Lecture – Southern California Chapter of the American Vacuum Society

Thin Film Filters and Coatings for UV Astronomy, Astrophysics, and Planetary Science

Presented by: Dr. April D. Jewell

July 21, 2020

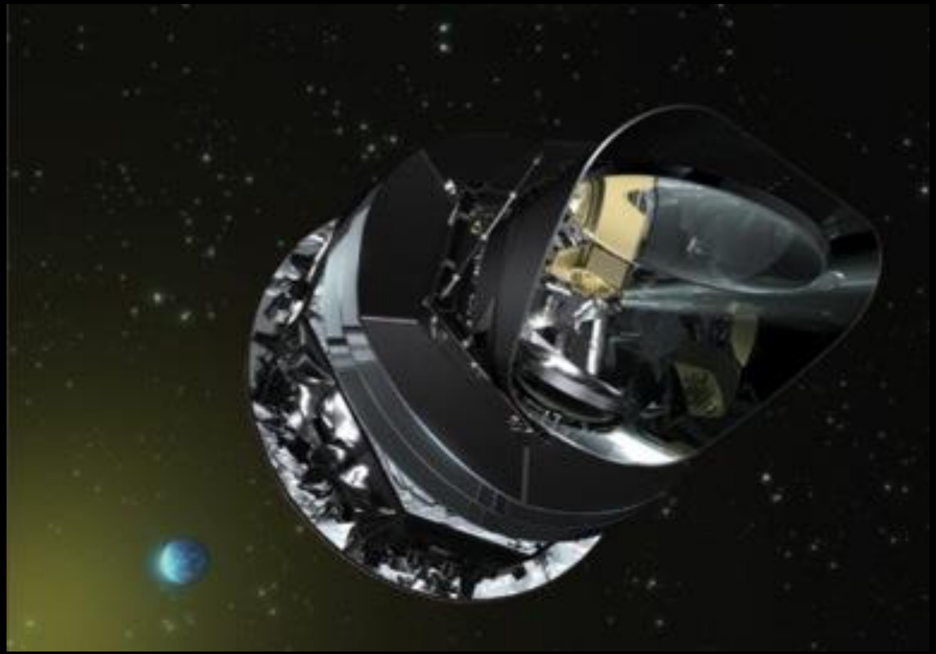
Jet Propulsion Laboratory
California Institute of Technology

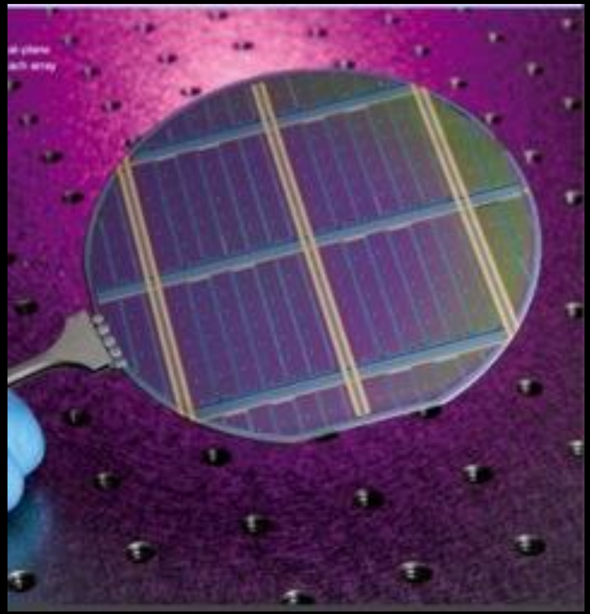
Jet Propulsion Laboratory

- Founded in 1936 as a graduate student project under Prof. Von Karman (Caltech)
- Transferred to NASA upon its creation in 1958
- JPL is 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
  - Defense programs and civilian programs of national importance compatible with JPL capabilities

NASA/JPL Mission Concept and Technology Development

- 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) – Curiosity
    - Goal: Examine the habitability of Mars
  - Hubble Space Telescope/Kepler/GALEX
    - Goal: Understand how stars, planets, galaxies, and the universe formed





Microdevices Laboratory (MDL)

- MDL invents and develops a broad spectrum of unique flight-worthy micro-devices that enable a wide variety of instruments and missions across the full range of JPL's activities in earth science, planetary exploration, and astrophysics and cosmology
- Core Competencies include:
    - UV-Visible Detectors + Systems
    - Mid-IR Detectors
    - Sub-mm Devices
    - Superconducting Devices
    - Semiconductor Lasers
    - Diffractive Optics
    - …

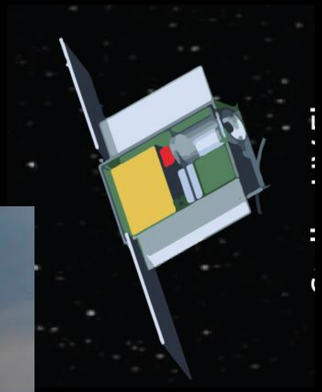
https://microdevices.jpl.nasa.gov/

Advanced Detectors, Systems, and Nanoscience
Overall Objective of Group/Team

Develop UV/Vis/NIR detectors, technologies, and systems focused on the needs of NASA (and NASA partners') missions and instruments

Suborbital Balloons

Sounding Rockets



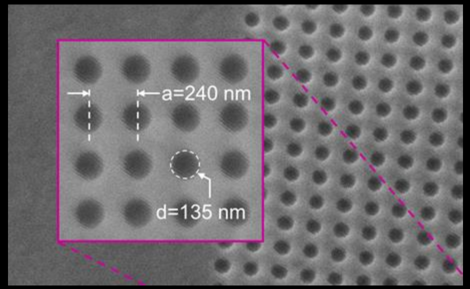
CubeSats & SmallSats

New Frontiers and Discovery Missions

Large Strategic Science Missions (Flagships)

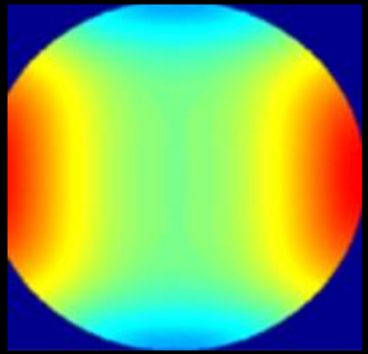
Develop detectors and systems to stay at the cutting edge and in response to non-NASA sponsors and to national needs

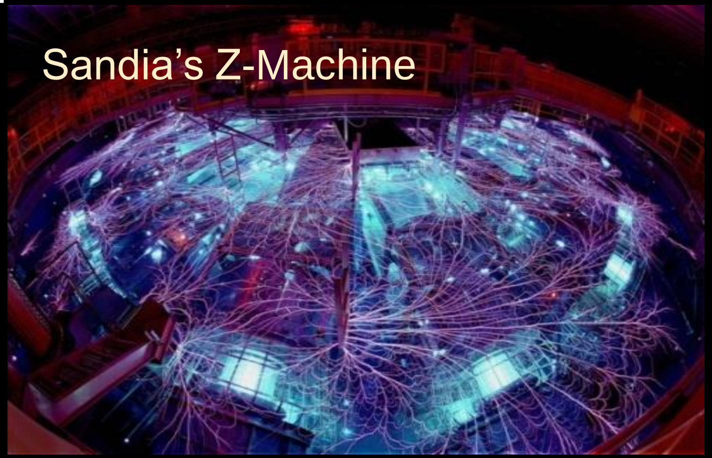
Metamaterials



Medical & Diagnostic Imaging

Semiconductor Fab/Wafer Inspection

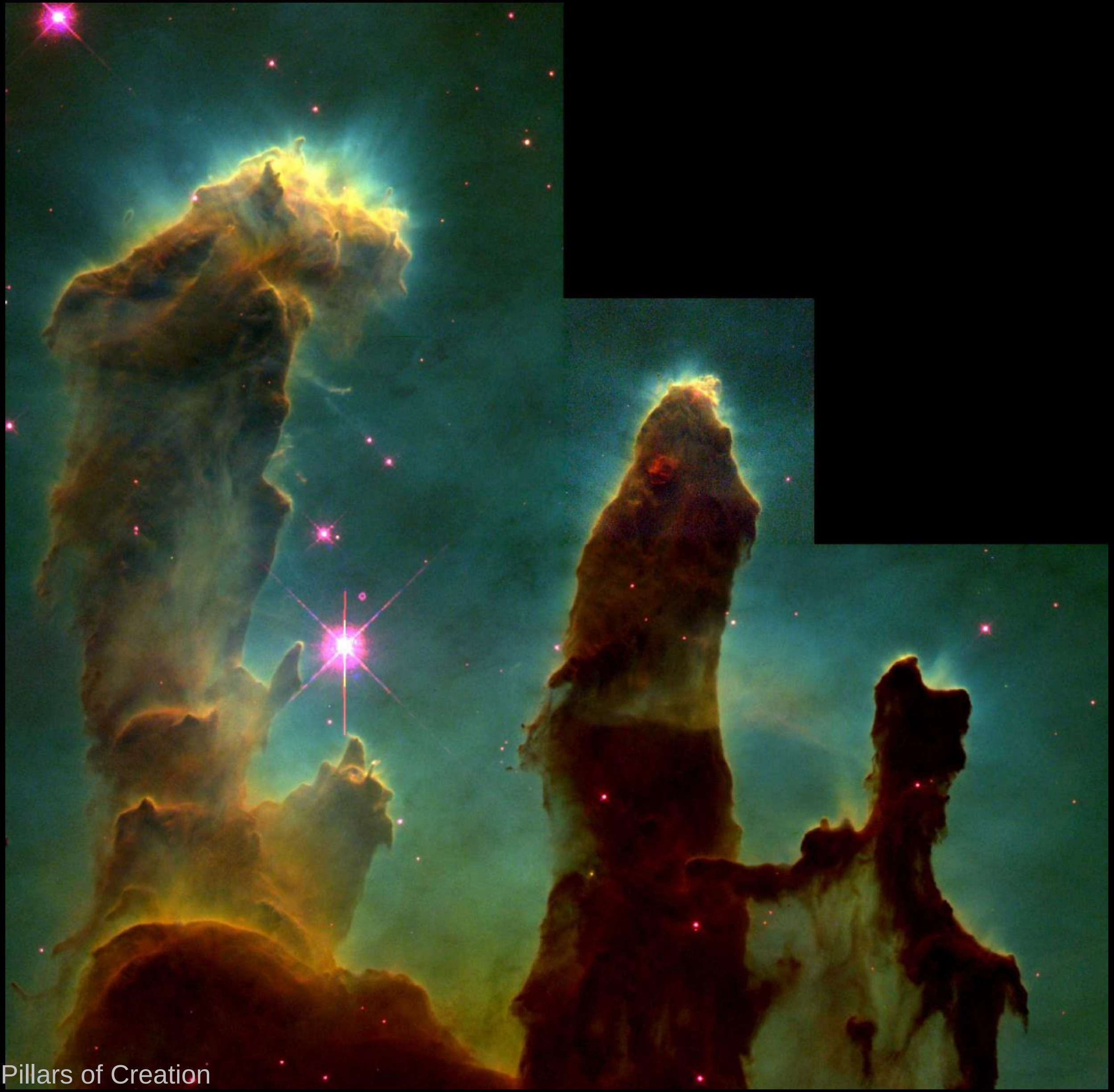




High Energy Physics

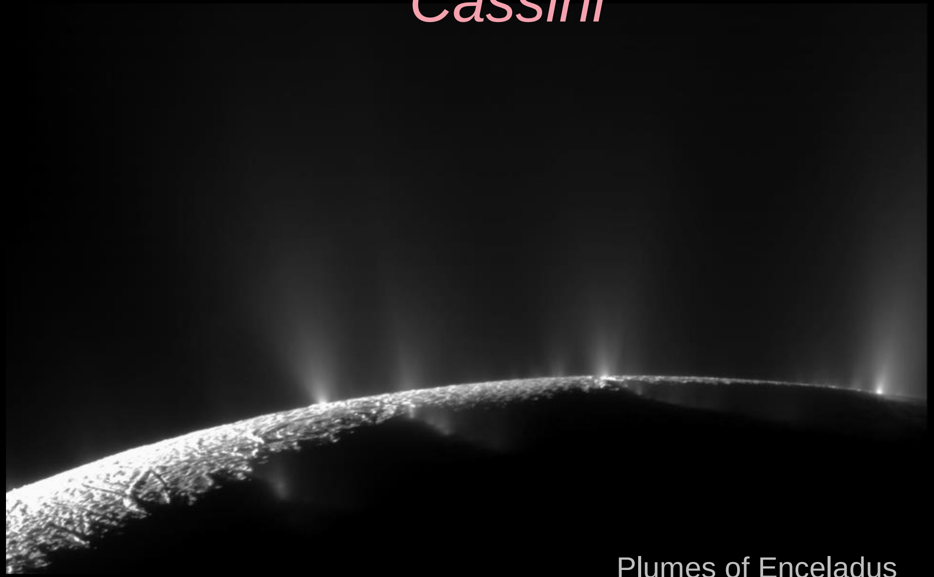
Silicon Detectors for Astronomy, Astrophysics & Planetary Science

