



Enabling High Performance Instruments for Astronomy and Space Exploration with ALD

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Outline



- Introduction to Jet Propulsion Laboratory
- Overview of Applications of ALD and Results
 - Anti-reflective coatings
 - Optical elements (mirrors/filters)
 - Superconducting detectors
- Conclusions and acknowledgements

Jet Propulsion Laboratory



- JPL is a child of Caltech: founded in 1936 as a graduate student project under Professor Theodore von Kármán.
- JPL led the development of US rocket technology in WWII.
- Developed the first U.S. satellite, Explorer I.
- JPL was transferred to NASA upon its creation in 1958.
- JPL spacecraft have explored all the planets of the solar system except Pluto.

- About JPL:
 - A Federally-Funded Research and Development Center (FFRDC) under NASA sponsorship;
 - A division of Caltech, staffed with > 5000 Caltech employees;
 - JPL Director is a Vice-President of Caltech.
- Programs:
 - NASA programs;
 - Defense programs and civilian programs of national importance compatible with JPL capabilities.





Microdevices Laboratory



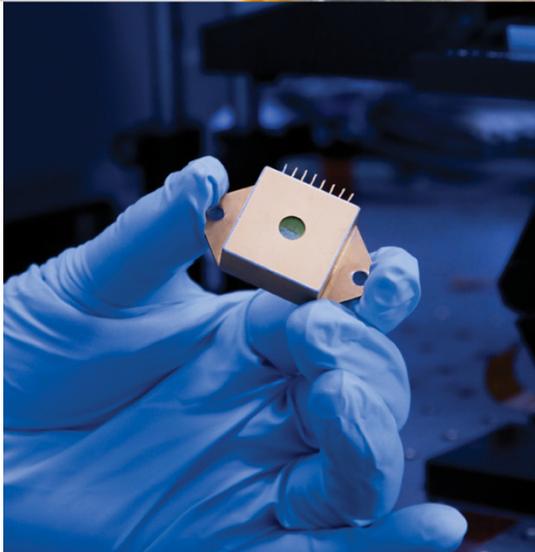
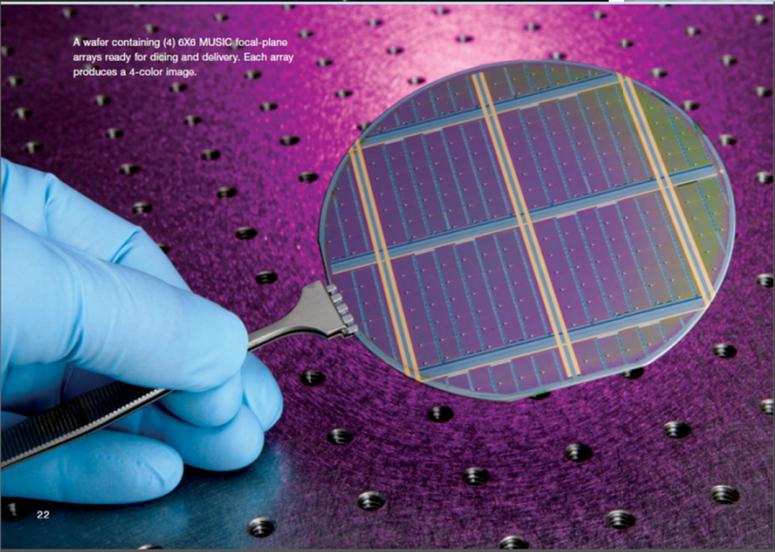
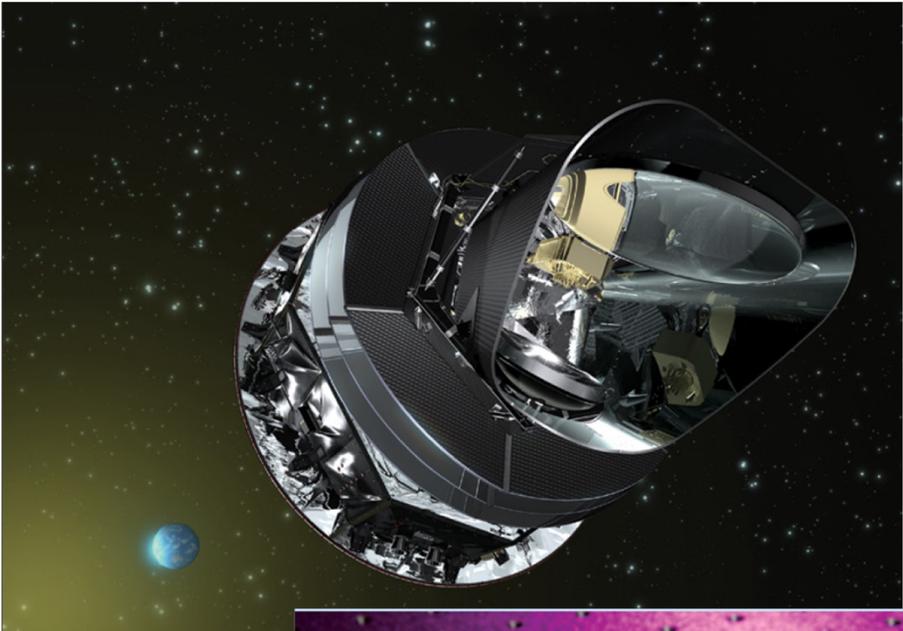
- MDL Facility built in 1989 to provide end-to-end capabilities for advanced electronic materials, device fabrication and characterization.
- Chartered to carry out innovative research and technology development for NASA applications and deliver instruments and components to flight applications
- Recent deliveries include superconducting detectors for the Herschel SPIRE and the Planck High Frequency Instrument that was launched by ESA in 2009
- Tunable Laser Spectrometer to fly on Mars Science Laboratory in late 2011





- **Start from broad questions asked by NASA Roadmaps**
 - Is there life on other planets? How did the universe form?
- **Missions are formulated to address these questions**
 - Mars Science Laboratory (MSL) – The Next Mars Rover
 - Goal: Examine the habitability of Mars
 - Hubble Space Telescope/Kepler/GALEX
 - Goal: Understand how stars, planets, galaxies, and the universe formed
- **Instruments are proposed to meet the mission goals**
 - Herschel/Planck – Mapped the cosmic microwave background (CMB) which remains from the Big Bang
 - Tunable Laser Spectrometer (TLS) – Designed to detect methane on Mars
- **New technology is funded by NASA and developed at JPL when there is no of-the-shelf method available to address the needs**
 - TLS – No laser was commercially available in the right wavelength range
 - Herschel/Planck – No commercial application for ultra-high sensitivity, cryogenically cooled, Far IR detectors

Examples of MDL Enabled Missions

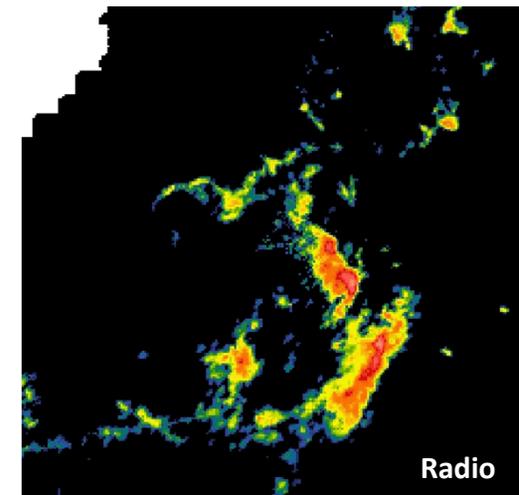
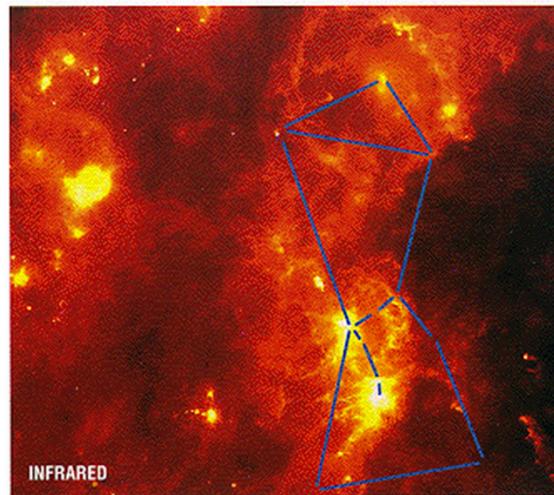
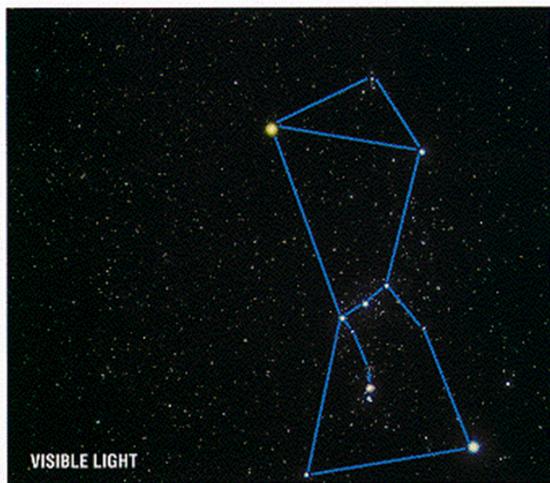
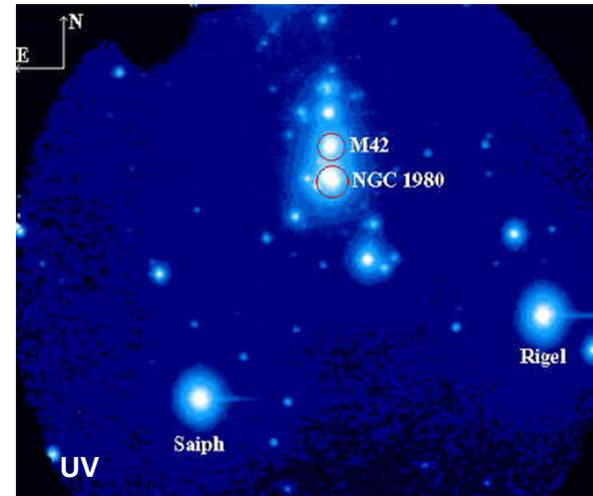
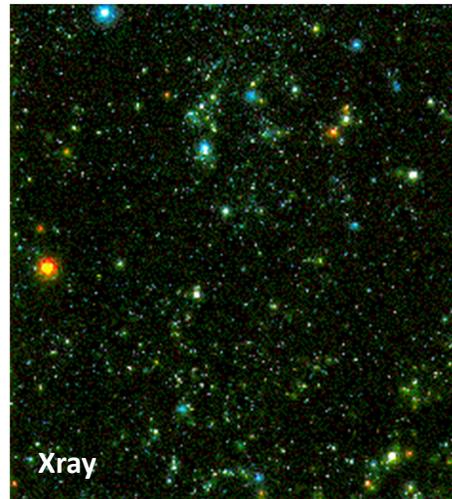


JPL/MDL Technology Opportunities



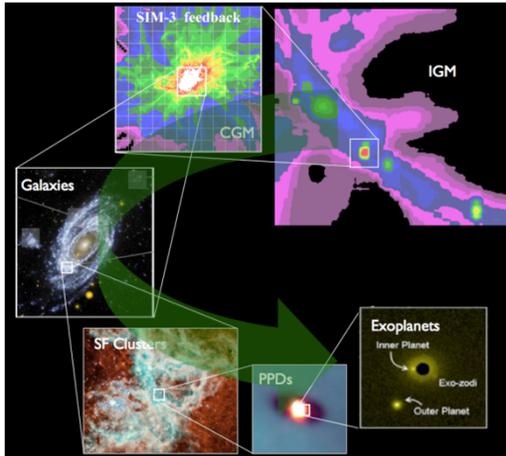
- New capabilities
- More sensitivity
- “Cheaper”
 - Lighter
 - Lower power
 - Easier to manufacture
- We are using ALD in all of these capacities to improve NASA technologies

Imaging at Different Wavelengths



Different information for astronomers at each wavelength

Example Applications and Motivations



Formation of structure and flow of baryons from the Intergalactic Medium (IGM) to planets.



GALEX

Imaging and Spectroscopy for Astronomy and Cosmology

e.g. Galaxy Evolution Explorer (GALEX)

Star formation/Dark Energy studies

UV detection is difficult

Most materials absorb strongly (optics/mirrors only ~10% efficient)

Space technology baseline for detectors (MCPs) are fairly insensitive in UV (~10% or less)

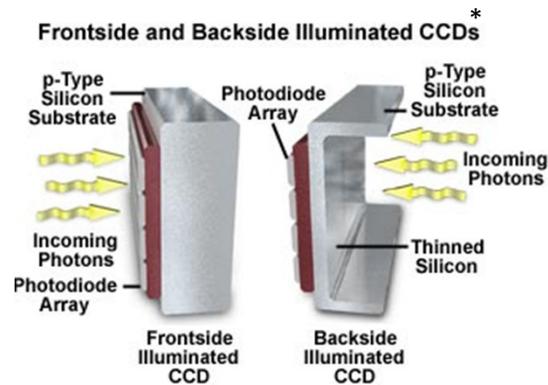
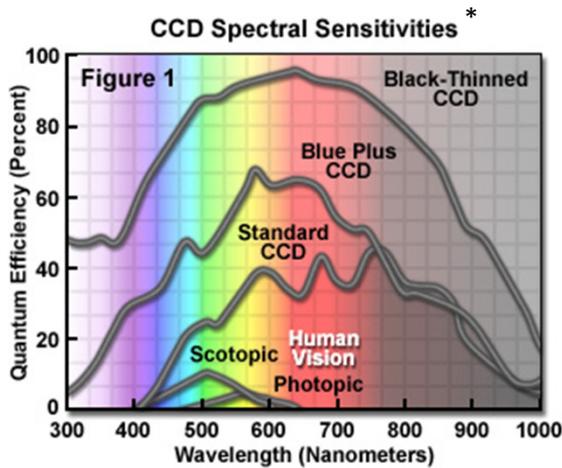
Effective sensitivity ~ 1% for state-of-the-art measurements



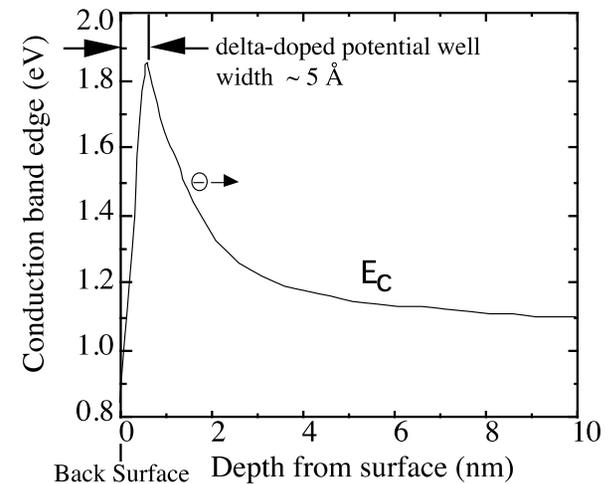
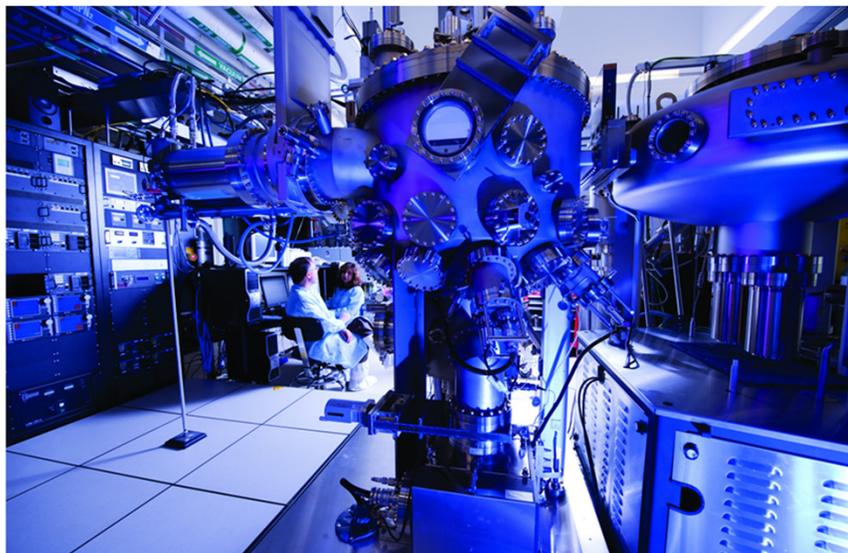
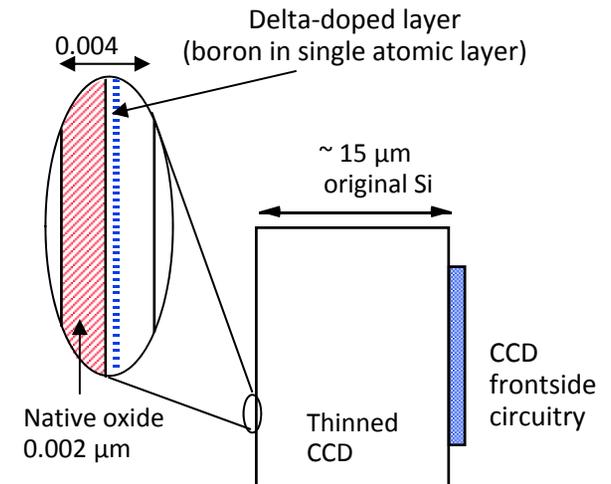
4x improvement in S/N

GALEX images of low surface brightness emission from the cloud of gas surrounding the star Mira

Back Illumination and Delta-Doping



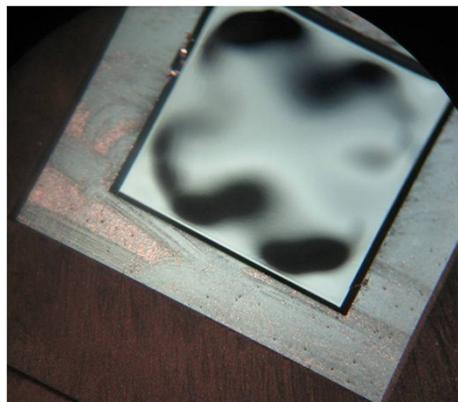
*Hamamatsu 2011



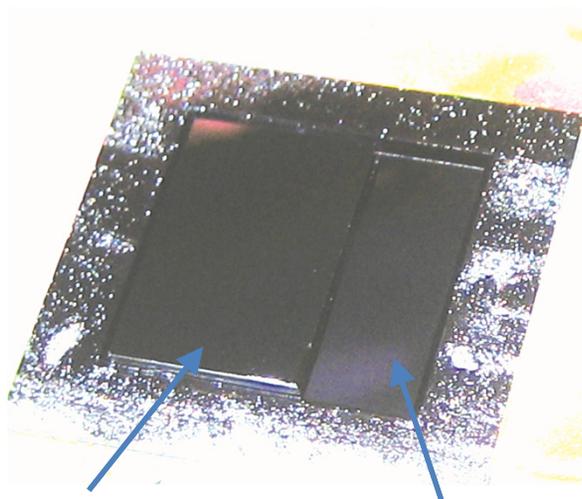
Hoenk et al., *Applied Physics Letters*, **61**: 1084 (1992)

Post fabrication processing gives best possible UV response

Anti-Reflective Coatings for UV Astronomy

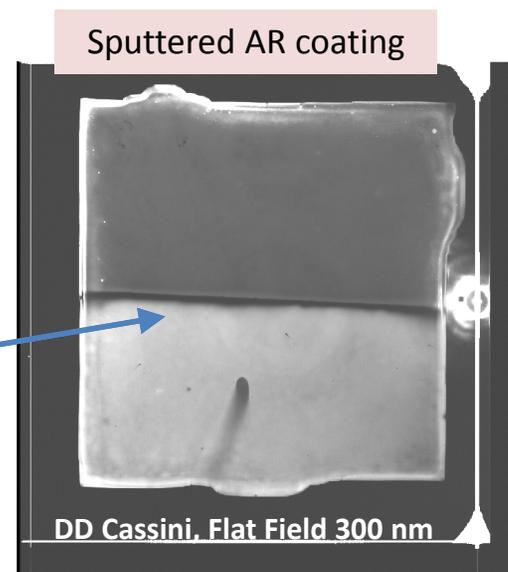


12um thick
Membrane is
unsupported



Shadow
mask

AR
Coated



Edge of
shadow
mask

Sputtered AR coating

DD Cassini, Flat Field 300 nm

- AR Coatings used to enhance quantum efficiency of silicon detectors.

