Atomic Layer Deposition (ALD) - An Enabling Technology for NASA Space Systems

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3/26/2019

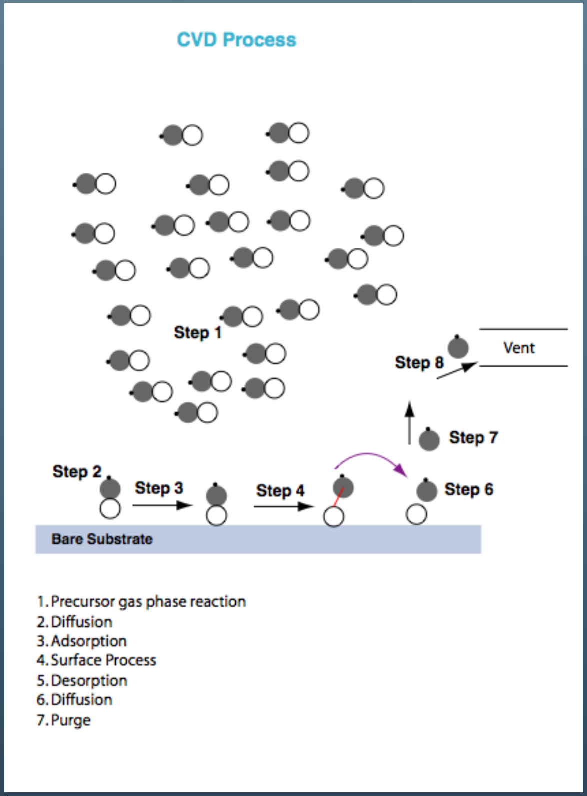
What is a Thin Film?

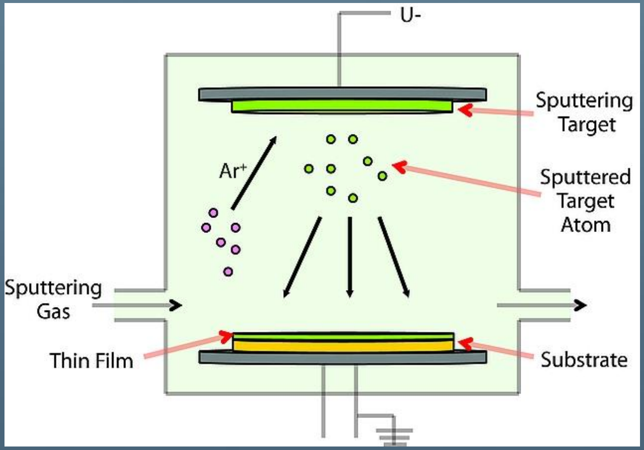
Thin film: thickness typically <1000nm.

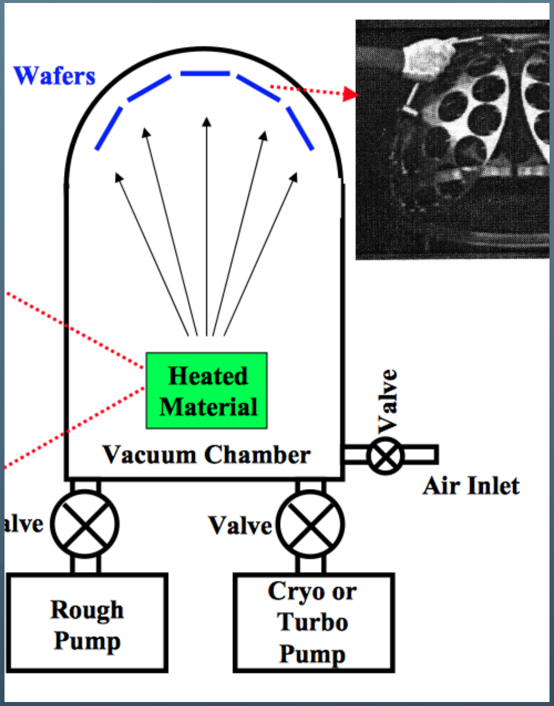
Special properties of thin films: different from bulk materials, it may be –

- Not fully dense
- Under stress
- Different defect structures from bulk
- Quasi - two dimensional (very thin films)
- Strongly influenced by surface and interface effects

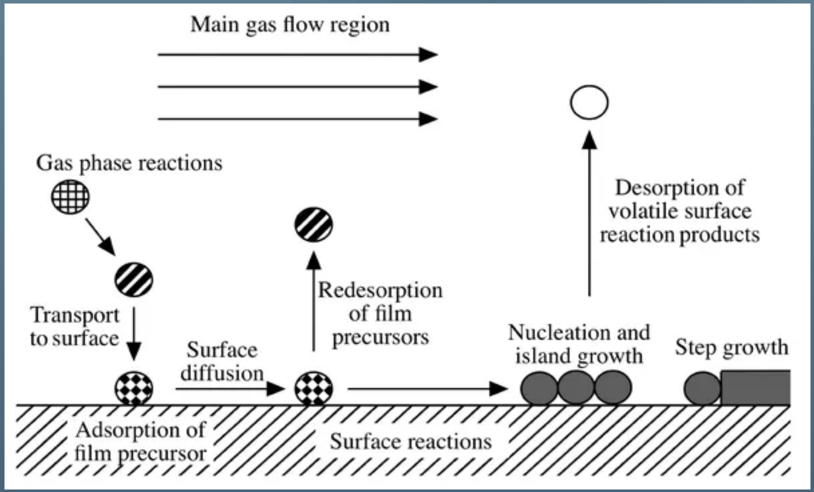
Other Deposition Techniques





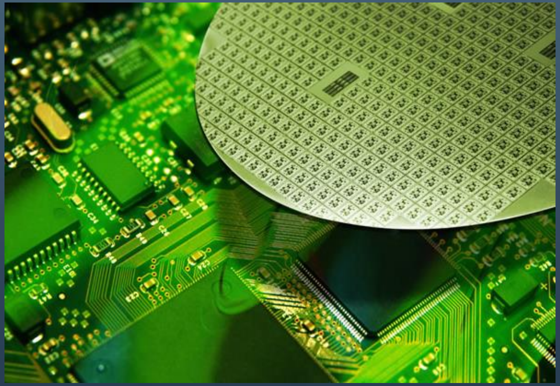


Thin-Film Engineering



Vapor-phase deposition of inorganic materials

Microelectronics



James River Semiconductor

Solar energy

First Solar

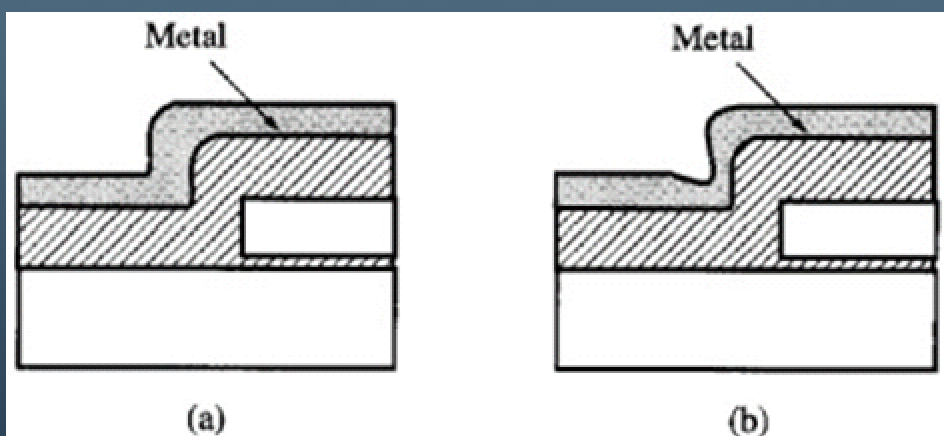
Solid-state lighting

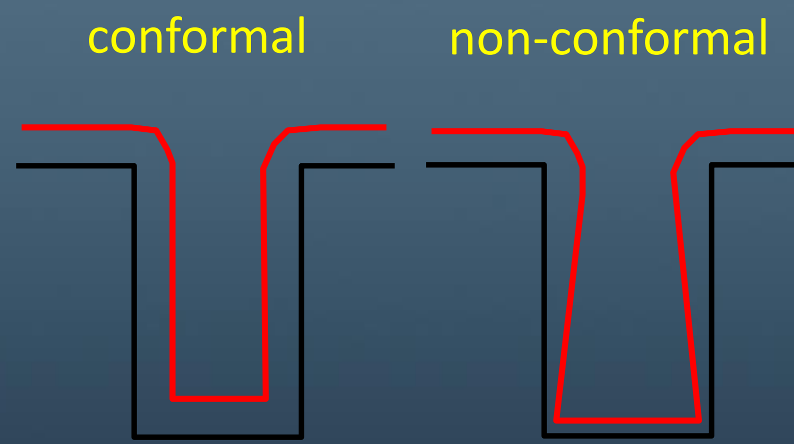
The New Ecologist

Common Denominator

- Deposition only occurs on substrates that “see” the target.
- Plasma process can damage the substrate
- Poor thickness control
- Poor Step Control
- High Pressure High Temperature Environment

Step Coverage Example





Step coverage of metal over non-planar topography.

(a) Conformal step coverage, with constant thickness on horizontal and vertical surfaces.

(b) Poor step coverage, here thinner for vertical surfaces.

