# Power Systems for the Lunar Surface

## Virtual Technical Workshop: Photovoltaics

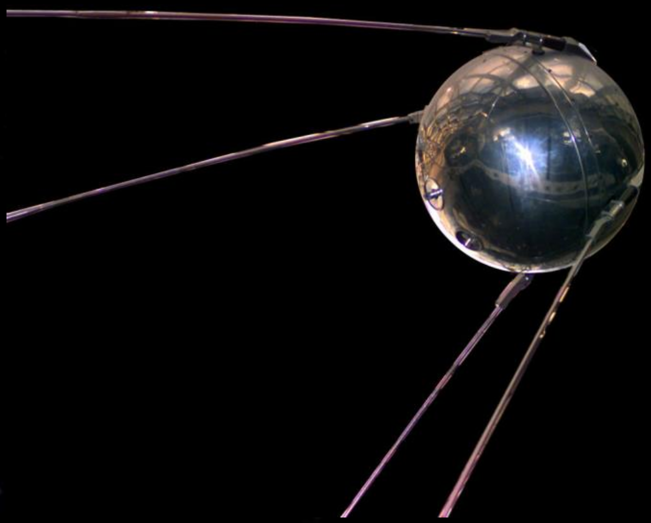
National Aeronautics and
Space Administration

Dr. Timothy Peshek, Chief Photovoltaic and Electrochem Branch
NASA Glenn Research Center
April 20, 2023

# Vanguard



- **Oct 4, 1957: Soviet Union launches Sputnik-1.**
- **US forms NASA, challenges NASA to respond**
- **NASA sends up Vanguard-1 in 1958**
- **Sputnik lasts 6 weeks**
- **Vanguard lasts 6 *years, and was PV powered***
- **The silicon solar cell was invented at Bell Labs just 4 years earlier**



https://en.wikipedia.org/wiki/File:Sputnik_asm.jpg

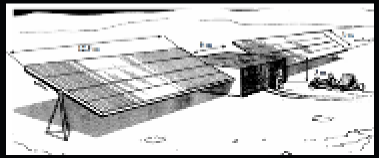
CC BY-SA 2.0

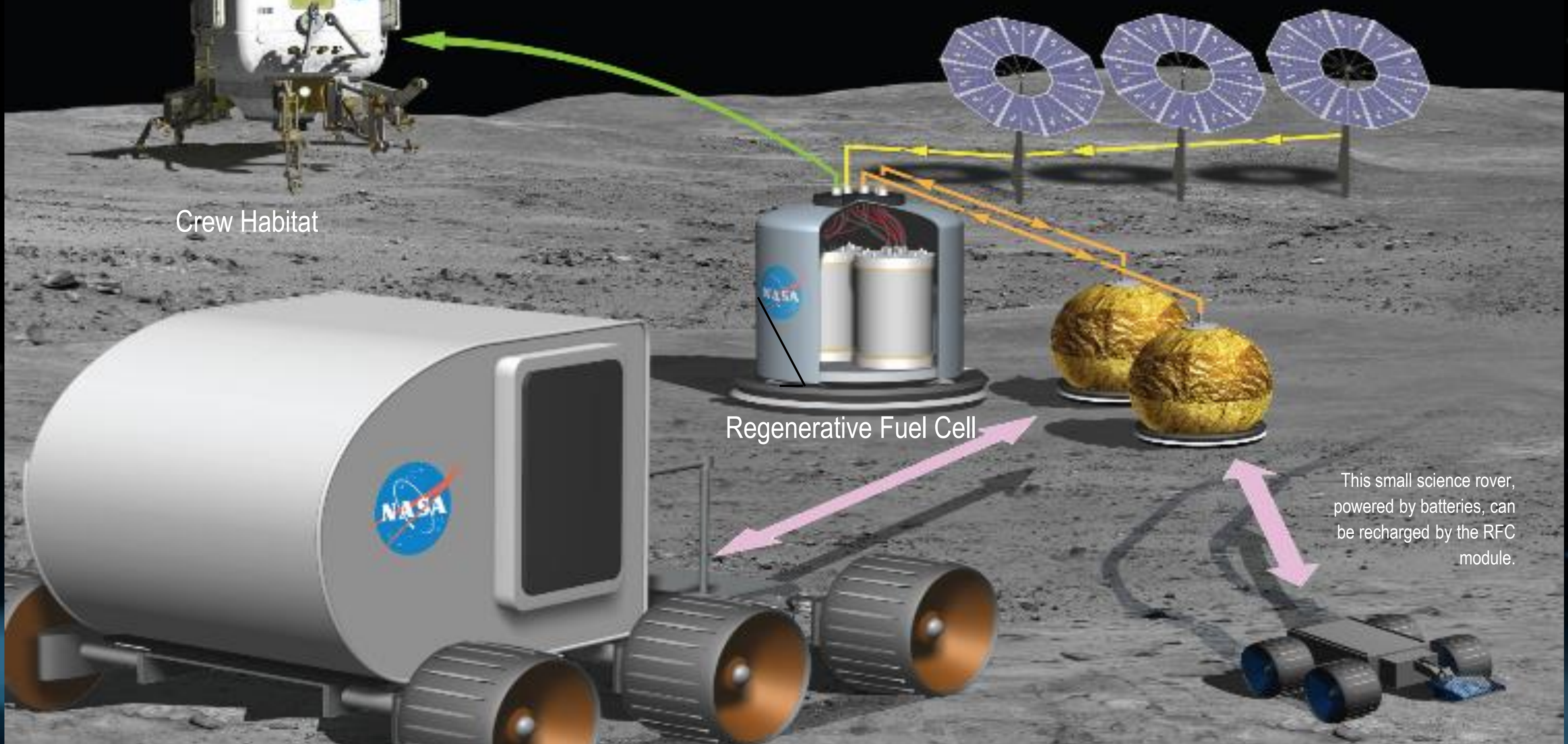
https://commons.wikimedia.org/wiki/File:Vanguard_1_composite.jpg

# Power for Crewed Surface Missions: Moon



- There has been interest in solar power for lunar applications spanning decades
- 28 Earth-day rotation period of the moon creates challenges to provide continuous power, will require advanced energy storage systems

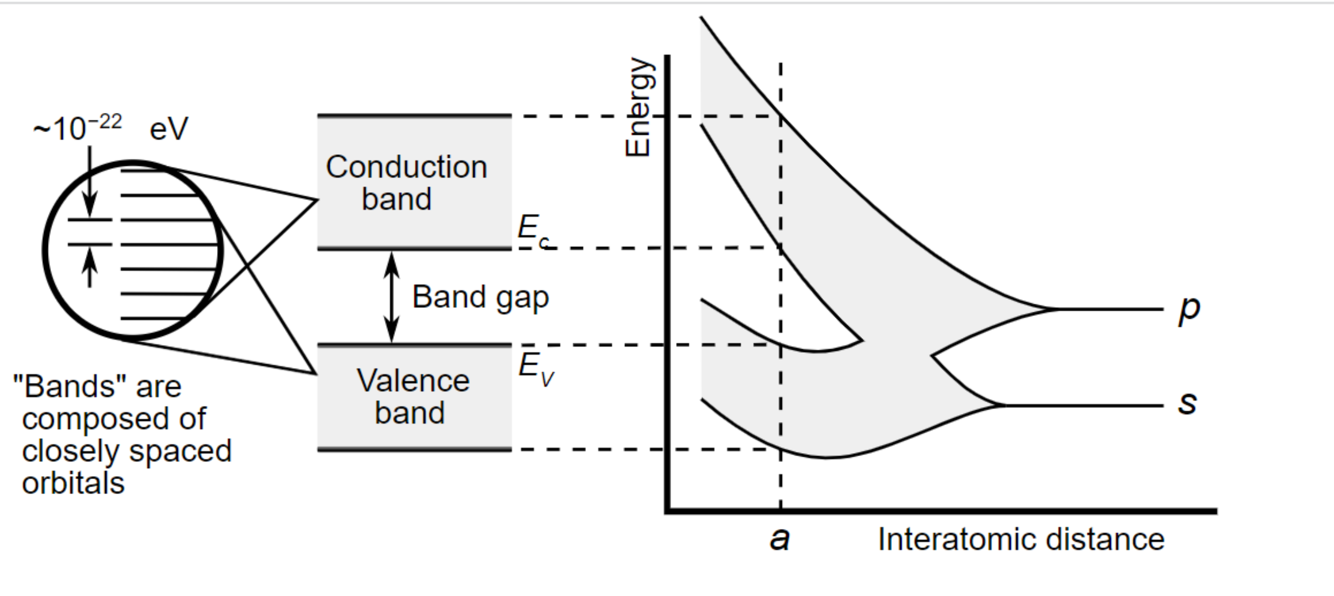




# Electronic structure and semiconductors



- Electrons exist about a nucleus in orbitals
- Crystalline materials: regular array of atoms
  - The influence of neighbors creates a near-continuum of states for electrons, called *bands*
  - Bands are like parking garage – bottom fills up first



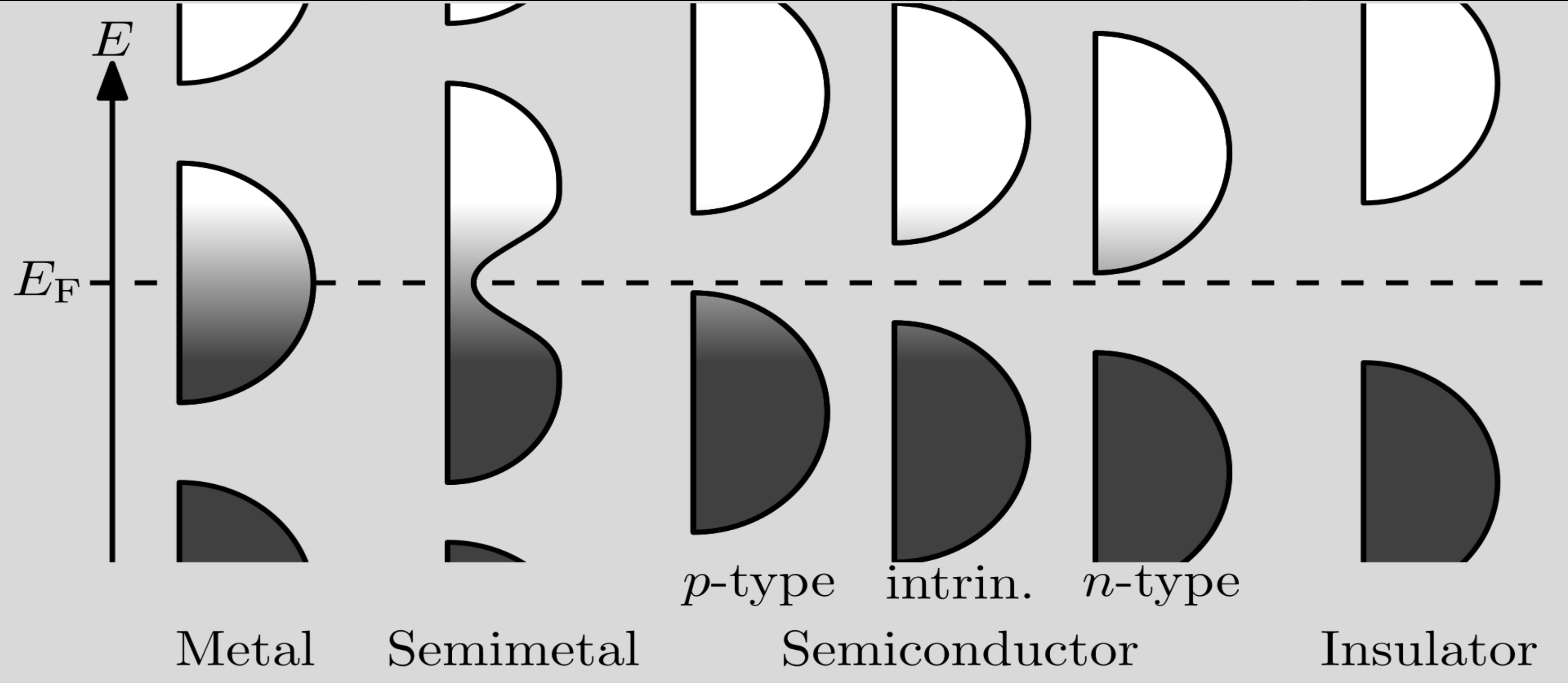

CC0

https://upload.wikimedia.org/wikipedia/commons/e/ef/Solid_state_electronic_band_structure.svg

# PV Basics: Traditional Semiconductor View



- Semiconductors: Band gap ($E_g$) = 0.25 – 3.0 eV
- Region in between valence/conduction bands where no electron states exist
- Conductivity altered by doping