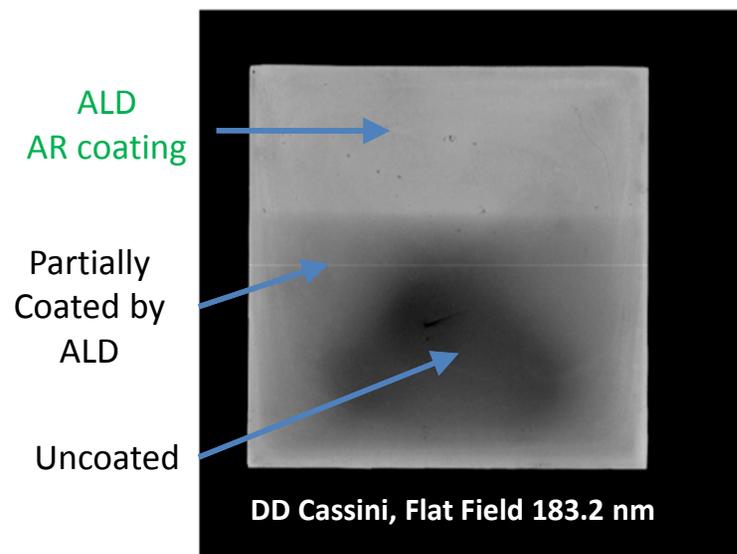
- Index of refraction of silicon changes significantly in the UV, requiring multiple materials for optimal performance

- Thin films required in UV (10-25nm)

- Flat field illumination during test

- Brighter → Higher QE

- Shadow masking used to ensure internal standard for comparison



ALD
AR coating

Partially
Coated by
ALD

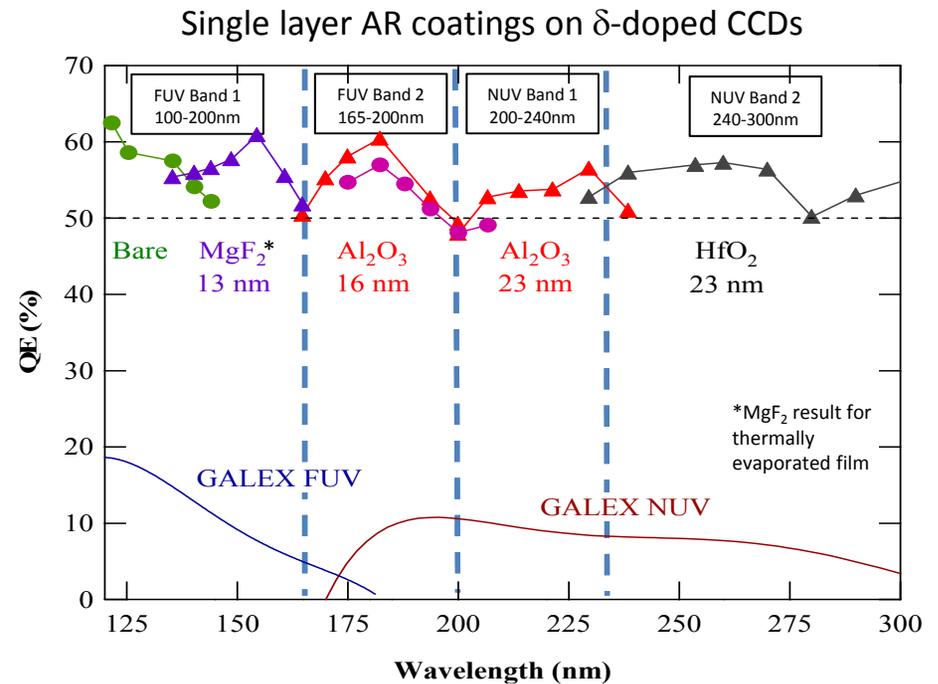
Uncoated

DD Cassini, Flat Field 183.2 nm

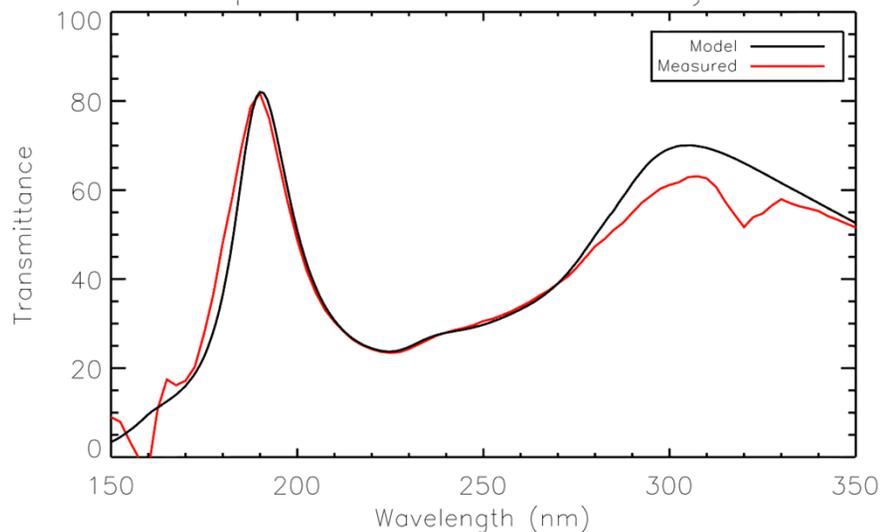
Effectiveness of ALD AR Coatings



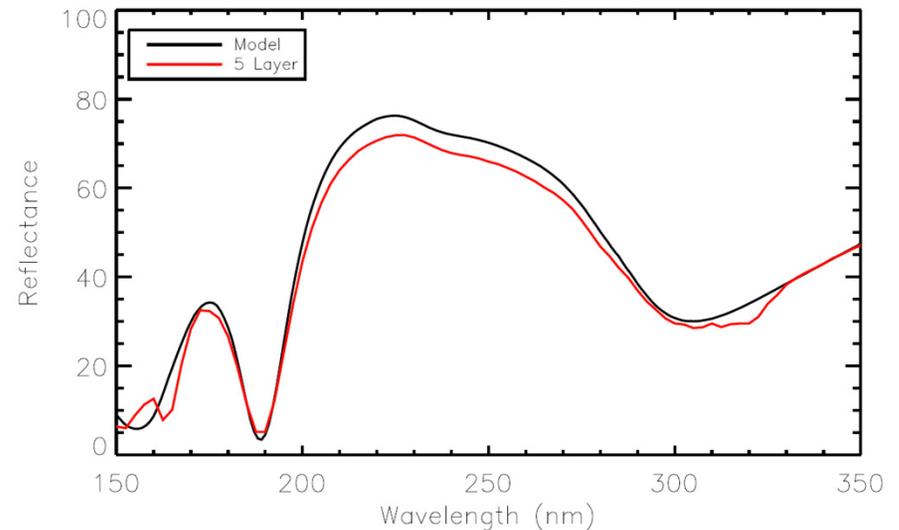
- Atomic Layer Deposition AR coated δ -doped CCDs provide up to **5x-50x improvement** over incumbent UV detector technology
- Multilayer AR coating stacks can target narrow wavelength ranges of particular interest
 - Al_2O_3 / SiO_2 multilayers studied on silicon and fused silica samples to enable tuning of response
 - 28nm Al_2O_3 /35nm SiO_2 /22nm Al_2O_3 /30nm SiO_2 /14nm Al_2O_3
 - Current combination targets 180nm, but future work will shift wavelength target to 200nm for maximum UV science



5 layer ALD AR coating on fused silica window



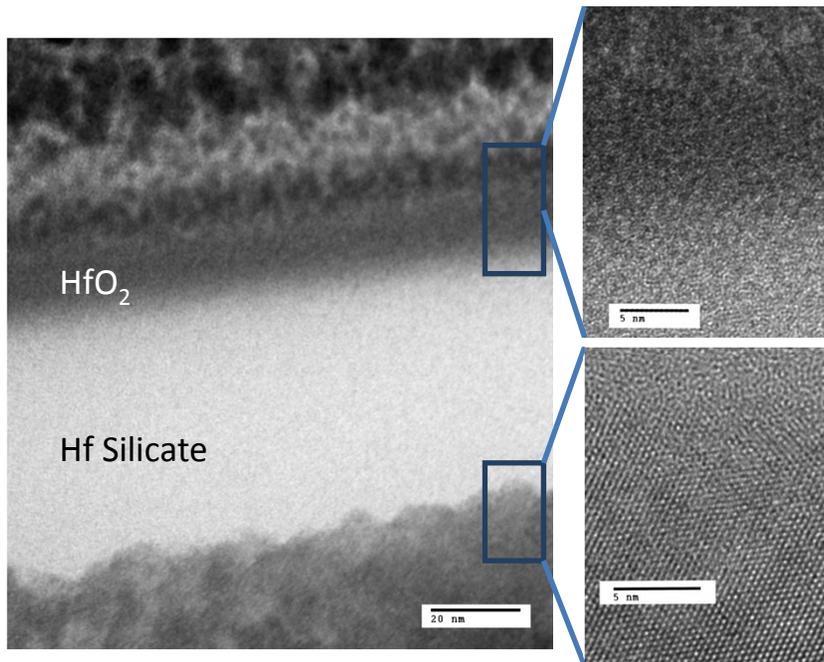
5 layer ALD AR coating on silicon wafer



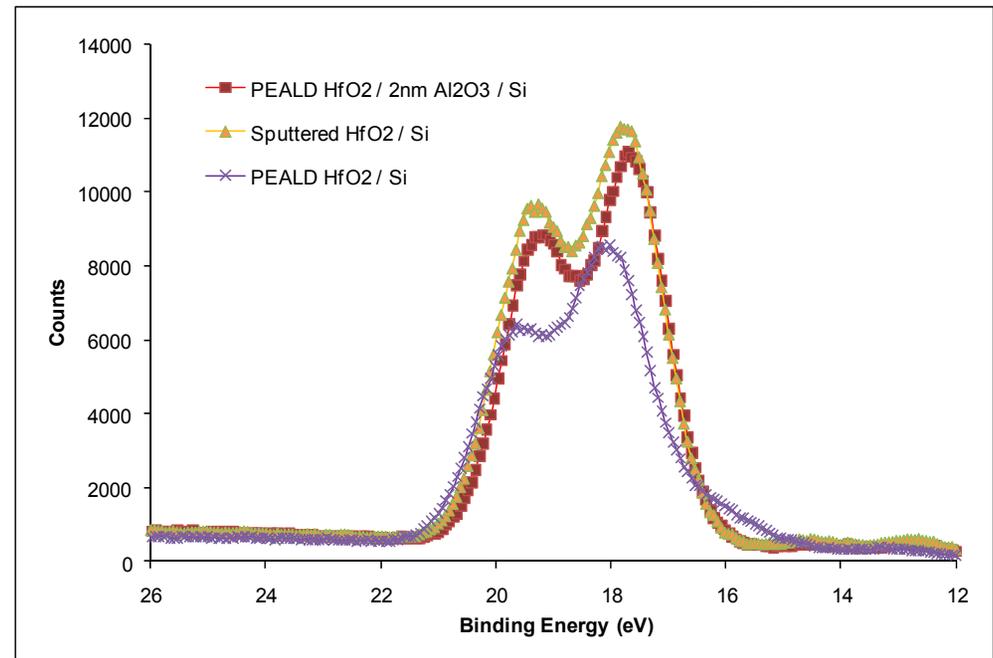
Importance of Chemistry in ALD AR Coatings



TEM of PEALD HfO₂ directly on Si

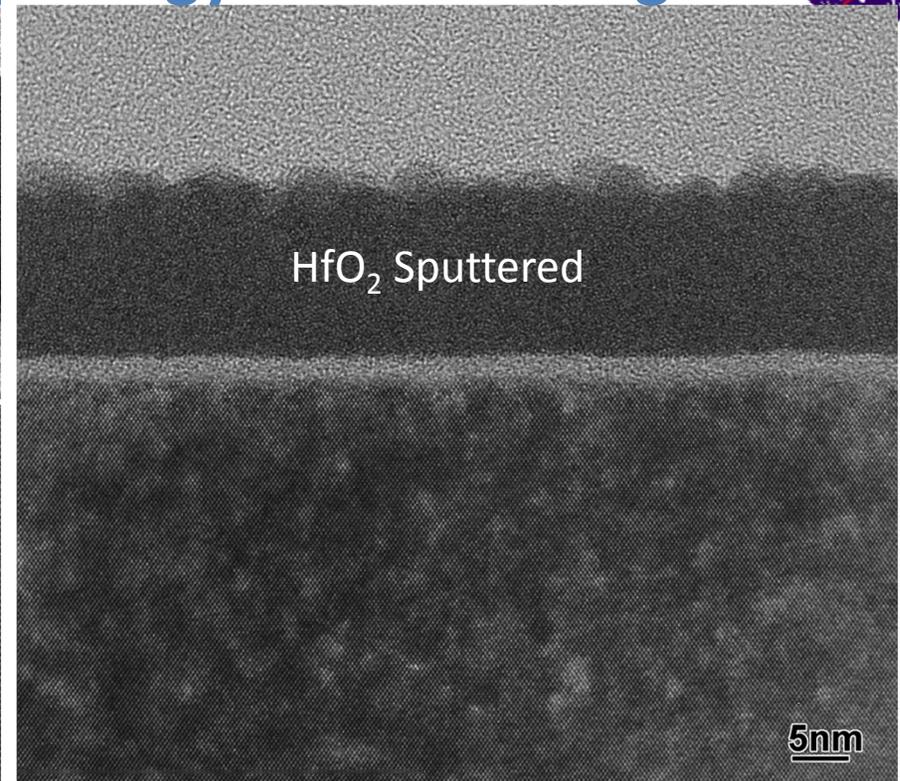
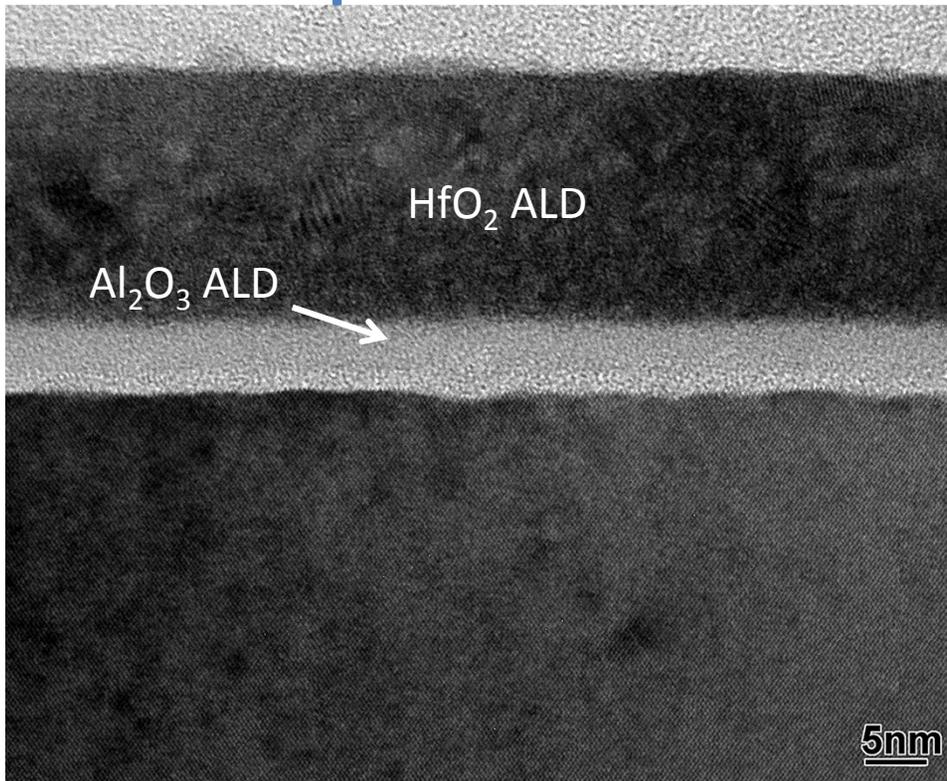


XPS Data from initial AR coating growth



- Chemical interaction of ALD coating with substrate is possible.
- ALD bilayers were utilized to successfully mitigate this effect

