Detectors and Coatings for Efficient Systems for Future UV Astronomy

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Outline

High Performance Silicon Detectors through Atomic-scale surface/interface engineering

- Enables *high efficiency, stable response, and reliable performance*
- Delta doping plus ALD AR coatings

Wafer Scale Processing for High Throughput and High Yield

- Large scale, high throughput, high yield production for mission applications
- Wafer scale devices (taking up the entire 8-inch wafer area)

Examples of Recent Devices and Application

- FUV EMCCD (FIREBall)
- UV P-channel CCDs (CHESS)
- Broadband (WaSP)

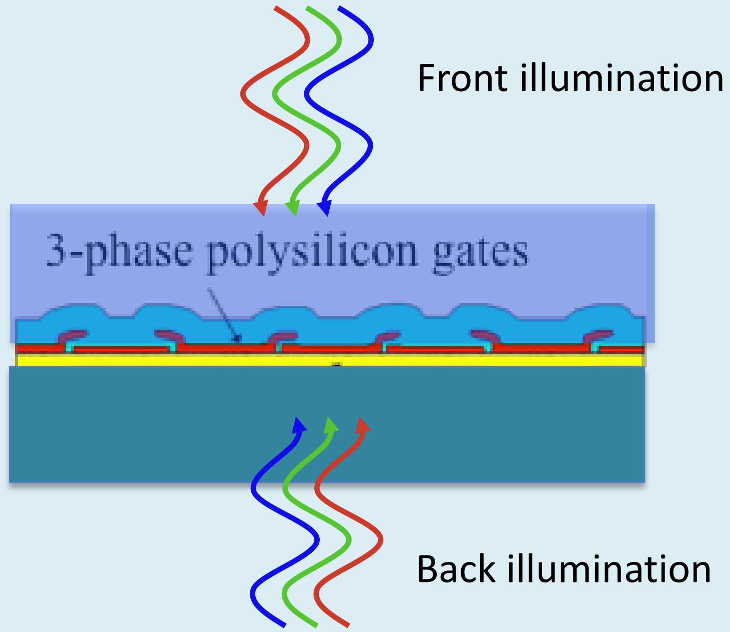
Work on Reflective Optical Coatings via ALD

High Performance Silicon Imaging through Back-illumination

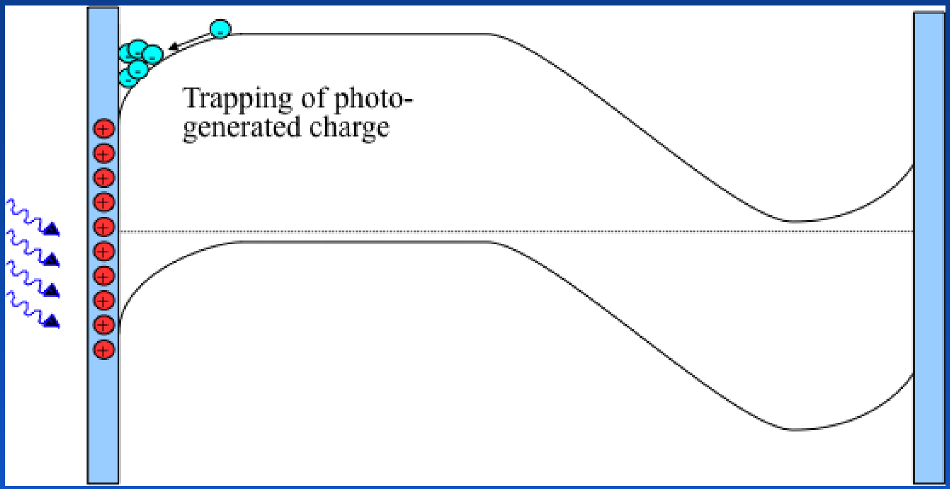
Key detector performance parameters depend on back illumination for *all* silicon imaging devices. Back illumination allows absorption of photons in silicon active area and "near" the collection well

These key parameters include wide spectral range, efficiency, resolution, stability of response, dark current, and high fill factor

Several 100 Å of poly silicon and oxide prevent absorption of UV photons into the device



Si Detector: Energy Band Cross-section

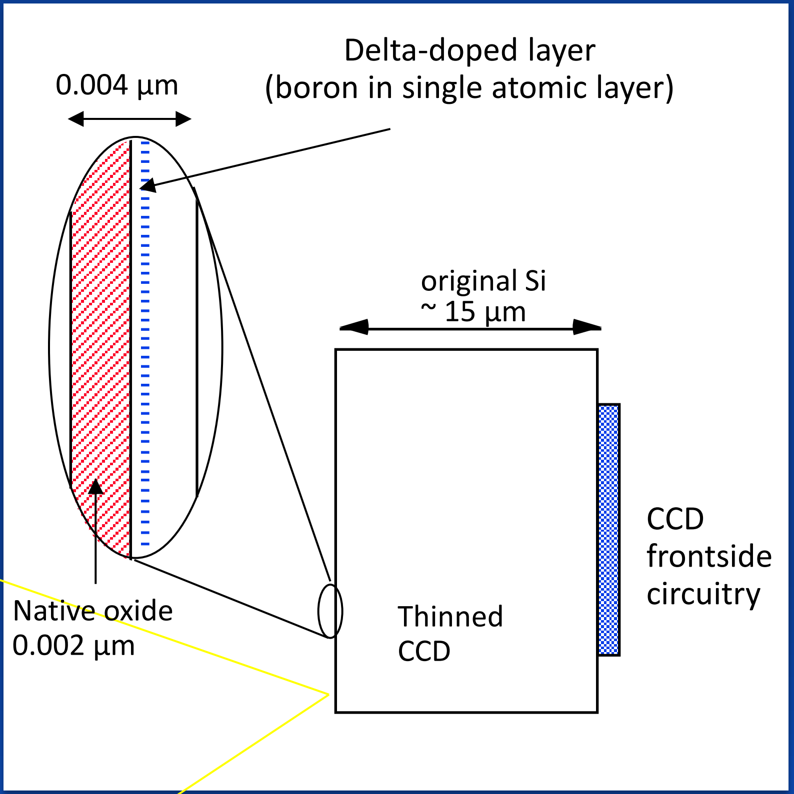


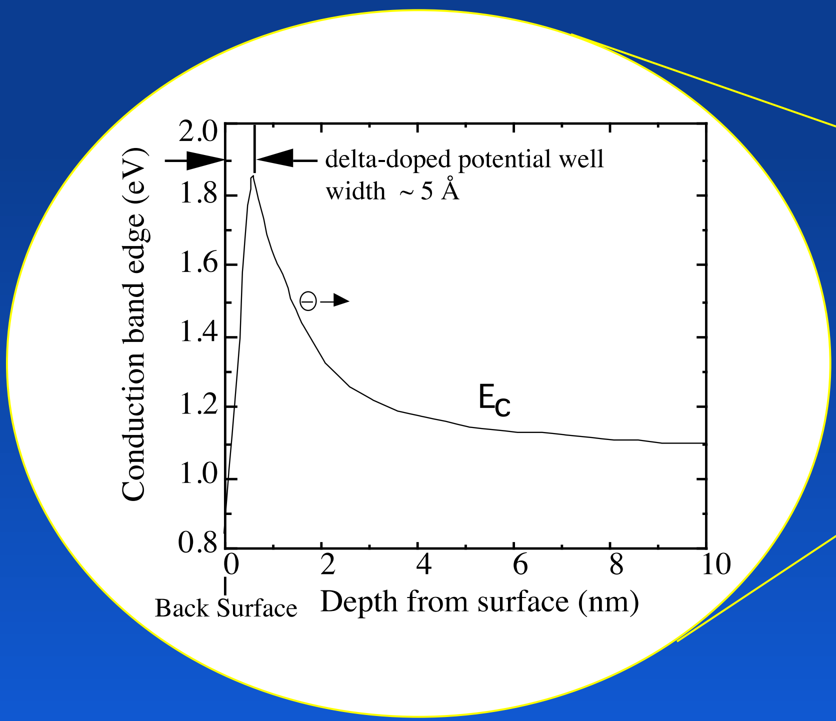
Back

Front

Delta doping technology via MBE

Bandstructure engineering for optimum device performance *with atomic layer control* over silicon surface