Atomic Layer Deposition

Atomic
Layer
Deposition

} **A thin film"nanomanufacturing" tool that allows for the conformal coating of materials on a myriad of surfaces with precise atomic thickness control.**

Based on:

- **Paired gas surface reaction chemistries**
- **Benign non-destructive temperature and pressure environment**
  - **Room temperature -> 250 °C (even lower around 45 °C)**
  - **Vacuum**

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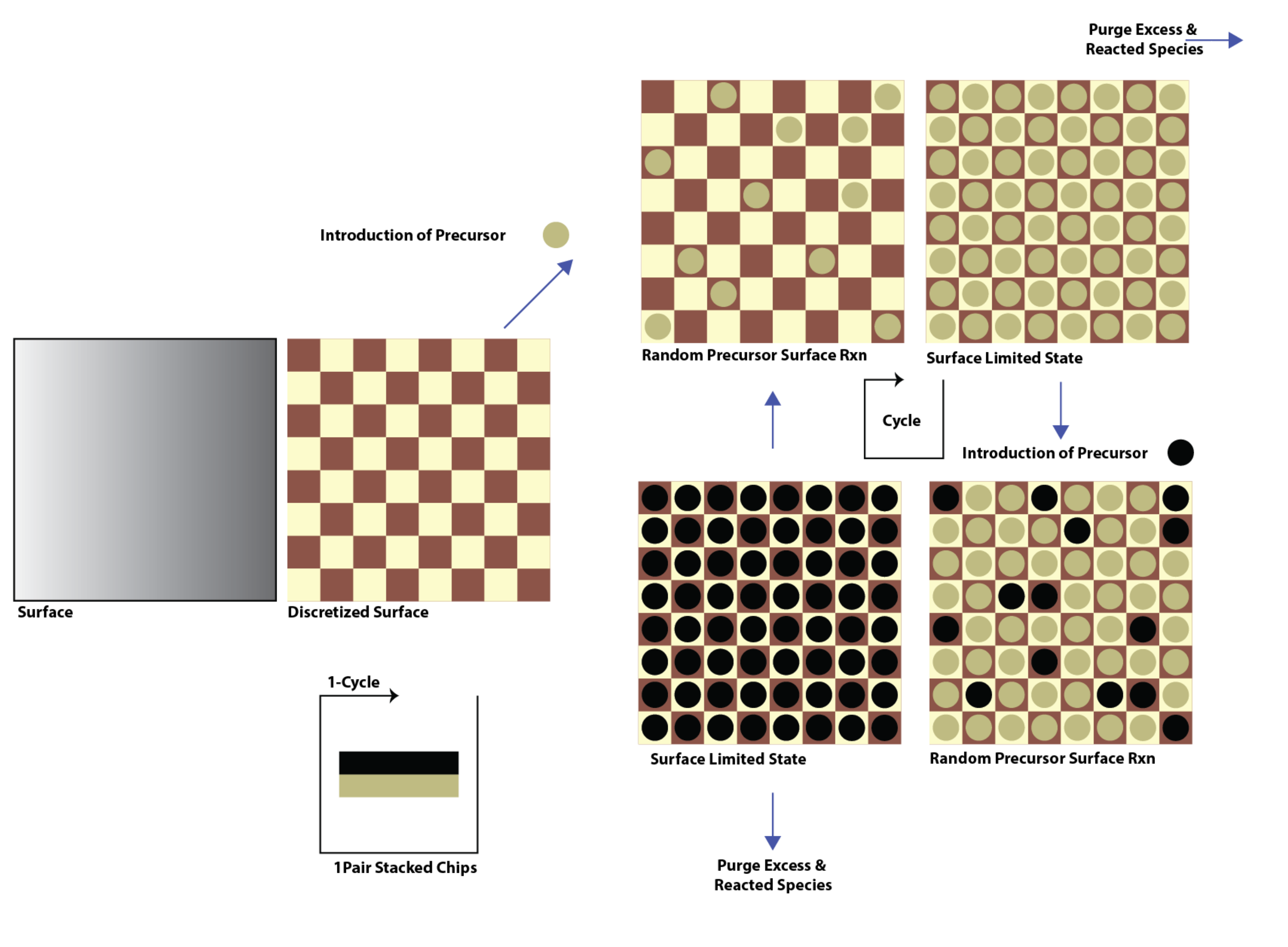
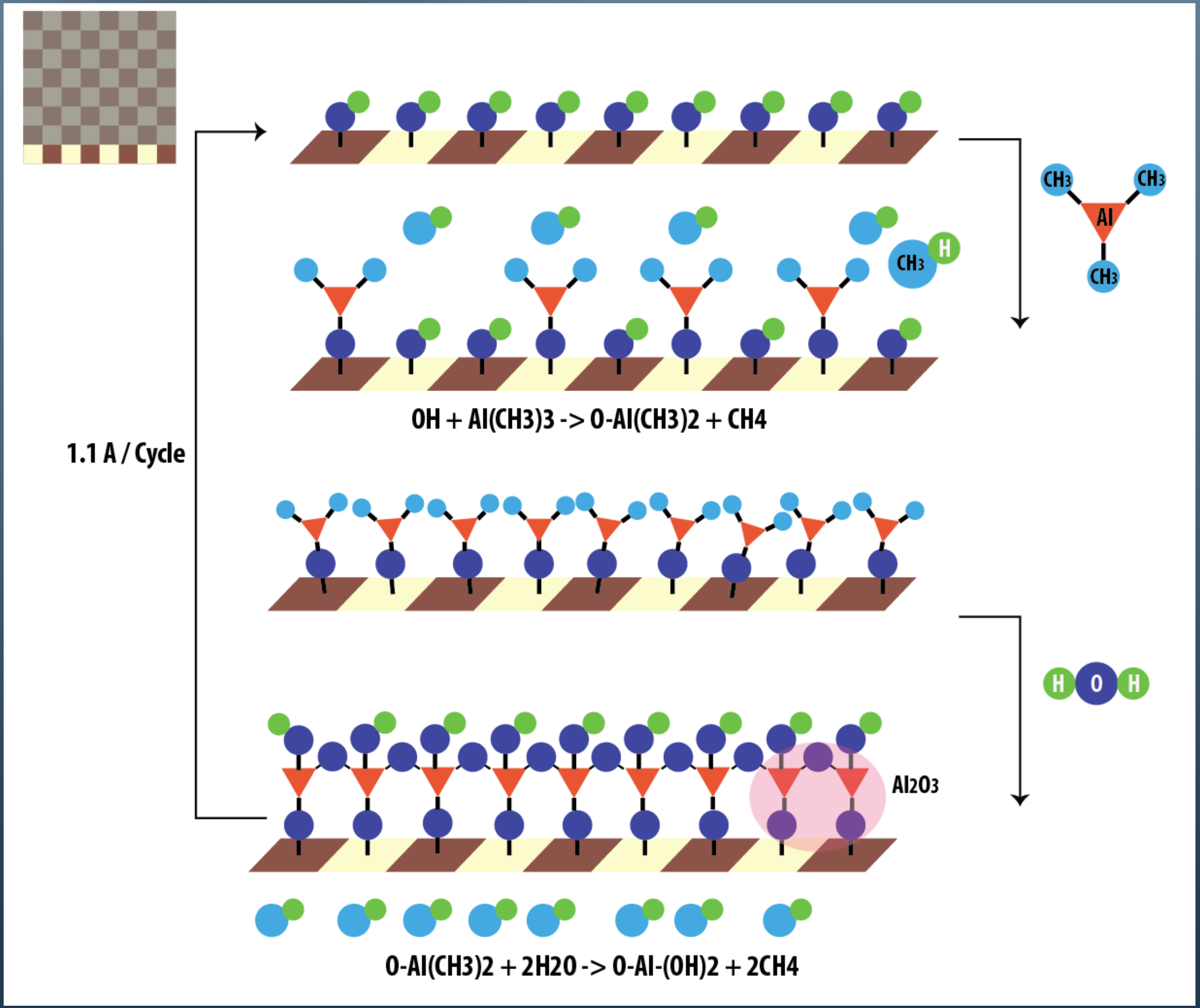
ALD Analogy (Checkers)