Comparison of Nanomorphology of AR Coatings

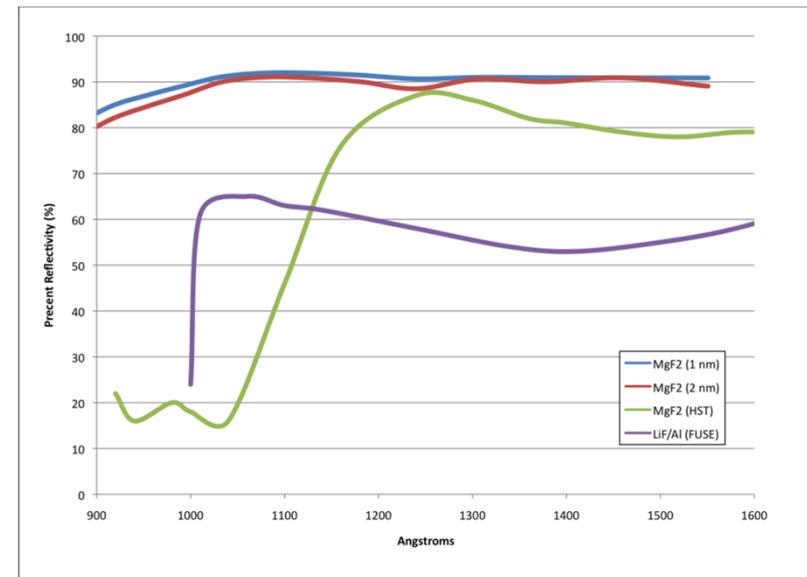
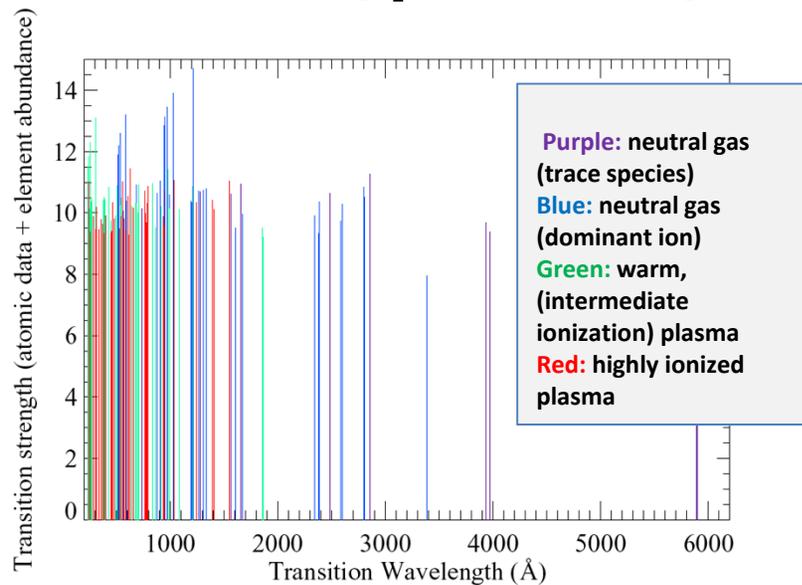


- ALD AR coating stack (Left) is significantly better than the Sputtered AR coating (right)
 - ALD is more dense (darker in the image)
 - ALD is smoother (potentially less scatter)
 - ALD is partially crystalline
- ALD AR coating technique allows for multilayers with sharp interfaces
 - Provides for optically transparent chemical barriers between films (Al_2O_3 film at left)
- ALD AR coating technique has atomic layer precision
 - Enables sub-nanometer control over film thickness, which is important for UV AR coatings as $<2\text{nm}$ thickness change impacts the performance



Benefits to Improved Mirror Coatings

- Reflective coatings determine the mission architecture for any UV mission (FUSE, HST/COS, etc)
- FUV has a significant number of spectral lines that are of great interest to astronomers
- Aluminum mirrors require protective coatings (*i.e.* LiF or thick MgF_2) to prevent oxidation which would otherwise destroy reflectivity in the FUV
- Coatings also important in optical wavelengths as they affect polarization
- By using very thin, but high quality, MgF_2 , both issues can be addressed simultaneously.
 - Very thin coatings minimize impact on polarization of incident light
 - Thin films of MgF_2 (1-2nm) enable higher reflectivity (due to lower absorption losses) than LiF or thick MgF_2

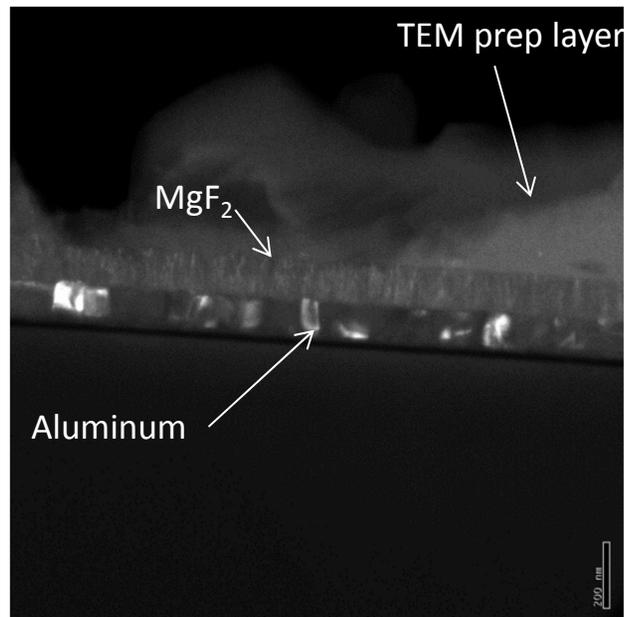


	Resolution	Aeff	Imaging?	Environmental	Size
FUSE	~20,000	~30 cm ² /channel from 1000 – 1180 ~10 cm ² /channel from 900 - 1000	No.	Hygroscopic Coatings	~6 m
FUSE w/ improved coatings	>40,000	Simpler optical design @ 100 cm ² From 900 - 1180 Angstroms	Yes.	Not hygroscopic	~3 m

The “Competition”



- Commercial-off-the-shelf (COTS) mirrors use IBD or thermal evaporation
 - High rate to avoid oxidation, but can be hard to control
- TEM used to characterize the microstructure and thickness of the Aluminum and MgF_2 layers a commercial off-the-shelf (COTS) mirror
 - Aluminum and MgF_2 layers are roughly 100nm each
 - Interfaces are crisp and films are extremely smooth
 - Note: Example mirror shown here is only 1” square
- State-of-the-art (non-ALD) is very good!



Dark field Image

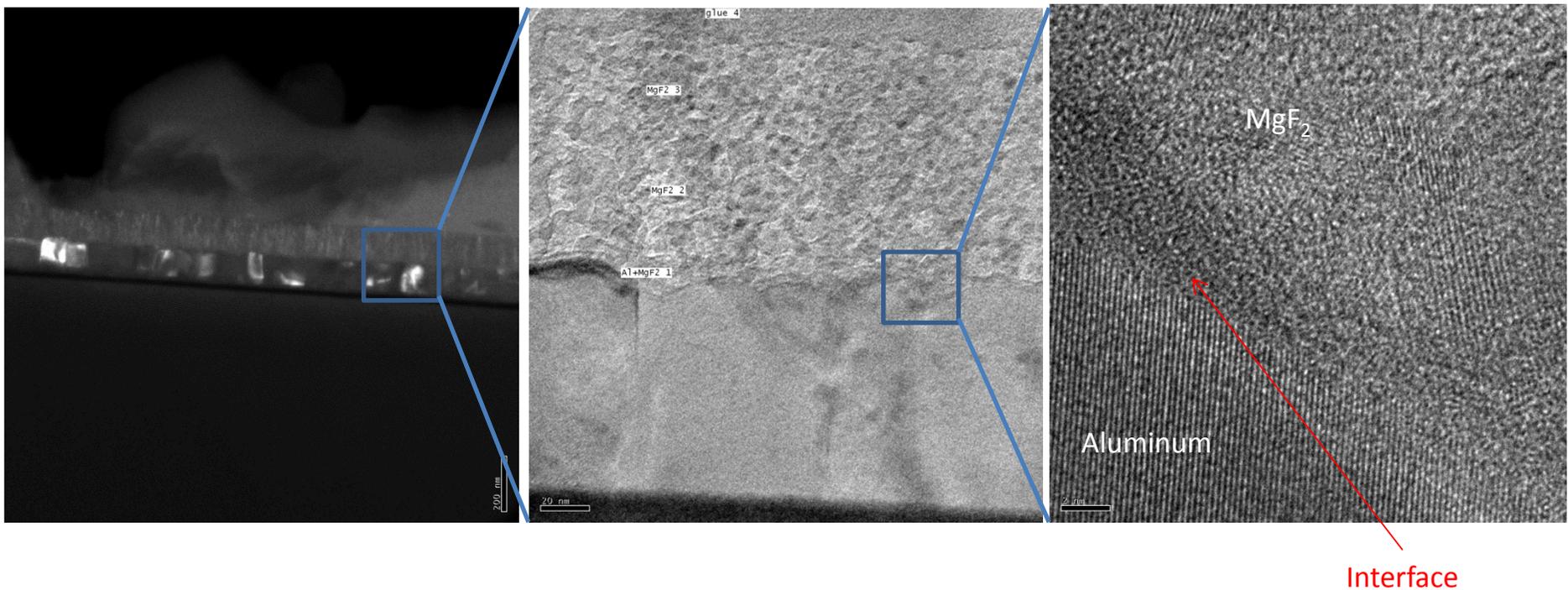


Bright field Image

COTS MgF₂ Microstructure



- MgF₂ is nanocrystalline with ~1nm thick amorphous interface layer with the aluminum
 - Small crystallites help improve oxidation resistance



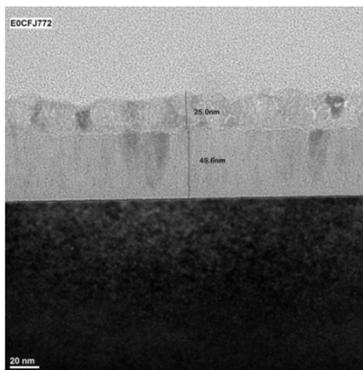
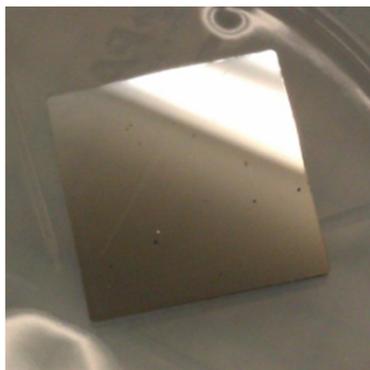
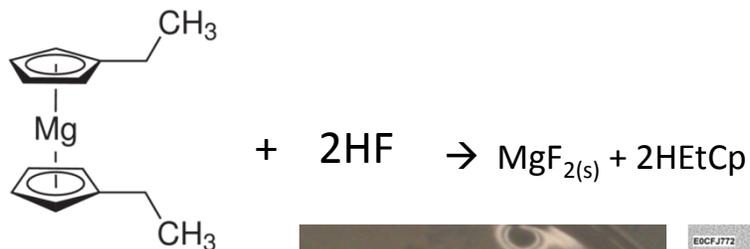
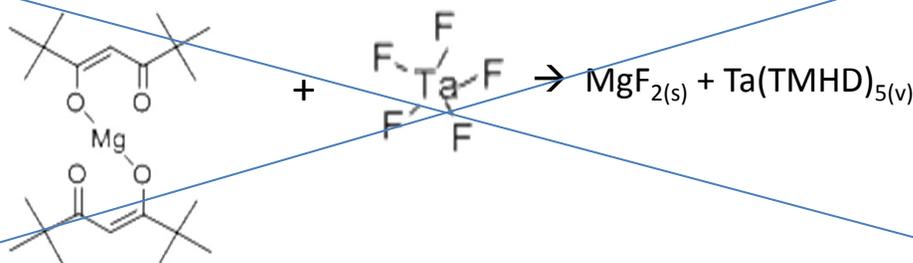
ALD Chemistry Pursued



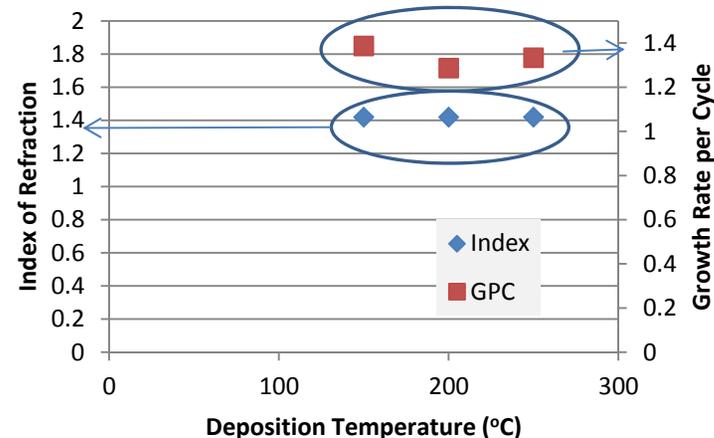
- Aluminum ALD



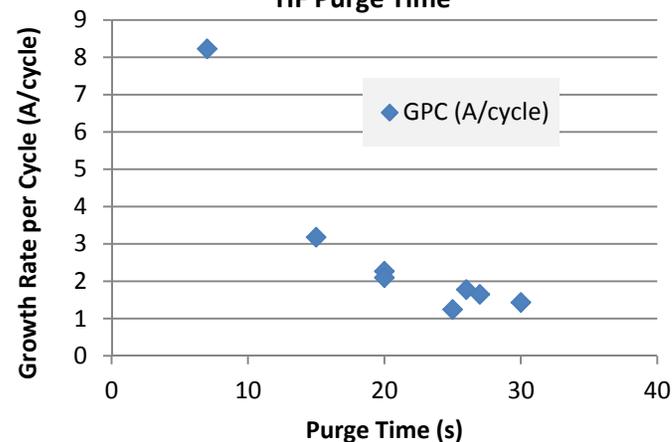
- Magnesium Fluoride ALD



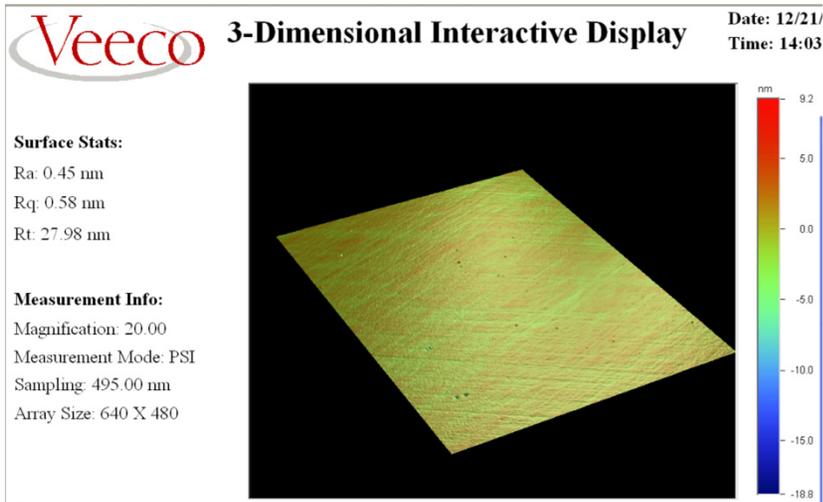
Temperature Dependence of MgF₂ Deposition



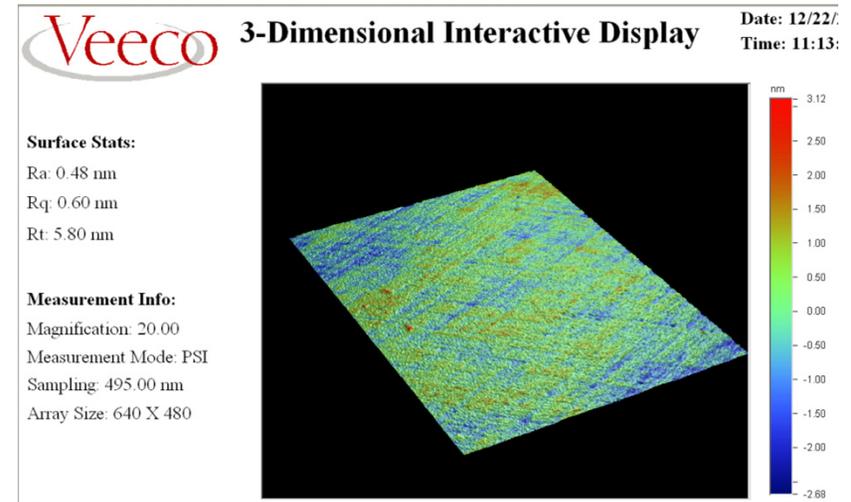
HF Purge Time



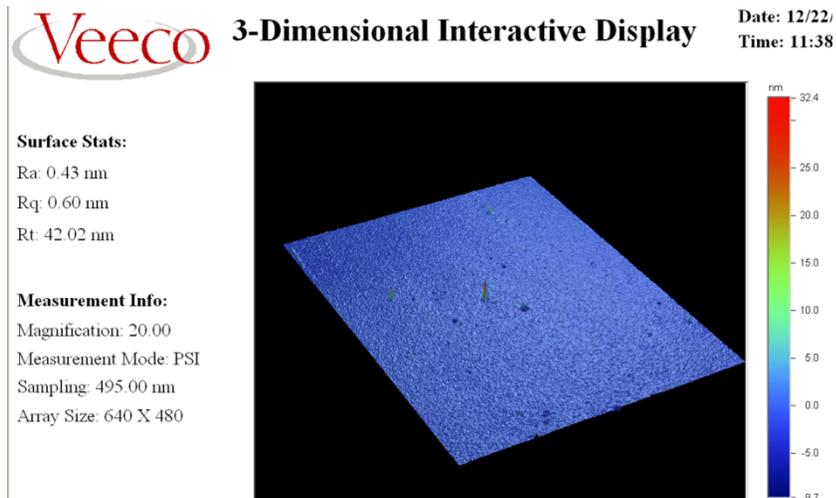
Smoothness of ALD Aluminum



As received Aluminum Mirror



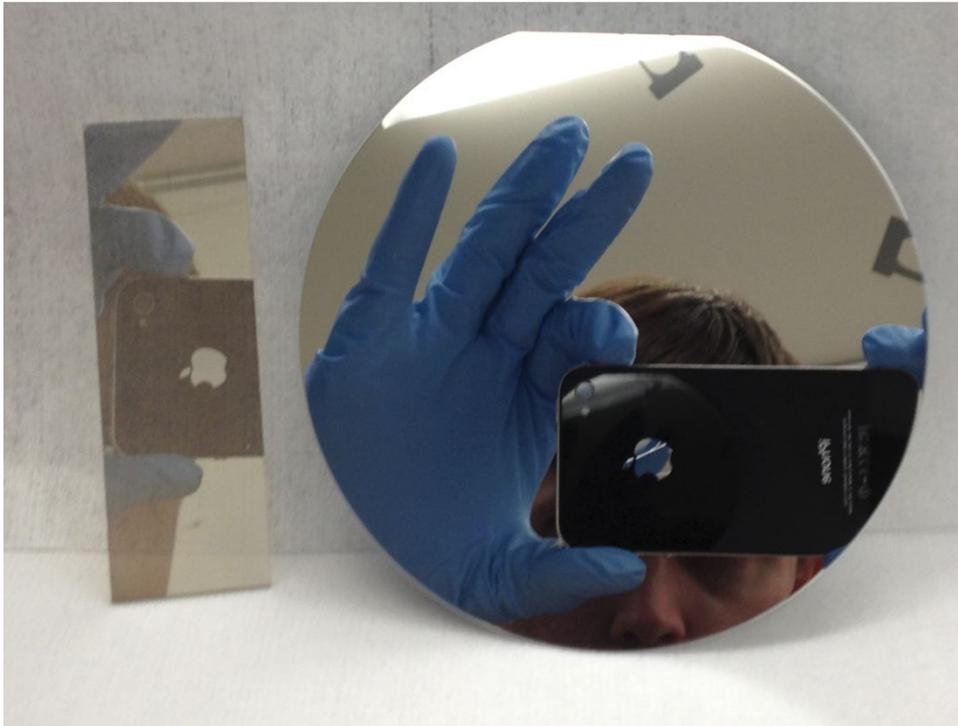
“Mirror” substrate after removal of Aluminum



