Atomically precise surface and interface engineering via atomic layer deposition to enable high-performance materials, detectors, and instruments

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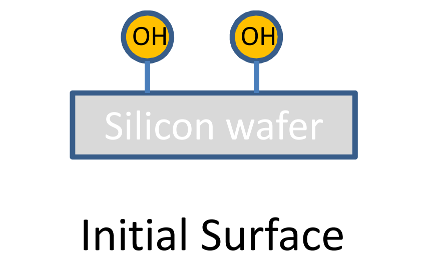
Outline

- Description of Technology
- Overview of Application Results
  - Anti-reflective coatings
  - Optical elements (filters)
  - Superconducting detectors
  - Surface treatments
- Conclusions/Future
  - Surface passivation

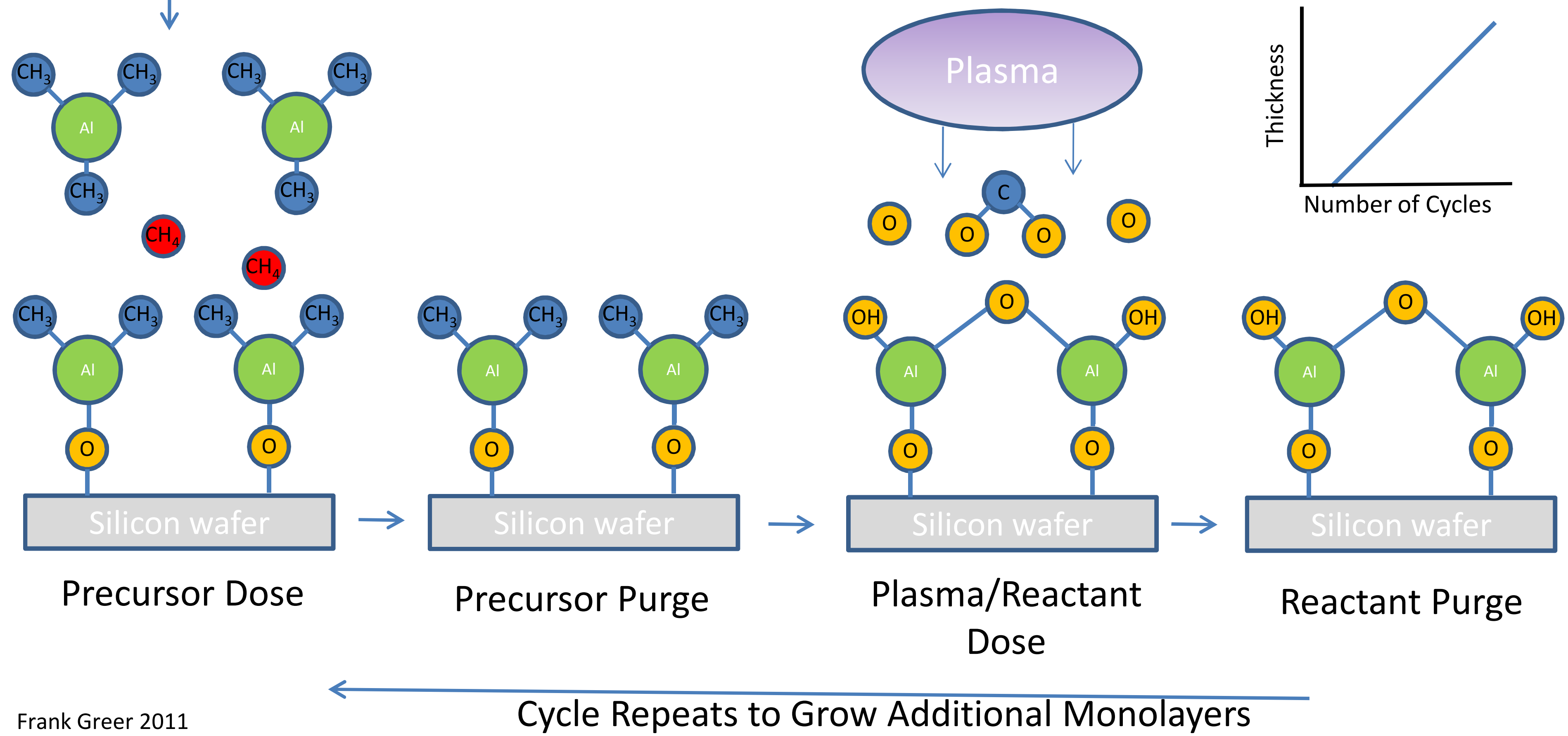
JPL's Oxford ALD System

Acknowledgements:
Novellus Systems (*i*ALD group: F. Greer *et al.*)

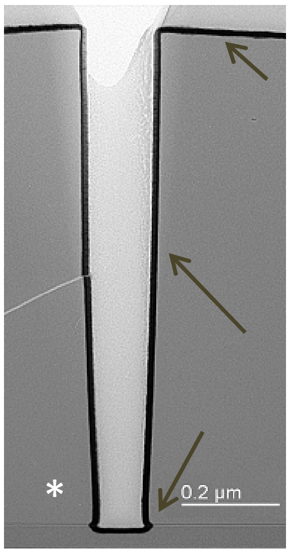
Atomic Layer Deposition Fundamentals



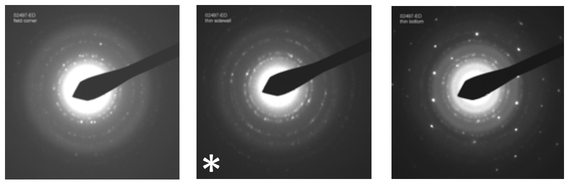
- Surface reaction mediated deposition
- ALD cycles are repeated until desired film thickness is achieved
- Metals, Nitrides, and Oxides are achieved through choice of precursor and reactant species
- Can achieve thin film deposition or surface modifications at near room temperature



