Atomic Layer Deposition Josephson Junctions for Cryogenic Circuit Applications

Christine A. Jhabvala, Peter C. Nagler, and Thomas R. Stevenson
NASA Goddard Space Flight Center, Greenbelt, Maryland USA

Objective:

Superconducting-insulating-superconducting (SIS) trilayers have been produced for Josephson Junction fabrication by thermal atomic layer deposition (ALD) processes. The trilayers are composed of alternating layers of $Ti_{0.4}N_{0.6}/Al_2O_3/Ti_{0.4}N_{0.6}$, deposited in situ, in a thermal ALD reactor. The self-limiting nature of ALD enables precise control the tunnel-barrier insulator thickness by counting the number of ALD cycles during the junction insulator deposition step. The conformal nature of the deposition process ensures that Josephson Junction sidewalls are uniformly insulated without the need for anodization.

Motivation:

The conformal nature of ALD makes this technique extremely attractive for depositing and patterning multiple layers of superconductors and insulators. ALD eliminates step-coverage problems, the need for sloped-sidewall etches, and the potential for a discontinuity when the superconductor crosses over a sharp step.

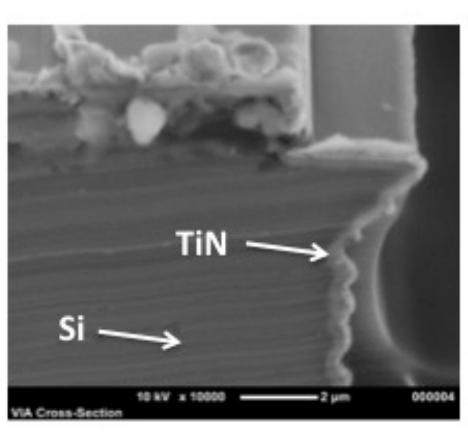


Figure 1. The Scanning Electron Microscope image at ***left*** demonstrates the conformal nature of ALD TiN, uniformly coating a very difficult, re-entrant, scalloped sidewall etched into silicon. This coating uniformity would be impossible with any other deposition technique.

Atomic Layer Deposition and Fabrication description:

TiN films with a stoichiometry of 2:3 are grown in a Beneq TFS 200™ multi-wafer, thermal reactor at 450°C. A Tc of 3.4 K is standard for our process and is measured periodically to ensure quality control. Atomic Layer deposition is a gas-phase deposition technique. Films are grown by alternating two reactant gases, or precursors. The growth is self-limiting in nature, with one molecular layer of material grown per alternating cycle of reactants. Measured transition temperature of $Ti_{0.4}N_{0.6}$ is shown in Figure 2. Film growth-rate and precursors for the titanium nitride and aluminum oxide used in this study are shown in Table 1.

Josephson Junction Fabrication flow:

1. ALD Base Electrode and Trilayer Dep, $Ti_{0.4}N_{0.6}/Al_2O_3/Ti_{0.4}N_{0.6}$ (1500Å/10Å/500Å)
2. JJ Etch, defines the junction area
    - Plasma Etch: $Cl_2/BCl_3/Ar$ (30/10/10 sccm) @ 200W ICP/50W RF, 10 mT
    - No etch stop. Etch slightly into Base Electrode layer (~500Å)
3. ALD Insulator Dep, Al^2O^3 insulates the JJ's top and sidewalls
4. Insulator Etch, opens vias on top of JJ's to connect to Top Electrode, Buffered HF Etchant
5. ALD TiN Top Electrode Dep (1000 Å)
6. Top Electrode Etch

Table 1. Growth rate and precursors for ALD

Film	Growth rate (Å/cycle)	Precursor 1	Precursor 2
Al_2O_3	0.68	Trimethylaluminum (TMA)	H_2O
$Ti_{0.4}N_{0.6}$	0.24	Titanium tetrachloride ($TiCl_4$)	Ammonia (NH_3)