ALD Aluminum Deposited on “Mirror” substrate

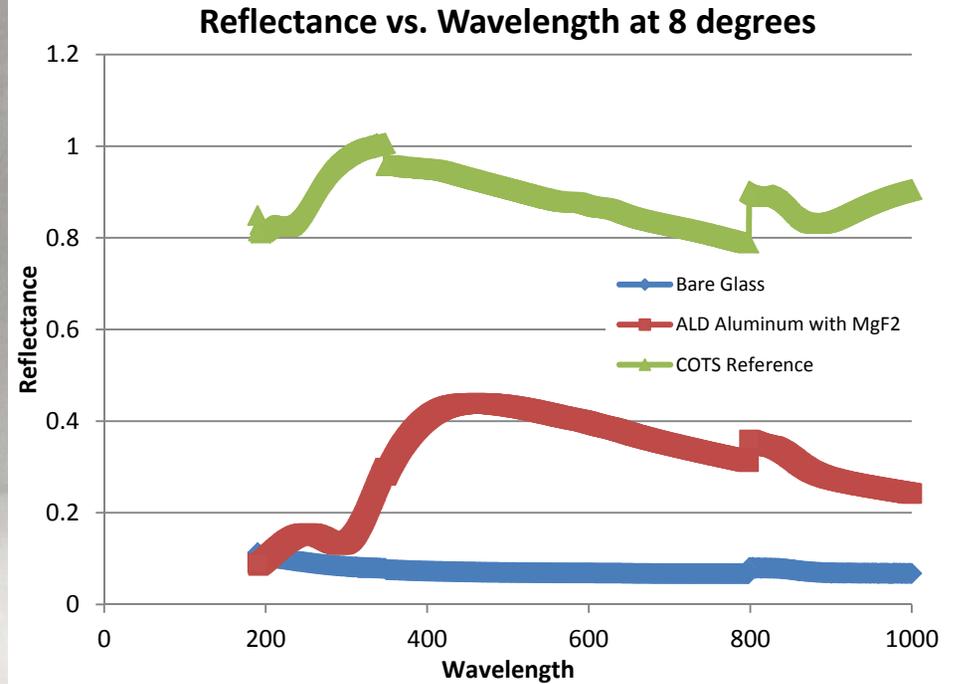
- Smoothness of original substrate is maintained (Ra: 0.45nm)
- Small particle on ALD sample skews map colors, but Ra and Rq show smoothness

Reflectivity of ALD MgF_2 Coated ALD Aluminum



Ultrathin (partially transparent) ALD Aluminum on Glass Slide

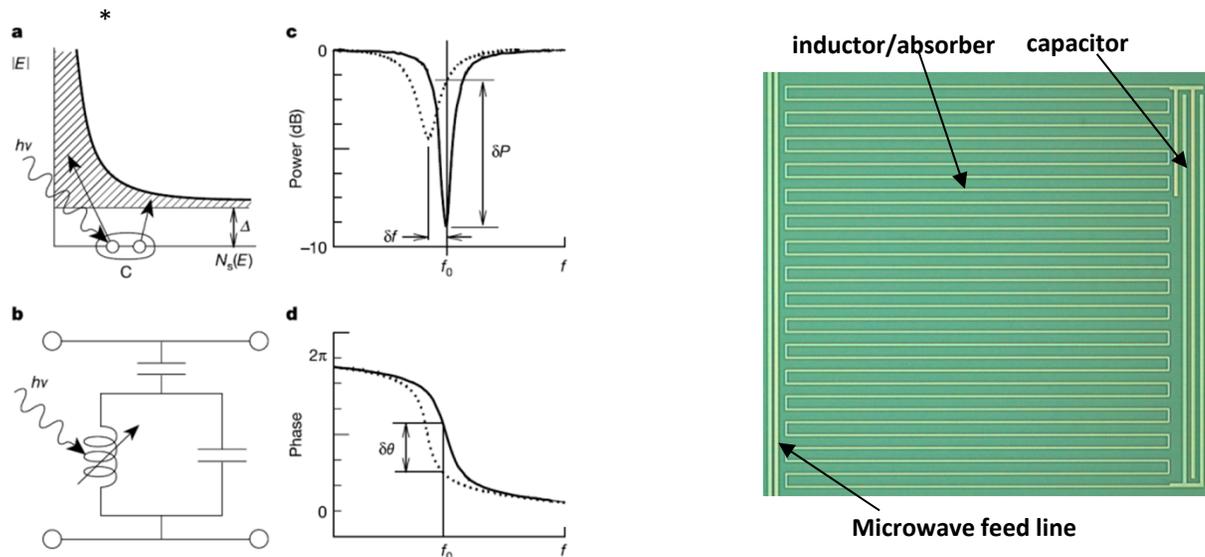
E-Beam Evaporated Aluminum on Silicon Wafer



ALD coatings are reflective, but need thicker aluminum films to achieve desired reflectivity

Superconducting Detectors

- MKID (Microwave Kinetic Inductance Detector)
 - Functionality
 - Photons excite quasiparticles by breaking the Cooper pairs of a superconductor
 - Measurements made by creating a resonant circuit and measuring phase and amplitude shifts in a probe signal that responds to the presence of the quasiparticles
 - MKID detector response can readily be tuned to many different wavelengths by changing the capacitive portion of the circuit



*P. Day, et al. *Nature* **425**, 817-821 (23 October 2003).

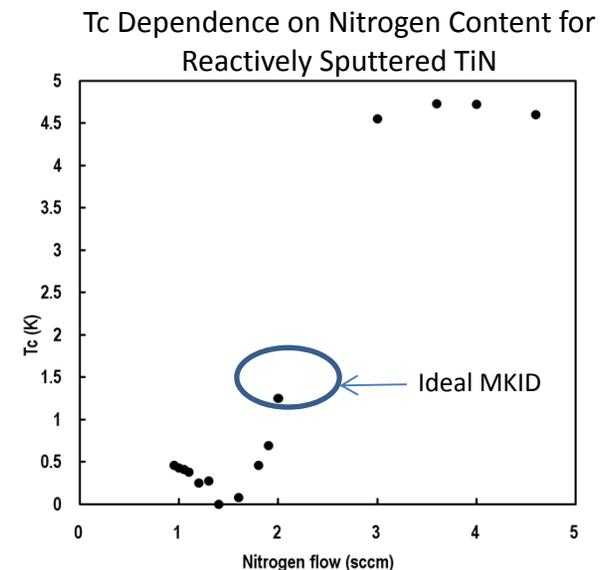


Superconducting Detectors

- MKID (Microwave Kinetic Inductance Detector)

- Key considerations:

- T_c of Transition metal nitrides (TiN/NbTiN/TaN) is strongly dependent on composition and film thickness
 - Lifetime of quasiparticles (which affects sensitivity) $\sim 1/T_c^3$,
 - T_c of 1.5K is ideal tradeoff between instrument performance and cost (since cooling becomes more expensive as T_c decreases)
 - T_c of 1.5K is on steepest portion of the composition curve
- T_c is a function of thickness
 - Thinner films have lower T_c than “bulk”
- Quality factor of the resonator governs the signal to noise ratio of the detector
 - Primarily a function of the substrate/superconductor interface



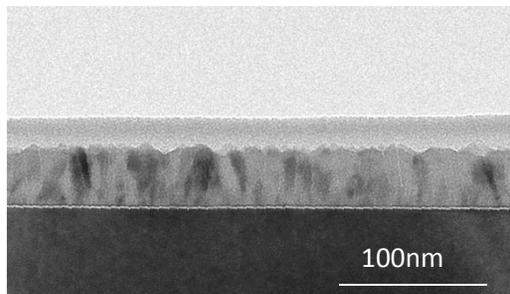
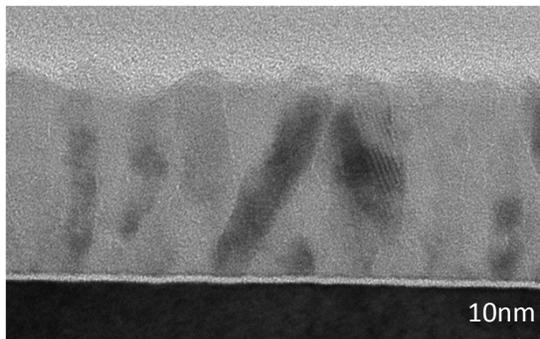
- **ALD should offer significant advantages for processing control and repeatability**

TiN ALD as a Superconducting Material

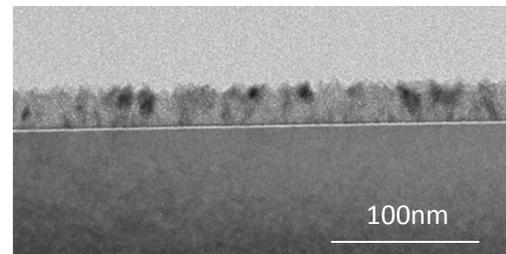
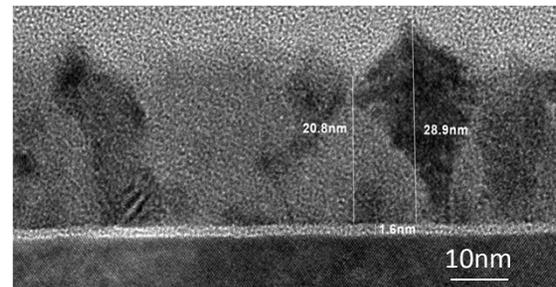


- Advantages:
 - Ability to tune transition temperature with stoichiometry (Ti/N ratio) or composition (Nb/Ti/N ratios)
 - Ability to grow films via thermal and plasma routes
- Disadvantages:
 - Titanium is an excellent getter for oxygen, making contamination a problem
 - Silicide formation occurs at ALD temperatures

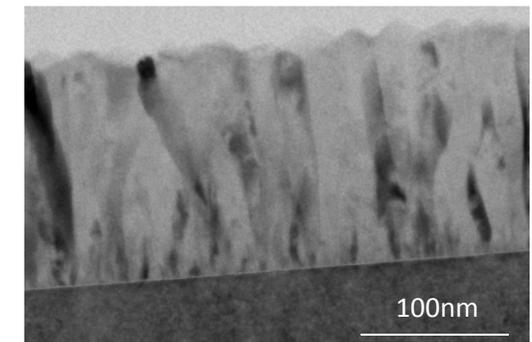
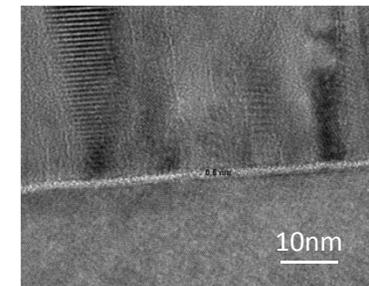
Condition 1



