

Photovoltaics for space

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Outline

1. A bit of history
2. Motivation
3. Space environment and Radiation Effects on Solar Cells
4. *Solestia*/ Ultra-Thin Silicon Solar Cell and its self-curing capabilities
5. Project details
6. Other Solar Cell Technologies for Space
7. Summary of the talk

A bit of history...

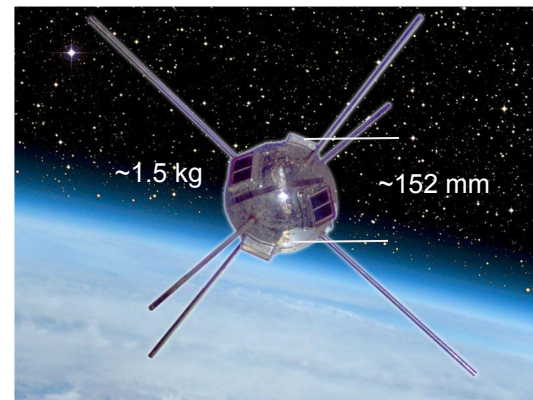
The history of space photovoltaics is in many ways the history of PV at large. Daryl Chapin, Calvin Fuller, and Gerald Pearson invented 'solar battery' as a the space solar power system at *Bell Labs* in 1953.

Vanguard 1 (1958 Beta 2):

- 1st solar powered satellite in space
- launched in March 1958 (video) for initially 90 days mission
- to test the launch capabilities of a 3-stage test vehicle
- track effects of space environment, geodetic measurements
- 6 single crystal Si solar cells with BOL efficiency 10% delivering ~1W
- still in orbit (~65 y 3 m)... record-holder of oldest man-made objects being launched to Space



The first operating c-Si solar cell was reported in 1954 ([Chapin et al., Bell Labs](#)), initially ~6% efficiency.