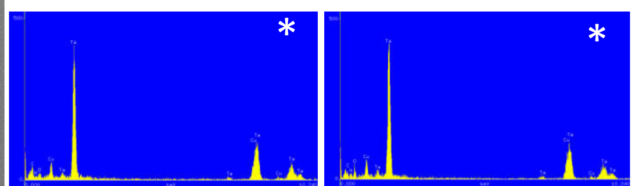
Properties and Advantages of ALD



Field Sidewall Bottom

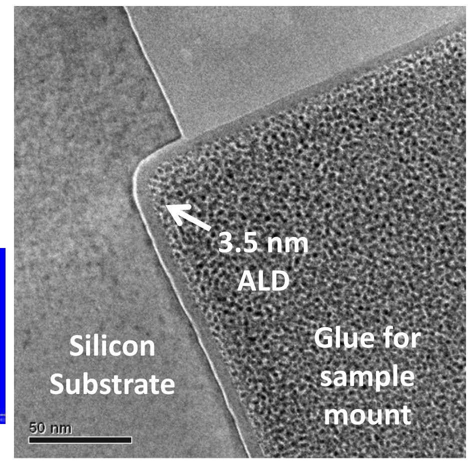


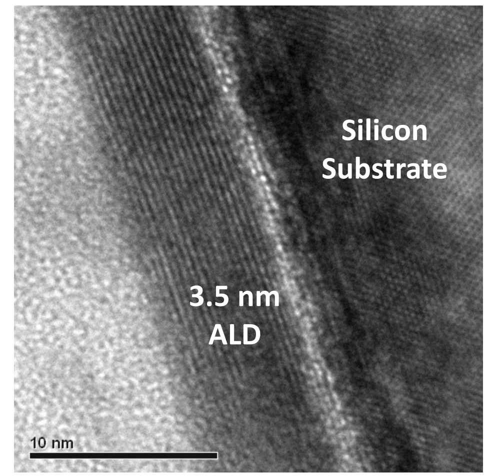
Field Sidewall



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

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



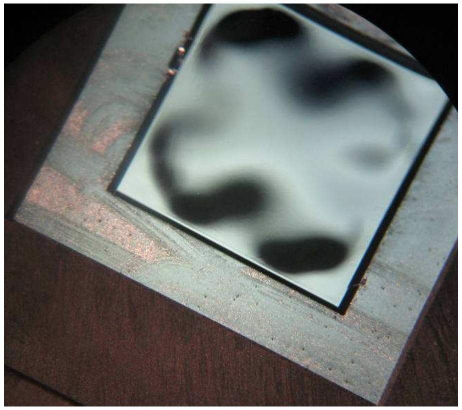


KNI TEM of a JPL ALD film (image credit Carol Garland/Bophan Chhim)

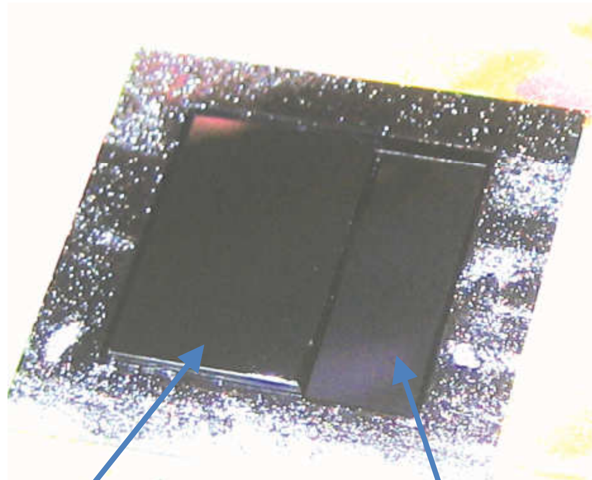
- Atomic Layer Deposition is inherently 100% conformal up to very high aspect ratios
- Film properties and composition are uniform throughout aggressive features
- Film properties and composition are uniform across arbitrarily large substrates

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

Anti-Reflective Coatings for UV Astronomy



12um thick Membrane is unsupported

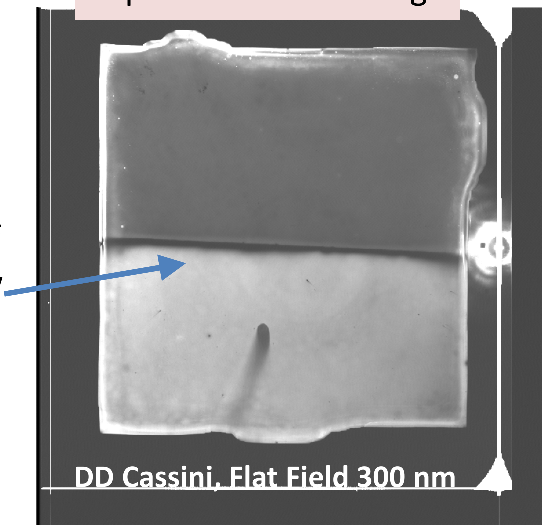


Shadow mask

AR Coated

Sputtered AR coating

Edge of shadow mask



- 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

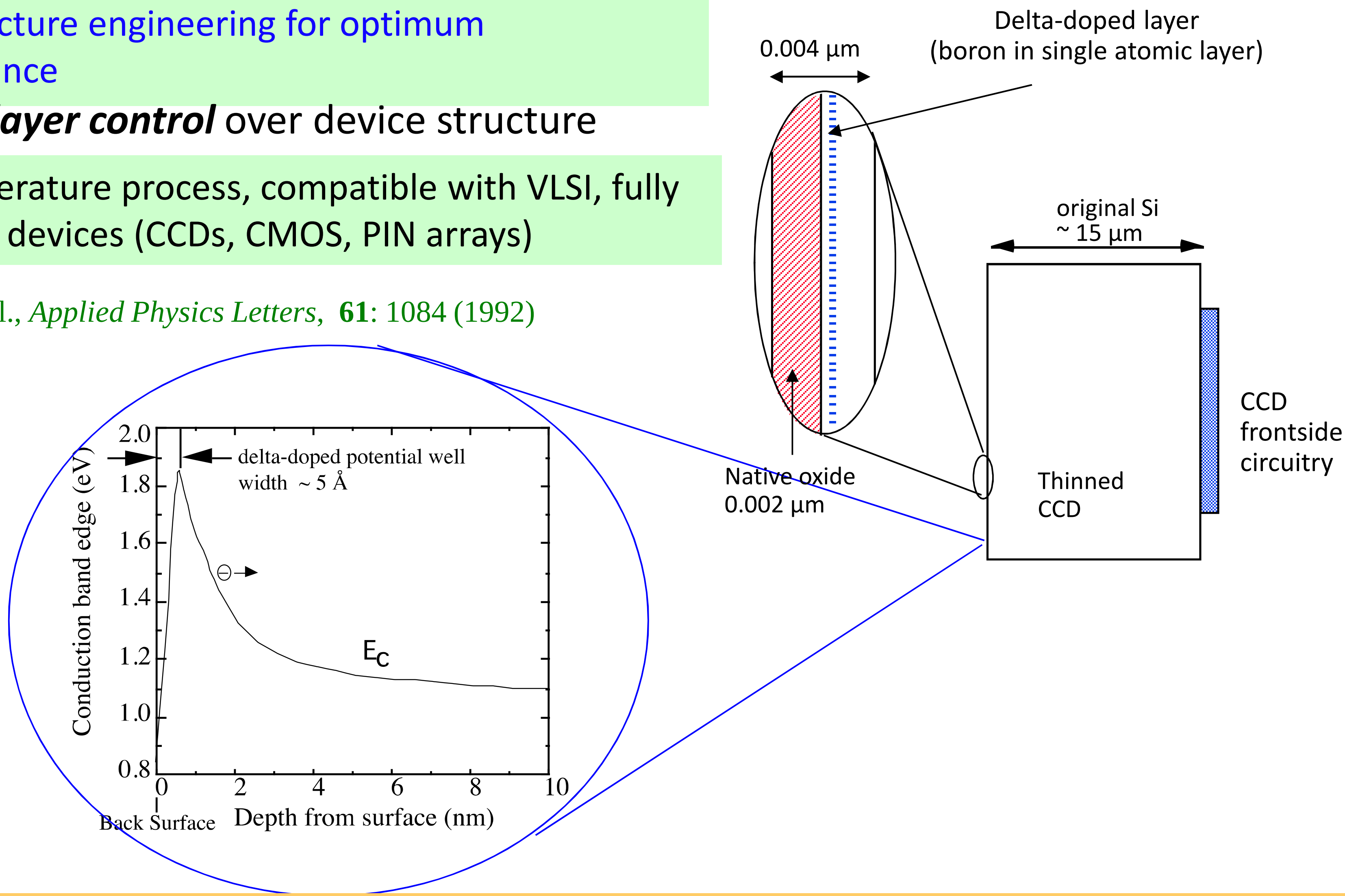
Delta doping technology as the ideal Back Illumination solution

