ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-THPOGE19

FIELD SHIELDING OF NbTiN BASED MULTILAYER STRUCTURE FOR ACCELERATING CAVITIES*

I. H. Senevirathne†, A. Gurevich, J. R. Delayen
Centre for Accelerator Science, Old Dominion University, Norfolk, VA 23529, USA
D. R. Beverstock[1], A.-M. Valente-Feliciano
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
[1]also at Applied Science Department, William & Mary, Williamsburg, VA 23185, USA

Abstract

Over the past few decades, bulk niobium (Nb) has been the material of choice for superconducting radio frequency (SRF) cavities used in particle accelerators to achieve higher accelerating gradients and lower RF losses. Multilayer (SIS) structures consisting of alternating thin layers of superconductor(S) and insulator(I) deposited on a bulk Nb have been proposed to enhance the sustained peak surface magnetic field and produce a higher accelerating gradient. In this study, multilayers based NbTiN and AlN deposited on bulk Nb are used to test the proposed enhancement using the DC magnetic Hall probe technique. The technique detects a penetrating magnetic field through the multilayer sample as it is placed under an external magnetic field produced by a magnetic coil. This work reports the characterization and measurements of the magnetic field of full flux penetration through single layers of NbTiN and bilayers of NbTiN/AlN on bulk Nb.

INTRODUCTION

Niobium (Nb) radio frequency cavities are widely used to accelerate a charged particle beam in particle accelerators. The performance of bulk Nb SRF cavities has significantly improved over the last decade and is approaching the peak magnetic field at the equatorial cavity surface close to the niobium dc superheating field $H_s \approx 240$ mT which gives the maximum accelerating field gradient to about 52 MV/m at 2 K for 1.3 GHz single cell cavities [1]. Since the best Nb cavities are already close to the fundamental limit of the material, new SRF materials with higher superheating magnetic fields than Nb are needed to reach accelerating gradients ~ 100 MV/m at 2 K or ~ 50 MV/m at 4.2 K.

The concept of multilayer structures comprised of alternating layers of superconductors and insulators fabricated on bulk Nb (Fig. 1) has been introduced as a feasible solution to overcome intrinsic material imitation in [2]. The type-II superconductor candidates with $T_c > T_c$ (Nb) and $B_{sh} > B_{sh}$ (Nb) such as Nb_3Sn [3], NbN [4], NbTiN [5], MgB_2 [6] and some Fe-based superconductors could potentially enhance the surface field at onset of vortex penetration, B_p above B_{c1} of Nb. The enhancement is achieved by depositing S layer films with thickness below its penetration depth, λ to screen the bulk Nb from external magnetic field. B_{c1} of a thin film with thickness, d<< λ, is given by

$$B_{c1} = \frac{2\phi_o}{\pi d^2}\left[ln\frac{d}{\xi} - 0.07\right], \qquad (1)$$

where ϕ_o is the flux quantum and ξ is the coherence length [7]. Eq. (1) shows that B_{c1} is greatly increased in the overlying superconducting layers. If a vortex penetrates at a defect in the first S layer, it can propagate into the next S layer and further in the bulk Nb triggering a thermomagnetic avalanche. An insulator layer between two superconductors provides a strong barrier for propagation of vortex to the bulk of the Nb cavity [7]. Materials such as MgO, Al_2O_3 and AlN are suitable candidates for I layers.

In this work, NbTiN and AlN based multilayers deposited on bulk Nb were studied for SRF accelerating cavity applications.

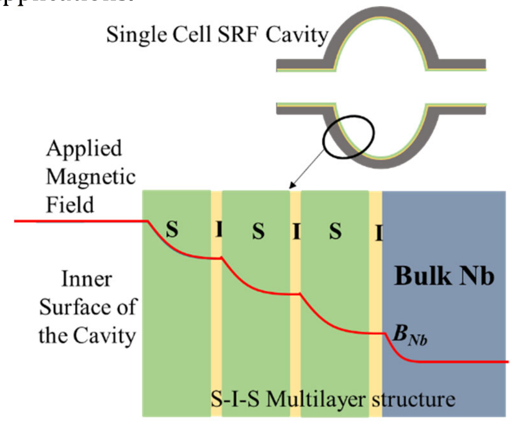

Figure 1: Superconductor (S)- Insulator (I)- Superconductor (S) multilayers to enhance the peak surface magnetic field of niobium RF cavities.