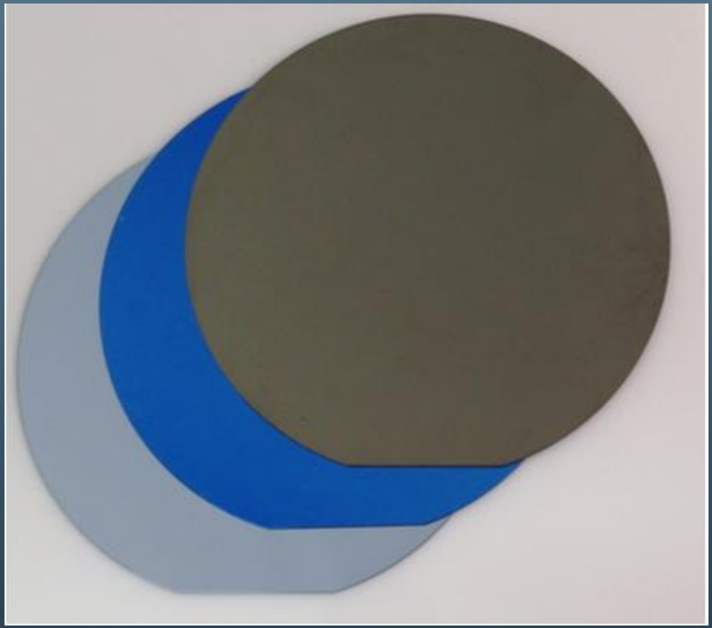
ALD Analogy Chemistry

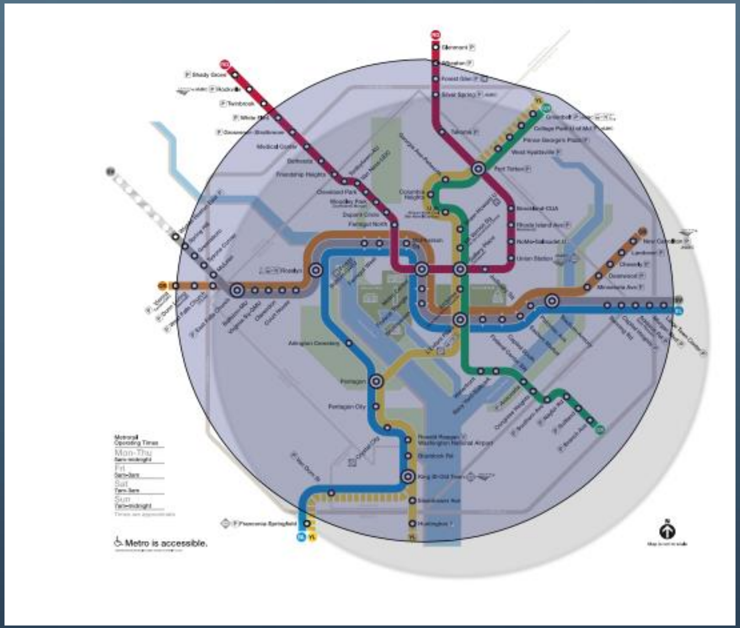


ALD

Precursor A + Precursor B → Solid film + Gas by-products
Cyclic operation: A → purge → B → purge → A → purge → ⋯

Atomic-level thickness control ...

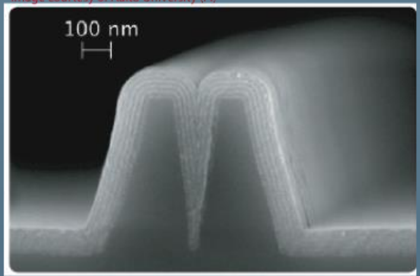


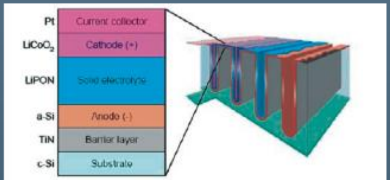


... equivalent to a 60 µm layer over a city-sized wafer

ALD Advantageous Property

Artificial trench filled with an ALD nanolaminate
Image courtesy of Aalto University (FI)





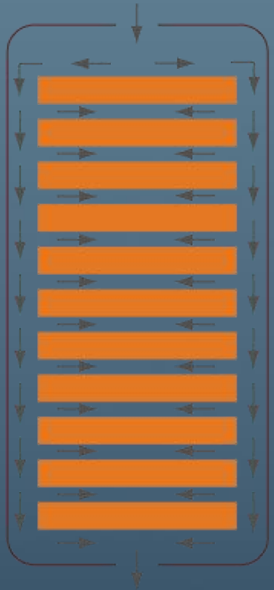
Schematic of a 3D battery integrated in a Si- substrate. The cross-section shows the various functional layers in the battery stack as well as the candidate materials.
Knoops, H.C.M. et al., ECS Trans., 25 (2009) pp. 333-344

Epitaxial Growth

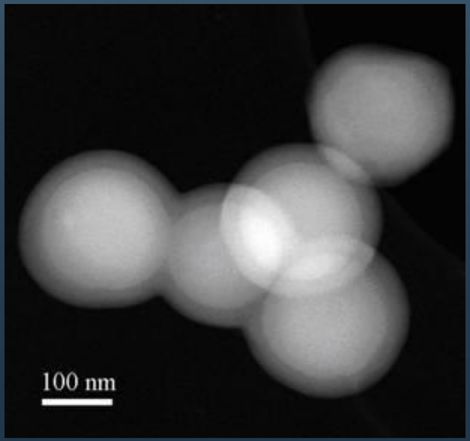
Multilayer consisting of:
Al2O3 - 25 nm
TiN - 20 nm
Al2O3 - 25 nm
Dr. Fred Roozeboom, NXP Semiconductors Research and Dr. Erwin Kessels, University of Technology, Eindhoventd

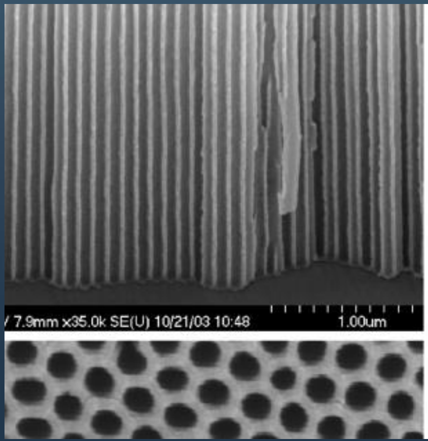
Batch Process

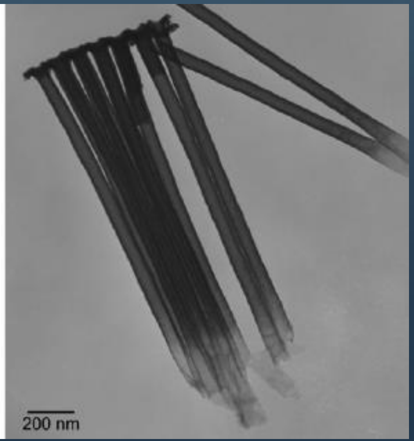
Coating Silver with Aluminum Oxide
http://www.glassonweb.com/

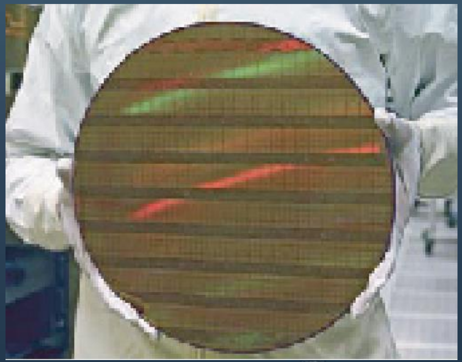


Substrate Independence









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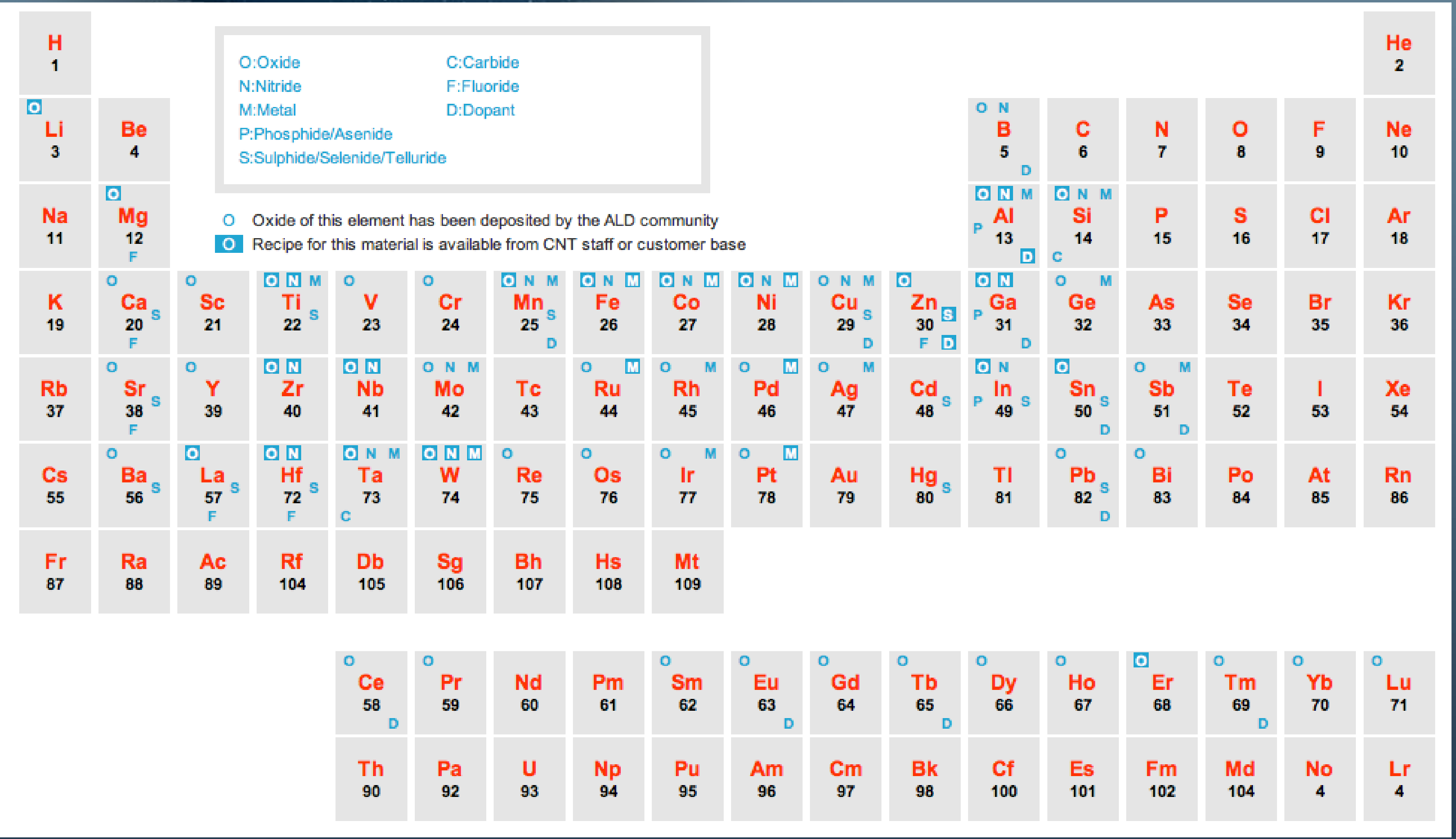
ALD Material Systems