Bandstructure engineering for optimum performance

Atomic layer control over device structure

Low temperature process, compatible with VLSI, fully fabricated devices (CCDs, CMOS, PIN arrays)

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



Fully-processed devices are modified using Si Molecular Beam Epitaxy (MBE)

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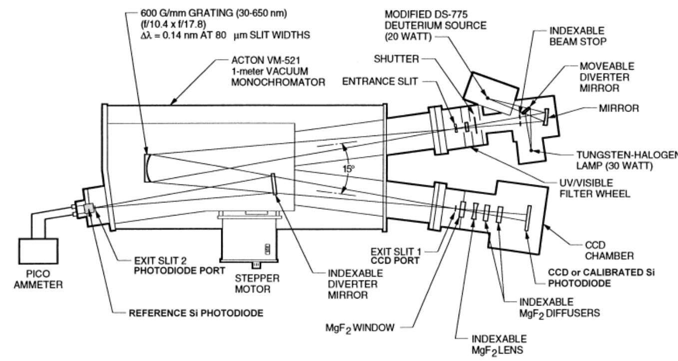
S. Nikzad, 2011

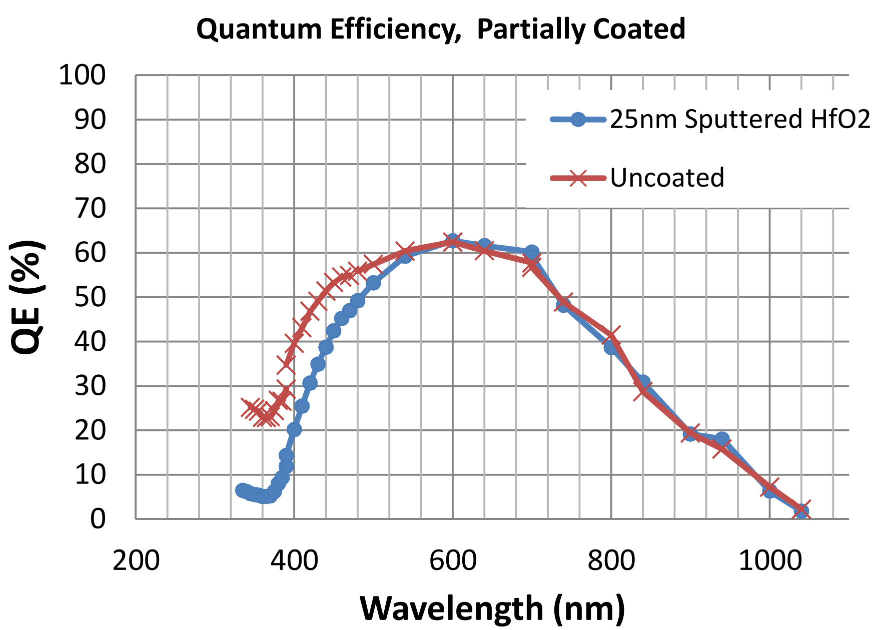
CCD Characterization

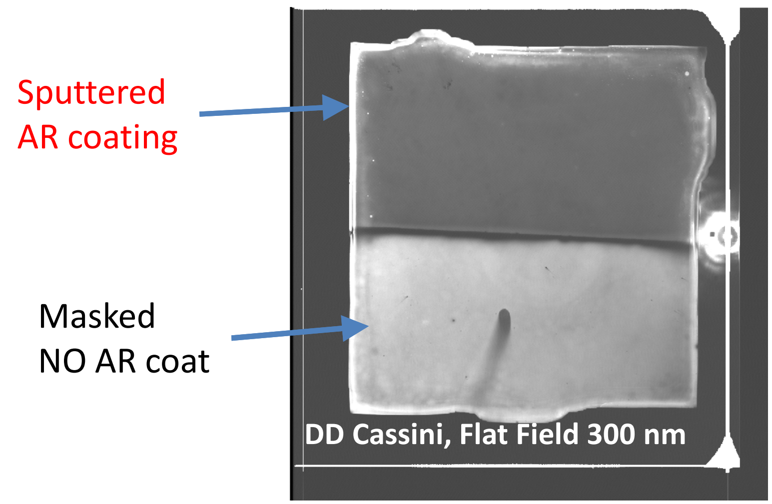
- Characterization of absolute quantum efficiency of detectors is very difficult in the UV
  - Atmospheric absorption occurs in wavelengths < 160nm
  - Silicon CCDs must be cooled to liquid nitrogen temperatures to reduce dark current
  - Quantum yield (electrons/photon) is greater that 1 for short wavelengths
- JPL has developed a system and methodology for these tests in our laboratory for rapid feedback during detector development and flight qualification*



*B.C. Jacquot, S.P. Monacos, M.E. Hoenk, **F. Greer**, T.J. Jones, and S. Nikzad**,** *Rev Sci. Inst.* 2011

