Development of Cryogenic Detector Arrays using ALD

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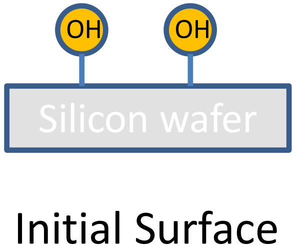
Motivation

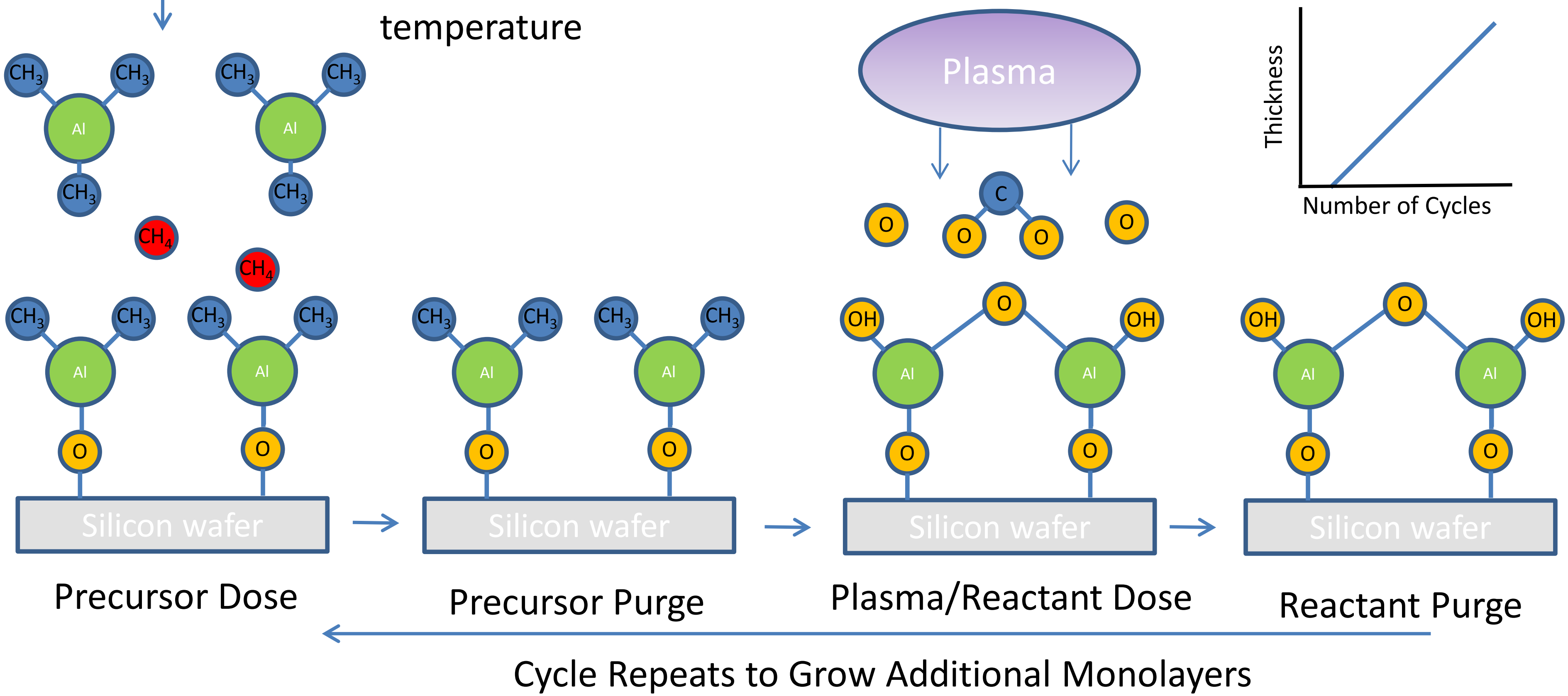
- ALD is a scalable deposition process which has high spatial uniformity, extreme conformity and monolayer control.
- A large number of metals and insulators have been grown by this technique – including superconductors.
- ALD has the potential to solve a number of issues associated with large pixel count FIR arrays of superconducting detectors, including:
  - Spatially uniform MKID detectors fabricated from transition metal nitrides (TiN, TaN, …).
  - Superconducting through-silicon vias (TSV) for hybridization and othe 3D structures.
  - Precisely controlled multilayered materials.
  - Etc….

Atomic Layer Deposition Fundamentals

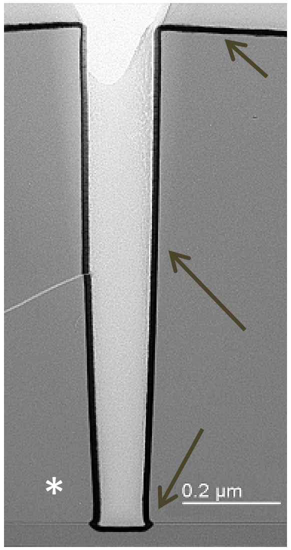
Example: AlOx



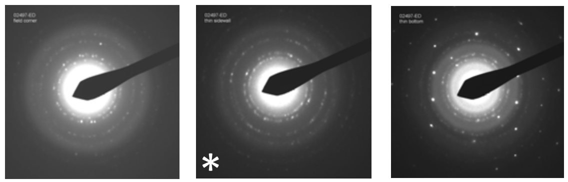
- Surface reaction mediated deposition
- ALD cycles are repeated until desired film thickness is achieved
- Metals, Nitrides, and Oxides are achieved through choice of precursor and reactant species
- Can achieve thin film deposition or surface modifications at near room temperature