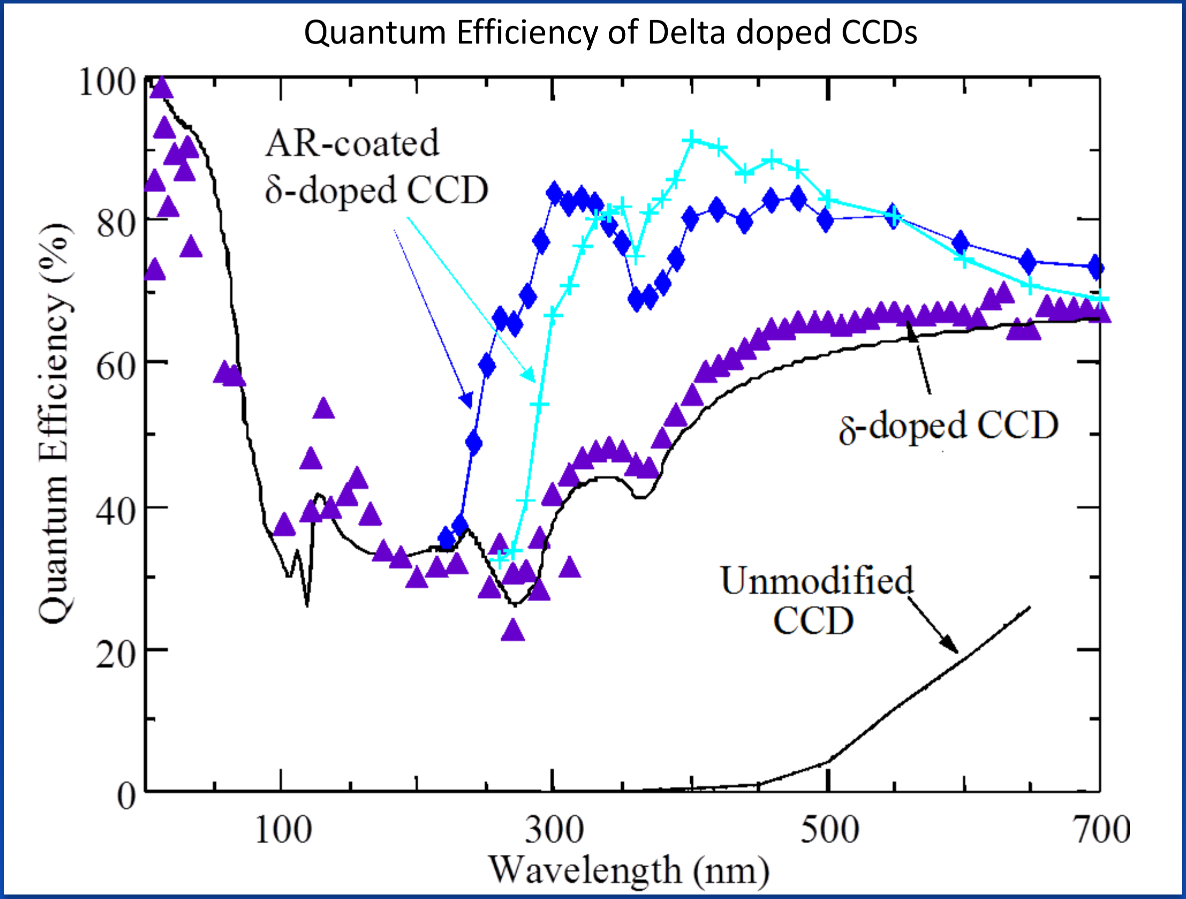




Low temperature process, compatible with VLSI, fully - fabricated devices (CCDs, CMOS, PIN arrays)

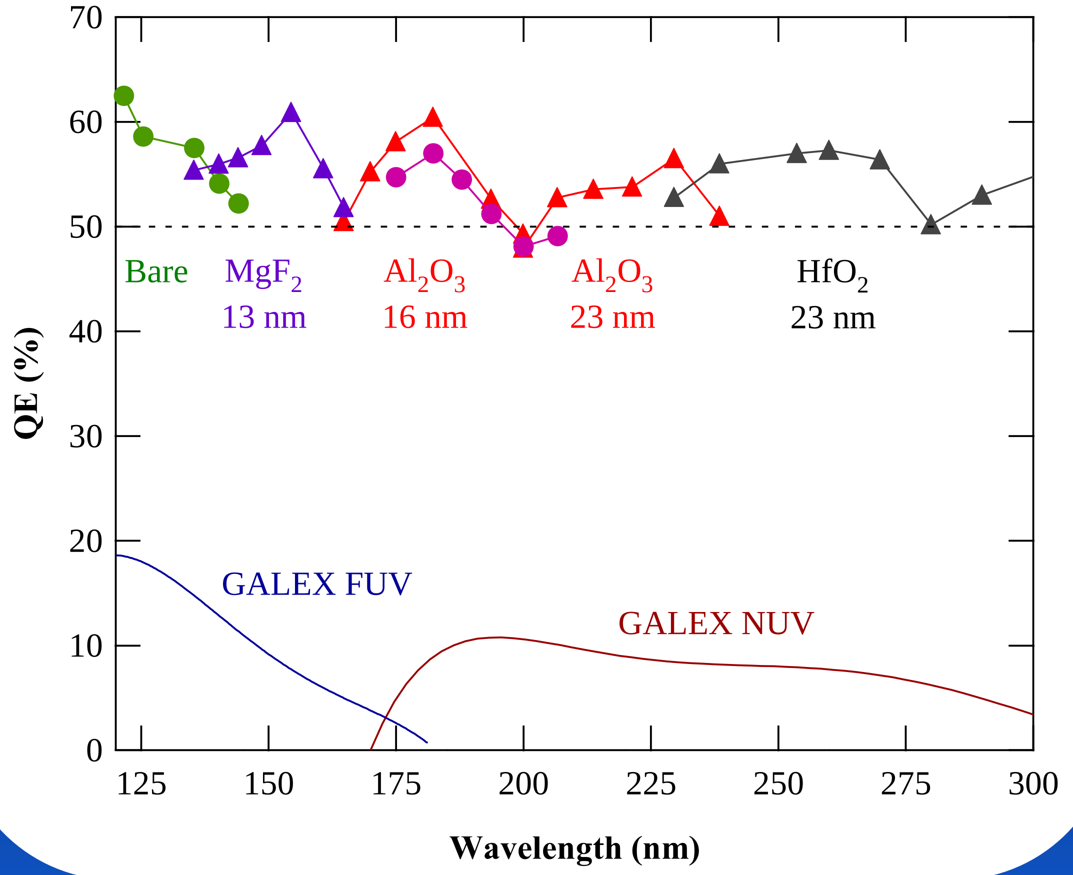
Hoenk et al., *Applied Physics Letters*, **61**: 1084 (1992)

100% Internal QE with Delta doping through Atomically Precise Interface Engineering



- 100% internal quantum efficiency, uniform, and stable (QY has been removed so maximum QE is 100%).
- Extreme UV measurements were made at SSRL
- Compatible with AR and filter coating: response can be tailored for different regions of the spectrum

> 50% External Quantum Efficiency Achieved in UV



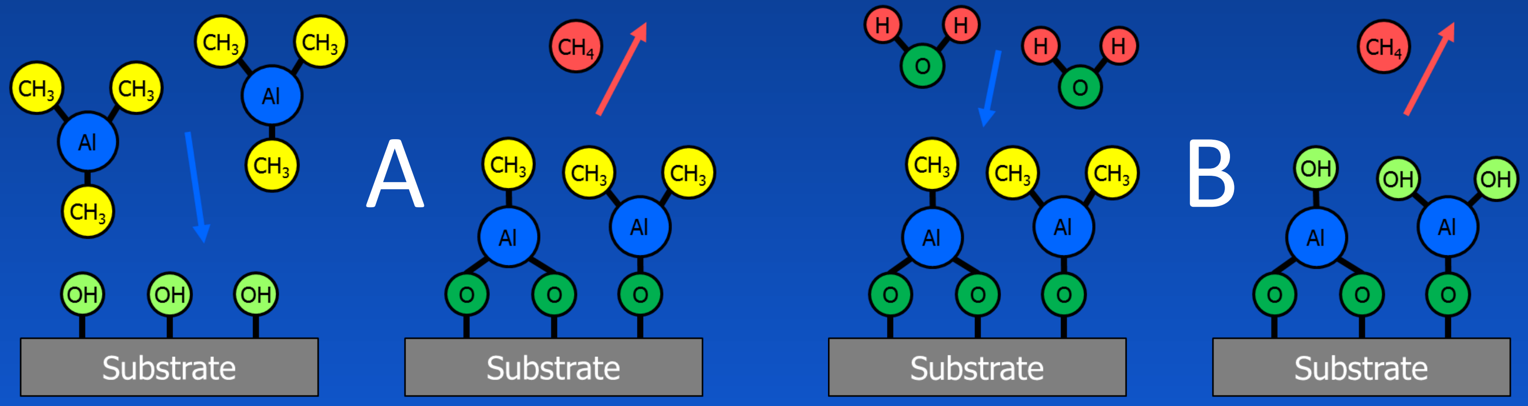
Delta doping & Atomic Layer Deposition of standard CCDs & EMCCDs