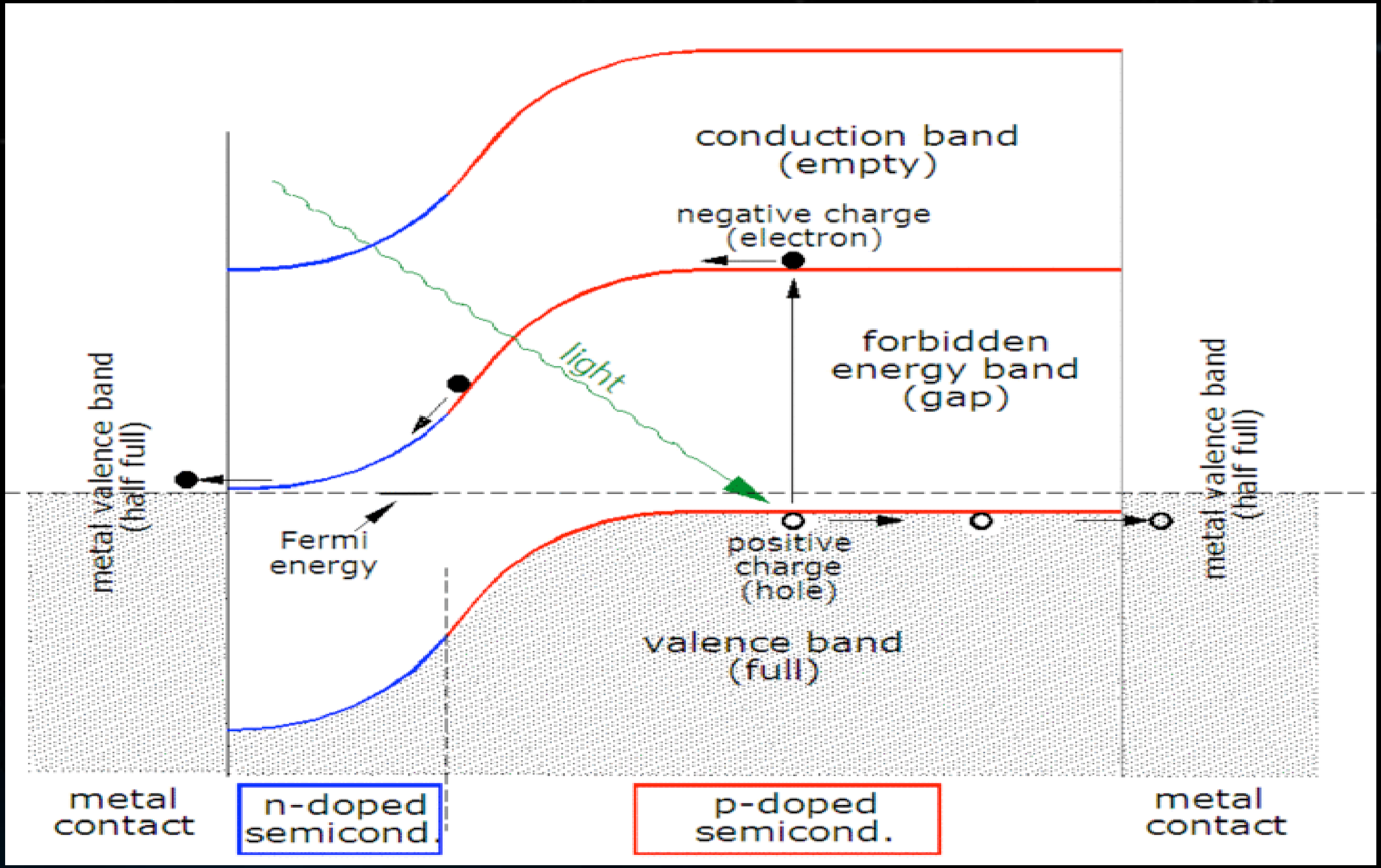

https://en.wikipedia.org/wiki/Semiconductor#/media/File:Band_filling_diagram.svg

CC0

# PV Basics: *pn* junctions



- Photons absorbed, create electron-hole pairs:
  - A photon with E > Eg is absorbed, exciting an $e^-$ from the valence band to the conduction band
  - The hole also moves through the lattice: bonded $e^-$s of neighboring atoms move into the "hole," leaving another hole behind.
- Separation of carriers by diffusion or drift
- Connection to an external load allows harvesting of current



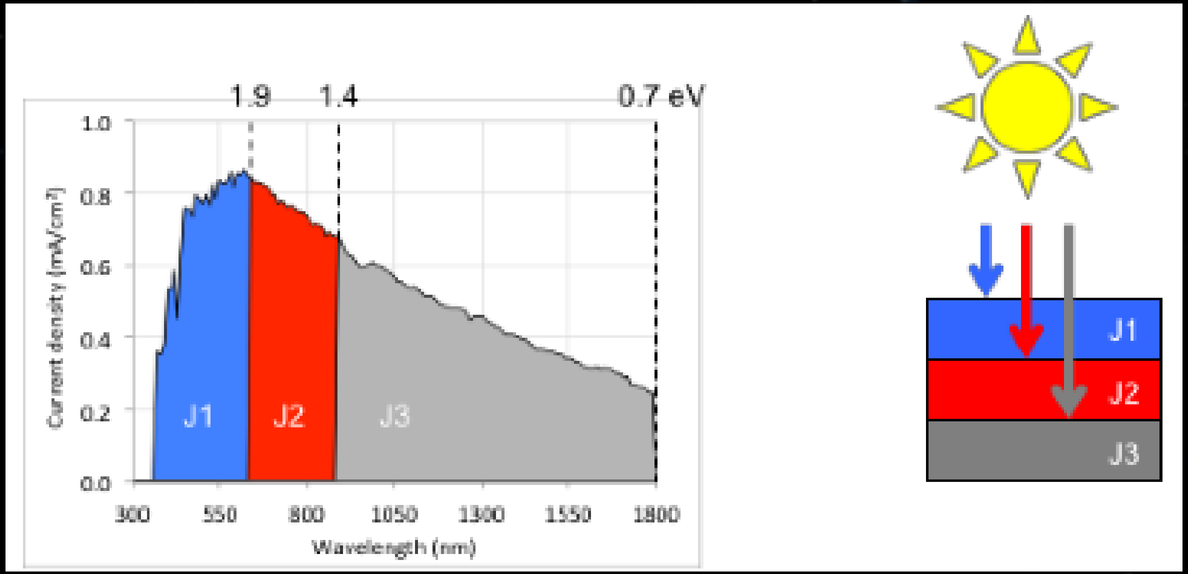

https://en.wikipedia.org/wiki/Theory_of_solar_cells#/media/File:Solargif1.gif

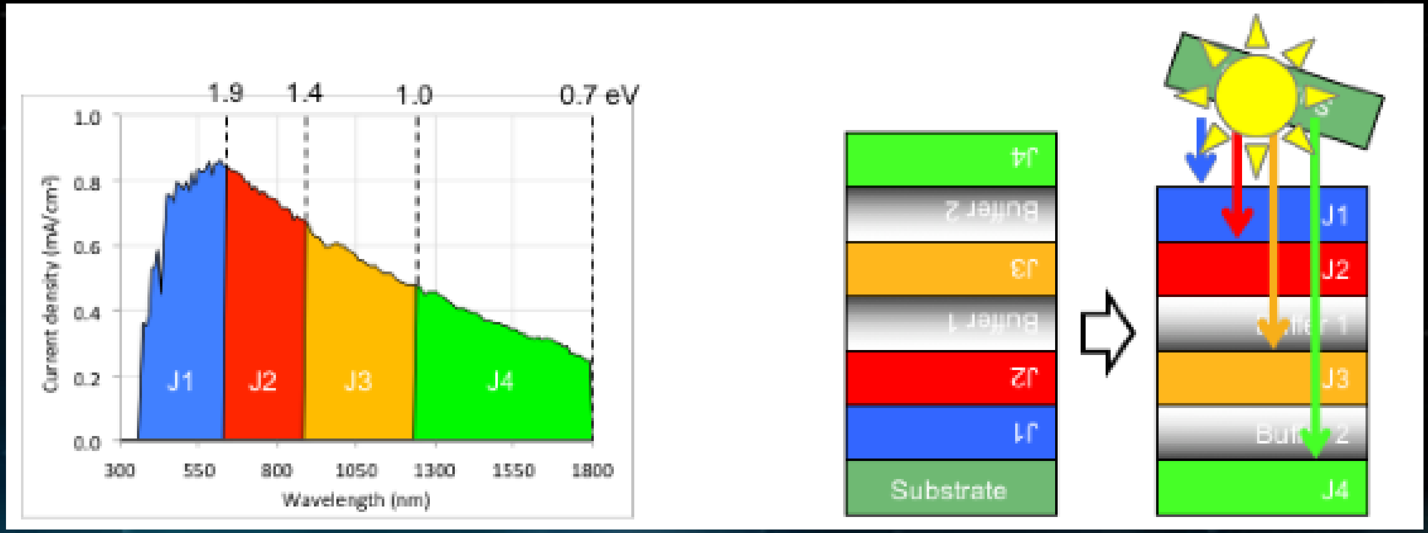
CC BY-SA 4.0

# Current PV Technology for Space

Triple Junction Solar Cell
- Ge/GaAs/InGaP structure
- ~ 30% AM0 efficiency
- Current balancing is not optimum
- Standard for over 15 years

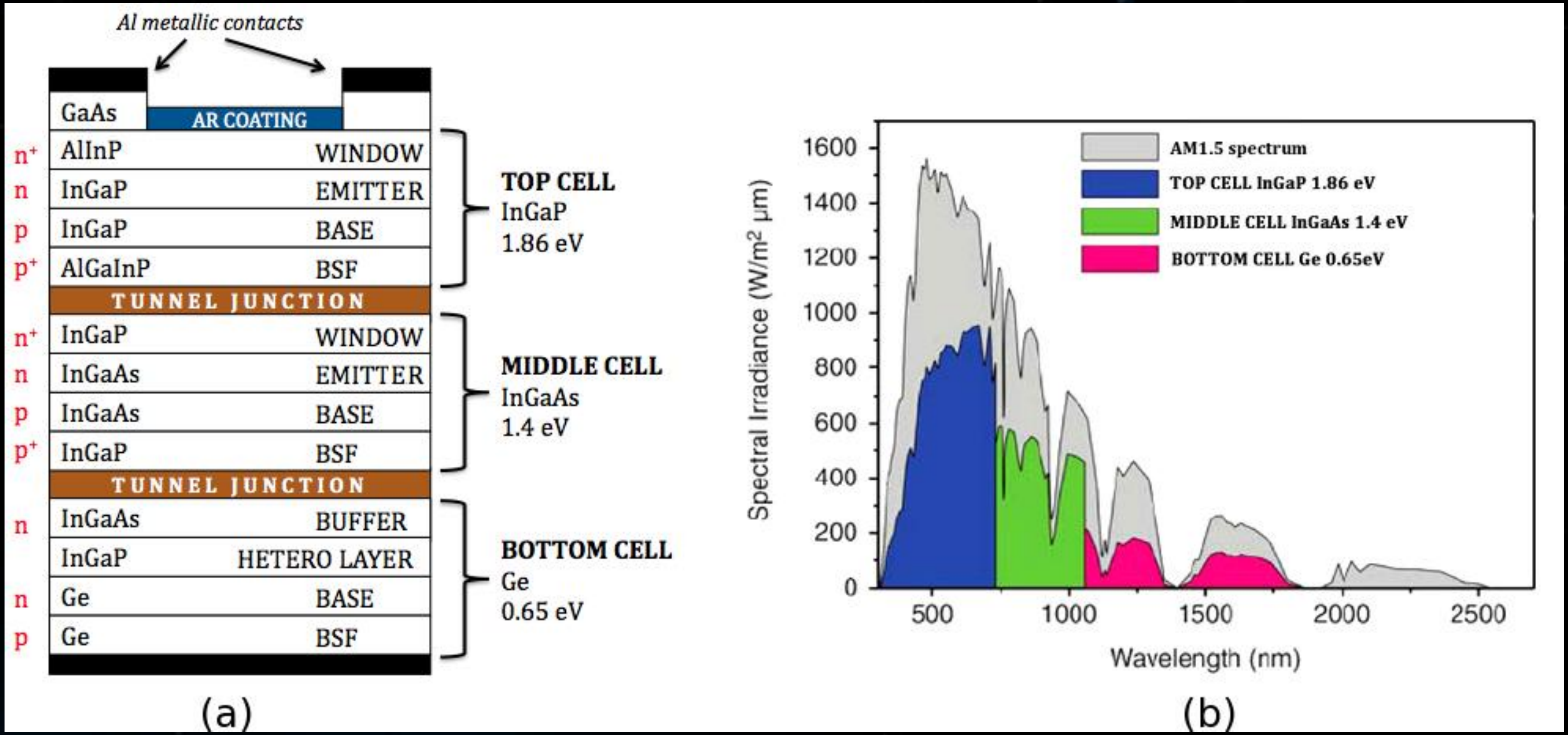
Inverted Metamorphic Multijunction (IMM) Solar Cell
- ~ 33% AM0 efficiency
- Improved current matching
- Space flight qualification in process



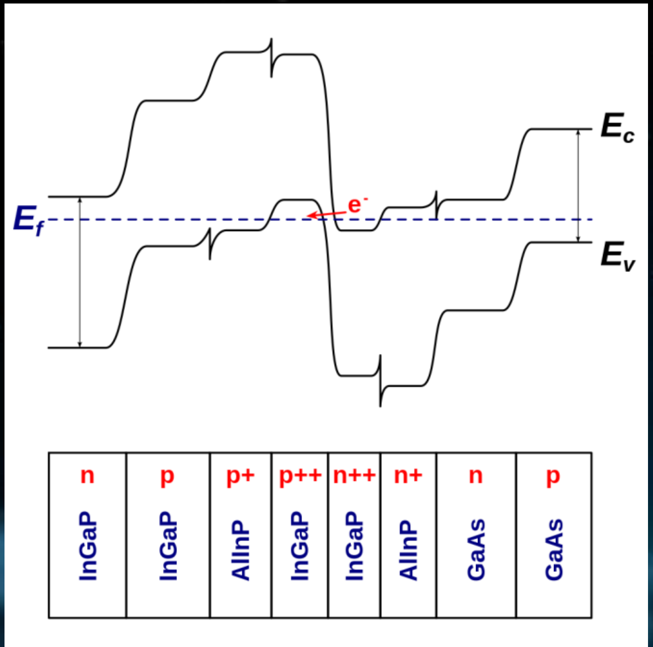



# Structure of MJ Solar Cells






https://en.wikipedia.org/wiki/Multi-junction_solar_cell#/media/File:StructureMJetspectre.png
CC BY-SA 3.0




https://en.wikipedia.org/wiki/Multi-junction_solar_cell#/media/File:Tunneljunction-mod.svg
CC BY-SA 4.0

# Crystal growth: Boules



- Obtaining a boule of single crystal material
- Czochralski growth is most typical
- Seed is lowered into a melt
- Crystal grows and is rotated and “pulled” out of melt
- This consumes the melt\
- Elemental semiconductors silicon and germanium created this way

# Energy and material intensive wafers

## Current process:

Sand

Add Carbon & Heat Energy

$CO_2$

metallurgical grade Si

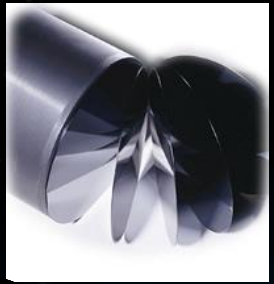
pure $SiHCl_3$ or $SiH_4$

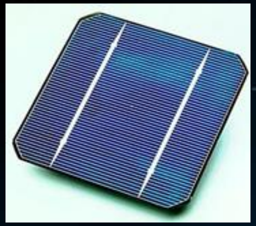
Add Heat Energy (1000 °C)

silicon feedstock

Add more heat energy (1500°C)