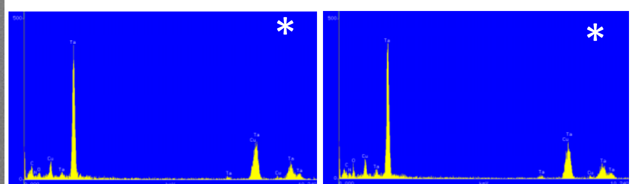
Properties and Advantages of ALD



Field Sidewall Bottom

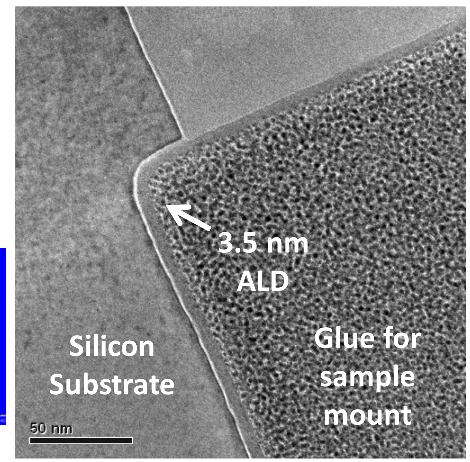


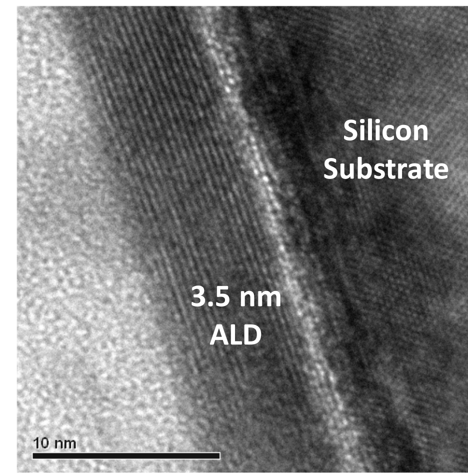
Field Sidewall



Selective Area Diffraction and EDS show uniform iALD film properties throughout high aspect ratio features

TEM images of ultra-thin TiO_2 (3.5nm), conformal ALD film





KNI TEM of a JPL ALD TiO2 film (image credit Carol Garland/Bophan Chhim)

- Atomic Layer Deposition is inherently 100% conformal up to very high aspect ratios
- Film properties and composition are uniform throughout aggressive features
- Film properties and composition are uniform across arbitrarily large substrates

* F.Greer, *et al.* *i*ALD TaN film, Novellus Systems, AVS-ALD Conference 2005

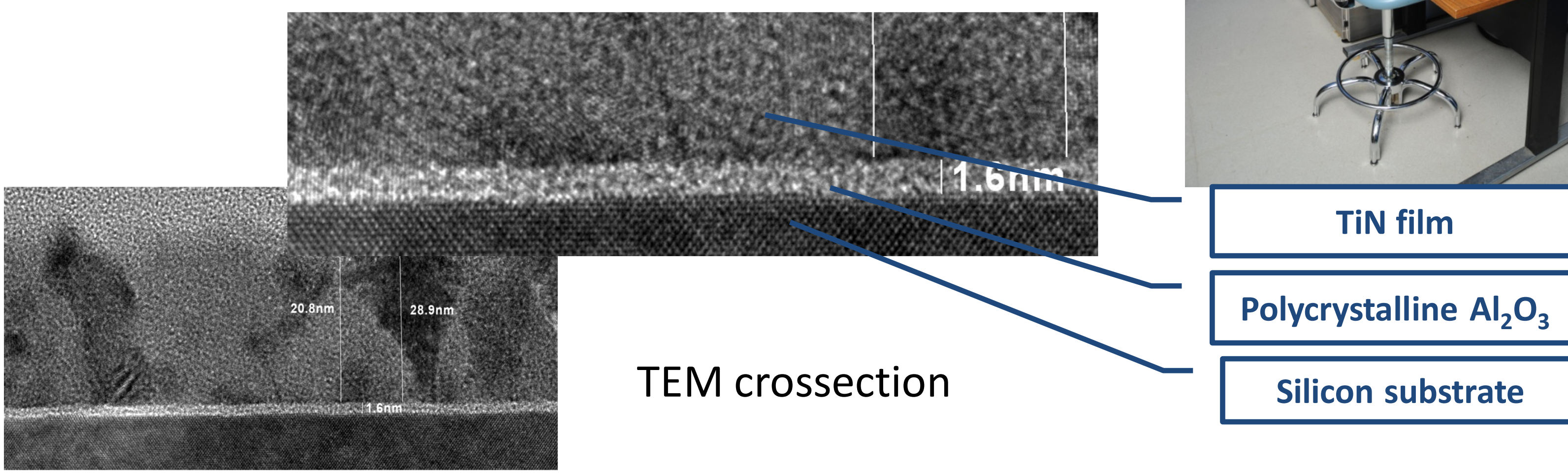
Primary Materials Studied

Transition Metal Nitrides

- Many materials of the form MN where M is a transition metal and N is nitrogen are superconductors with moderate T_cs – TiN, TaN, MoN, VN, NbN, NbTiN,…
- The superconducting phase (B1 – NaCl) is stable over a range M/N different from 1.
- The T_c of the films can be reduced from T_c^{max} by controlling the N content.
- The resistivity of the films is typically large >100 microOhm- cm. (Kinetic inductance is large).
- Microwave loss is low (thin film resonators with internal Qs of 10s of millions demonstrated.)
- Are typically grown by reactive sputtering. Can be made uniform but more difficult.