Nikzad, et al. Applied Optics, 2012

High External QE with Atomic Layer Deposition through Atomically Precise Interface Engineering

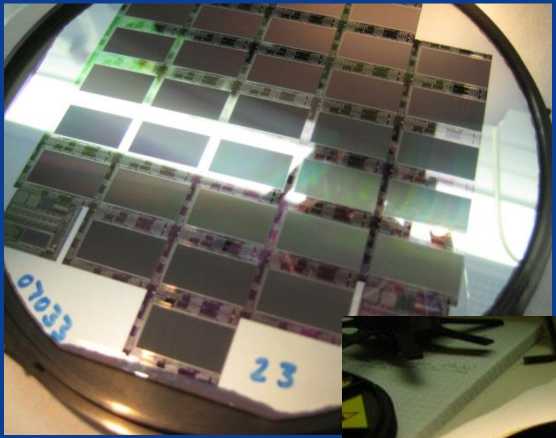
<u>What is ALD?</u>

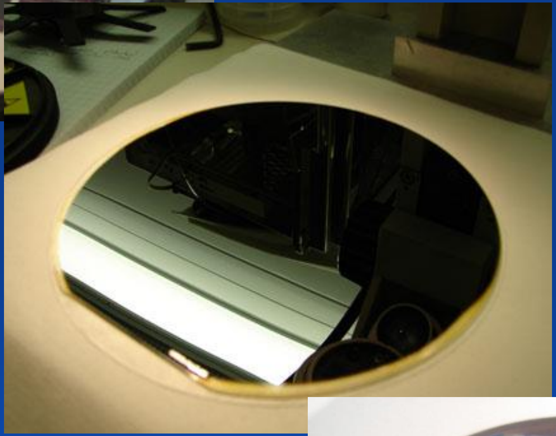
- Surface reaction mediated deposition
- ALD cycles are repeated until desired film thickness is achieved
- Metals, Nitrides, and Oxides are achieved through choice of precursor and reactant species
- Can achieve thin film deposition or surface modifications at near room temperature
- Results in smooth, stoichiometric, thin layers.
- Abrupt interfaces and precision control makes ALD perfectly suitable for multilayer coatings

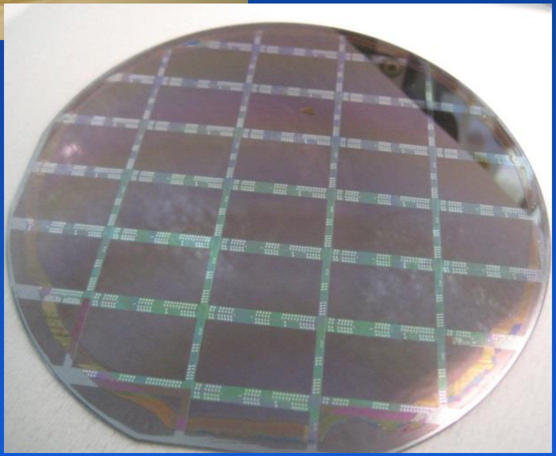


Cycle Repeats to Grow Additional Monolayers

Wafer-Scale Processes

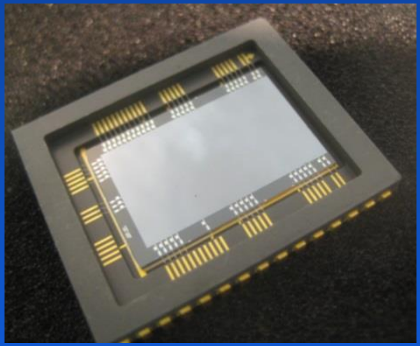




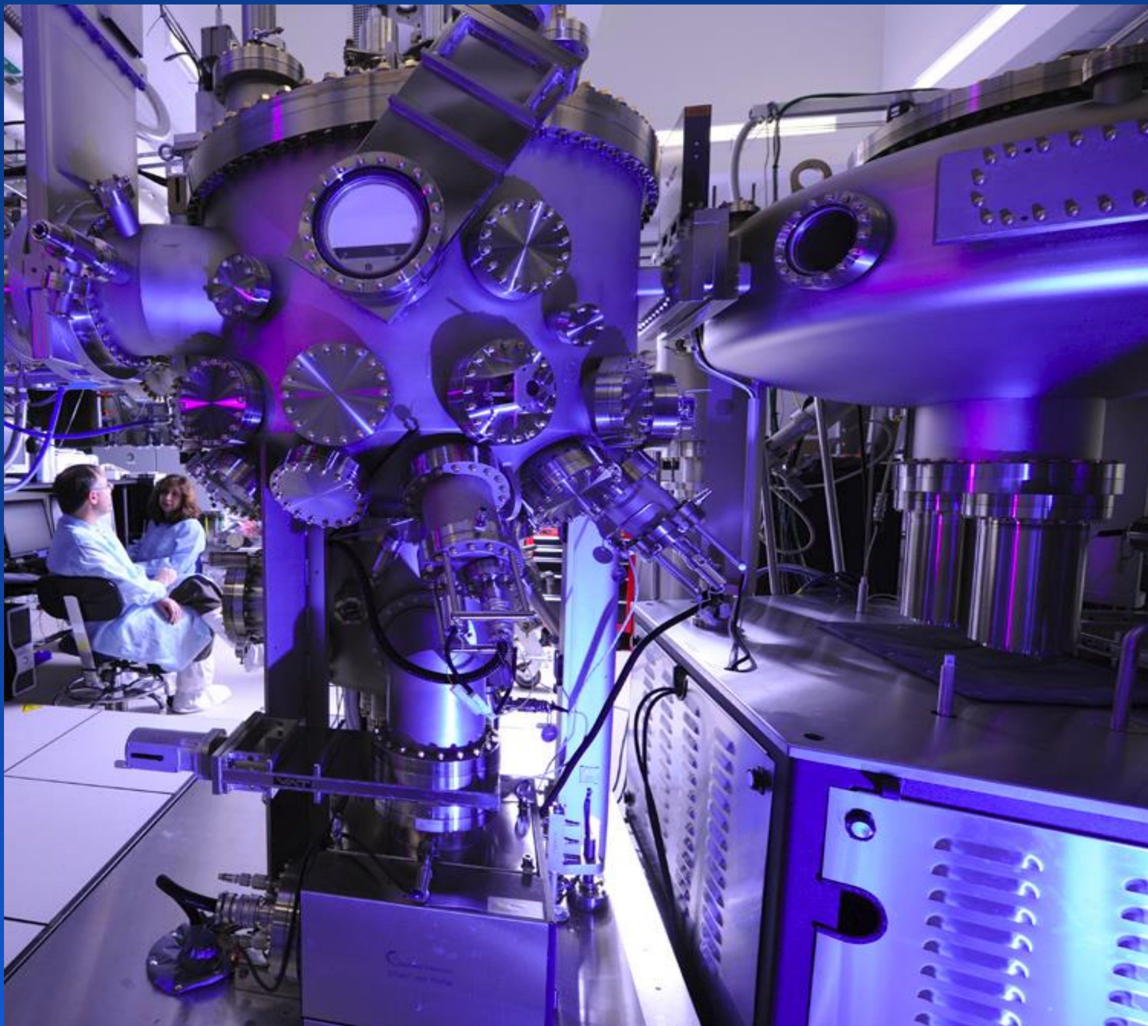


Process steps…

- Wafer-wafer bonding
- Thinning
- MBE growth
- ALD coating
- Patterning
- Etching
- Dicing
- Packaging