NbTiN is a suitable S layer material for SIS structures which is a B1-compound with a critical temperature of 17.8 K. It has a NaCl structure where Ti and Nb form a face centred cubic (fcc) lattice and N atoms occupy all the octahedral interstices. NbTiN adheres well with the substrate. AlN is the chosen insulator that can be grown with a wurtzite hexagonal close-packed or sphalerite B1 cubic structures. The deposition method was optimized to deposit the superconductor and insulator layers on bulk substates and on top of each other maintaining the quality and properties of each layer and of the base substrate [8, 9]. In this work, the focus is on the magnetic field penetration measurements on NbTiN monolayers (SS' structure) and NbTiN/AlN multilayers (SIS' structure) on bulk Nb.

*Work supported by NSF Grants PHY-1734075 and PHY-1416051, and DOE Awards DE-SC0010081 and DE-SC0019399.
†isene001@odu.edu

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-THPOGE19

THIN FILM DEPOSITION

NbTiN and AlN thin layers are deposited on bulk Nb using reactive Direct Current Magnetron Sputtering (reDCMS) in an Ultra-High Vacuum (UHV) system with a base pressure of 10^{-10} Torr. The Nb substrates are prepared by buffered chemical polishing (BCP) removing 5um from the surface. Multiple Nb substrates with 2-inch diameter and 250 µm thickness were used as substrates along with witness samples that are used to probe the films' quality and their properties. The films were deposited in a same run to ensure the identical environmental conditions. The films were deposited at 450 °C on bulk Nb after a 24 hour-bake at 600 °C, then post-annealed at 450 °C for 4 hours.

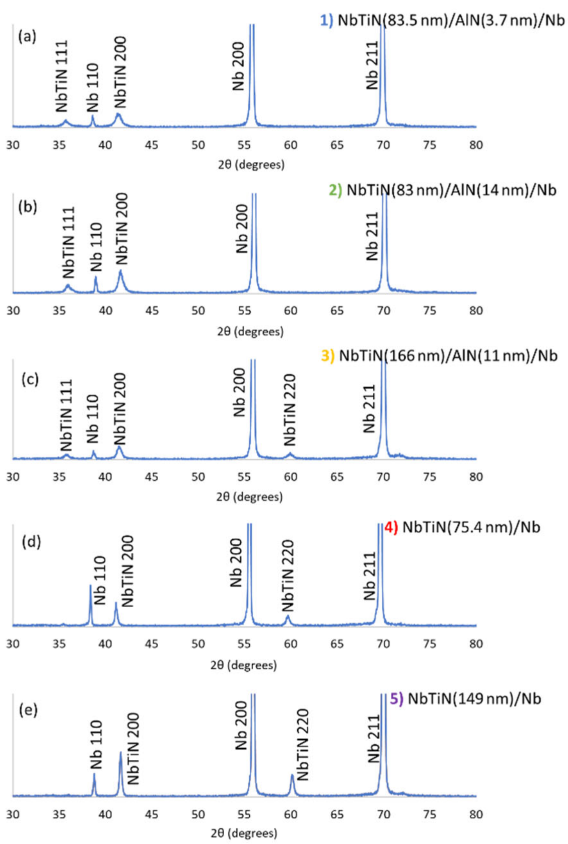

Figure 2: XRD scans for (a) NbTiN (83.5 nm)/AlN (3.7 nm) (b) NbTiN (83nm)/AlN(14 nm) (c) NbTiN (166 nm)/AlN (11 nm) (d) NbTiN (74.5 nm) (e) NbTiN (149 nm) on bulk niobium substrates.

Even though bulk-like properties can be achieved at the deposition temperature of 600 ºC both for NbTiN, highest T_c and AlN, more pronounced dielectric properties, the successive deposition of these layers on top of each other requires the temperature to be reduced to 450 ºC to limit Al diffusion into Nb and NbTiN which results in amorphous structures and diffuse interfaces [8, 9].

Table 1 describes the thicknesses measured using witness samples and NbTiN transition temperatures extracted from resistivity measurements (Figure 3) on deposited thin films.

