Fabrication and Structural Analysis of Trilayers for Tantalum Josephson Junctions with Ta_2O_5 Barriers

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Background

- Tantalum (Ta) has emerged as a promising low-loss material for superconducting quantum circuits, with Ta-based qubits achieving record life-times (T_1) of 0.5 ms.
- Nevertheless, aluminum oxide remains the predominant choice for Josephson junction (JJ) barriers in most qubit architectures, due to ease of fabrication.
- Here, we investigate techniques for forming high-quality oxide layers on α-phase tantalum films to develop tantalum-oxide JJs.

Methods

- $\alpha-$Ta films deposited via DC magnetron sputtering on: (1) Heated sapphire substrates at 500°C or (2) Nb seed layer on Si at room temperature (RT).
- Three oxidation methods compared: Tube furnace annealing at 400°C, Rapid Thermal Annealing (RTA) at 700°C, RF Plasma oxidation from RT - 400°C.
- Trilayers were then formed by depositing a Ta layer on the oxide – tested with and without a Nb seed layer on top of the barrier.

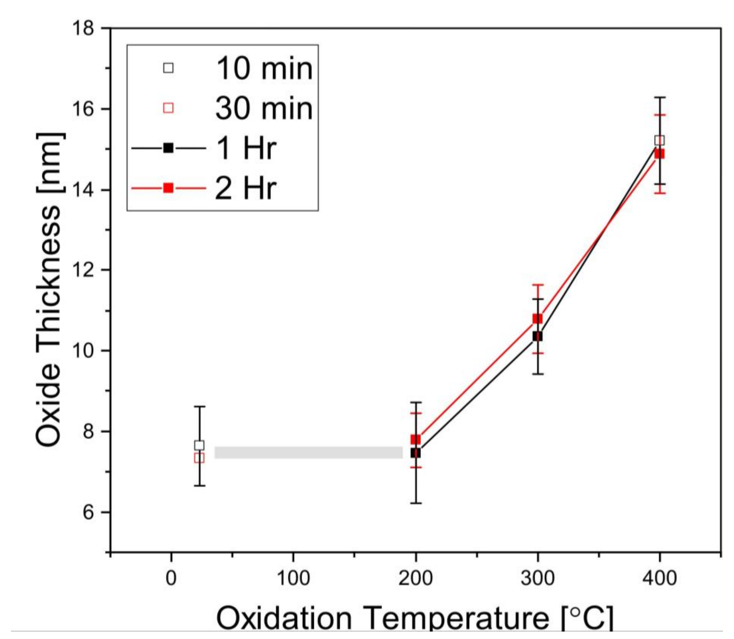


Fig 1: Oxidation Temperature vs Thickness for different plasma oxidations. A clear trend can be seen with approximately equal thicknesses for different temperatures irrespective of time.

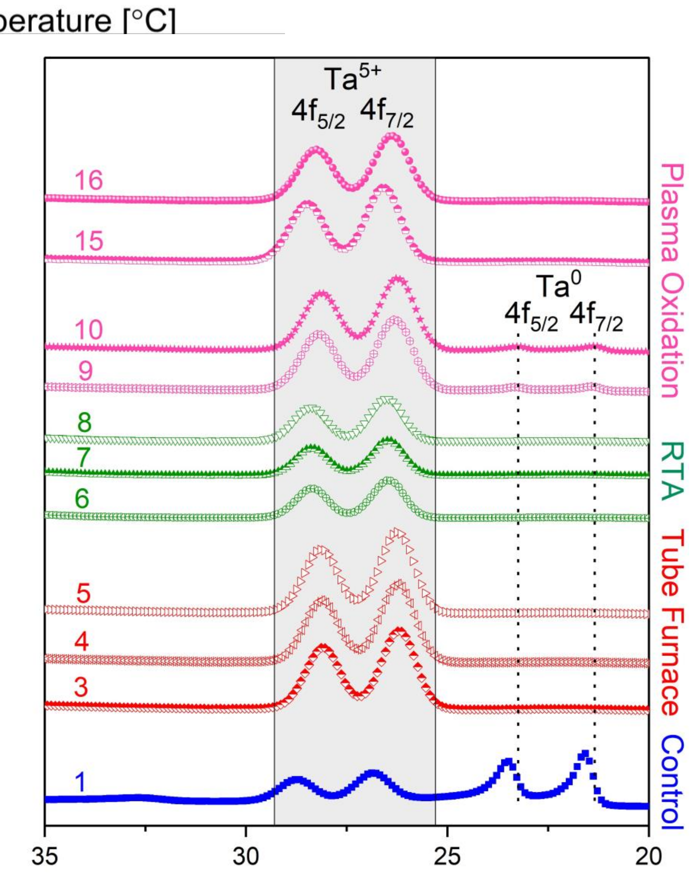


Fig 2: High-resolution Ta(4f) XPS spectra of tantalum films showing the characteristic Ta_2O_5 doublet peaks at binding energies of approximately 26.2 eV (Ta $4f_{7/2}$) and 28.1 eV (Ta $4f_{5/2}$).