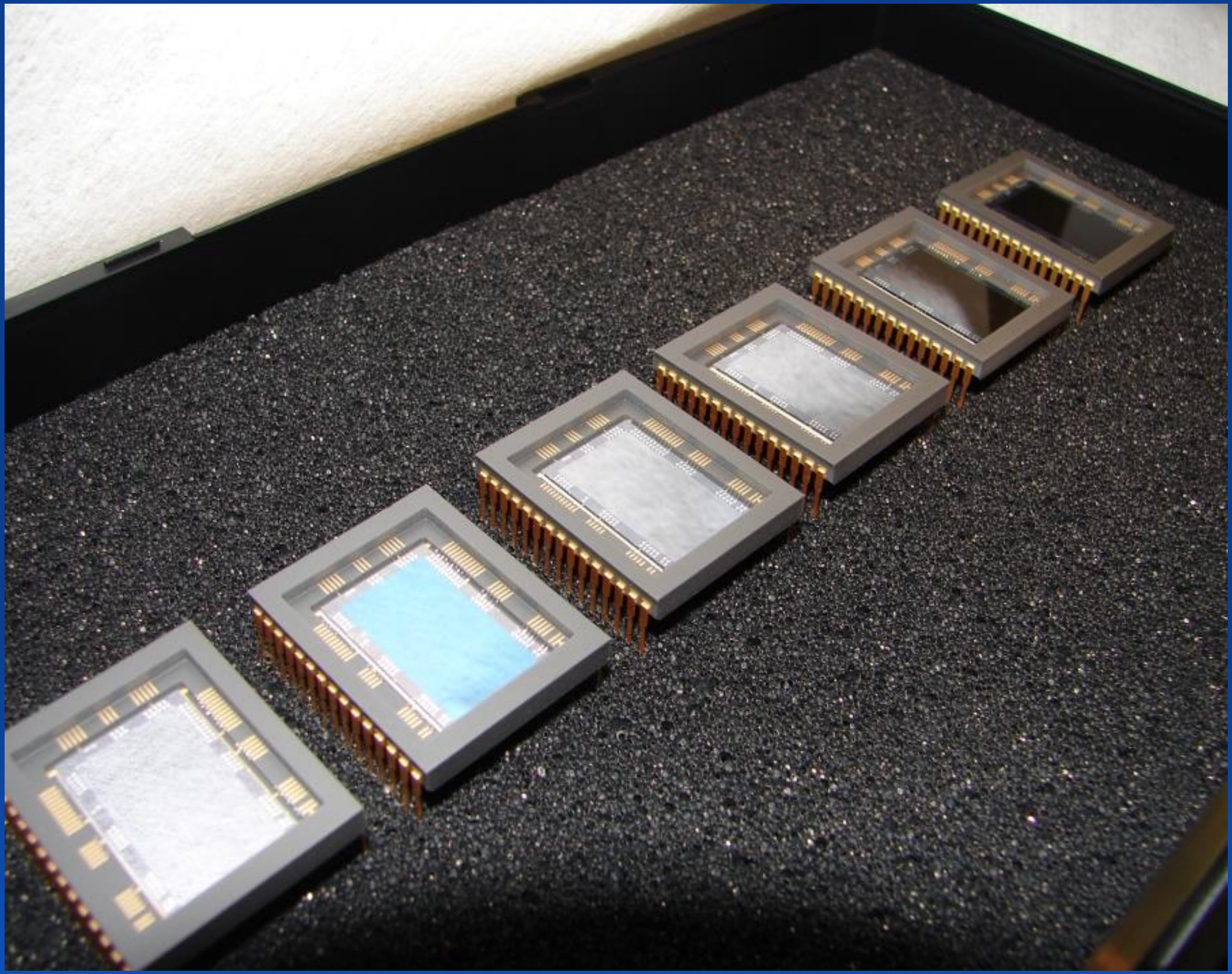
8-inch Wafer Silicon Molecular Beam Epitaxy (MBE)



High throughput, high yield processing of high performance detectors

Delta doping up to 8-inch diameter wafers

Batch processing multiple wafers



Six R-grade e2v CCD97's from the bonded, thinned, delta-doped wafer 18 have been packaged, wire-bonded and are being tested. One is AR coated with the FIREBALL multilayer design

FIREBall-2

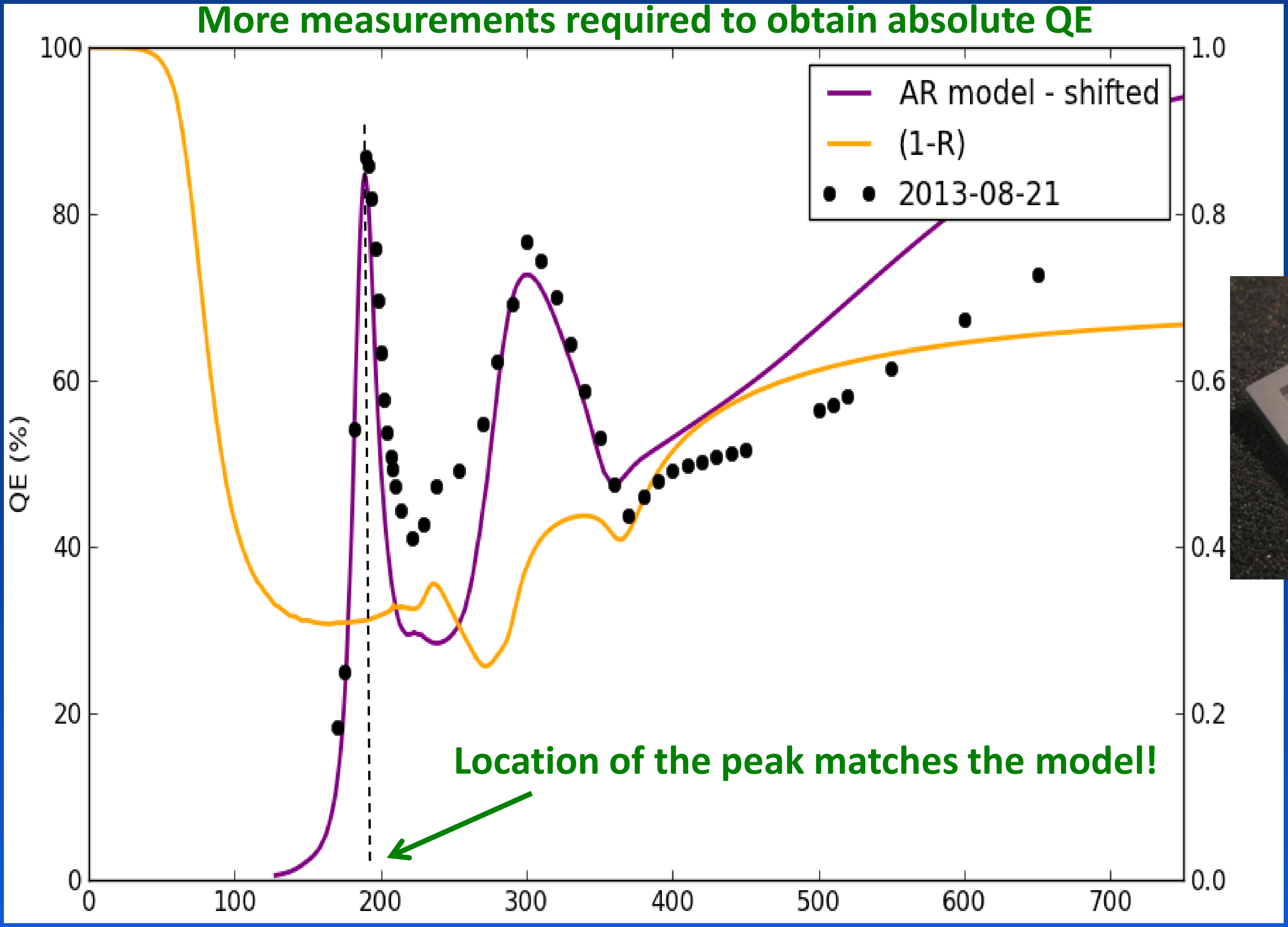
Funded balloon under ROSES-APRA
PI: Chris Martin

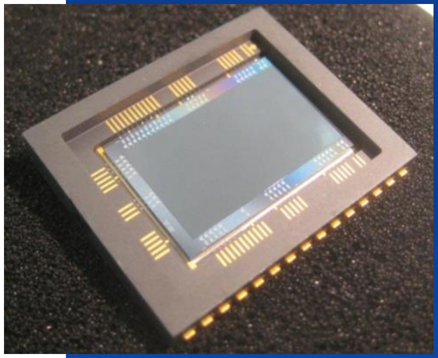
Detector range: 195-205 nm, 200 nm center requires QE > 50%

FIREBall-1 flew a GALEX spare detector which was an MCP.