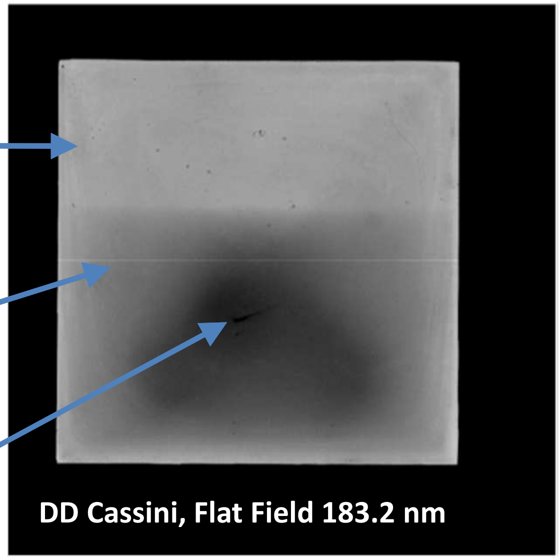
Sputtered anti-reflective coatings

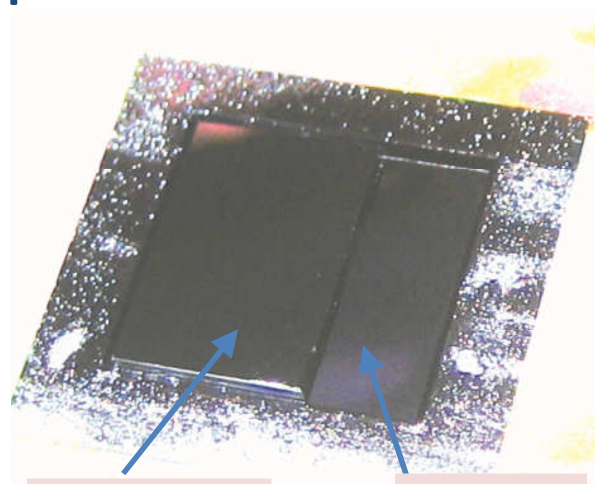


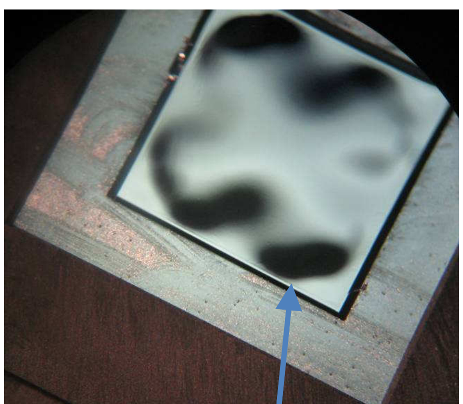


- Sputtered film QE far below that of uncoated reference. Effect also observed for sputtered MgO.
- Poor UV response of HfO_2 suggests AR coating problem is at the nanometer length scale

ALD AR Coating Experiments







- Shadow masking is somewhat difficult due to conformality of the ALD coating process
  - Mask does not sit flat on unsupported membrane so partial coating is observed over most of CCD
- Aluminum oxide AR coating does improve UV response

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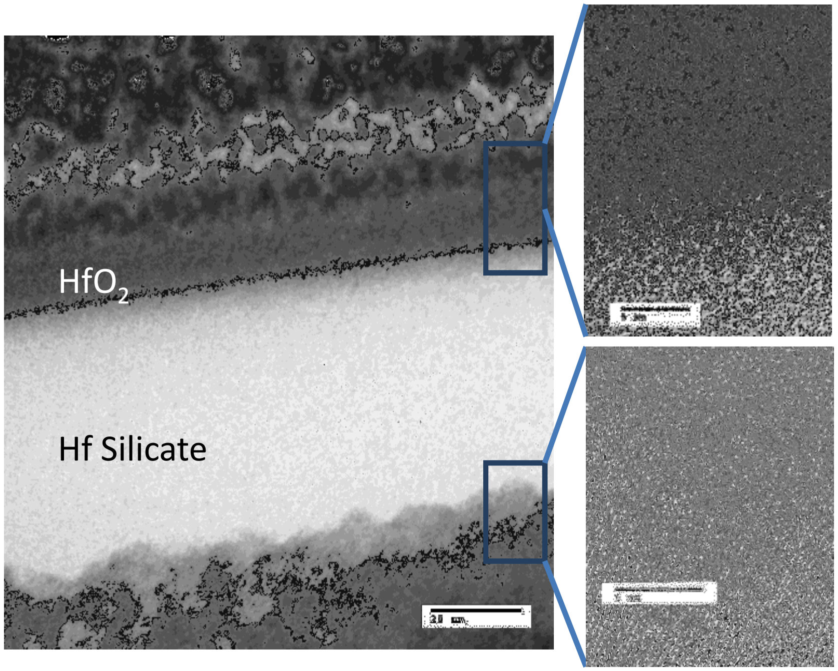
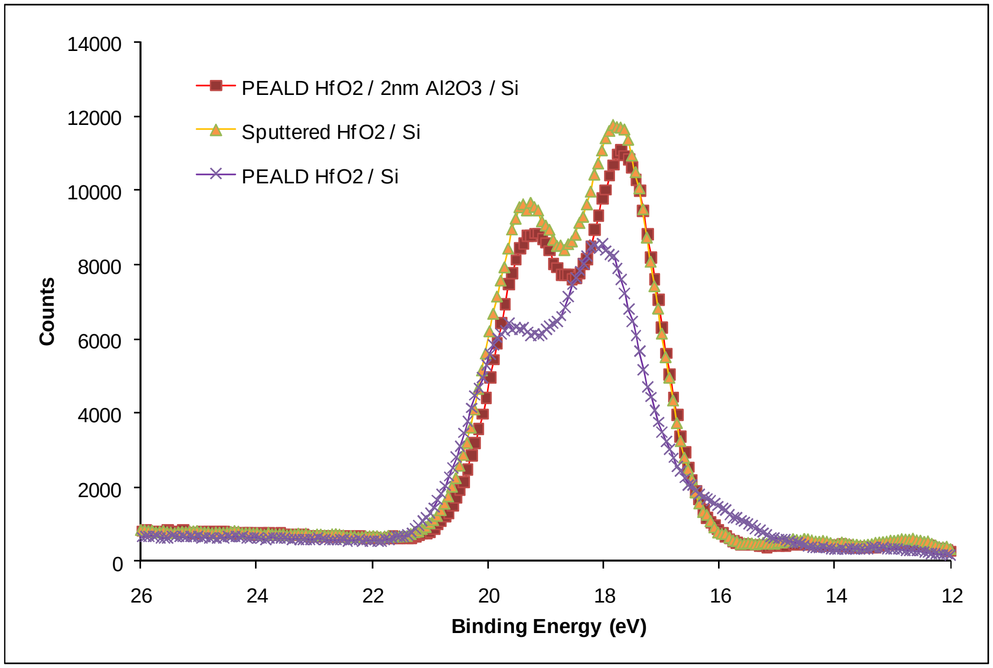
Importance of Chemistry in ALD AR Coatings

