Material and Interface Engineering Strategies to Mitigate Decoherence in Superconducting Qubits

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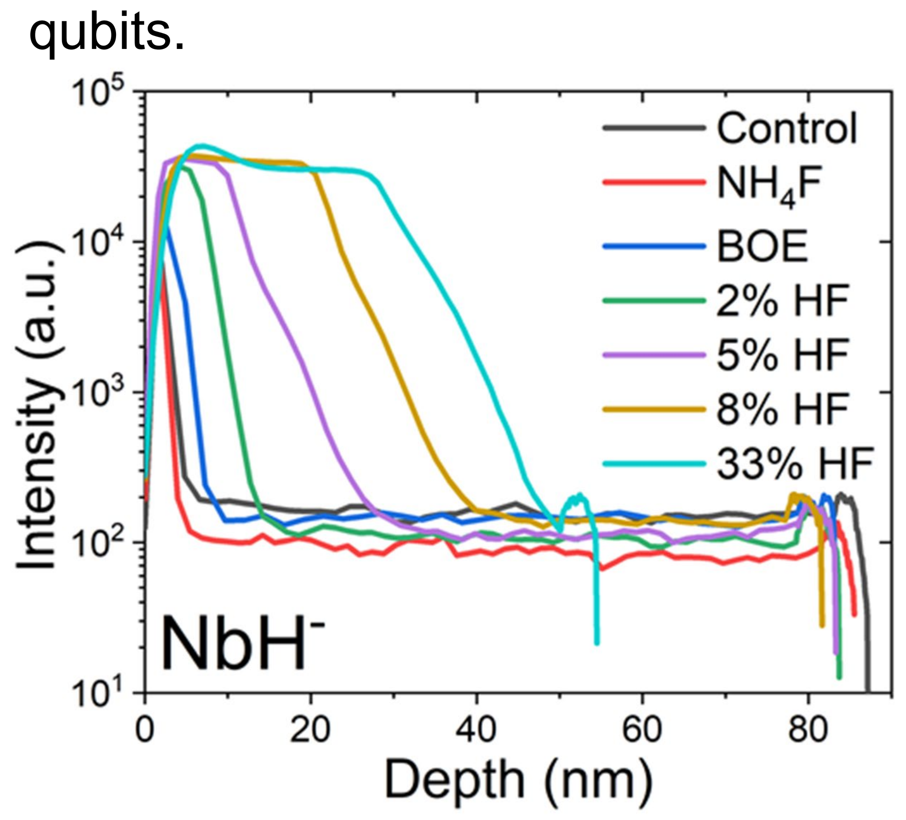
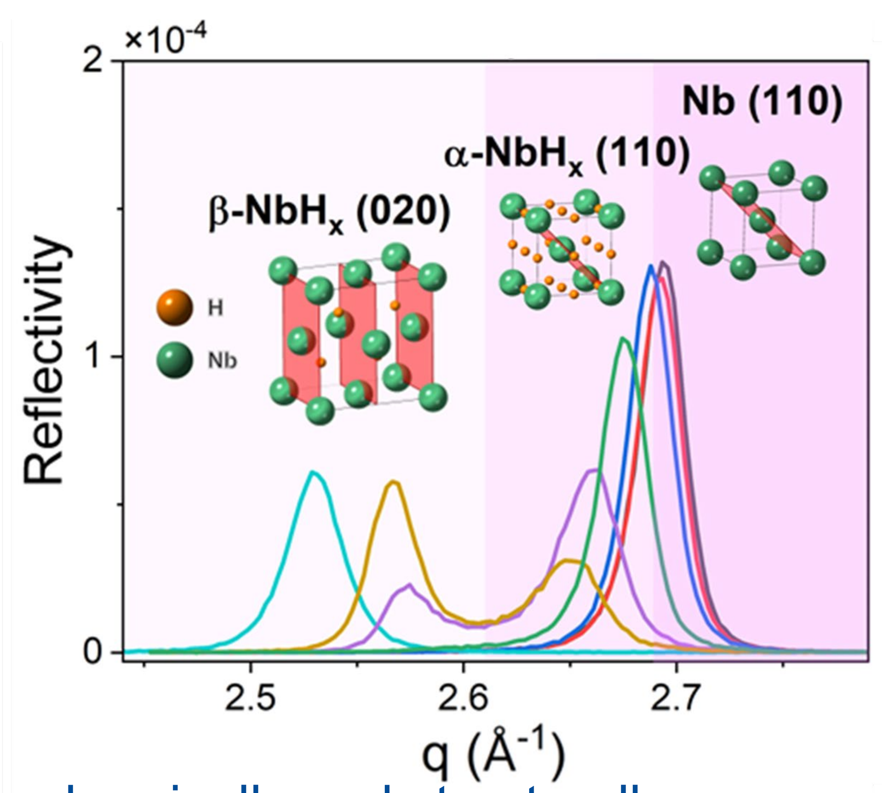
Formation of Niobium Hydrides due to Exposure to Wet Chemical Etchants

