vacuum system for each cavity mounting, with the consequent loss of time and possibility of increased contamination.

A small sample study of Nb films on Cu substrates was performed in order to investigate the effect of peak pulse power on the resulting Nb film properties. Cu substrates were pre-processed by performing mechanical polishing on a Buehler Planarmet 300, then electrically polished to achieve the final desired finish. Prior to growth, the substrates were ultrasonically cleaned in an alternating acetone and methanol bath.

The 1.5GHz C100 end cell low loss Nb cavity went through many pre-processing steps prior to thin film deposition and after RF testing. Prior to the initial baseline RF test, the cavity was exposed to a buffered chemical polish (BCP) etch followed by a high pressure rinse (HPR). Before coating the cavity was degreased, cleaned and assembled in a cleanroom to limit particulate contamination on the deposition surface. After the cavity was coated with a fresh Nb film and RF tested, the cavity had the film stripped from the interior surface by an adequately long BCP etch based upon the thickness of the deposited Nb film. For all the assembly stages, as well as for coating or RF testing, the cavity was assembled in a ISO-4 cleanroom following stringent quality procedures. The cavity was 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.

After growth, the structural properties of the coupon samples (lattice parameter, grain size…etc.) were determined via X-Ray diffraction (XRD) using a PANalytical 4-circles diffractometer, while the surface morphology was investigated by atomic force microscopy (AFM) using a Digital Instruments Scanning Probe Microscope (SPM). The cavity coatings were RF tested at Jefferson Lab in their Vertical Test Area (VTA).

Small Samples

A series of small samples were deposited using a cylindrical Nb cathode in a Kr atmosphere with a fixed target to substrate distance of 10cm, the same distance as to the equator region of a 1.3GHz low surface field SRF cavity. As can be seen from Table 1, samples were deposited at a constant Kr pressure of 3.6mTorr, substrate temperature of 350 Celsius, sample bias of -100V and constant pulse parameters while peak power (voltage) of each pulse was changed between samples. Power values were varied between 41 and 135 kWatts.

The desired goal was to achieve films with superconducting properties as close to bulk like as possible. After deposition, coupon samples were analyzed using XRD to determine the resulting out of plane lattice parameter, grain size and mosaicity. From the XRD scans in Fig. 1, we note that our samples exhibit polycrystalline texturing dominated by the Nb(011) phase suggesting that heteroepitaxial growth. Average grain sizes were obtained using the Scherrer equation and the FWHM of the Nb(011) peak, evidencing that all the samples had grain-size values between 24 and 31 nm. Also, the lattice parameters varied between 0.331 and 0.3326 nm, which are all slightly greater than the bulk value of 0.33nm.

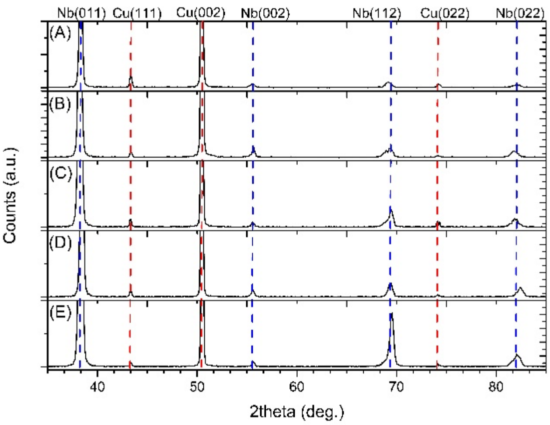

Figure 1: XRD scans from the power series calibration samples measured. The letter labels correspond to those in Table 1. Samples exhibit polycrystalline texturing with a strong Nb(011) peak and smaller reflections seen from other phases.

Analysis of the surface morphology of the samples was performed at the W&M Applied Research Center (ARC) labs by Olga Trofimova using the surface profiler system mentioned above. A representative scan of the AFM results can be seen in Fig. 2. All the samples exhibited RMS roughness values between 19 and 28nm, on a 50x50μm scale, showing a qualitatively smooth surface similar to the underlying copper substrate. It is noticeable that no sharp features were observed on the surface, which would be detrimental to the RF performance in an actual SRF cavity, however the samples did contain slight pitting similar to the Cu substrate.

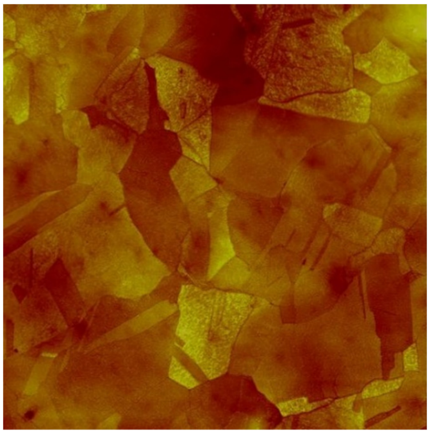

Figure 2: Representative AFM scan of the resulting Nb surface of the power series samples grown for this study. Scans show qualitatively smooth surface with crystal structure similar to the underlying copper substrates.