TEM of PEALD HfO_2 directly on Si



XPS Data from initial AR coating growth



- ALD is a chemical process that occurs at elevated temperatures
  - Chemical interaction of ALD coating with substrate is possible.
  - Surface nucleation and reactions must be carefully considered
- ALD bilayers were utilized to successfully mitigate this effect

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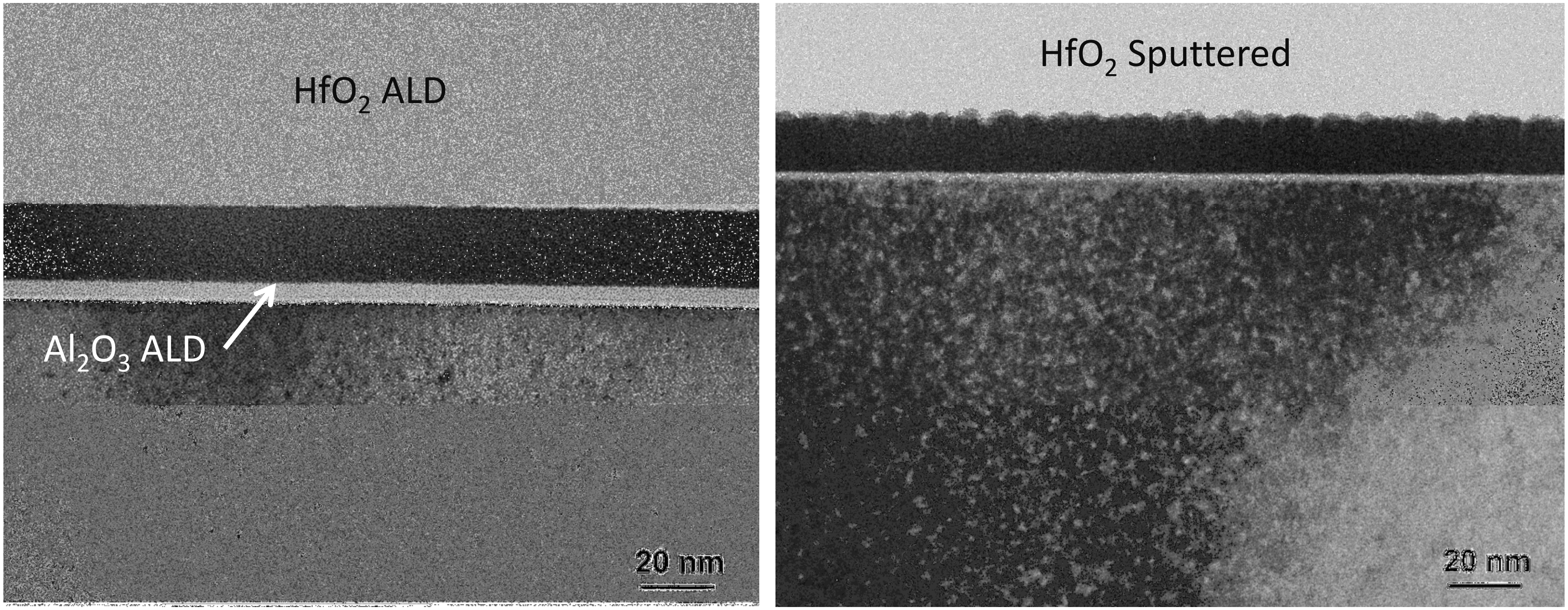
Comparison of Nanomorphology of AR Coatings



- Appearance of 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 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 <2nm thickness change impacts the performance

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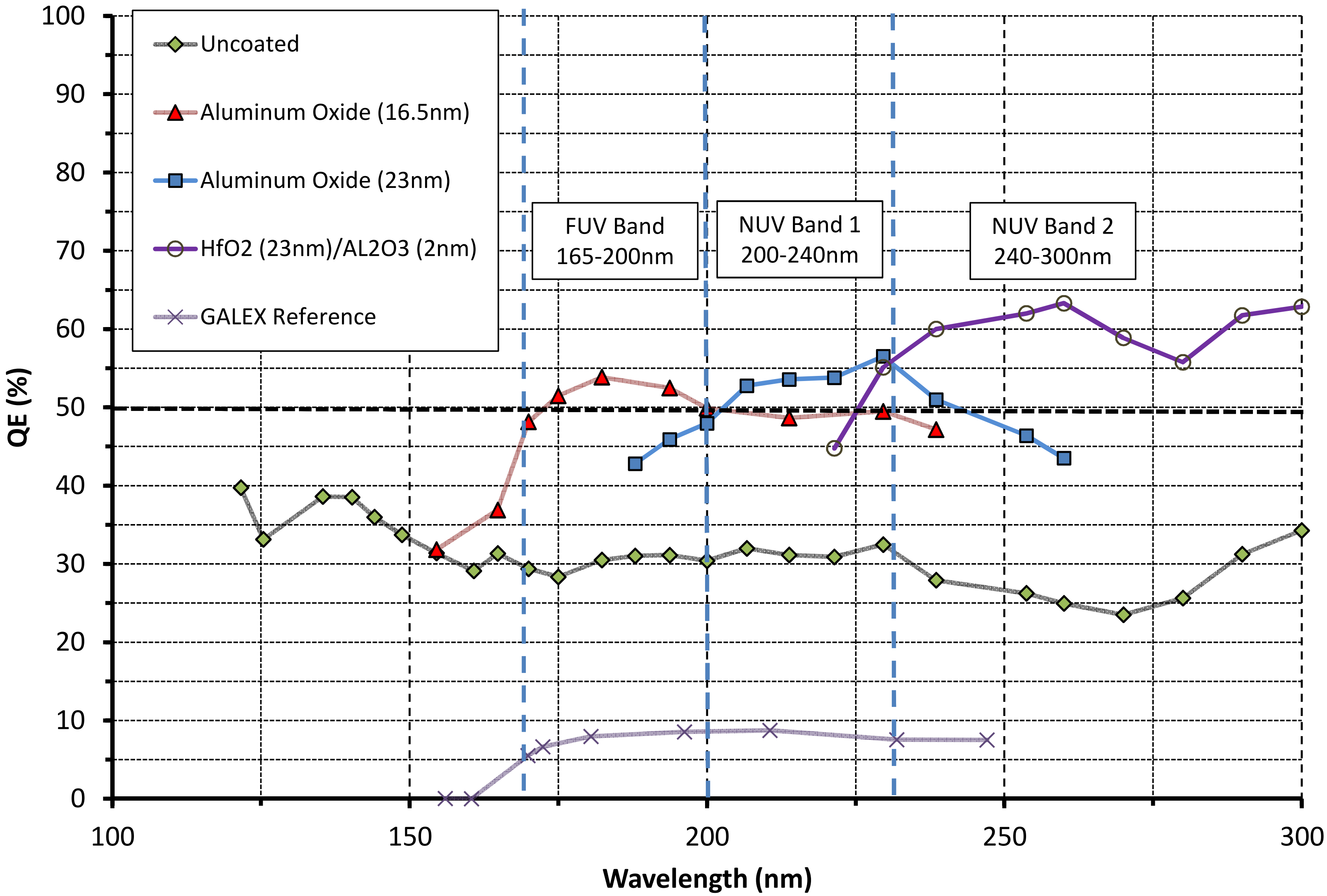
QE of FUV-NUV Bands