Hubble Space Telescope



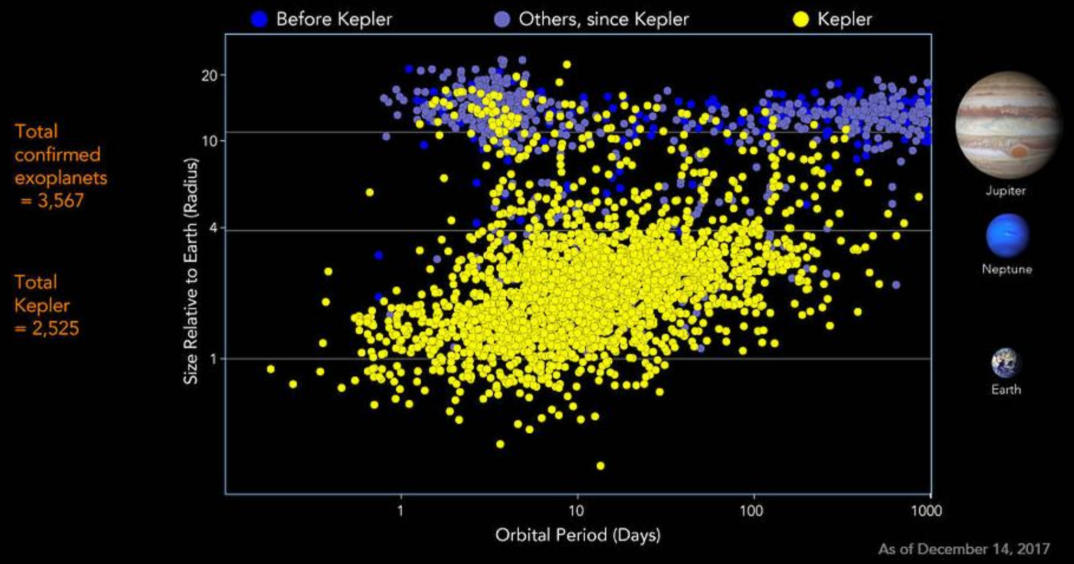
Pillars of Creation

Cassini

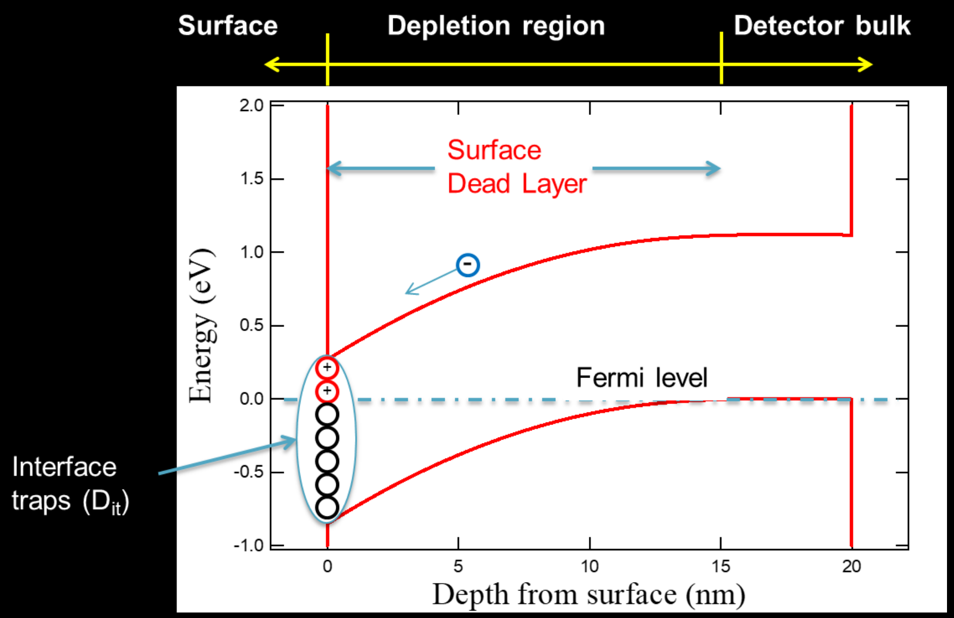


Plumes of Enceladus

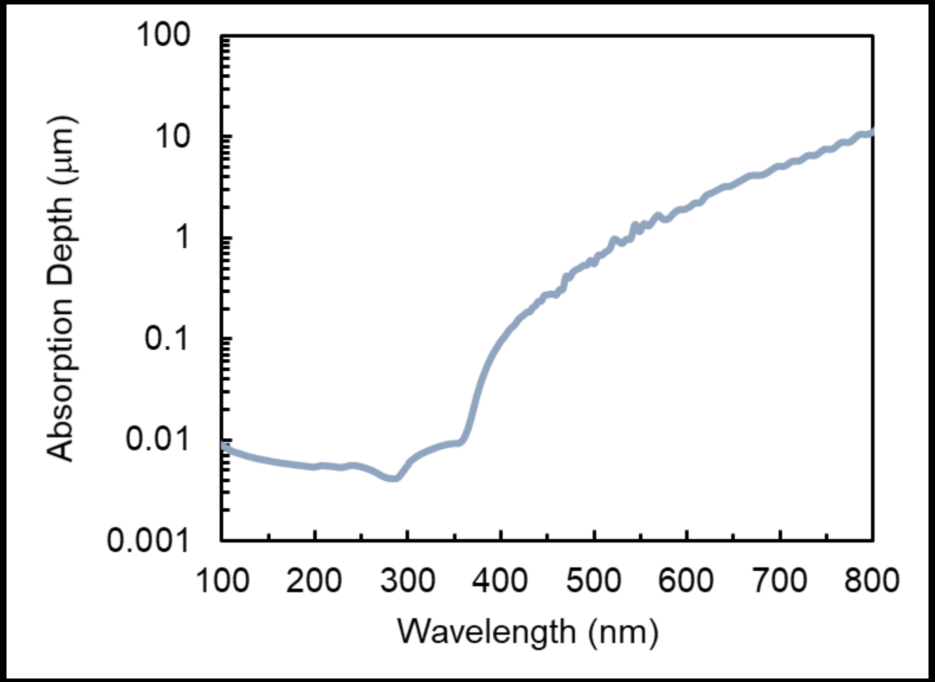
Kepler Space Telescope

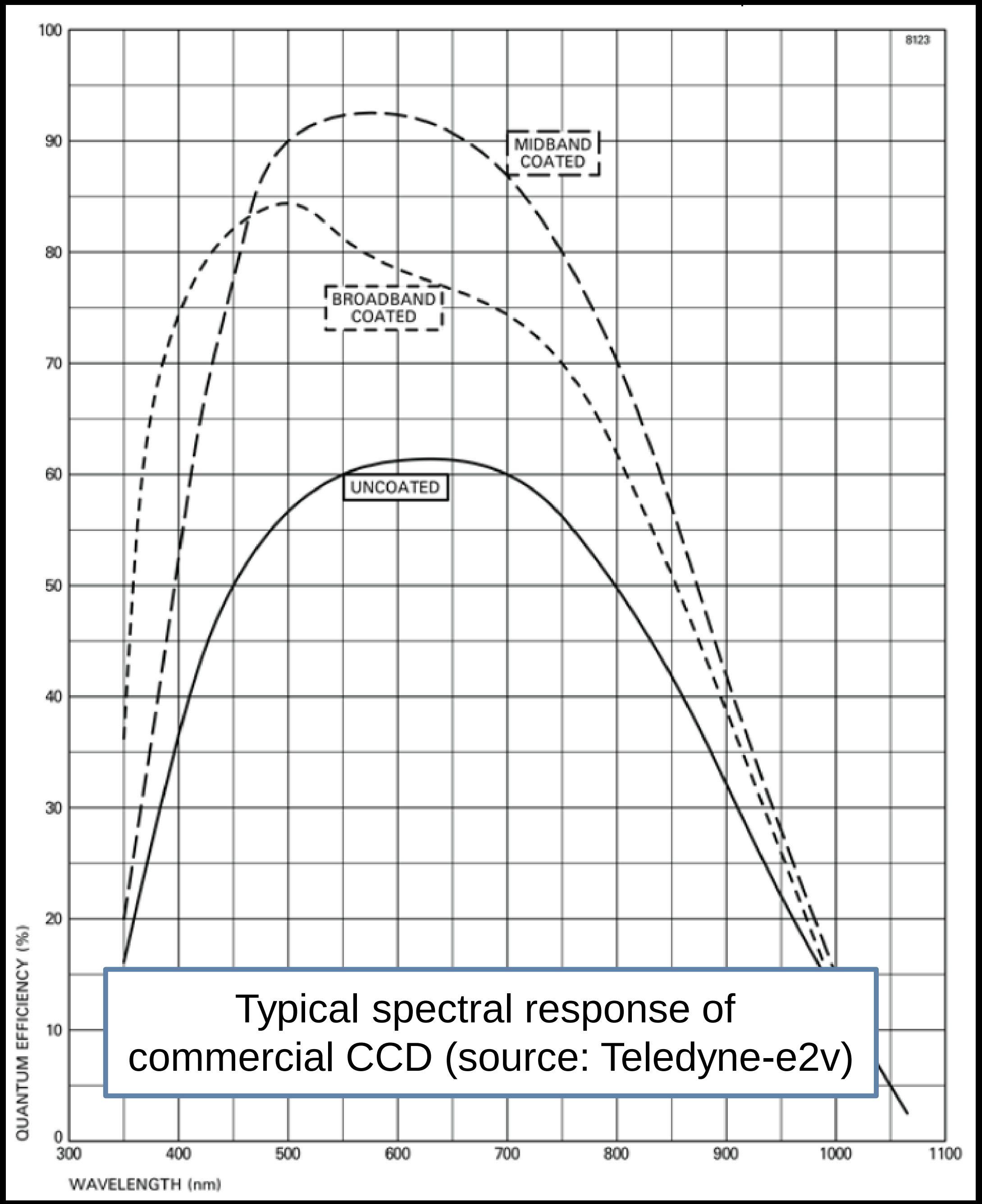


The Surface/Interface Problem – Dead Layer



Hoenk et al., *APL*, **61** (1992) 1084





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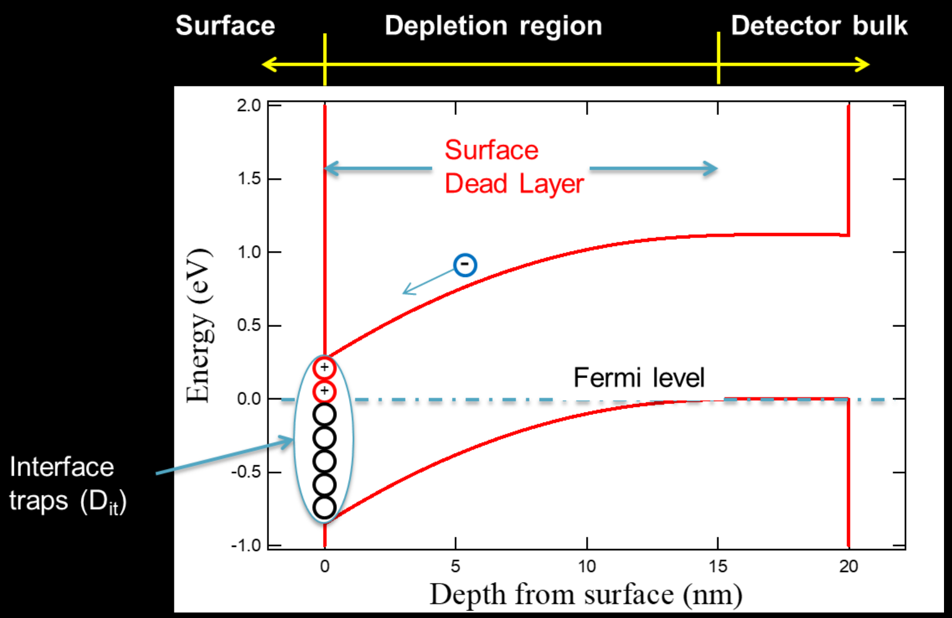
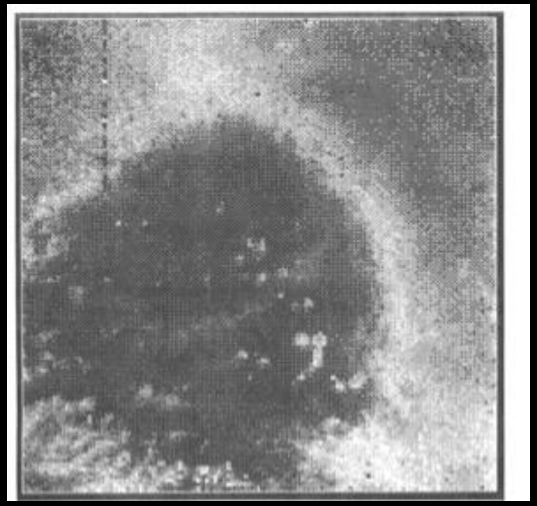
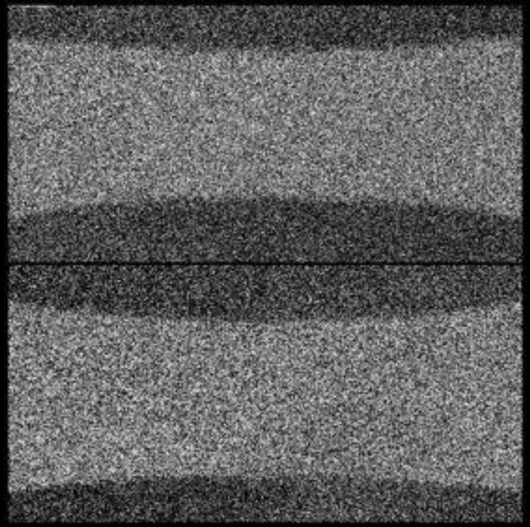


Hoenk et al., *APL*, **61** (1992) 1084

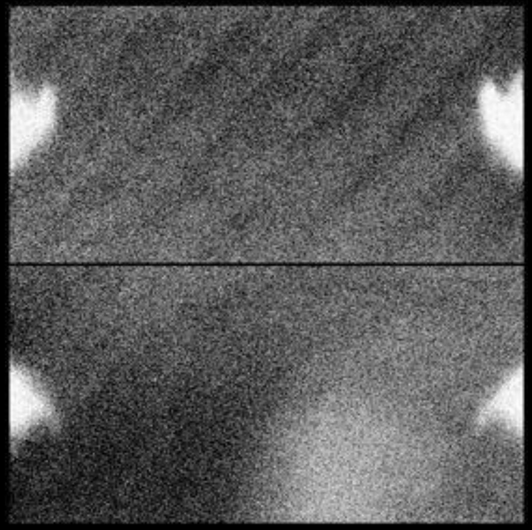
Surface Charging; QE Hysteresis



WF/PC 1



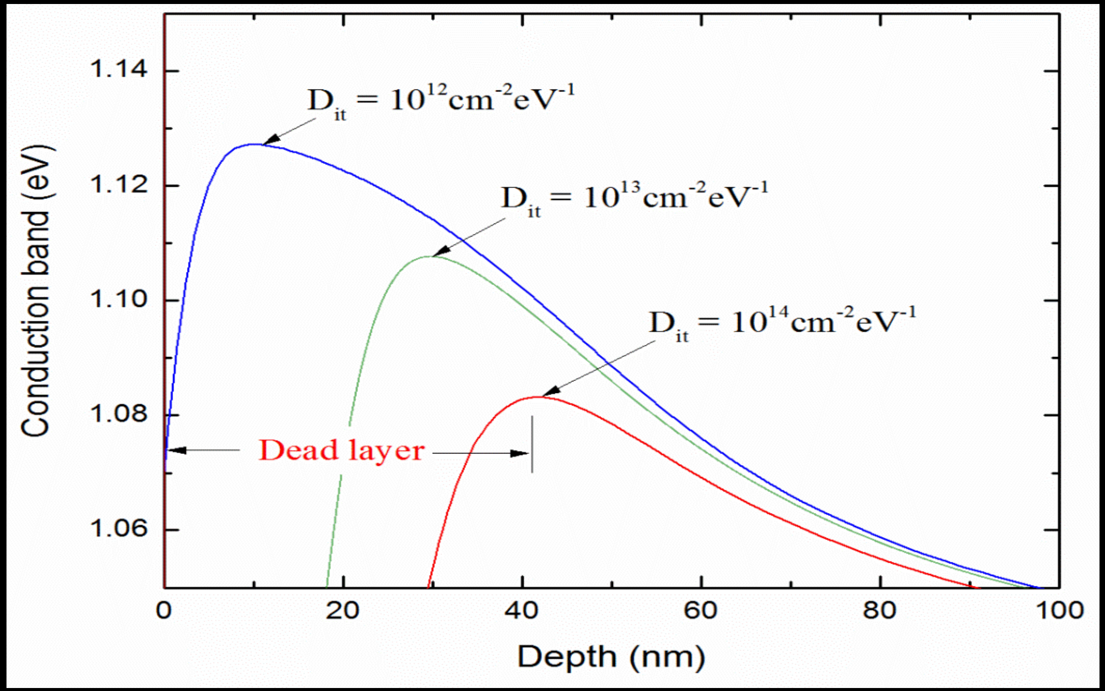
WFC3



WFC3

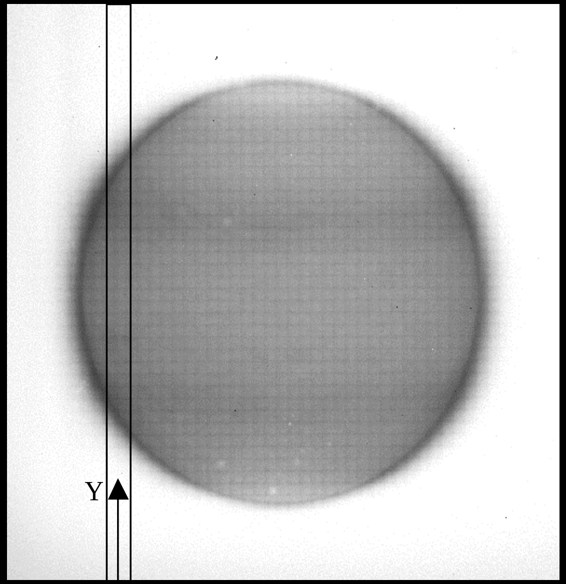
Wong, *Inst. Sci. Rep. WFC3, 2009-07*

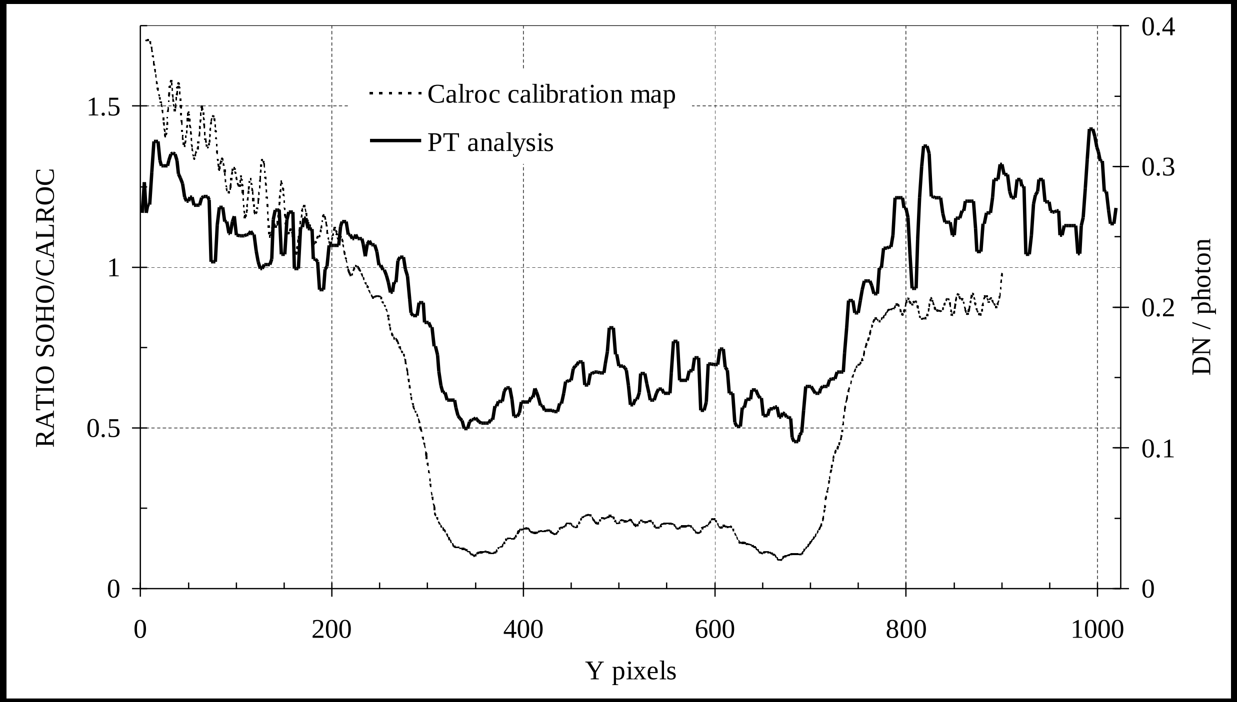
Surface/Interface Damage



Hoenk et al., *Proc. SPIE*, **9154** (2014) 13

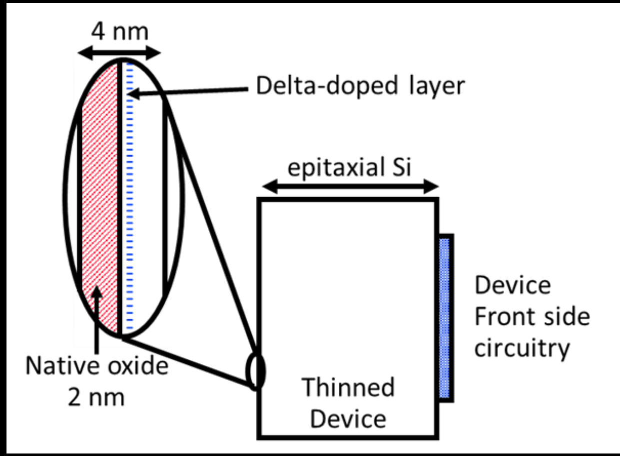
ESA's Solar & Heliospheric Observatory (SOHO) Extreme UV Imaging Telescope (EIT)

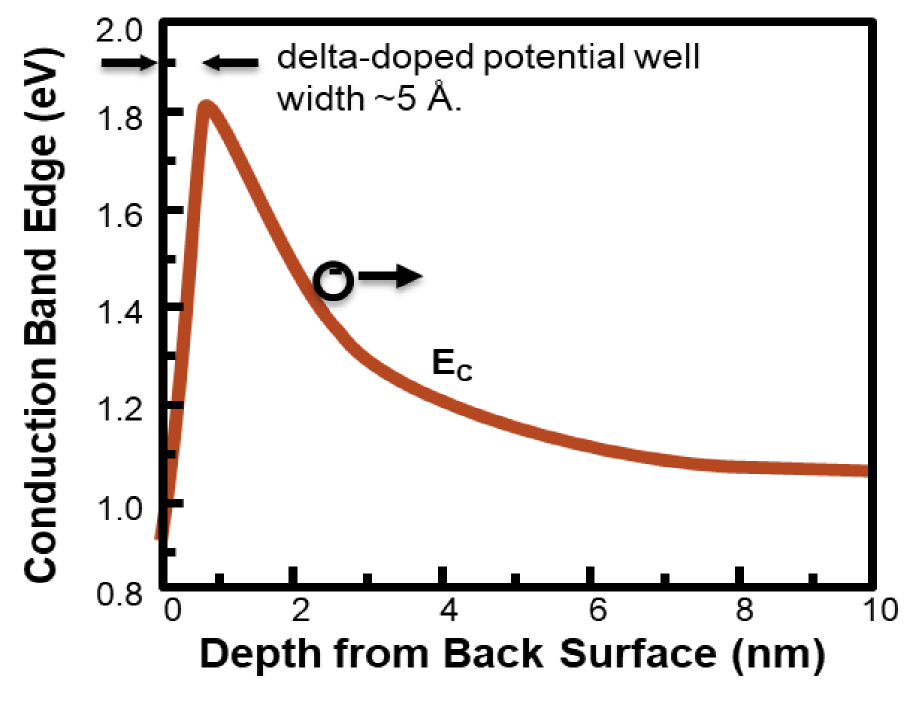


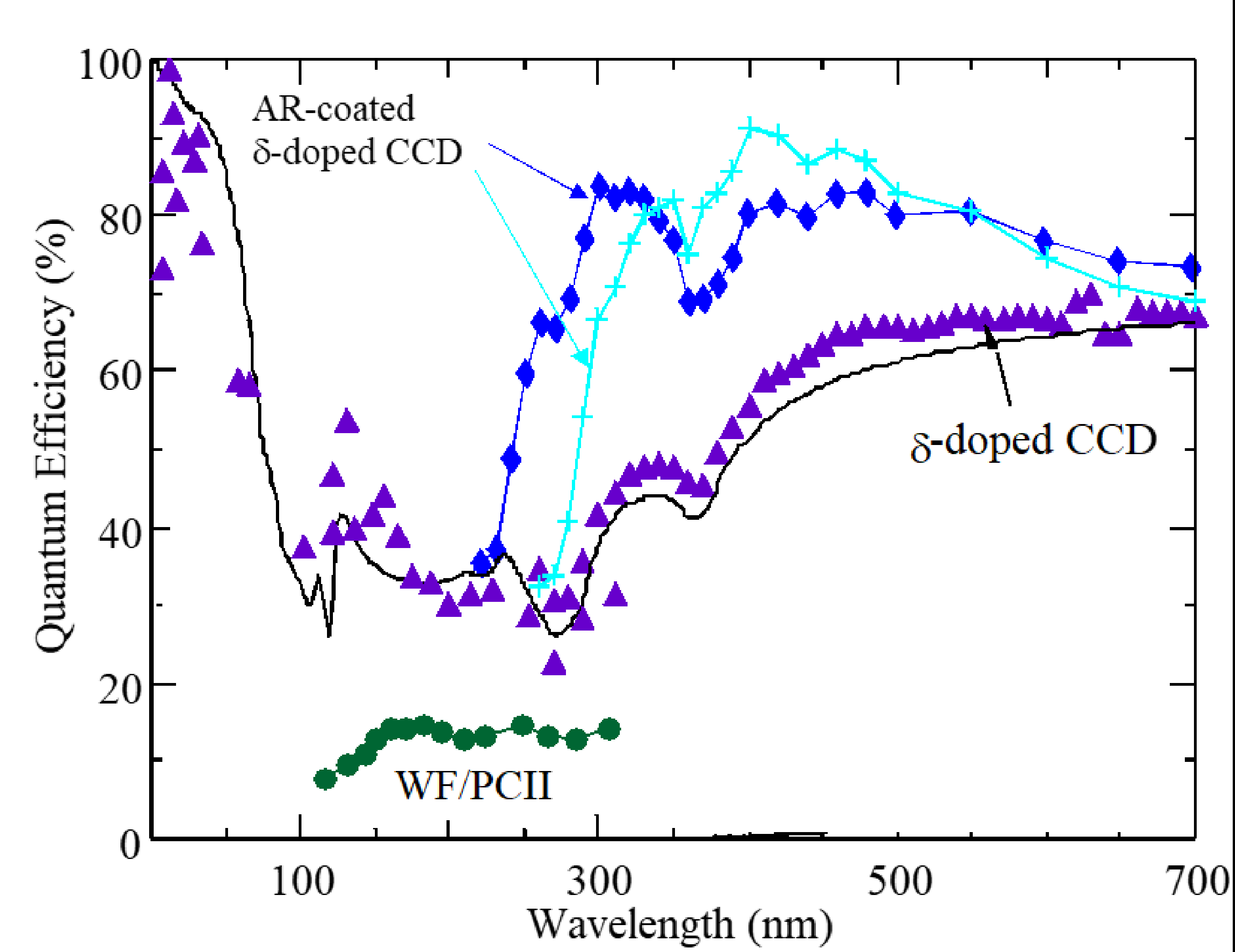


Defise et al., *Proc. SPIE* **3442** (1998) 126
Moses et al., *Solar Physics* **175** (1997) 571