ALD-TiN Progress

- Growth done in Oxford OPAL plasma assisted ALD
  - Not load locked.
- TiN growth chemistry: $TiCl_4$ + N_2/Plasma @ 400C on bare silicon substrates.
- Preconditioning with Trimethyl Aluminum required for good films.
  - Remove background contaminates.
  - Precondition silicon surface.

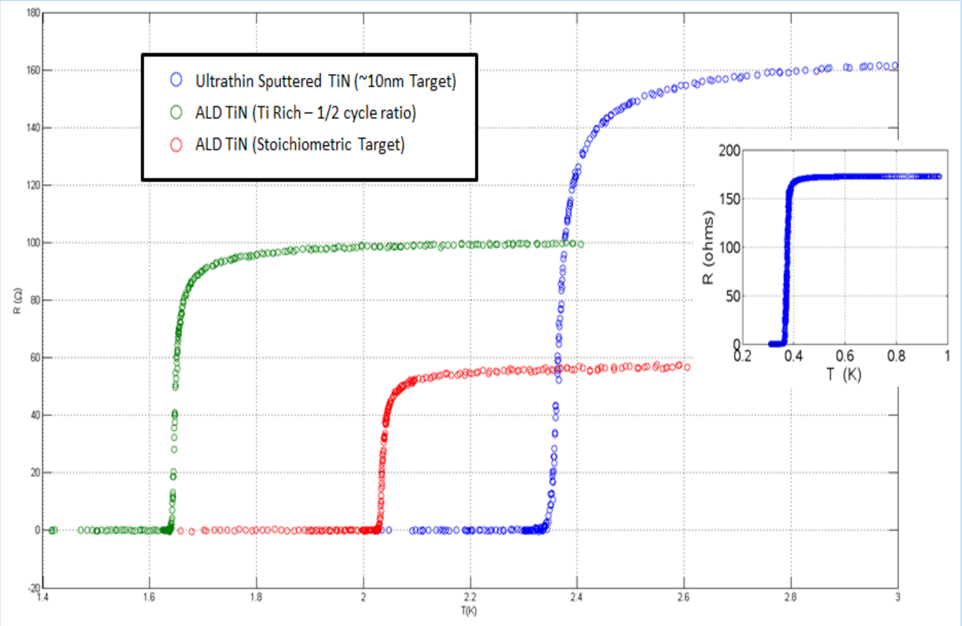


TEM crossection

ALD-TiN Superconducting Properties

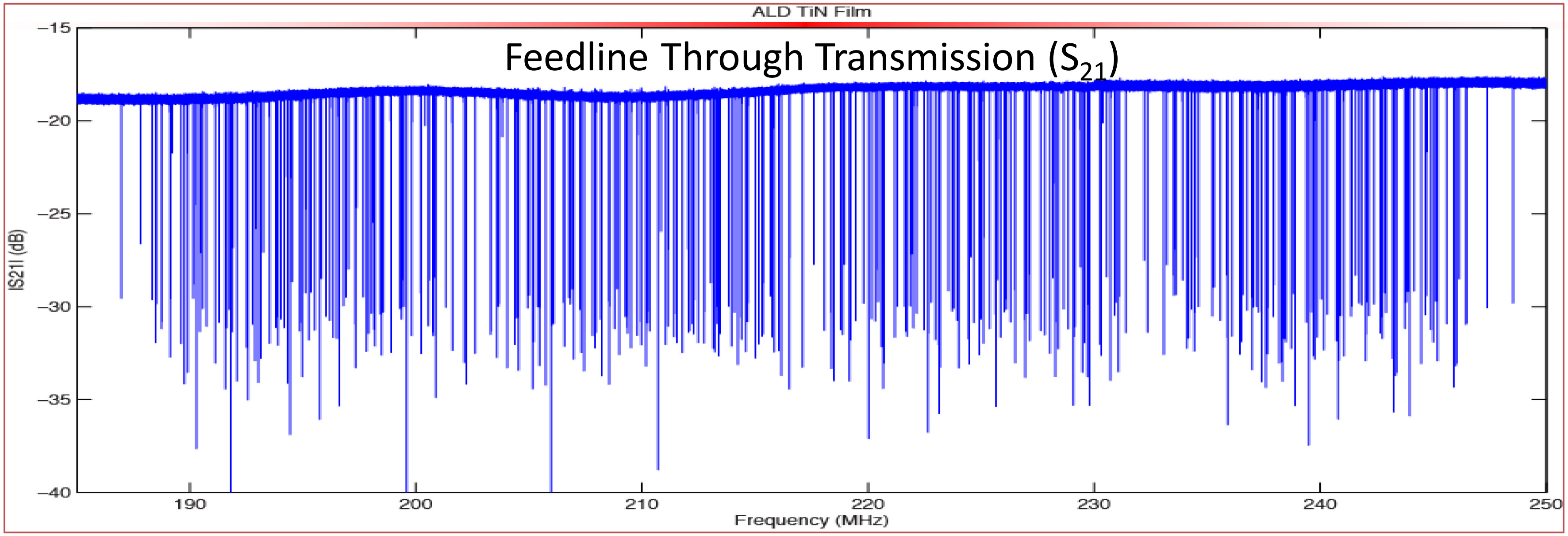
TiN films grown by ALD:

- T_c lower than sputtered films with the same stoichiometry.
    - XPS indicates some contamination.
- Resistivity x2 higher.
- Quality factors (Q) ~10^6 measured.
- T_c control demonstrated.
    - Atomic-multi-layer growth modulation (i.e. grow N layers stoichiometric TiN to M layers pure Ti)
- Shown at right:
    - Red circles - stoichiometric TiN (repeated many times to produce a 50nm film)
    - Green circles – 2 layers stoichiometric TiN and 1 layer pure Ti (repeated many times to produce 50nm film)

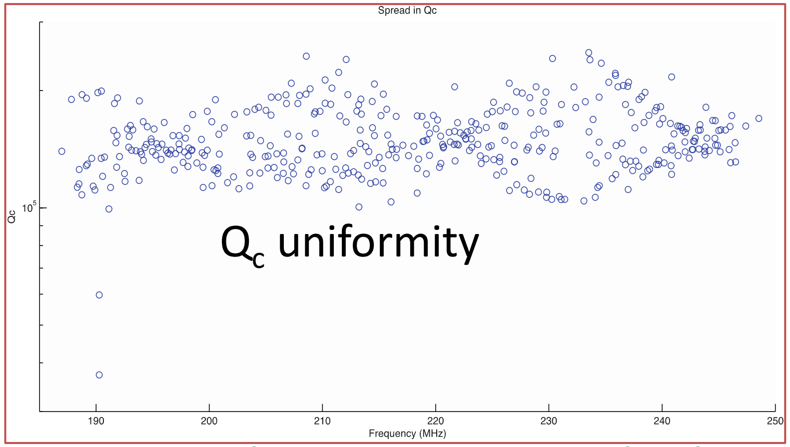


T_c control and comparison to sputtered films

ALD-TiN – KID Detector Demonstration

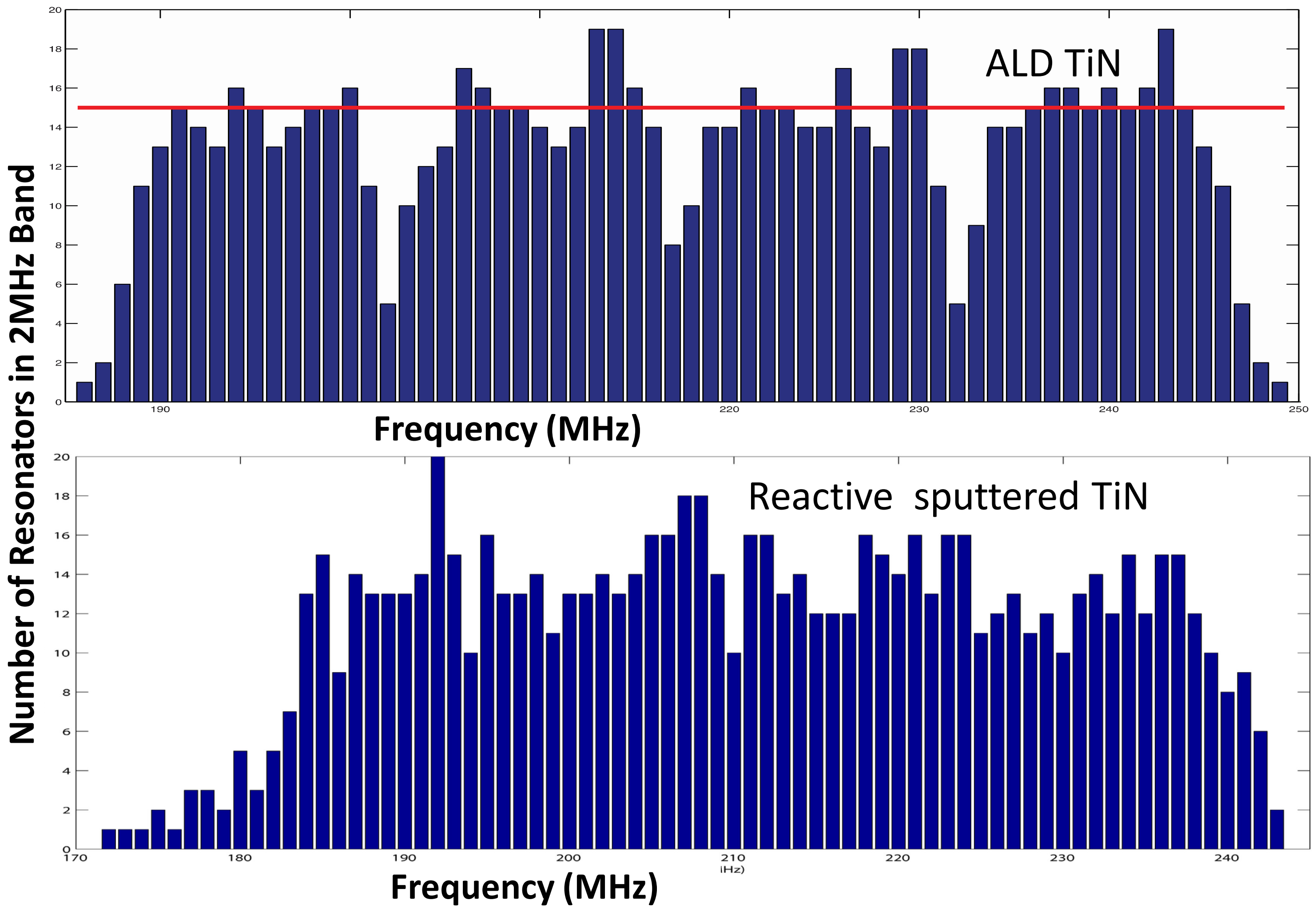


- Lumped Element Kinetic Inductance Detector (LeKID type) arrays fabricated .
- Fairly good yield 415/432 pixels active (resonator depth >6dB).