Collaboration also with David Schiminovich, Erika Hamden, Columbia U
Alice Reinheimer, Peter Pool, P. Fochi, et al e2v

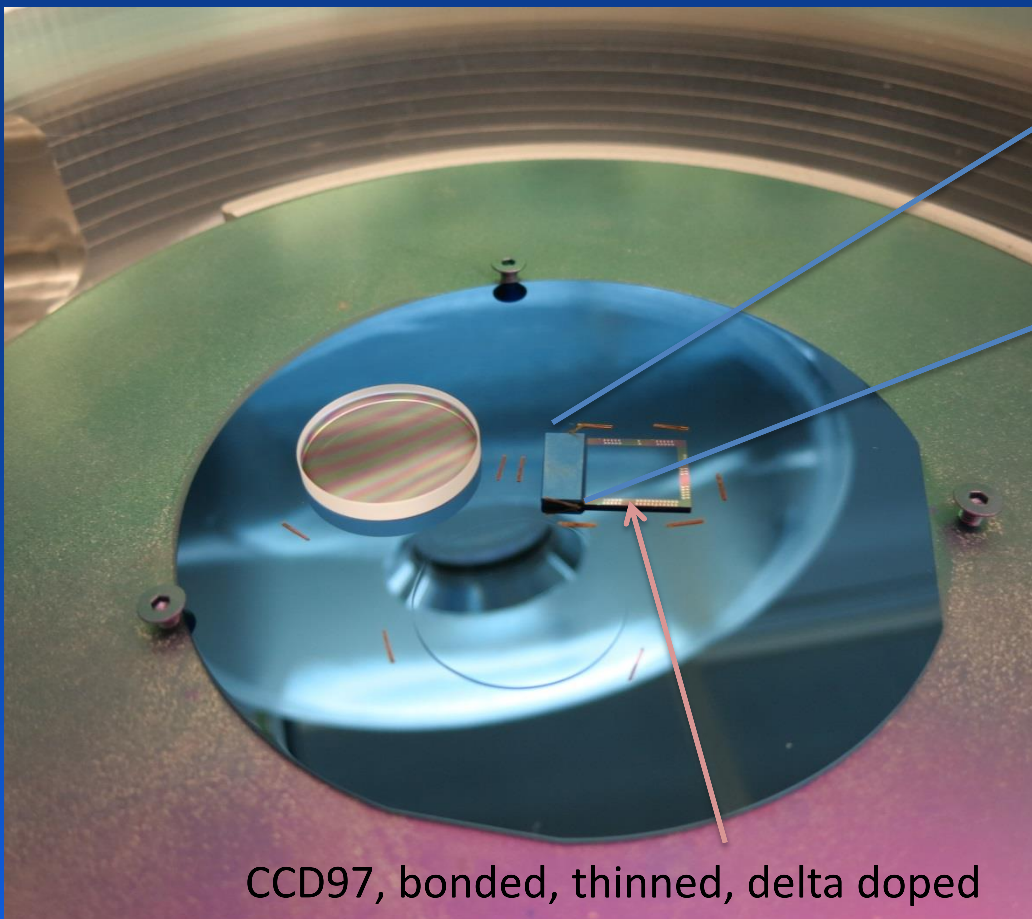
Preliminary QE Results on AR Coated (5-Layer), Delta Doped EMCCD

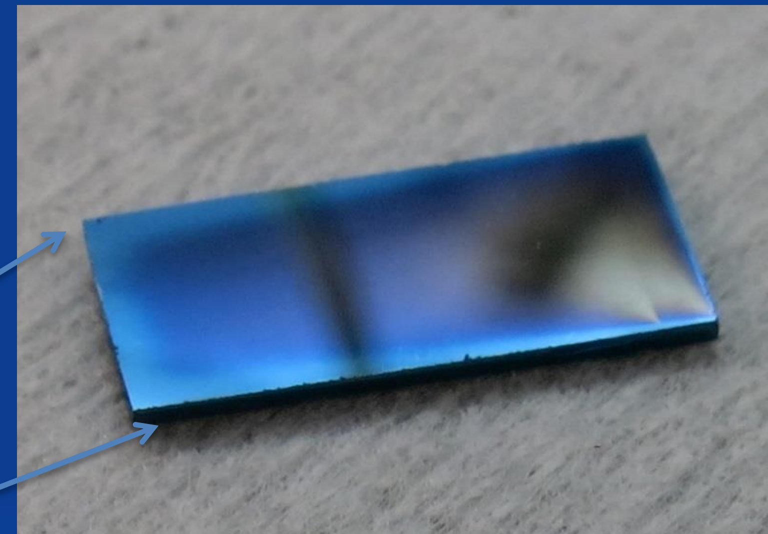




ALD AR coatings, using CCD97

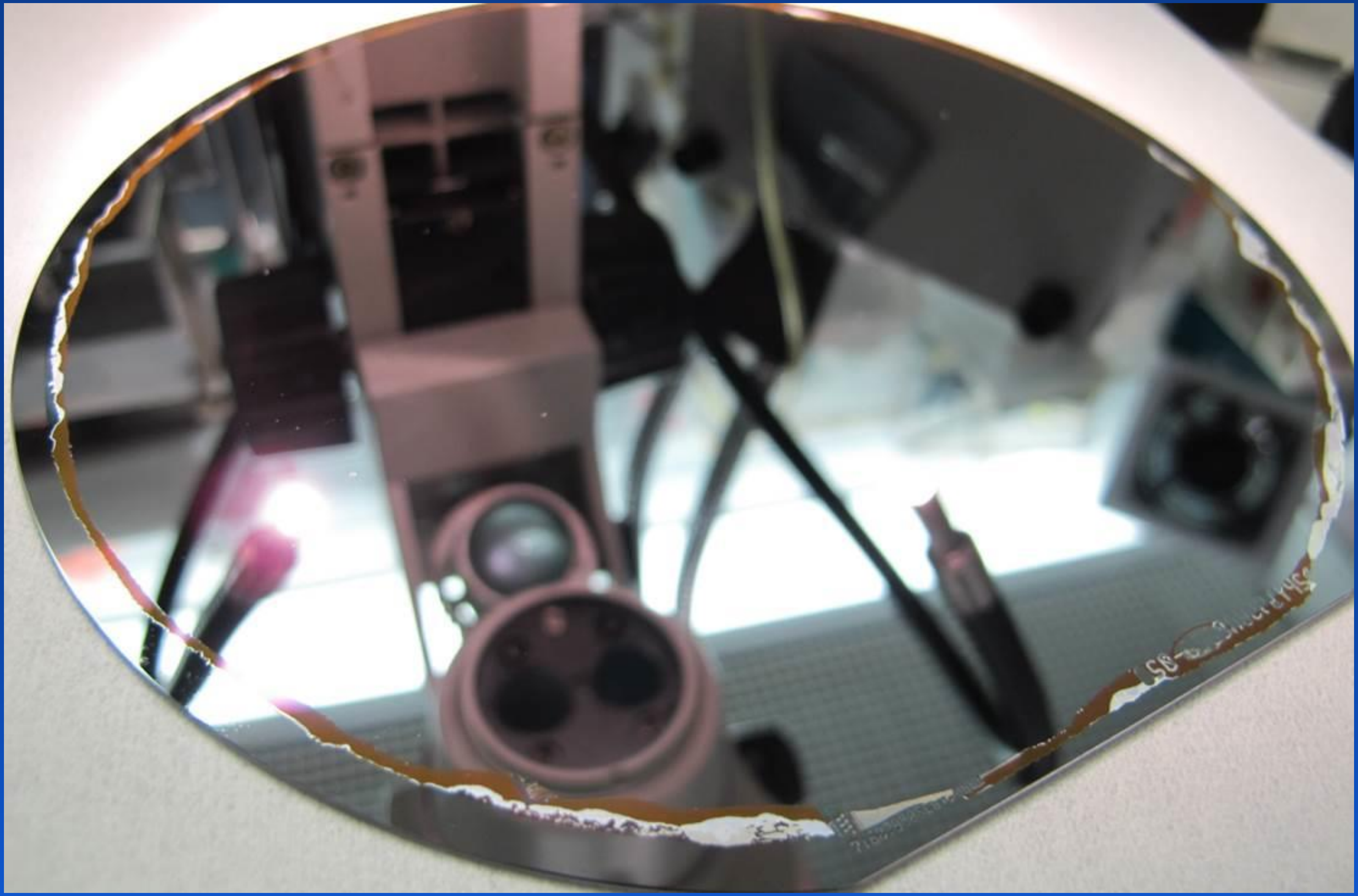
New ALD system greatly improves multilayer throughput