Passivation by Two-dimensional Delta Doping



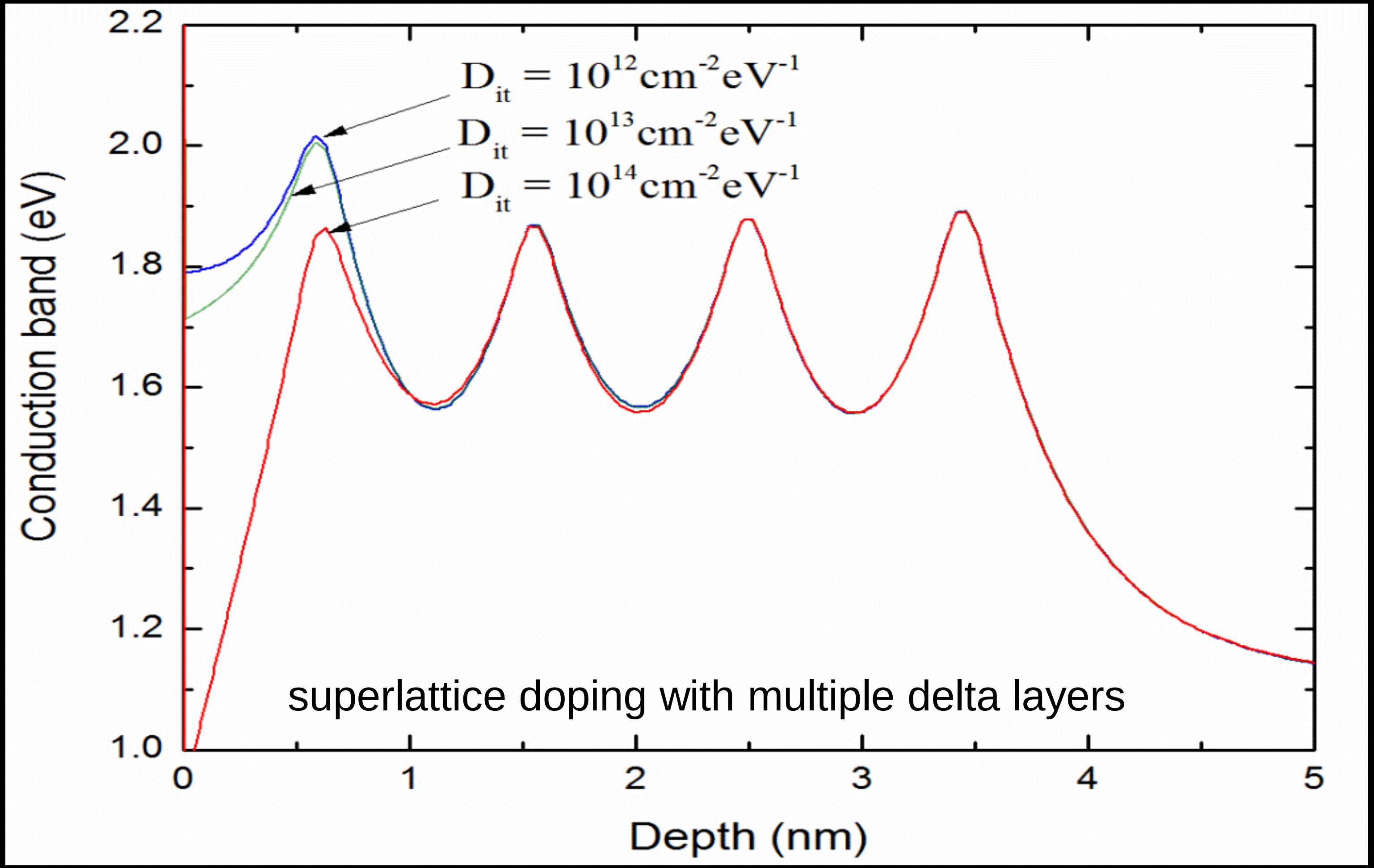




Delta doping provides the maximum possible QE

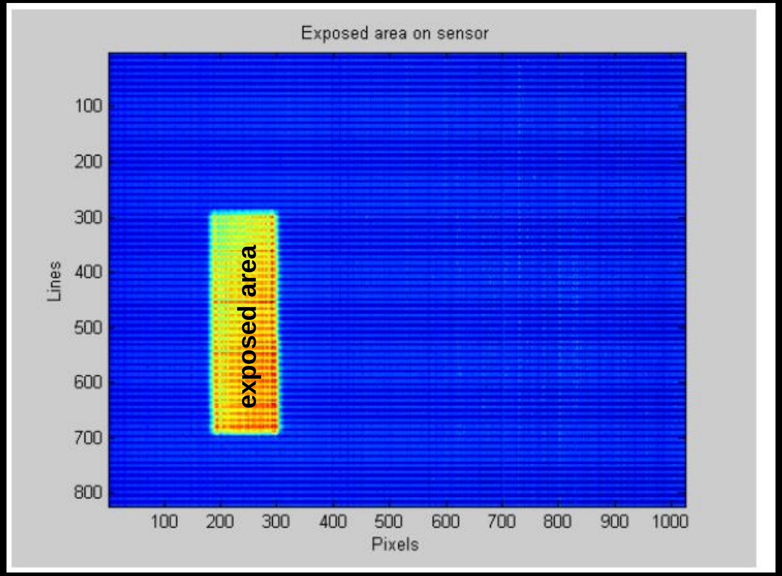
Hoenk et al., *APL*, **61** (1992) 1084
Nikzad et al., *Proc. SPIE* **4139** (2000) 250

Stability of 2D-doped Surface

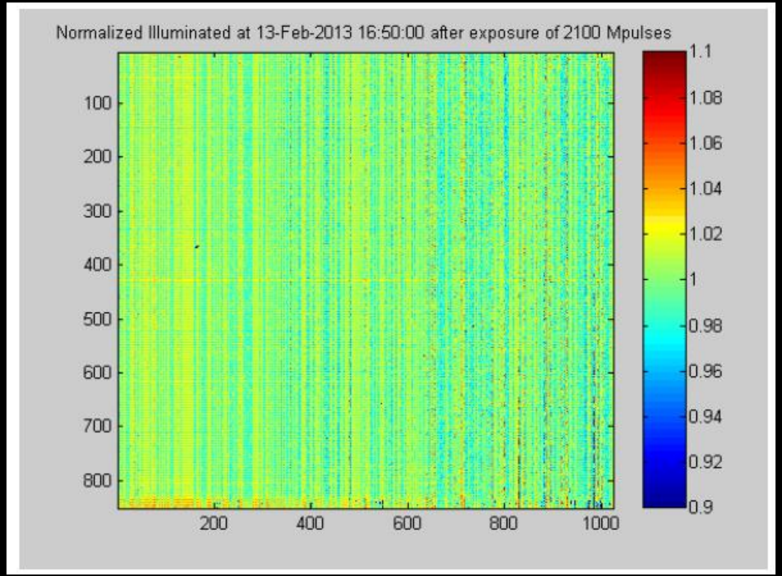


Hoenk et al., *Proc. SPIE*, **9154** (2014) 13

Superlattice-doped CMOS Detector



Normalized Illuminated Image

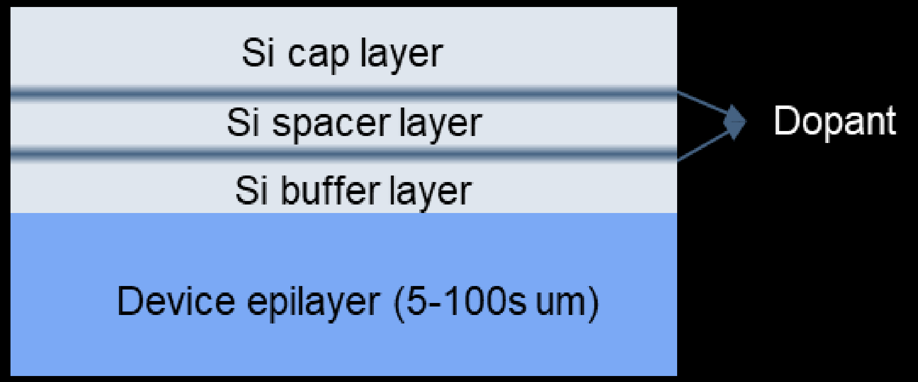


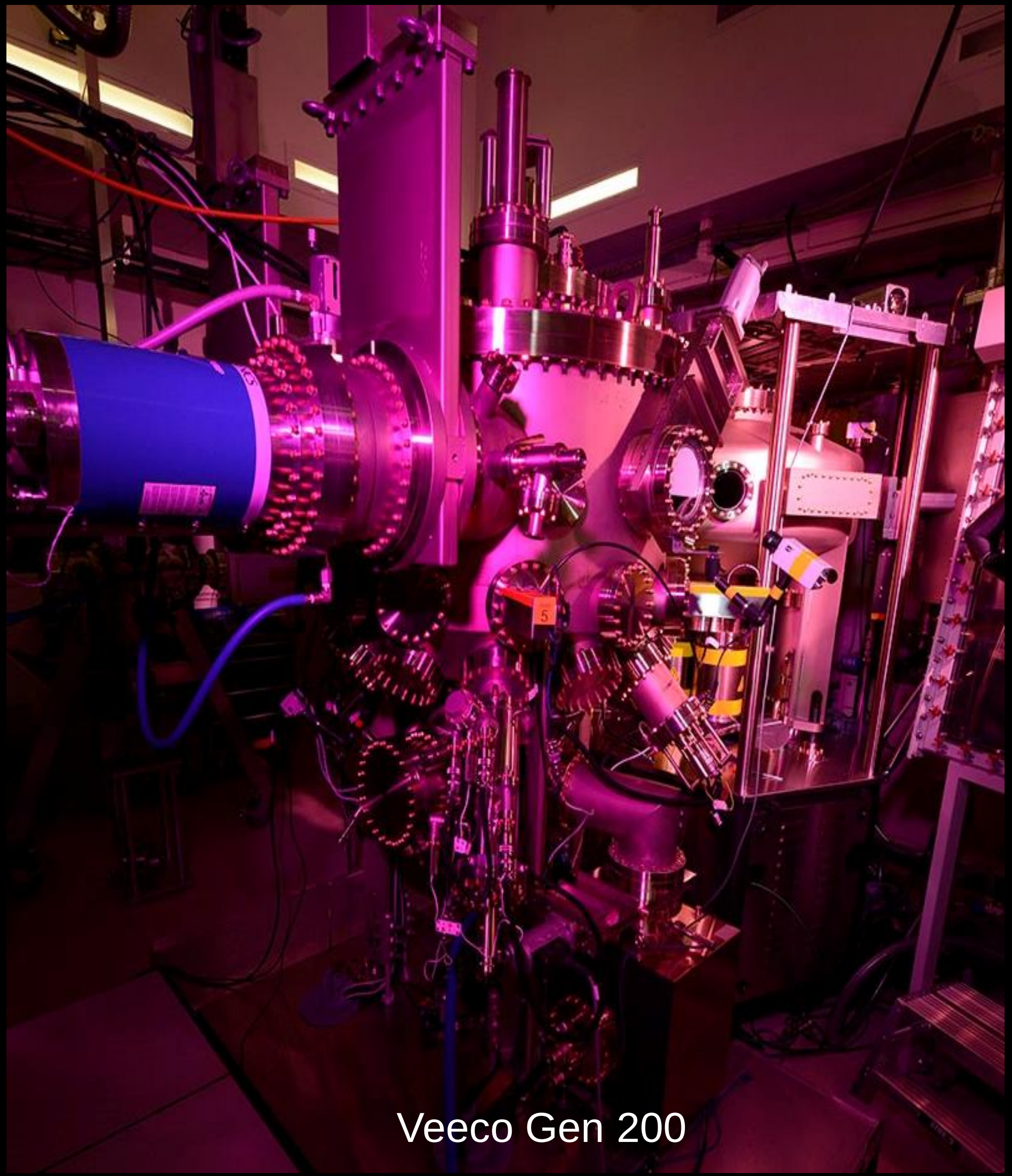
No change in response after 2.1 Billion saturating pulses in the deep UV

Growth Structure/Process

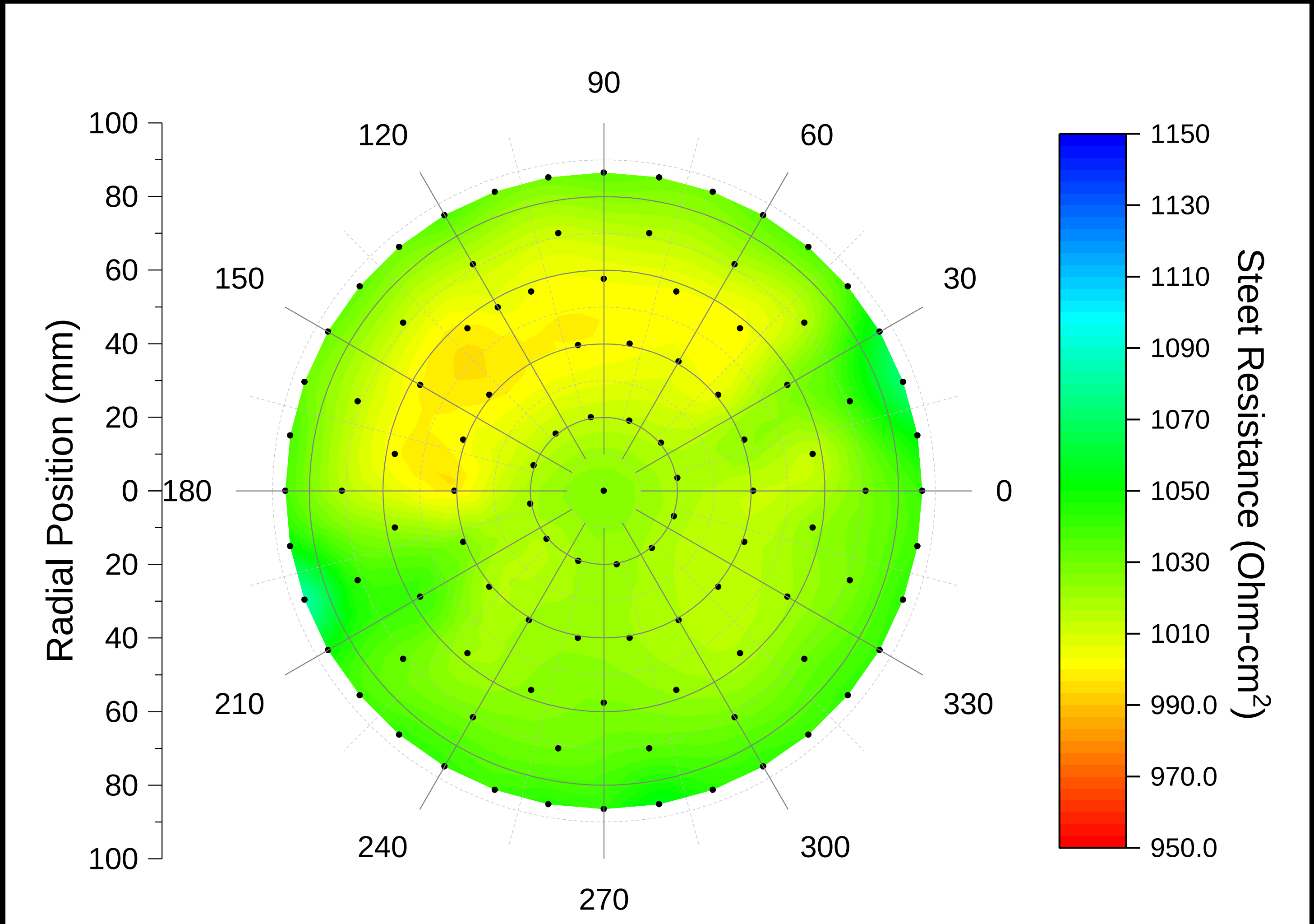
Low Temperature MBE

- Performing passivation as a post-fabrication step
- T≤450 ºC
- Silicon deposited by e-beam evaporation (<0.5 Å/s)
- P-type doping with B from effusion cell
- N-type doping with Sb from cracker cell
- Deposited silicon layers typically 1-3 nm
- Dopant concentration <1 monolayer (where 1 ML ~ 7E14 cm^{-2})
    - Typical 1E14 or 2E14

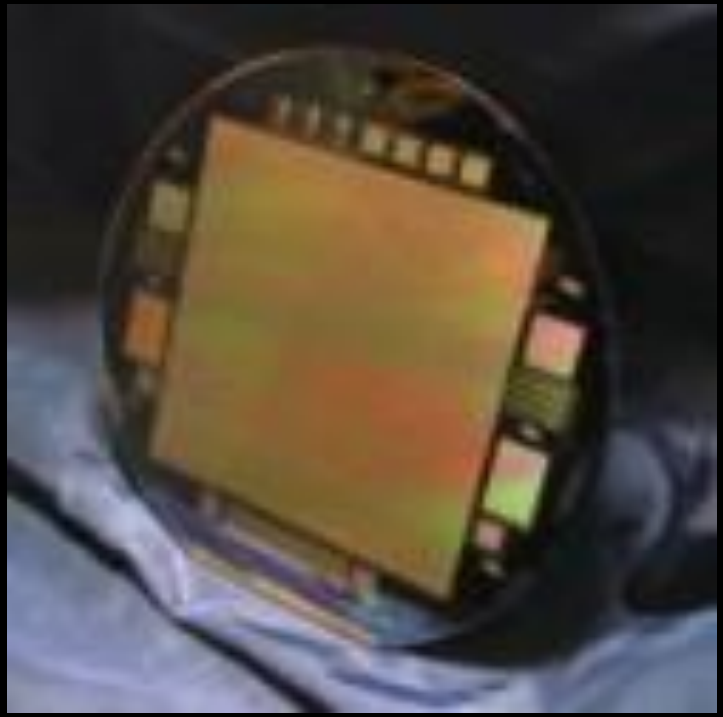


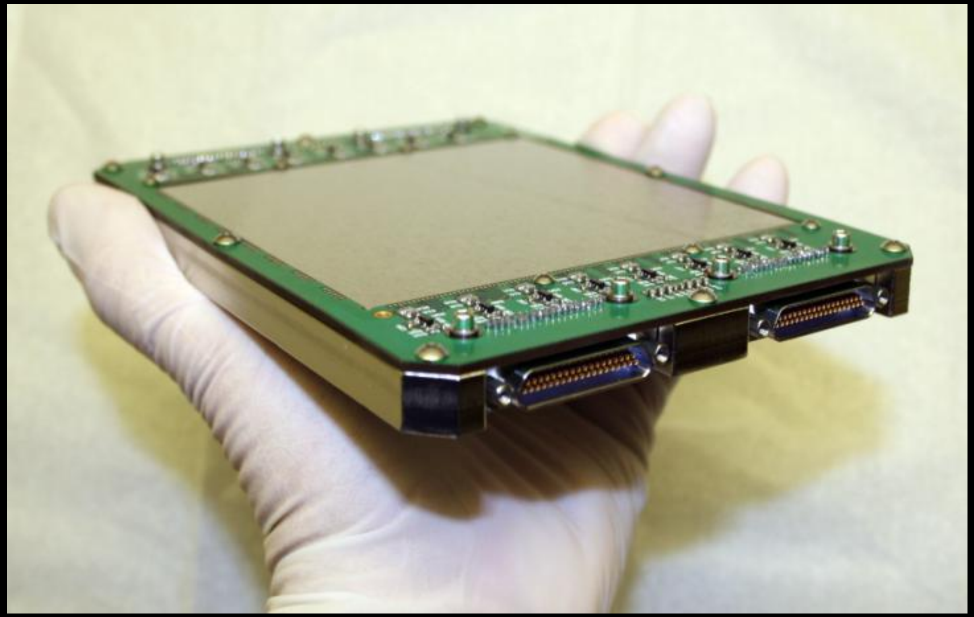


Wafer-scale Processing



<2% variation across 8” wafer





Images Courtesy: Semiconductor Technology Associates, Inc.

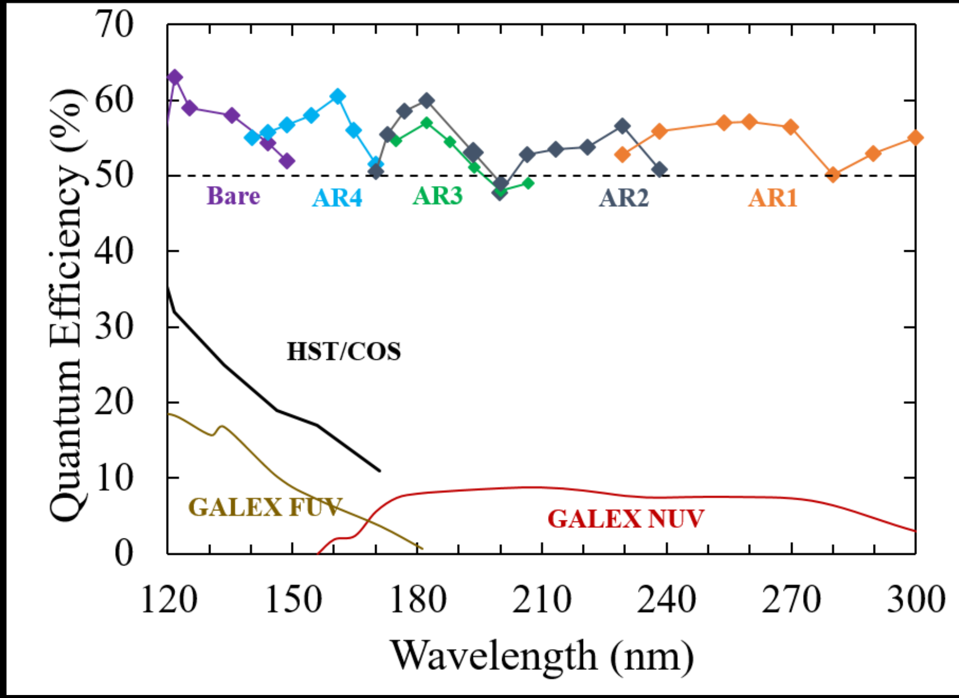
Jewell et al., *JVSTA*, **936** (2018) 061513

Tailoring Detector Response with Thin Film Filters and Coatings

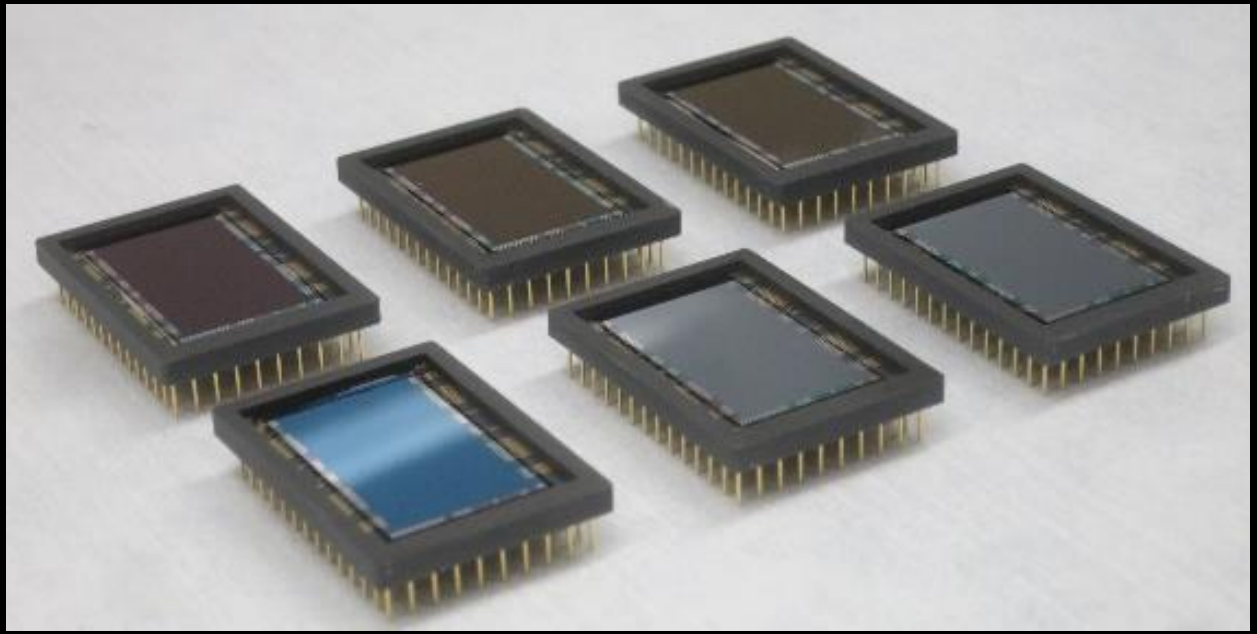
Antireflection Coatings

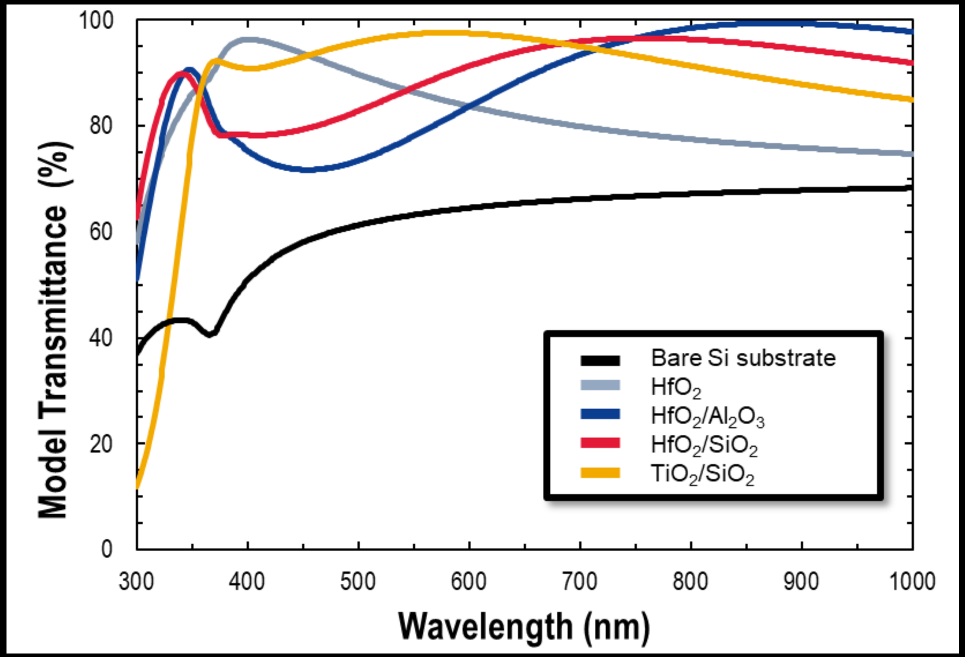
Single and Multilayer Films

Specified wavelengths or bands for targeted applications can be optimized depending on coating materials and overall design.