Table 1: Thicknesses of NbTiN and AlN Layers and Transition Temperatures

Sample #	Thickness (nm)		Tc (K)	ΔT (K)
	NbTiN	AlN		
1	83.5	3.7	14.5	1.47
2	83.0	14.0	14.4	1.49
3	166.0	11.0	15.7	0.79
4	75.4	0	16.2	0.40
5	149.0	0	16.3	0.30

The crystallographic structures of deposited thin films were examined by X-ray diffraction (XRD) analysis from a Rigaku Miniflex II X-ray diffractometer. NbTiN crystal structure mostly contains 111, 200 and 220 crystal orientations (Fig. 2).

The resistances of the films were measured from 4.5 to 300 K using standard four-point probe method. The resistance decreased as the temperature is lowered. As shown in Fig. 3, a sharp resistance decrease observed for monolayer NbTiN on bulk Nb around 16.2 K (red and purple curves). NbTiN/AlN films on bulk Nb show two transitions around 15 K (NbTiN transition) and 9.2 K (Nb transition).

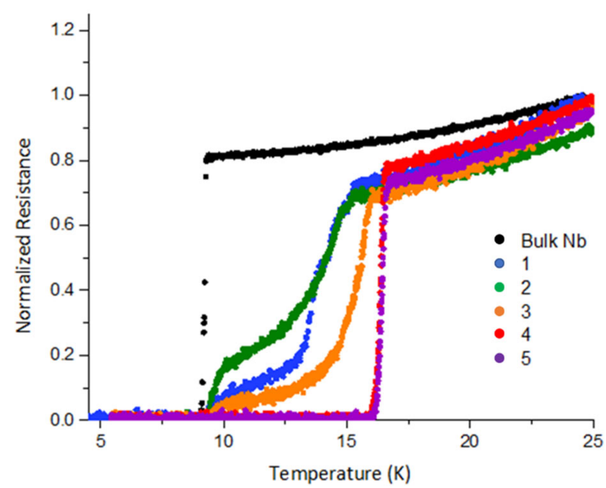

Figure 3: DC resistance as a function of temperature for monolayer NbTiN on bulk Nb, exhibits sharp superconducting transition around 16.2 K and NbTiN/AlN structure on bulk Nb exhibits two transitions one at 9.2 K and other around 15 K.

Electron backscatter diffraction (EBSD) indicates multi crystal nature of the deposited film on bulk Nb (Fig. 4). Monolayer NbTiN on Nb shows a higher quality crystal structure compared to NbTiN/AlN on Nb.

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-THPOGE19

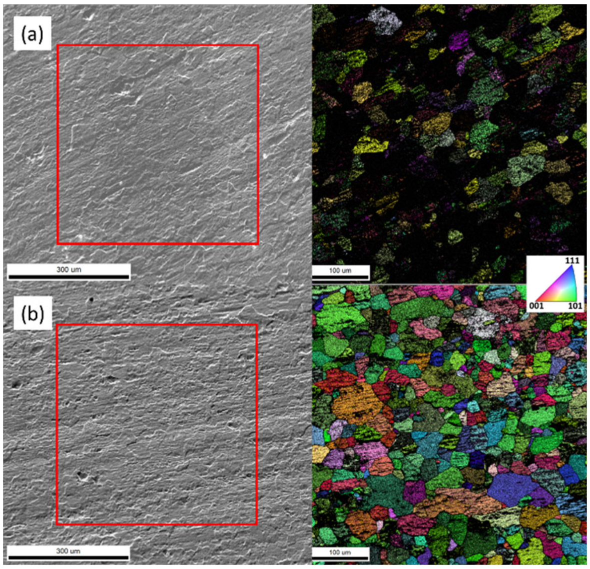

Figure 4: SEM images and relevant Inverse Pole Figure (IPF) map from EBSD showing the poly-crystallinity of films for (a) NbTiN/AlN and (b) monolayer NbTiN structure coated on BCP bulk niobium. The IPF map is filtered for confidence index above 0.1.

DC MAGNETIC FIELD PENETRATION MEASUREMENTS

DC magnetometers have been commonly used for planner sample characterization. In some other techniques like SQUID, the magnetic signal is affected by demagnetization effect of flat samples immersed in a homogeneous DC field. In order to overcome this issue, a dc magnetic Hall probe technique has been developed to perform the measurement emulating the magnetic field configuration at the equator of SRF cavities [10].