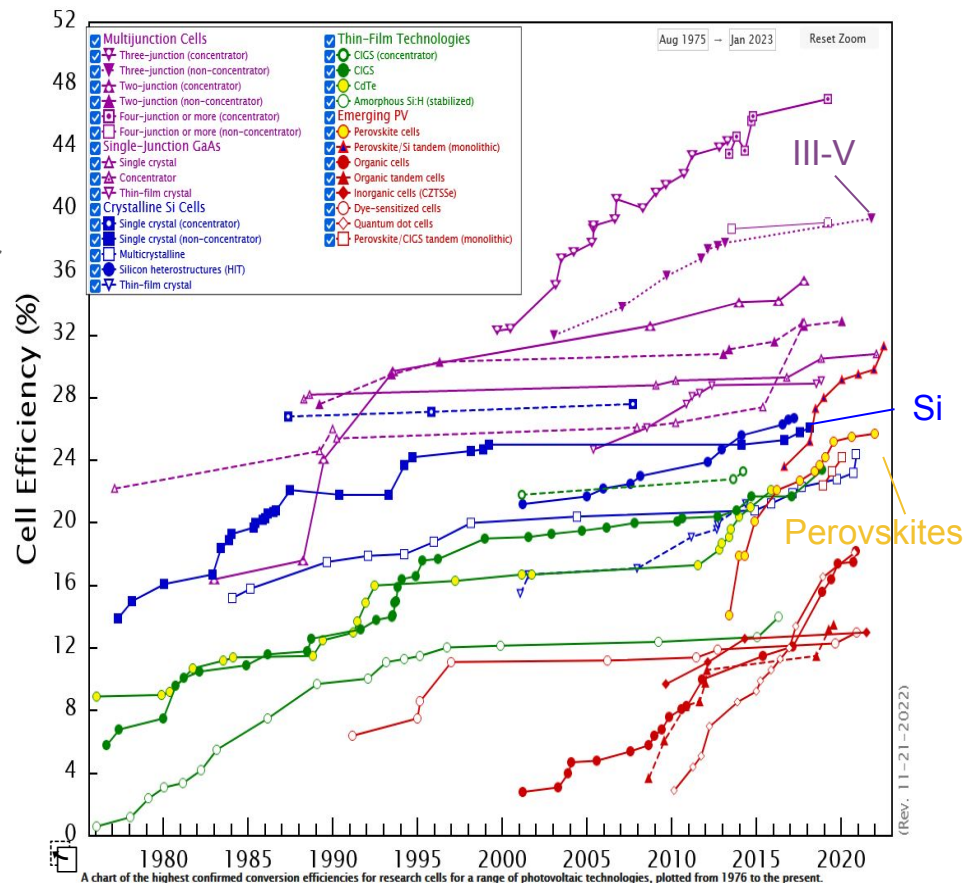


Vanguard 1, remaining in MEO for >60 years

Today

- Since early 2000s III-V multi-junction solar cells dominate space market, which is not easy to enter for new technologies
- Why?
III-V: 4-junctions by Azur Space:
 - high BOL efficiency (31.8%), 1.3W/cell (30cm²)
 - >2×EOL efficiency to Si
 - higher radiation hardness
- Cost around 3 orders of magnitude higher than Si
- Environmental compatibility ?

➡ benefit on system level cost



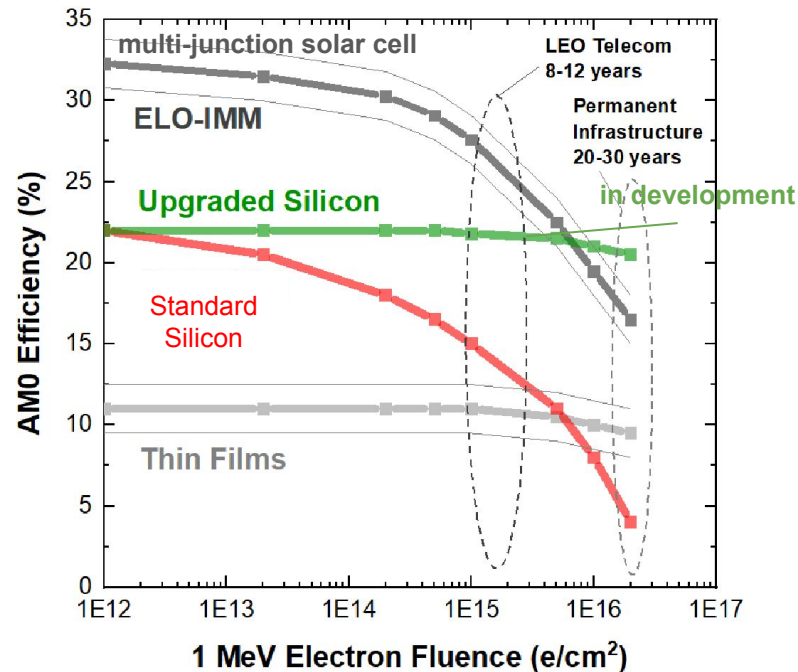
[Interactive efficiency chart](#) by NREL

Motivation

Converting light to electricity \Rightarrow key strategy for Space

Ultimate solution:

- Low cost (<\$1/W potential)
- Low-mass
- Flexible
- Rigid
- Manufacturable (multi-GW scaling potential)
- Best EOL efficiency for long missions (>10 years)



Solar cells EOL efficiency degradation after electron irradiation

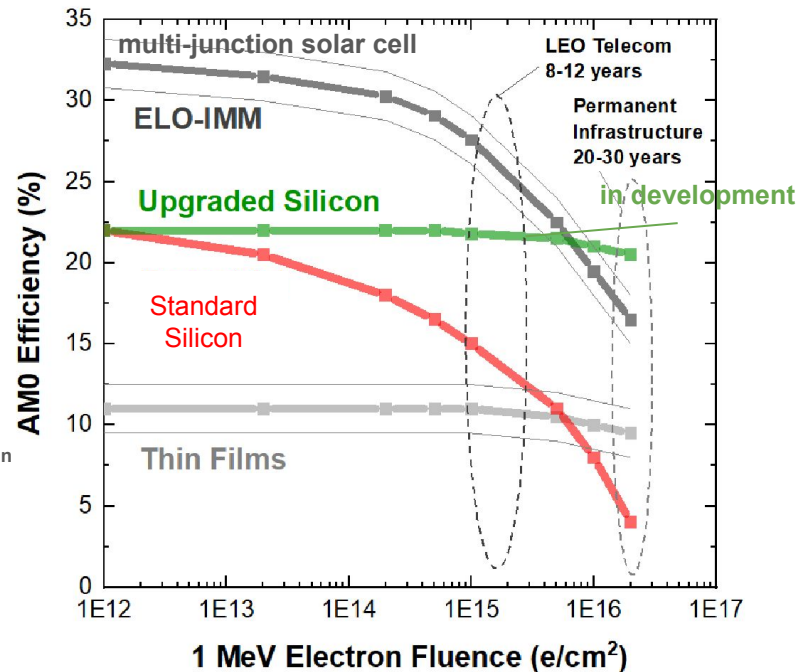
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Silicon:



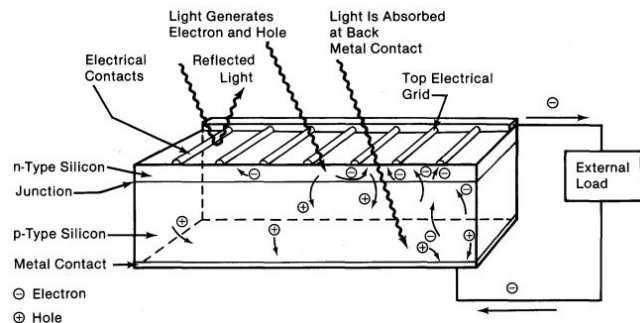
Solar cells EOL efficiency degradation after electron irradiation

! Need to solve the radiation-damage problem riddle !

What is a solar cell?

A **solar cell**, or *PV cell*, is an electronic device based on *p-n junction* that converts the energy of light (☀) directly into electricity by the photovoltaic effect. Basic processes of PV effect:

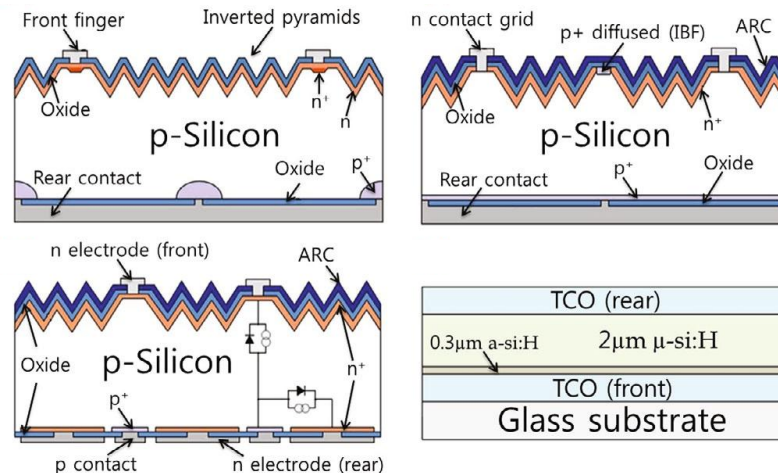
- generation of charge carriers due to absorption;
- subsequent separation of photo-generated charge carriers in junction;
- collection of photo-generated charge carriers at the terminals.



Basic photovoltaic principle:

incident light hitting the cell creates *e-h* pairs, which are separated by potential barrier at junction creating a voltage that drives current through external circuit.

Evolution in Si solar cell design



Structure of the PERL (top-left), HES-IBF (top-right), both-side junction (bottom-left) and thin-film solar cells for space application.