Delta Doped, Partial ALD AR Coatings



Atomic Layer Deposition AR coatings provide up to ***2X improvement*** over uncoated baseline and ***5x improvement*** over incumbent UV detector technology

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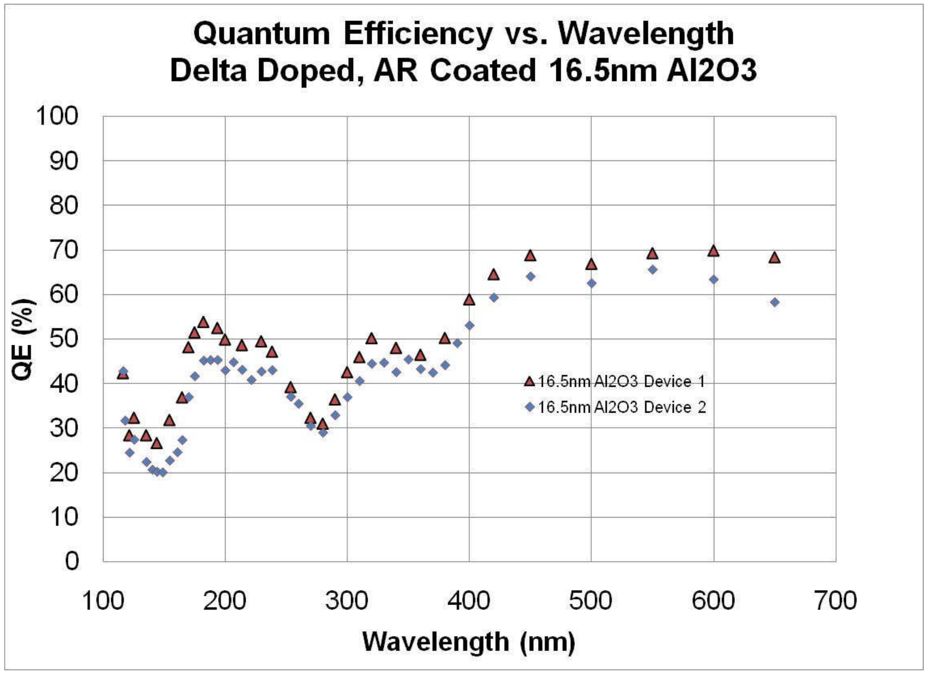
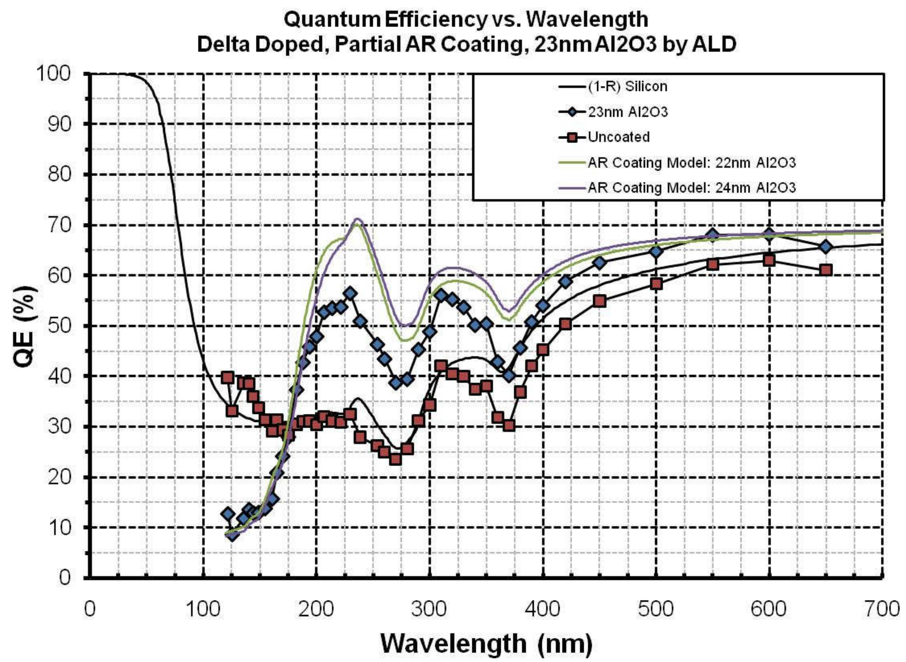
ALD Enables Atomic Control of Coatings



Same exact recipe run on JPL ALD system on two different devices separated by ***a month***