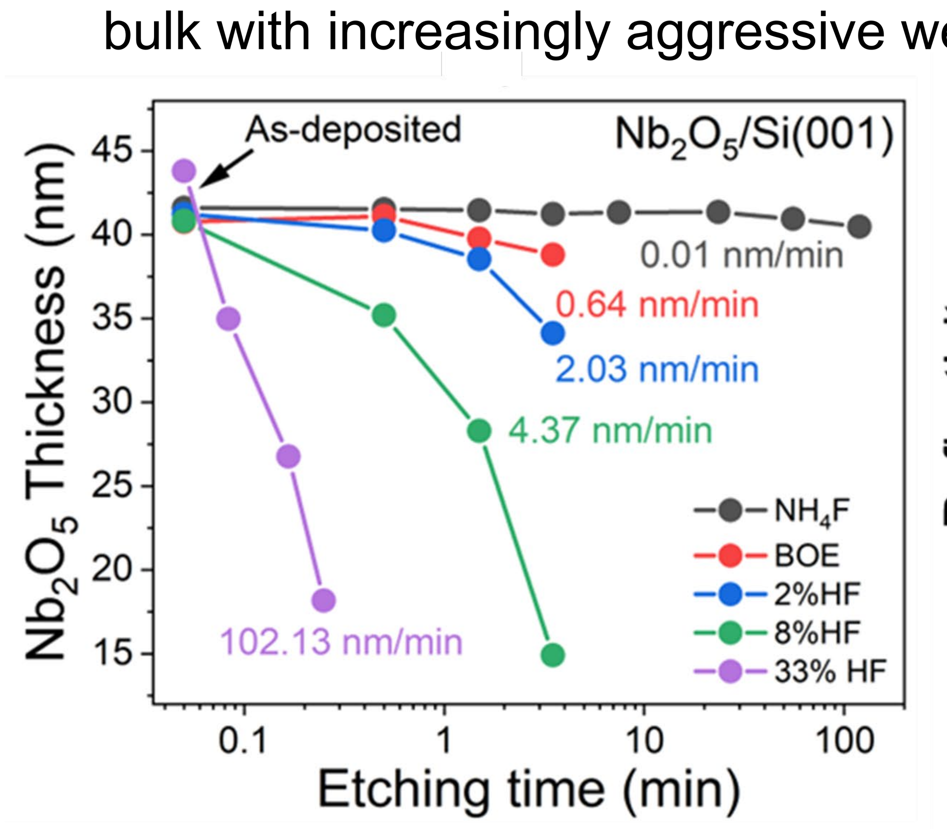
Niobium has a strong affinity for the absorption of hydrogen leading to the formation of niobium hydrides. These hydrides have been shown to be detrimental to internal quality factor in superconducting niobium cavities.[a] Here we examine the role of wet chemical etchants in hydride formation and the effects of niobium hydrides on resonator performance, critical towards advancing the performance of two-dimensional superconducting qubits.