Waste ~1/2 in sawing



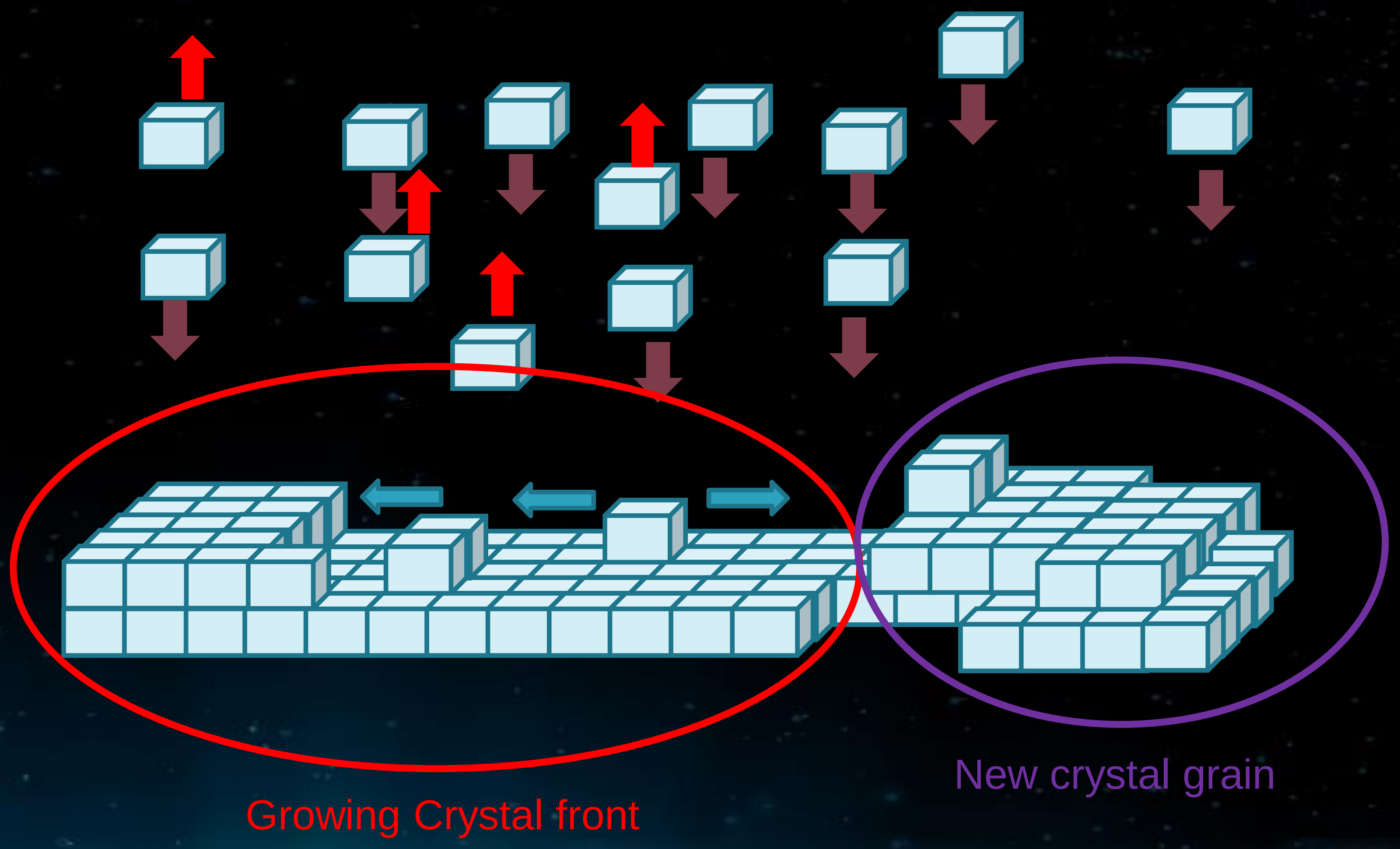


Use 10X more than needed

# Vapor phase deposition



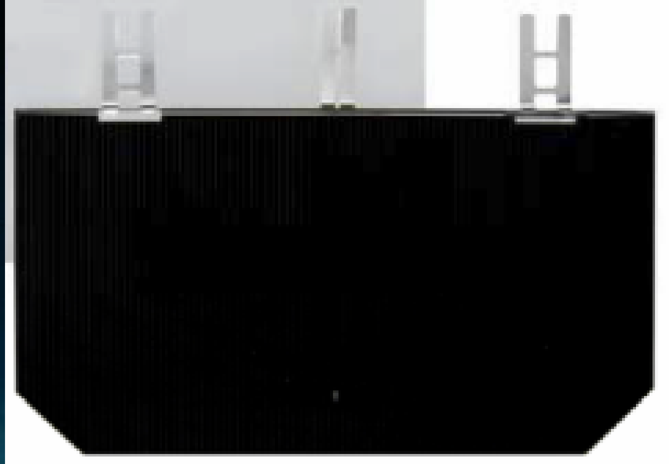
- Chemical vapor deposition
  - Reaction must occur
  - Often metalorganics are used
  - Highly volatile and toxic
- Physical vapor deposition
  - Vapor is material of interest
  - Need to heat to vaporization temperature
  - Vacuum is needed for purity



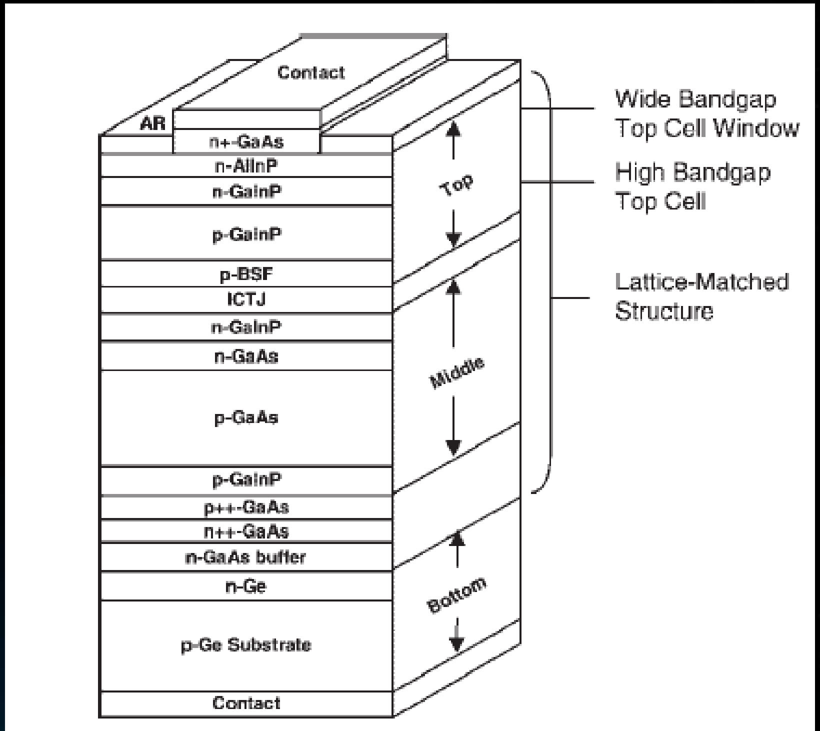
# SOA USA MJ Photovoltaic Solar Cells (many kW's flown)

- Use the Sun's AM0 (space) spectrum
- Series-stacked, monocrystalline III-V Semiconductors; QE, N on P, P-I-N, P on N
- tunnel junctions, contacts, metallization
- SolAero ZTJ, 29% class efficiency

- Spectrolab XTJ, 29% class efficiency



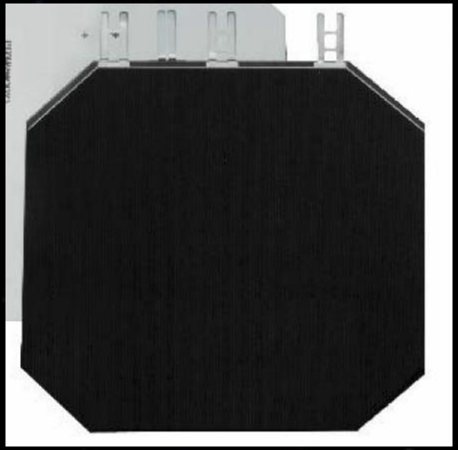
- 2 cells diced per wafer
  - 10 cm diameter wafer
  - 30 cm2 class per cell

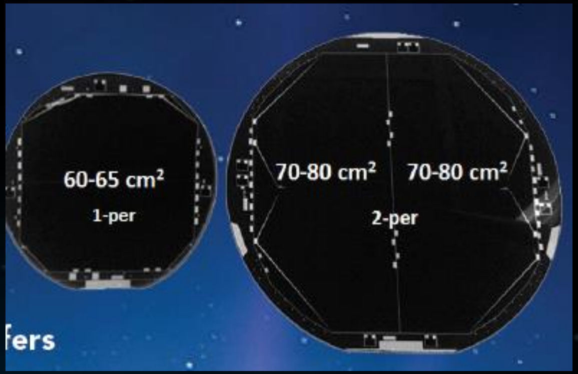


# SOA MJ Photovoltaic Solar Cells – Bigger Area



- 60 cm2 class, single cell per 10 cm dia wafer
  - SolAero “Luna” ZTJ, Spectrolab “LeOne” XTJ
- 72 cm2 class, 2 cell per 15 cm dia wafer
  - Spectrolab XTJ Supercell

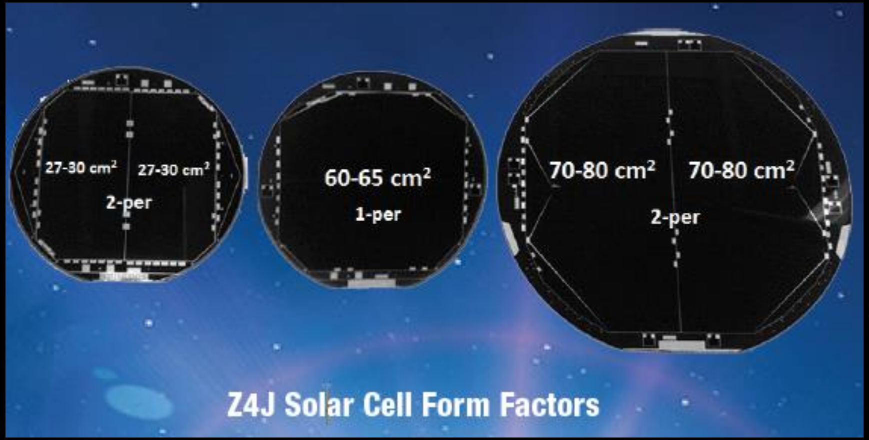





- Bigger cell area increases string current, decreases SAW string/cell count (& SAW recurring fabrication costs), $/W cell cost could be higher or lower, scrap cell costs higher
- Desire to cut cells out of wafer to maximize area use (to reduce $/W)
- Dicing cells to custom dimensions is possible, but more costly
  - Less optimum wafer usage, custom photolithography & metallization masks

# SOA MJ PV Solar Cells (past qual, not in flight production)

- SolAero Z4J, 30% class efficiency
  - EOL rad hard cell with extra ~1 pt in efficiency over ZTJ gained by using 4 subjunctions

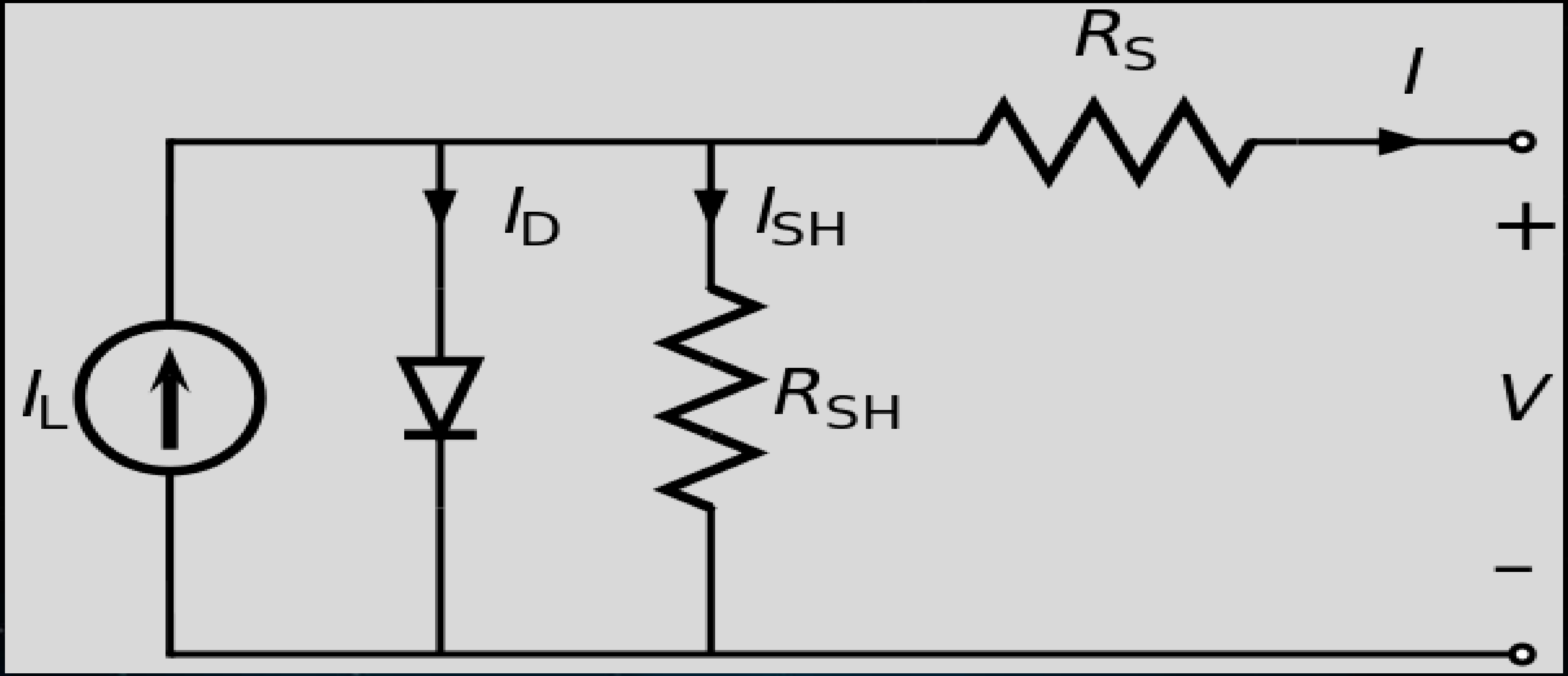




- Spectrolab XTE, 32% class efficiency
  - Triple junction cell with adjusted subcell bandgaps