Condition 2

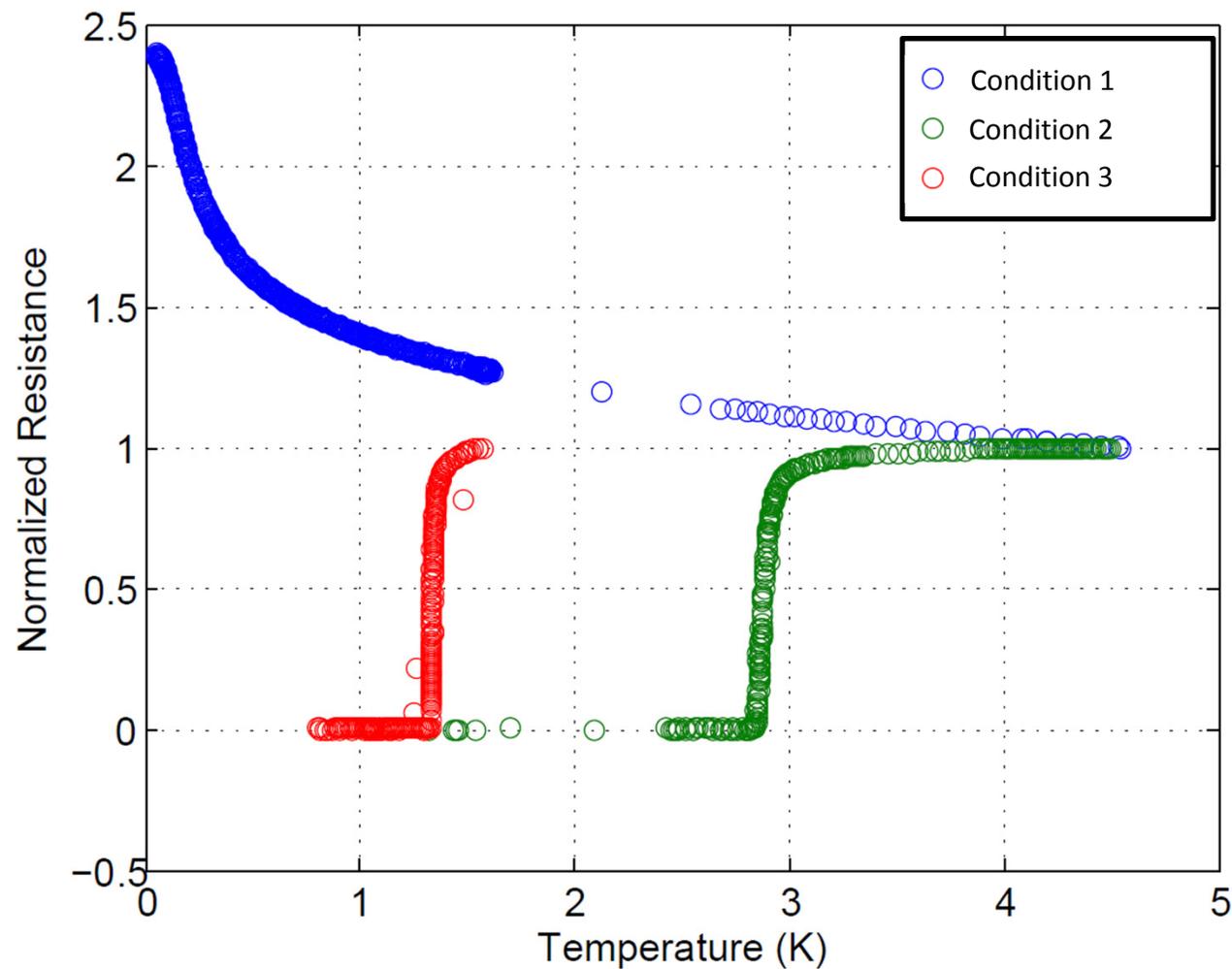


Condition 3





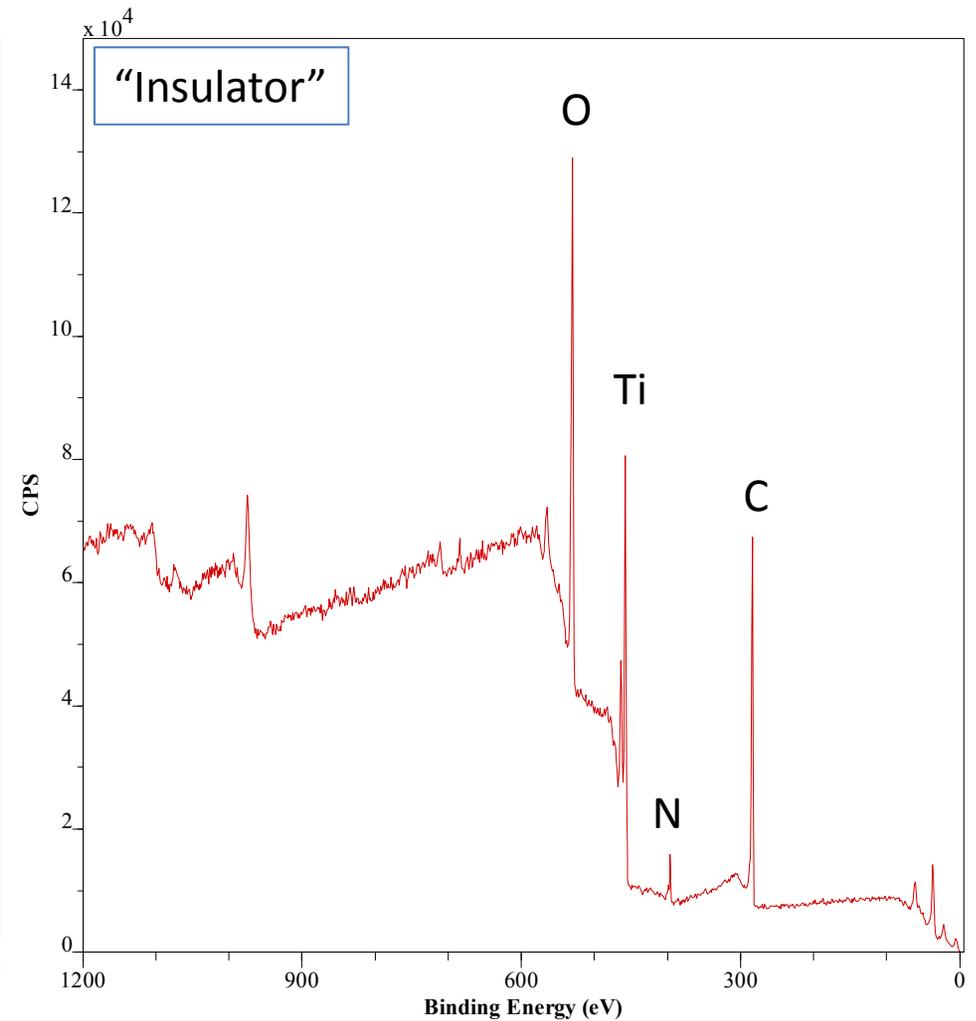
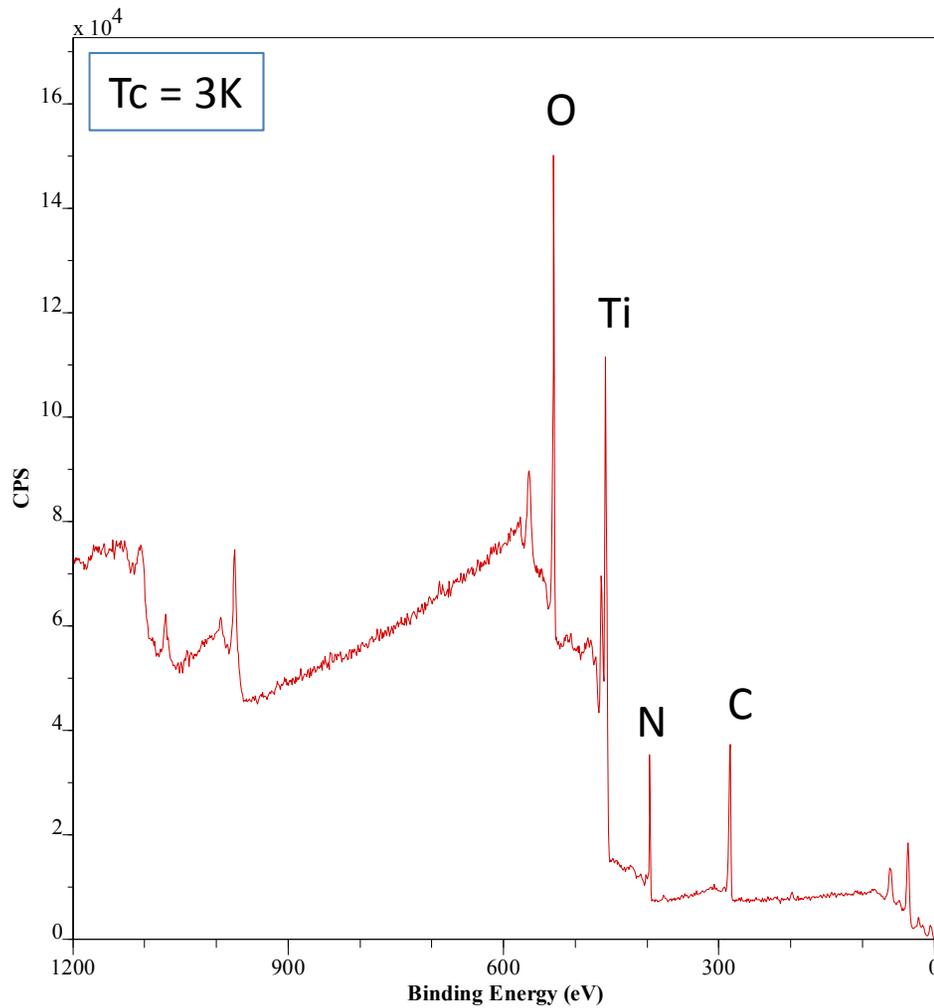
TiN Transition Temperature



- All processes utilized TiCl_4 deposition chemistry, but significantly different results achieved depending on ALD film quality

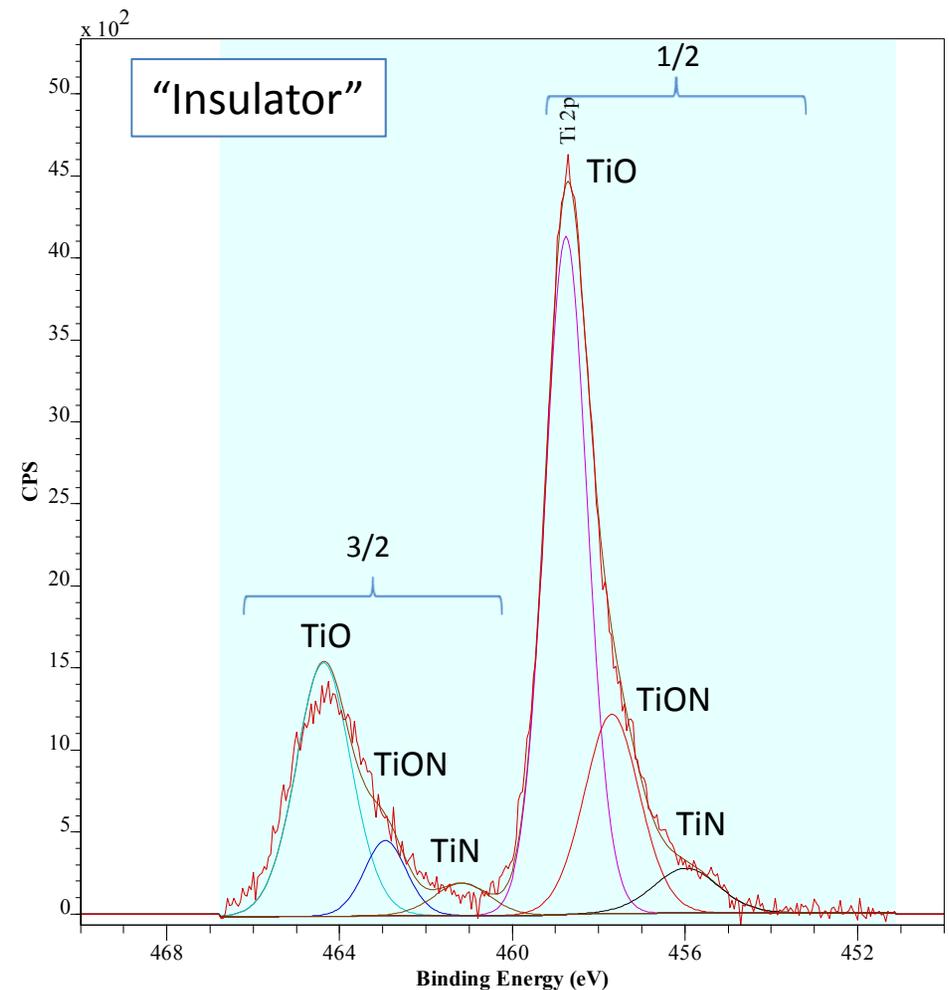
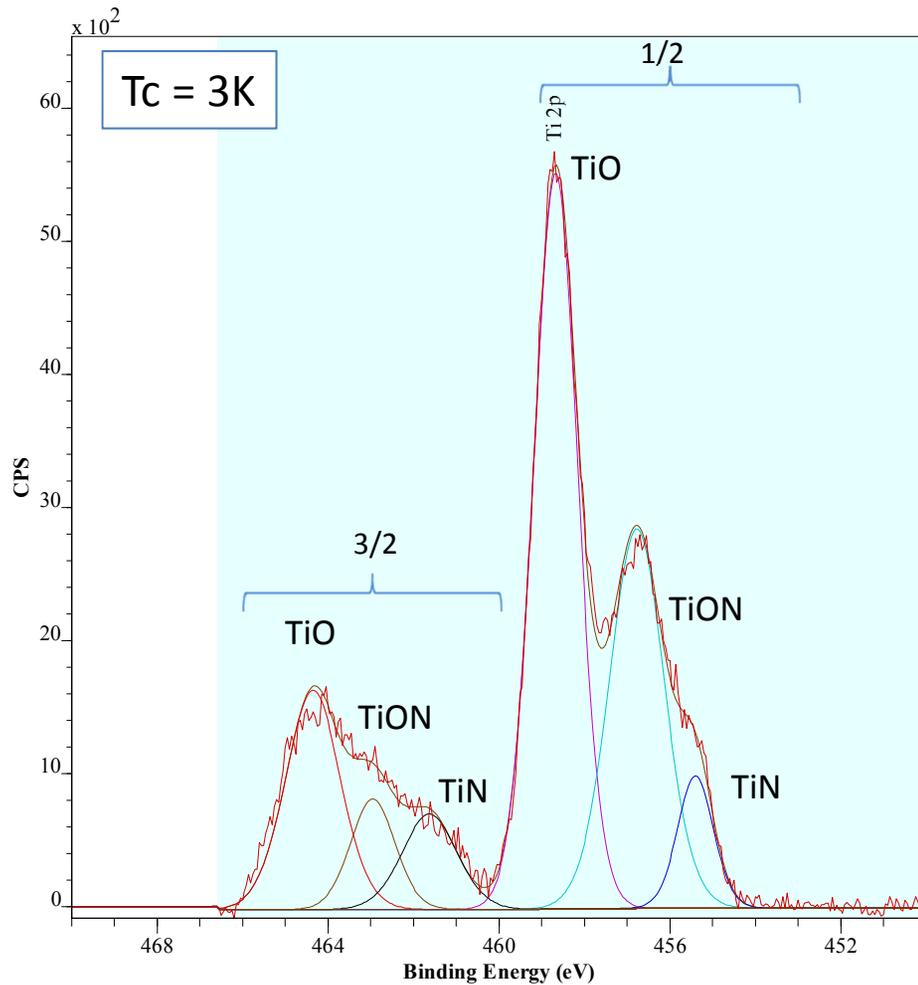


Native Surface Survey Spectra



- Survey spectra consistent with oxidized surface
- Insulator appears to have more adventitious carbon

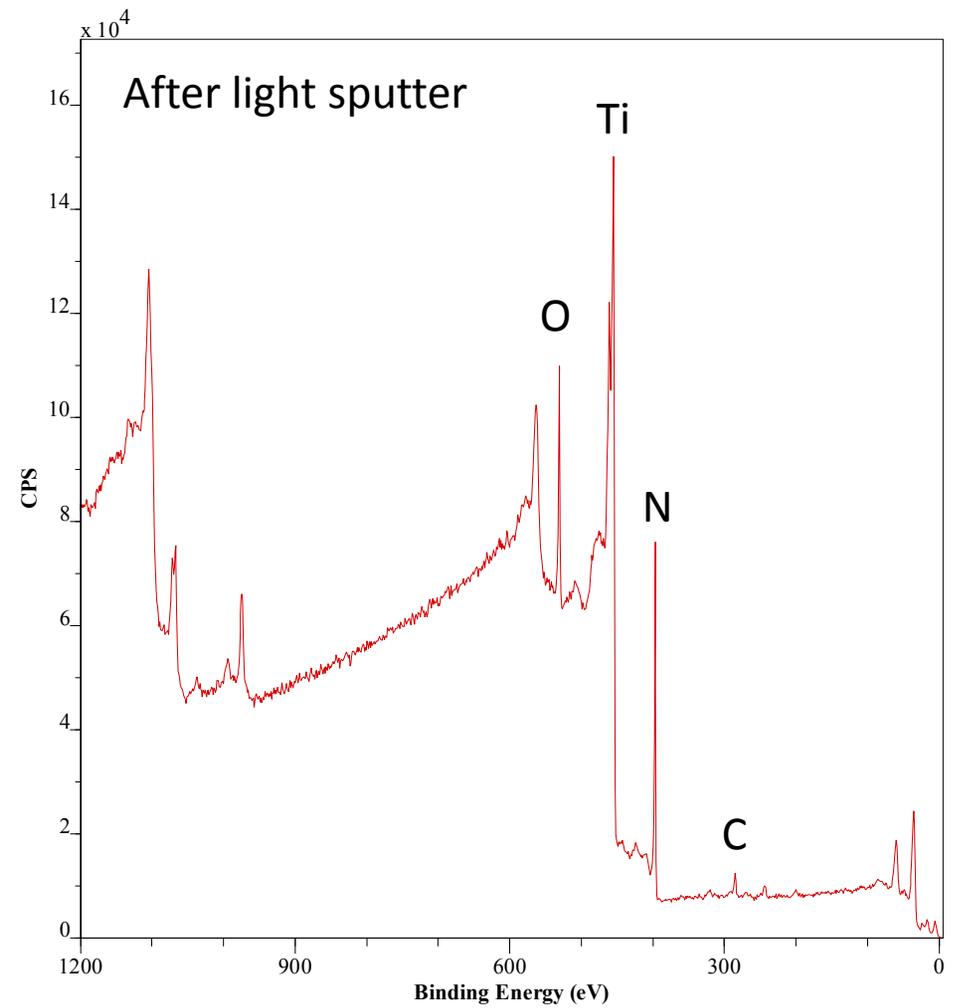
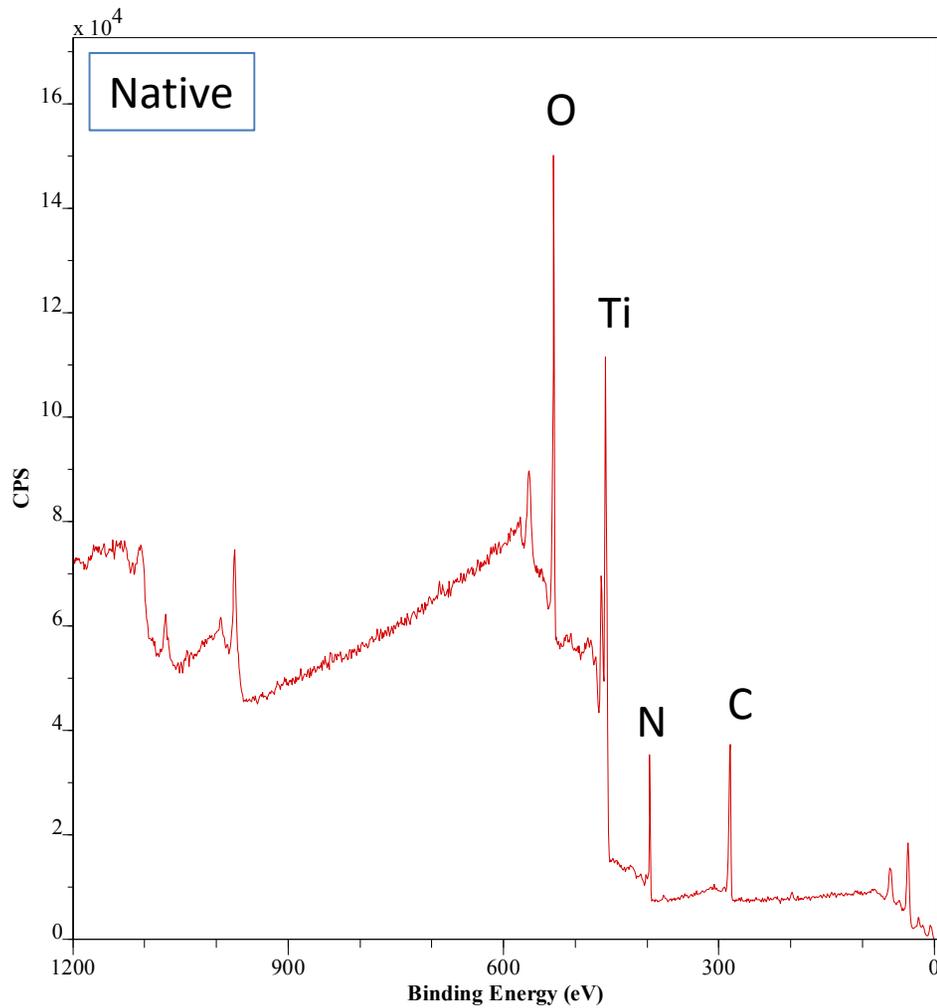
High Resolution Ti Spectra (Native Surface)



- The samples have comparable Ti(2p) spectra from surface, dominated by surface oxide layers