The goal of the small sample power series performed above was to observe correlations between film properties and the applied peak pulse power and to determine the optimal power parameter for performing cavity depositions. When determining the optimal deposition parameters for a film on a cavity, a logical starting point would be to use such parameters that led to films with the most bulk-like properties, such as lattice parameter. Figure 3 shows the results from the small sample tests plotting the lattice parameters of the samples and RMS roughness versus the peak power. As can be seen from the graphs, the parameter set that exhibits the most bulk-like lattice parameter and a minimum in the RMS surface roughness is around 110kW peak power. This information set the starting point for the deposition parameters during cavity deposition.

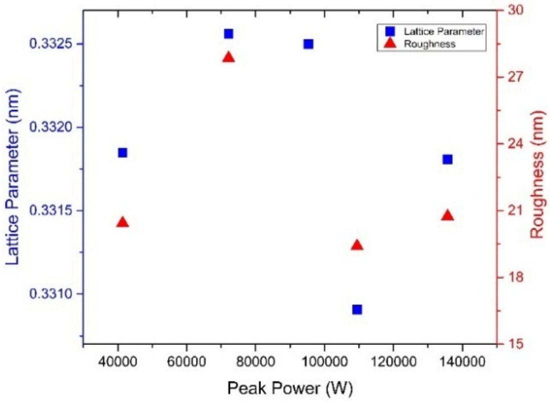

Figure 3: Plot of the Nb sample lattice parameter and surface roughness as a function of the peak deposition power. A minimum in the surface roughness and the most bulk like lattice parameter coincide at the approximate 110kW peak power setting.

Cavity RF Results

Using the optimized parameters determined in the small sample power series, cavities were deposited to test the resulting RF properties of the film. The first cavity coating was deposited using a preliminary design for the cavity deposition system immediately before the entire system was overhauled, cleaned and rebuilt with a multitude of upgrades to the vacuum hardware while keeping the overall deposition design fundamentally unchanged. Therefore, the second cavity coating was meant as a confirmation of the consistency between the RF results of the respective films and system designs.

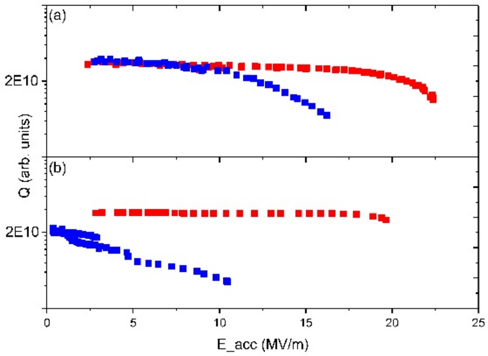

Figure 4: Plot of the quality factor of the Nb cavities before (red) and after (blue) coating. (a) corresponds to the first coating attempt done at JLab while (b) corresponds to the second. Coating (a) exhibits high low field Q and shallow Q-slope up to 10MV/m while coating (b) exhibits behavior indicative of a thermal switch.

The RF tests were performed at JLab in the VTA where a large variety of accelerating structures are tested on a regular basis. The main graph of interest in the present study is the cavity Q-value vs the accelerating gradient. Since the main challenge facing thin film cavities is the Q-slope, it is very valuable to observe the relative Q-slope between various thin film cavities and compare how the low field Q values behave for various parameters. Figure 4 shows the RF results for both cavity coatings done at JLab overlaid with their respective baseline RF test results. As can be seen, the first cavity coating showed a low field Q equivalent to that of the bulk Nb, even slightly larger than baseline, and maintained a reasonably flat Q up to 10 MV/m. The second cavity coating yielded more unique results. The graph shows a good low field Q, but also a sharp drop in the Q value around 1.5 MV/m. This drop is also part of a hysteresis curve. The behavior exhibited here is indicative of a thermal switch. This is a phenomenon usually occurring due to a non-superconducting contaminant on the surface of the RF cavity. As the applied power is increased, the contaminant begins to heat up and raise the temperature of the surrounding cavity. This causes and at a certain point causes a small area to rise above the critical temperature and results in a sharp decrease in the cavity Q. Due to the transient nature of superconductors this scenario then has a different behavior when reducing the applied field and cooling resulting in a hysteresis curve as observed.

CONCLUSION

The results presented here have shown that HiPIMS has great promise for future work in creating high quality superconducting thin films for RF applications. We have created small coupon samples with bulk-like lattice parameters and relatively smooth surfaces free from sharp defects that are detrimental to RF surfaces. 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 10MV/m. Even with the observed thermal switch present in the second cavity coating, the results are promising for future SRF thin film cavities. They give a starting point to begin pursuing control over the flaws observed in the technology over the last 40 years. Overall, the results of films deposited on small coupon samples and cavities have shown good results and show promise for HiPIMS technology to be used to create high quality RF thin films.

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