- Better frequency control than sputtered films(indirect evidence of better T_c uniformity).
  - Less frequency collisions
  - Better definition of frequency bands.



Data: Chris McKenney - Caltech

Resonator density (sputtered vs ALD TiN)

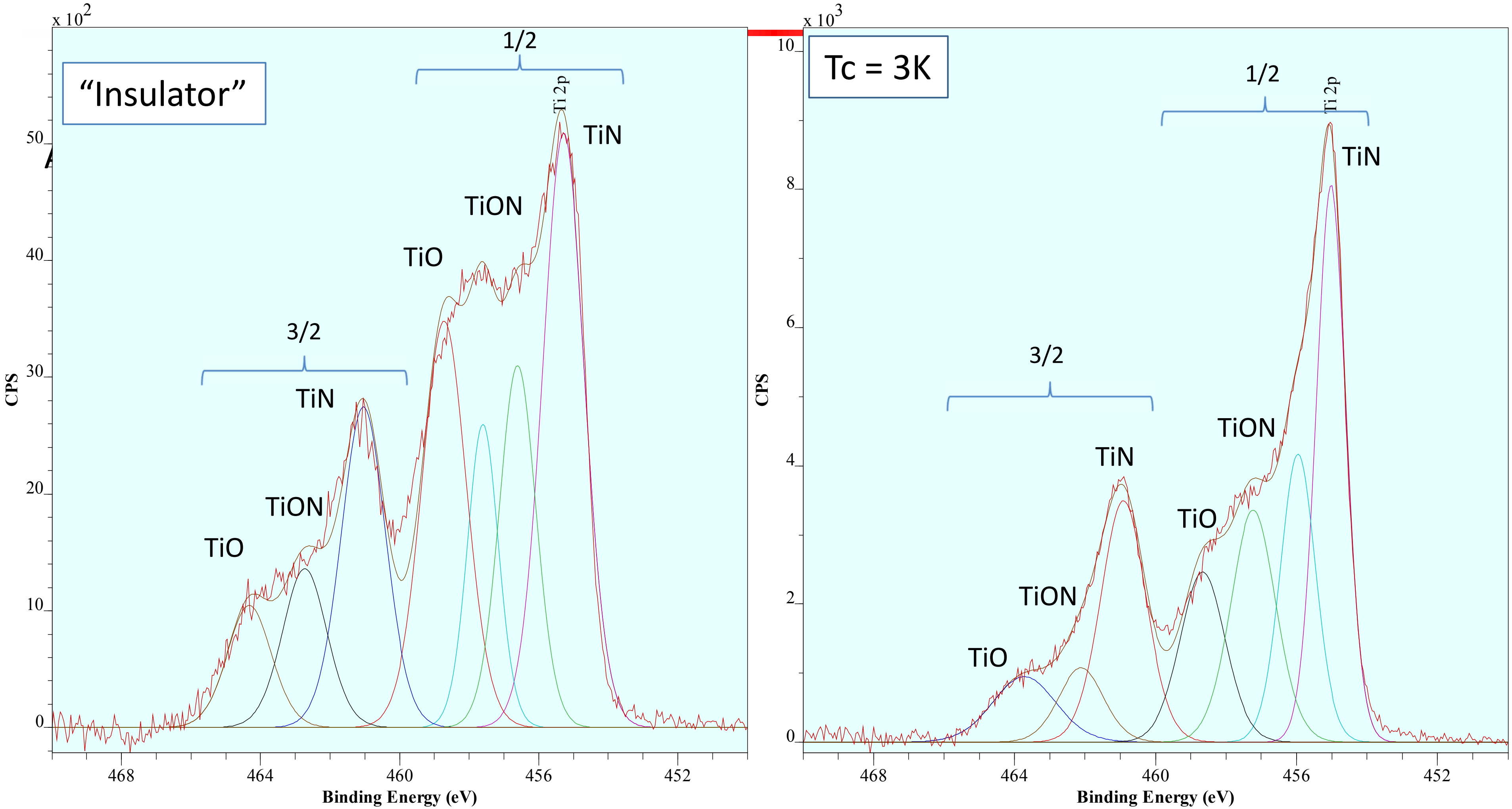


- Density of resonators in 2 MHz bands at 1 MHz intervals
- Four bands are visible
- Red line is design goal for in-band density (~130 kHz separation)

TaN, NbN and NbTiN progress

- We run a small number of films of higher Tc superconductors.
- Films so far have been semiconducting.
- Analysis indicates incorporation of contaminants from system and precursors.
- Future work will done in our new load-locked-ALD tool (Beneq Inc.)
- Example: Growth of TiN can result in insulator or metal dependent on growth conditions.