## Qualifications are AIAA-S111 and S112

# The equivalent circuit: the unsolvable problem

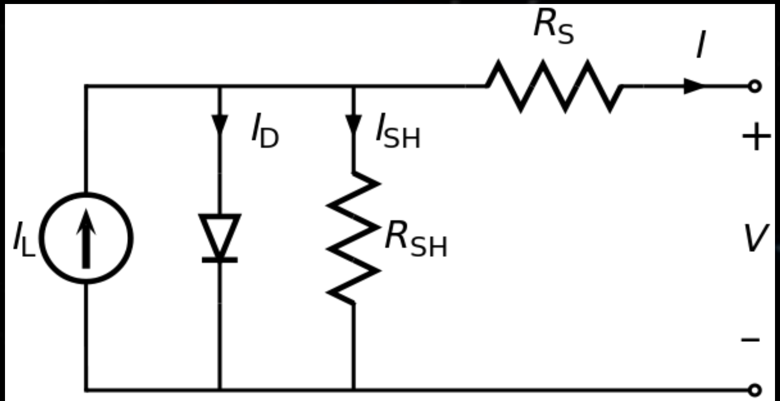



https://en.wikipedia.org/wiki/Theory_of_solar_cells#/media/File:Solar_cell_equivalent_circuit.svg\

CC BY-SA 3.0

# What is efficiency?

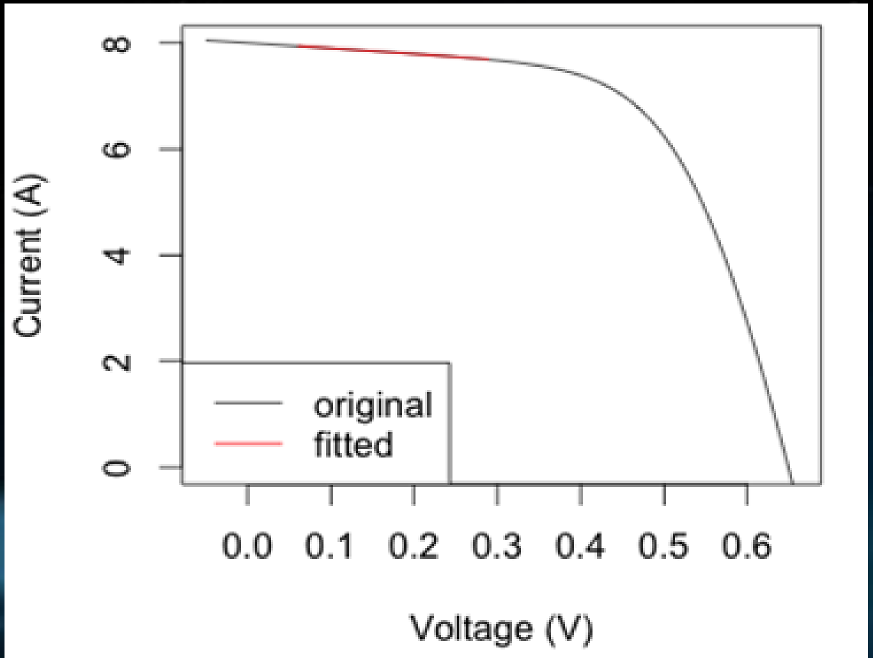
**The *pn* junction makes a diode, and light is modeled as a current source**

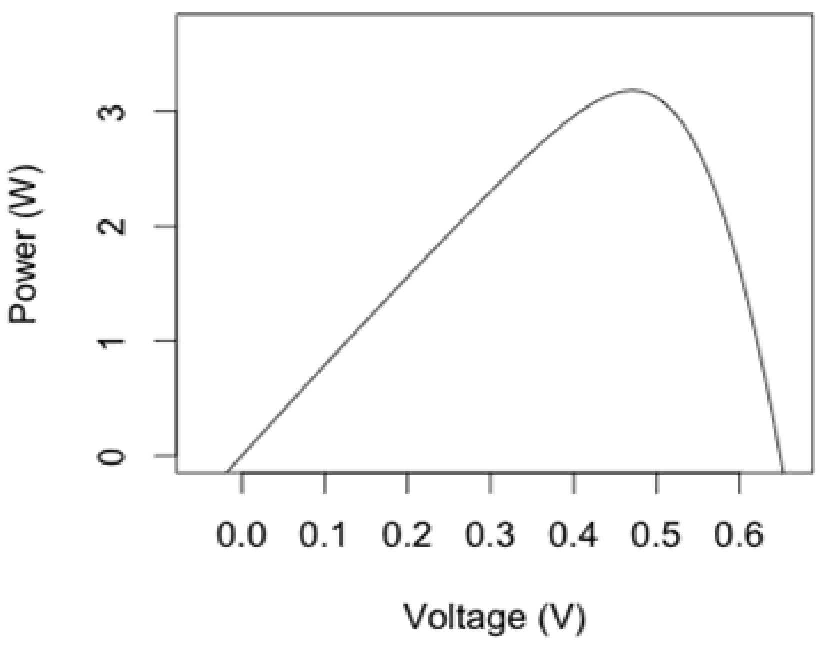



$$I = I_L - I_0 \left\{ \exp\left[\frac{V + IR_S}{nV_T}\right] - 1 \right\} - \frac{V + IR_S}{R_{SH}}.$$

A transcendental equation that cannot be solved

Use current vs voltage to find efficiency



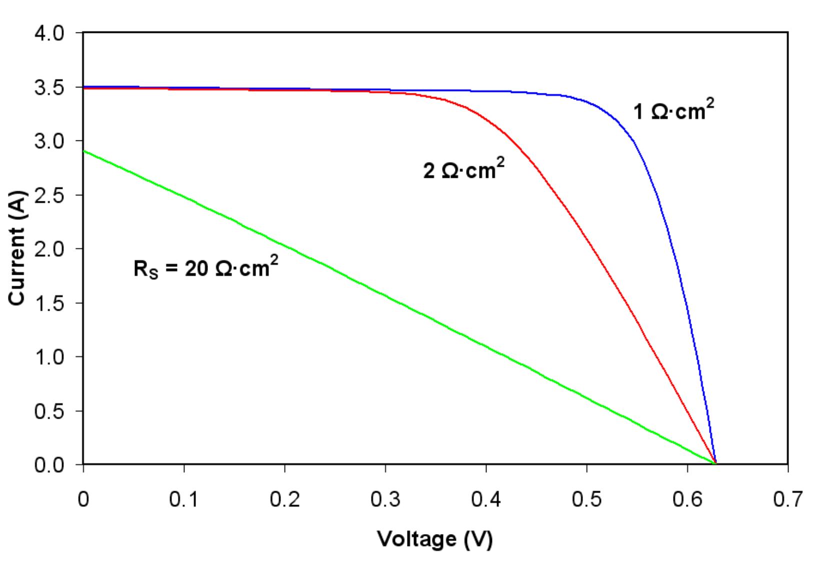



# Electrical losses

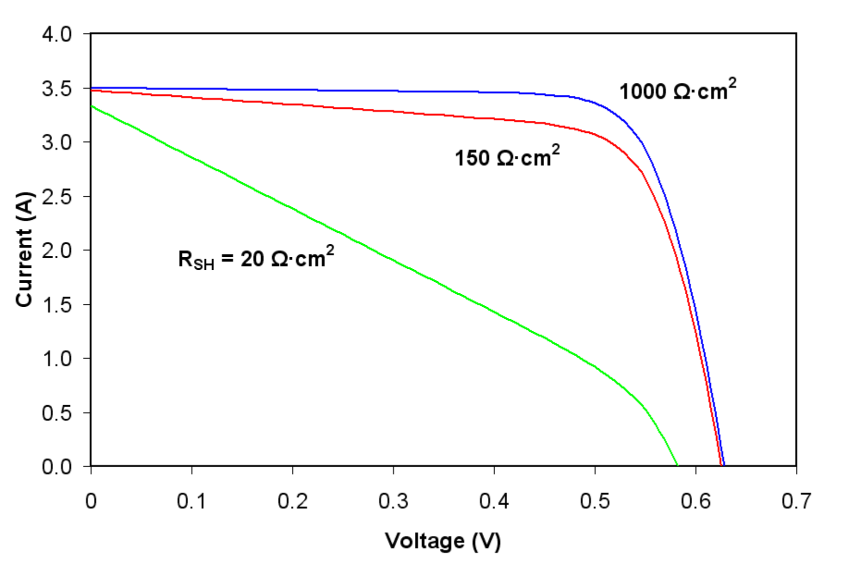


**Shape profile of I-V curve provides details on loss factors**

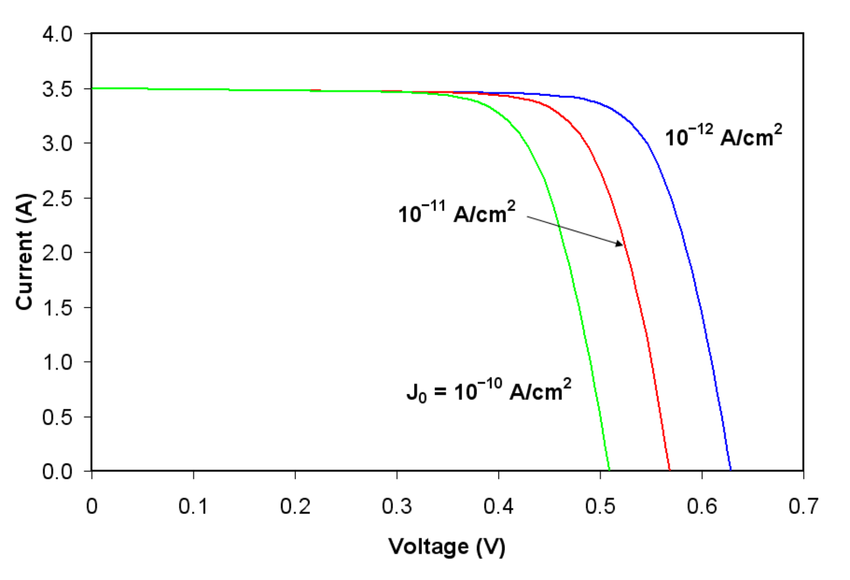
**Series resistance -> linearizing at higher V**
**Shunt resistance -> linearizing at lower V**
**Traps increase reverse saturation current**




https://upload.wikimedia.org/wikipedia/commons/e/e4/I-V_Curve_RS.PNG
CC BY-SA 3.0



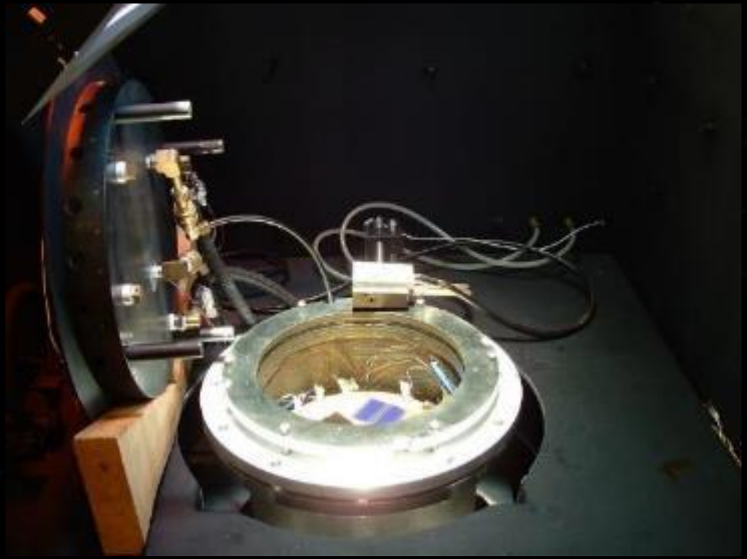

https://upload.wikimedia.org/wikipedia/commons/a/a9/I-V_Curve_RSH.PNG
CC BY-SA 3.0




https://upload.wikimedia.org/wikipedia/commons/2/2d/I-V_Curve_J0.PNG
CC BY-SA 3.0-

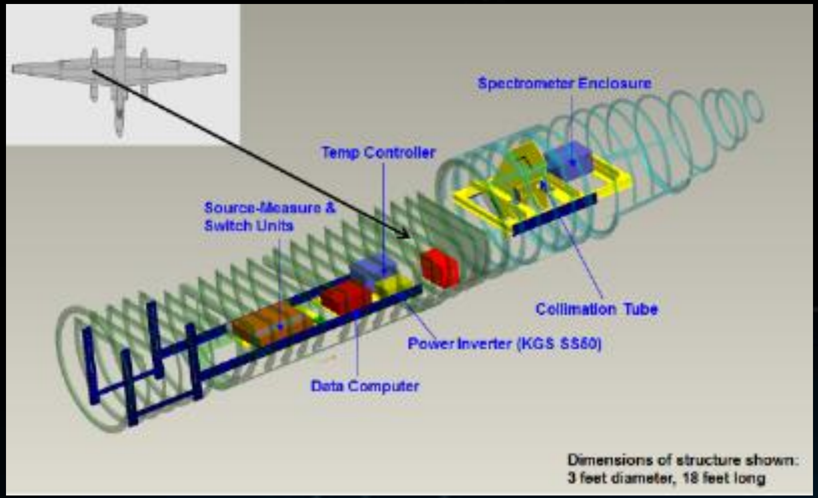
# X-25 Triple Source Solar Simulator

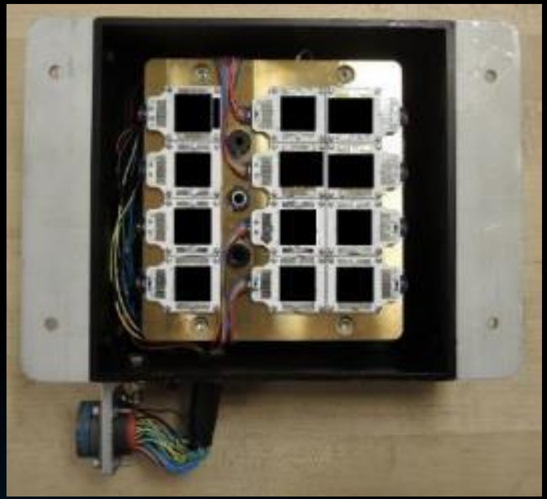




- Unique asset developed at GRC
- LILT and Temperature Coefficients
- Temperature Range: -160°C to 100°C
- Main workhorse for past 10-15 years

