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INVESTIGATION OF HiPIMS-COATED S(I)S STRUCTURES FOR SRF CAVITIES

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Abstract

The sustainable next generation particle accelerators require innovative solutions to overcome the current technological challenges set by existing bulk niobium superconducting radio-frequency (SRF) cavities. Thin film-based multilayer structures in the form of superconductor-insulator-superconductor (SIS) may be the long-sought-after breakthrough for higher performance SRF cavities by enhancing both accelerating gradients and quality factors. In order to understand better the underlying mechanisms of SIS structures to be coated onto (S)RF cavities, we study various material properties with the resultant superconducting properties of high-power impulse magnetron sputtering (HiPIMS)-coated S(I)S structures of Nb-(AlN)-NbN with different thicknesses which are designed to be coated mainly on OFHC copper (Cu) samples for more efficient SRF cavities. This contribution presents materials properties of the aforementioned HiPIMS-coated S(I)S structures as well as the superconducting and RF behaviours of these multilayers which are assessed comparatively via DC and AC magnetization techniques.

INTRODUCTION

The existing bulk niobium (Nb) superconducting radio-frequency (SRF) cavity technology, which has been the leading accelerator technology so far, is close to its theoretical field limit. Besides, field-dependent performance degradation along with local breakdown phenomena restrict not only achievable accelerating gradients, but also quality factors of bulk niobium SRF cavities [1]. Accordingly, innovative solutions need to be introduced to realize ever increasing high performances with reduced infrastructural and operational costs so as to build the next generation compact particle accelerators which would outperform the state-of-art particle accelerators based on bulk Nb, and surpass the expected accelerating gradients of 50 MV/m together with reduced RF losses.

In order to achieve these breakthroughs, one of the promising solutions is coating inner surface of (S)RF cavities with alternating thin film-based multilayers in the form of superconductor-insulator-superconductor (SIS) structure given the fact that magnetic field penetration is a surface phenomenon (i.e., RF field penetration depth for bulk Nb is only about 40 nm.).

The theory, proposed by A. Gurevich, for *the alternating multilayer structures for SRF cavities* [2], especially for bulk niobium cavities, says that the simplest alternating multilayer structures (SIS), made of superconductive thin films with thicknesses less than the London penetration depth of the cavity wall material, enhances not only the quality factor (Q_0) with lower surface resistance (R_s), but also the vortex penetration field by means of the insulating layers.

Theoretically, the SIS structure is a stronger candidate to increase the theoretical field limit as well as the onset of the vortex penetration by means of the insulating layer, provided that the optimum layer thicknesses and material combinations are realised, as compared to the SS bilayer structure without any insulating layer. However, the SS bilayers are also worth studying as being a simpler structure with promising RF performance of the SRF cavities by enhancing the vortex penetration onset via SS boundary [3].

As being an emergent scalable sputtering technique, high-power impulse magnetron sputtering (HiPIMS) provides means to improve the quality of the deposited films by producing higher quality deposited films in the recent years thanks to its highly ionized denser plasmas, as compared to conventional physical vapor deposition techniques, yielding more effective control of the kinetic energy of the sputtered species with high ionization fractions, which arrive onto the substrate surface, so as to allow fine tuning of parameters of deposition processes [4].

In this paper, the assessment results of the HiPIMS-coated SS and SIS structures based on materials characterizations such as scanning electron microscopy (SEM) as well as superconducting and RF characterization techniques such as vibrating sample magnetometer (VSM), and quadrupole resonator (QPR), respectively are detailed.

EXPERIMENTAL METHODS

The multilayer SS and SIS structures in the form of Nb / NbN and Nb / AlN / NbN were coated mainly onto silicon

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as witness samples, in order to study in detailed the deposition parameters, as well as onto the OFHC Cu substrates (QPR) by (reactive)-HiPIMS technique via a fully automated coating machine (CC800) of CemeCon AG GmbH at University of Siegen as shown in Fig. 1.

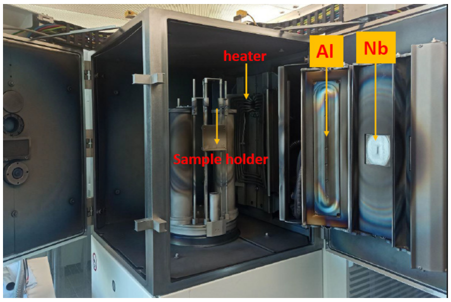

Figure 1: The overview of the sputtering machine (CC800) capable of DCMS and HiPIMS at University of Siegen (USI).