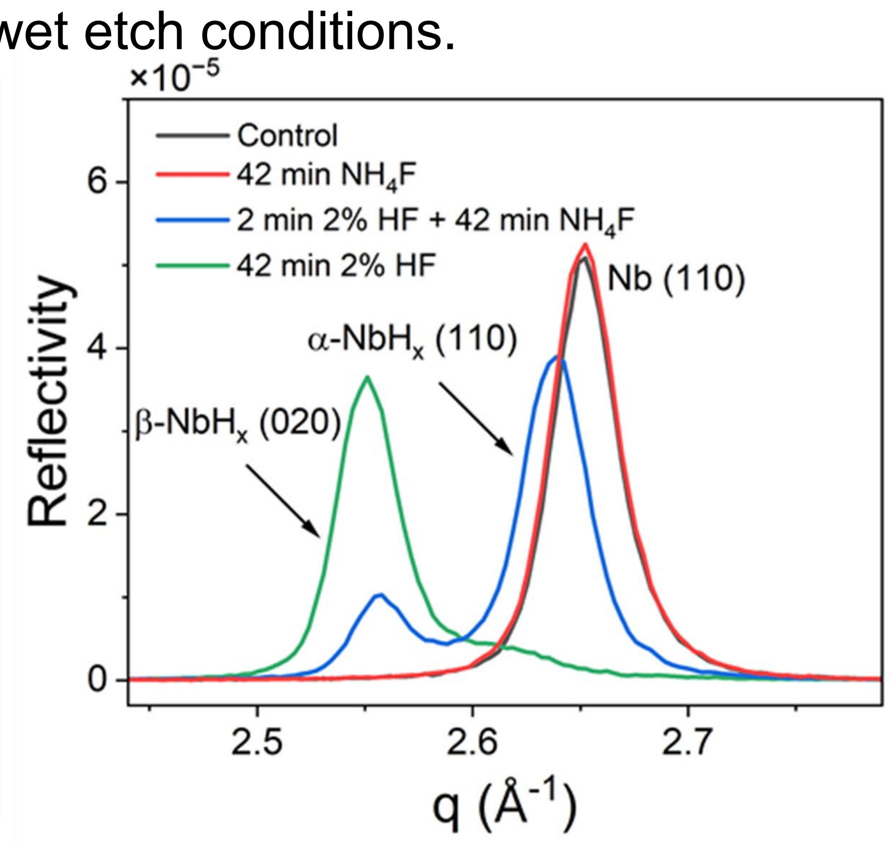




Tracking the incorporation of hydrides chemically and structurally

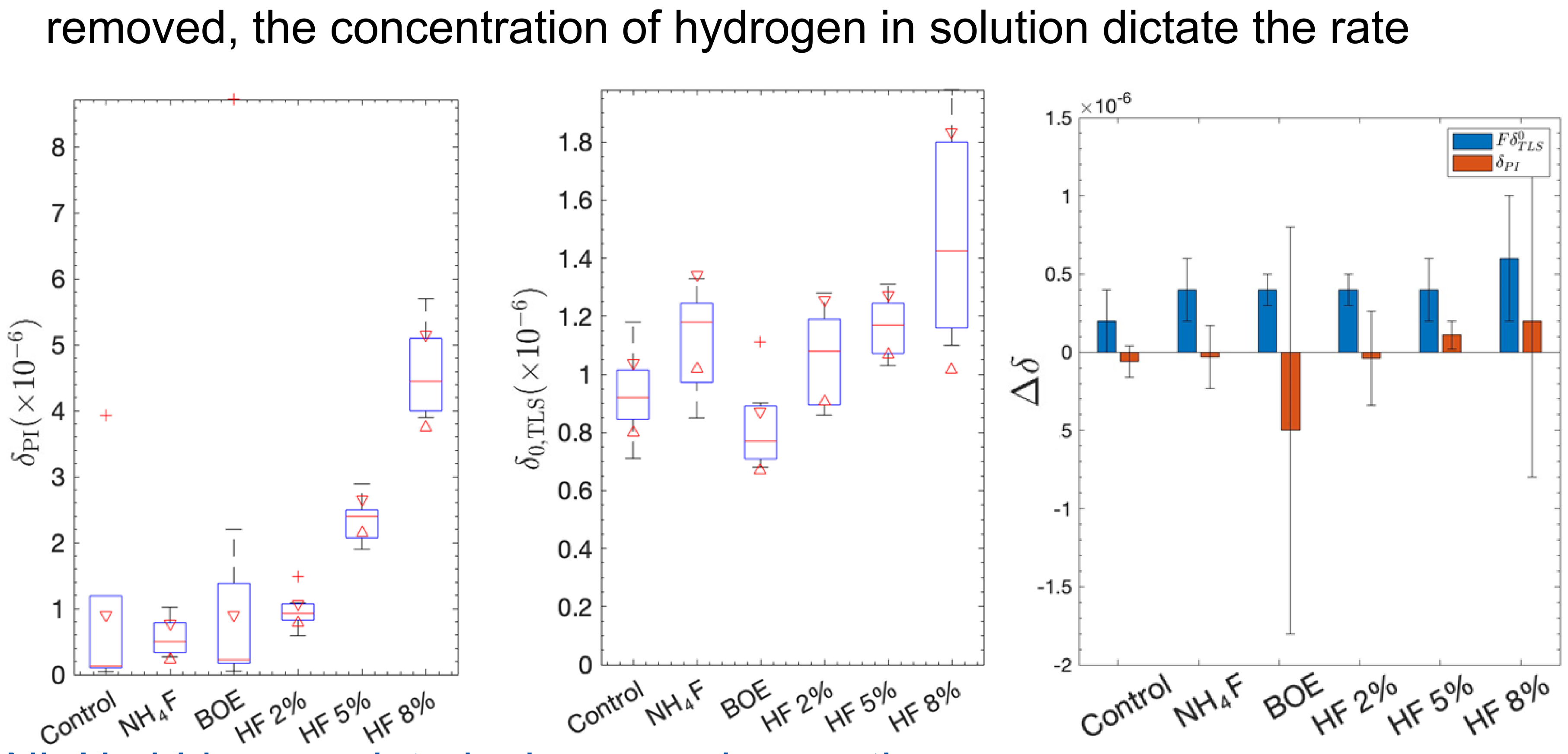
- TOF-SIMS used to track the NbH^- ions as a function of depth into the film.
- XRD pattern shows shift in the Bragg peak towards lower scattering vector, corresponding to an increase in lattice spacing.
- Both methods show the increase in hydrogen ions/interstitials in the Nb bulk with increasingly aggressive wet etch conditions.





Identifying the mechanisms of hydrogen incorporation

- XRR results indicate that the etch rate of Nb_2O_5 increases with the acidity of the etchant and correlates strongly with the rate at which hydrogen is incorporated into the Nb film, indicating that Nb_2O_5 is a passivating barrier.
- Sequential etch tests also show that once the passivating native oxide is removed, the concentration of hydrogen in solution dictate the rate