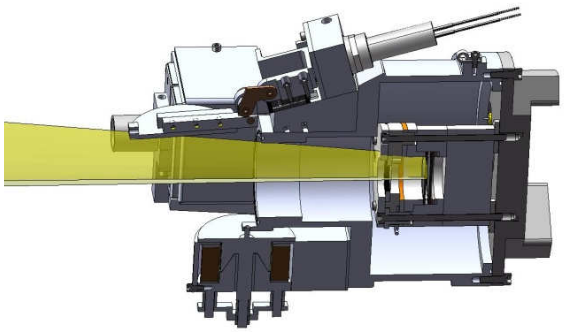


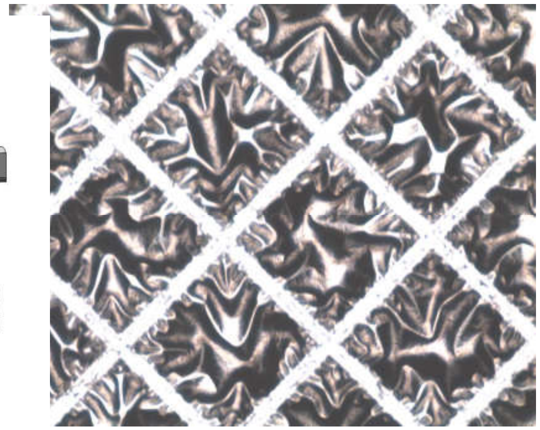
Wavelength dependence of coating performance ***correctly predicted*** by AR coating models based on precision UV ellipsometry measurements

- Reproducibility and accuracy of the ALD technique enables rational design and fabrication of anti-reflective coatings at the nanometer scale
- Multilayers feasible when required to prevent interactions or to provide for integrated filters (*e.g.* bandpass)

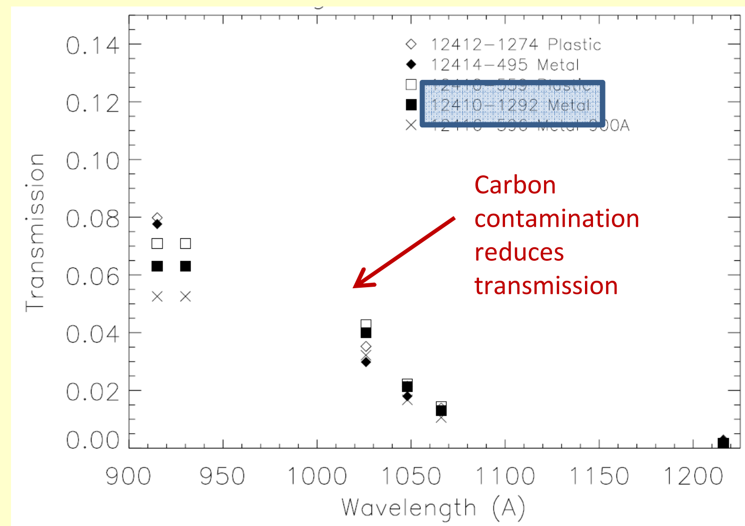
UV Filter Enhancement/Fabrication

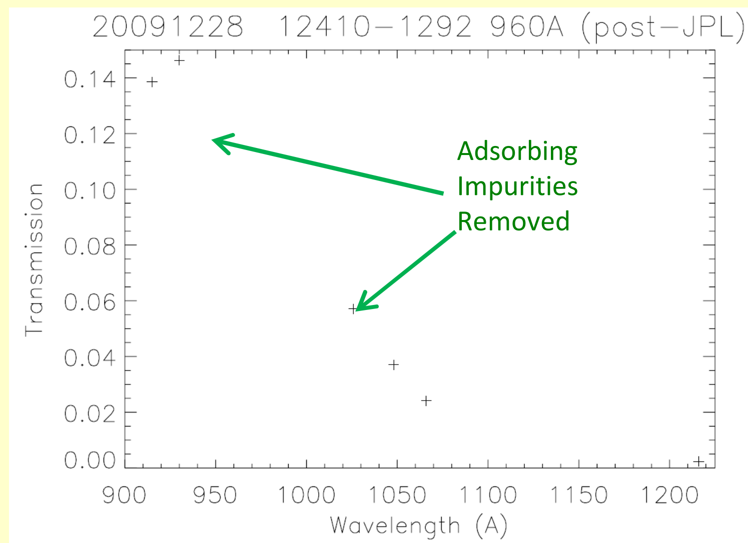
FIRE telescope





Indium foil on Ni mesh





- FIRE Telescope objective to image the very hottest stars, with no interference from Lyman alpha
  - Thin Indium Foil (0.1um thick) supported by Ni mesh acts as UV filter cutting off transmission above 1100A
- JPL post treatments yielded improvement in filter transmission
- AR coatings results demonstrate that ALD can be applied to live devices
- Thus, ALD, with appropriate interfacial layers, can be used to monolithically integrate filters into detector elements

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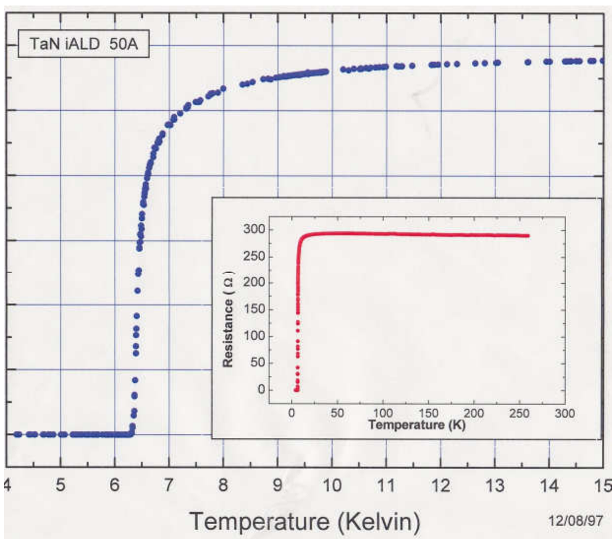
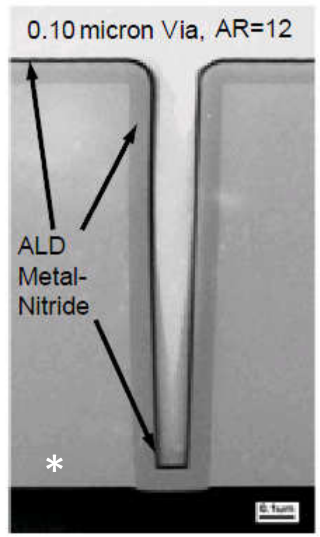
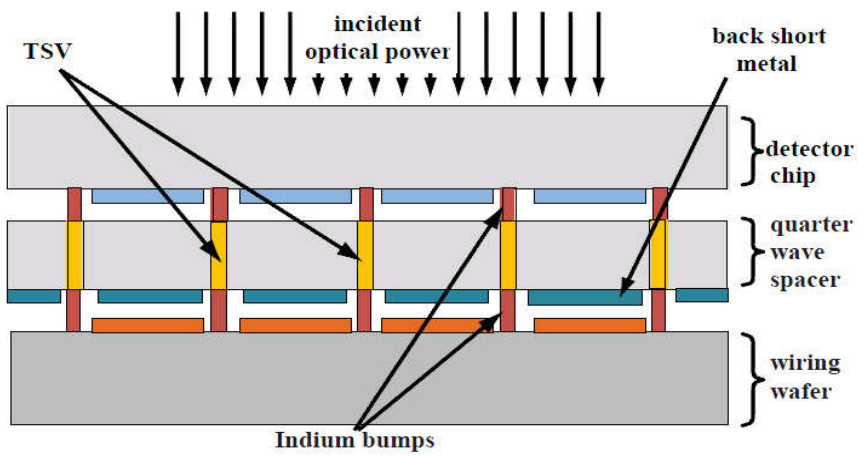
Superconducting Detectors for Submillimeter Astronomy