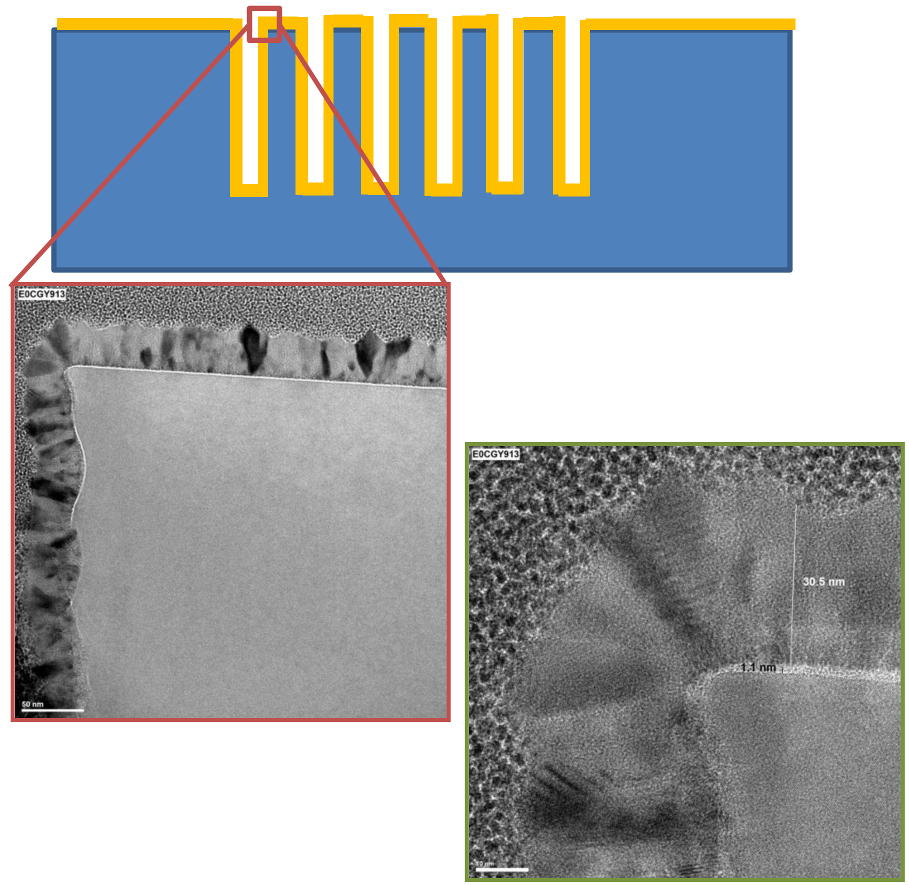
XPS Comparison for TiN Samples



- Titanium is more oxidized in the "insulator"

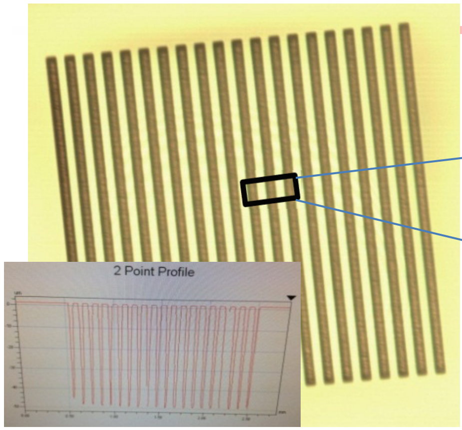
ALD-TiN Conformality Tests

- Patterned slots in Silicon using DRIE (Line space(μm) 10/10, 50/50, 50/100) ~50μm deep.
- Coat using plasma assisted ALD – TiN.
- Good conformal coatings on top sides and bottoms of trench structures.
- Electrical continuity to be tested.
  - Pattern top to form strip.
  - Measure thru- conductance electrically.