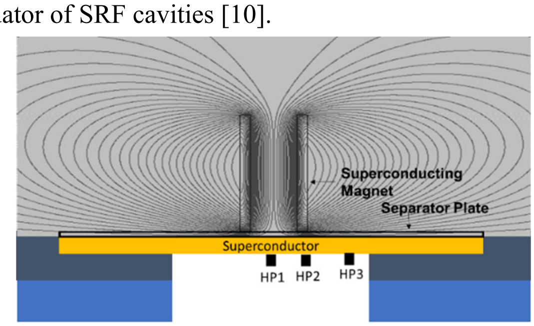

Figure 5: Basic experimental setup of dc magnetic Hall probe technique with magnetic field profile in the Meissner state which emulates the magnetic field configuration at the equator of accelerating cavity. HP1, HP2 and HP3 are Hall probes which are mounted at the center, 4.4 mm and 10.0 mm respectively along the sample radius.

As shown in Fig. 5, the magnetic field is applied with a multiturn coil which size is much smaller than the sample size. In this case the radial field decays rapidly away from the coil, the sample can be considered as an infinite plane.

In this technique, the magnetic field is applied to one side of the sample and three Hall probes mounted on the other side at the sample centre, 4.4 mm and 10.0 mm from the centre, detect magnetic fields penetrating through the sample.

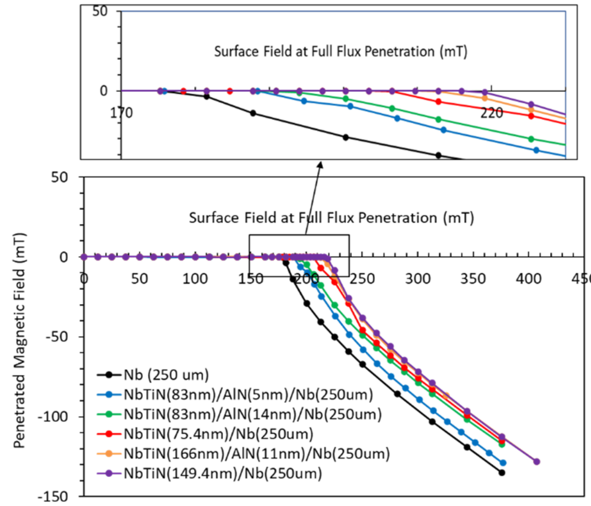

Figure 6: Full flux penetration detected by the centre Hall probe through the layered niobium comparing with the bare niobium substrate at 4.35 K.

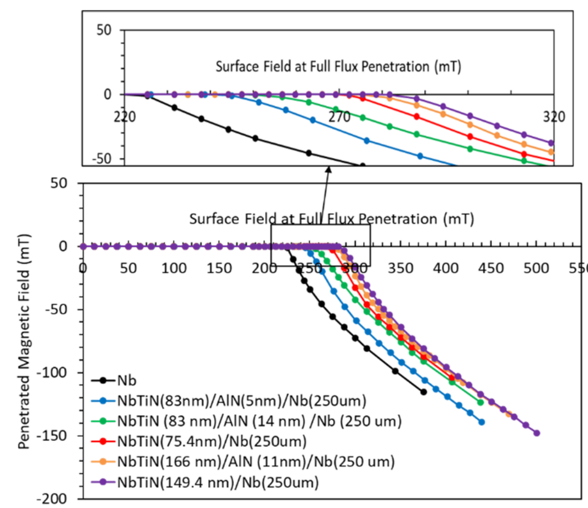

Figure 7: Full flux penetration detected by the center Hall probe through layered niobium comparing with the bare niobium substrate at 2.00 K.

Figures 6 and 7 show the penetrating magnetic fields detected by the centre Hall probe as functions of the surface field at 4.35 and 2.00 K, respectively. In the Meissner state current loops induced at the surface of the superconductor produce the magnetic field which cancels the applied field and does not let it penetrate through the sample. Above a certain applied magnetic field $B>B_p$ the magnetic flux penetrates through the sample and the Hall probes detect the magnetic field on the other side of the sample. The field of full flux penetration B_p is a useful characteristic of the shielding effect of multilayer structure coated on bulk Nb

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-THPOGE19

as it shows the enhancement of B_p of multi-layered samples relative to B_p of bulk Nb.