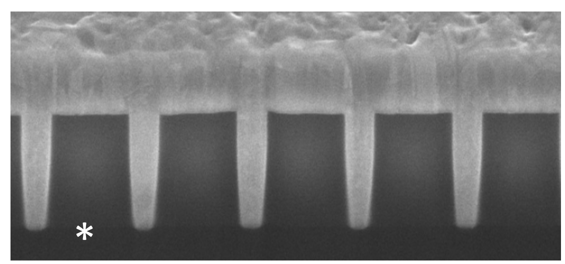


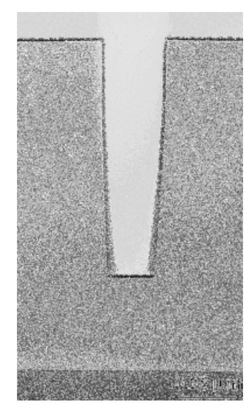


- ALD TiN, TaN, and NbN films are all ***superconducting***
- Enables ***uniform*** production of superconducting detector arrays across ***8" wafers.***
- Enables ***3D integration*** of arrays for ***hybrid, buttable*** detectors



Electroplated array of vias using 100A of ALD as barrier/seed





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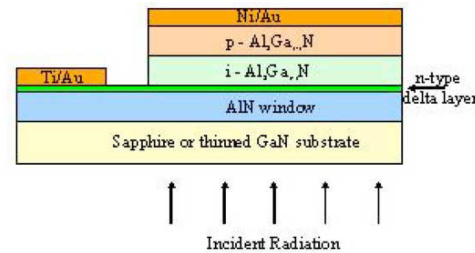
* F.Greer, *et al.* *i*ALD TaN film, Novellus Systems, AVS-ALD Conference 2005

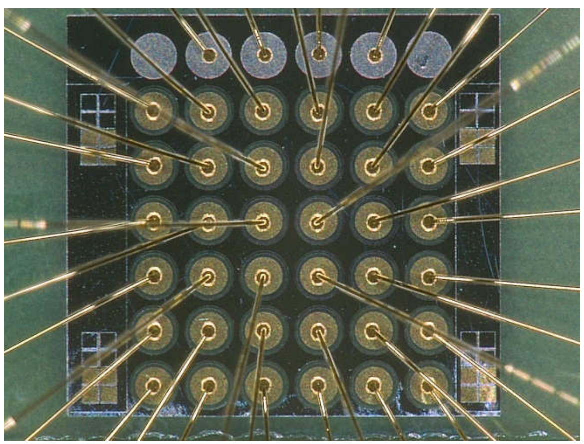
ALD for III-N Detectors

•Exploring ALD as a means to reduce dark current in III-N APD UV detectors.

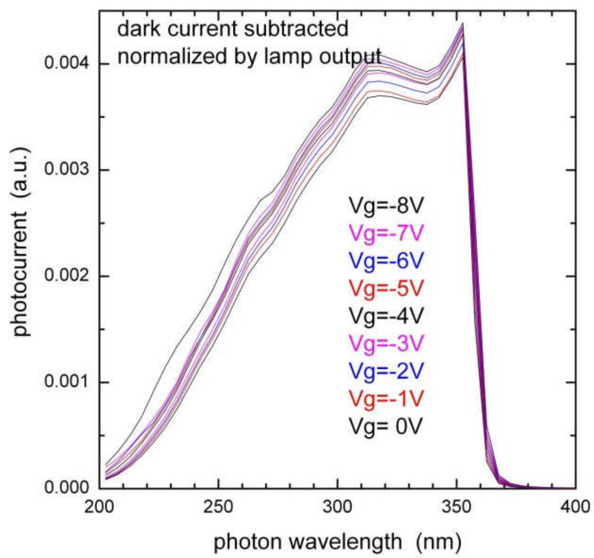
III-N Mesa Structure



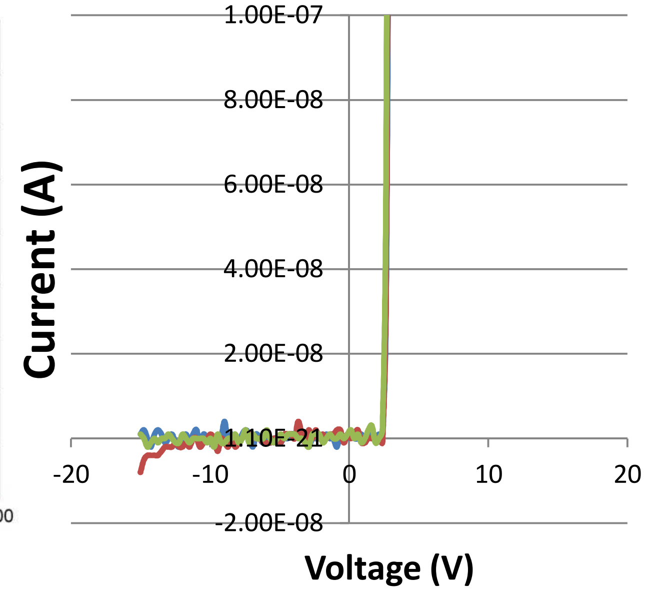
6x6 250um pixel QE test array



Responsivity for different biases



Leakage currents for 250um pixels



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Conclusions

- Benefits of ALD and Plasma Treatments
  - Ultrathin, highly conformal, and uniform films over arbitrarily large surface area
  - High quality films (density, roughness, conductivity, *etc.*)
  - Angstrom level control of stochiometry, interfaces, and surface properties
    - Multilayer nanolaminates/nanocomposites
    - Low temperature surface engineering
- Applications
  - Anti-reflective coatings/Mirrors/Filters/Optics for UV/Vis/NIR Detectors
  - Superconducting Detectors
  - Surface Passivation

Acknowledgements

- APRA
- JPL R&TD Funding