• Gordon, Roy (2008). Atomic Layer Deposition (ALD): An Enable for Nanoscience and Nanotechnology. PowerPoint lecture presented at Harvard University, Cambridge, MA.
• Elam, Jeffrey (2007). ALD Thin Film Materials. Argonne National Laboratory

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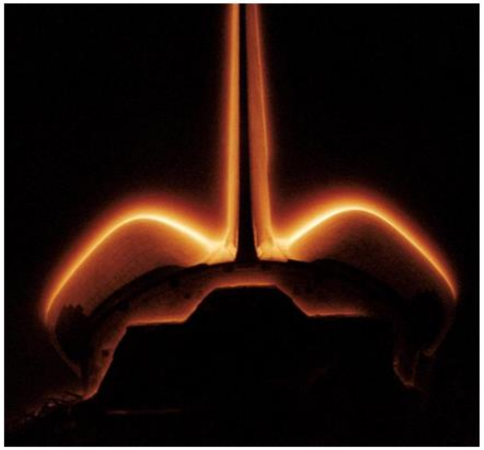
NASA Impacts



NASA STS-062; *Nature*, **354** (1991)

ISS Orbit 400 km
Atomic O Density = 1×10^{8} cm^{-2} s^{-1}
v = 7.2×10^{5} cm s^{-1}
-> 1 O impact nm^{-2} s^{-1}
KE = 4.2 eV

Alumina ALD on Kapton substrate

$$Al_2(CH_3)_6 + 3H_2O \rightarrow Al_2O_3 + 6CH_4$$

- Conformal, flexible, $\mathcal{O}$(100 nm), **nonvolatile oxide** coating
- Low temperature (100 °C) deposition process

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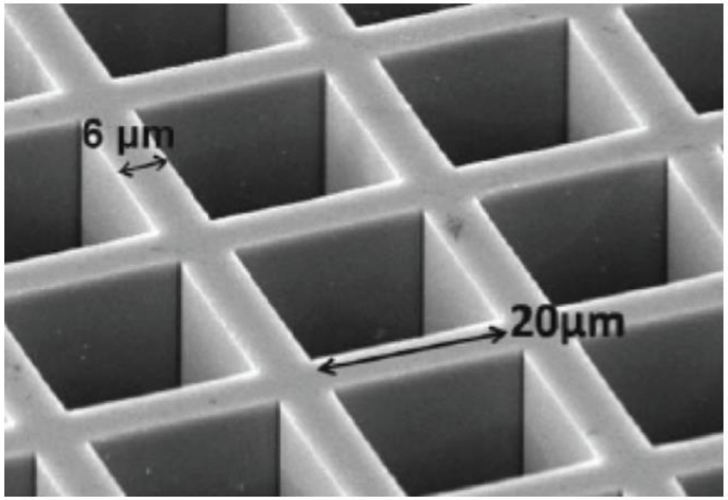
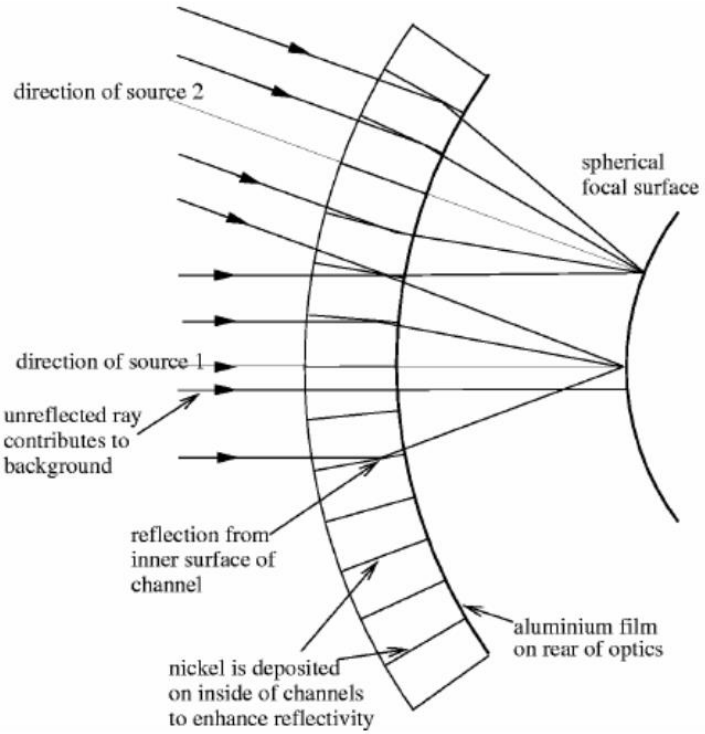
STORM XRI