Nikzad, *et al*., *Applied Optics*, **51**, (2012) 365

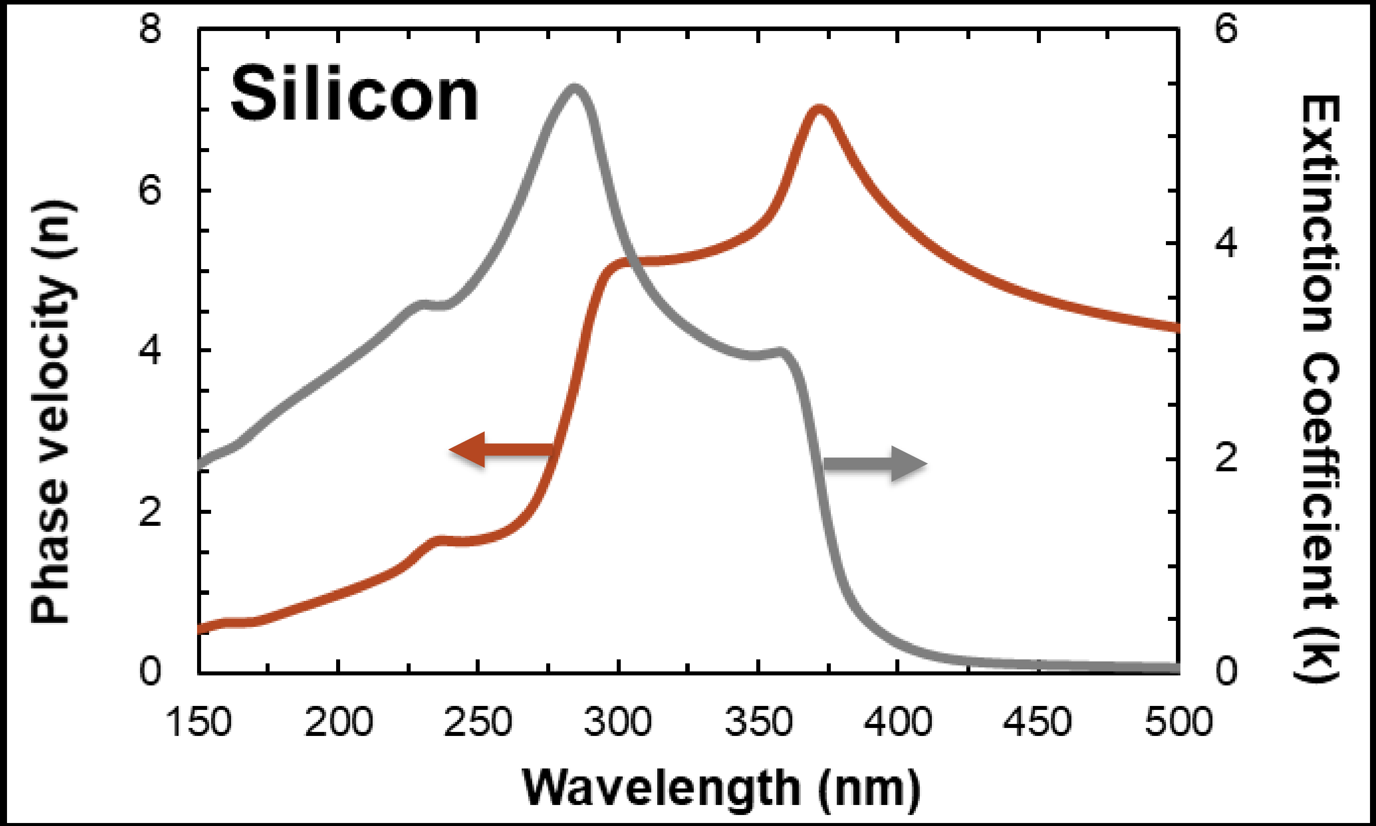




Jewell, *et al*., *Proc. SPIE* **8820** (2013) 88200Z

Antireflection Coatings

- Baseline response of our detectors is reflection limited (i.e. follows 1-R)
- AR coatings can be used to minimize reflection losses
- Index of refraction (n) of silicon changes significantly in the UV
- Maximum performance requires that AR coatings be used
  - Thin films (10-25 nm) required in UV
  - Intermediate thickness films (30-100 nm) for visible
- Specified wavelengths or bands for targeted applications can be optimized depending on coating materials and overall design

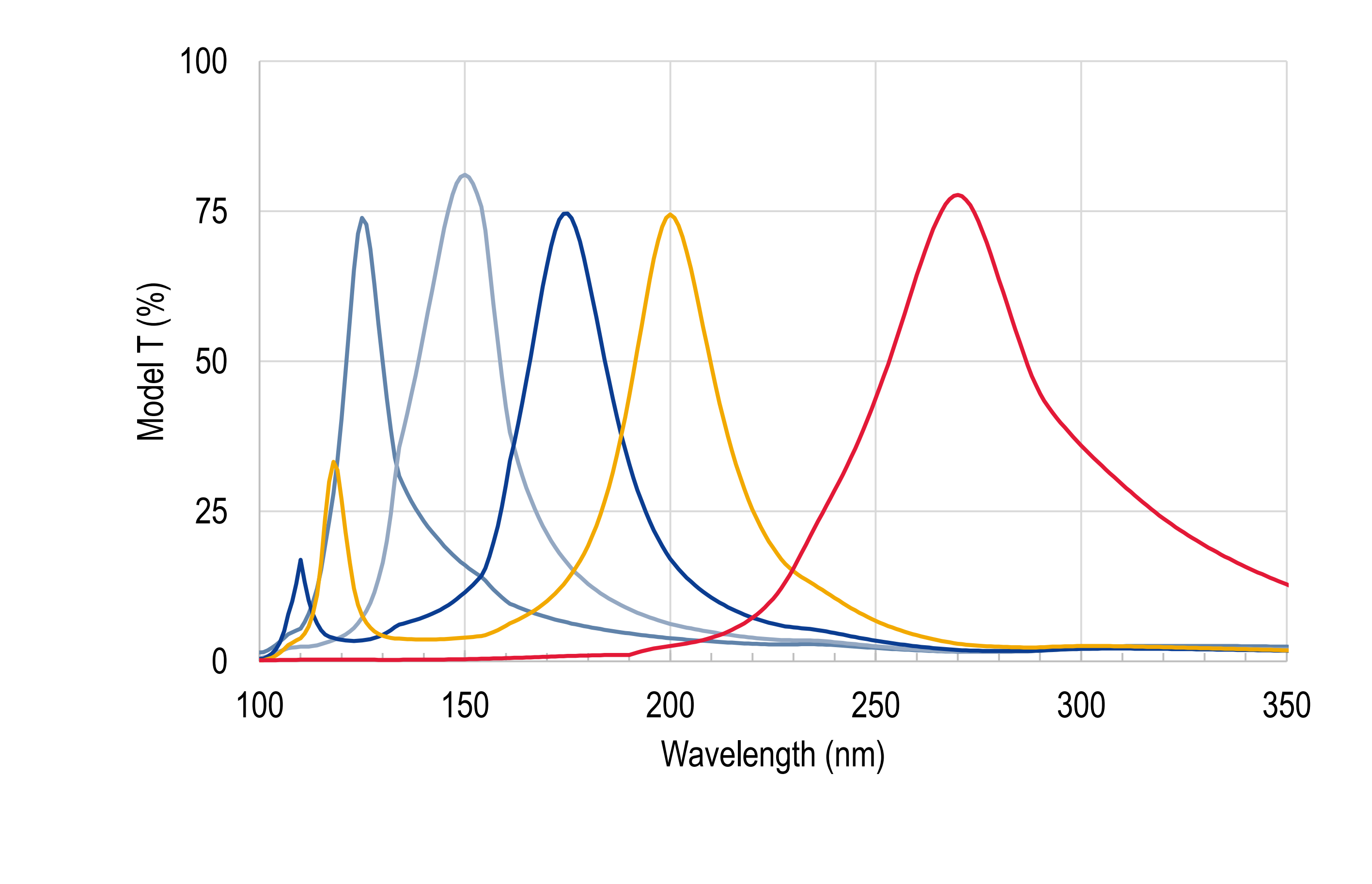


Solar-Blind Silicon

2D-doped Detectors with Integrated Fabry-Pérot Filters

Metal-dielectric filter (MDF) stack deposited directly on silicon detector's substrate

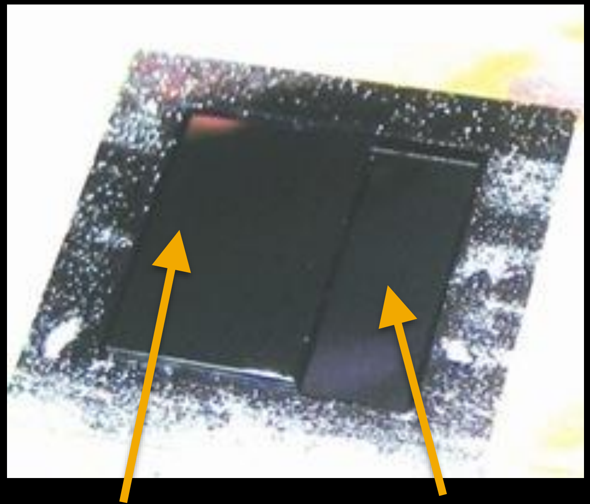
- Eliminate separate filter element
- Can match dielectric to bandpass
- Number of layers and thickness dictate in-band throughput and out-of-band suppression



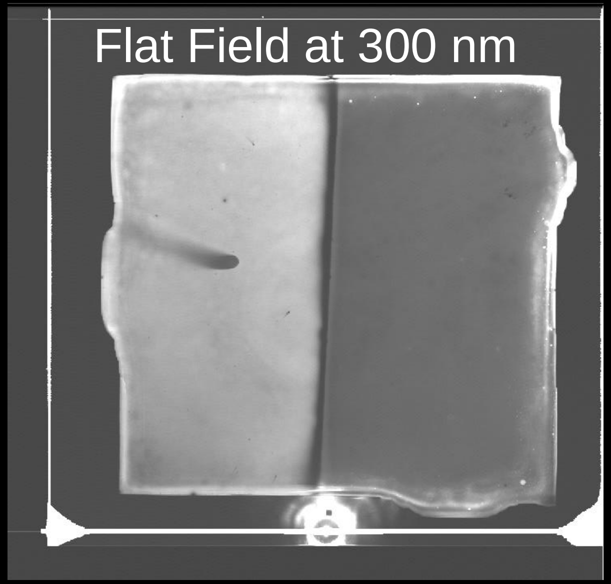
Sputtered, E-beam, and Thermal Evaporation

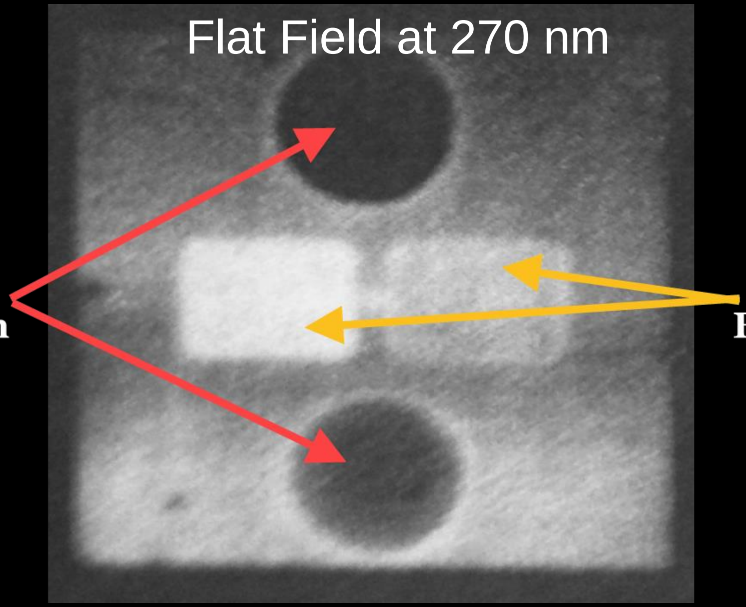
Case studies with HfO_2 (cutoff ~240 nm)

- Shadow mask used so that we have internal standard for comparison
- Flat field images and QE measurements
  - Brighter → Higher QE
- Sputtered film: coated region showed lower QE at 300 nm. TEM showed low density, rough, amorphous film
- E-beam evaporation: also lower QE in coated region. Possible x-ray damage?
- Thermal evaporation: worked well, but challenges with uniformity and reproducibility



Sputtered Film

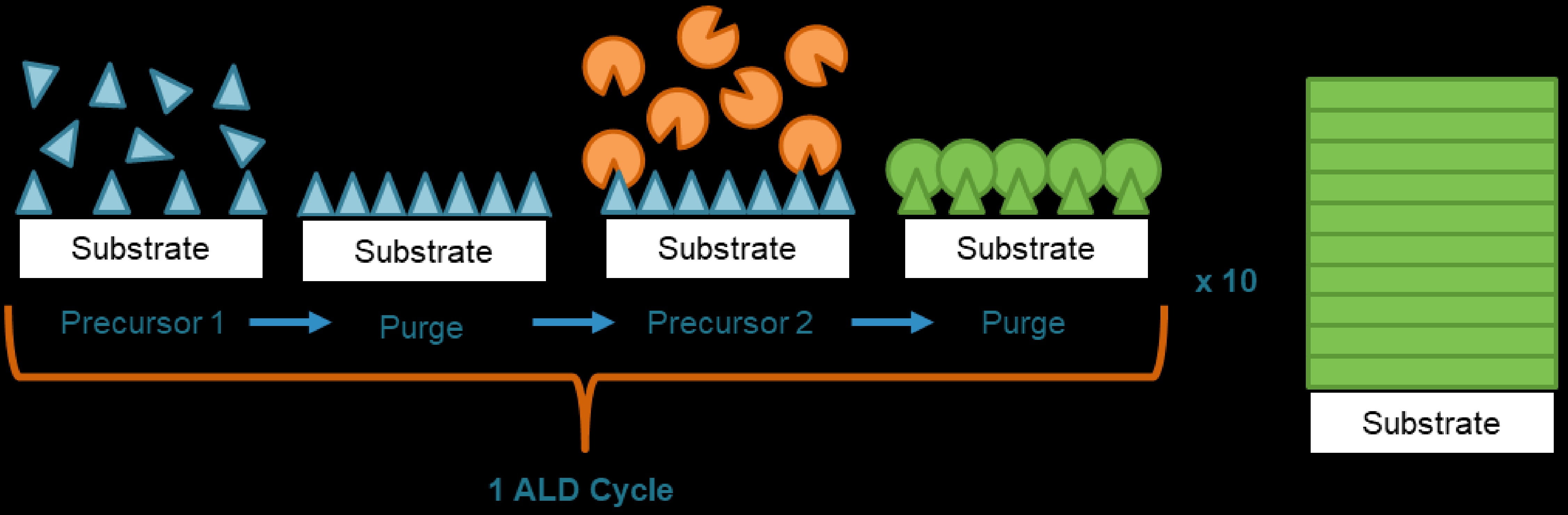




Greer, F., *et al.*, *JVSTA*, **31**, (2013) 01A103.

Atomic layer deposition

- Thin film deposition technique based on sequential, self-limiting chemical reactions.
- Chemical reactants (precursors) are introduced to the substrate in separate steps isolated by purges with a non-reactive gas (e.g., N_2, Ar, etc.)
- ALD growth is typically based on thermally driven reactions or plasma enhanced reactions and can be used to grow conformal films with *nanometer-scale control* over film thickness, composition and structure, even at high aspect ratios



Growth rates measured in Å/cycle

ALD Materials (Old Slide!)

Oxides: Al_2O_3, HfO_2, SiO_2, TiO_2, ZnO, ZrO_2, MgO, $SrTiO_3$, $HfSiO_x$, $HfAlO_x$, $LaAlO_x$, Ta_2O_5, VO_x, Y_2O_3, CaO, CuO, Er_2O_3, Ga_2O_3, La_2O_3, Nb_2O_5, Sc_2O_3 etc.

Nitrides: AlN, GaN, TaN_x, TiAlN, TiN, NbN etc.

Carbides: TaC, TiC, NbC, etc.

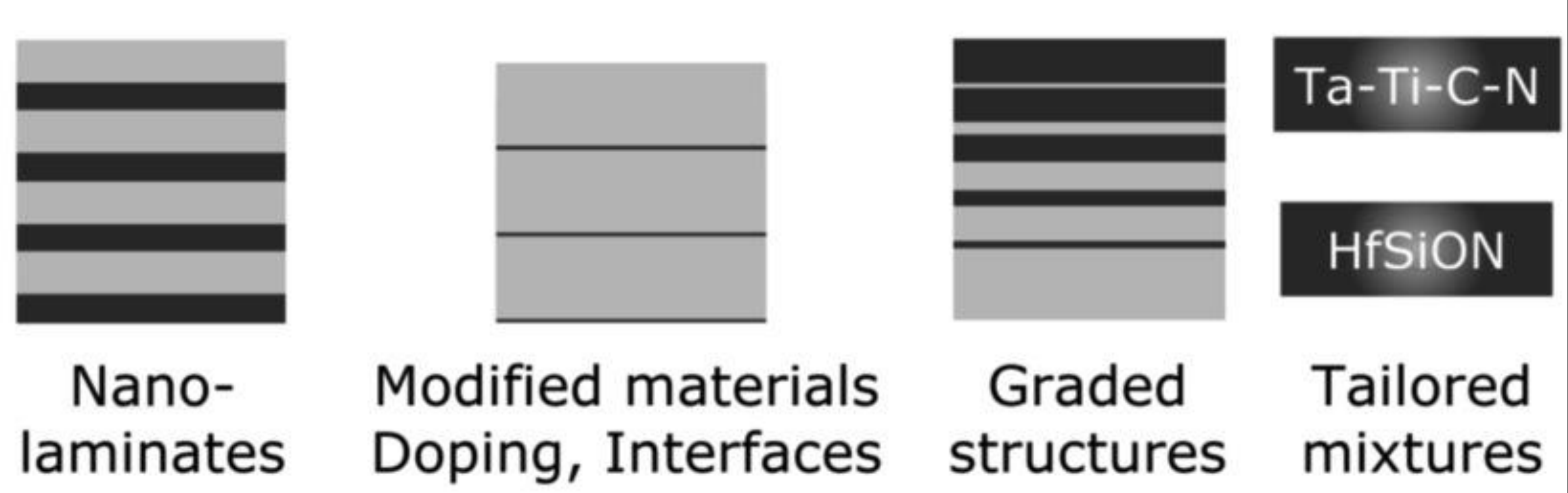
Metals: Ir, Pd, Pt, Ru, W, Mo, Cu, Ag, Au, etc.

Sulfides: ZnS, SrS, CuS, FeS, MoS_x, etc.

Fluorides: CaF_2, LaF_3, MgF_2, AlF_3, LiF, SrF_2, etc.

Biomaterials: $Ca_{10}(PO_4)_6(OH)_2$ (hydroxyapatite)

Polymers: PMDA-DAH, PMDA-ODA, etc.