# ER-2 High Altitude Calibration Platform



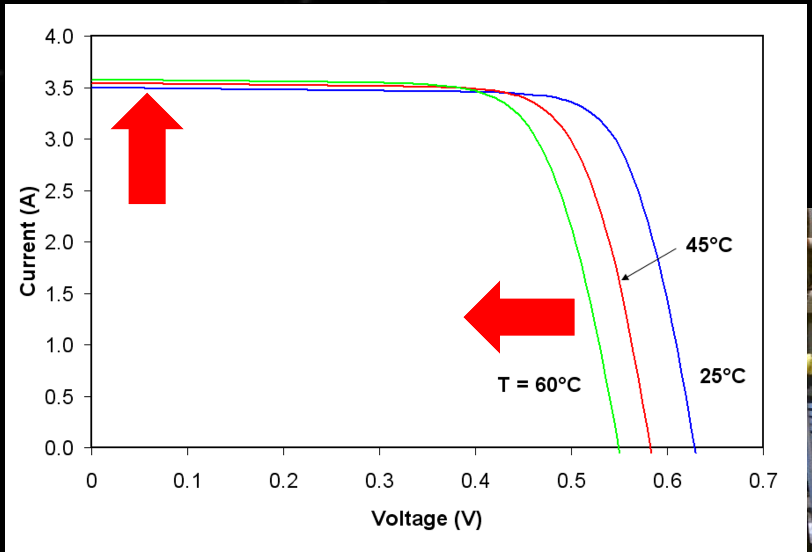
- Generates primary AM0 Standards for GRC
- Supports testing for GRC programs
- Cells flown for PV community including other government and industry

# Thermal environments

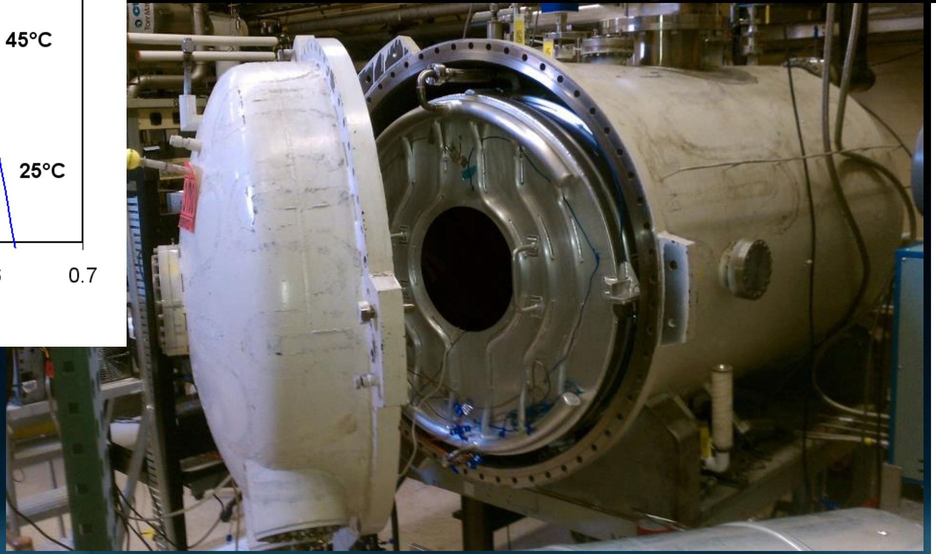


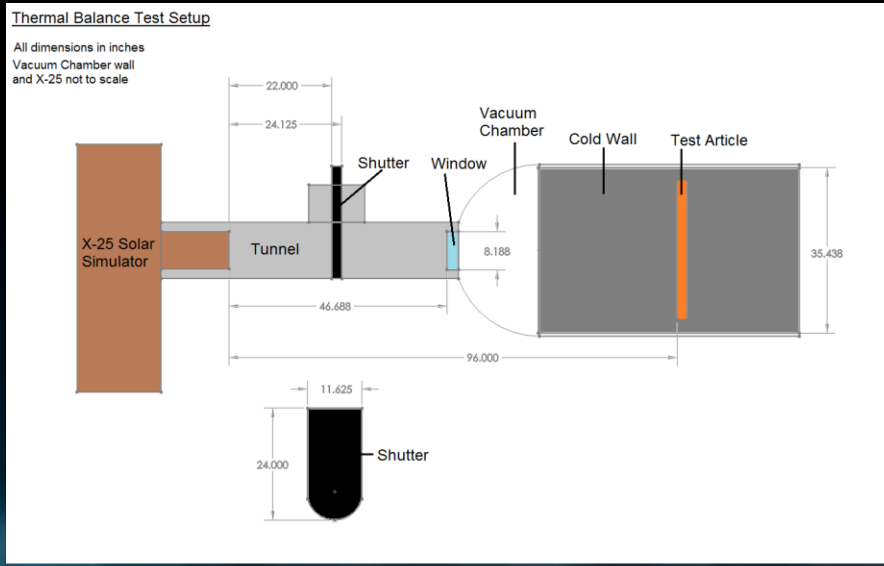
- Cycling:
- Thermal cycling can cause fatigue-related issues such as hardening/embrittlement of leads.

- Thermal extremes
- Affect power, voltages and currents
- It is important to determine the thermal balance of the system through modeling/empirical measurement



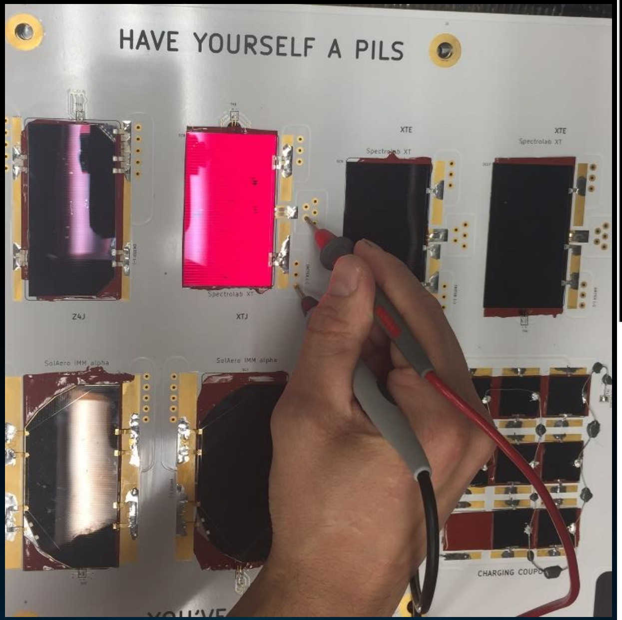

https://upload.wikimedia.org/wikipedia/commons/5/55/I-V_Curve_T.png
CC BY-SA 3.0

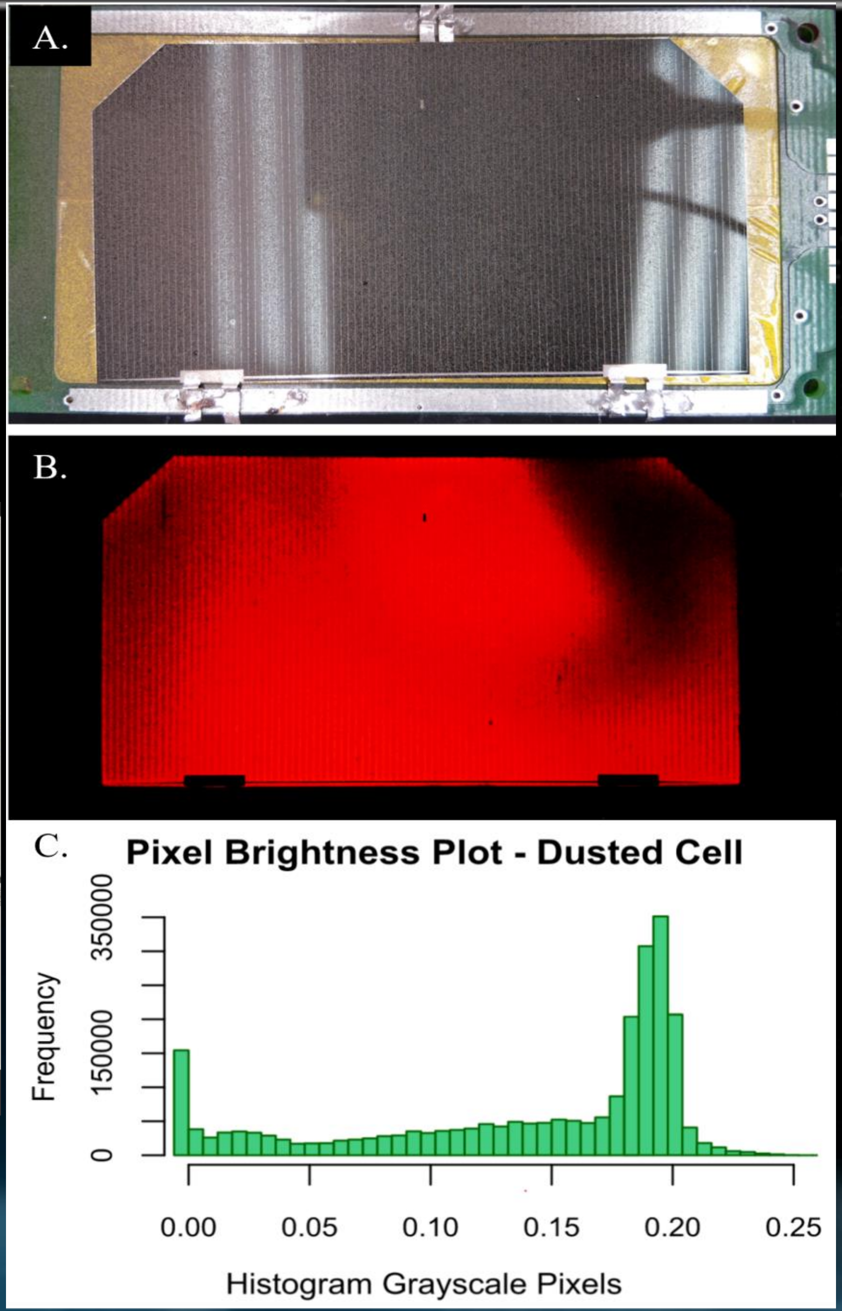




# Band Edge Luminescence

- Injecting carriers into the conduction band with nowhere to go will force some to recombine and give off characteristic photons
- Essentially forcing a solar cell to reverse operation.
- Can happen with photons (photoluminescence) or voltage bias/current injection (electroluminescence)