Results of field penetration measurements shown in Figs. 6 and 7 indicate that the field of full flux penetration is higher for both NbTiN monolayer and NbTiN/AlN multilayer on bulk Nb as compared to bare Nb. The percentage increase of the magnetic field at the full flux penetration of each layered samples at 4.35 K and 2.00 K is listed in table 2. The maximum shielding effect was observed on the NbTiN on Nb, SS structure. Further studies of the field enhancement of NbTiN multilayers are planned in future work.

Table 2: Percentage Increase of Field at First Penetration of Layered Nb Compared to Bare Nb

Sample #	Percentage increase %	
	At 4.35 K	At 2.00 K
1	7.5	10.3
2	8.9	12.9
3	19.6	24.3
4	16.1	22.9
5	21.4	27.1

CONCLUSION

NbTiN based SS and SIS structures have been grown on BCP bulk Nb. The film quality depends strongly on the presence of an AlN layer. The prepared SS' and SIS' samples were used to investigate the shielding effect of layered Nb to characterize them for SRF cavity applications. We observed that the magnetic shielding depends on the layer thickness and the quality of the samples. The maximum increase of field at full flux penetration of 21.4 % at 4.35 K and 27.1 % at 2 K compared to bulk Nb was achieved in this study.

AKNOWLAGEMENT

The authors thank to the technical staff at Jefferson Lab. This work was supported by the National Science Foundation (Grant Nos. PHY-1734075 and PHY-1416051) and the Department of Energy (Grant Nos. DE-SC0010081 and DE-SC0019399).

REFERENCES

[1] H. Padamsee, J. Knobloch and Y. Hays, "RF Super-Conductivity for Accelerators", 2nd edn (New York: Wiley), 2008

[2] A. Gurevich, "Enhancement of rf breakdown field of superconductors by multilayer coating," Appl. Phys. Lett., vol. 88, p. 012511, 2006. doi.org/10.1063/1.2162264

[3] C. Sundahl, J. Makita, P.B. Welander et al., "Development and characterization of Nb_3Sn/Al_2O_3 superconducting multilayers for particle accelerators", Sci Rep 11, 7770, 2021. doi.org/10.1038/s41598-021-87119-9

[4] W. M. Roach, J. R. Skuza, D. B. Beringer, Z. Li, C. Clavero1 and R. A. Lukaszew, "NbN thin films for superconducting radio frequency cavities", Supercond. Sci. Technol. 25 125016, 2012. doi:10.1088/0953-2048/25/12/125016

[5] M. C. Burtona, M. R. Beebe, K. Yang, R. A. Lukaszew, A-M. Valente-Feliciano and C. Reece, "Superconducting NbTiN thin films for superconducting radio frequency accelerator cavity applications " , J. Vac. Sci. Technol. A 34, 021518, 2016. doi.org/10.1116/1.4941735

[6] E. W. Collings, M. D. Sumption, and T. Tajima, "Magnesium diboride superconducting RF resonant cavities for high energy particle acceleration", Supercond. Sci. Technol. 17, S595, 2004. doi:10.1088/0953-2048/17/9/026

[7] A. Gurevich, "Theory of RF superconductivity for resonant cavities", Supercond. Sci. Technol. 30 034004, 2017. doi:10.1088/1361-6668/30/3/034004

[8] A-M Valente-Feliciano, M. Burton, G. Eremeev, R. Lukaszew, C. Reece, J. Spradlin, "Growth and Characterization of Multi-Layer NbTiN Films", in Proceedings, 17th International Conference on RF Superconductivity (SRF2015), Whistler, Canada, September 13-18, 2015. doi:10.18429/JACoW-SRF2015-TUBA08

[9] A-M Valente-Feliciano, G. Eremeev, H. Phillips, , C. Reece, J. Spradlin, y. Qiquang, D. Batchelor and R. Lukaszew "NbTiN Based SIS Multilayer Structures for SRF Applications", presented at *Proc., 15th International Conference on RF Superconductivity (SRF2013) :* Paris, France, Sept. 23-27, 2013, paper TUP088, pp. 670-673.

[10] I. H. Senevirathne, A. Gurevich and J. R. Delayen, "Direct current magnetic Hall probe technique for measurement of field penetration in thin film superconductors for superconducting radio frequency resonators", Rev. Sci. Instrum. 93, 055104, 2022. doi.org/10.1063/5.0083309