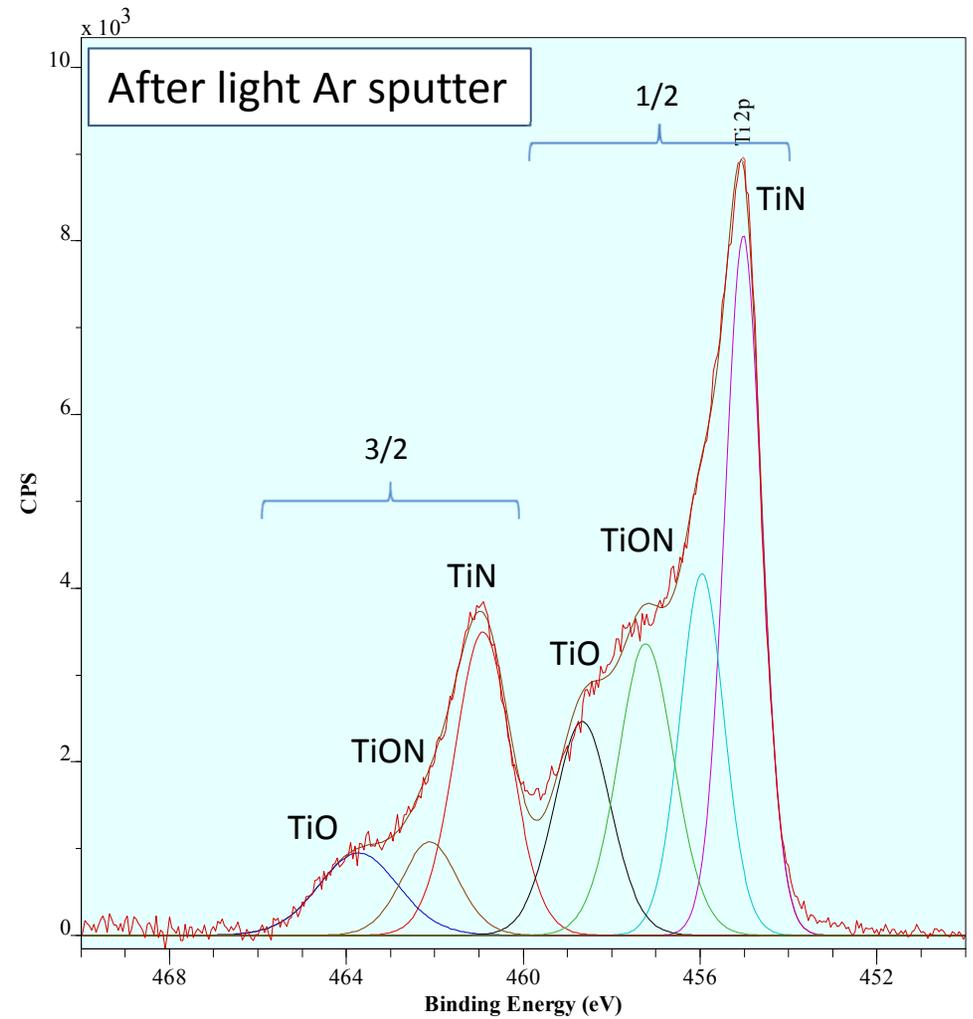
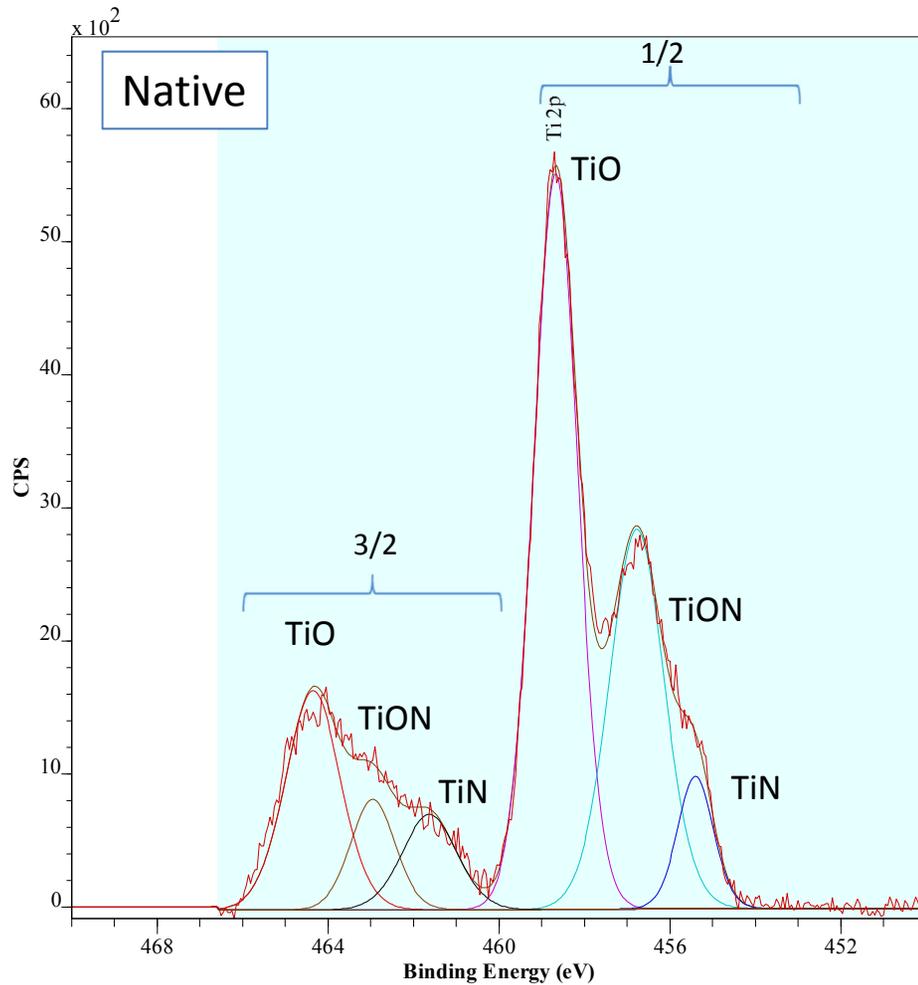
*Peak assignments made according to N. Jiang, et al. Physica B 352 (2004) 118-126.

Survey Spectra Comparison ($T_c=3K$)



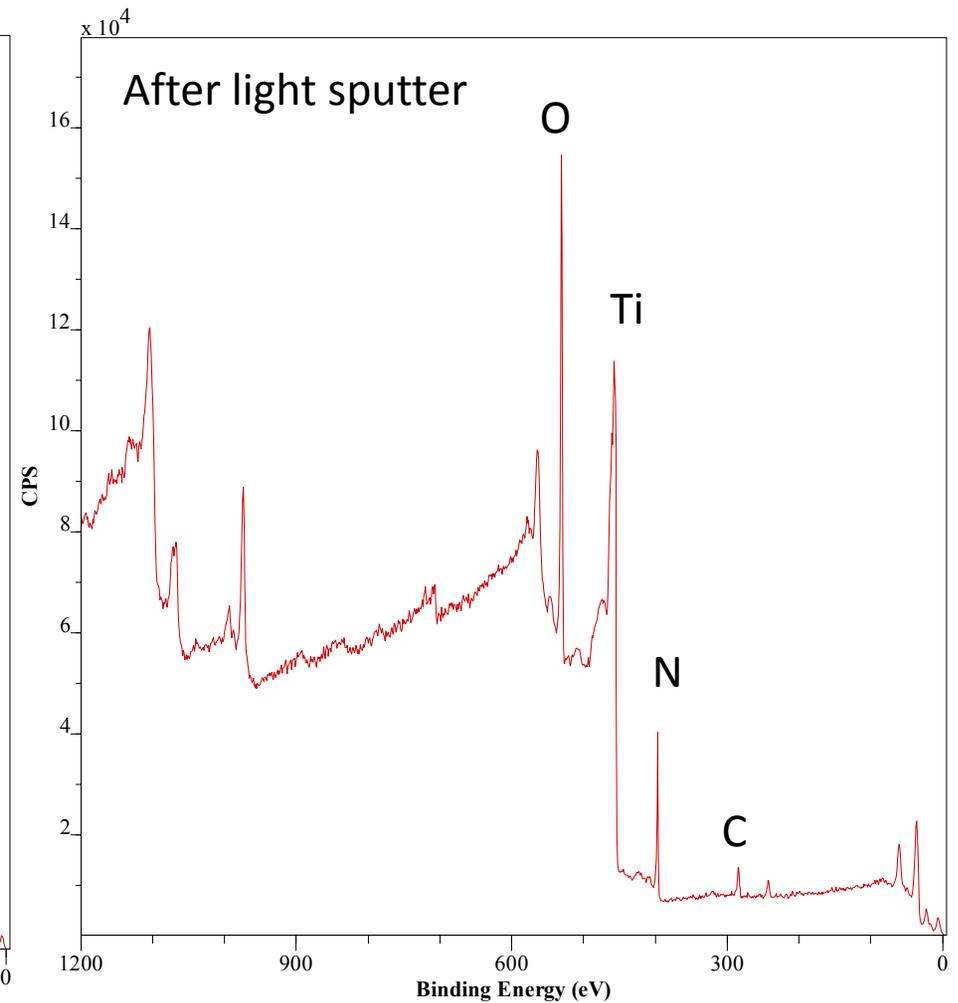
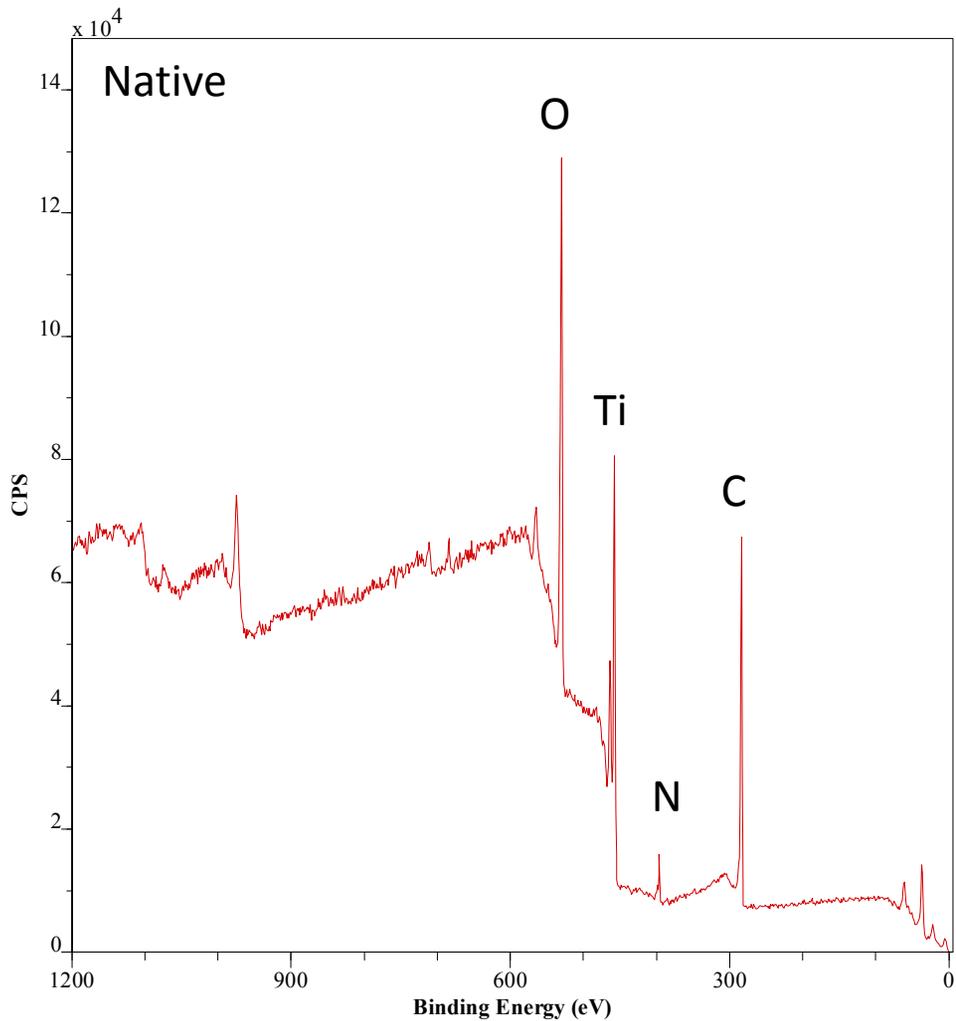
- Sputtering largely removes adventitious carbon and significant portion of the oxide

Characterization of 3K Sample



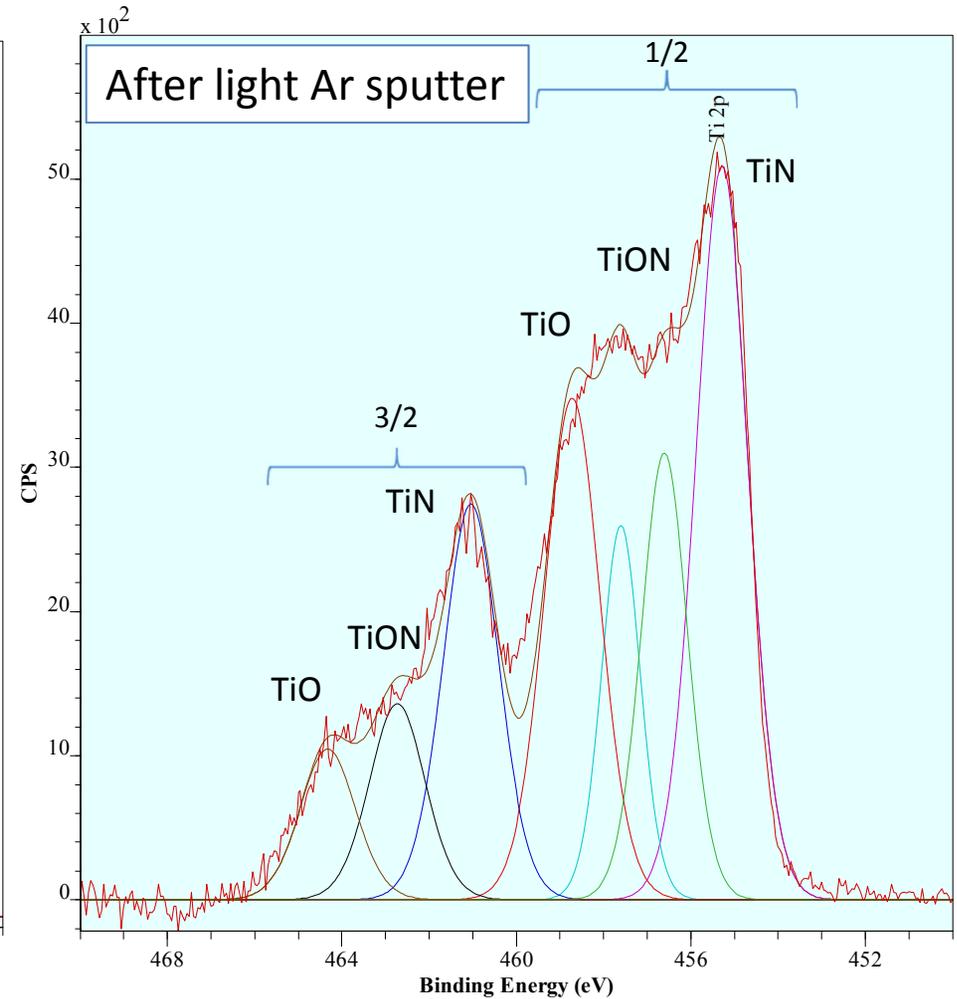
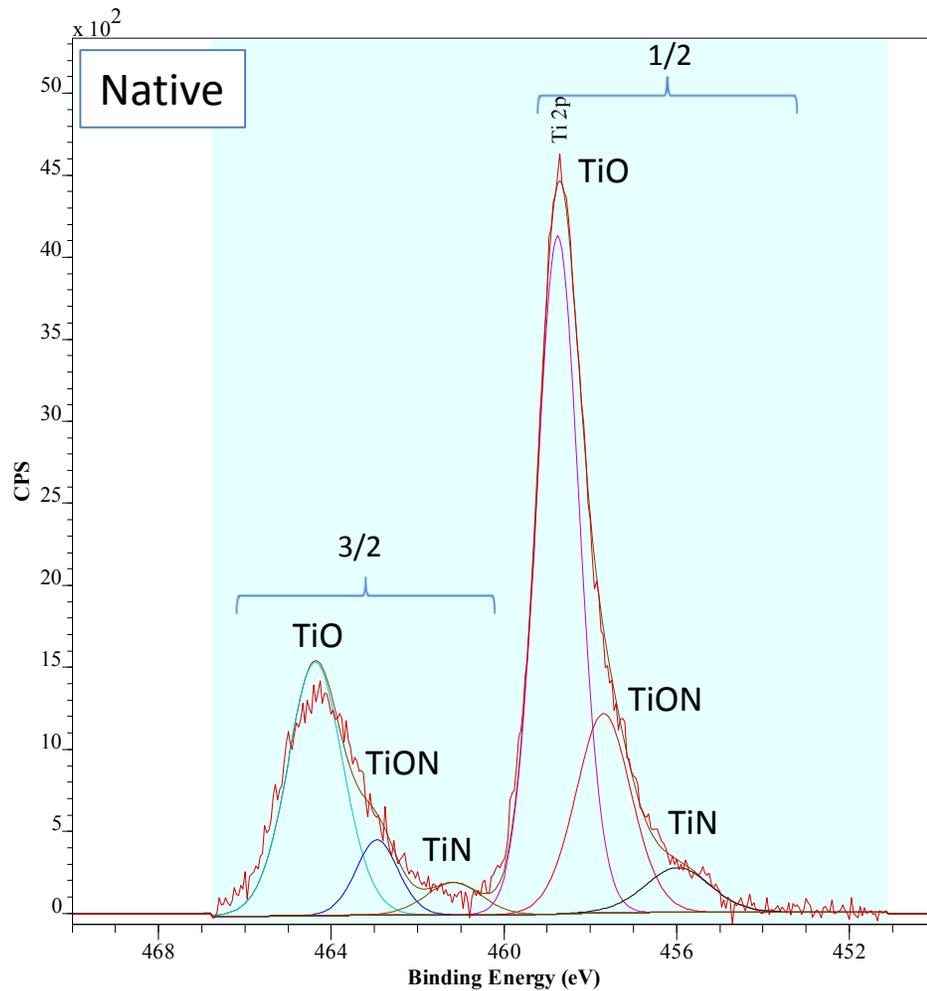
- TiN peaks are enhanced as surface oxide is removed

Survey Spectra Comparison (“Insulator”)