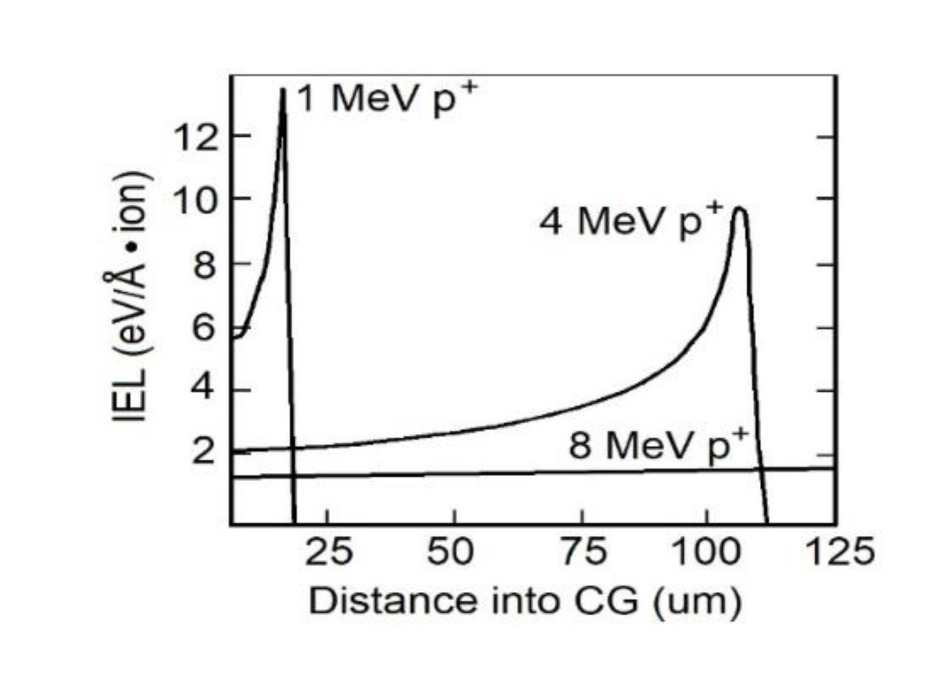
# Solar Cell Coverglass

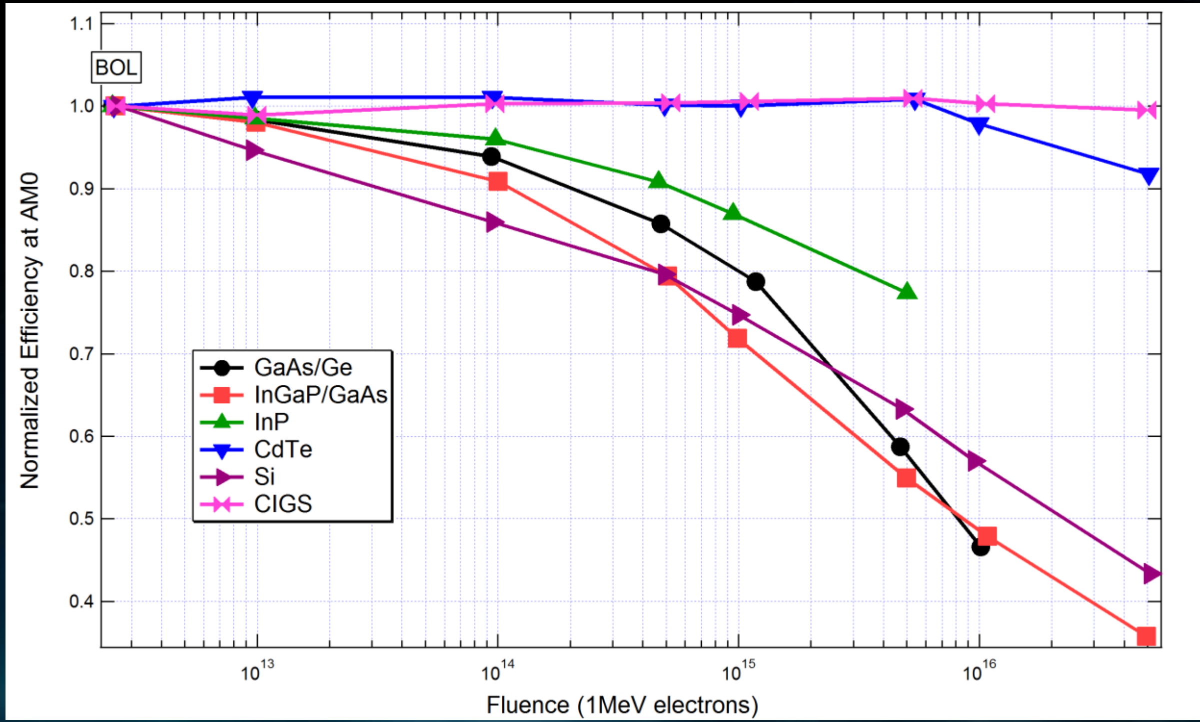


- Ceria-doped borosilicate glass (UV absorptive)
- 3-mil to 20-mil standard thicknesses (proton/electron radiation shielding)
- Qioptiq supplier of space qualified covers
  - Qioptiq CMG, CMX, CMO; matched to CTE of Ge & Si PV technology, various UV absorption
    - $SiO_2+Al_2O_3+B_2O_3$ 81-91 mol %, $Li_2O+Na_2O+K_2O$ from 7.6-10.6 mol % and one or more of MgO, CaO, SrO, BaO, ZnO and PbO 0-7 mol % total ; <5wt% Cerium Oxide
- Coatings
  - AR ($MgF_2$)
  - AR-conductive ($MgF_2$/ITO) – conductive silicone dot for electrical bonding of coating to interconnect
  - UVR
- Coverglass adhesive
  - DC93500 clear silicone
  - ***Sylgard®* 184**

# Radiation considerations

- Crudely, energetic particle penetration into a material is governed by the Bethe-Bloch formula
- Stopping power tends to scale with atomic mass
- GaAs tends to be considered radiation susceptible, and Si is also subject to radiation degradation
- These are estimable from standardized tests DESIGNED to mimic/accelerate the specific damage to those materials.
- https://apps.dtic.mil/sti/pdfs/AD1184233.pdf (approved for public release)
- https://apps.dtic.mil/sti/trecms/pdf/AD1191592.pdf (approved for public release)



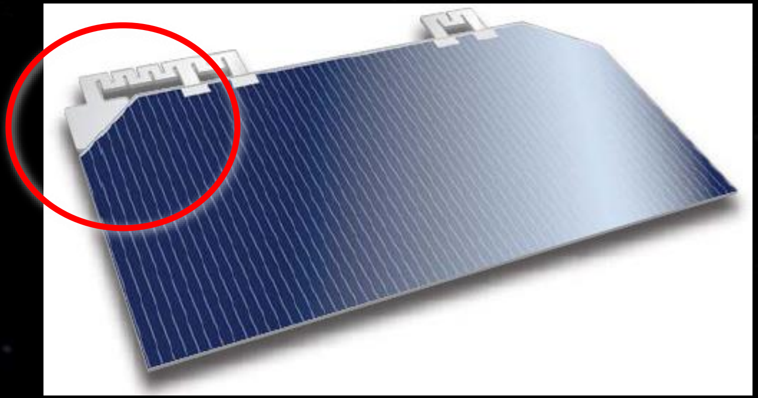



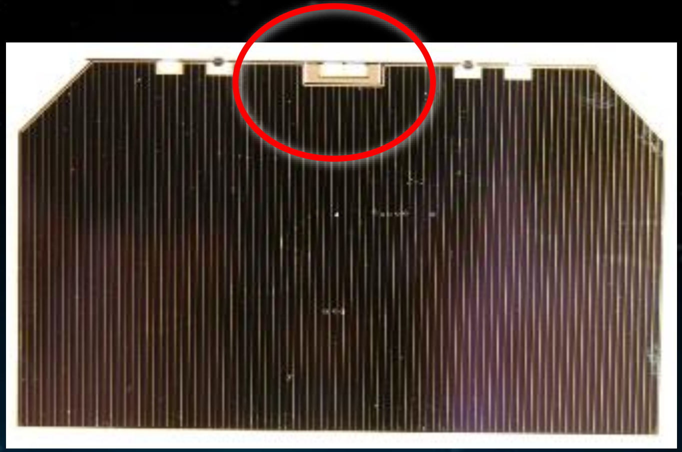

Data from: Jasenek, A.; Rau, U.; Weinert, K.; Schock, H. W.; Werner, J. H. *3rd World Conf. Photovoltaic Energy Conversion* **2003,** *1*, 593-598.

# Solar Cell By-pass Diode



- Protects the cell from reverse bias damage
- Maintains solar cell string continuity in case of weak cell output
- ZTJ discrete silicon corner diode
- ZTJM epi-grown III-V monolithic diode
- XTJ discrete silicon back pocket diode
- Large area SSDI flat pack diode (ISS SAW- 8 cell bypass)



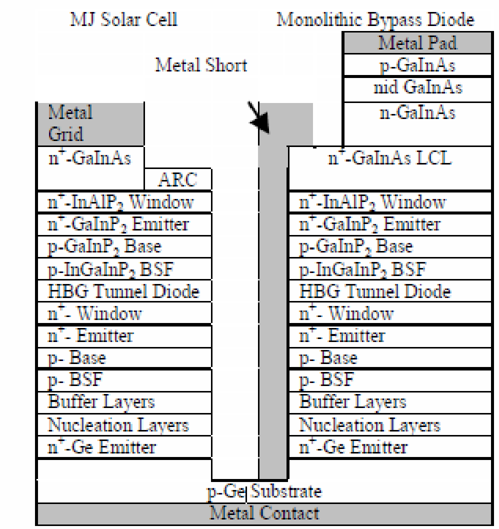
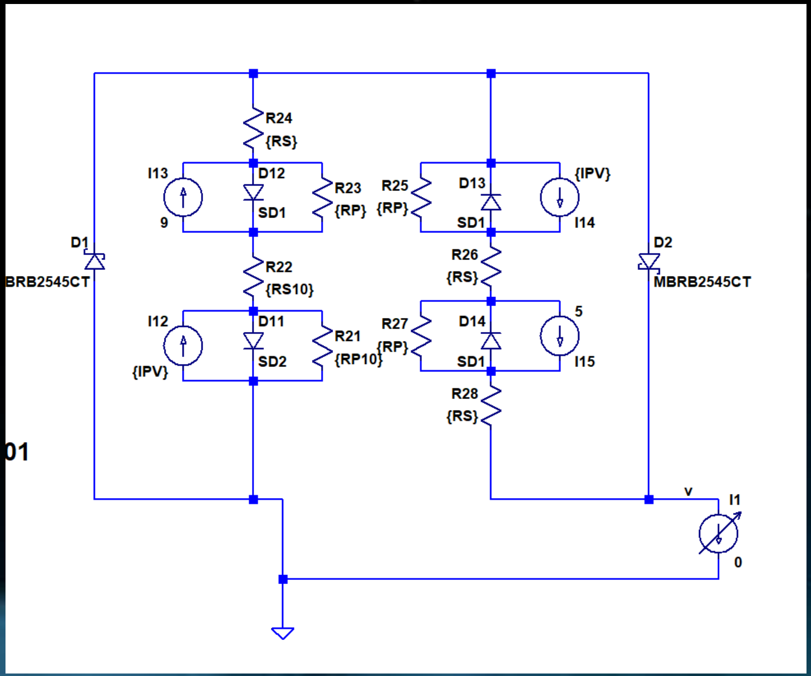
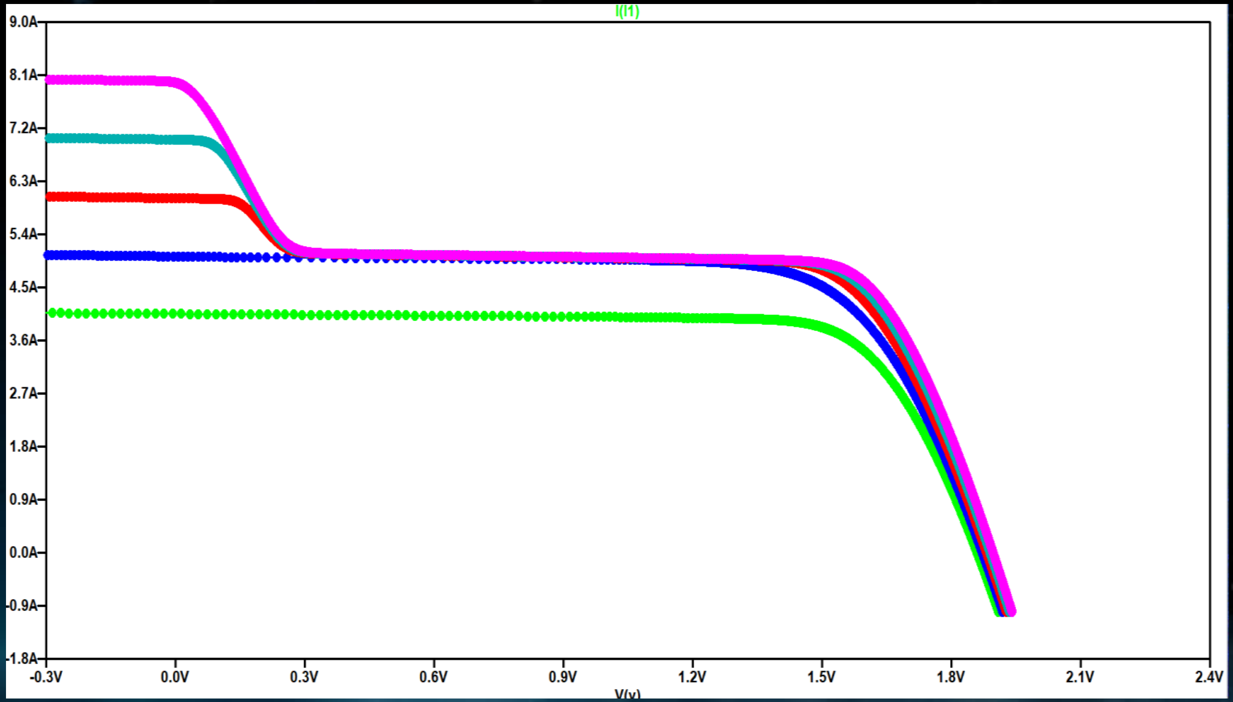



Figure 1. Schematic cross section of the ZTJM triple junction solar cell.

# Bypassing in IV curves

- Bypass diodes turn on for an underperforming cell or substring
- Prevents reverse bias, which can destroy cell and more severely reduce string output
- Example in SPICE is shown,  4 cell string with 2 bypass