The detailed description of the deposition processes as well as the details of the machine (CC800) components at USI were reported previously [5].The materials characterizations of all deposited films were done at USI as well.

The superconducting properties (e.g., the superconducting critical temperature (T_c), and the entry field ($B_{en} \sim B_{c1}$)) of the deposited SS (Nb / NbN) and SIS (Nb / AlN / NbN) samples with thicknesses of (2.5 µm / 1µm) and (3 µm / 40 nm / 200 nm), respectively, whose deposition parameters are detailed in Table 1, were characterized at IEE SAS via vibrating sample magnetometer (VSM) technique as shown in Fig. 2.

Table 1: The deposition parameter window of HiPIMS-coated S(I)S structures for VSM measurements

Material	Cathode Power Density [W/cm^2]	Substrate Bias [V]	Deposition Pressure [mbar]	N$_2$ Content [vol%]
Nb	6.82	50	2.0 x 10^{-2}	0
(AlN)	7.14	0	6.0 x 10^{-3}	100
NbN	6.82	50	2.0 x 10^{-2}	8

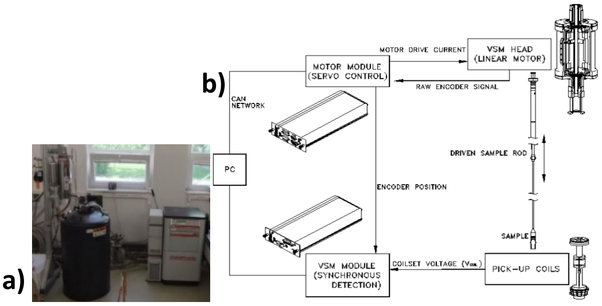

Figure 2: The vibrating sample magnetometer, a) Quantum Design Inc., model 6000 with the VSM option at IEE SAS, b) the operating principle of VSM technique – adapted from [6].

The deposition parameters of HiPIMS-coated SIS and SS structures with thicknesses of (3 µm / 180 nm) and (3 µm / 35 nm / 180nm nm), respectively, analysed with Cu-QPR sample tests at HZB as shown in Fig. 3, are detailed in Table 2.

Table 2: The deposition parameter window of HiPIMS-coated S(I)S structures for QPR tests

Material	Cathode Power Density [W/cm^2]	Substrate Bias [V]	Deposition Pressure [mbar]	N$_2$ Content [vol%]
Nb	4.55	50	8.0 x 10^{-3}	0
(AlN)	7.14	0	6.0 x 10^{-3}	100
NbN	4.55	50	2.5 x 10^{-2}	10

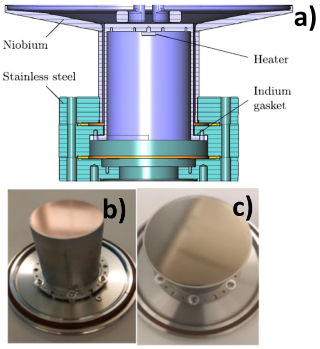

Figure 3: a) The schematic overview of the QPR system at HZB - adapted from [7], b) The uncoated Cu-QPR sample, c) The HiPIMS-S(I)S (Nb/(AlN)/NbN)-coated Cu-QPR sample.

RESULTS AND DISCUSSION

The effects of the certain deposition parameter space of HiPIMS technique on morphological, microstructural, stoichiometric, and interfacial properties of the SS and SIS multilayer structures were assessed through various materials characterization techniques and those results were published [5].

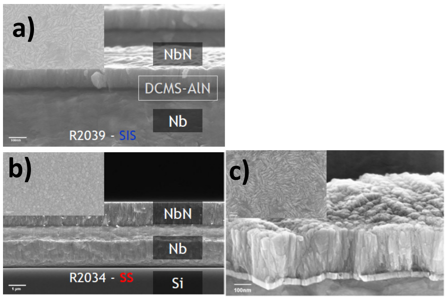

Figure 4: The SEM images of surface and cross-section of a) SIS, and b) SS structures deposited for VSM measurements – adapted from [5], c) SIS structure deposited for QPR test.

The morphology of the HiPIMS-coated SIS for QPR shows more faceted features along with enhanced columnar microstructure, as shown in Fig. 4, compared to HiPIMS-coated SIS structure for VSM measurements.