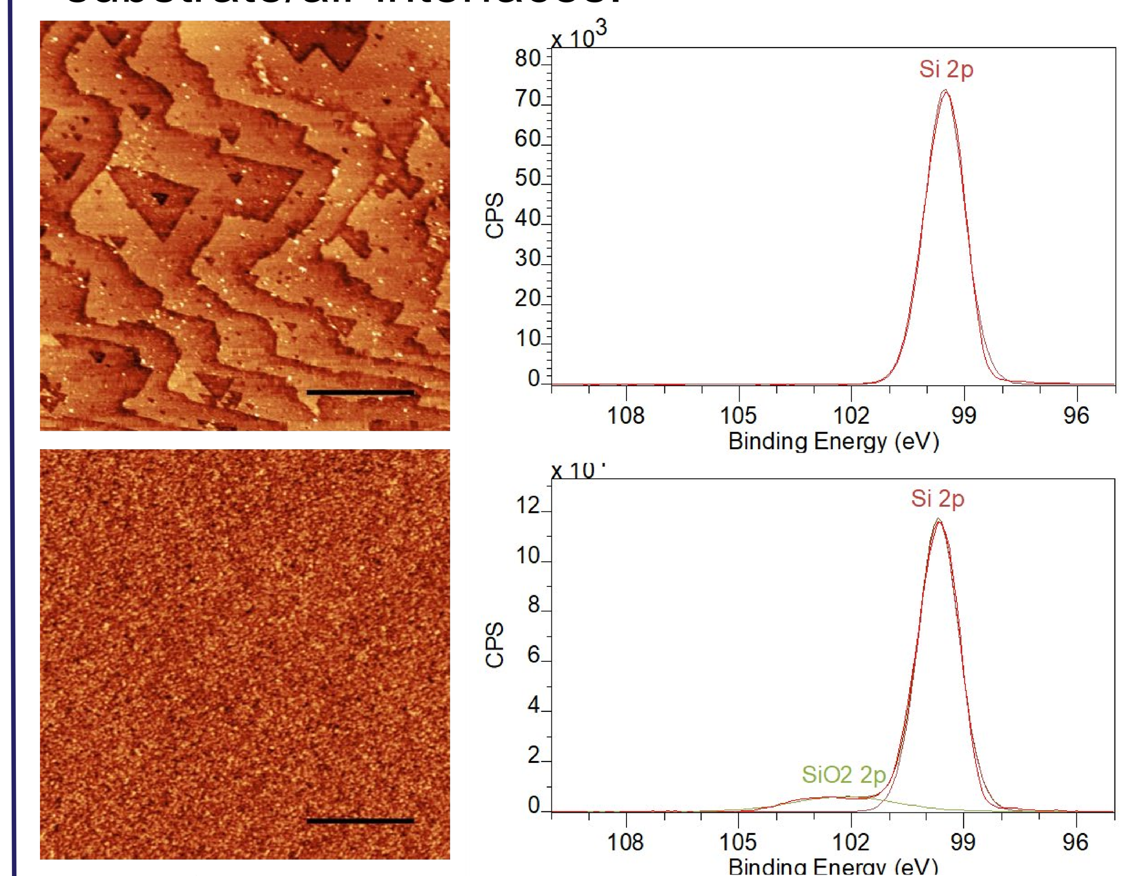


Nb Hydride associated microwave loss pathways

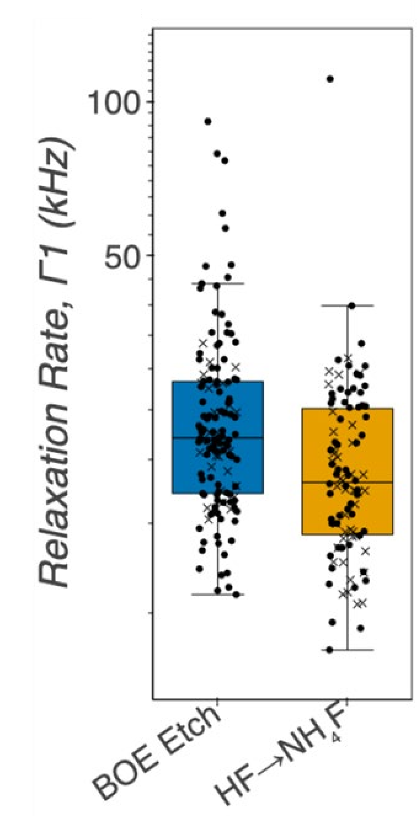
- In 2D resonator testing of Nb with different levels of hydrogen incorporation due to wet chemical etching a correlation is observed between hydrogen loading and power independent loss.
- Weak to no correlation is observed with TLS loss or aging effects.

