

SEY REDUCTION USING ULTRATHIN TiN/NbN MULTILAYERS FOR ACCELERATOR APPLICATIONS

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Abstract

Multipacting and electron cloud formation remain major limitations for the performance of modern particle accelerators. In superconducting radio-frequency (SRF) cavities, multipacting can prevent stable cavity operation and restrict achievable accelerating gradients. In positively charged particle machines such as the LHC, the build-up of electron clouds results in beam instabilities, vacuum degradation, and additional heat loads on the cryogenic systems. Reducing the secondary electron yield (SEY) of vacuum-facing surfaces is therefore a key strategy to mitigate these effects. To mitigate these effects, several strategies have been proposed, in particular the deposition of thin films designed to reduce the secondary electron yield (SEY) of the relevant surfaces. We investigated the SEY behaviour of ultrathin TiN/NbN multilayers, with particular attention to the influence of both the number of layers and the TiN/NbN stacking sequence. Multilayers composed of individual 3 nm films were deposited by PVD to probe interfacial effects and possible electronic confinement phenomena. SEY measurements performed before and after electron conditioning reveal a dependence on the multilayer architecture. One particular multilayer configuration achieves a significantly reduced SEY, reaching 0.98 after conditioning.

INTRODUCTION

Particle accelerators such as the Large Hadron Collider (LHC) are limited by secondary electron emission, which can trigger electron cloud formation through multipacting (secondary electron yield (SEY) > 1), leading to beam instabilities. SEY originates from electrons produced by residual gas ionization or synchrotron radiation interacting with beam pipe walls. Mitigation strategies include increasing surface roughness to enhance electron trapping, but these are not always compatible with component constraints. An alternative is the deposition of intrinsically low-SEY coatings. In this work, we investigate TiN/NbN multilayer thin films, combining low intrinsic SEY with interface-engineered electron trapping. These multilayers create potential barriers (~0.2 eV) that reduce electron transmission and promote confinement, especially for low-energy secondary electrons. Increasing the number of interfaces enhances energy dissipation and lowers effective SEY.

TiN and NbN are particularly suitable due to their low SEY, structural compatibility, and ease of deposition. This approach offers a promising route for next-generation anti-multipacting coatings in accelerator environments.

EXPERIMENTAL

Thin films were deposited by PVD using a Plassys MP500S system equipped with DC/RF cathodes, enabling co-sputtering and reactive deposition under argon plasma. Films were grown on mirror-polished Si (110) substrates under high vacuum (~10⁻⁷ mbar) to minimize contamination. TiN/NbN multilayers were fabricated by alternating sputtering from TiN and Nb targets, with optimized conditions (0.3 Pa, 40 sccm Ar, 200 mA) to ensure slow, uniform growth. Individual layer thicknesses (~2–3 nm) were controlled via deposition time (1 min 30 s per layer), and various architectures were explored by adjusting the number of layers and the top layer composition. The substrate temperature (300 °C) was chosen to obtain dense, slightly rough films (Thornton transition zone), while avoiding excessive roughness effects on SEY. Characterization was performed using XRR, XRD, XPS, TEM, along with SEY measurements.

RESULTS

Structural and Chemical Characterization

To investigate the chemical structure of the multilayer, X-ray photoelectron spectroscopy (XPS) depth profiling was performed. The depth profile was acquired using a 500 eV argon ion beam with an abrasion spot size of 400 μm. A total of 200 sputtering steps were carried out, each lasting 5 s. After each step, a survey spectrum was recorded, along with high-resolution spectra for the elements of interest (C, N, Nb, and Ti). The XPS depth profile (Fig. 1) shows the elemental distribution across the alternating NbN and TiN layers. The oxygen concentration remains approximately constant at ~8 at.% throughout the multilayer, while nitrogen is stable at ~35 at.%. The Nb 3d and Ti 2p core-level spectra confirm the presence of Nb–N (binding energy ~203.6 eV) and Ti–N (~455 eV) bonds, respectively. As shown in Fig. 2, titanium appears to be present within Nb-rich layers and, conversely, niobium within Ti-rich layers. This may result from partial interdiffusion during deposition. It may also reflect an intrinsic limitation of XPS: its information depth (~5–10 nm) exceeds the individual layer thickness (~3 nm), leading to signal contributions from adjacent layers.