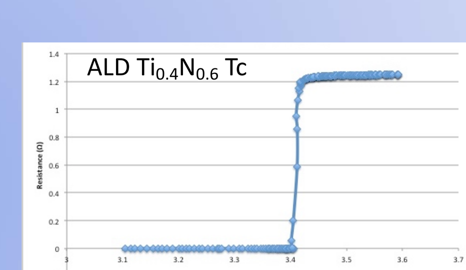
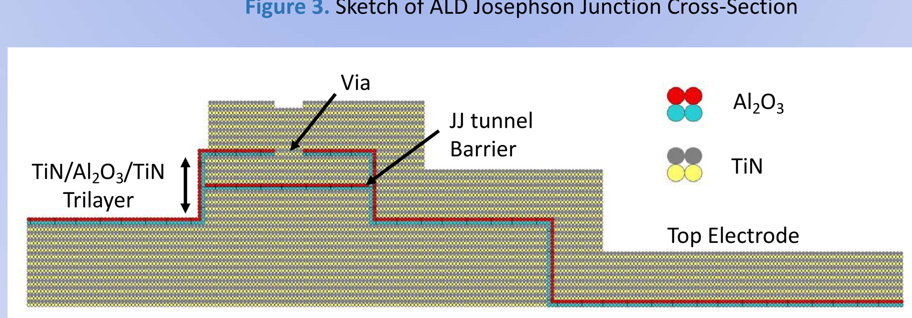


Figure 2. Superconducting transition temperature of ALD Titanium Nitride

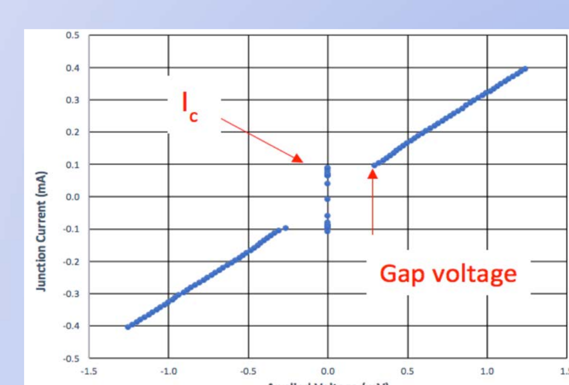
Figure 3. Sketch of ALD Josephson Junction Cross-Section



The sketch in Figure 3 above is intended to illustrate the molecular growth of ALD deposition. (Not to scale)

Test results for ALD Josephson Junctions:

Current Voltage plot and Gap-Voltage of an ALD Josephson Junction



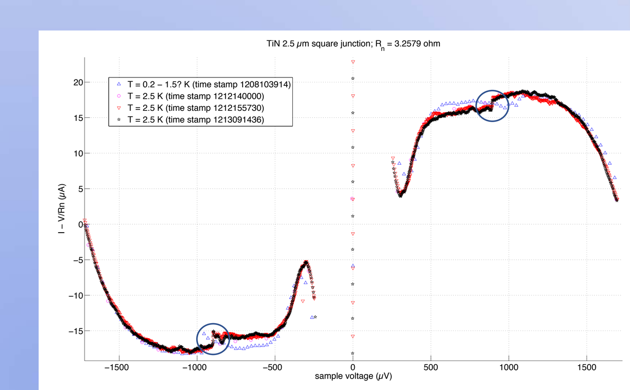
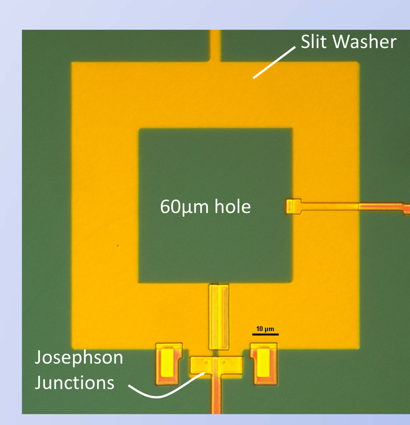


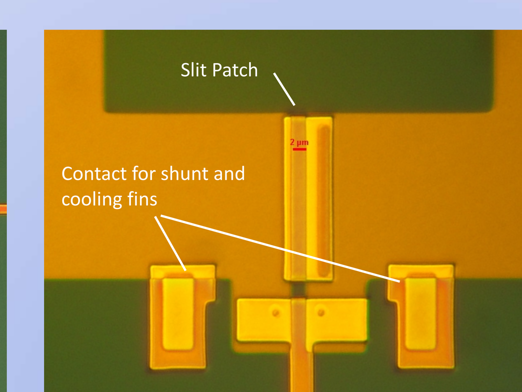
Figure 4. *(Above Left)* We have demonstrated Josephson Junctions produced using all ALD, $Ti_{0.4}N_{0.6}/Al_2O_3/Ti_{0.4}N_{0.6}$ processes. The measured supercurrent (Ic) is 100 µA. Gap voltage 320 µV, considerably lower than BCS theory predicts, given a Tc of 3.4K.