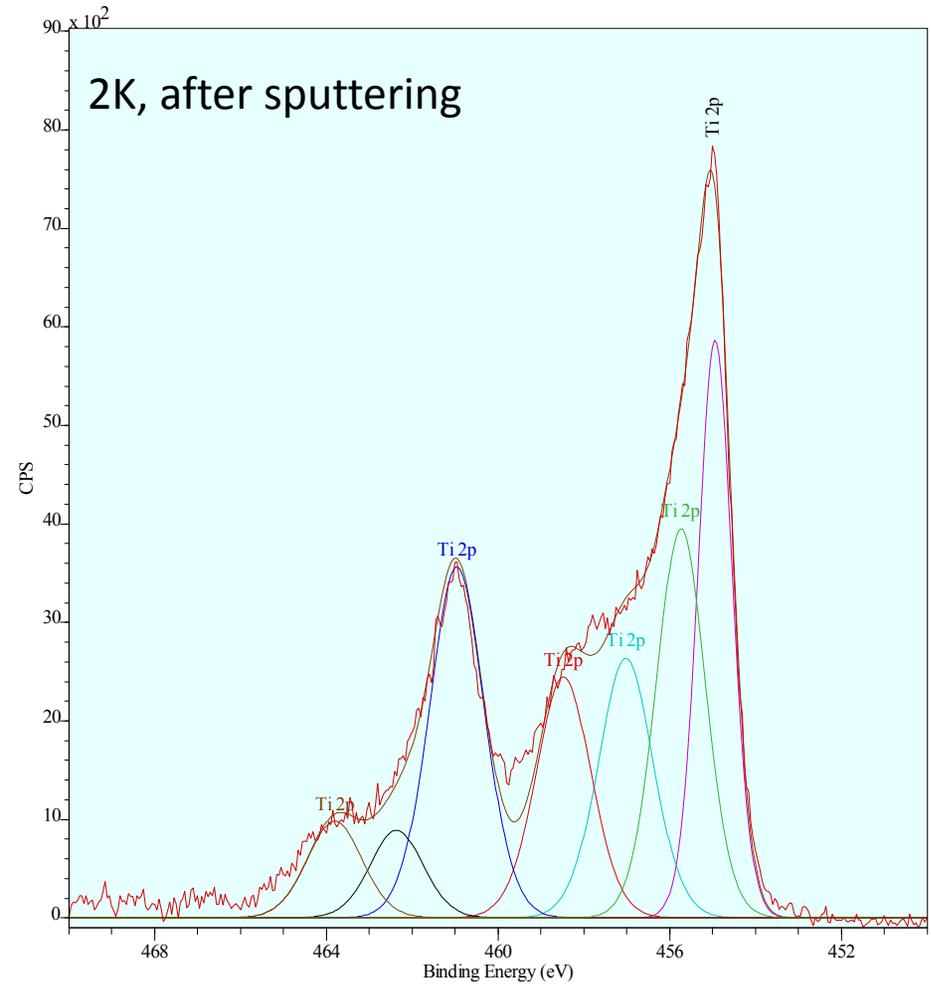
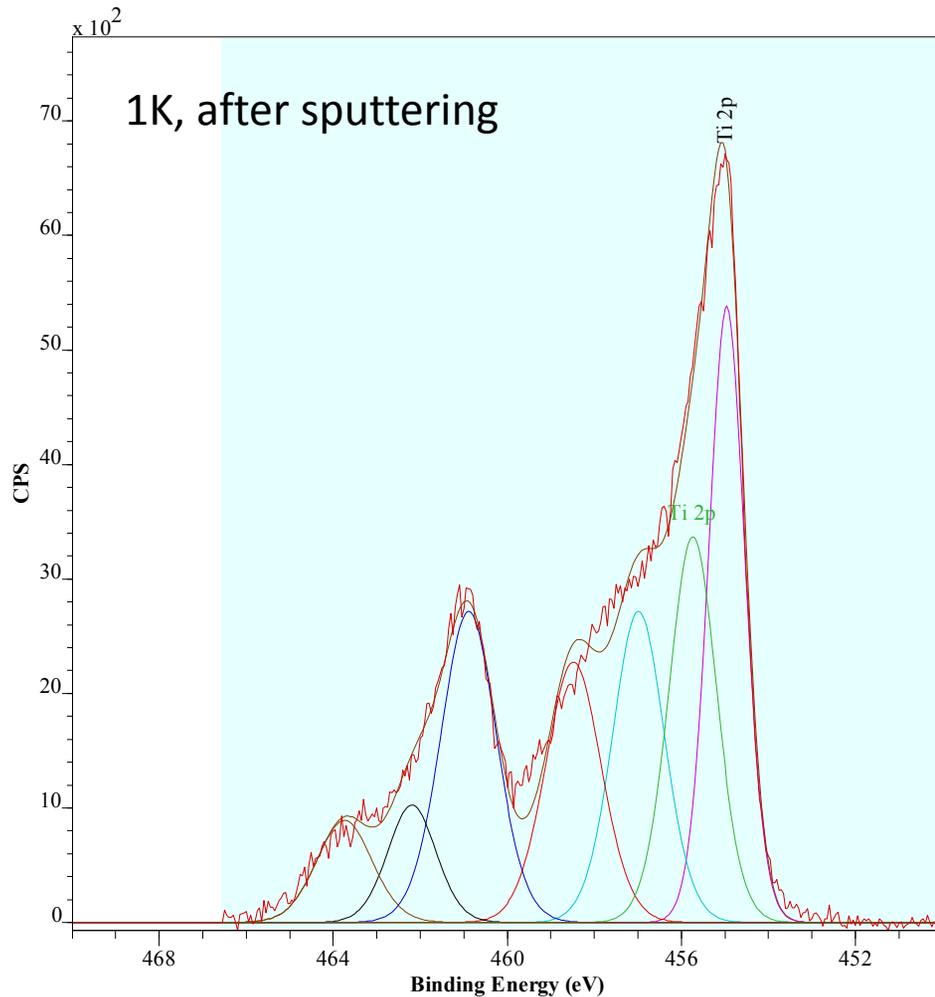
- Sputtering removes adventitious carbon, but oxide still appears to be present

Characterization of “Insulator”



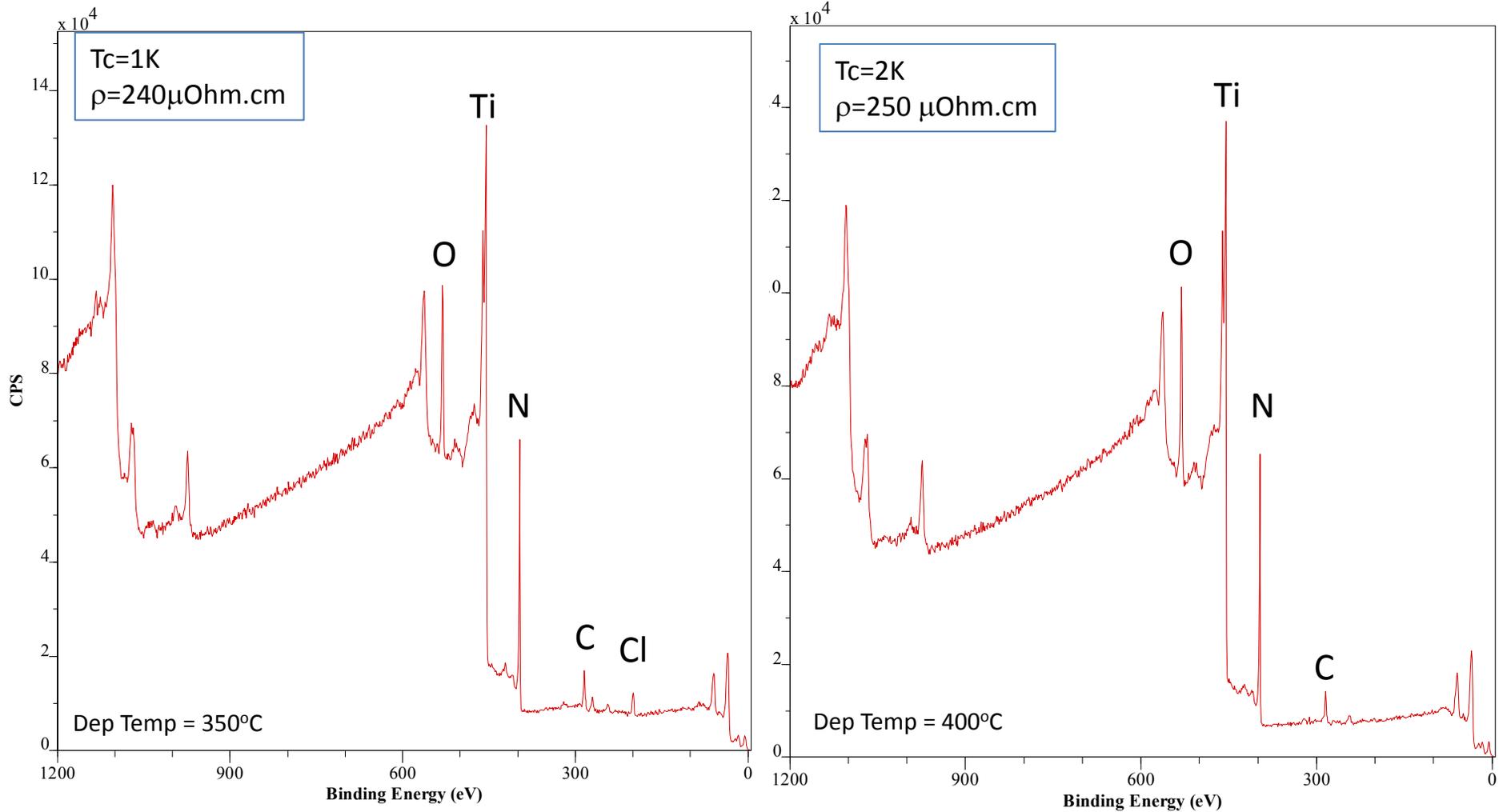
- Oxide peaks are still prominent after sputtering for the same amount as 3K sample

Other Superconducting TiN



- TiN peaks appear very similar to the 3K sample (TiN peaks enhanced by sputtering)

Variation Between Superconductors



- Films are nominally similar, but chlorine contamination is present in film grown at lower temperature

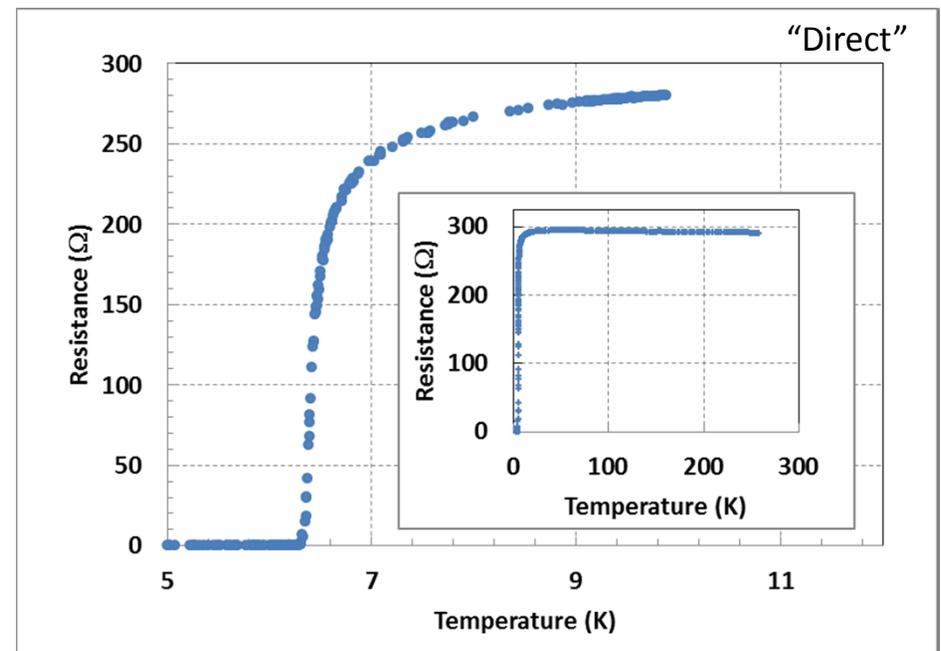
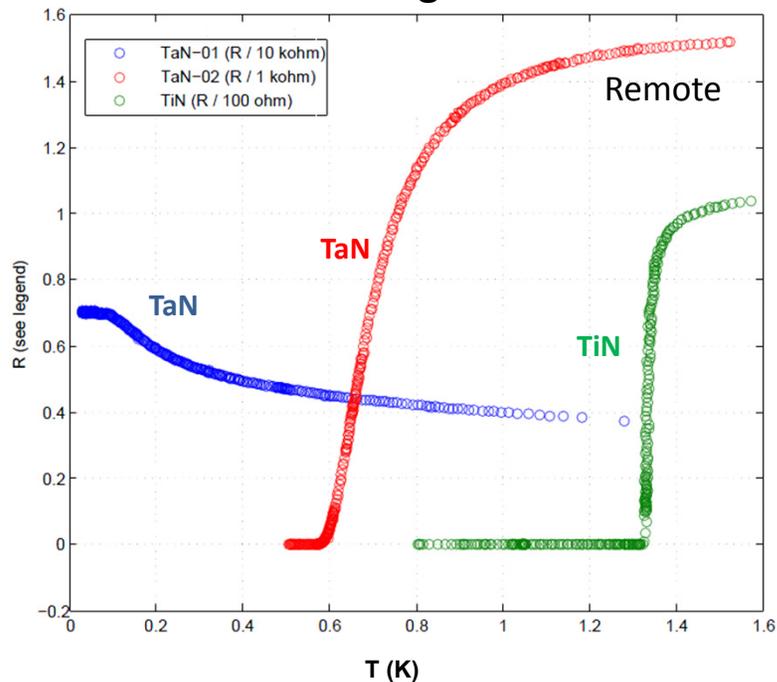
TaN ALD for Superconducting Detectors



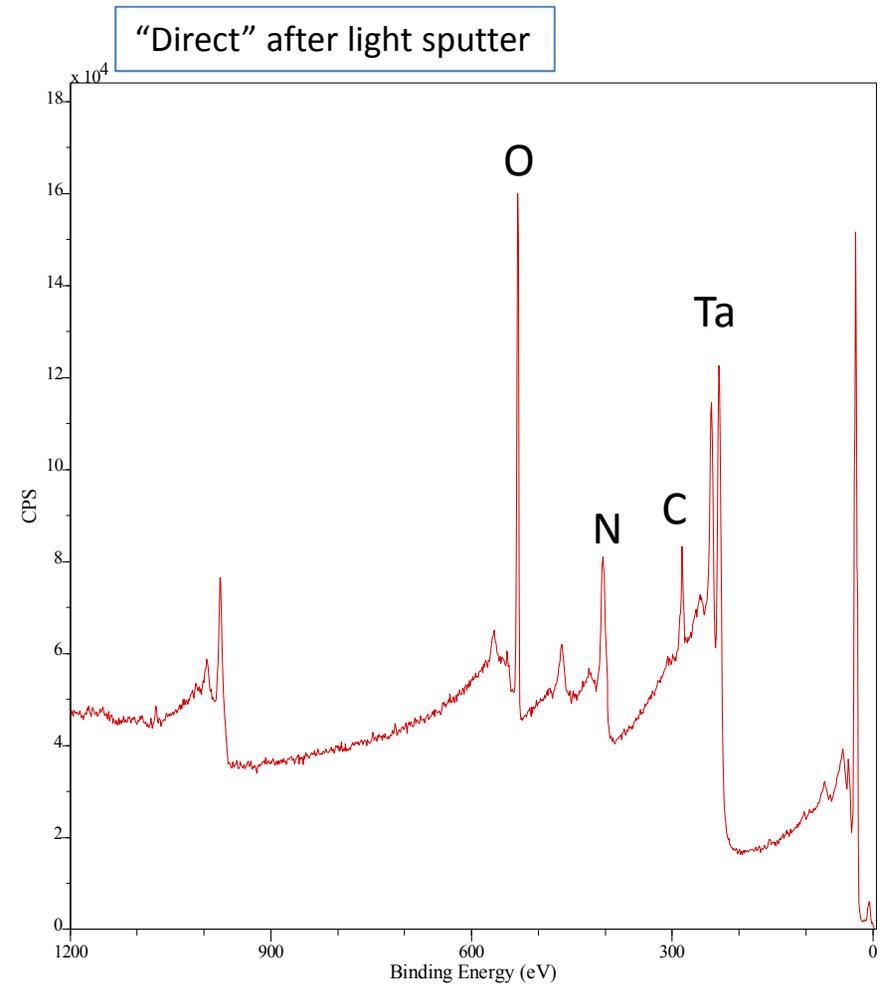
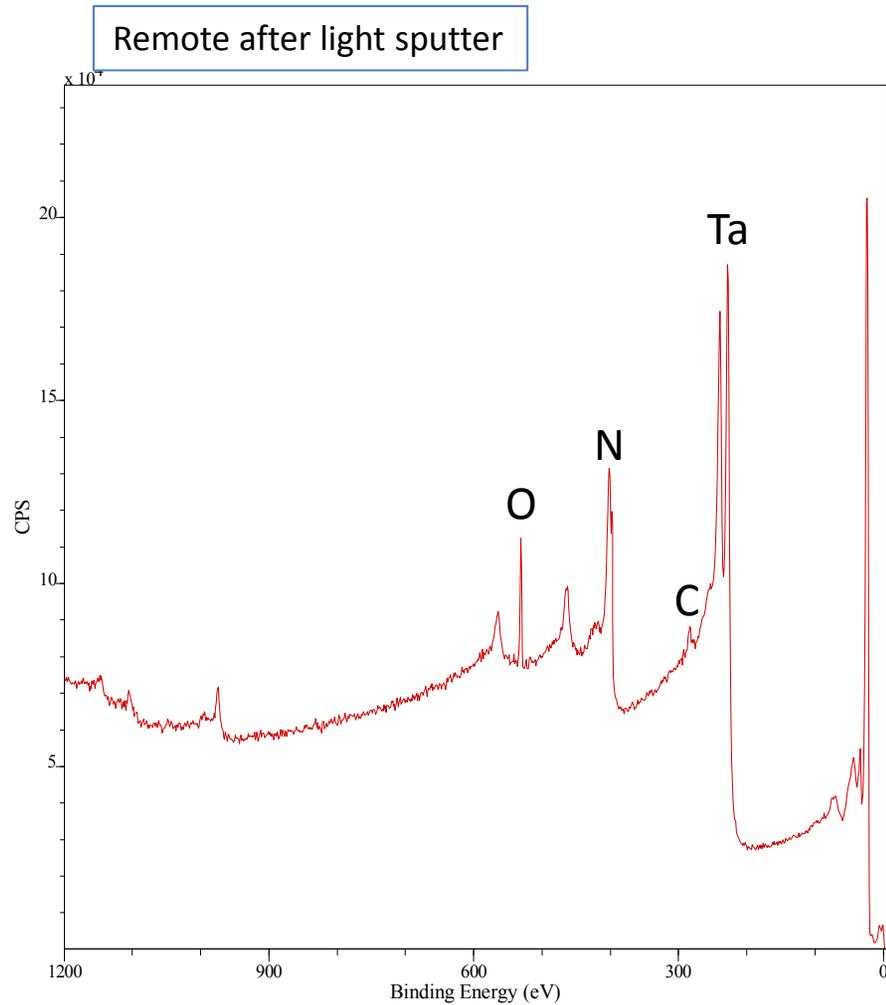
- Advantages
 - TaN and TaCN have inherently higher T_c than TiN
- Disadvantages
 - TiN superconducting transition is sharper
 - Performance sensitive to deposition method
 - Thermal ALD TaN is not conductive
 - Remote and “direct” plasma ALD thus far yield different results, even for “saturating” doses

TaN Process Conditions:

TBTDDET + Ar/H₂ plasma
Dep. Temperature 300C



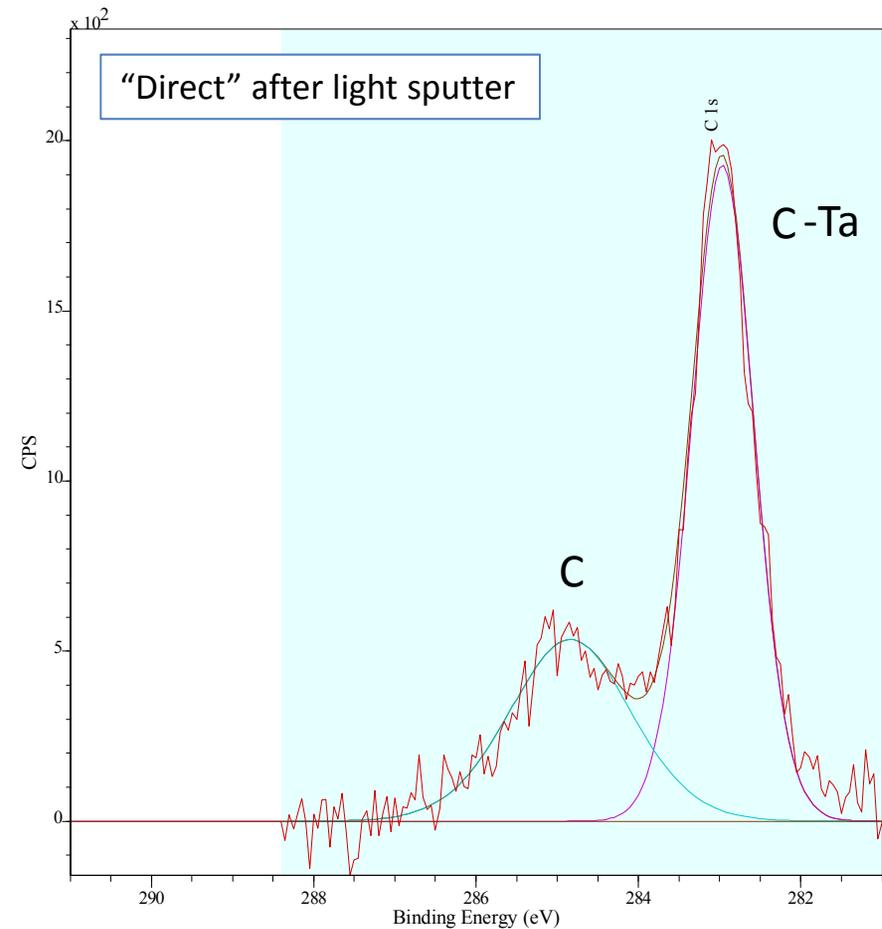
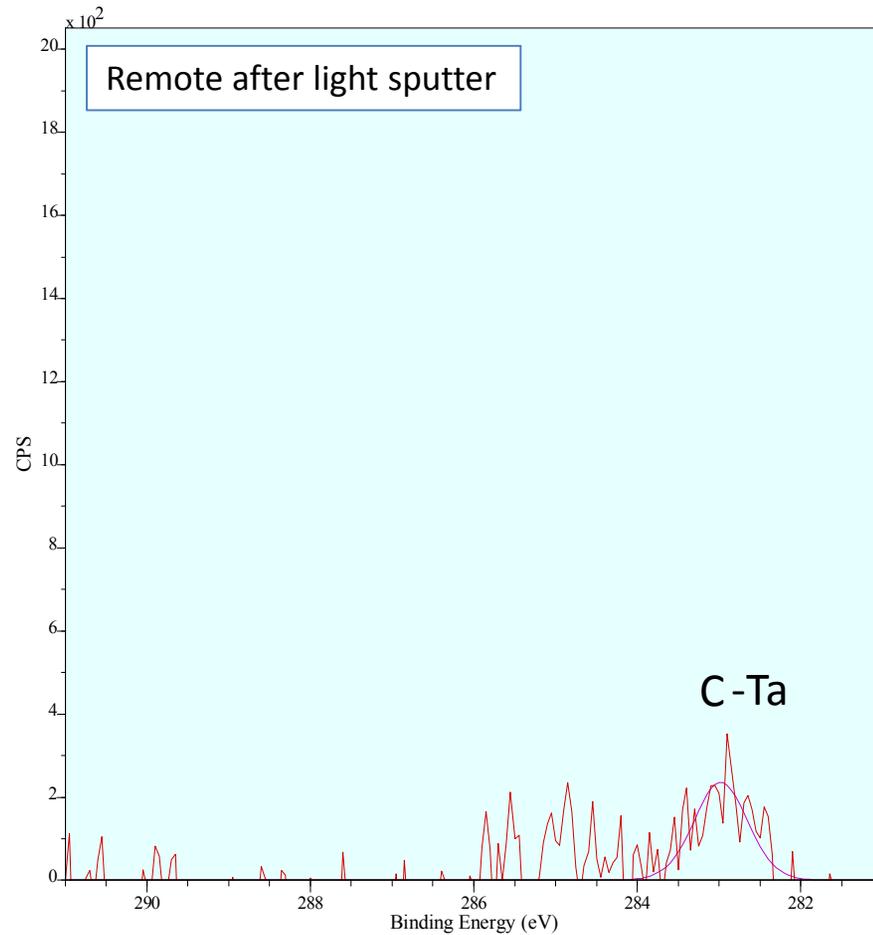
ALD TaN XPS Spectra After Sputtering



- XPS results would suggest that the remote plasma is more TaN-like, but clearly that's not a desirable trait for a superconducting film



Comparison of C1s Spectra

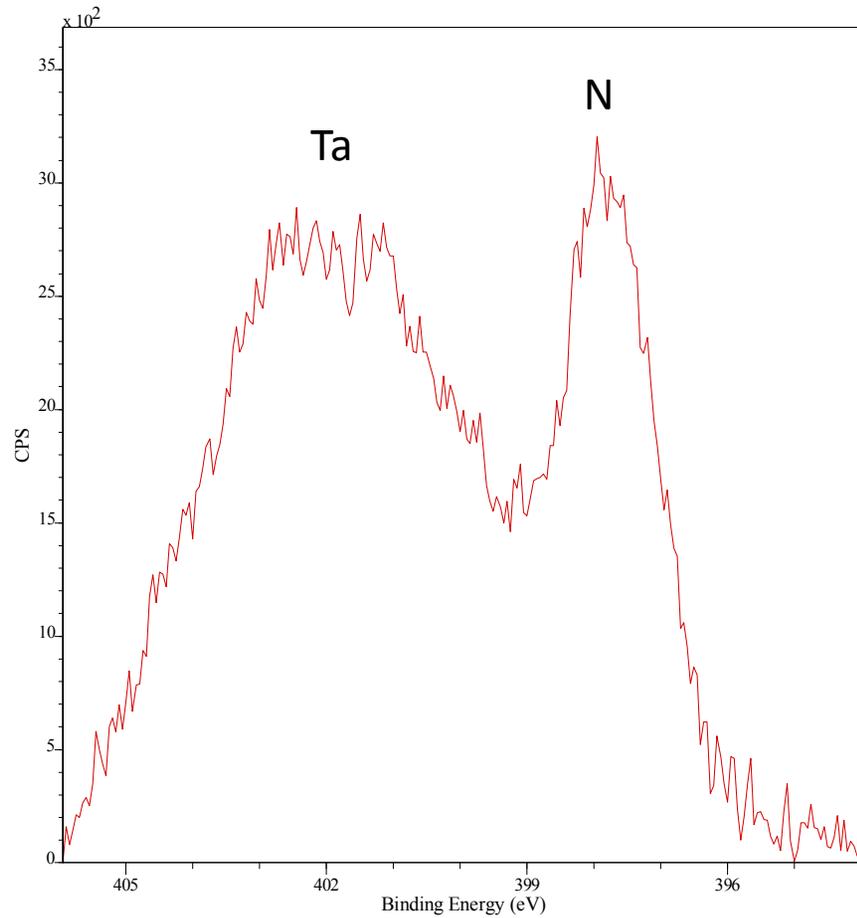


- Very little carbide signature in the remote plasma ALD film

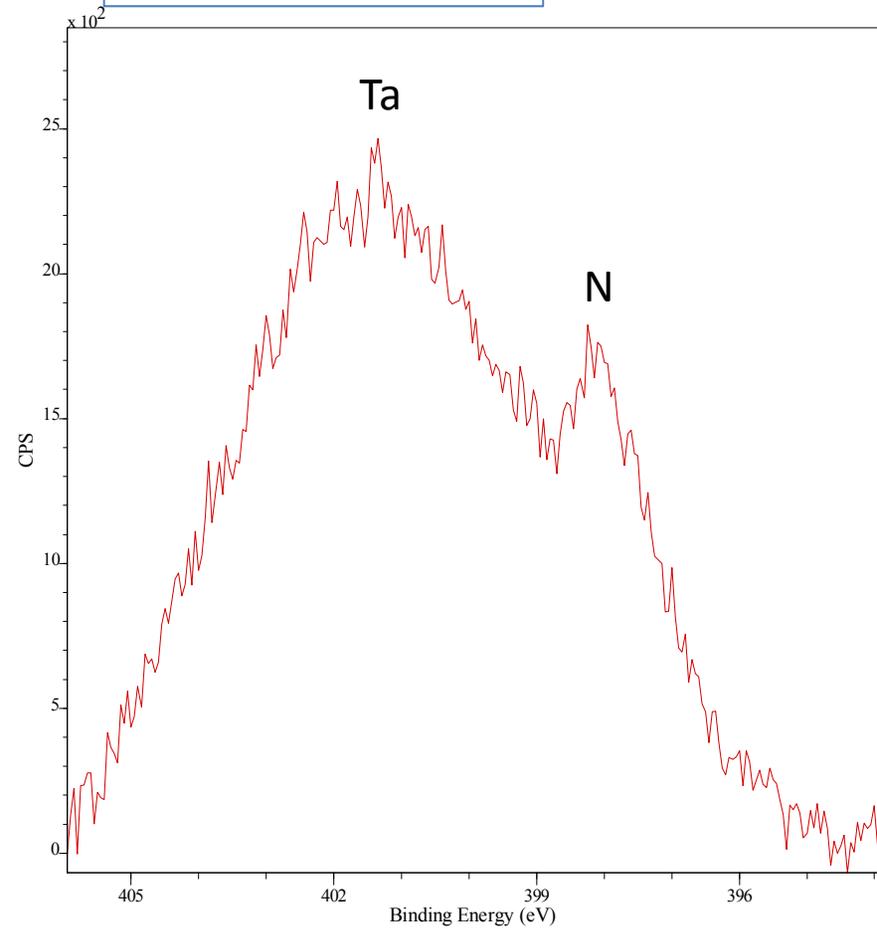
Comparison of N1s Spectra



Remote after light sputter



"Direct" after light sputter



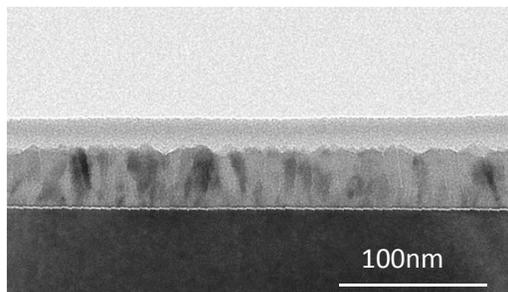
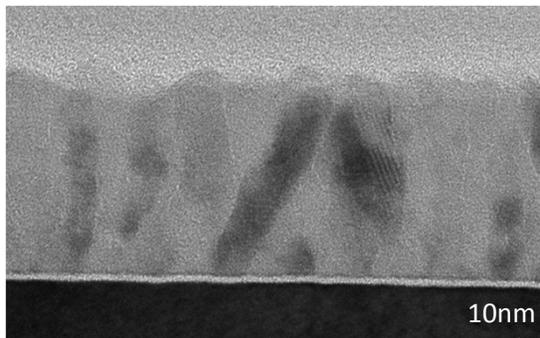
- Nitrogen appears enhanced in the remote plasma ALD film



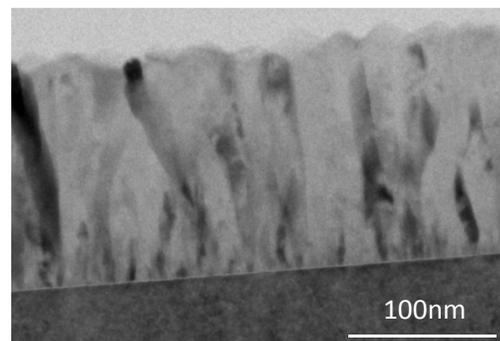
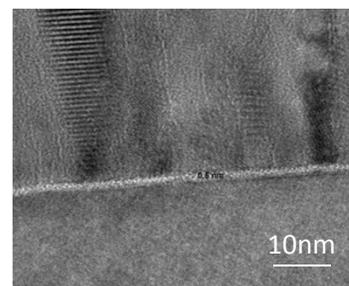
Importance of Interface

- Superconductor/Substrate interface determines, in part, the quality factor of the resonant circuit
 - Amorphous layers act as sources of noise
- Experimented with different surface treatments
 - Solvent clean (degrease)
 - HF dip (oxide removal)
 - TMA exposures (surface treatment)

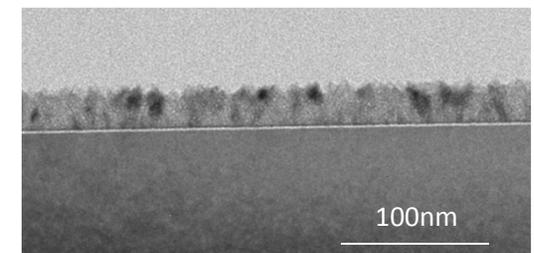
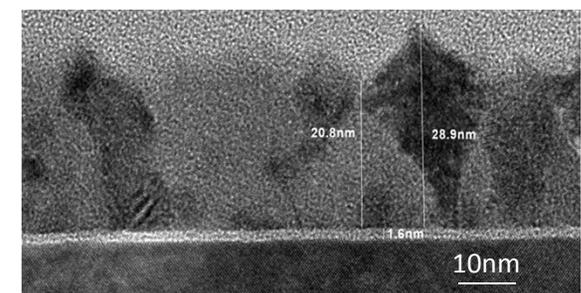
Condition 1



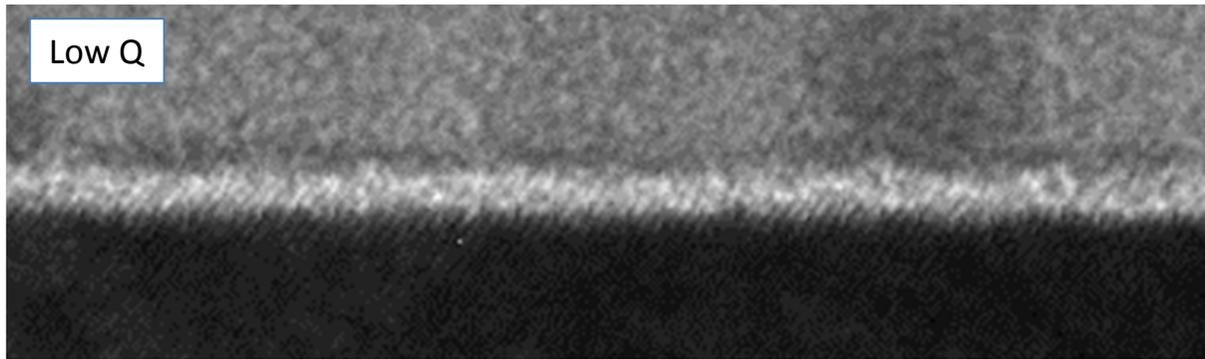
Condition 2



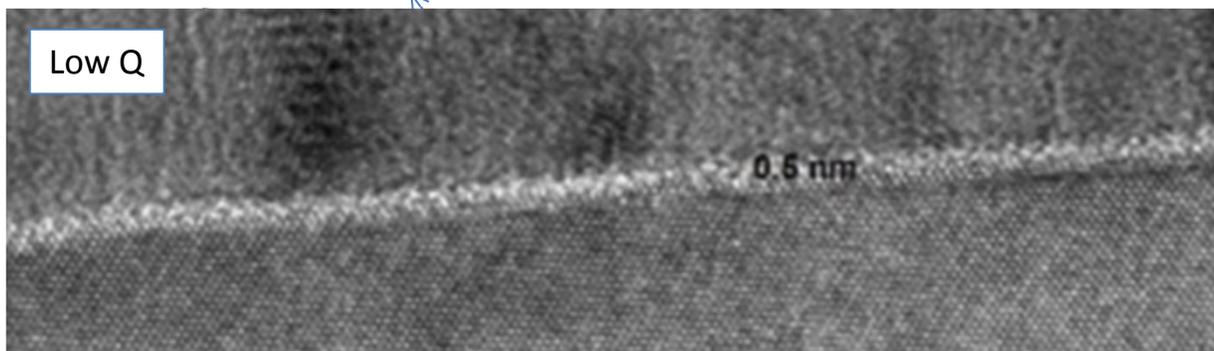
Condition 3



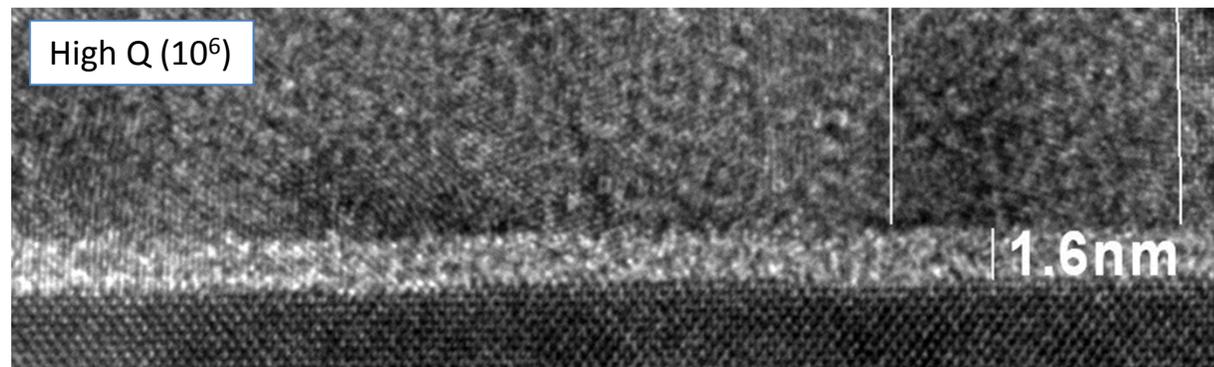
Surface Preparation



Condition 1
No surface treatment
(amorphous native oxide)



Condition 2
HF Dip
(silicide?)



Condition 3
TMA exposures
(alumina silicate? /
Some crystallinity evident?)

Although all samples are superconducting, but only the TMA exposure method appears compatible with sensor fabrication.



Conclusions

- Benefits of ALD for NASA instruments and applications
 - Ultrathin, highly conformal, and uniform films over arbitrarily large surface area
 - High quality films (density, roughness, conductivity, *etc.*)
 - Angstrom level control of stoichiometry, interfaces, and surface properties
 - Multilayer nanolaminates/nanocomposites
 - Low temperature surface engineering
- Flight applications enabled by ALD
 - Anti-reflective coatings/Mirrors/Filters/Optics for UV/Vis/NIR Detectors
 - Superconducting Films for Submillimeter Astronomy

Acknowledgements



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