NASA GSFC

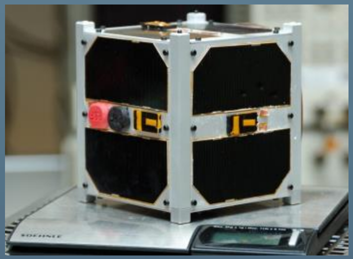


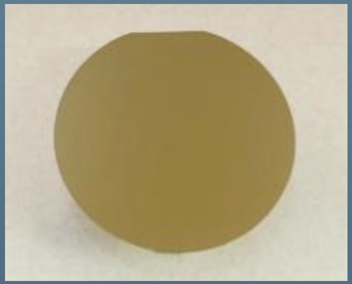
Black et al. 2003, arXiv

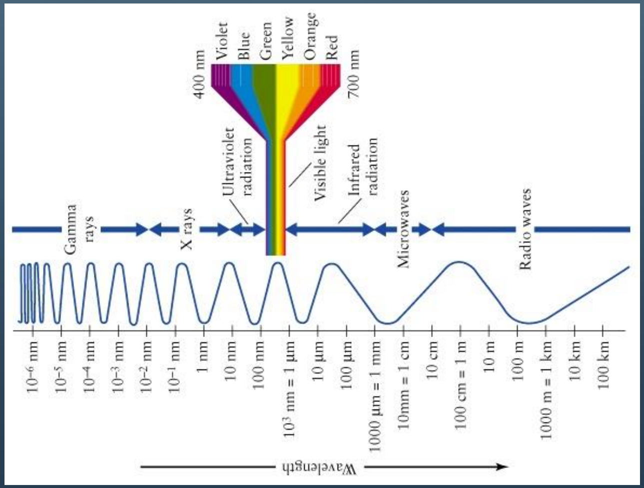
Ni ALD

$$\mathrm{Ni(acac)_2(g) + MeOH(g) \rightarrow Ni(s) + 2Hacac(g) + CH_2O(g)}$$

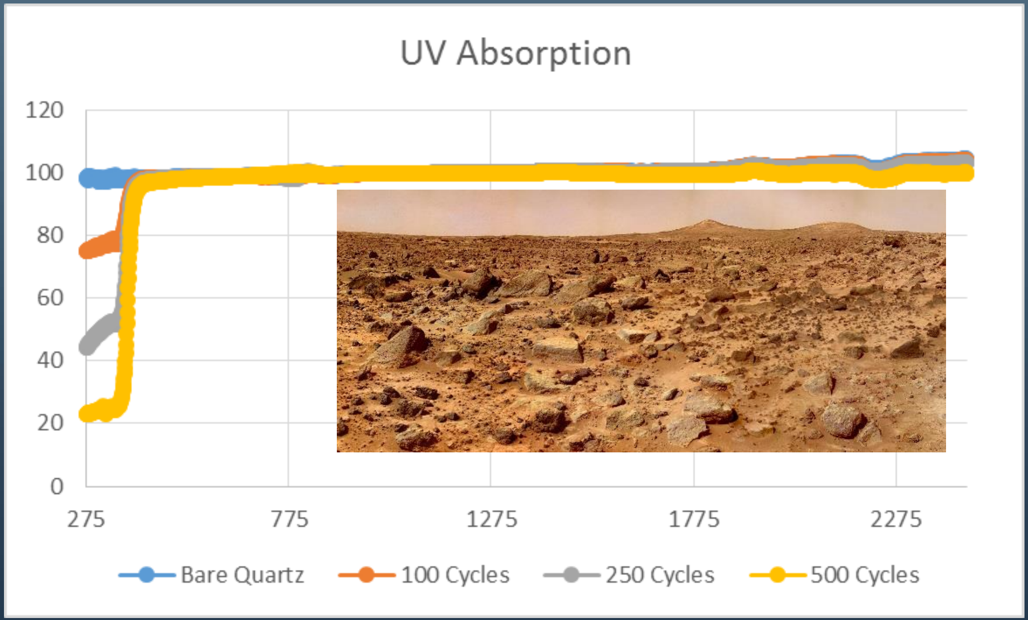
ZnO





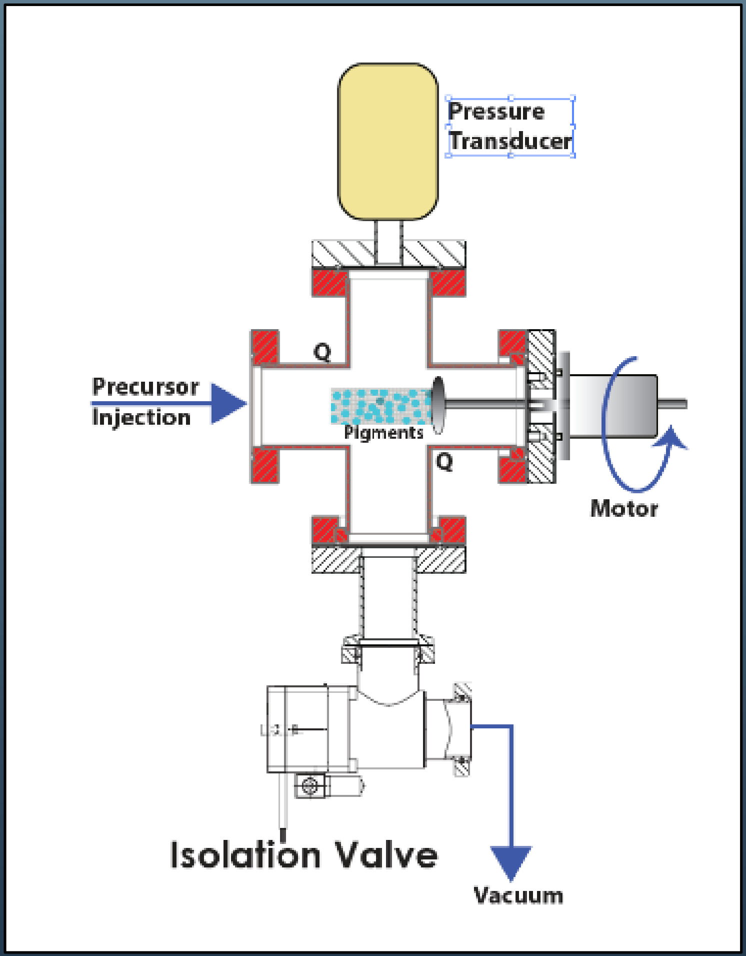


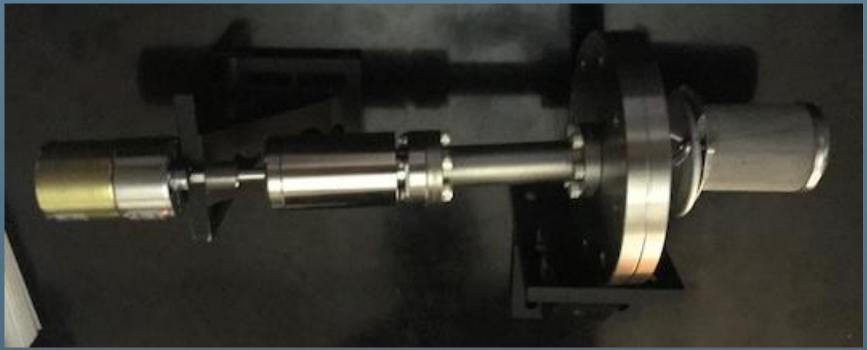
400 nm
Violet
Blue
Green
Yellow
Orange
Red
700 nm
Ultraviolet radiation
Visible light
Infrared radiation
Gamma rays
X rays
Microwaves
Radio waves
10⁻⁶ nm
10⁻⁵ nm
10⁻⁴ nm
10⁻³ nm
10⁻² nm
10⁻¹ nm
1 nm
10 nm
100 nm
10³ nm = 1 μm
10 μm
100 μm
1000 μm = 1 mm
10mm = 1 cm
10 cm
100 cm = 1 m
10 m
100 m
1000 m = 1 km
10 km
100 km
Wavelength

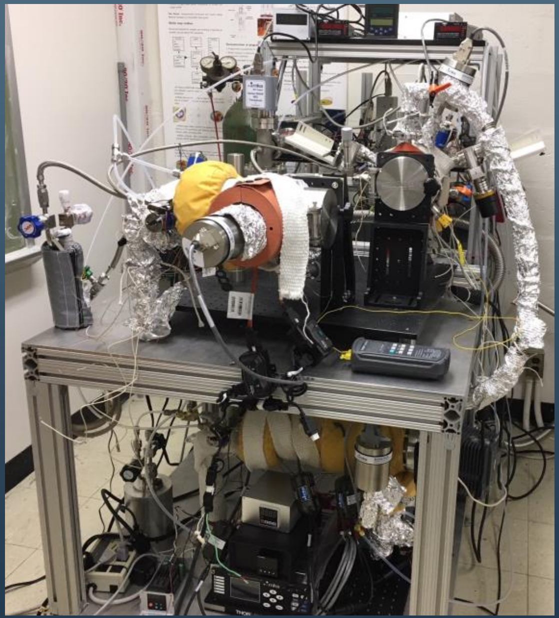


UV Absorption
120
100
80
60
40
20
0
275
775
1275
1775
2275
Bare Quartz
100 Cycles
250 Cycles
500 Cycles

ALD For Radiators - Pigments







Problem

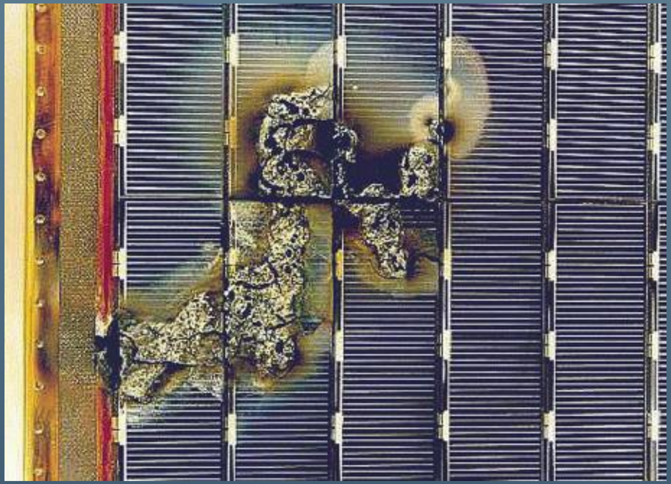
Spacecraft charging is the condition that occurs when a spacecraft accumulates excess electrons or ions. For a conducting spacecraft, the excess charges are on the surface. The term spacecraft surface charging (absolute charging) is used to clearly denote charging on the spacecraft surface as opposed to other charge distributions such as the voltage differences between electrically isolated parts of the spacecraft (differential charging).

HAZARD

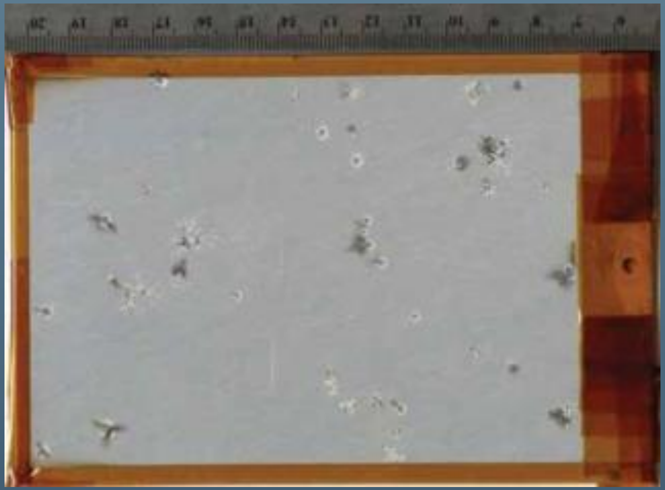
If a charge builds up that is too big for the spacecraft's material to hold, discharge arcs, which are essentially strong electrical currents, will occur.

And depending on where those arcs go, they can damage electronic components, destroy sensors, or damage important materials such as thermal control coatings.

Problem

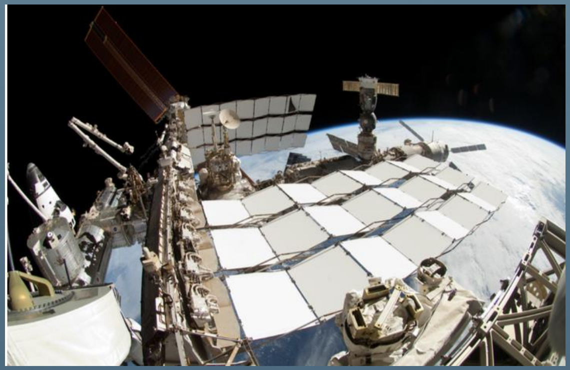


ESA EURECA satellite solar array sustained arc damage.
Credits: ESA

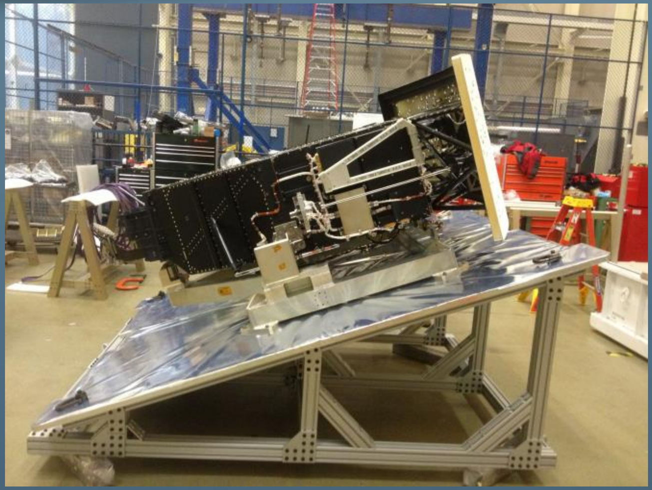


Arc damage in laboratory tests of the chromic acid anodized thermal control coating covering ISS orbital debris shields.
Credits: NASA/T. Schneider