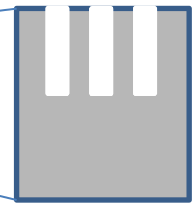


ALD TiN Step Coverage Characterization

Top down view

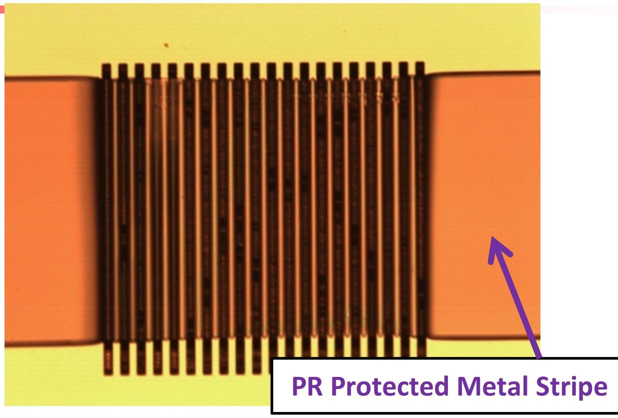


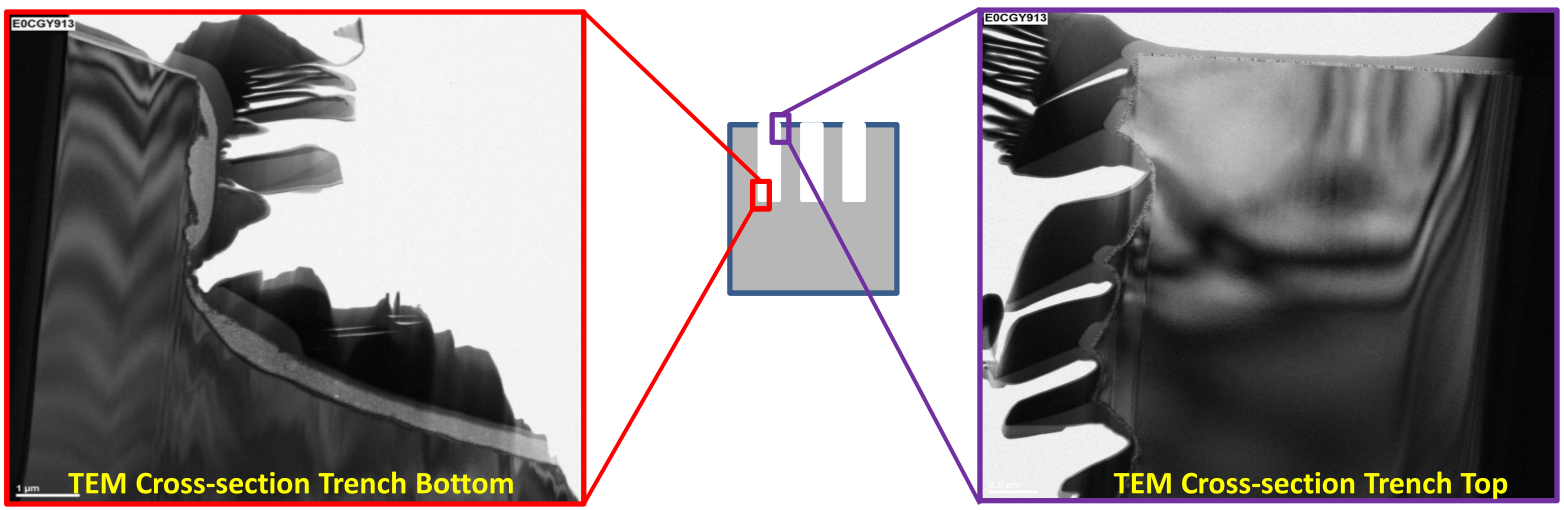
Cross-sectional view



Trench Dimensions
DRIE etched in silicon
50 micron deep:10 micron wide:10 micron space