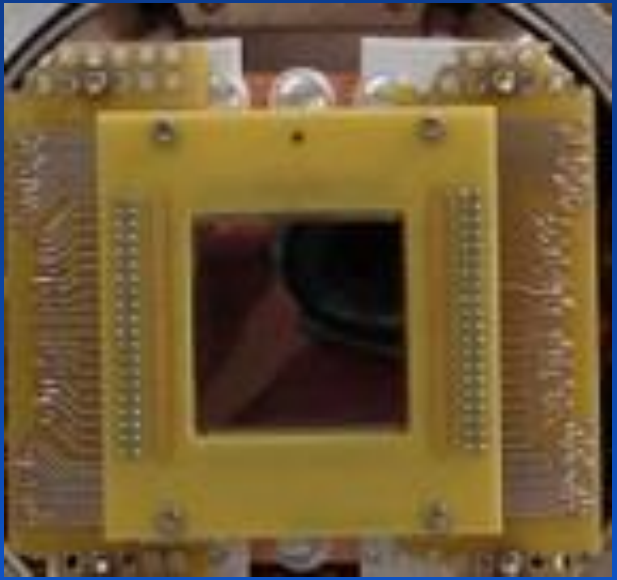
Shadow mask

CCD201, bonded and thinned

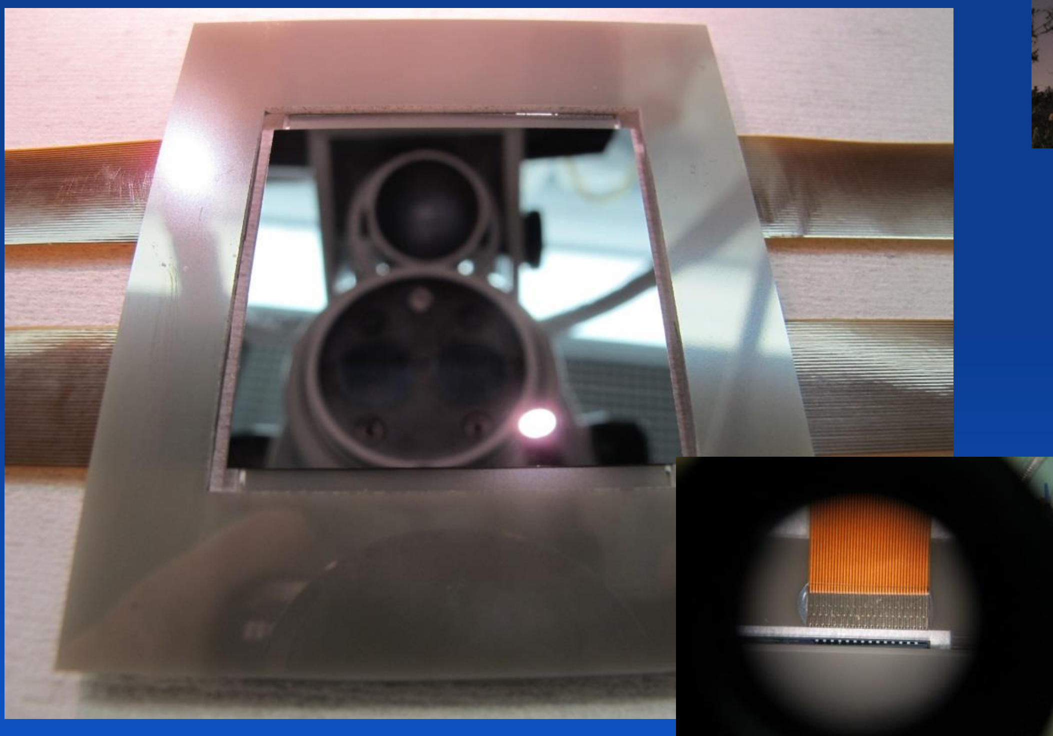


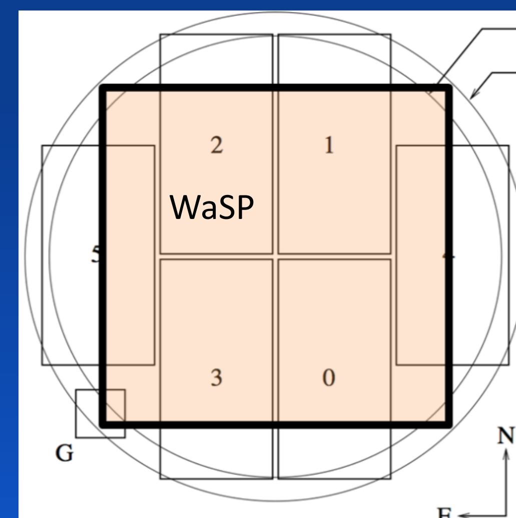
Far UV Rocket

CHESS (sounding rocket, PI:Kevin France, Matt Beasley *CU)
Collaboration with Paul Scowen, Todd Veach*, Alex Miller, ASU
FUV, 3.5kx3.5k (100 – 160 nm) delivered to CHESS



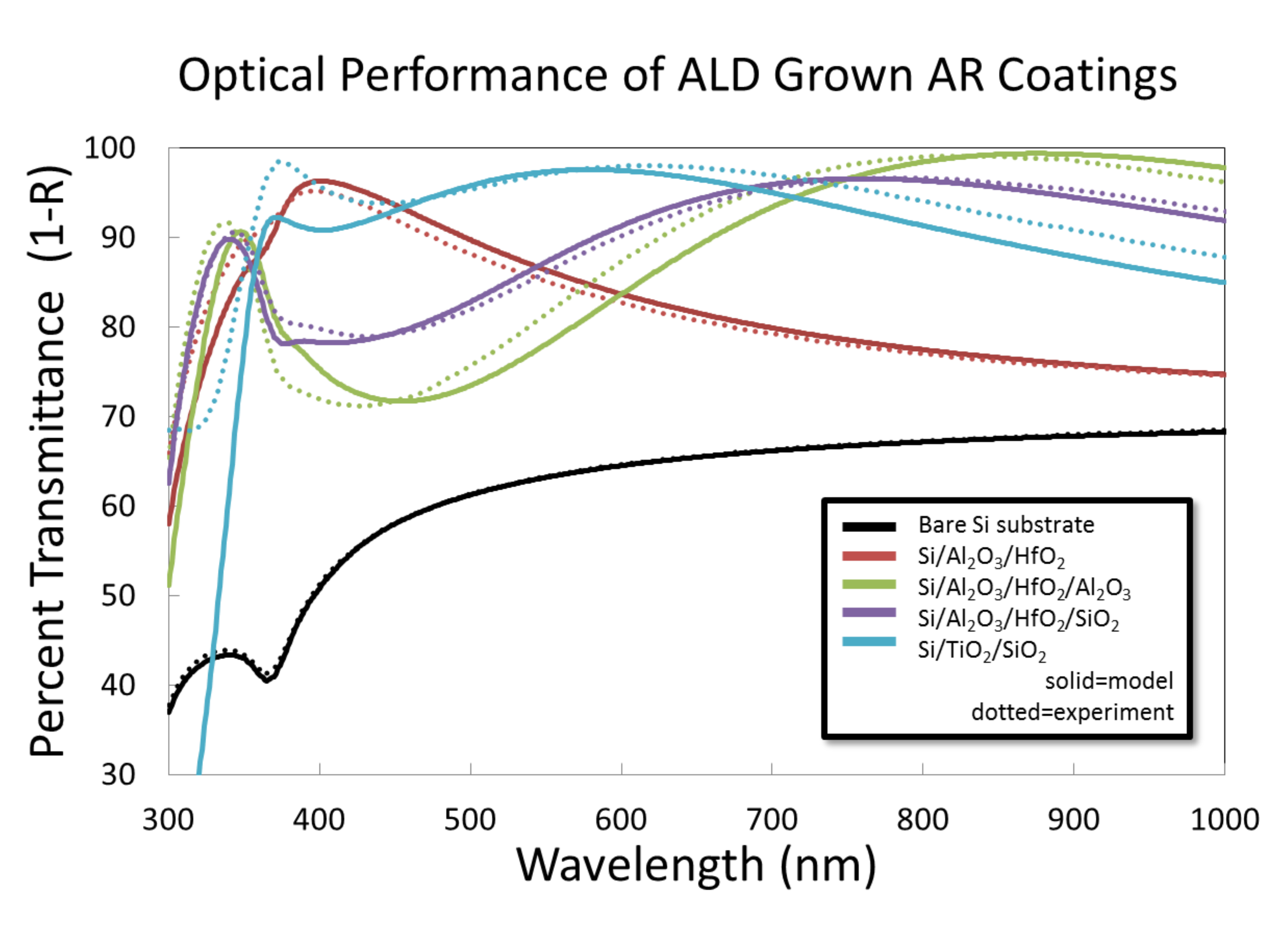
Delta-doped, AR coated fully depleted 2kx2k STA devices for WaSP guide and focus CCDs (320 – 1000 nm)





Photographs of an STA 3600 imager diced from a delta doped 200 micron wafer. It has been flattened against AlN and mounted in a AlN frame prior to wire bonding to flex.

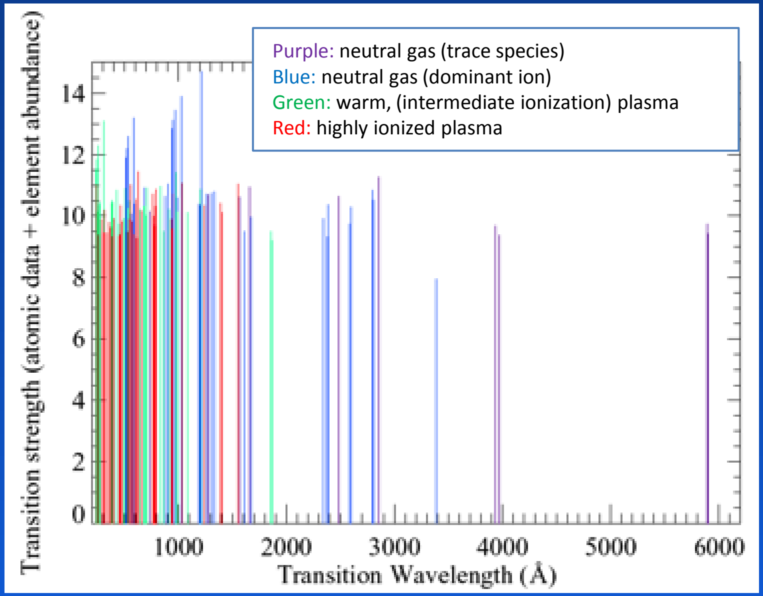
New packaging to accommodate WaSP requirements are under development


Optical Performance of ALD Grown AR Coatings
Percent Transmittance (1-R)
100
90
80
70
60
50
40
30
300
400
500
600
700
800
900
1000
Wavelength (nm)
Bare Si substrate
Si/Al2O3/HfO2
Si/Al2O3/HfO2/Al2O3
Si/Al2O3/HfO2/SiO2
Si/TiO2/SiO2
solid=model
dotted=experiment

Reflective Coatings for Astrophysics & Planetary Applications

PI: Kevin France
CU - CASA

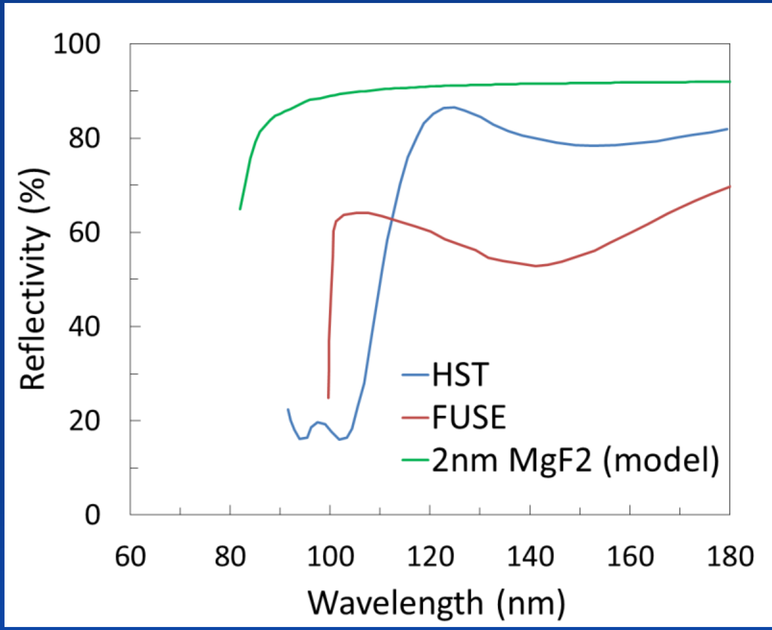
- Reflective coatings determine the mission architecture for any UV mission (FUSE, HST/COS, etc.)
- FUV has a significant number of spectral lines that are of great interest to astronomers



Credit: T.A. Rector and B.A. Wolpa, NOAO, AURA, and NSF.

Benefits to Improved Mirror Coatings

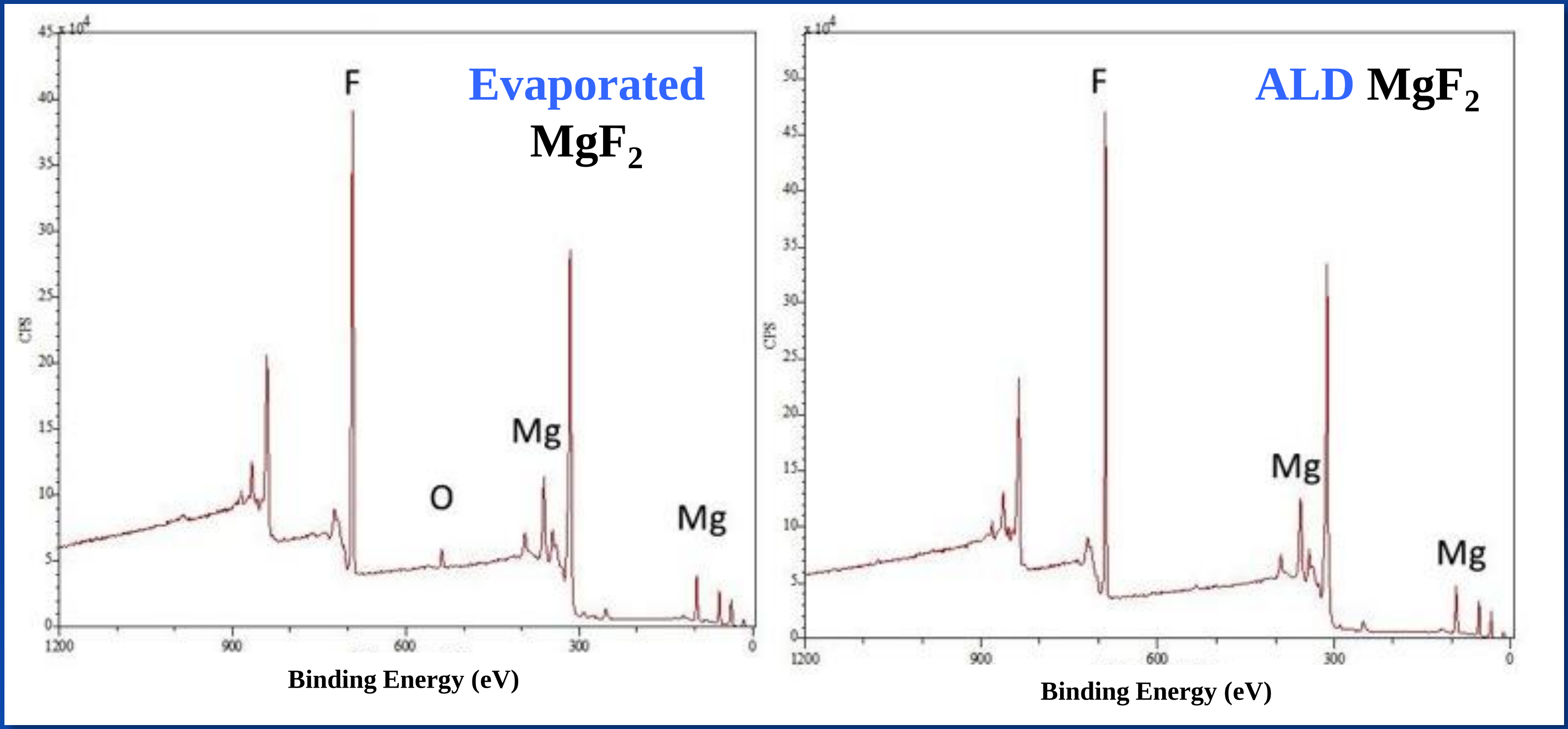
- Aluminum mirrors require protective coatings (*i.e.* LiF or thick MgF_2) to prevent oxidation which would otherwise destroy reflectivity in the FUV
- Coatings also important in optical wavelengths as they affect polarization
- By using very thin, but high quality, MgF_2, both issues can be addressed simultaneously.
  - Very thin coatings minimize impact on polarization of incident light
  - Thin films of MgF_2 (1-2 nm) enable higher reflectivity (due to lower absorption losses) than LiF or thick MgF_2



	Size
FUSE	~6 m
FUSE w/ improved coatings	~3 m

Collaboration with K. France, M. Beasley (CU) F. Greer* (JPL)*

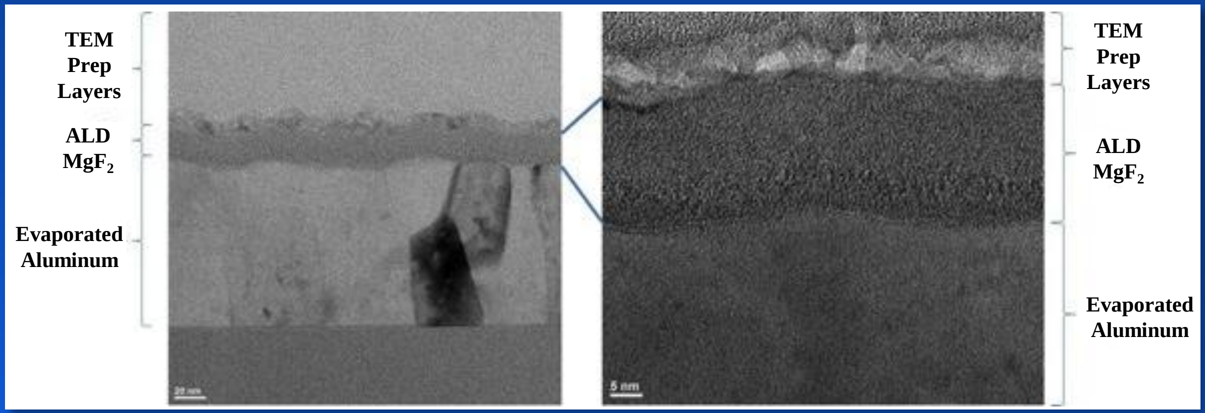
XPS Characterization of ALD MgF_2



ALD MgF_2 yields similar film stoichiometry to a thermally evaporated film, but with higher resistance to oxidation after air exposure.

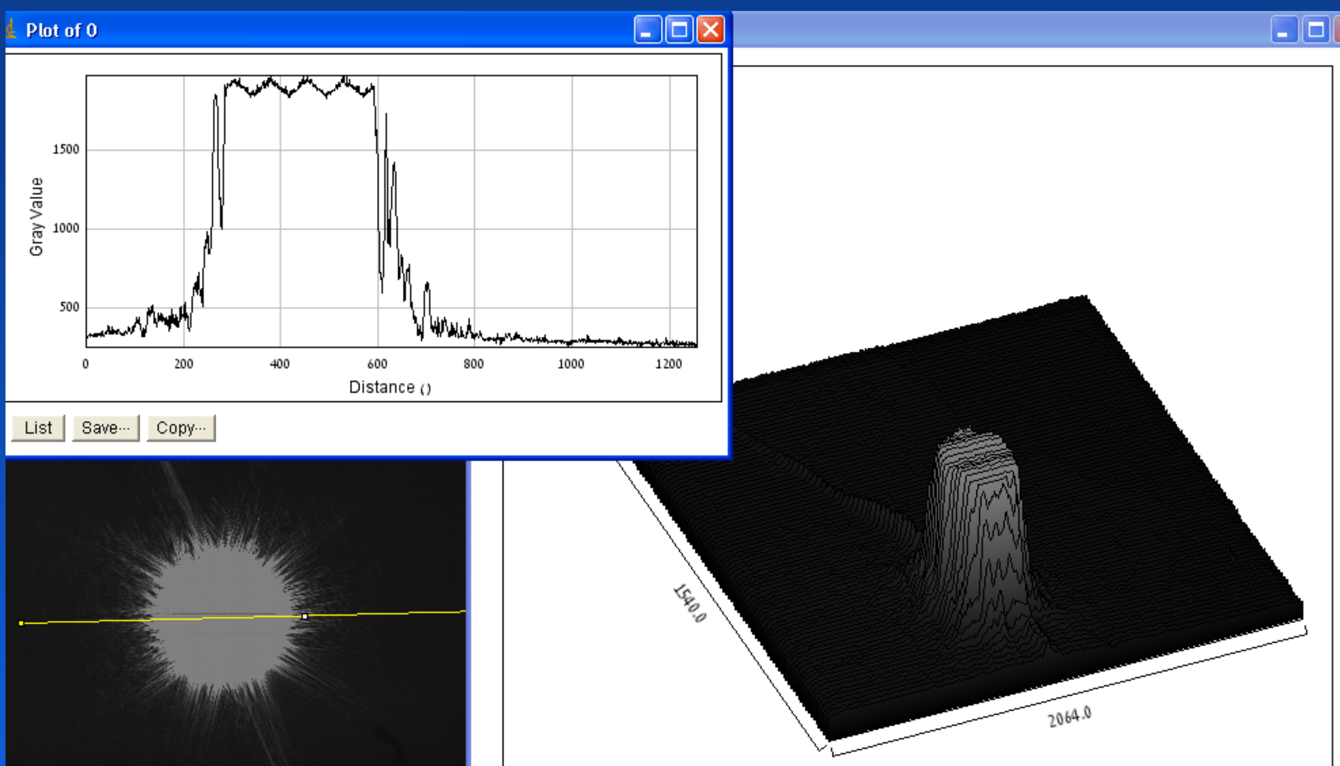
ALD MgF_2 - Performance

- Took simplified approach to mirror coating problem initially to look at just the performance of ALD MgF_2 itself
  - No complications of ALD Al nucleation and cross-contamination of the films in same chamber
  - Ellipsometry data satisfactory down to 190 nm
- ALD MgF_2 is amorphous as deposited at 250˚C.
  - Surprising, but extremely good result for application as protective layer



Breakthrough Results in Deep UV with Alacron/Fastvision

PI: Michael Hoenk. “Superlattice-doped”, new design, Hoenk (US patent)
3 Mpxl CMOS, low noise, 150 frames/ second, 8” wafers.
Demonstrated unprecedented stability. 500x saturation exposure to Excimer laser (2 billion high energy pulses of the laser hitting the device!!).
Called a breakthrough by industry!!



Summary

- Atomic scale surface engineering through MBE and ALD enable high efficiency, stable response in detectors

- Wafer scale and batch detector processing enable high throughput, high yield compatible with mission delivery time scale and cost

- Delivery to FIREBall, CHESS, WaSP progress

- Optical coatings using ALD under development. Characterization of ALD MgF_2 underway