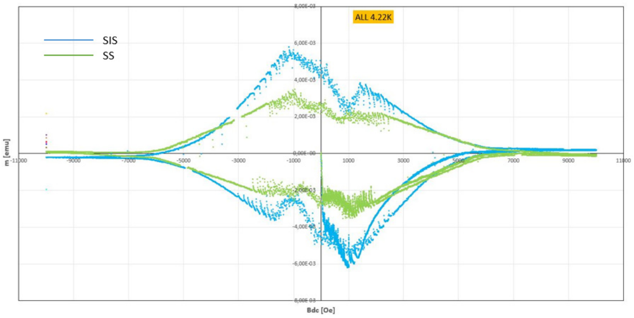

Figure 5: The dc magnetization curves of SIS and SS structures measured via VSM technique.

The determination of the B_{en} [Oe] for both SIS and SS structures were not straight forward given the fact they do show several flux jumps as shown in Fig. 5. The meaningful comparison that could be done from the obtained dc magnetization curves of SIS versus SS structures was that the flux jumps start to appear at lower magnetic field for the SS structure with respect to the SIS structure, hinting that SIS structures could be indeed a better candidate for magnetic field screening with respect to SS structures as the theory suggests, excluding the possible effects of the specific size and shape of the samples on the reported dc magnetization loops. While the determined critical temperatures were 9.25 K and 9.3 K for the base layers (Nb) of SIS and SS structures, respectively, the critical temperatures of the top superconducting layers (NbN) could not be determined as being relatively thin layers with respect to the thicker Nb base layers. Therefore, AC susceptibility technique, with higher sensitivity compared to the dc magnetization technique (VSM), should be implemented to determine T_c values more reliably for thin multilayer structures.

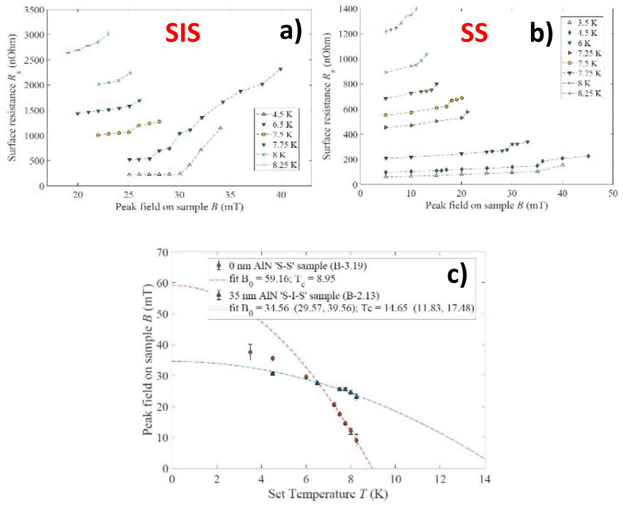

Figure 6: Surface resistance as a function of peak field on sample for, a) HiPIMS-coated SIS, b) HiPIMS-coated SS structures at different temperatures. c) The combined peak field on sample versus set temperature curves of both HiPIMS-coated SS and SIS structures.

When it comes to the other SS versus SIS structures, coated with HiPIMS for QPR tests at HZB, SS seems to outperform SIS structure by sustaining its Meissner state up to higher magnetic fields within the lower temperature range with lower surface resistance values, albeit having lower T_c as shown in Fig. 6a-c. We may speculate that the SS structure behaves *more like bulk Nb* as compared to the SIS structure. Both multilayer structures had similar surface resistance (R_s) values during the initial cool down at low frequency measurements as shown in Fig. 7a. However, it was also observed that R_s values for these two multilayer structures seem to deviate from each other at lowest possible trapped flux during vertical test stand (VTS) heat cycles as shown in Fig. 7b. The SIS structure seems to be more sensitive to flux trappings with respect to the SS structure. Further assessments of the observed RF phenomena are to be detailed in the dissertation of D. Tikhonov.

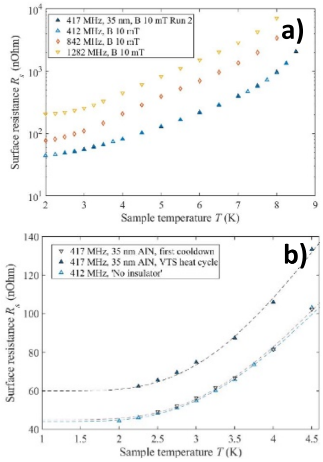

Figure 7: Surface resistance of HiPIMS-coated SS and SIS structures as a function of sample temperature, a) at three different resonant frequencies, b) during the first cool down and VTS heat cycle - adapted from [8].

CONCLUSION

The recent RF characterization results suggest that SS structure is worth studying in depth along with SIS structures for a more comprehensive understanding of the fundamental mechanisms responsible for potentially higher SRF performance of the multilayer structures for the next generation compact particle accelerators.

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