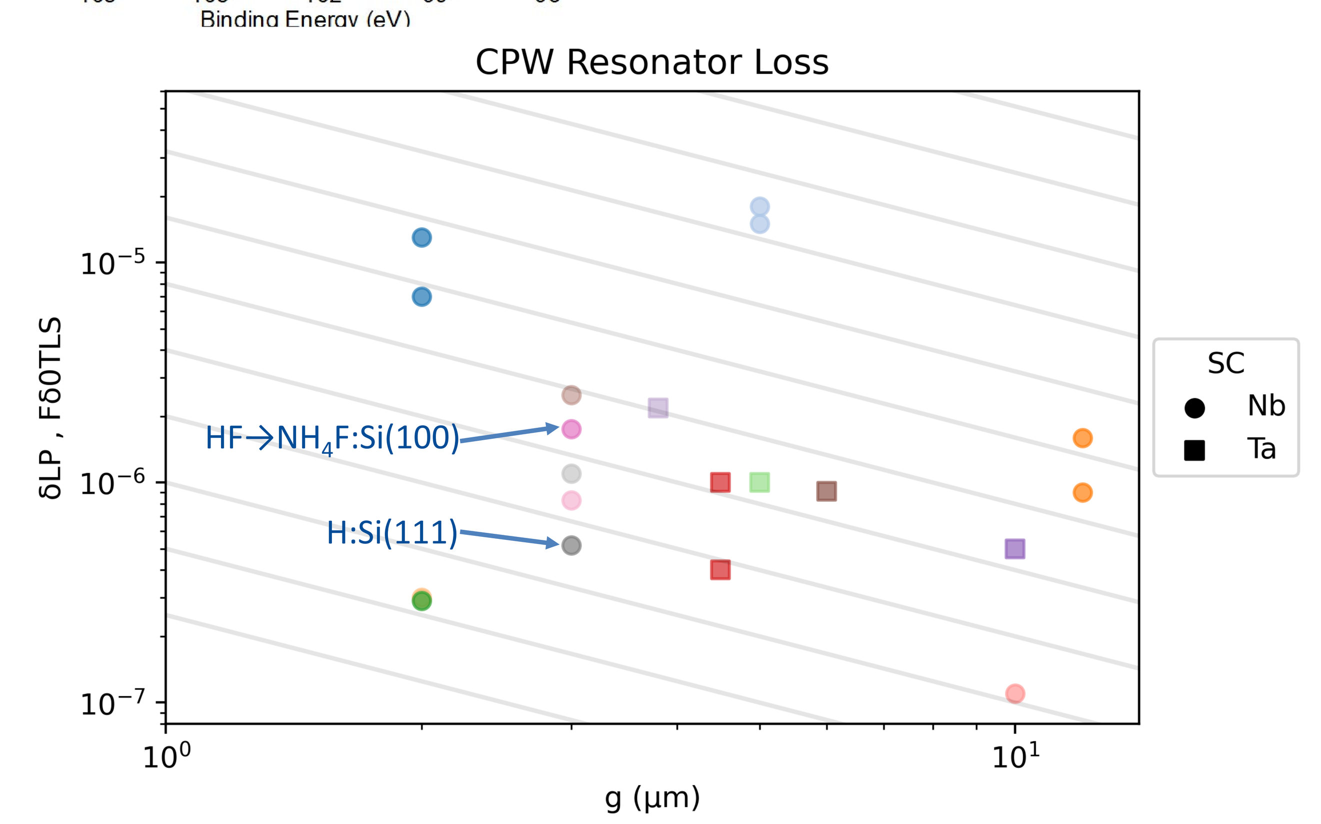
Wet Chemical Surface Treatments of Silicon for Low Loss Interfaces

The Si substrate surface, having both amorphous Si and native oxide, is a significant sources of TLS loss. As seen in the previous study, NH_4F can effectively etch the Nb thin film and the Si substrate with minimal introduction of hydrides, as opposed to other commonly used etchants. We have developed etching procedures using deoxygenated NH_4F solution to produce atomically smoother, oxidation resistant surfaces on Si(100) and Si(111) which provide a better interface at both metal/substrate and substrate/air interfaces.