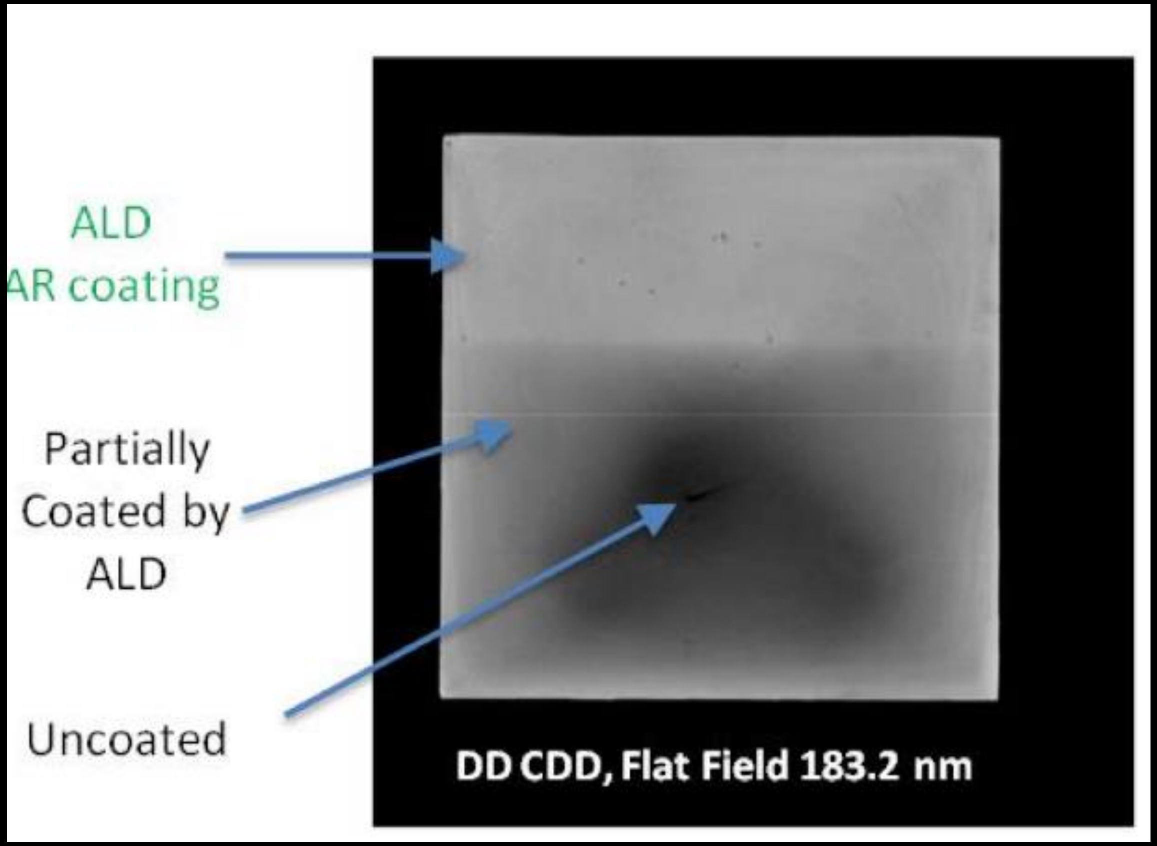
ALD for AR Coatings

Advantages of ALD

- Uniform, pinhole-free films
- Dense, amorphous films
- Excellent thickness control
- Sharp interfaces
- Conformal coating to high aspect ratios (not a line of site technique)

Challenges with ALD

- Shadow masking does not work
- Patterning ALD films is an active field of study



ALD in JPL's Microdevices Lab

High-Throughput/Load Locked
Beneq TFS-200

Five reactive metal precursors & H_2O
Four thermal reactive sources for low vapor pressure precursors
Reactive gases for thermal and plasma enhanced deposition (H_2, N_2, NH_3 and O_2)
T_{sample} 25-400 ^{o}C
Configurable plasma source
200 mm wafer handling

ALD in JPL's Microdevices Lab

Four reactive metal precursors + H_2O
Thermal gas precursors (NH_3, O_2)
Plasma gases (O_2, H_2, N_2)
200 mm wafer handling
T_{sample} setpoint 25 - 400 ^oC
$T_{precursor}$ setpoint up to 200 ^oC
300 W plasma power

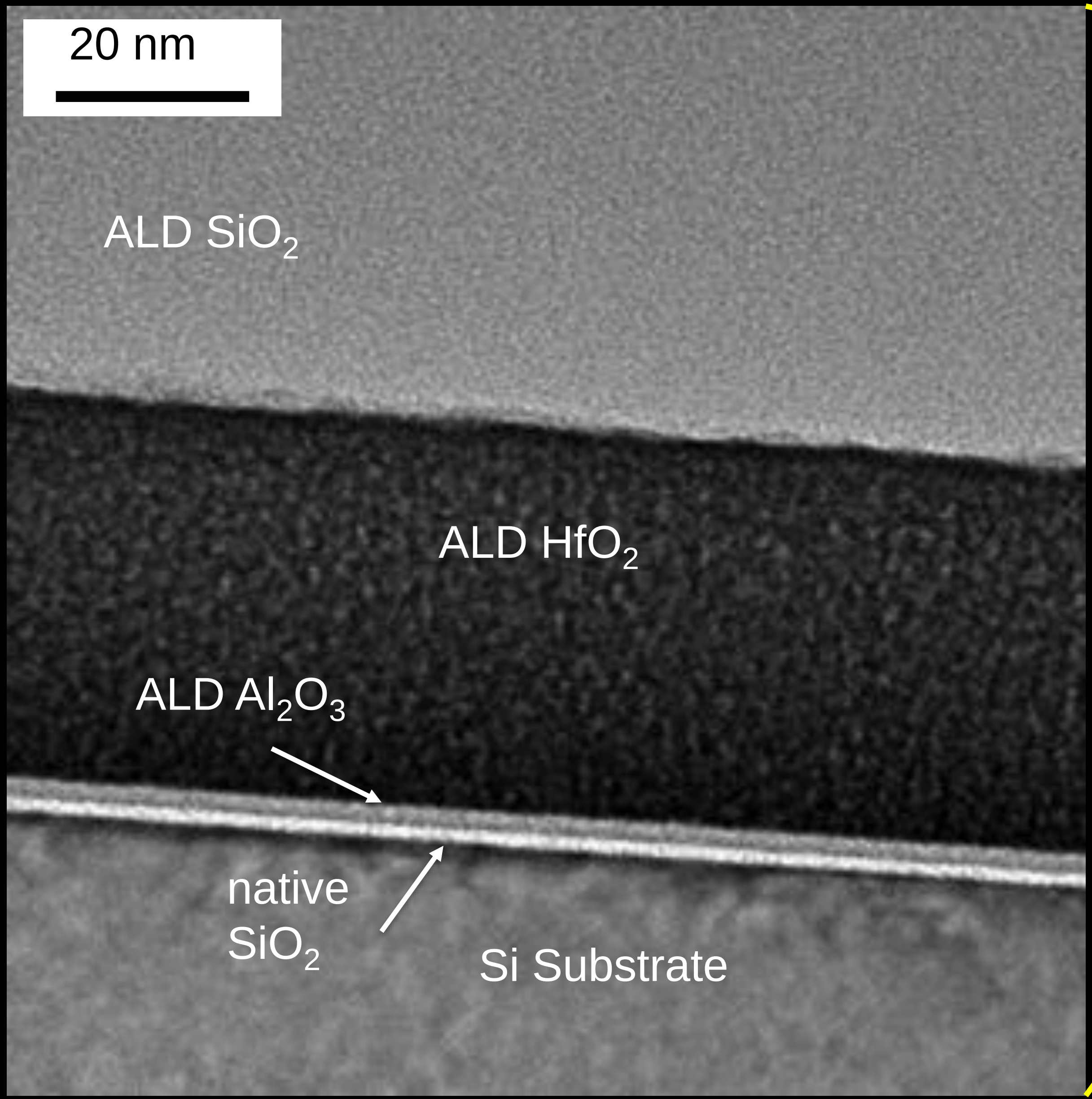
Oxford OpAL ALD System

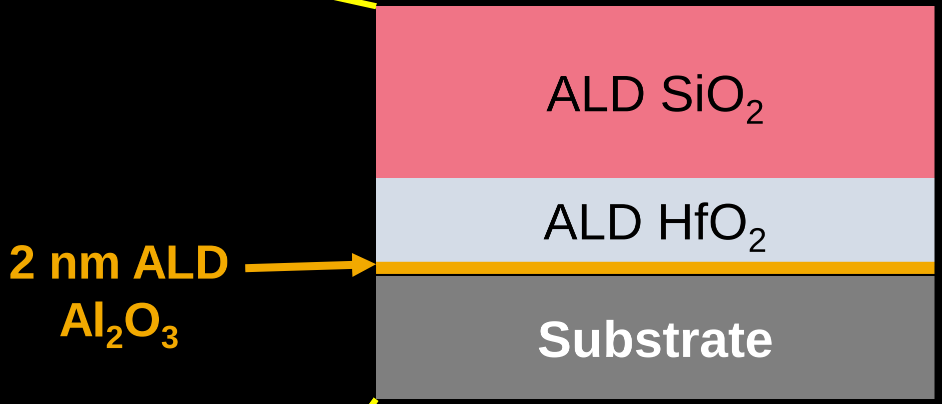
ALD – Uniformity and Repeatability

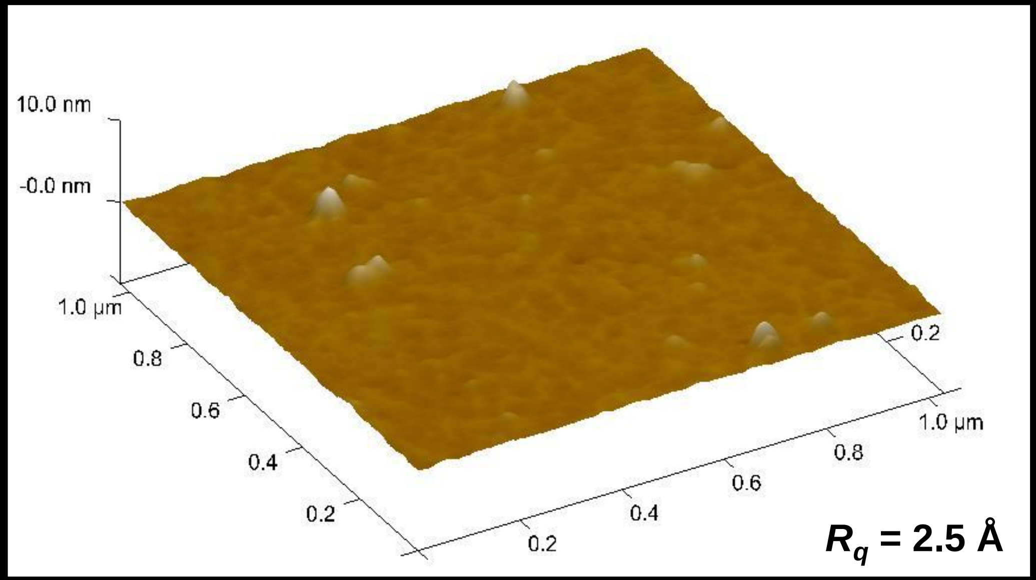
8” wafer before/after 3 layer AR coating

Test Wafer Device Wafer

ALD – Surface Roughness & Interfaces







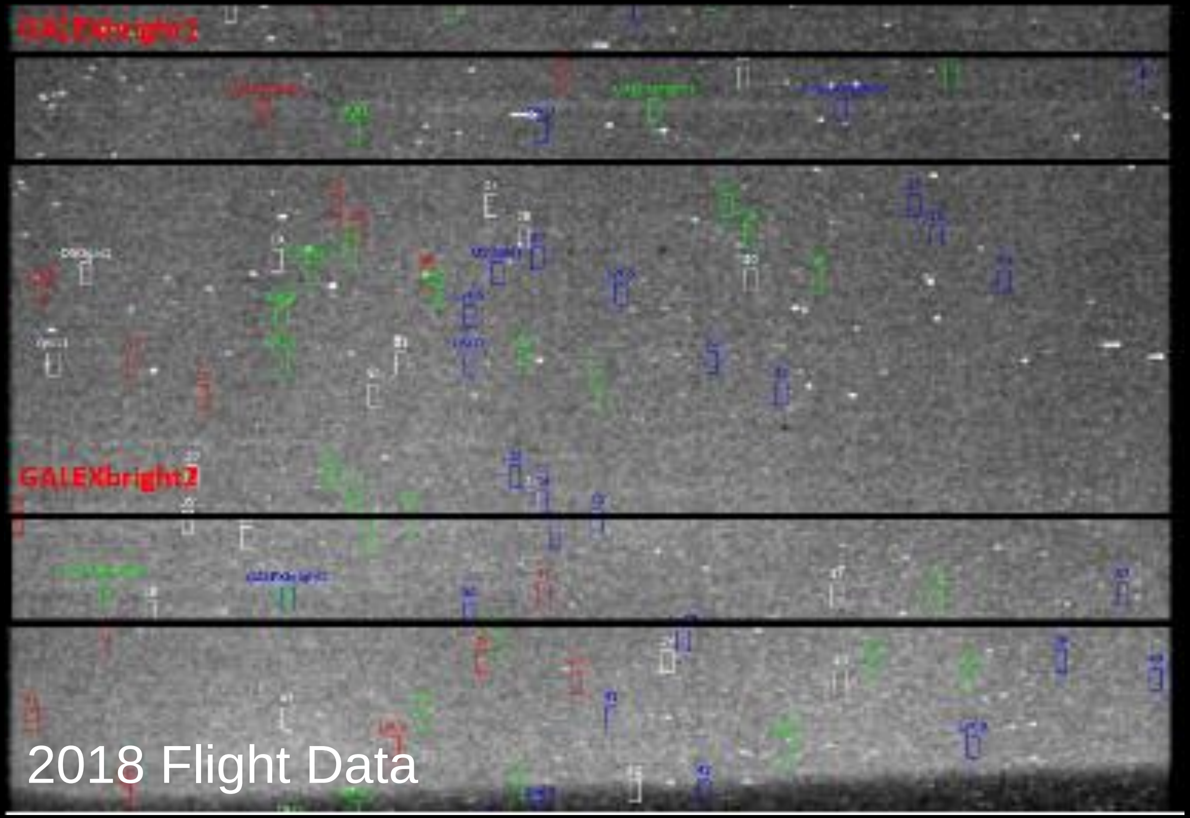
Recent and Ongoing Projects

PI – C. Martin, Caltech
@FIREBall2_scope

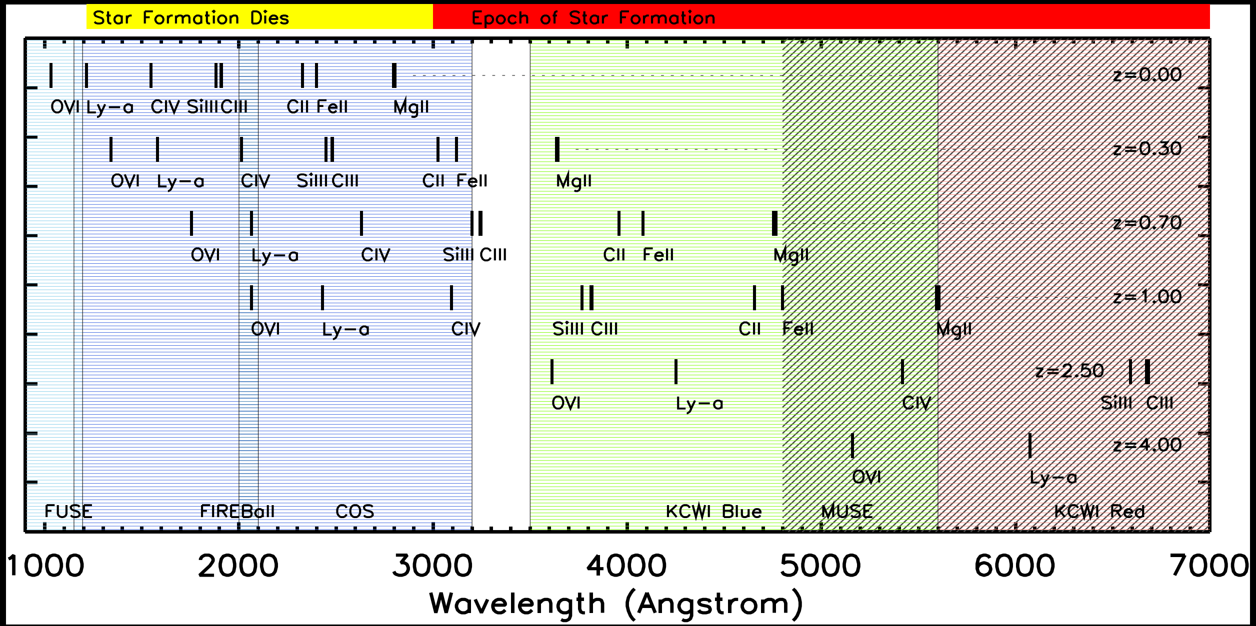
Recent/Ongoing Suborbital Mission – FIREBall-2

Faint Intergalactic-medium Red-shifted Emission Balloon

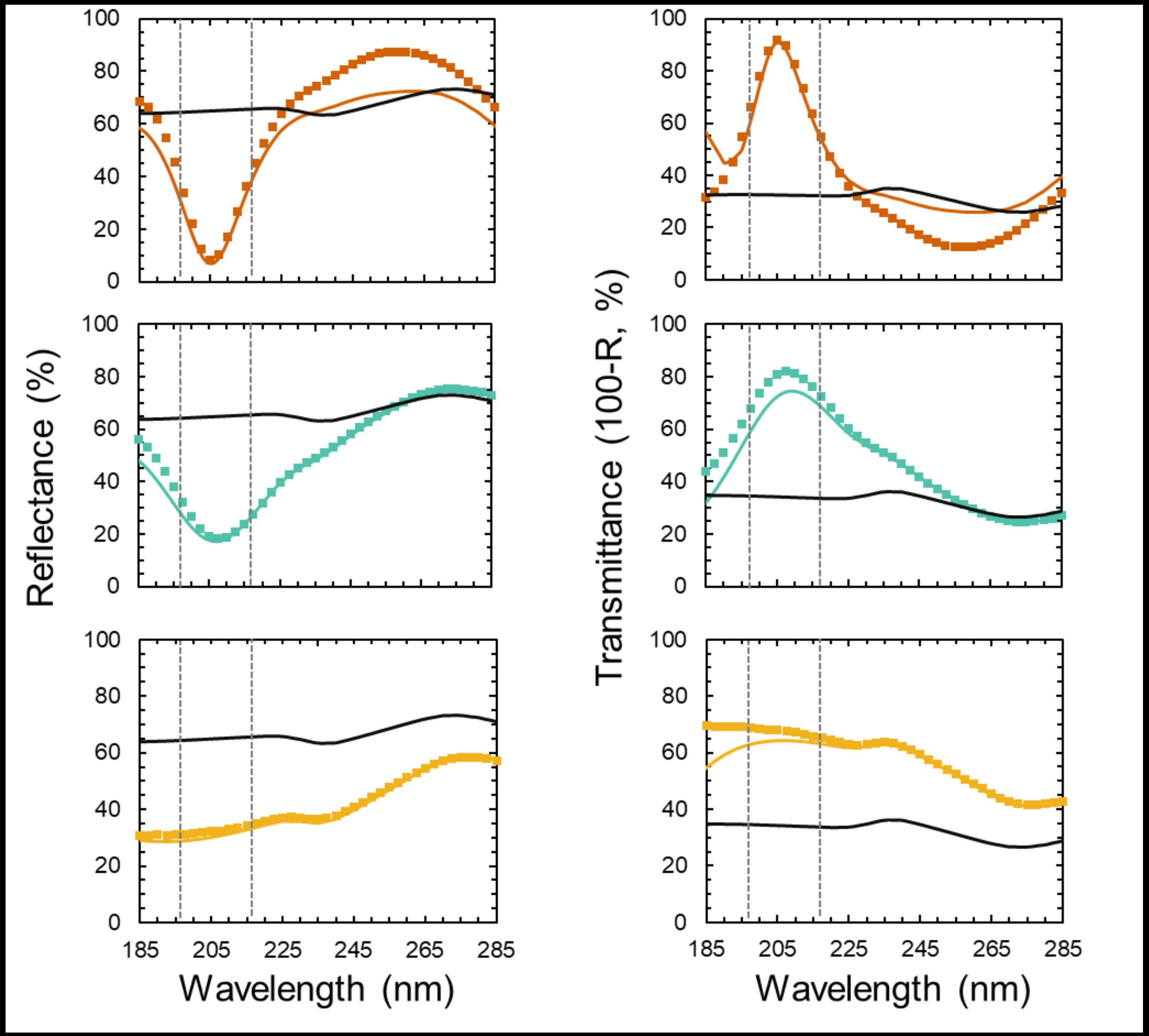
- Discover and map faint emission from the intergalactic medium of low redshift galaxies in the stratospheric UV window ~200-225 nm
- Delta-doped and AR coated detector
- Flight in 2018 complete; two more flights planned