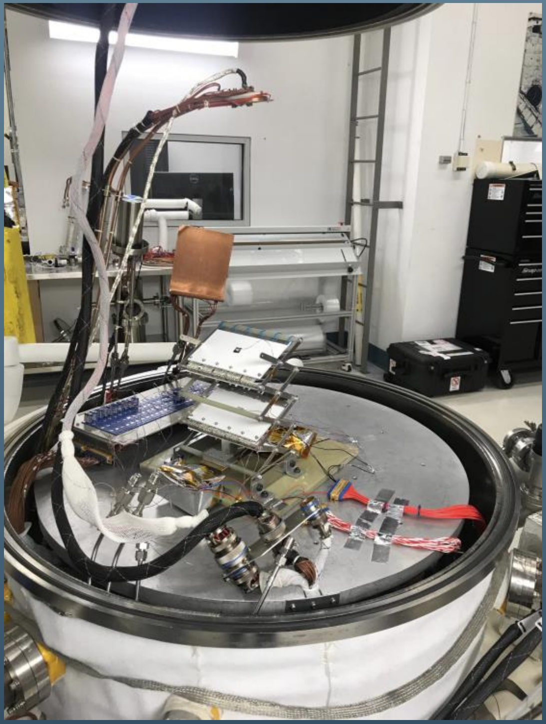
Radiator - Vary in Size



The space station's radiator system, which is a critical component of the active system, consists of seven panels (each about 6 by 12 feet)



Wide Field Planetary Camera 2 (WFPC2) that was installed on the Hubble Space Telescope in December 1993, and removed during the last servicing mission in 2009



Origami Inspired

Motivation

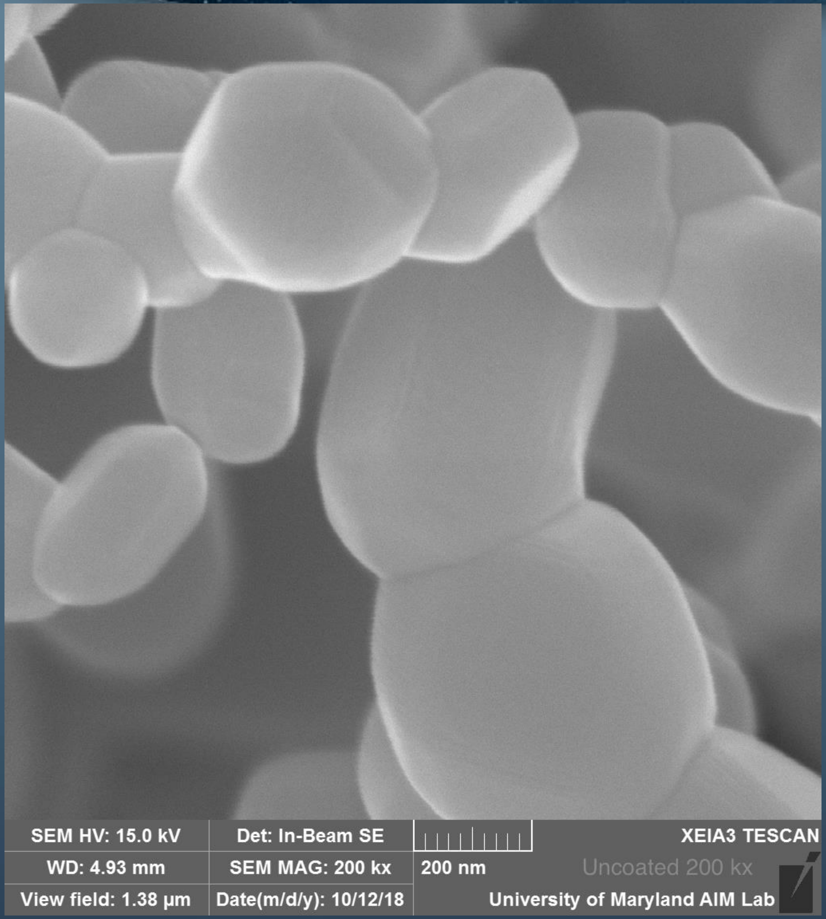
- Most white pigments do not dissipate electrical charge without a dopant or additive
- Two most commonly used dissipative thermal coatings (Z93C55 and AZ2000) rely on indium hydroxide or tin oxide as charge dissipative additives utilizing sol gel wet chemistry
- ITO formed locally on a macroscopic scale due to seeding and ITO crystal formation on the boundaries of the pigment grains. Thickness and dispersion throughout the coating are difficult to control.

Instead of postprocessing the dissipative coating can we preprocess the dissipative coating before binding directly on the pigment itself?

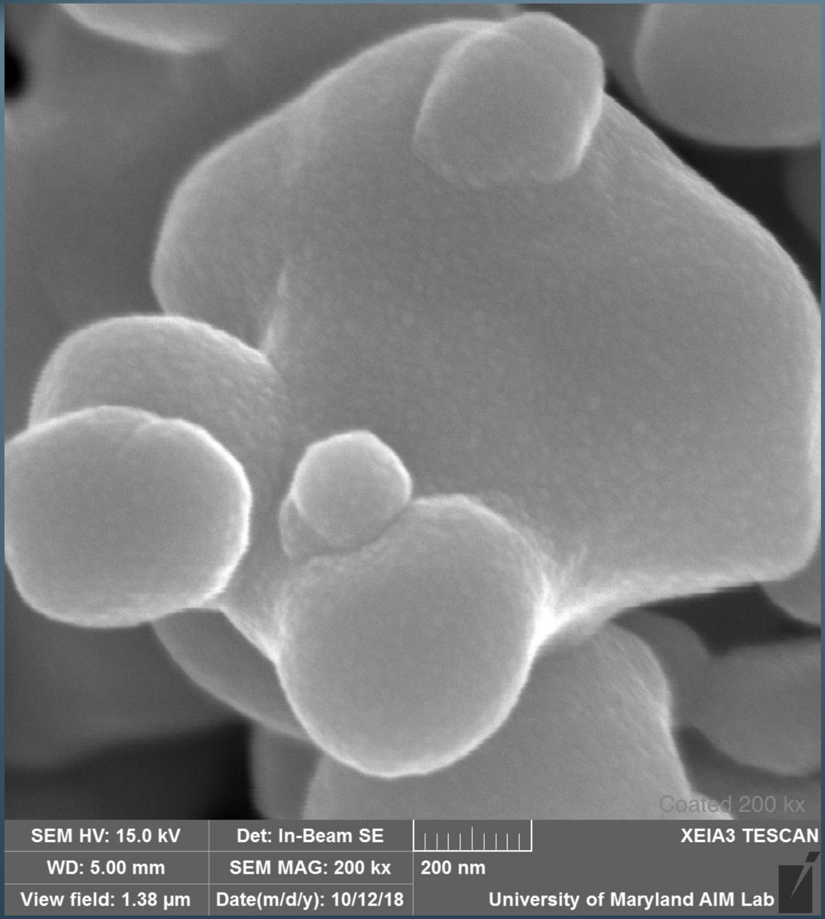
Experimental Procedures

- The first set of experiments were conducted on flat substrates for the ALD of In_2O_3 and ITO, the films were deposited on a variety of substrates including n-type Si(100) wafers for thickness measurements and glass microscope slides for sheet resistivity determination.
- The In_2O_3 ALD on the particle substrates was applied to Z93P pigments provided by Alion Science and Technology; these particles had a mean size of 2 microns.
- Thickness and conformity of the ALD films on the Si wafers of In_2O_3 and ITO were measured using a J.A. Woollam M-2000D Spectroscopic Ellipsometer. The sheet resistivity of the ALD films on the microscope glass substrates was measured using a Lucas Signatone S-302 four-point probe
- The bulk resistivity of the ALD deposited pigment system is measured in air after the formation of a pellet of 1 in. diameter and a thickness of approximately .5 in. The pigment is compressed lightly by hand and held in place by a 3D printed electrically insulating hollow nylon/Teflon annulus spacer held on an aluminum plate.   Resistivity was measured in air and vacuum.