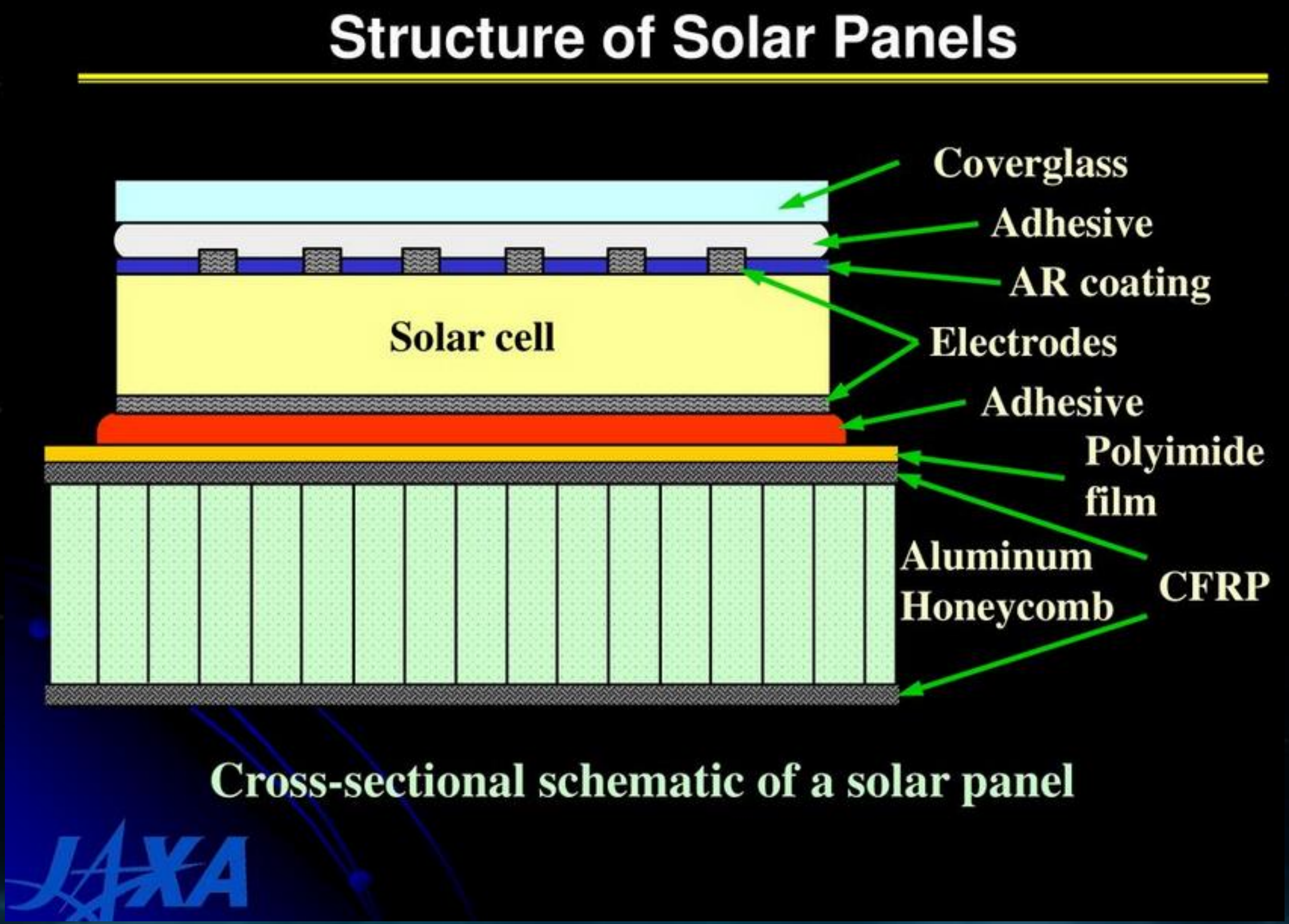


# Solar Cell CIC / Rigid Panel Cross Section



- Generic solar panel



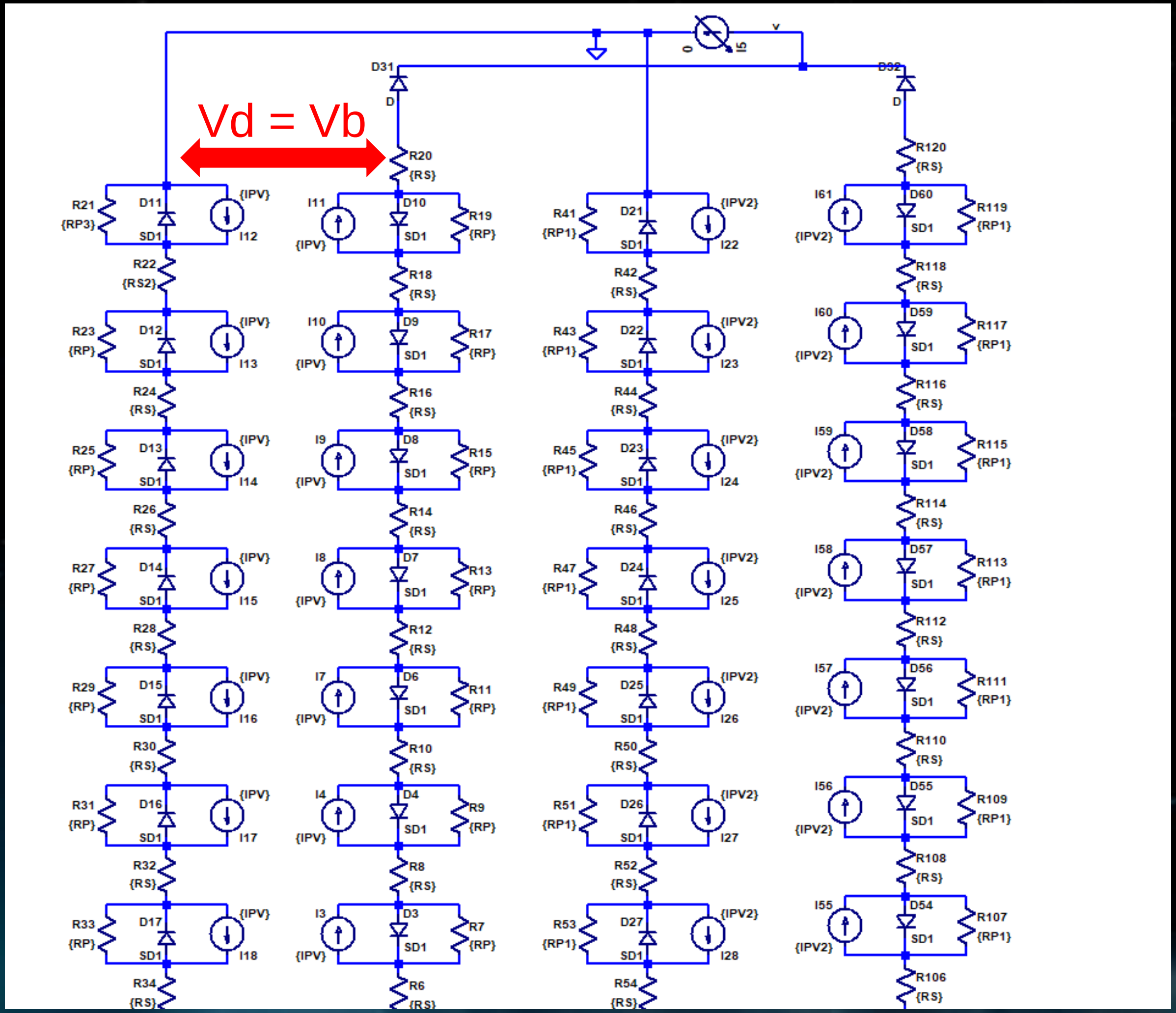
# Solar Cell Interconnects

- Kovar interconnects (Ni, Ag and/or Au plating/flashing)
  - Better conductivity, environmental durability
  - Thermal strain relieve loops in plane
- Out of plane Kovar interconnect
  - Thermal strain relieve loops out of plane
- Kovar interconnects are welded for best durability
- Rear of cell is metallized

# Stringing, bus voltage and differential voltages

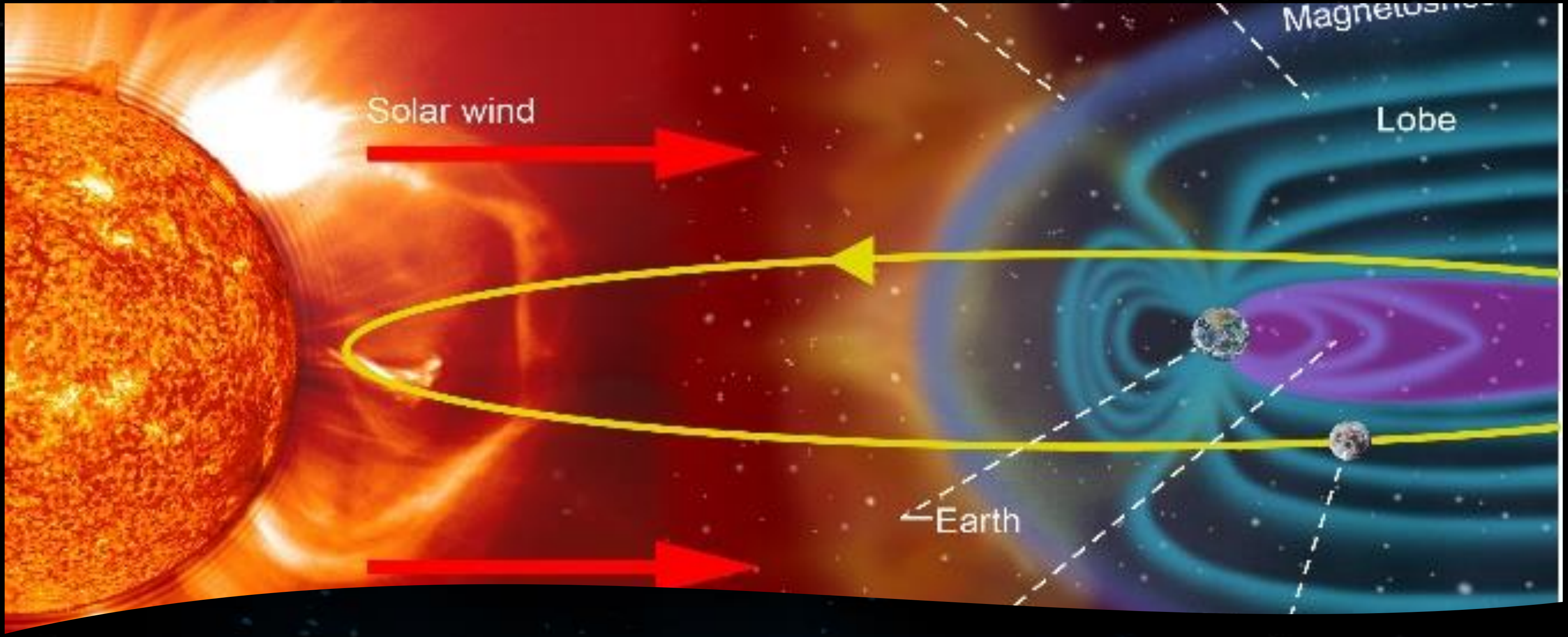


- Cells strung together in series will force a single current
- Voltages sum together up to the desired string voltage (typically 28 V or so)
- Temperature will affect voltages and currents
- Separate strings will combine at junction points through a “blocking diode”, to preclude one string biasing another.  Power loss is I_string * Vf
- Cell-to-cell differential voltages must also be carefully designed during layout



# The Charging Environment






- The plasma environment around the moon is challenging to understand.  The UV component of sunlight combines with plasma to charge the lunar dust.
- The charging of solar arrays limits bus voltage – primary arcs can lead to arcs generated by the arrays
- We want high voltage because of efficiency, mass and utility concerns.
- We will get data from at least half of lunar cycle and possibly through a day-night terminator

# It’s only a paper moon

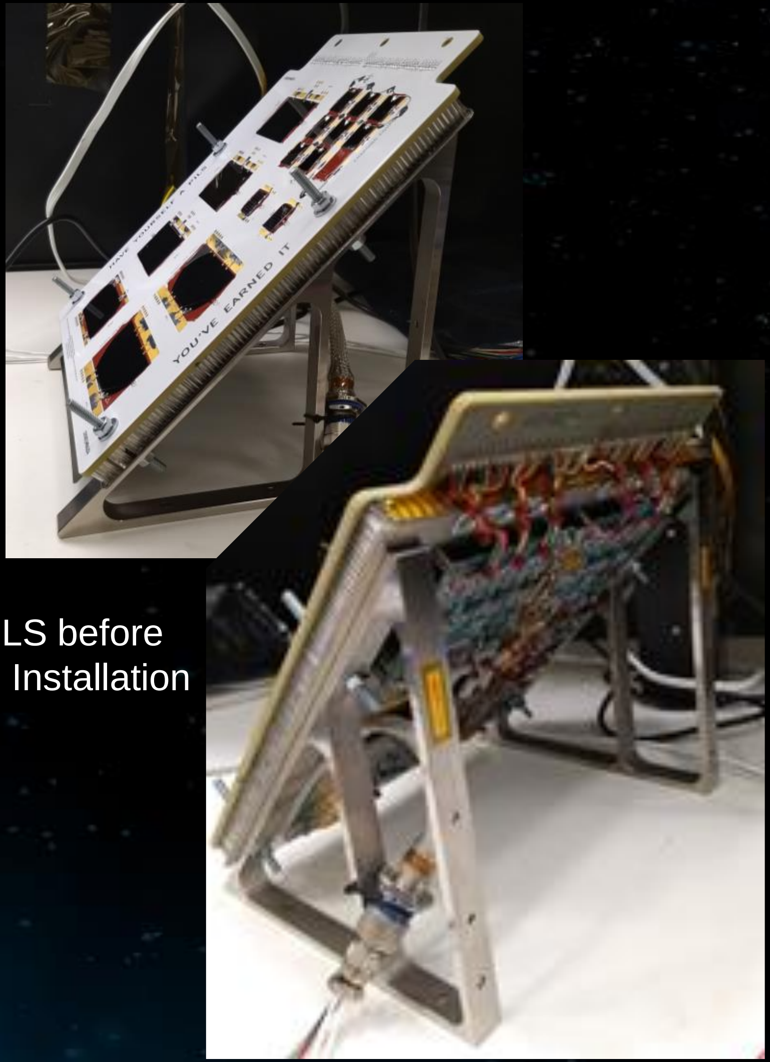


**Background:**

- PILS proposed to Lunar Development Exploration Program (LDEP) call
- Determine charge buildup on solar arrays and arcing hazards in the lunar environment
- Characterize charging phenomena on lunar surface
- Mitigate risk for future high voltage solar arrays on the moon
- Enhance existing models for future power generation systems
- Measure plasma properties for ground-based simulation, arc threshold, and damage rate
- Shape design rules for large solar arrays on the lunar surface
- Increase TRL of cells and arc detection capability

**Summary:**

- Lunar surface demonstration and validation of select *solar cells* and a *solar array equipped with NASA-developed plasma charging measurement circuitry*
- Solar cells include state-of-the-art, next-gen, and thin-film
- Heritage on “Materials on the International Space Station Experiment” (MISSE) solar cell flight test platform
- Dimensions: 30 x 30 x 4cm (without mounting brackets)
- Delivery: November 2020