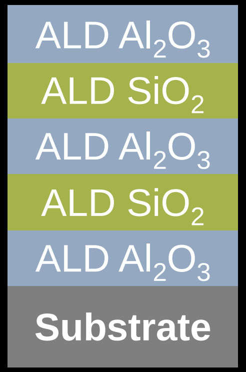


Kyne et al., *JATIS,* (2020) 011007



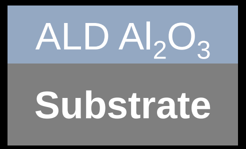
FIREBall-2 Multilayer AR Coatings





Five Layer AR Coating

Three Layer AR Coating

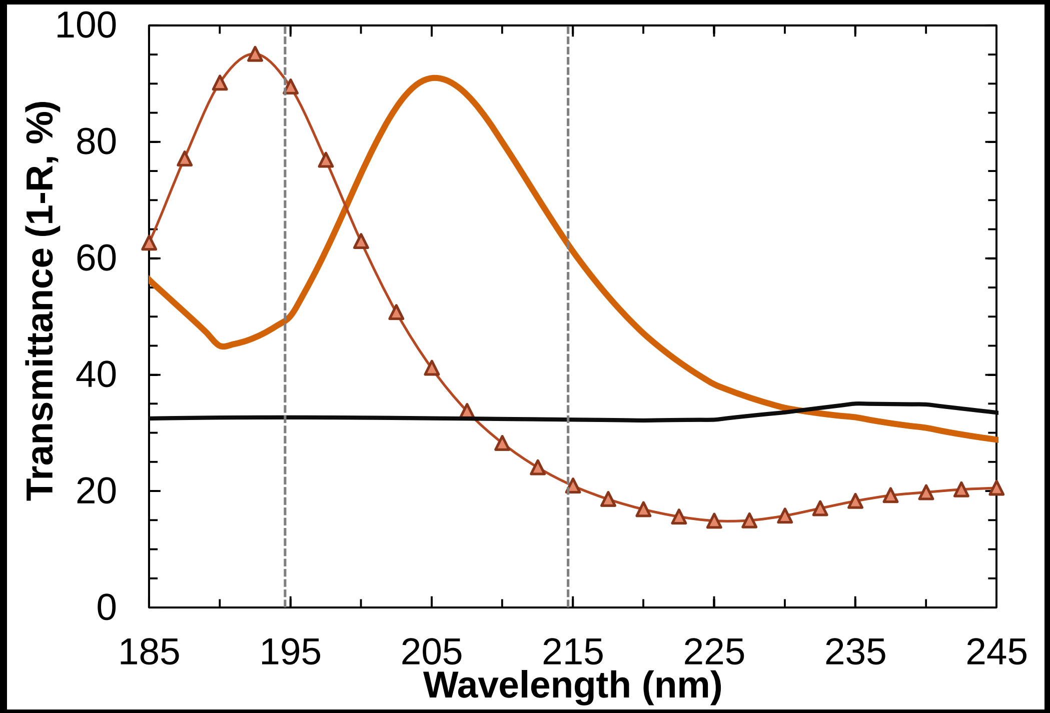


Single Layer AR Coating

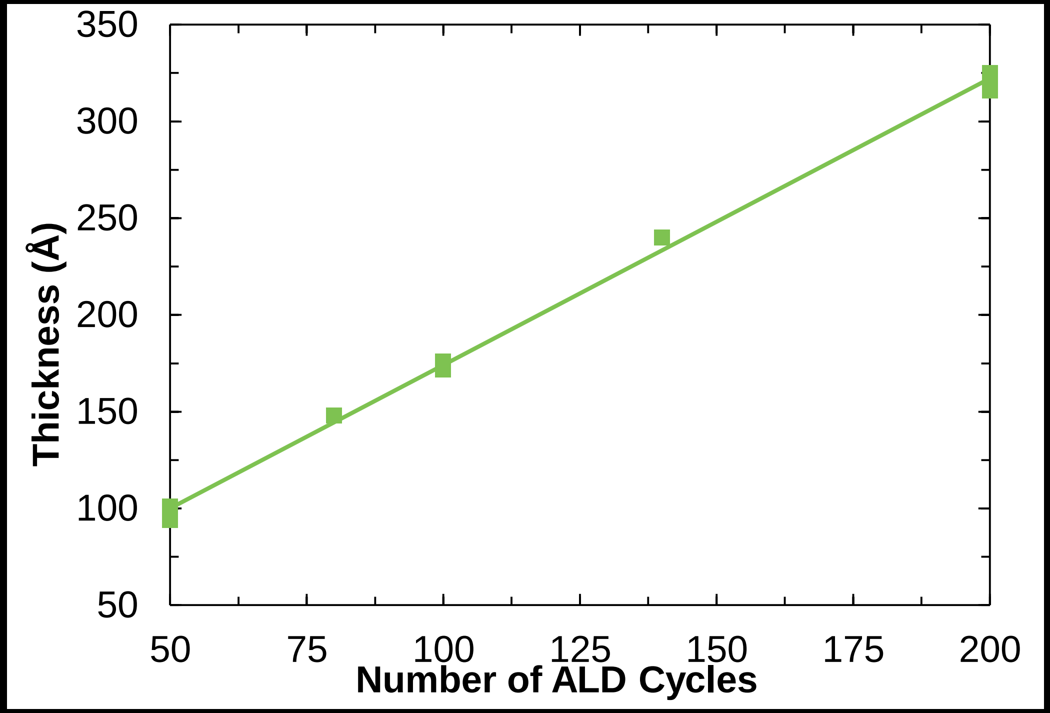
Layer thicknesses for these coatings are 17-40 nm

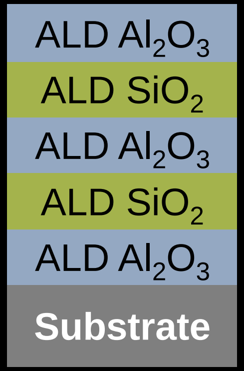
ALD Stacks & Film Nucleation

Growth based on initial calibration



ALD SiO_2 growth rate calibration



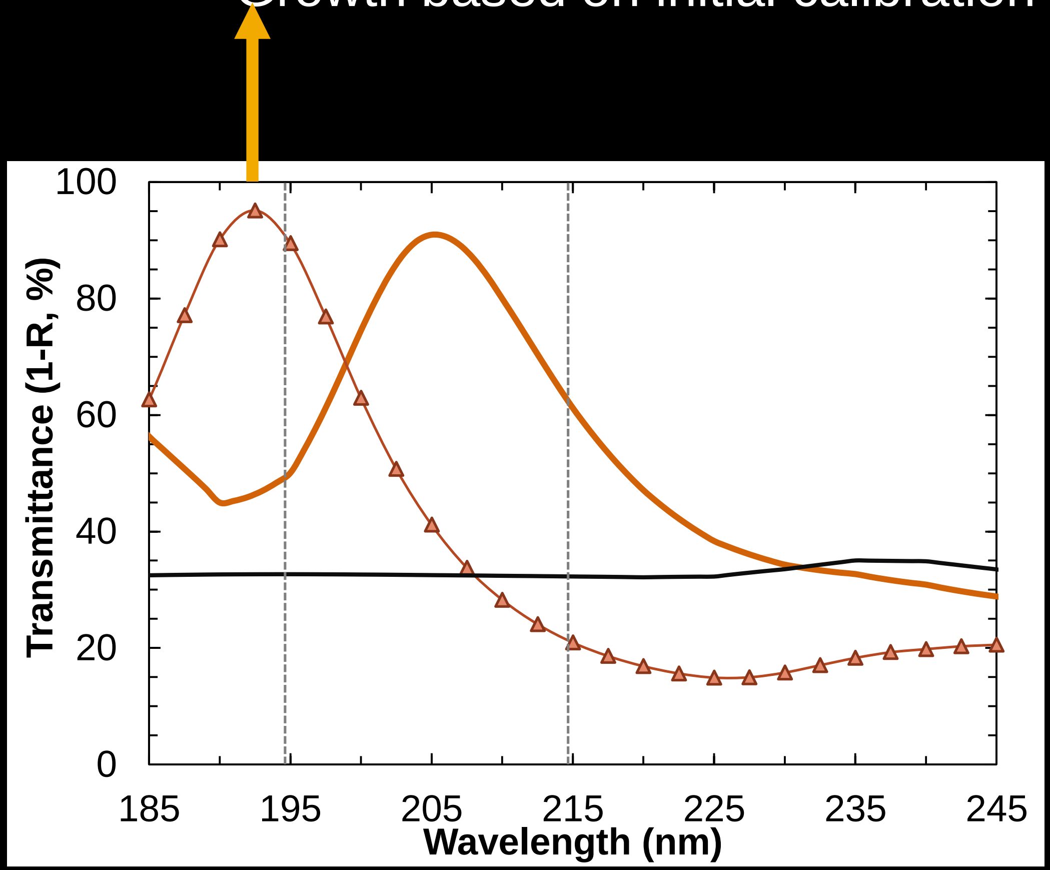


Five Layer AR Coating

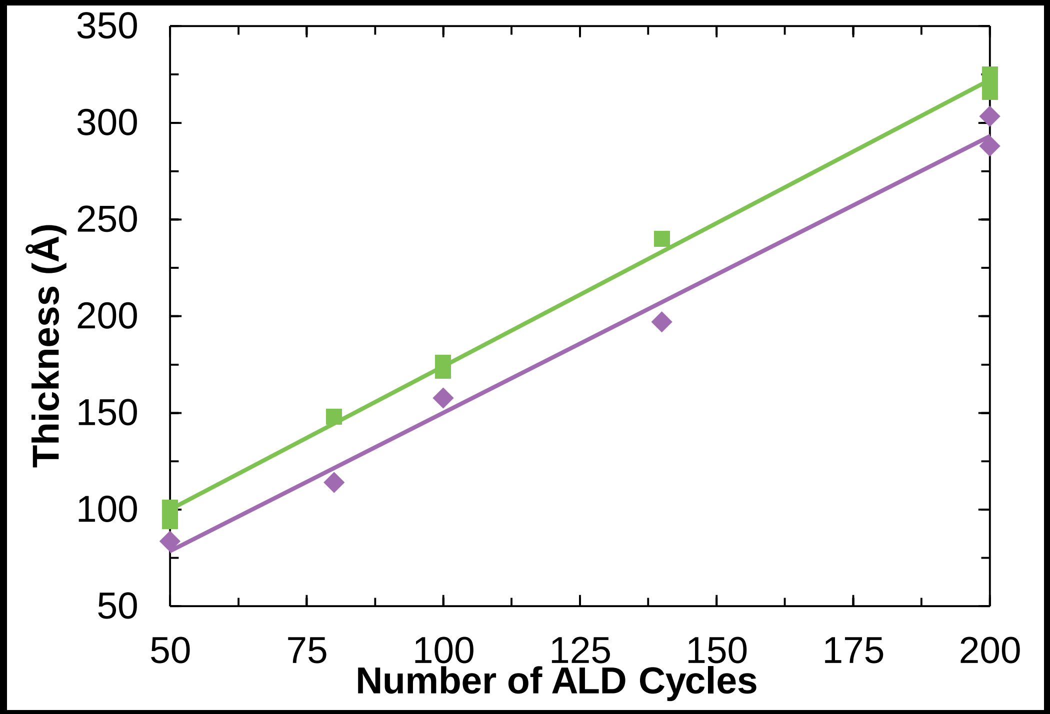
Jewell, *et al.*, *Proc. SPIE* **9601** (2015)

ALD Stacks & Film Nucleation

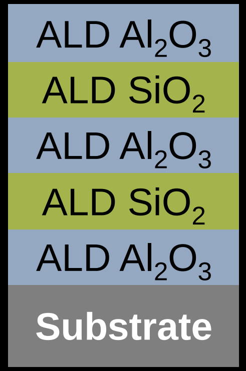
Growth based on initial calibration



ALD SiO_2 growth rate calibration



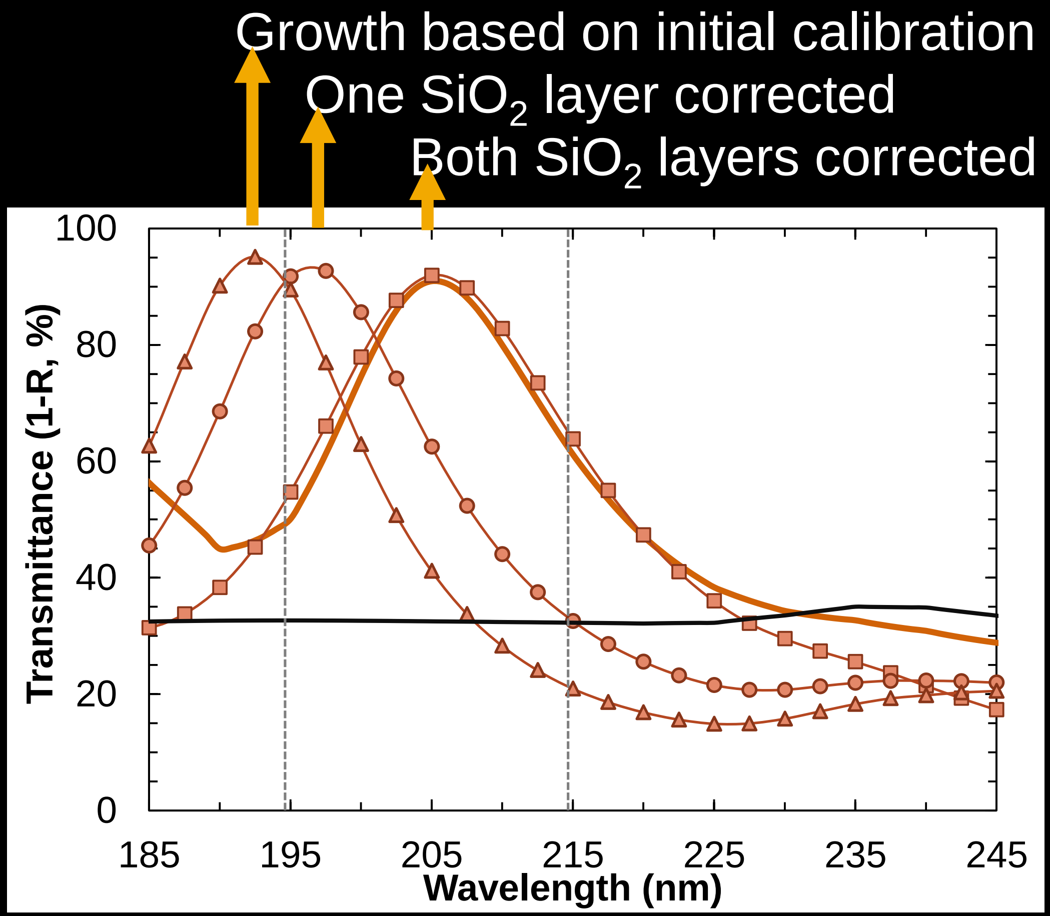
ALD SiO_2 nucleation on an existing ALD-Al_2O_3 layer is slower than on the bare substrate.



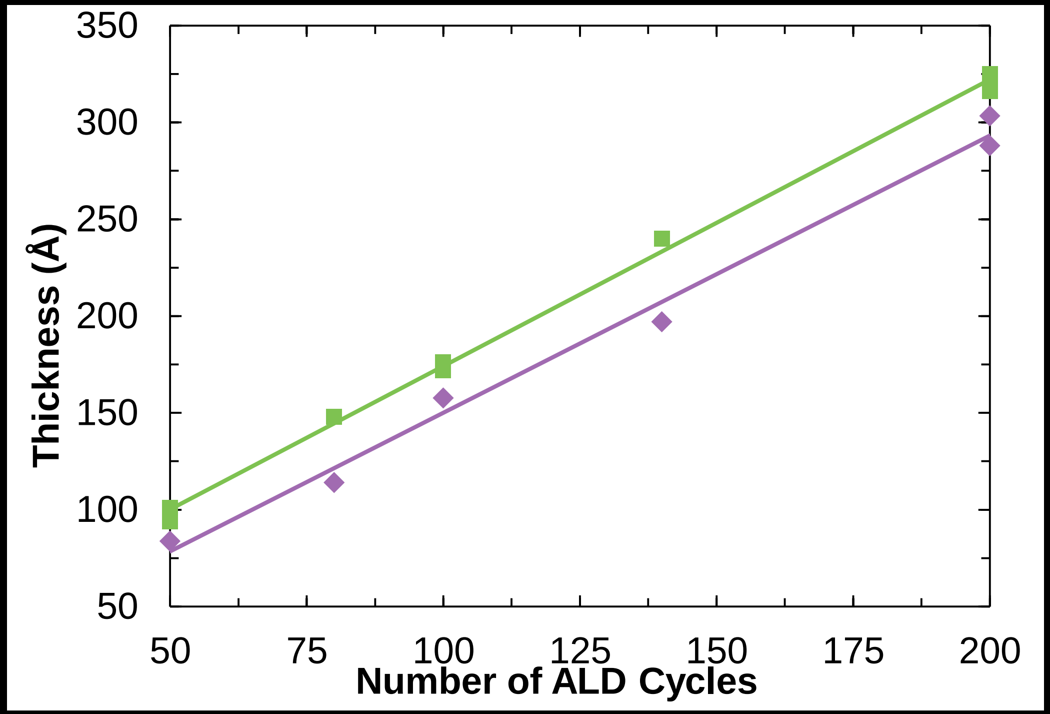
Five Layer AR Coating

Jewell, *et al.*, *Proc. SPIE* **9601** (2015)

ALD Stacks & Film Nucleation



ALD SiO_2 growth rate calibration



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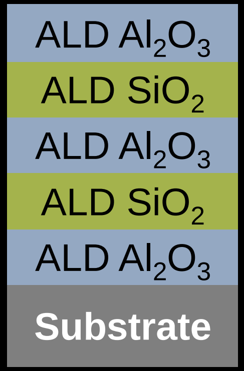


Five Layer AR Coating

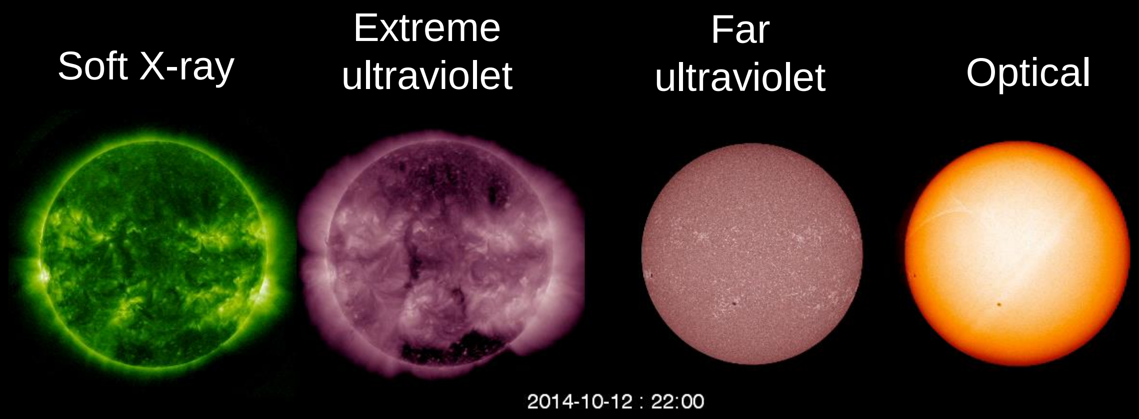
Jewell, *et al.*, *Proc. SPIE* **9601** (2015)

PI – E. Shkolnik, University of Arizona
https://sparcs.asu.edu/

Current CubeSat Mission – SPARCS

Star-Planet Activity Research CubeSat

- M dwarf (or "red dwarf") stars in our galaxy host roughly 40 billion terrestrial planets in the habitable zone
- The stellar UV emission from M dwarfs is strong and highly variable, and impacts planetary atmospheric loss, composition, and habitability
- M dwarfs are much more active than the sun, but long term UV monitoring has not been done for M dwarfs.
- We want to know how active they are across the UV range and across planet formation and evolution timescales



NASA/SDO/J. Llama
https://sparcs.asu.edu/

Mission: Scowen et al., *Proc. SPIE* **10699** (2018) 106990F
Detector: Jewell et al., *Proc. SPIE* **10709** (2018) 107090C

PI – E. Shkolnik, University of Arizona
https://sparcs.asu.edu/

SPARCS Payload

- 9-cm aperture telescope
- Dichroic element
    - Transition at λ≈233 nm
- NUV Bandpass Filter
- SPARCam: Two channel UV camera
    - Band NUV: 260-300 nm
    - Band FUV: 150-170 nm

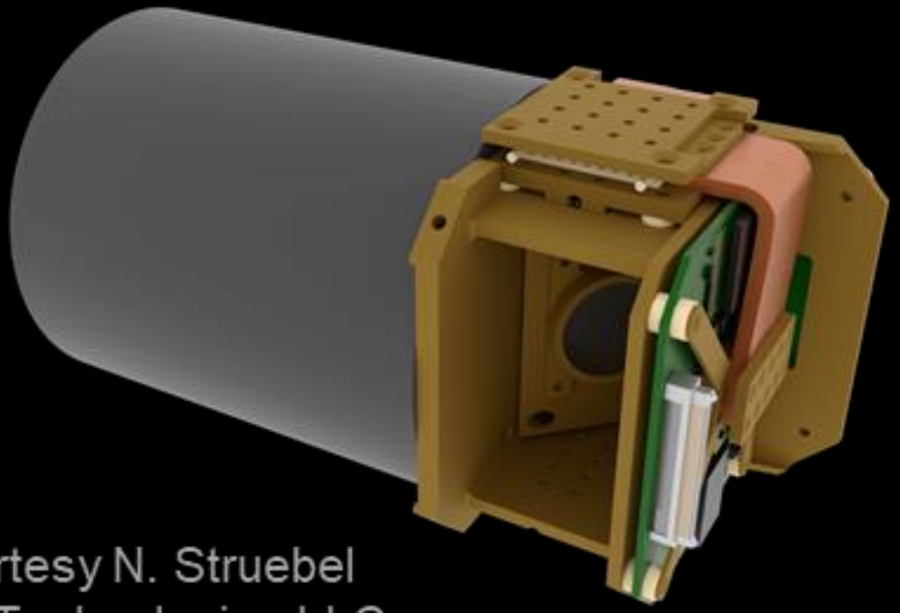
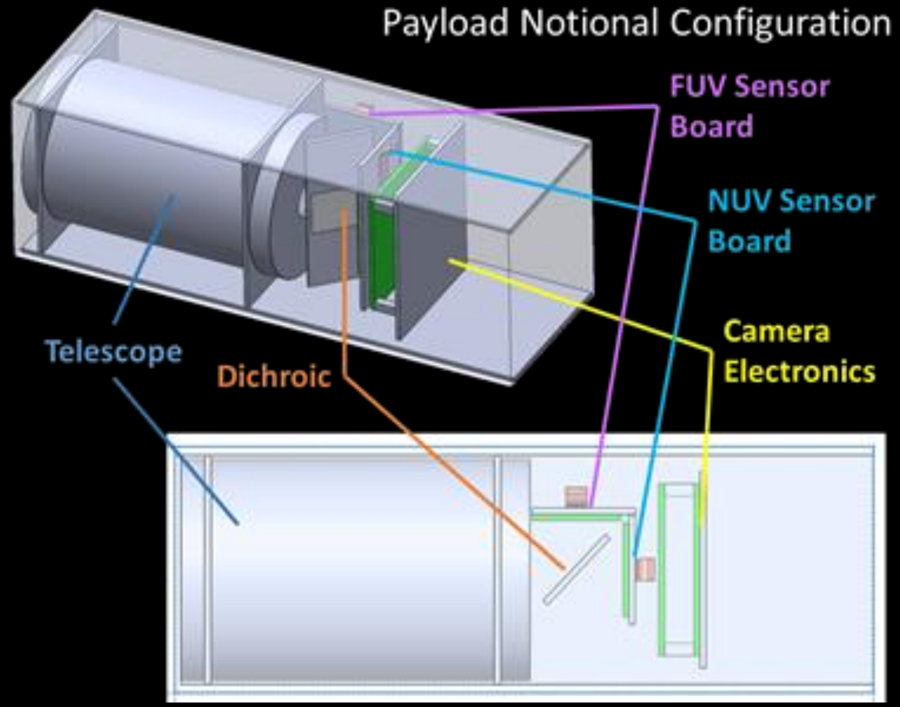