Oxide Characteristics

- X-Ray Photoelectron Spectroscopy (XPS) confirmed Ta_2O_5 (Ta^{5+}) as the dominant species for all methods. Suboxides were only detected in RT- plasma oxidized samples.
- Films oxidized using RTA delaminated due to thermal stress from lattice mismatch. Tube furnace produced thick oxides in the range of 37-60 nm.
- Plasma Oxidation produced the smoothest oxides (roughness < 0.5 nm) in the thickness ranges of 7-15 nm, which can be **tuned by the temperature of oxidation; insensitive to the oxidation time past 1hr.**

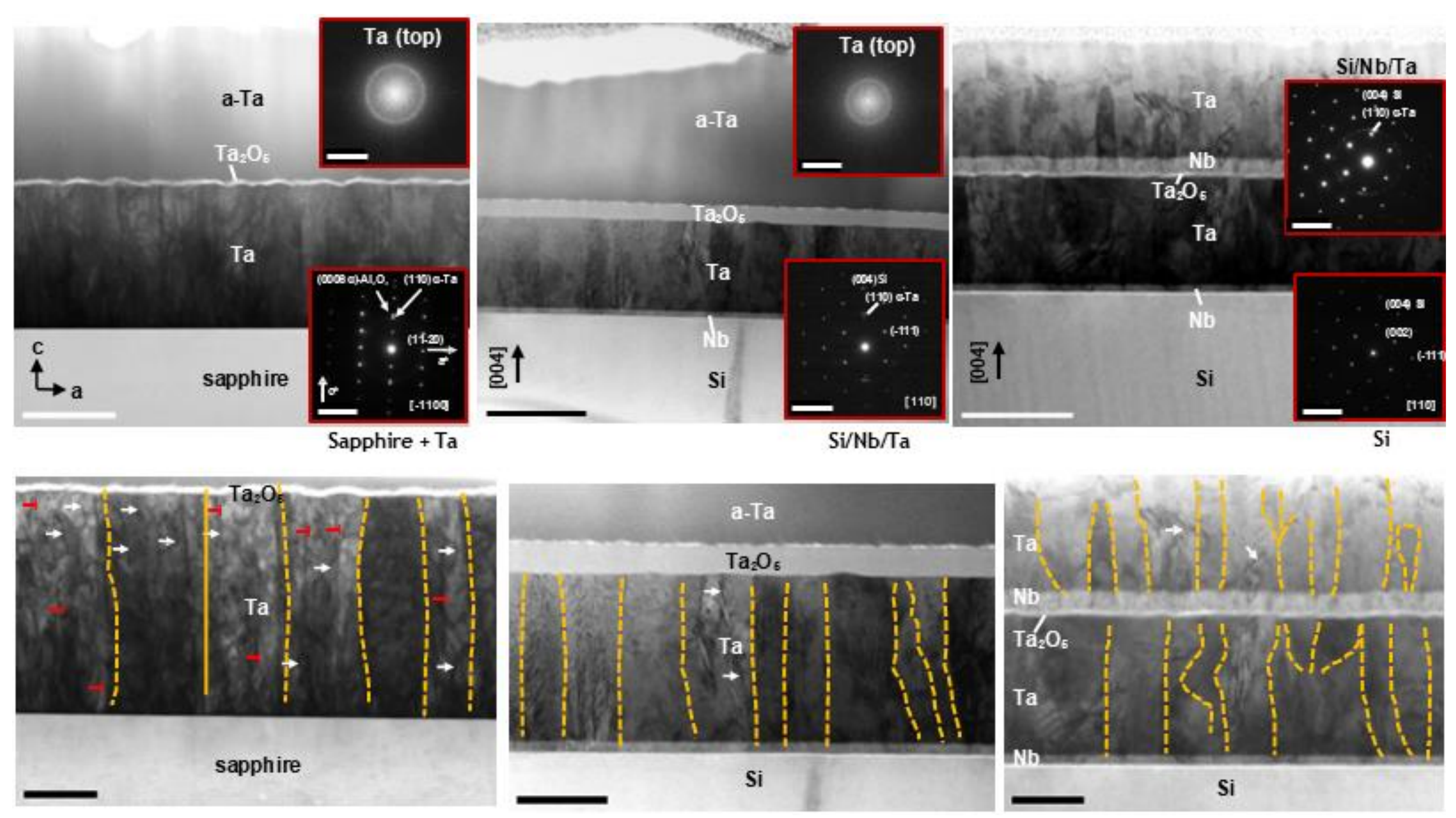


Fig 3: Cross-sectional STEM-BF images of three different trilayers. Insets show the FFT and SAED patterns from the indicated layers, confirming the crystallinity and orientation. Bottom row images show grain boundaries (yellow dashed lines), threading dislocations (red arrows), and mixed dislocations (white arrows). Scale bars correspond to a length of 50 nm.

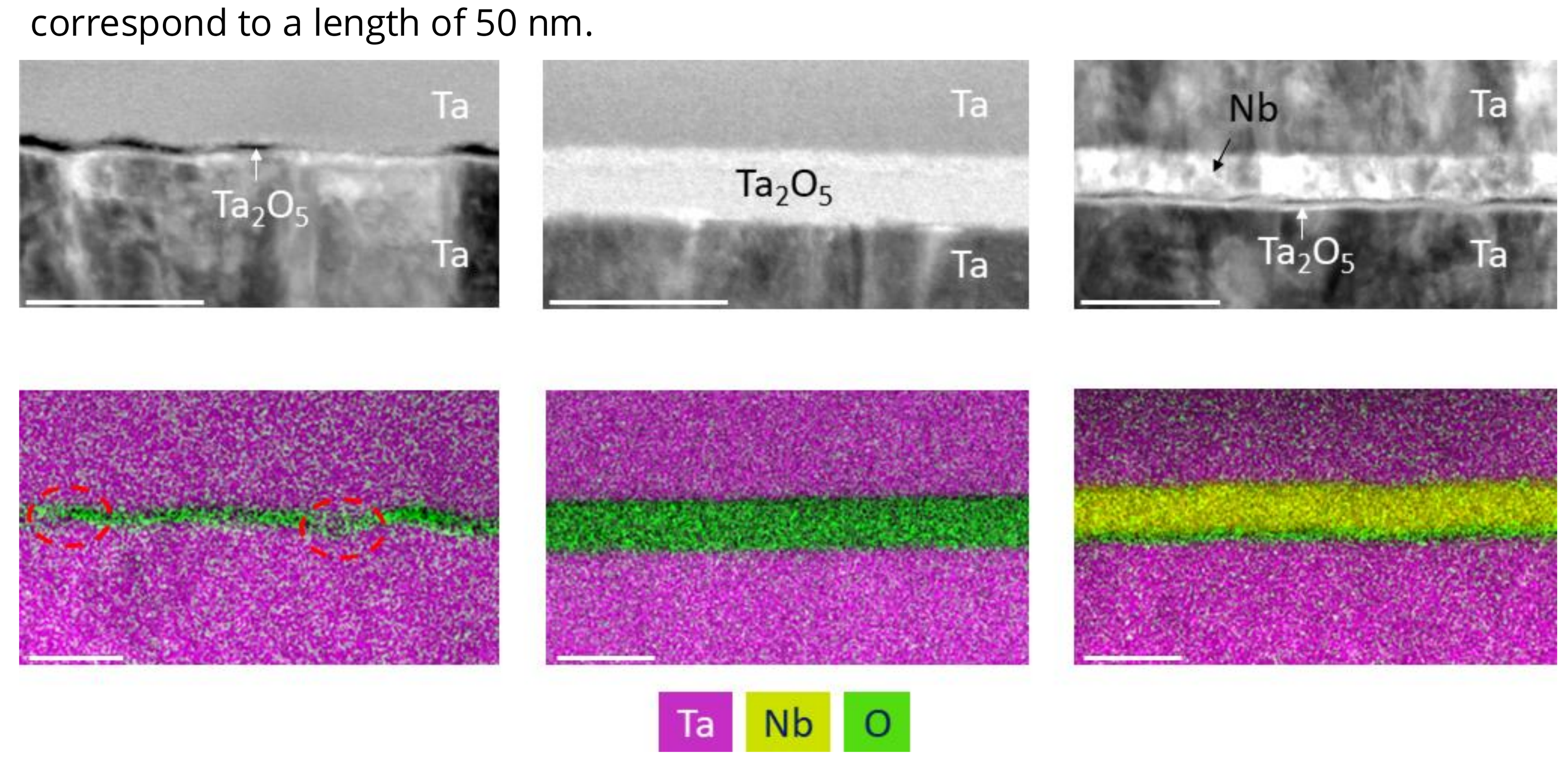
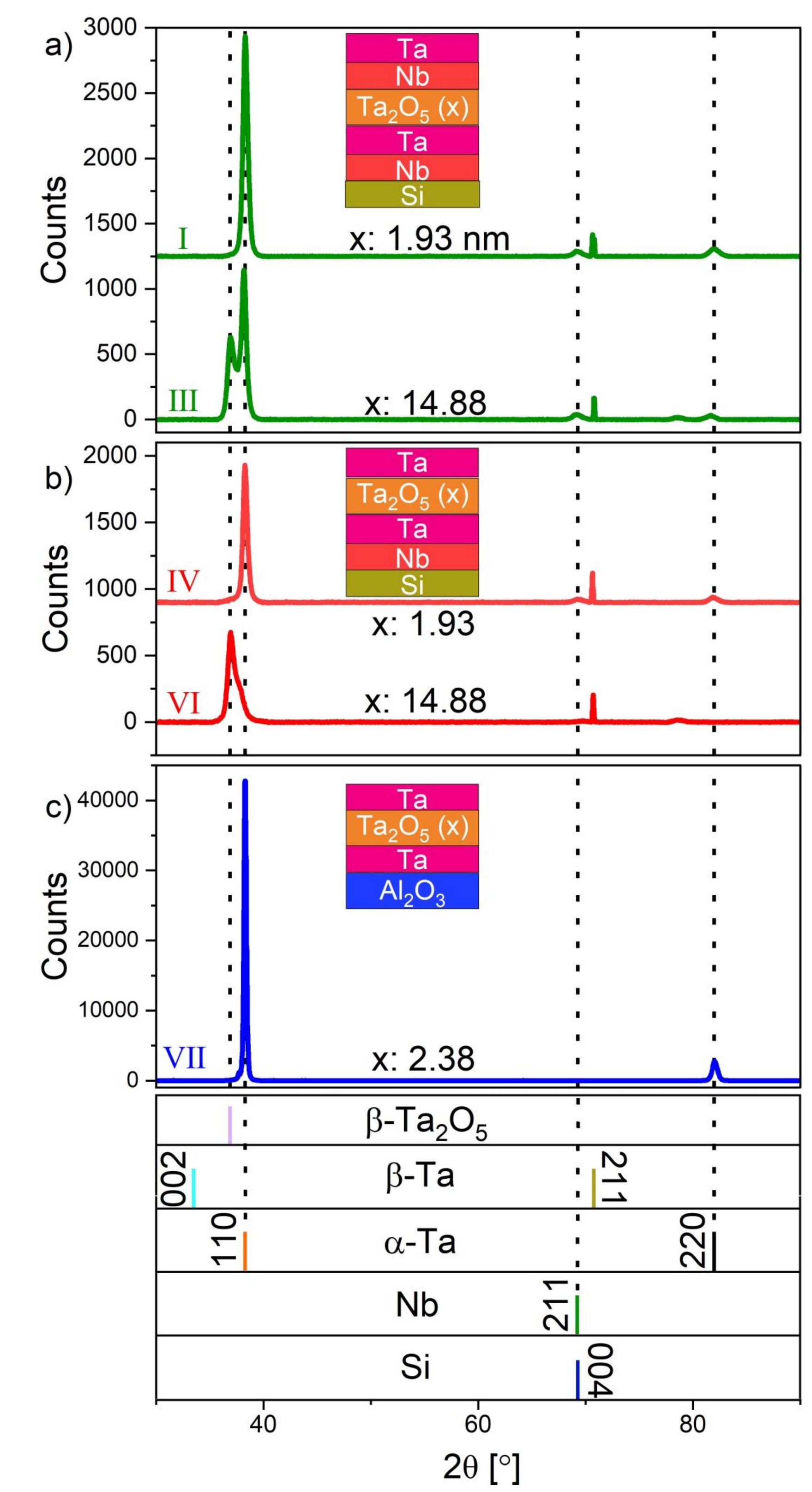


Fig 4: [Top row] STEM-HAADF overview images of three different trilayer samples. [Bottom row] STEM-EDX elemental mapping of Ta, O, and Nb. Scale bars correspond to a length of 50 nm.