Results



Uncoated Pigment



Coated Pigment

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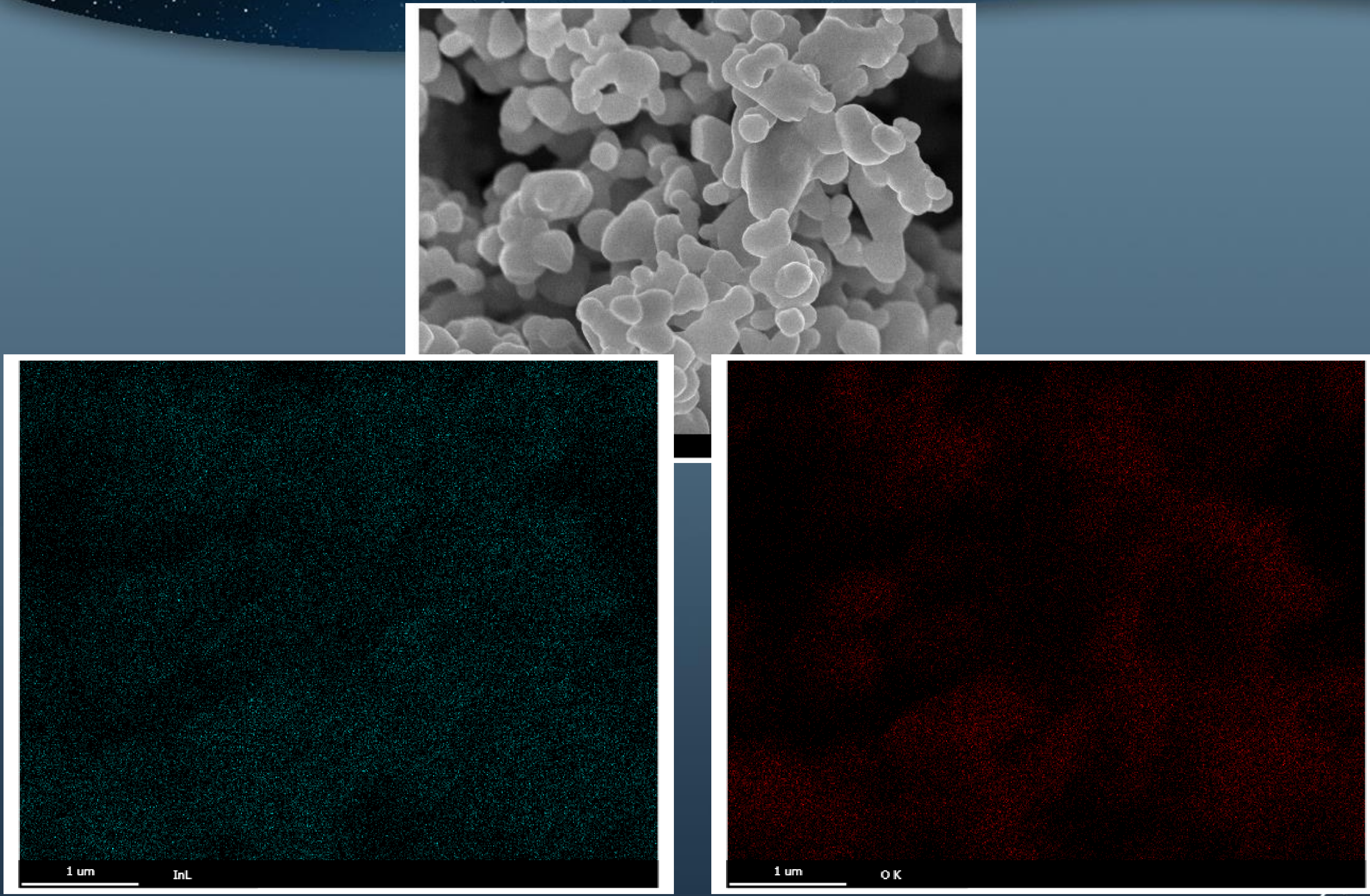
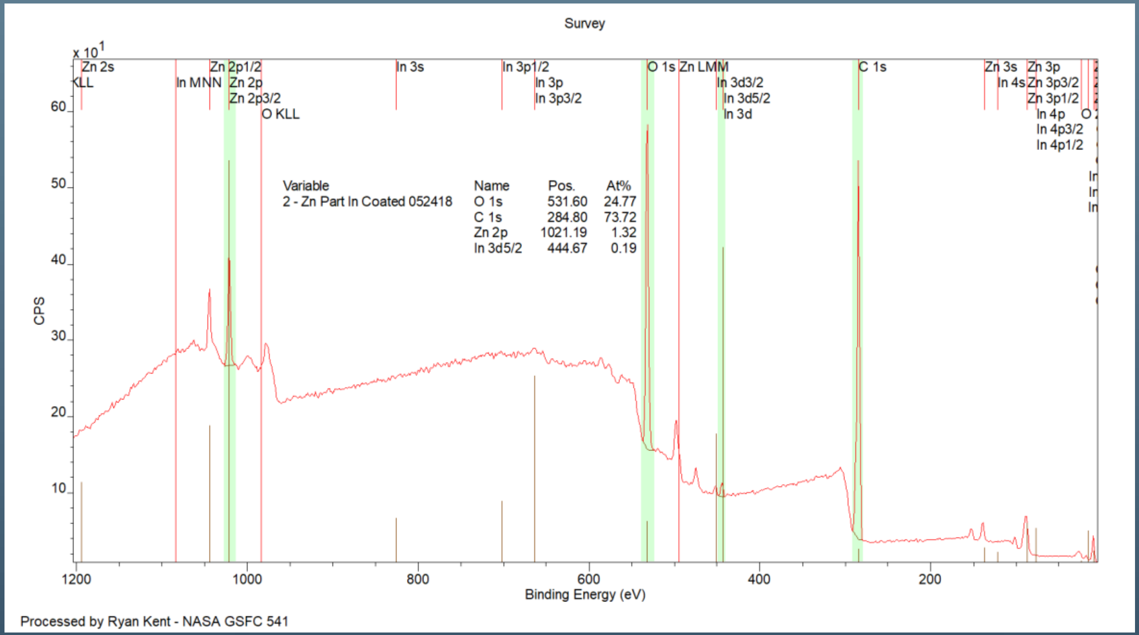
Results



Results



Spectrum Label	Zinc Oxide Particles	Indium Oxide Coated
C	57.73	73.72
O	33.23	24.76
Zn	9.04	1.28
In	-	0.23

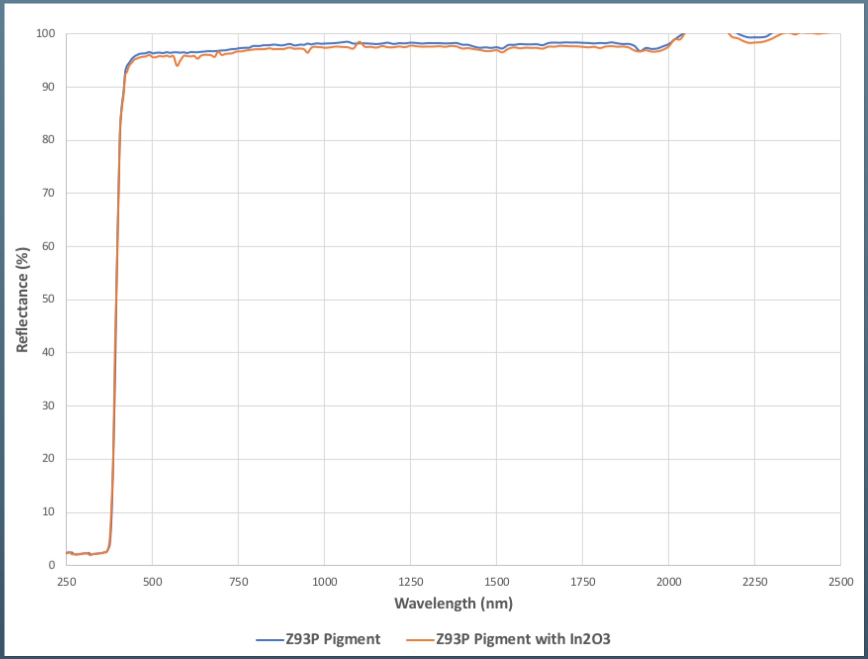
XPS of Particle Composition

Results

Pressure (Torr)	Sample	Voltage (V)	R (ohms)
7.60E+02	In_2O_3 ALD Z93	40	1.30E+08
	Z93	40	5.10E+08
7.00E+01	In_2O_3 ALD Z93	40	1.60E+08
	Z93	40	8.00E+10
7.00E-02	In_2O_3 ALD Z93	40	1.80E+08
	Z93	40	1.80E+11
6.00E-02	In_2O_3 ALD Z93	100	7.00E+07
	Z93	100	6.00E+10