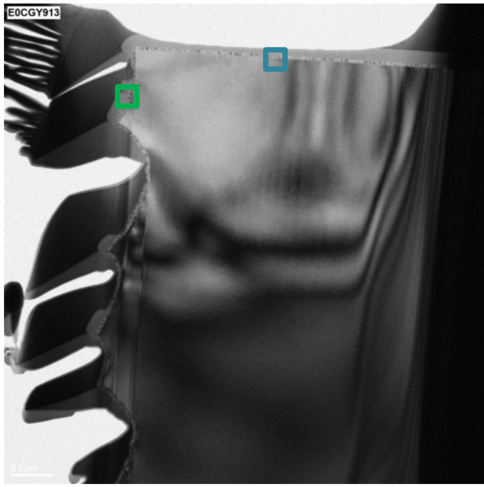
Top down view – after patterning



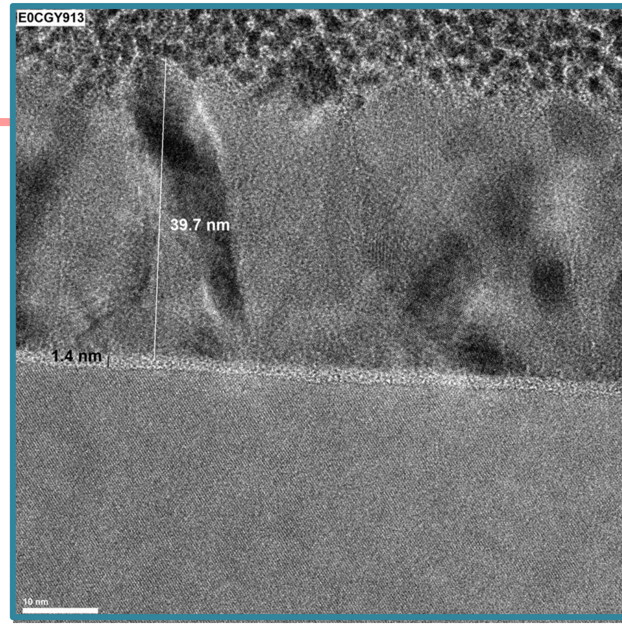


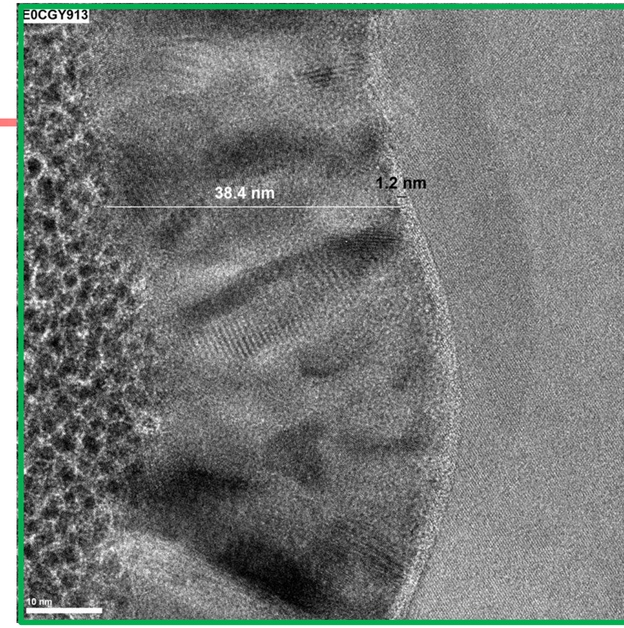
Simple trench structure created to characterize ALD TiN superconductor quality on sidewalls
Metal stripe patterned to traverse all 20 trenches – Tc measurement to be made

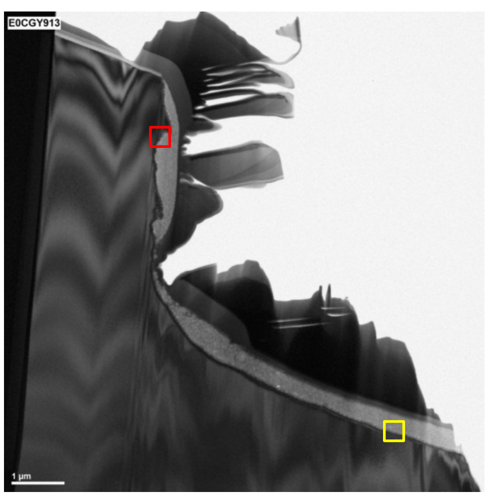
ALD TiN Step Coverage Characterization



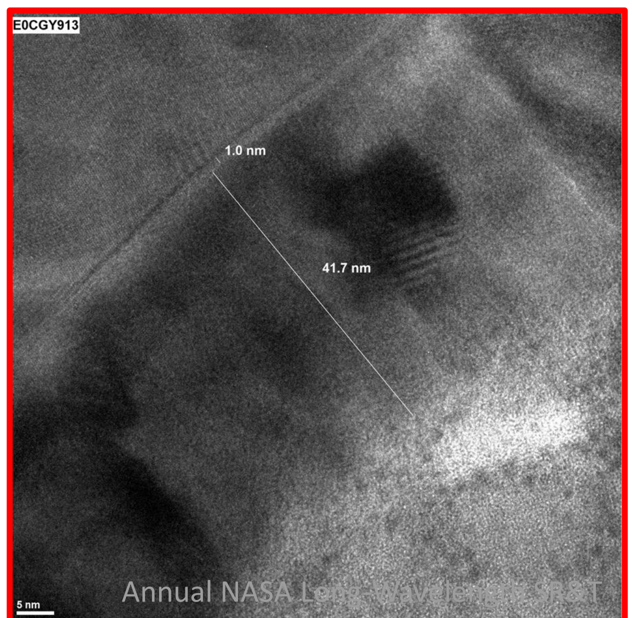
Top Corner

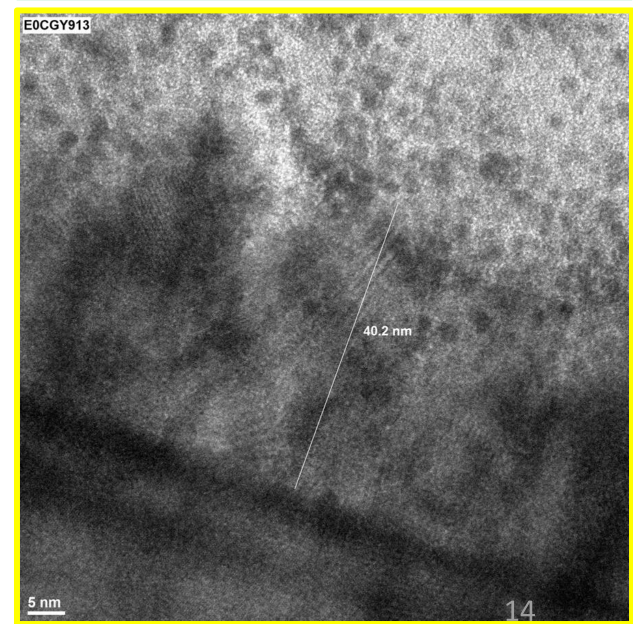






Bottom Corner





~100% Coverage achieved throughout trench, even on re-entrant parts of the feature!

New ALD equipment status

Side view of new Beneq ALD

Beneq ALD being brought into MDL cleanroom

- Load locked for better contamination control.
- Direct ion bombardment for better control of surface reactions.
- Chamber within a chamber for smaller cross contamination.

Conclusions

- We have deposited high quality TiN films using ALD.
  - Demonstrated high Q.
  - Demonstrated T_c control.
- Prototype arrays of LeKID type detectors show evidence of better spatial uniformity of T_c.
- We conformally coated deep trenches.
- Future continue to optimize TiN for detector applications
- Develop high-T_c films for via applications.