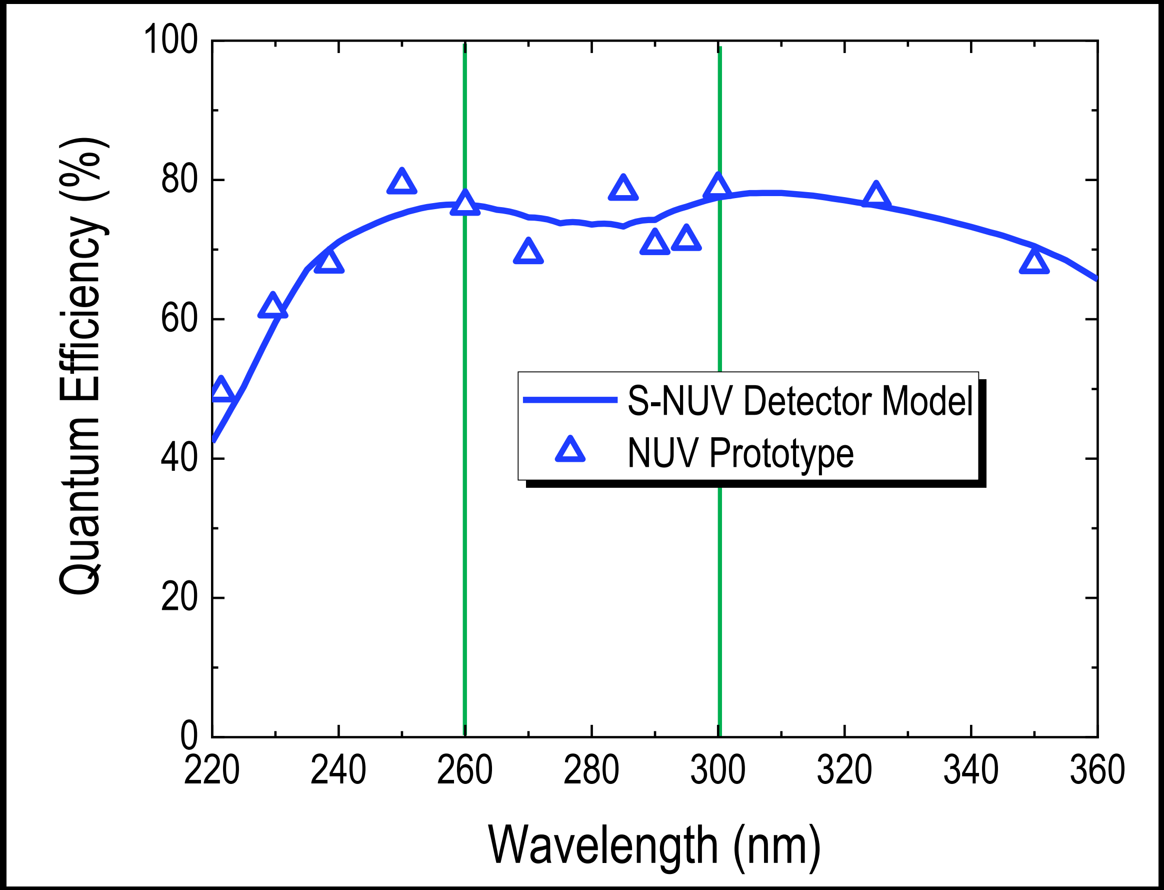
Image courtesy N. Struebel
AZ Space Technologies LLC



Mission: Scowen et al., *Proc. SPIE* **10699** (2018) 106990F
Detector: Jewell et al., *Proc. SPIE* **10709** (2018) 107090C

Delta-doped CCD with High UV QE

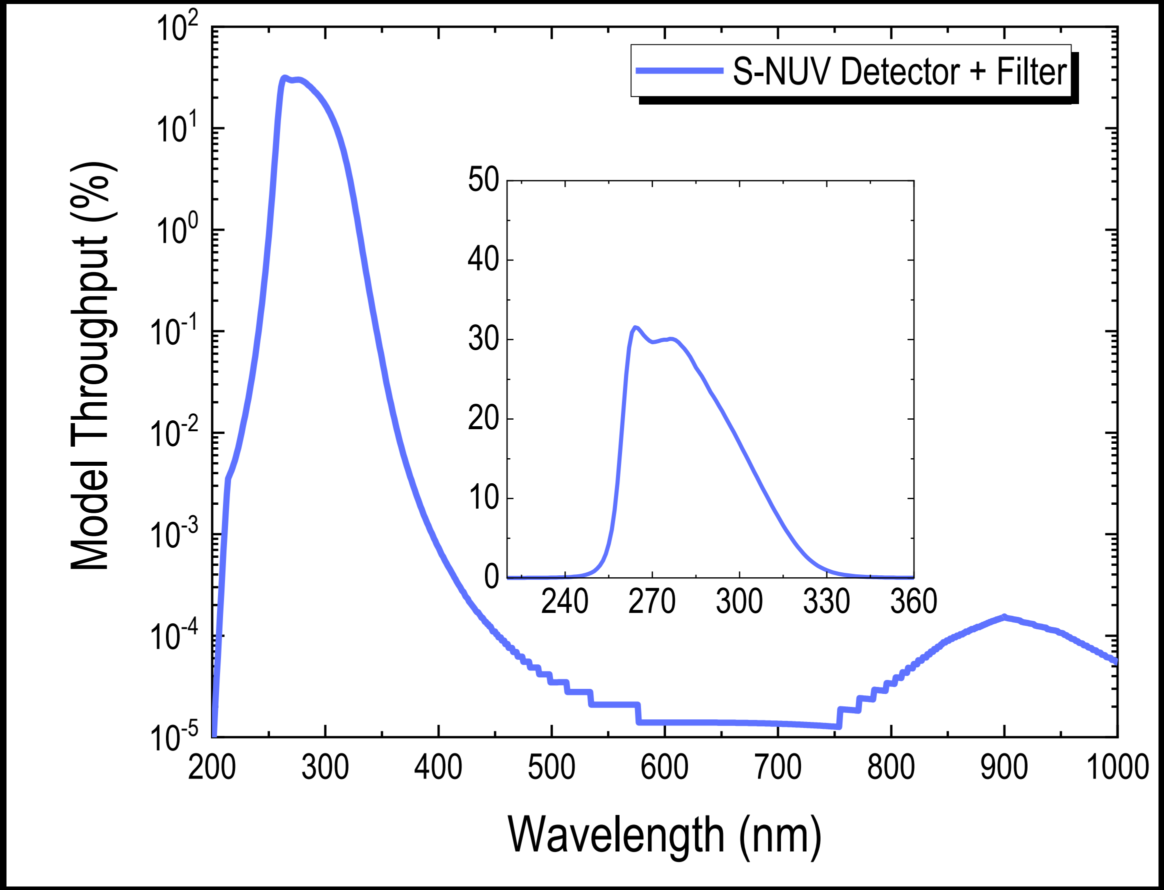
- JPL's doping processes yield nearly 100% internal QE
- Simple, single layer HfO_2 AR coating used to improve in-band response
- The SPARCS NUV prototype detector exhibits >70% QE throughout the S-NUV band



Jewell et al., *Proc. SPIE* **10709** (2018) 107090C

Red Leak Suppression

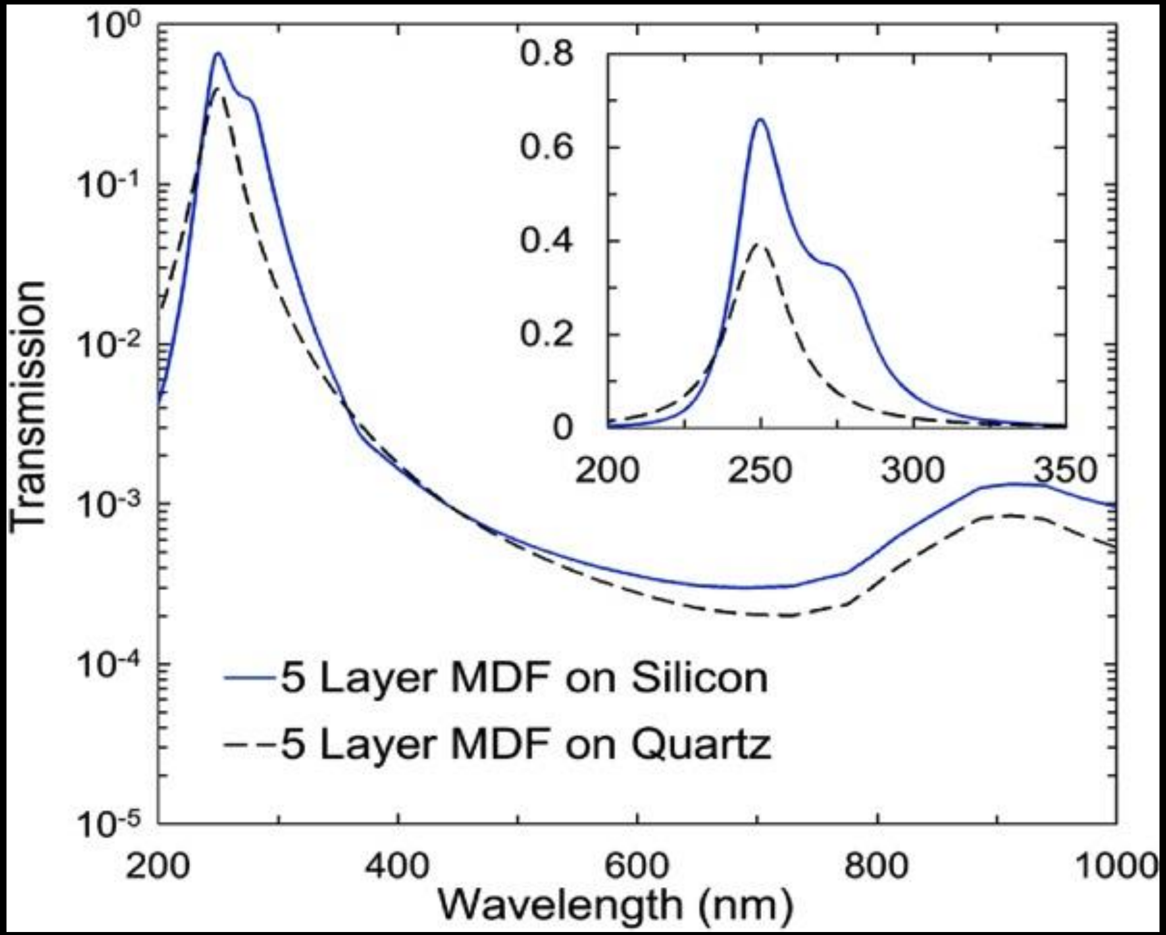
- SPARCS will use bandpass filters to minimize red leak
- We will use a commercial bandpass filter in the NUV channel
- Defines bandpass and central wavelength
- Results in throughput of ~30% in NUV channel
- Provides ≥OD3 to 1000 nm



Jewell et al., *Proc. SPIE* **10709** (2018) 107090C

Solar-blind Silicon

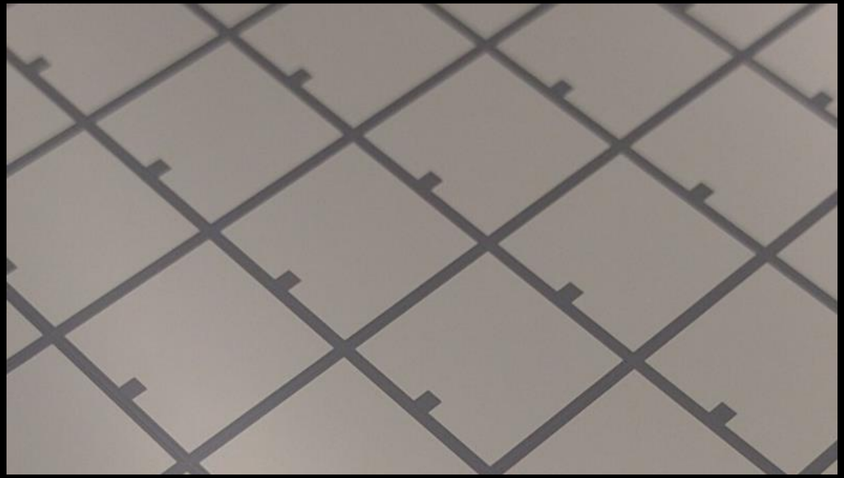
- No commercial filter available meets SPARCS' needs
- JPL has developed solar-blind filters for silicon detectors
  - Metal-dielectric filter (MDF) stack (i.e., Fabry-Perot structure) deposited directly on silicon substrate
  - Allows for index matching
  - Can match dielectric to suit our needs

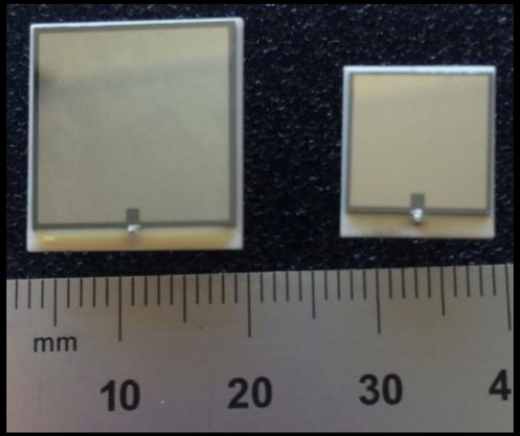


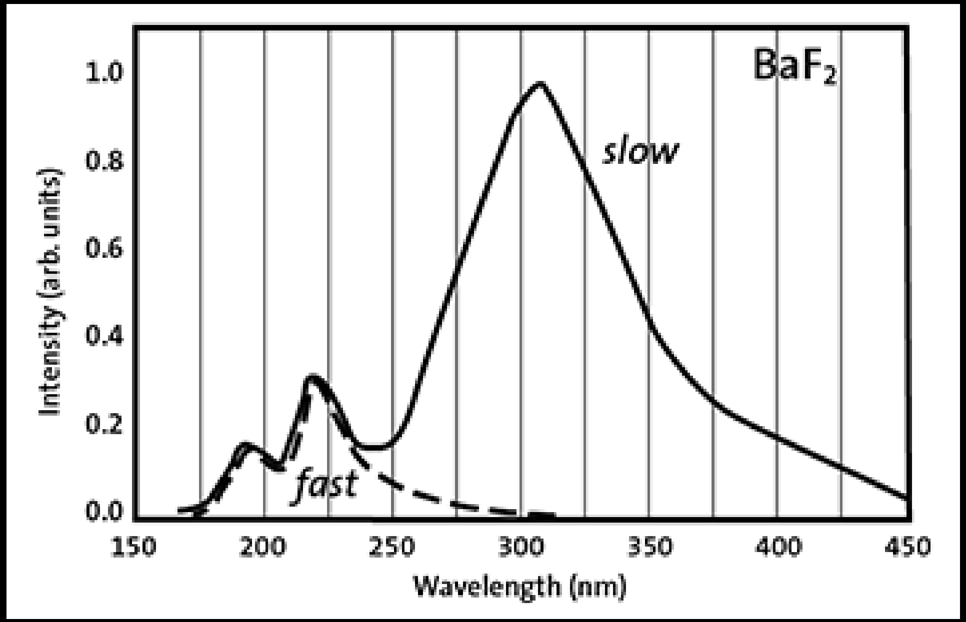
Hennessy et al., *Appl. Opt*. **54** (2015) 3507

Solar-blind Silicon for Physics Applications

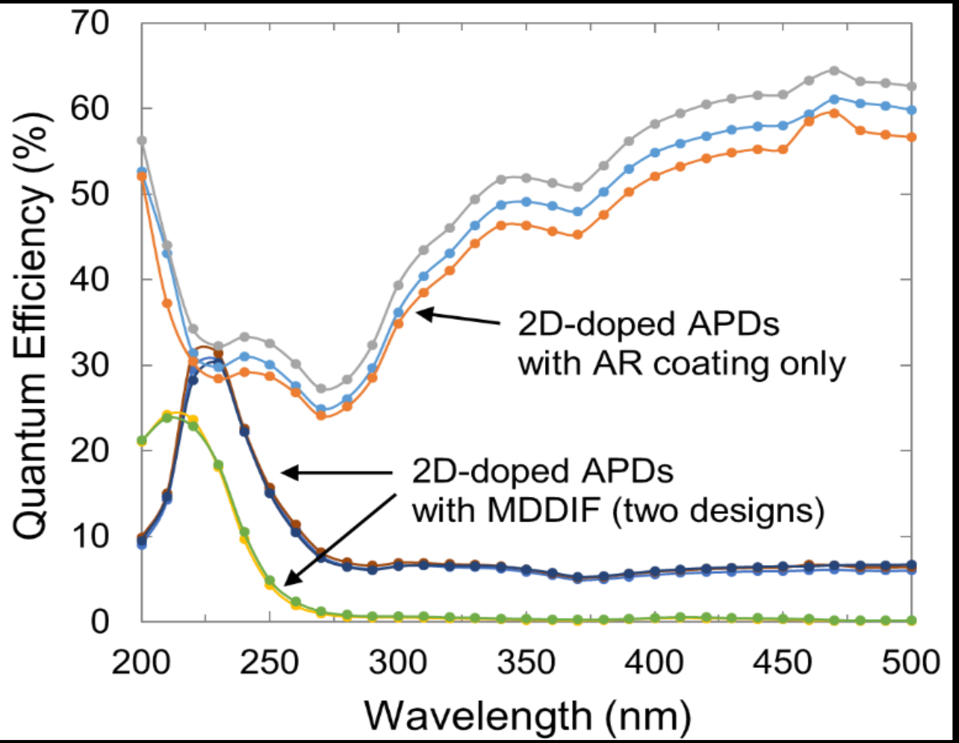
- Previously developed for use with Si avalanche photodiodes (APDs) for fast scintillation detection with BaF_2
  - Filter made with Al/Al_2O_3 stack
  - λ_o=220 nm ($\Delta\lambda$=20 nm FWHM)







