ENHANCED SUPERCONDUCTING PROPERTIES OF Nb FILMS VIA A HIGH-POWER IMPULSE MAGNETRON RE-SPUTTERING/SPUTTERING APPROACH FOR Nb–Cu 1.3 GHz RF CAVITIES

J. Xiao[1,2], P. Dong[1,2], Y. Wang[1,2], Z. Chen[†,3], J. Chen[3], D. Wang[3], Y. Chen[1,2], Z. Liu[2,3], J.Li[1,2]
[1]State Key Laboratory of Quantum Functional Materials, School of Physical Science and Technology, ShanghaiTech University, Shanghai, China
[2]ShanghaiTech Laboratory for Topological Physics, School of Physical Science and Technology, ShanghaiTech University, Shanghai, China
[3]Center for Transformative Science (CTS), Shanghai, China

Abstract

Conformal deposition of high-performance superconducting films on complex cavity geometries, particularly ensuring robust film-substrate adhesion, remains a fundamental challenge. We address this by introducing a novel high-power impulse magnetron re-sputtering and sputtering (HiPIMRS) system designed for uniform niobium (Nb) film deposition on the interior surfaces of 1.3 GHz copper cavities. A key innovation is an in-situ copper substrate re-sputtering step prior to Nb deposition, which eliminates interfacial oxides and degradation, ensuring atomic-scale interfacial integrity. Through in-situ re-sputtering prior to deposition, we achieve oxide-free Nb/Cu interfaces with atomic-scale integrity. Crucially, electrical transport measurements demonstrate a significant enhancement in the superconducting transition temperature (T_c) from 8.5 K to 9.3 K for HiPIMRS films, along with smooth surfaces ($R_a < 20$ nm) and a preferred (110) orientation. This work establishes HiPIMRS as a viable pathway for next-generation superconducting radiofrequency (SRF) cavity production, with its interfacial engineering protocols offering significant advancements in film conformity and superconducting properties.

INTRODUCTION

Superconducting radio frequency (SRF) cavities are critical components in particle accelerators and quantum computing infrastructures [1-5]. While bulk niobium has been the traditional material of choice, copper-based niobium film cavities provide significant advantages including reduced material costs, enhanced thermal conductivity, and superior mechanical properties [6-9].

Depositing high-quality Nb films on Cu cavities requires uniform coverage in complex geometries and strong adhesion. High power impulse magnetron sputtering (HiPIMS), pioneered at CERN [5, 8], has achieved accelerating gradients up to 21 MV/m for 1.3 GHz Nb-Cu cavities [10]. However, Nb films often exhibit residual resistance and Q-slope issues [11, 12]. Preventing Cu substrate oxidation is acknowledged as pivotal for enhancing performance [13-15], necessitating in-situ surface cleaning techniques [16].

In this work, we present a high-power impulse magnetron re-sputtering/sputtering (HiPIMRS) system for fabricating 1.3 GHz Nb-Cu SRF cavities. The system integrates translational target positioning, dynamic power control, and optimized magnetic fields for conformal Nb deposition under ultra-high vacuum ($<10^{-7}$ Pa). In situ substrate re-sputtering enables oxide-free, atomic-scale interfacial preparation. The superconducting Nb films are observed with a high critical temperature of 9.3 K, flat surface roughness ($R_a < 20$ nm for 4 μm films). The Nb films exhibit a strong (110) preferred orientation, accompanied by a minor (211) peak. This work demonstrates exceptional film uniformity and interface integrity, establishing HiPIMRS as a scalable pathway for next-generation SRF cavities.

EXPERIMENTAL SETUP AND METHODS

Instrument Design

Fig. 1(a) illustrates the HiPIMRS apparatus used for conformal Nb deposition on 1.3 GHz Cu cavities. The system integrates an adaptable magnetron target system and a water-cooled magnetron target containing a high-purity Nb cylindrical tube cathode and ring-shaped NdFeB magnets, all housed within a 316 stainless steel ultra-high vacuum (UHV) chamber with a base pressure below 10^{-7} Pa. A precision translation stage (±0.1 mm) enables axial positioning of the target over a 1.0 m range, allowing full coverage of the single-cell cavity (length ~50 cm) in Fig. 1(b).

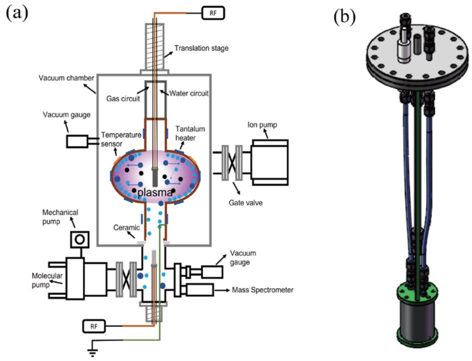

Figure 1: (a) Schematic diagrams of the modular apparatus for high-energy pulsed magnetron re-sputtering/sputtering (HiPIMRS); (b) The sputtering module of the HiPIMRS apparatus.

Multi-step Sputtering Process

The HiPIMRS deposition involves a multi-step in-situ process [9]:

(a) Ti-target pre-sputtering. A Ti target at the cavity base is sputtered for 2 min, depositing a getter film that reduces pressure from 10^{-6} Pa to $\leq 10^{-7}$ Pa by binding residual gases;

(b) Ti-target re-sputtering. The Ti target is positioned at the cavity center as anode, while the Cu cavity serves as an RF-powered cathode (40 kHz). Ar^+ ions (50-200 eV) generated at 0.5 Pa bombard the Cu surface, removing native oxides and contaminants;

(c) Nb-target pre-sputtering. The Nb target at the cavity aperture is RF-powered for 2 min to remove the native Nb_2O_5 layer;

(d) Nb-target sputtering. The Nb target is translated to cavity center for film growth under optimized conditions.

RESULTS AND DISCUSSIONS

HiPIMRS-deposited Nb films on Cu substrates were characterized to evaluate their superconducting properties, microstructure, and interfacial integrity with and without in-situ re-sputtering.

Superconducting Properties and Microstructure

Superconducting properties of the Nb films were characterized via four-point probe resistivity measurements using a Physical Property Measurement System (PPMS, Quantum Design). Fig. 2(a) shows the temperature-dependent resistance of the Nb-Cu sample, from which the superconducting transition temperature (T_c) is determined to be 9.3 K at 90% of the normal-state resistance (R_N). Magneto-transport measurements in Fig. 2(b) give $\mu_0 H_c^2$ = 3.3 T at 1.8 K, 45% higher than bulk. AFM reveals a smooth surface (R_a = 16.0 ± 1.5 nm for 4 μm films), while XRD exhibits a strong (110) preferred orientation, accompanied by a minor (211) peak. These microstructural features underpin the enhanced superconducting performance.

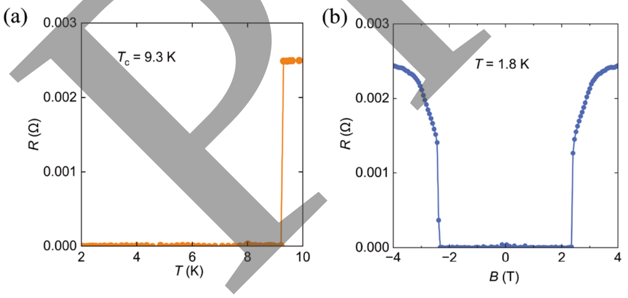

Figure 2: Electrical transport characterization of superconducting films on copper-based substrates.

Interfacial Analysis

Cross-sectional SEM analysis compares films deposited with and without in-situ re-sputtering. Conventionally deposited films (no re-sputtering) exhibit interfacial voids with oxygen enrichment, as shown in the upper panel of Fig. 3(a). Such interfacial features led to film delamination after 90 days of ambient storage (left panel of Fig. 3(b)). In contrast, re-sputtered Cu substrates enable void-free Nb/Cu interfaces with an interdiffusion zone (lower panel of Fig. 3(a)) and no delamination after 90 days ((right panel of Fig. 3(b)). The in-situ re-sputtering effectively removes the native oxide layer (Cu_2O/CuO) via low-energy Ar+ bombardment, yielding oxide-free interfaces that enhance adhesion and thermal stability.

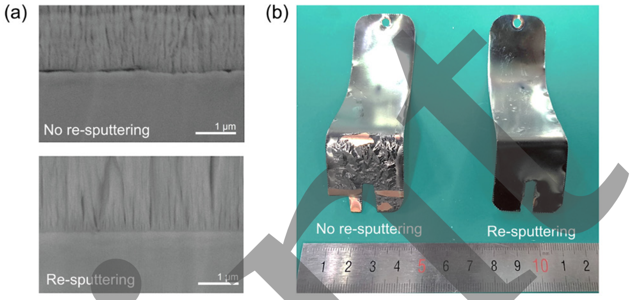

Figure 3: Comparative analysis of interfacial properties of HiPIMRS-deposited niobium films on no-resputtering and re-sputtering-treated Cu substrates.

1.3 GHz Nb-Cu Cavity

Using the optimized HiPIMRS protocol, niobium films were deposited onto the interior surface of a 1.3 GHz copper cavity, which had been subjected to coarse polishing and precision mirror-finishing using commercial-grade machining equipment. The upper panel of Fig. 4 presents photographs of the Nb films deposited on the inner wall of the copper cavity. Uniform film growth with full coverage was achieved across the cavity interior, and the film surface exhibited a smooth, specular reflective appearance. During Nb deposition, the sputtering parameters were as follows: the base pressure reached 5.4×10^{-6} Pa. A re-sputtering step was then performed at a pressure of 1.2×10^{-1} Pa with a power of 100 W to remove surface oxides from the copper substrate. Subsequently, niobium deposition was carried out under the following sputtering parameters: RF source operated in constant-power mode at 60 W, frequency 40 kHz, duty cycle 50%, Ar gas pressure maintained at 1.2×10^{-1} Pa, and the copper cavity heated to 500 °C.

A comparison of the surface morphology before and after process optimization reveals that the film deposited under the initial sputtering conditions exhibits a pronounced columnar structure, non-uniform grain size, and a few micropore defects, resulting in a dull metallic gloss. After optimization (Fig. 4), the film shows a smooth surface with fine, uniformly distributed grains, a significantly enhanced metallic sheen, and clear reflectivity. These improvements indicate that optimizing key sputtering parameters—such as power, working pressure—effectively suppresses columnar grain growth and reduces defect density, leading to a dense, high-quality film with substantially improved surface quality and metallic appearance.

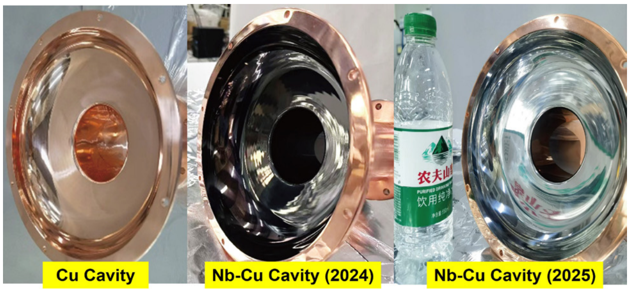

Figure 4: 1.3 GHz copper cavity with inner wall coated by superconducting niobium film.

CONCLUSION

Achieving uniform, adherent superconducting films on copper SRF cavities remains challenging due to extreme target-substrate distance variations inherent in cavity geometries. This work presents a novel high-power impulse magnetron sputtering apparatus featuring a movable target system with integrated magnets and in-situ re-sputtering substrate treatment. The design enables wide-range target movement while maintaining consistent magnetic field configuration, significantly improving film uniformity and adhesion across complex cavity surfaces. Characterization of electrical and structural properties confirms the feasibility and enhanced performance of Nb films deposited using this approach. These results establish that miniaturized target design with integrated magnet assembly provides a scalable pathway for high-quality superconducting coatings on next-generation copper SRF cavities.

ACKNOWLEDGEMENTS

This research was supported in part by the Ministry of Science and Technology (MOST) of China (No. 2022YFA1603903), the National Natural Science Foundation of China (Grants No. 62571327, 92565112, 92565305), the Science and Technology Commission of Shanghai Municipality, the Shanghai Sailing Program (Grant No. 21YF1429200), Natural Science Foundation of Shanghai (Grants Nos. 25ZR1402374, 25ZR1402368, and 25ZR1401252), the Science and Technology Commission of Shanghai Municipality, the Shanghai Leading Talent Program of Eastern Talent Plan, and the Double First-Class Initiative Fund of ShanghaiTech University.

REFERENCES

[1] H. Padamsee, "50 years of success for SRF accelerators—a review," *Supercond. Sci. Technol.*, vol. 30, no. 5, p. 053003, Apr. 2017. doi:10.1088/1361-6668/aa6376

[2] H. Padamsee, RF Superconductivity: Science, Technology, and Applications. Wiley, 2009. doi:10.1002/9783527627172

[3] G. Ciovati et al., "Development of a prototype superconducting radio-frequency cavity for conduction-cooled accelerators," Phys. Rev. Accel. Beam*s*, vol. 26, no. 4, Apr. 2023. doi:10.1103/physrevaccelbeams.26.044701

[4] H. Padamsee, Superconducting Radiofrequency Technology for Accelerators: State of the Art and Emerging Trends. Wiley, 2023. doi:10.1002/9783527836314

[5] S. Calatroni, "20 Years of experience with the Nb/Cu technology for superconducting cavities and perspectives for future developments," *Physica C*, vol. 441, no. 1–2, pp. 95–101, Jul. 2006 doi:10.1016/j.physc.2006.03.04

[6] C. Benvenuti *et al.*, "Study of the surface resistance of niobium sputter-coated copper cavities," IEEE Transactions on Appiled Superconductivity, vol. 9, no. 2, pp. 900–903, Jun. 1999. doi:10.1109/77.783442

[7] C. Benvenuti, S. Calatroni, P. Darriulat, M. A. Peck, A.-M. Valente, and C. A. V. Hof, "Study of the residual surface resistance of niobium films at 1.5 GHz," *Physica C*, vol. 351, no. 4, pp. 421–428, Apr. 2001. doi:10.1016/s0921-4534(00)01645-2

[8] J. Tuckmantel, "The LEP2 superconducting RF system," IEEE Transactions on Appiled Superconductivity, vol. 9, no. 2, pp. 270–275, Jun. 1999. doi:10.1109/77.783288

[9] P. Dong *et al.*, "High-power impulse magnetron re-sputtering/sputtering apparatus for Nb–Cu 1.3 GHz RF cavities," *Rev. Sci. Instrum.*, vol. 96, no. 10, Oct. 2025. doi:10.1063/5.0287381

[10] M. C. Burton, A. D. Palczewski, H. L. Phillips, C. E. Reece, A-M. Valente-Feliciano, and R. A. Lukaszew, "RF Results of Nb Coated SRF Accelerator Cavities via HiPIMS", in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp. 427-430. doi:10.18429/JACoW-LINAC2018-TUPO042

[11] F. Zimmermann, "The Future Circular Collider and Physical Review Accelerators & Beams", in *Proc. NAPAC'19*, Lansing, MI, USA, Sep. 2019, pp. 975-980. doi:10.18429/JACoW-NAPAC2019-THAHC2

[12] A. Ramiere, C. Z. Antoine, and J. Amrit, "Model for hot spots and Q-slope behavior in granular niobium thin film superconducting rf cavities," *Phys. Rev. Accel. Beams*, vol. 25, no. 2, Feb. 2022. doi:10.1103/physrevaccelbeams.25.022001

[13] R. Ries, E. Seiler, F. Gömöry, A. Medvids, C. Pira, and O. B. Malyshev, "Superconducting properties and surface roughness of thin Nb samples fabricated for SRF applications," Journal of Physics: Conference Series, vol. 1559, no. 1, p. 012040, Jun. 2020. doi:10.1088/1742-6596/1559/1/012040

[14] M. Ghaemi *et al.*, "Growth of Nb films on Cu for superconducting radio frequency cavities by direct current and high power impulse magnetron sputtering: A molecular dynamics and experimental study," *Surf. Coat. Technol.*, vol. 476, p. 130199, Jan. 2024. doi:10.1016/j.surfcoat.2023.130199

[15] V. Palmieri and R. Vaglio, "Thermal contact resistance at the Nb/Cu interface as a limiting factor for sputtered thin film RF superconducting cavities," *Supercond. Sci. Technol.*, vol. 29, no. 1, p. 015004, Nov. 2015. doi:10.1088/0953-2048/29/1/015004

[16] E. Chyhyrynets *et al.*, "Plasma Electrolytic Polishing Technology Progress Development for Nb and Cu Substrates Preparation", in *Proc. SRF'23*, Grand Rapids, MI, USA, Jun. 2023, pp. 75-79. doi:10.18429/JACoW-SRF2023-MOPMB009