Trilayer Characteristics

- Nb layer above the barrier is essential to grow $\alpha-$Ta, as not using this led to growth of amorphous (non-superconducting) Ta.
- STEM-EDX shows sharp, uniform interfaces for plasma-oxidized trilayers with ~15 nm oxide; native oxide trilayers show Ta-rich inclusions indicating potential microshorts.
- All bottom Ta layers show c-axis columnar growth; sapphire gives larger grains but higher dislocation density than Si substrates.

Fig 5: XRD patterns of the trilayer films. Stack order for each set is shown in the cartoon insets, with "x" indicating the thickness of the oxide in nm. (Bottom panel) Reference peak angles for the phases of interest.



Conclusions

- Plasma oxidation yielded especially smooth oxide surfaces, with thickness controllable through the annealing temperature.
- We further demonstrated successful growth of α-Ta on Nb-seeded tantalum-oxide atop α-Ta films, establishing a route toward trilayer Josephson junctions incorporating Ta_2O_5 barriers.
- These structures provide a promising platform for fabricating highly oriented Ta-based Josephson junctions, enabling quantitative studies of TLS defect densities in the barrier and interfaces.

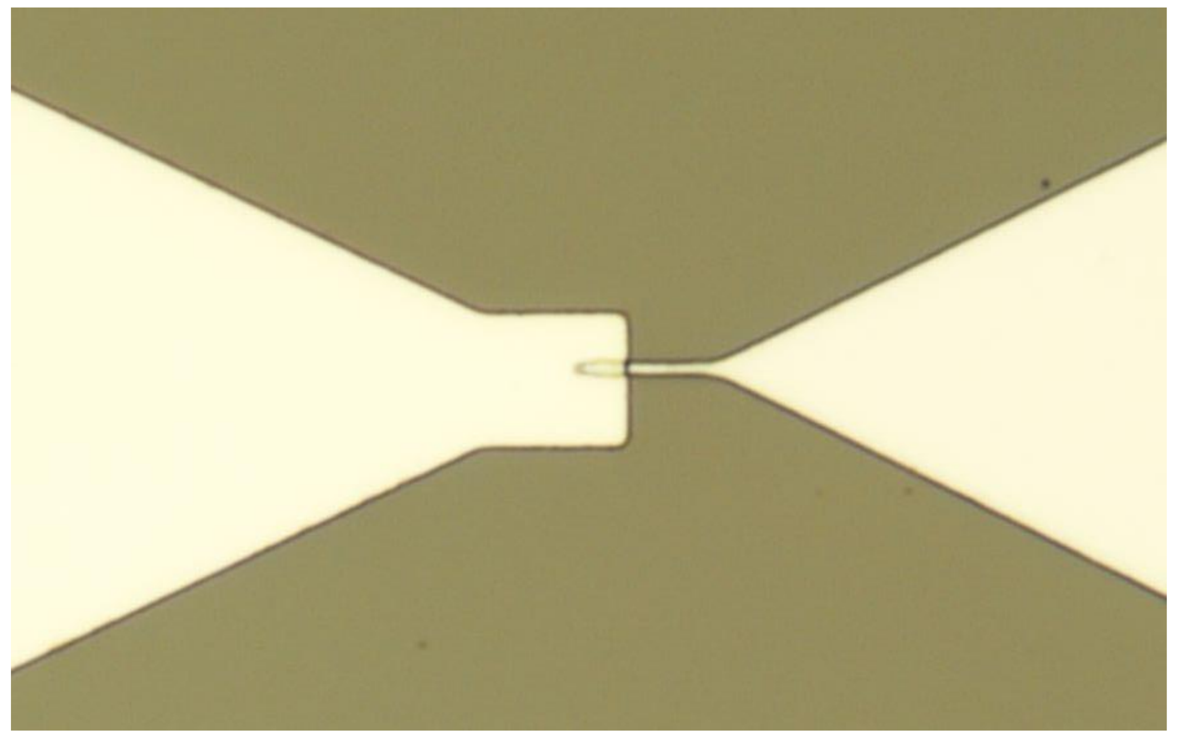


Fig 6: Image of the new planar Ta/TaO_x/Ta Josephson junction

Future Work

- We plan on fabricating and measuring a new planar Josephson junction architecture, which involves creating $\alpha-$Ta islands, oxidizing these islands and then depositing another layer of $\alpha-$Ta. Currently fabricated junctions can be seen in Figure 6.

Acknowledgements

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