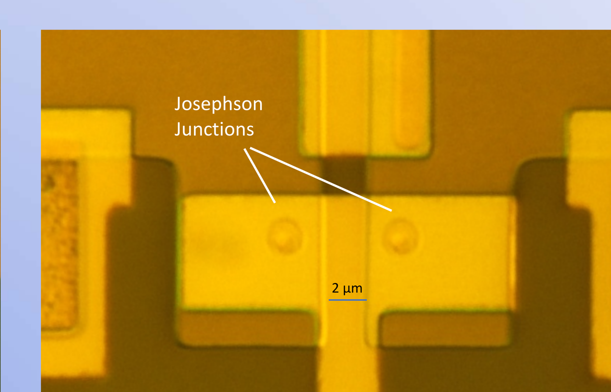
To adjust Ic, additional Al_2O_3 cycles will be added during trilayer growth. The junction measured in the above plot is a 2.5 µm square junction.

(Above Right) With the resistive component removed from the above-gap region of the data, features (circled) are revealed near the area where BCS theory predicts the energy gap should be, ~900 µV. This may indicate that the $Ti_{0.4}N_{0.6}$ has multiple transitions, the dominant of which occurs at 3.4K.

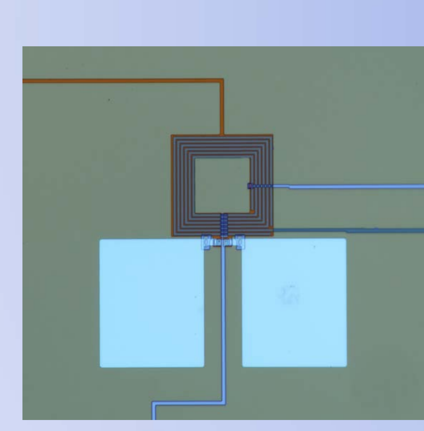
Progress toward ALD SQUIDs:



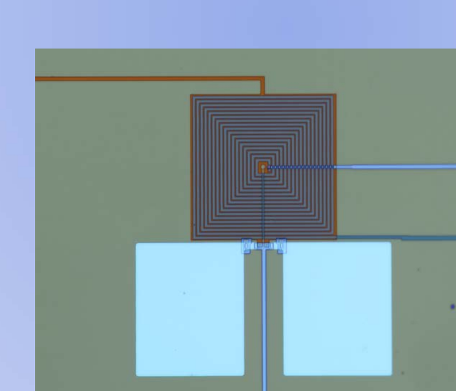




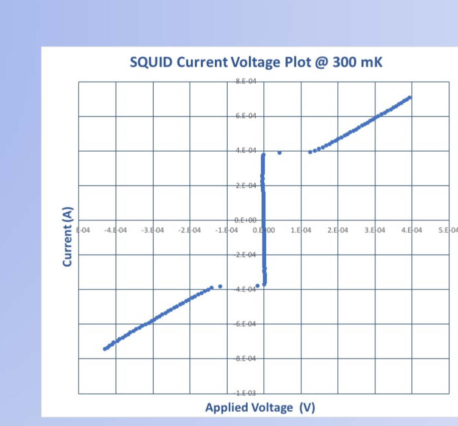
Using design rules established during the production of ALD Josephson Junctions, we designed and fabricated a single-element, slit-washer-base-electrode SQUID.



SQUID 1 Design parameters:
Ic (target) – 10 µA
Junction area – 2.5 µm x 2.5 µm
Washer hole – 60 µm, Slit 2 µm
N turns – 4



SQUID 2 Design parameters:
Ic (assumed) – 100 µA
Junction area – 2.5 µm x 2.5 µm
Washer hole – 4 µm, Slit 2 µm
N turns – 17



Above: IV plot of a single element SQUID. Ic is ~400 µA, too high to modulate without exceeding the inductor critical current. Further development is needed to reduce Ic by adding more Al2O3 cycles during trilayer deposition.

Summary:

We have demonstrated Josephson Junctions fabrication with Atomic Layer Deposition titanium nitride/aluminum oxide/titanium nitride trilayers. The conformal nature of ALD obviates the need for anodization of junction side-walls. Junctions produced have 100 µA critical current, which can be reduced by depositing additional cycles of Al_2O_3 during trilayer growth. The IV characteristics and gap voltage of a single junction indicate the possible presence of a second superconducting transition at higher temperature, which has not been observed in Tc checks of ALD $Ti_{0.4}N_{0.6}$, where a single transition at 3.4K has been recorded. Progress has been made toward producing ALD SQUID devices, although the critical current of the Josephson Junctions needs to be reduced significantly, by adding cycles of Al_2O_3 to the junction barrier.

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