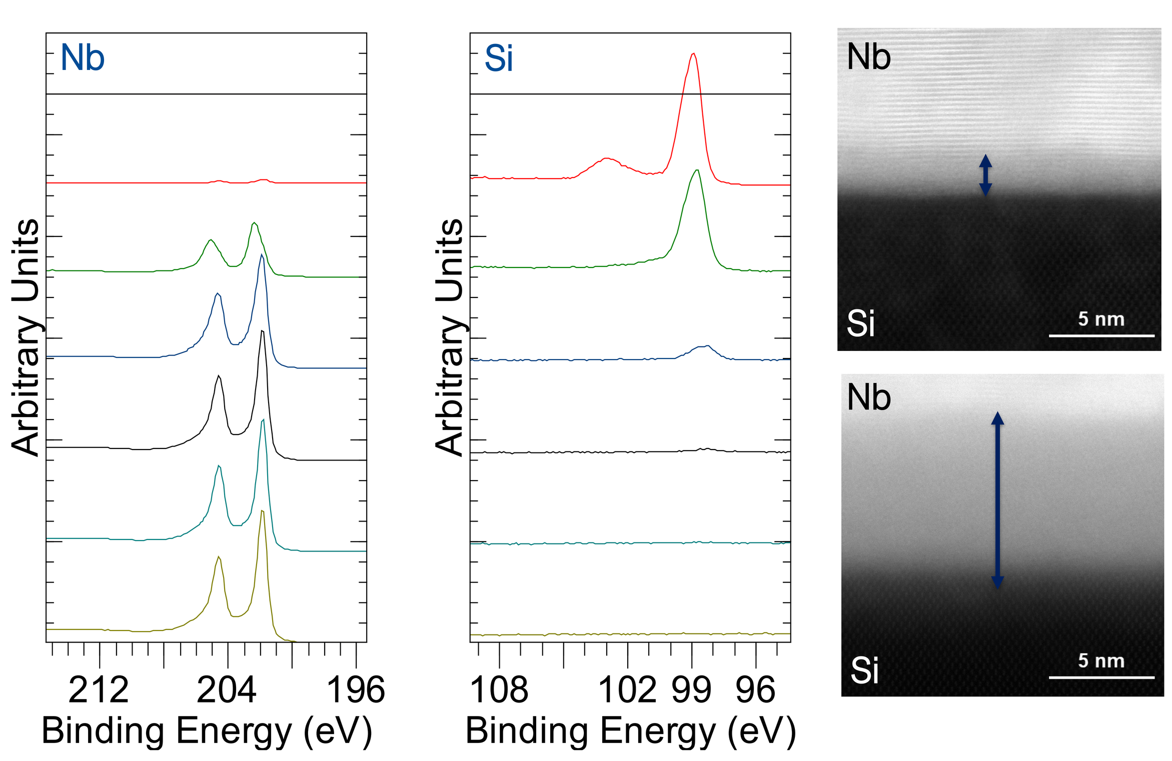
AFM and XPS of (Top) a H:Si(111) surface showing atomically terraced features and no detectable surface oxide. (Bottom) Comparative data of a Si(100) surface prepared using standard etch protocol, showing an atomically undefined surface and the presence of a surface oxide. AFM scale bars are 500 nm.





Qubits and resonators fabricated with NH_4F sequential etch protocols show decreased relaxation rate (increased T_1) and decreased TLS losses versus standard buffered oxide etch (BOE) protocols.

Understanding Niobium Silicides at Buried and Exposed Interfaces



Depth Profile XPS of (Left) Nb and (Middle) Si of a Si encapsulated Nb surface showing no oxide formation. (Right) TEM of the buried Nb/Si interface for (Top) an as-deposited film and (Bottom) an annealed film, showing a growth of the silicide intermixing layer.

Relevant Publication and Patents

1. Torres-Castanedo, C. G.*, Goronzy, D. P.*, et al., Adv. Funct. Mater., 2401365 (2024)
2. Lu, X., Goronzy, D. P., et al., Phys. Rev. Materials 6, 064402 (2022)
3. Berti, G., Appl. Phys. Lett. 122, 192605 (2023)
4. Kopas, C. J., Goronzy, D. P., et al., arXiv:2408.02863 (2024)
5. Goronzy, D. P.; Torres-Castanedo, C. G.; Bedzyk, M. J.; Hersam, M. C. "Monohydride Passivation of High Resistivity Si(111) for Quantum Information Technologies," Appl. No. PCT/US24/11920

[a] Romanenko, A. *Supercond. Sci. Technol.* **2013**, 26

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