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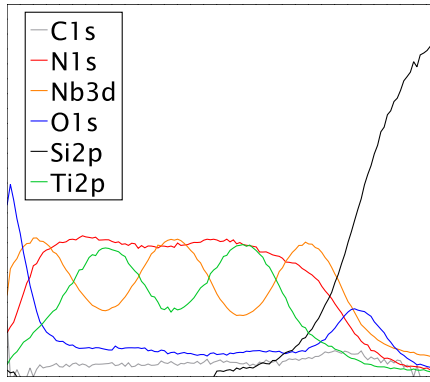


Figure 1: Depth distribution of C, O, N, Ti, Nb, and Si elements in a five-stack NbN/TiN/NbN/TiN/NbN/Si multilayer structure.

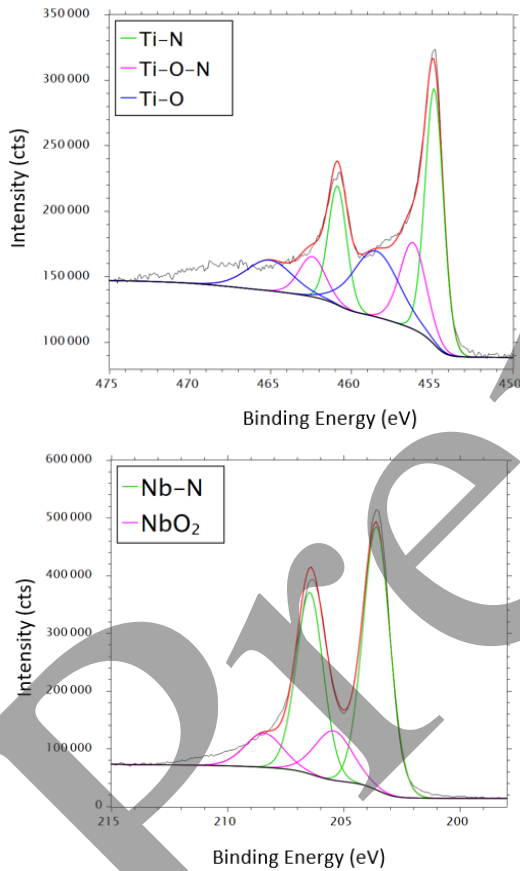


Figure 2: XPS spectra of a NbN/TiN/NbN/TiN/NbN/Si multilayer deposited by PVD: Ti $2p_{3/2}$ peak (top) and Nb $3d_{5/2}$ peak (bottom).

Finally, the multilayer architecture was confirmed by scanning transmission electron microscopy (STEM) coupled with energy-dispersive X-ray spectroscopy (EDX). The cross-sectional STEM image (Fig. 3) clearly reveals the layered structure, while EDX maps show the spatial distributions of Ti, Nb, and O. These results confirm an alternating NbN/TiN multilayer, along with an oxidized NbN surface layer and a native SiO_2 interfacial layer. The

observed monolayer thickness (~ 3 nm) demonstrates the reliability of the PVD process used in this study.

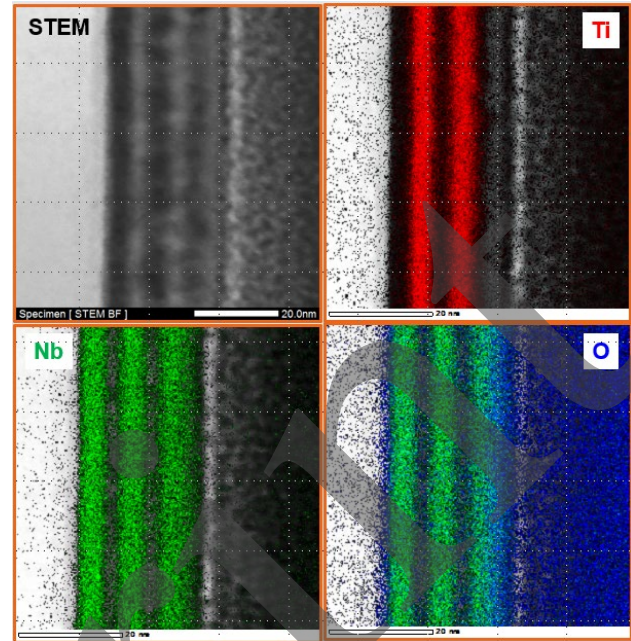


Figure 3: STEM study of the five-layer NbN/TiN/NbN/TiN/NbN/Si multilayer deposited by PVD: (top left) STEM image, (top right) STEM-EDX map of Ti, (bottom left) STEM-EDX map of Nb, and (bottom right) STEM-EDX map of Nb and O.