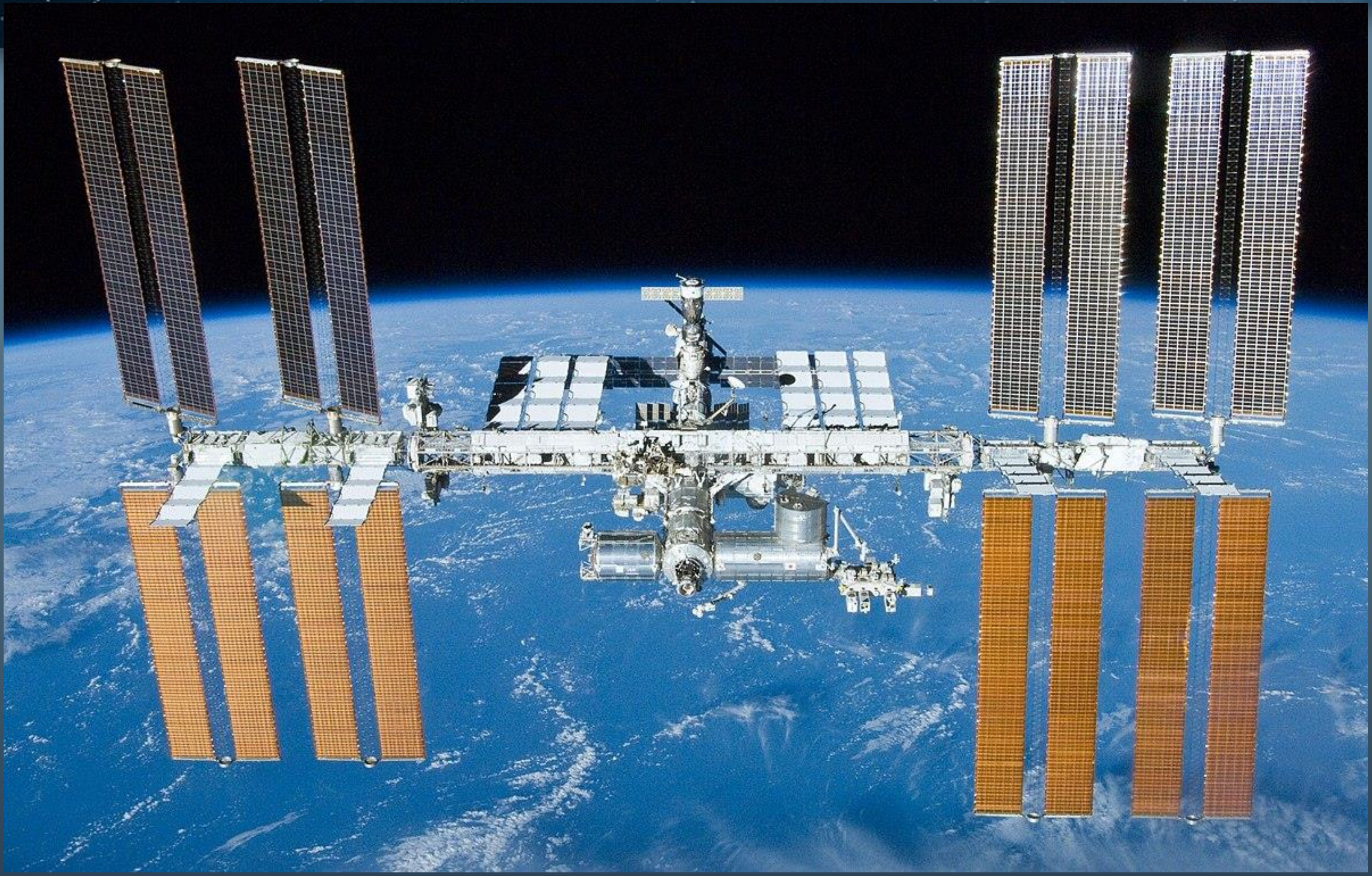
As vacuum is increased the resistivity of the Z93 pigment powders increases several orders of magnitude while the indium oxide treated Z93P pigment remains relatively stable. This increase in resistivity can be attributed to either the removal of moisture within the bulk powder or the compression of the powder filling the void space allowing for an increased number of conduction paths.

Results



Reflectance measurements were taken on lightly compressed pellets of the untreated and indium oxide treated Z93P pigment and show approximately one percent reflectance differences across the solar spectrum

ISS Opportunity



MISSE-FF

The Materials ISS Experiment Flight Facility (MISSE-FF) with MISSE Sample Carriers (MSCs) in the fully open position exposing samples/experiments to the harsh environment of space in low-Earth Orbit (LEO). Image courtesy of Alpha Space.

An earlier MISSE mission

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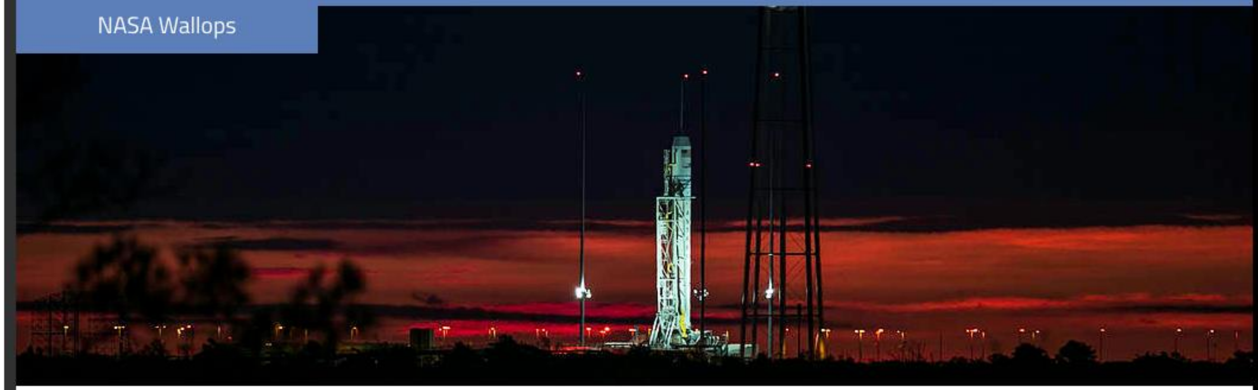
NASA Wallops



Nov. 8, 2018

Catch the Nov. 15 Antares Launch from Wallops

16

Get up early Nov. 15 to view the Northrop Grumman's Antares rocket launch from the Mid-Atlantic Regional Spaceport at NASA's Wallops Flight Facility.

The NASA Wallops Flight Facility and Virginia's Mid-Atlantic Regional Spaceport are set to support the launch of the Antares rocket, carrying the company's Cygnus cargo spacecraft to the International Space Station at 4:49 a.m. EST, Nov. 15.

The launch may be visible, weather permitting, to residents throughout the East Coast of the United States.

The NASA Visitor Center at Wallops opens at 1 a.m. on launch day for public viewing. Additional locations for catching the launch are Robert Reed Park on Chincoteague Island or Beach Road spanning the area between Chincoteague and Assateague Islands. Assateague Island National Seashore/Chincoteague National Wildlife Refuge in Virginia will **not** be open for viewing the launch.

Viewing map for the U.S. East Coast of the upcoming NG-10 Antares launch from NASA's Wallops Flight Facility. Much of the East Coast should be able to see the rocket if the skies are clear. ***Credits: Northrop Grumman***

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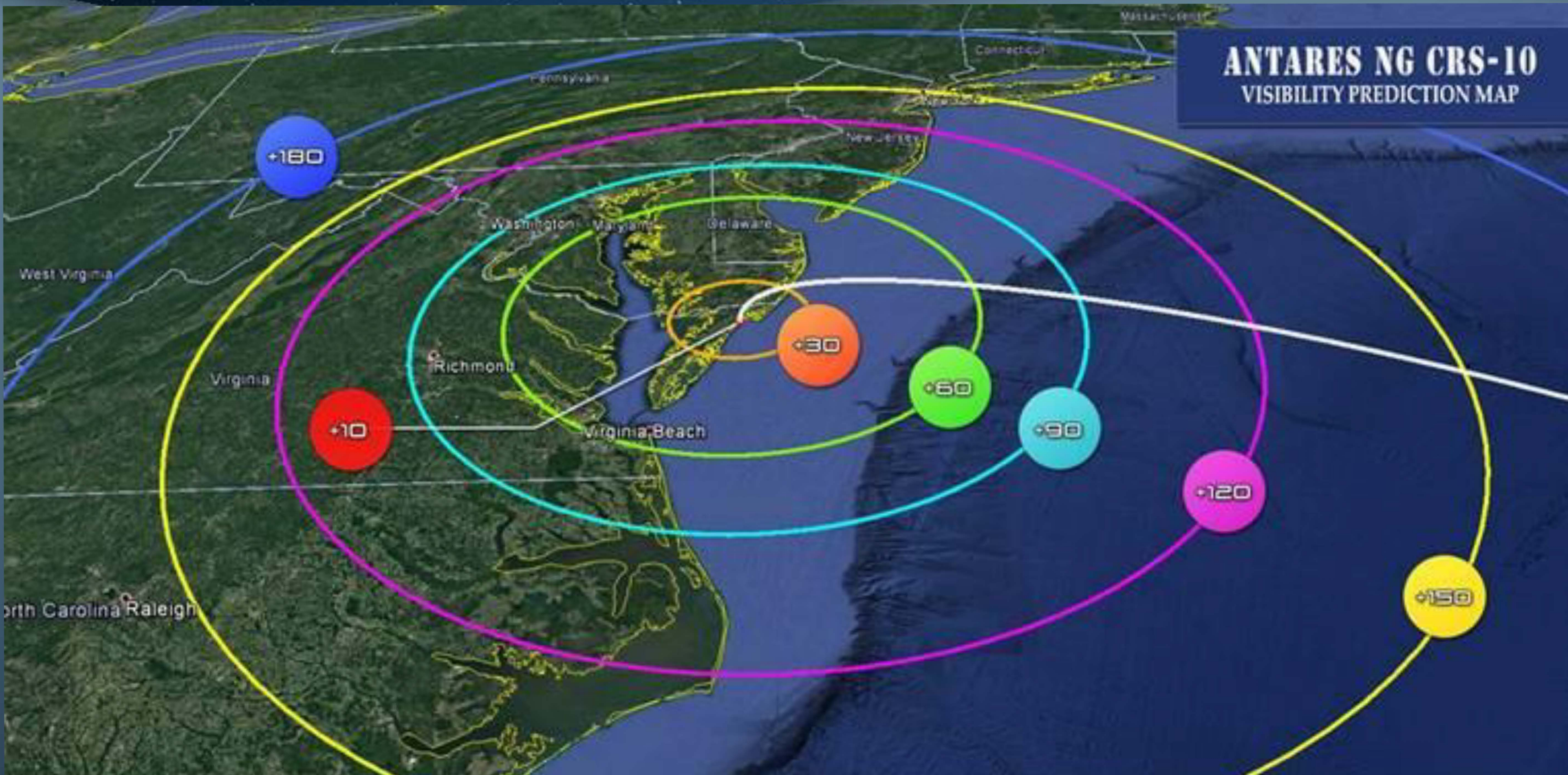
ANTARES NG CRS-10
VISIBILITY PREDICTION MAP



The numerical values in each colored cirle indicate the time (in seconds) after liftoff. This value can be used to determine when the rocket become visible within the associated colored region. Viewing availability is based on clear weather conditions.

Acknowledgments

Adomaitis Research Group

Mark Hasegawa

Goddard Space Flight Center