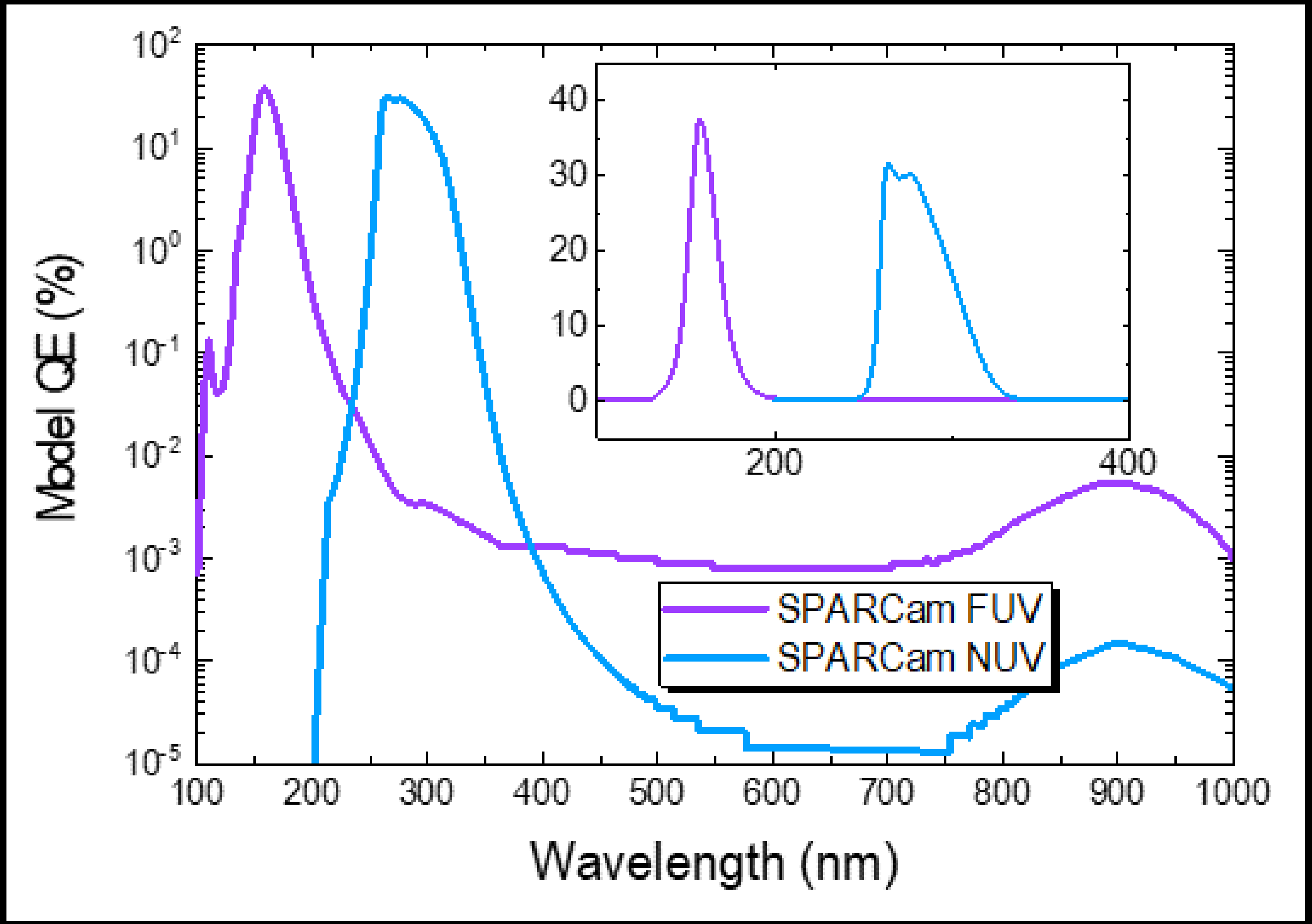
www.crystals.saint-gobain.com/



Nikzad et al., *JATIS* **3** (2017) 3507

Optimized Solar-blind FUV Detector

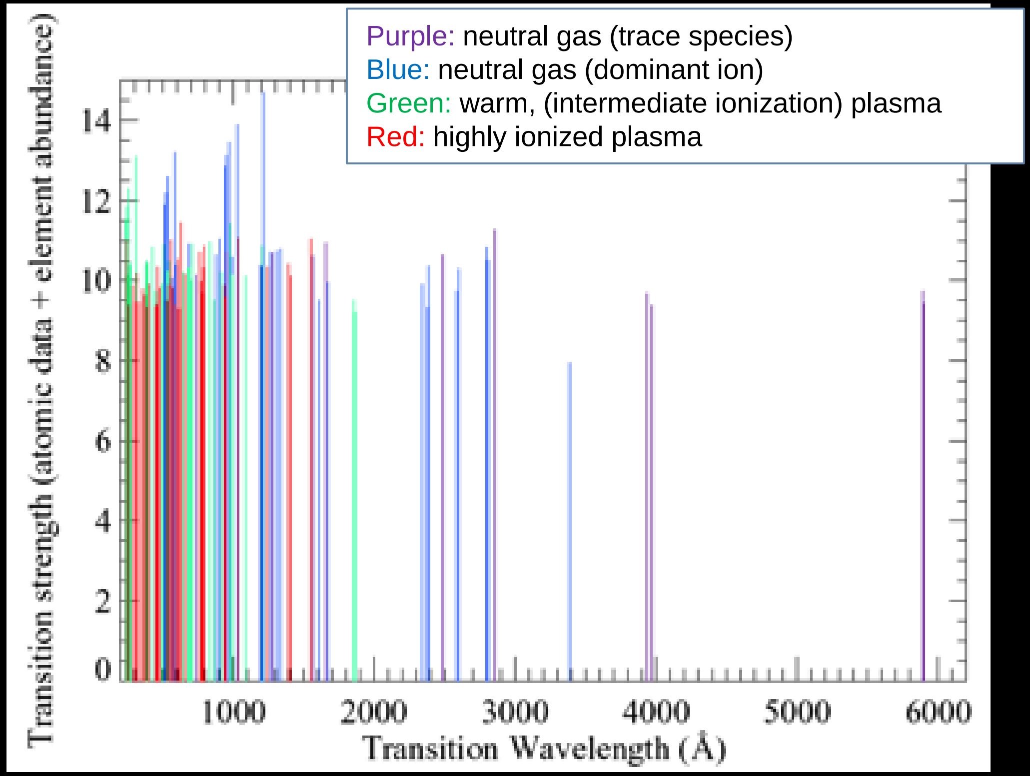
- MDF design will be optimized for SPARCS
- Filter is based on Al/AlF_3 where the thickest layer is <40 nm



Jewell et al., *Proc. SPIE* **10709** (2018) 107090C

Thin Film Coatings for Reflective Optics

Materials challenges in the far ultraviolet



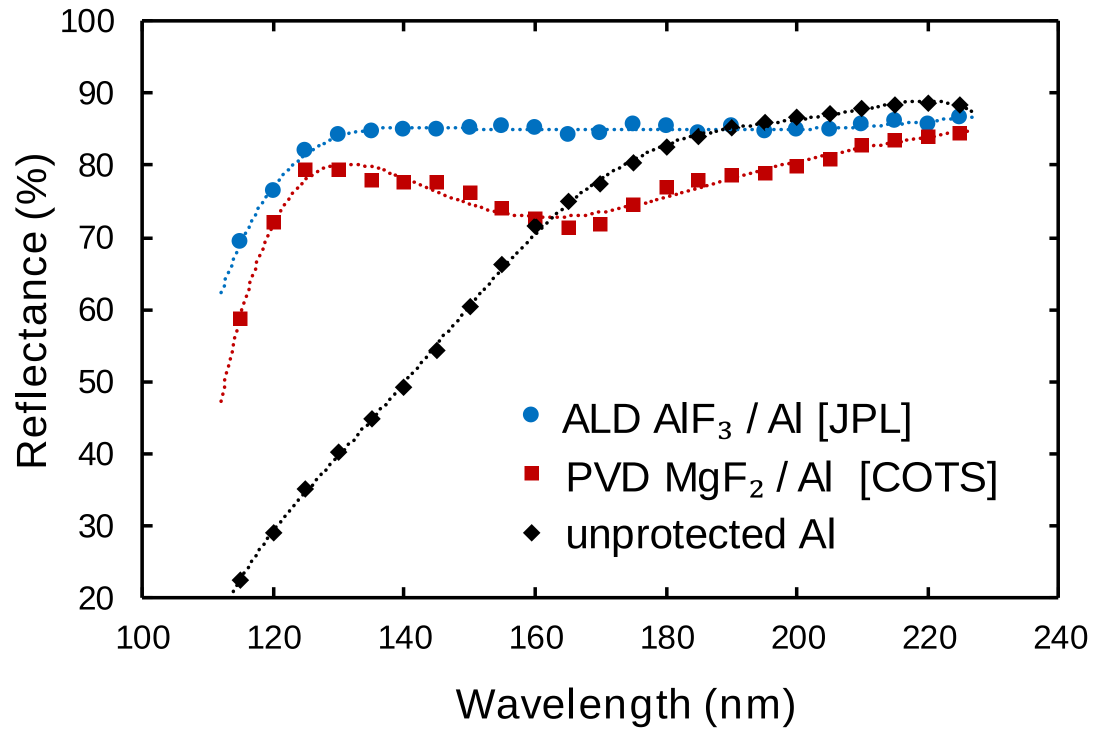
[Scowen, P.A., *et* al., Proc. SPIE 10398, 1039807 (2017)]

Reflective metals for the UV

Material	Plasma Frequency (eV)
aluminum	15
silver	3.7
gold	5.8
palladium	7.7
nickel	9.5

- Earth's atmosphere is opaque below 320 nm
- The high density of diagnostic lines in the FUV motivates interest for astrophysics
- The free-electron behavior of Al makes it highly reflective in the UV, but also very reactive and its oxide is strongly absorbing in the UV
  - → 90-115 nm is an interesting part of the spectrum but the same physics make high throughput challenging

Protecting Al Mirrors with Metal Fluoride Materials

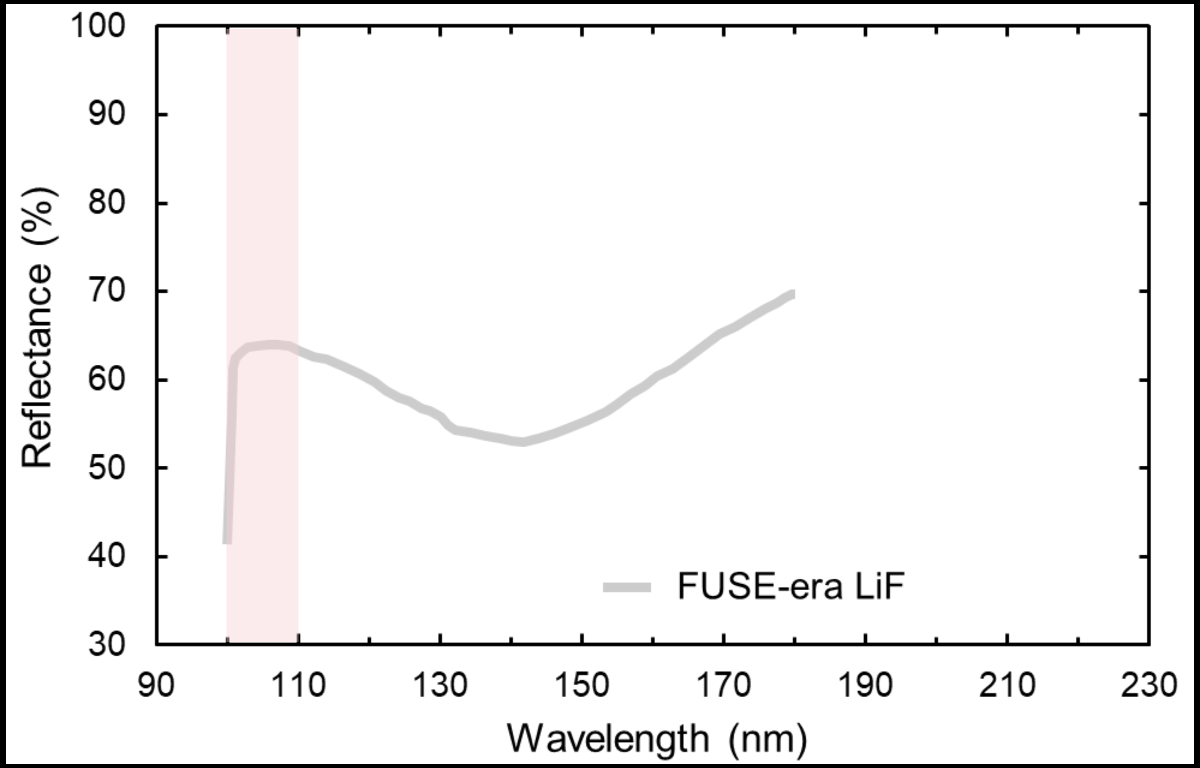


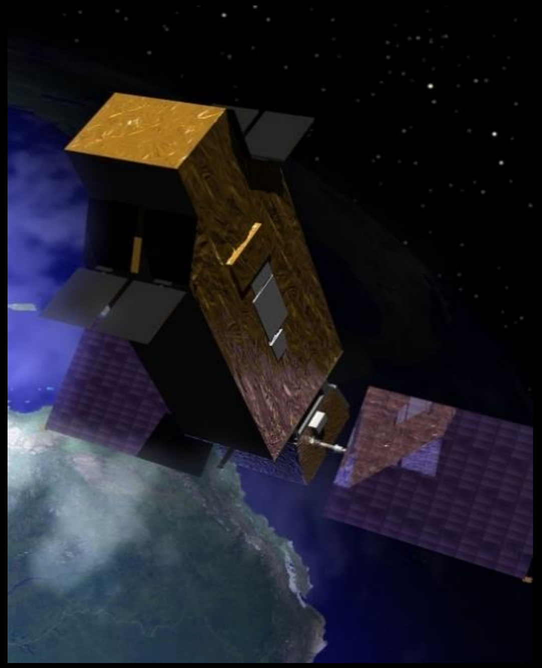
Material	Co-reactant with Anhydrous HF	$T_{substrate}$ (°C)	~λ Cutoff (nm)
MgF_2	bis(ethylcyclopentadienyl) magnesium	100-250	115-120
AlF_3	trimethylaluminum	100-200	105-110
LiF	lithium bis(trimethylsilyl)amide	100-250	95-100

- Utilize anhydrous HF as the fluorine-containing precursor
- Large dependence on temperature for all processes
- Can deposit all materials at 100 °C

[Hennessy, J., *et* al., JVST A 33, 01A125 (2015)]
[Hennessy, J., *et* al., JVST A 34, 01A120 (2016)]
[Hennessy, J., et al., Inorganics 6, 46 (2018)]

LiF as a mirror coating material

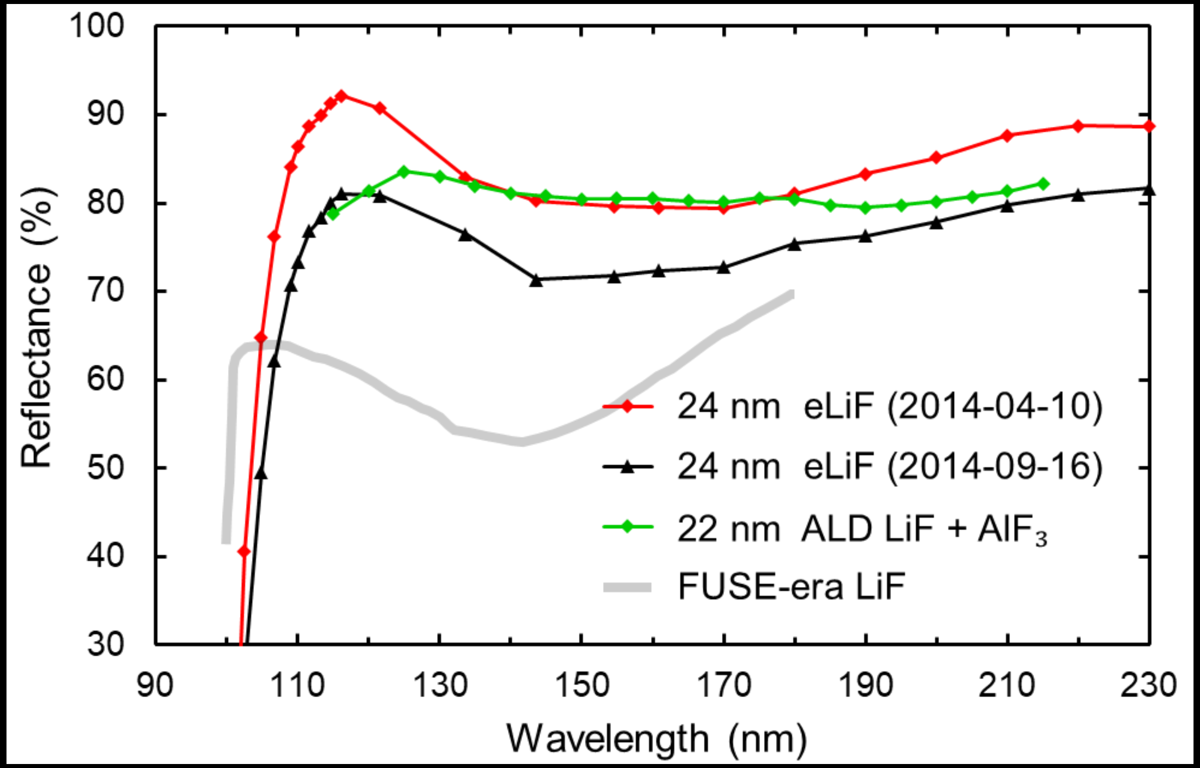


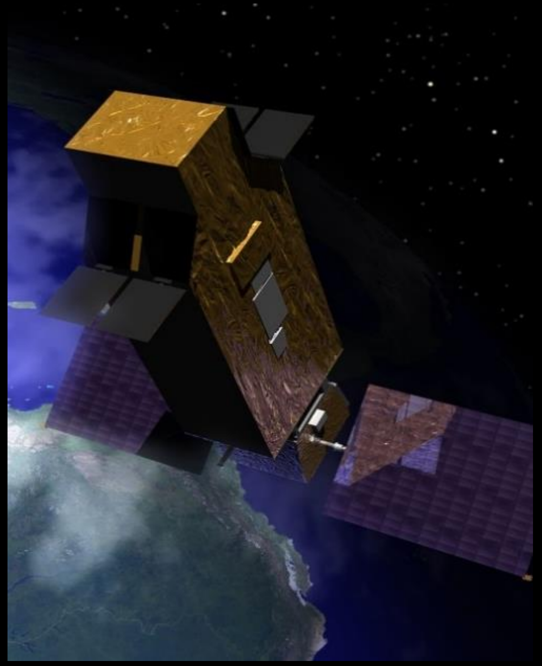


FUSE
Launched 1999
~0.4 m Mirror/Channel
15 nm of LiF on Al
λ_{min}^{*} ~ 100 nm

- Far ultraviolet spectroscopic explorer (FUSE) used LiF-protected Al to operate 100–110 nm bandpass
- Overall reflectance was moderate, entire instrument was ‘bagged’ and purged with nitrogen during assembly, integration, and testing

LiF as a mirror coating material





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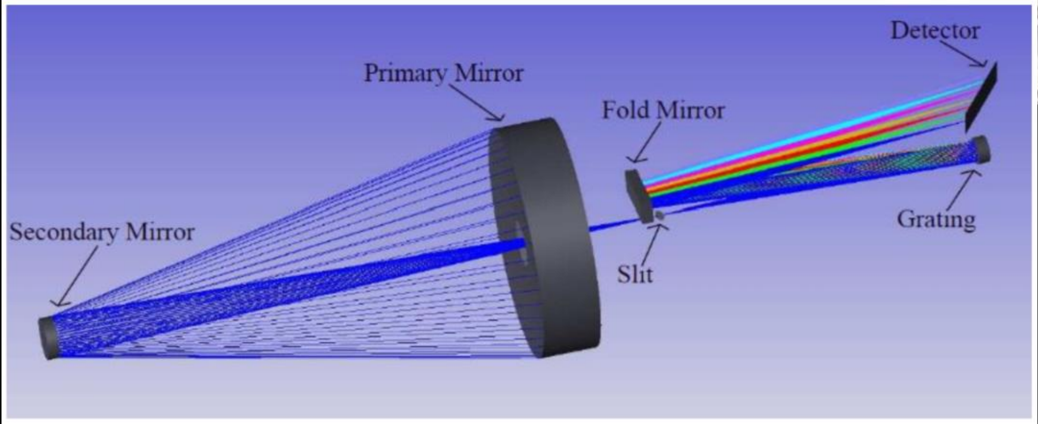
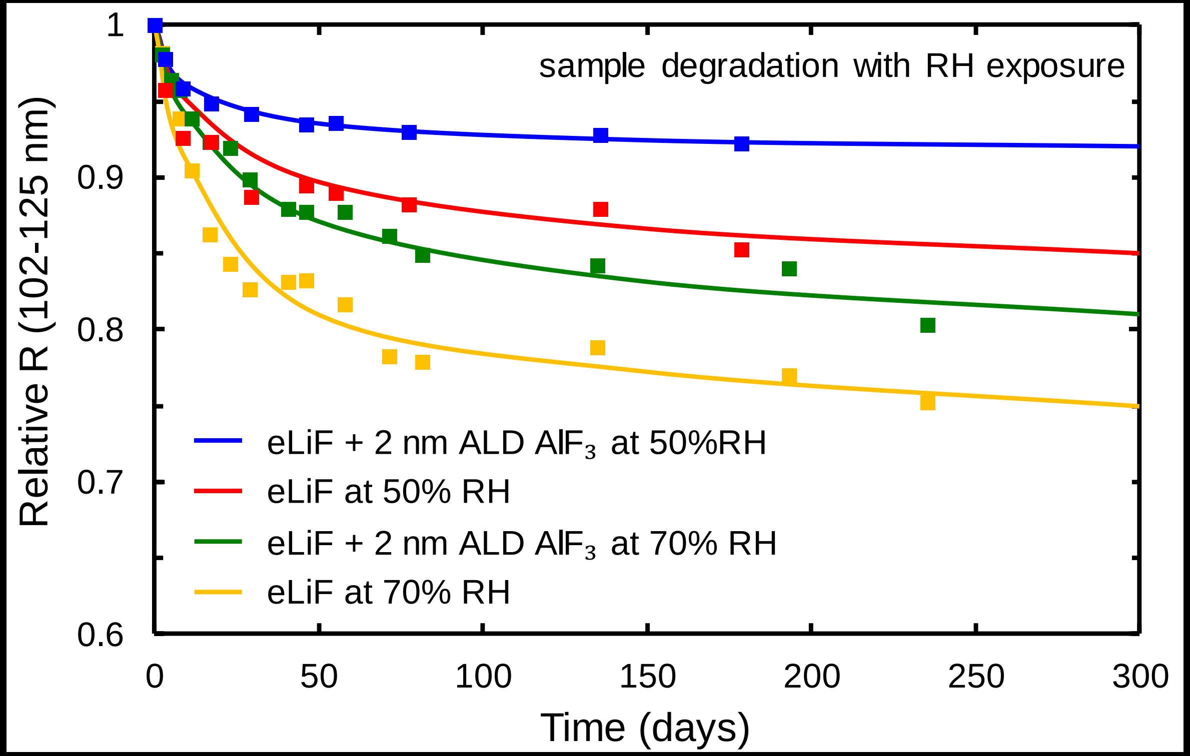
Encapsulating the Protective Layer

100 mm convex SISTINE secondary overcoated at JPL





- Coating LiF with another ultrathin (<2 nm) fluoride can enhance stability
- SISTINE sounding rocket launched July 2019
  - Look at UV radiation from low mass stars
  - Collaboration with K. France & B. Fleming (CU-Boulder)

Team and Collaborators

Jet Propulsion Lab
Shouleh Nikzad
Michael Hoenk
Alex Carver
Sam Cheng
John Hennessy
Todd Jones
Gillian Kyne

Arizona State University
Prof. Evgenya Shkolnik
Prof. Paul Scowen

University of Arizona
Prof. Erika Hamden
Prof. Walt Harris

Caltech
Prof. Chris Martin
Keri Hoadley

Columbia University
Prof. David Schiminovich

University of Colorado - Boulder
Prof. Kevin France
Prof. Brian Fleming

Teledyne-e2v
Paul Jerram
Giuseppe Borghi
David Morris
Katherine Lawrie

april.d.jewell@jpl.nasa.gov

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov