Fabrication of Superconducting Resonators on hBN Thin Films

CNF Summer Student: River Chen
Student Affiliation: Materials Science and Engineering, University of Illinois Urbana-Champaign

Summer Program(s): 2024 Cornell NanoScale Facility Research Experience for Undergraduates (CNF REU) Program
Principal Investigator(s): Professor Zhiting Tian, Sibley School of Mechanical and Aerospace Engineering, Cornell
Mentor(s): Joyce Christiansen-Salameh, Sibley School of Mechanical and Aerospace Engineering, Cornell University

Primary Source(s) of Research Funding: National Science Foundation under Grant No. NNCI-2025233; AFOSR Award Number FA9550-22-1-0177

Contact: riveryc2@illinois.edu, zt223@cornell.edu, jc3496@cornell.edu

Summer Program Website(s): https://cnf.cornell.edu/education/reu/2024, https://ztgroup.org/
Primary CNF Tools Used: AJA Sputter 1 and 2, ABM Contact Aligner, Plasma-Therm 770 Etcher

Abstract:

Studying loss in superconducting devices is essential for high coherence quantum devices. Dielectric loss at the metal-substrate interface is a significant contributor to overall loss [1], which is why methods to study this important factor have been developed [2,3]. Hexagonal boron nitride (hBN) is a 2D material with several applicable properties, including low dielectric loss, chemical stability, and atomically flat surfaces free of dangling bonds, properties that make it an attractive material for integration into superconducting circuits [4]. In this research we employed a coplanar waveguide resonator design that is sensitive to dielectric loss at the metal substrate interface, comparing a "control" niobium (Nb)-on-sapphire resonator and an Nb-on-hBN-on-sapphire resonator.

Summary of Research:

Superconducting resonators are used to characterize materials loss in superconducting quantum computers [5]. The chip design used in this research implements eight multiplexed quarter wave resonators inductively coupled to a feedline with tapered bond pads as shown in Figure 1a. Areas where metal is removed are shown in orange, and metallized areas are shown in white. This design allows for 1:1 comparisons of dielectric losses at the metal substrate interface [2].

Any given resonator, as visible in Figure 1c, exhibited a gap width g of 3 μm and conductor width s of 6 μm. This was also true for the feedline, and we qualified the resolution of our device features throughout our process development based on these metrics.

The original design, shown in Figure 1a, supports a 7.5 x 7.5 mm device size, and we were fabricating on 10 x 10 mm sapphire substrates. Upon completion of our devices, they would be brought to a controlled facility which supports a 6x6mm chip testing platform. We shrunk the design and added a guideline box around the device for improved mask alignment, better centering the new 6x6 mm device design (Figure 1b).

All 10 x 10 mm chips were cleaned via sonication for 10 minutes each in acetone, IPA, and water.

Molecular Beam Epitaxy (MBE). The first step in our device fabrication process was the growth of high-quality BN thin films via MBE on our ~ 500 μm thick sapphire substrate. Figure 2(a) shows resonant high-energy electron diffraction pattern indicating epitaxial quality of hBN film, Figure 2(b) is a Raman spectra showing the sharp characteristic hBN peak, and Figure 2(c) displays an AFM map of the film surface.

Sputter Deposition. After verifying the quality of our 5 nm thick hBN film, 600 Å of Nb were sputtered at the default 400 Watts on an AJA Sputter Deposition tool. In Figure 3, on the left side column, TEM of the hBN -Nb interface is shown to be damaged by the high-power metal ion bombardment.

We found, as shown in Figure 3 on the right-side column, that a lower sputter power of 50 watts maintained a pristine hBN film surface. Using a P7 profilometer, we determined that a sputter time of 10 minutes at this lower power yielded a 161Å thick layer of Nb. Therefore, a sputter time of 37.27 minutes or 2236.03 seconds would yield our desired 600Å of metal.

We were also interested in later comparing aluminum (Al) on sapphire and Al on hBN on sapphire resonators, so we also sputtered Al at 50 W for 10 minutes. Again, we used profilometry to determine an experimental

PROCESS & CHARACTERIZATION

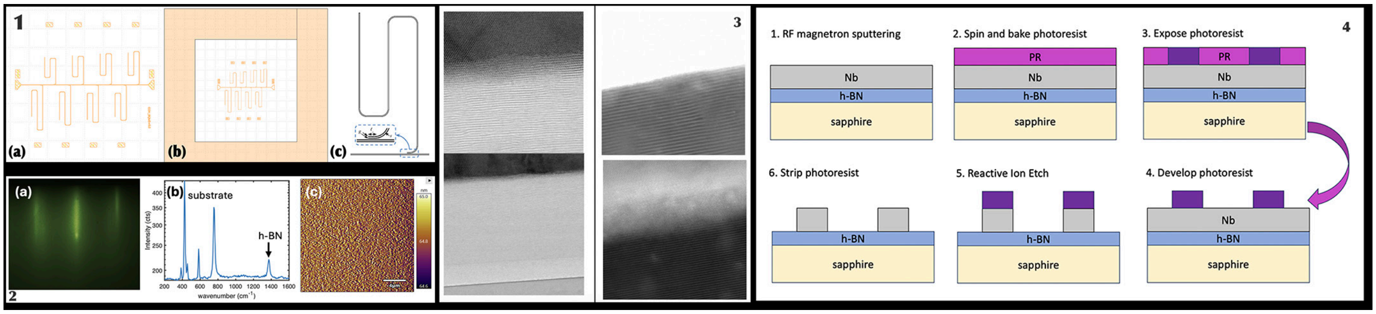

Figure 1: Device mask design. (a) Original 7.5 x 7.5 mm design. (b) Modified 6 x 6 mm design with border for alignment. (c) A single superconducting resonator with gap width g and conductor width s. Diagram from Kopas, et al. [2]. Figure 2: (a) Electron diffraction pattern, (b) Raman spectra, and (c) AFM map of hBN thin film. Figure 3: TEM of Nb sputter at 400W (left) and 50W (right) on hBN thin film. Figure 4: Complete fabrication process.

average of 265Å of sputtered Al through the 10-minute period.

Photolithography. We sputtered 60 nm Nb onto several 10 x 10 mm sapphire substrates in order to test and establish our photolithography process.

S1805 photoresist spun at 4000 rpm for 60 seconds yielded an average thickness of 500 nm. Our several resist-coated substrates were subsequently exposed at varying doses on the ABM Contact Aligner to determine the exposure time for optimal feature definition. The best exposure time was found to be 1.6 seconds.

Reactive Ion Etch (RIE). It was predicted that the RIE Cl2 etch chemistry on the Plasma-Therm 770 etcher could also affect the hBN thin film upon etching through the Nb. Thus, the first step to mitigate this issue was to accurately determine the Nb etch rate. After 36.7 seconds of etching our device pattern, we found that 36.8 nm of Niobium was etched and 36.57 nm of resist was etched. These measurements establish a 1:1 etch selectivity and 1nm/second etch rate.

A similar process was performed on the hBN where a pattern was etched for 15 seconds. We determined that the hBN thin film experienced an etch rate of ~ 1 nm/3 seconds after performing atomic force microscopy on a sample.

Conclusions and Future Steps:

After establishing our etch process parameters, we would similarly verify the niobium was etched through by using a probe station to measure resistance between the gaps and the conductor, determining whether there is Nb in the gaps.

It has been shown that the superconducting transition temperature Tc of a metal can be affected by the substrate material [6]. We will observe this change using a Physical Property Measurement System, examining the change in resistance with varying extremely low temperatures.

As the pieces are required to conform to a 6 x 6 mm testing platform, they will be sent to DISCO laser dicing services.

Finally, the completed devices will be wirebonded and tested in a facility equipped with a He dilution fridge.

Acknowledgements:

I would like to thank Cornell University, NNCI, and the NSF for funding this research via grant NNCI-2025233. Thank you to Joyce, Professor Zhiting Tian, and the staff at the Cornell NanoScale Facility for all the guidance and support throughout this project.

References:

[1] C. R. H. McRae, H. Wang, J. Gao, M. R. Vissers, T. Brecht, A. Dunsworth, D. P. Pappas, J. Mutus, Rev. Sci. Instrum. 1 September 2020; 91 (9): 091101. https://doi.org/10.1063/5.0017378.

[2] Kopas, et al. arXiv 14 Apr 2022. https://arxiv.org/abs/2204.07202.

[3] Woods, W., Calusine, G., Melville, A., Sevi, A., Golden, E., Kim, D. K. Oliver, W. D. (2019). Phys. Rev. Appl., 12, 014012. doi:10.1103/PhysRevApplied.12.014012.

[4] Wang, J.IJ., Yamoah, M.A., Li, Q., et al. Nat. Mater. 21, 398–403 (2022). https://doi.org/10.1038/s41563-021-01187-w.

[5] C. McRae, H. Wang, J. Gao, M. R. Vissers, T. Brecht, A. Dunsworth, D. P. Pappas, and J. Mutus. Review of Scientific Instruments 91, 091101 (2020).

[6] J. Liu, J. Li, T. Li, T. Li, W. Wu and W. Chen. IEEE Transactions on Applied Superconductivity, vol. 19, no. 3, pp. 245-248, June 2009, doi: 10.1109/TASC.2009.2019233.