# Microscopic Origins of Surface Loss in Ultra-Thin Silicon Nitride Quantum Membranes: A Multi-Technique Structural and Chemical Profiling Approach

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High-stress silicon nitride (SiN) thin membranes are premier mechanical resonators for quantum optomechanics and sensing, offering exceptionally high quality factors ($Q$) [1]. To advance their performance well in the quantum regime, improving their intrinsic, i.e., material-related, quality factor is critical. Energy dissipation in these membranes scales with thickness, and for the ultra-thin, highly sensitive ones, is dominated by surface loss, making the membrane surface the primary bottleneck for $Q$-factor enhancement [2]. However, a microscopic understanding of the origin and distribution of these loss channels remains elusive, largely due to the challenges of performing accurate, quantitative analysis on nanometre-scale membranes.

This work introduces a metrology framework that advances and integrates complementary techniques to provide a detailed microscopic characterization of SiN quantum-grade membranes. Ion beam analysis (Rutherford Backscattering Spectrometry and Elastic Recoil Detection Analysis) enables quantitative elemental depth profiling (including H; **Fig 1a,b**). X-ray Photoelectron Spectroscopy (XPS) and Hard X-ray Photoelectron Spectroscopy (HAXPES) probe chemical states and bonding environments (**Fig 1c**), while infrared nanomechanical photothermal sensing extends chemical-state sensitivity to light species such as hydrogen. X-ray reflectivity (XRR) and spectroscopic ellipsometry constrain film thickness, mass density, and optical constants and are jointly modelled with IBA data to reduce parameter degeneracy and improve accuracy (**Fig 1d)**. Electron Paramagnetic Resonance (EPR) reveals paramagnetic defect centres—a novel and strong candidate for surface loss channels.

By optimizing these various techniques for ultra-thin SiN membranes, we are able to build a complete microscopic picture of the membranes and their surfaces. This provides the experimental foundation needed to engineer next-generation, ultra-low-dissipation mechanical resonators for quantum applications.

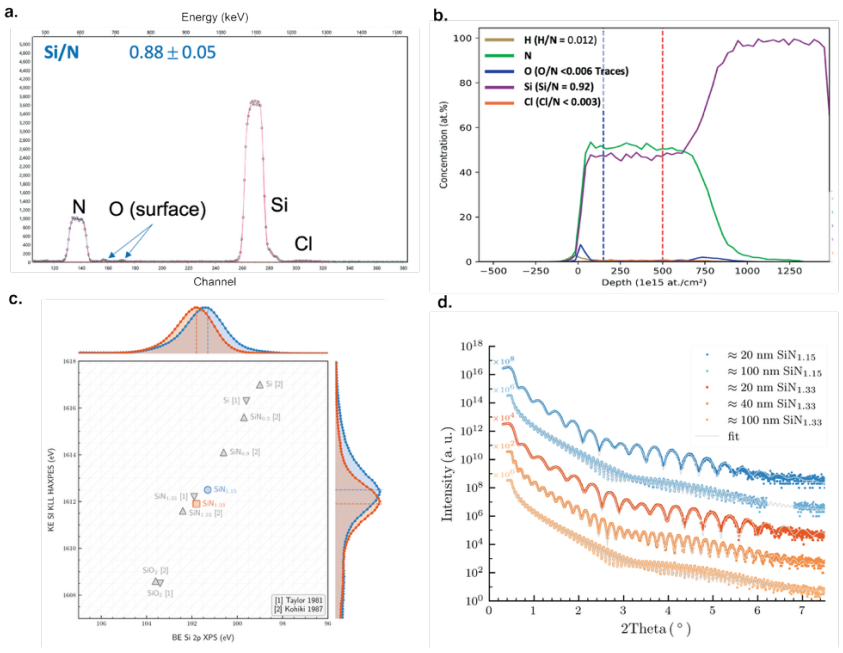



***Figure 1.*** *(a) RBS and (b) ERDA data for a 100 nm thick Si-Rich membrane. (c) XRR data for membranes of various thicknesses and stoichiometries. (d) Wagner plot os Si KLL verus Si 2p peaks.*

[1] Y. Tsaturyan, Nat. Nanotechnol. (2017). 12, 776.
[2] Villanueva, Phys. Rev. Lett. (2014). 113, 227201.