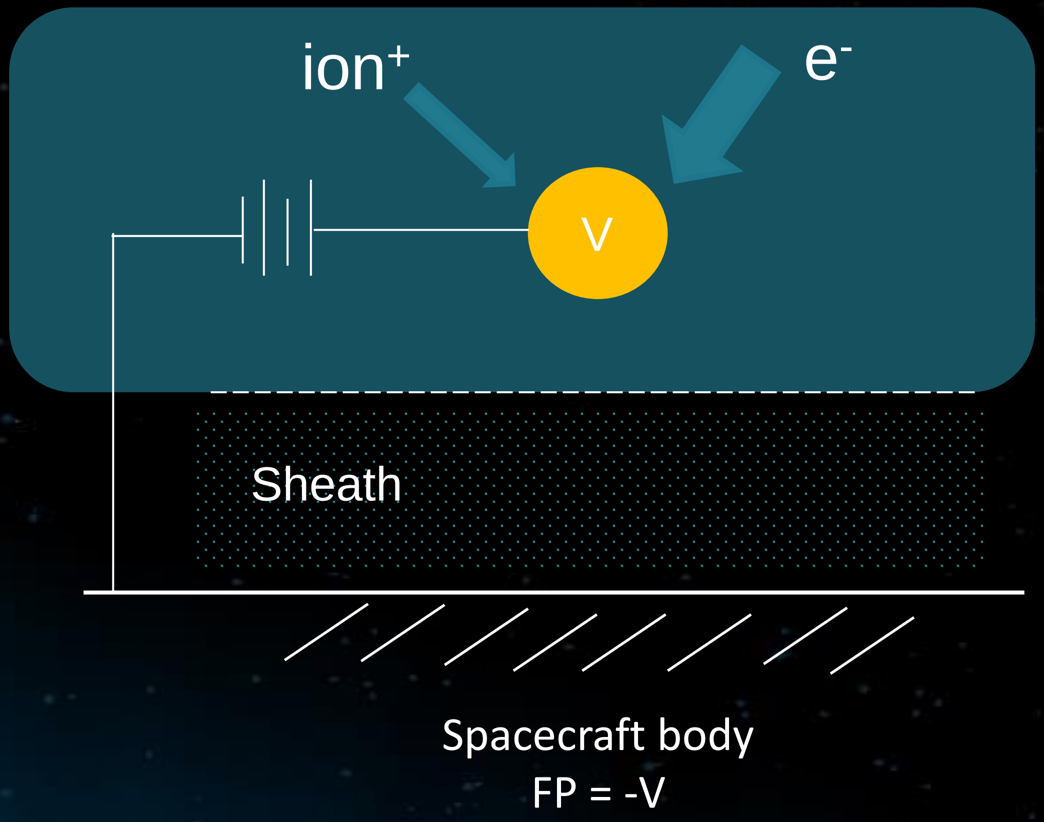
PILS before MLI Installation



30

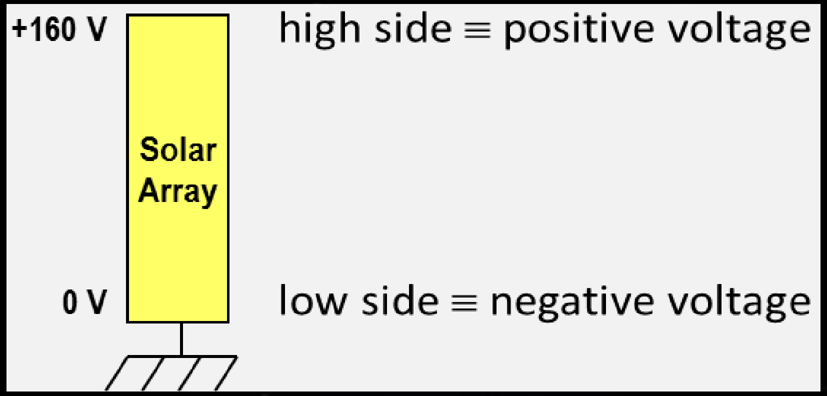
# Floating Potential

- The potential of a body in the space plasma is determined by a balance of the various charging currents: ram ion current, electron thermal currents, secondary ion and electron currents, photoemission currents, etc
- Floating Potential (FP) is defined as the potential where the net current to a body is zero.
- Measurement of the FP: place a conducting surface under high impedance isolation at a distance beyond the body sheath and determining the voltage (V) at which the total current $I_{total} = 0$



# Ionospheric Currents to High Voltage Solar Arrays drive ISS Charging

## Spacecraft View

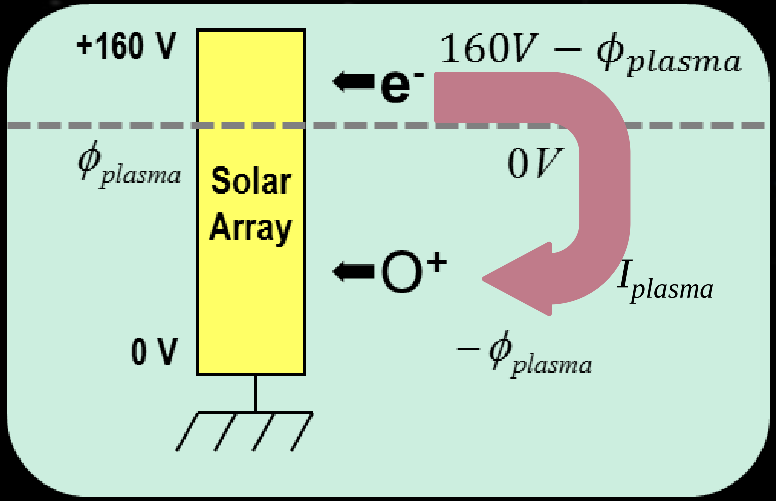



Idealized representation of a 160-V solar array connected to spacecraft chassis ground.

$$n_{O^+} \approx n_e \approx 10^{10} - 10^{13}\ m^{-3}$$
$$T_e = 0.1 - 0.2\ eV$$

ISS ionospheric plasma constituents mainly oxygen ions ($O^+$) and electrons (e)

## Plasma View




Solar array driven current through the ionosphere. The voltage scale on the left is with respect to spacecraft chassis ground; the voltage scale on the right is with respect to the local ionospheric plasma ground. This figure omits the magnetically induced potential.

# Sustained Arcs



- Long Duration ~1 ms to seconds
- Low Current ~0.5 – 3 amps
- Two cells coupled electrically, requires differential voltage ~30V
- Current limited by cell size, current determines length in time of arc pulse
- Pyrolysis of support structure polymers

# What is happening???



- A primary (trigger) arc occurs at the right place, and arcs out to space
- Through a process called ‘flashover’ the arc acts in vacuum as an expanding plasma of energetic charged particles
- The flashover pulse interacts with surface charging of neighboring cells and may offer a low resistance path between cells
- The path is then coupled to the cell performance and the current from the cells feeds the arc.
- Sometimes the arc never ceases
- Don’t let this happen to you!
- Test per ISO 11221

# Testing to ISO 11221



- At GRC we have decades-long experience testing flight-like solar arrays to ISO11221 to determine LEO/GEO effects of charge buildup and arc inception
- Efforts underway to develop testing protocols to represent lunar surface
- GEO is good place to start

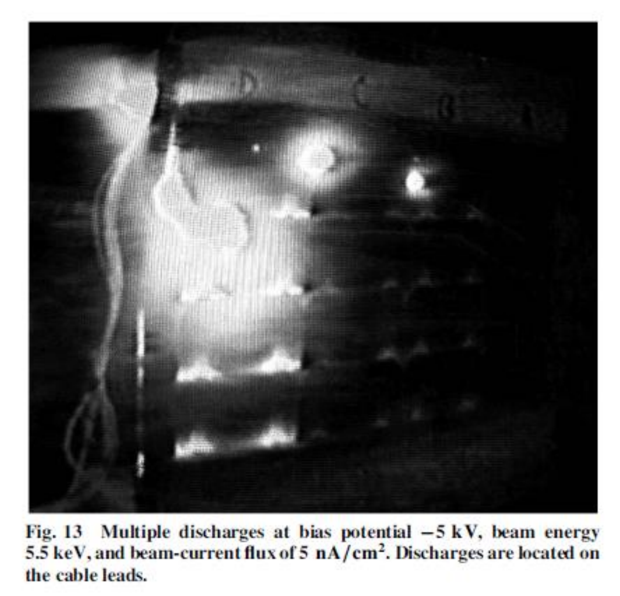


Fig. 13 Multiple discharges at bias potential −5 kV, beam energy 5.5 keV, and beam-current flux of 5 nA/cm². Discharges are located on the cable leads.

**Experimental Charging Behavior of Orion UltraFlex Array Designs**

Joel T. Galofaro,* Boris V. Vayner,† and Grover B. Hillard*
*NASA John H. Glenn Research Center at Lewis Field, Cleveland, Ohio, 44135*

DOI: 10.2514/1.47285

# Conclusions and other things



- Other environments: AO, which effects LEO, and may degrade polymers or impact silver interconnects
- There is support work that can be done at GRC for photovoltaic testing through a space act agreement
- Including thermal balance, charging, I-V curve collection and analysis, post flight data analysis, environmental exposures…
- Solar cells/arrays are complicated power conversion devices that require care in design and development

# Photovoltaic Research and Development at GRC



**Research and development on a wide variety of solar cell, blanket component, and array concepts to support NASA missions and aerospace technology needs.**

**Partners range from universities, non-profit organizations and small/large businesses to various NASA Centers and other Government agencies.**

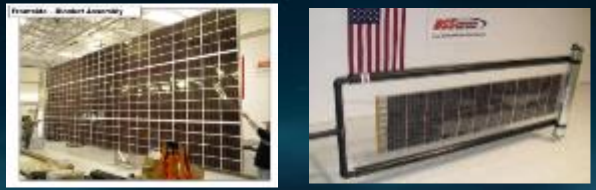
**Solar Cell Measurement and Performance Evaluation**

**High Efficiency III-V, Nanomaterials and Nanostructures Photovoltaic Development**

**Extreme Environment Operation of Solar Arrays**

**Solar Cell Air Mass Zero Calibration**

**Advanced Blanket and Array Technologies**



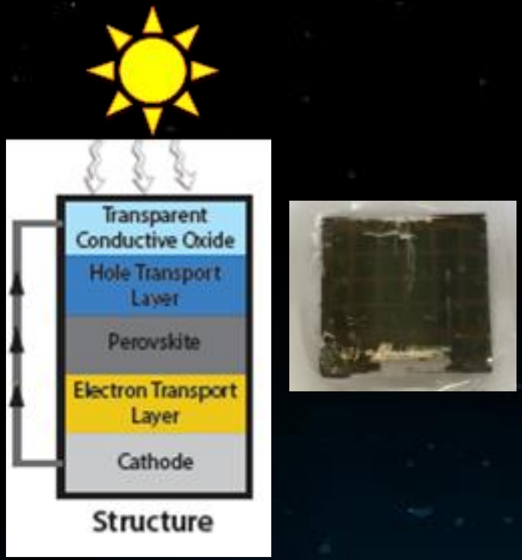
**Solar Array Arcing and Charging Effects**

# PV Supports Broad Range of TRL Activities



## TRL 2-4

Examples:
- Advanced Solar Cell Materials and Designs
- Blanket Designs, Materials and Array Concepts




Perovskite solar cell

## TRL 5-6

Examples:
- Advanced Technology Performance, Reliability, and Environmental Interactions R&D and Evaluation

Thermal balance & arcing of blanket technology

Accurate cell efficiency measurements

## TRL 7-9

Examples:
- Support NASA Missions Through Technical Expertise
- Evaluate Flight Data for New Technology
- Development of Standards and Guidelines

SCARLET array on Deep Space 1

Mars Rover Experiments

- backup

# Solar Array Development – Lunar Orbit

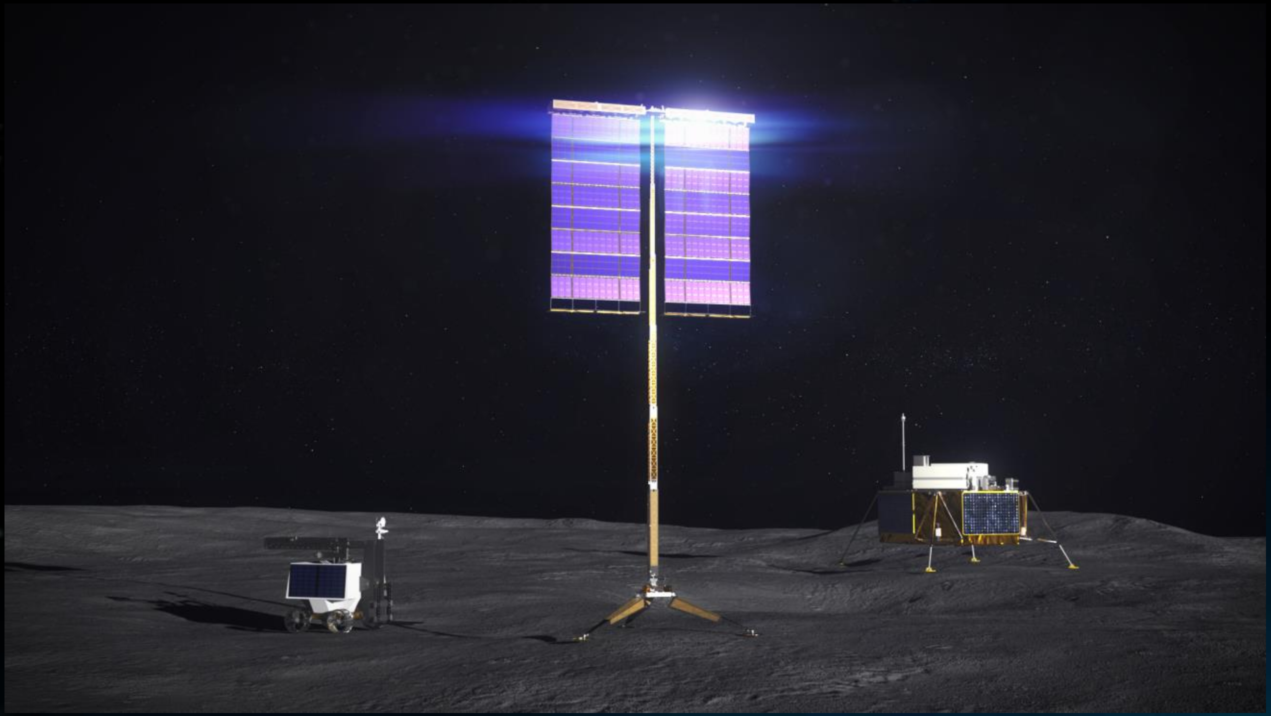


- PV Systems will be used to power many near-term lunar missions
- Gateway Power and Propulsion Element (PPE) will be powered by 2 ROSA solar arrays (50 kW class)
- Human Landing System (HLS) includes elements of photovoltaics

# Solar Array Development – Lunar Surface



- Vertical Solar Array Technology (VSAT) project led by STMD’s Game Changing Development program and NASA Langley in collaboration with NASA Glenn
- Autonomous deployment 10kW class systems of 10 meter (at the base of the array) masts, stable on steep terrain, resistant to abrasive lunar dust and minimized both mass and packaged volume for ease in delivery to the lunar surface



Government reference design concept.

Base period contracts, valued at up to $700,000 each, awarded as 12- month fixed price contracts to:

- Astrobotic Technology, Pittsburgh, PA
- Northrop Grumman (ATK), Goleta, CA
- Honeybee Robotics, Brooklyn, NY
- Lockheed Martin, Littleton, CO
- Maxar Technologies, Palo Alto, CA

The companies will provide system designs, analysis, and data.

The agency plans to down select and provide additional funding, up to $7.5 million each, to build prototypes and perform environmental testing, with the ultimate goal of deploying one of the systems on the Moon’s South Pole near the end of this decade.

Photo credit: NASA