Secondary Electron Yield Measurements

Secondary electron yield (SEY) measurements were performed on various multilayer configurations to investigate the influence of both the total number of layers and the nature of the topmost layer. We compared the maximum SEY values of the different multilayer architectures in the fully conditioned state, after electron bombardment at 500 eV. (Fig. 4). Multilayers with TiN as the topmost layer exhibit relatively high maximum SEY values ($\delta_{\text{max}} \approx 1.2$), comparable to or slightly higher than those of single TiN films [1], except for the five-layer stack, where δ_{max} decreases to 1.08. For multilayers with NbN as the topmost layer, the SEY of the NbN/TiN/NbN/Si trilayer approaches that of single NbN films. Notably, a δ_{max} value of 0.99 is obtained for the five-layer NbN/TiN/NbN/TiN/NbN/Si multilayer.

These results are particularly promising, as the objective is to achieve δ_{max} values close to or below unity. In five-layer NbN/TiN/NbN/TiN/NbN/Si multilayer, δ_{max} falls below 1 after full conditioning, highlighting the potential of multilayer architectures as an effective strategy for low-SEY surfaces. For comparison, copper typically exhibits $\delta_{\text{max}} \approx 1.2$ after an electron dose of $\sim 10^{-2} \text{ C/mm}^2$ [2], whereas the multilayer studied here reaches similar values with a significantly lower dose ($\sim 2 \times 10^{-3} \text{ C/mm}^2$).

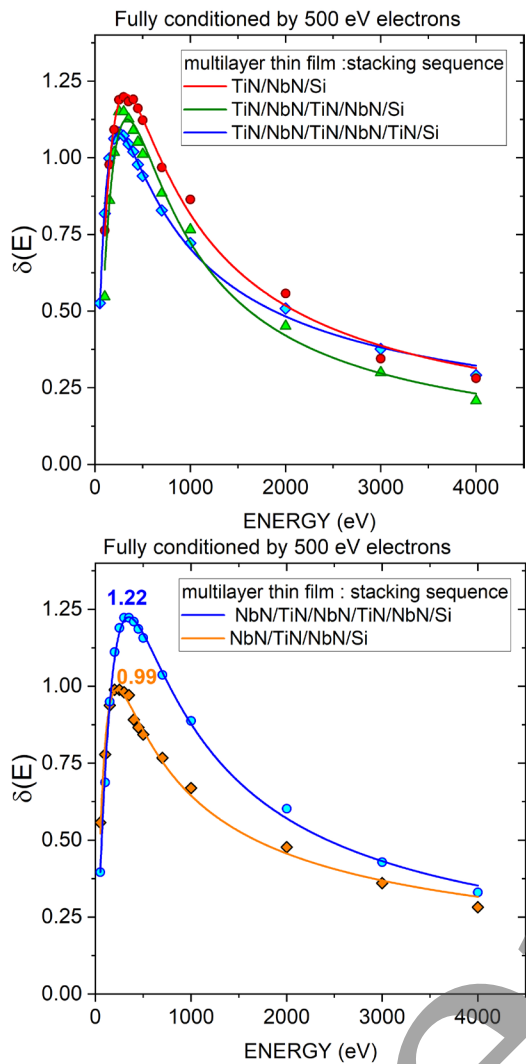


Figure 4: Fully conditioned SEY curves of: (top) multilayers with TiN as the surface layer, and (bottom) multilayers with NbN as the surface layer.

CONCLUSION

TiN/NbN thin-film multilayers show significant potential for reducing the secondary electron yield (SEY) of surfaces. The most promising results are obtained for a five-layer NbN/TiN alternating stack, with individual layer thicknesses of approximately 3 nm. Although TiN is widely recognized as an efficient antimultipacting coating, the best performance is unexpectedly observed when NbN forms the topmost surface layer. Additional experiments are underway to further substantiate these results, including SEY measurements at cryogenic temperatures (~ 10 K).

REFERENCES

- [1] F. Le Pimpec, F. King, R. E. Kirby, M. Pivi, and G. Rumolo, "The continuing story of secondary electron yield measurements from TiN coating and TiZrV getter film", SLAC, Menlo Park, CA, USA, Rep. SLAC-TN-04-046/LCC-0146, Aug. 2004.
- [2] R. Valizadeh, O. B. Malyshev, S. Wang, S. A. Zolotovskaya, W. Allan Gillespie, and A. Abdolvand, "Low secondary electron yield engineered surface for electron cloud mitigation," *Applied Physics Letters*, vol. 105, no. 23, Dec. 2014. doi:10.1063/1.4902993