Space Environment

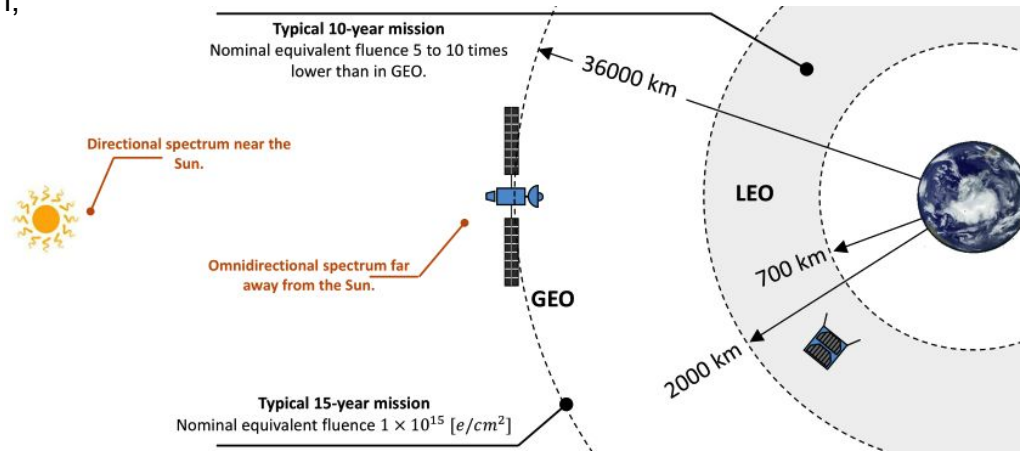
Satellites, spacecrafts operating in inner Solar system: to power sensors, active heating-cooling are mainly designed for 2 kinds of missions, known as:

LEO (Low Earth Orbit):

- 500-2000 km from Earth;
- orbit used for ISS, satellite imaging;
- low level of radiation, mostly electrons;
- Earth's shadow → >5k thermal cycles/year;
- Earth atmosphere → aerodynamic drag;
- short missions (up to 10 years) - SC with high BOL efficiency.

GEO (Geostationary Orbit):

- 35 786 km above equator;
- weak geo-magnetic shield → high level of radiation;
- extreme temperatures;
- satellites rotate at the same speed as Earth;
- weather monitoring, telecommunication, surveillance;
- long missions (15-20 years) - SCs with longer operation lifetime.



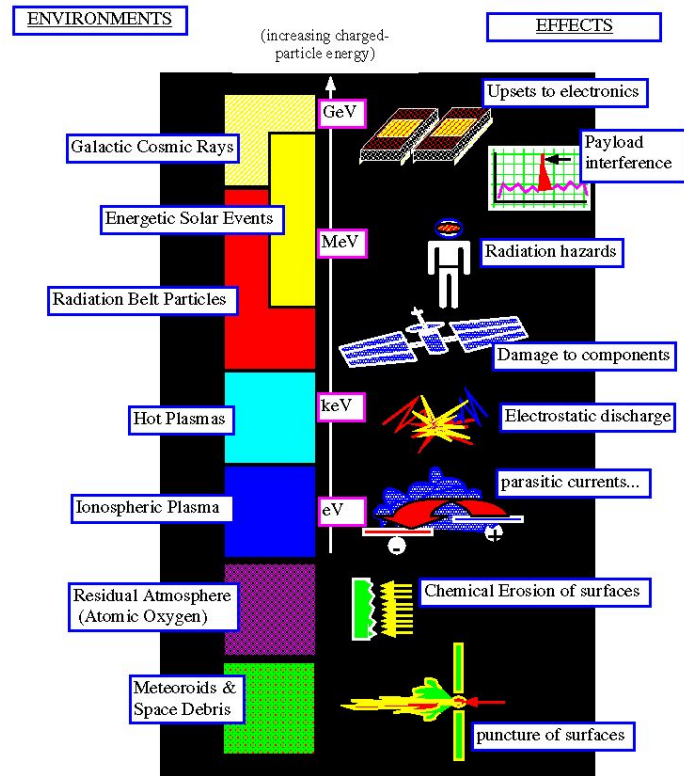
Space environment and types of orbits

Effects of Space Environment

Overview of Space radiation and other conditions that can affect solar cell performance, such as ionizing radiation, energetic particles, *etc.*

Severe conditions:

- High energy (up to hundreds of MeV) high fluence $\sim 10^{16}$ **electron and proton irradiation;**
- Vacuum;
- Very high UV content (AM0);
- Thermal cycles - several k (e.g. $-170 \rightarrow +150^\circ\text{C}$, strongly depends on mission);
- Electrostatic discharge (ESD) events;
- Micrometeorites/debris;
- Launch: vibration, acoustic, shock depressurisation;
- On ground: humidity;
- ...



Space environment and typical effects on space systems

Effects of Space Environment

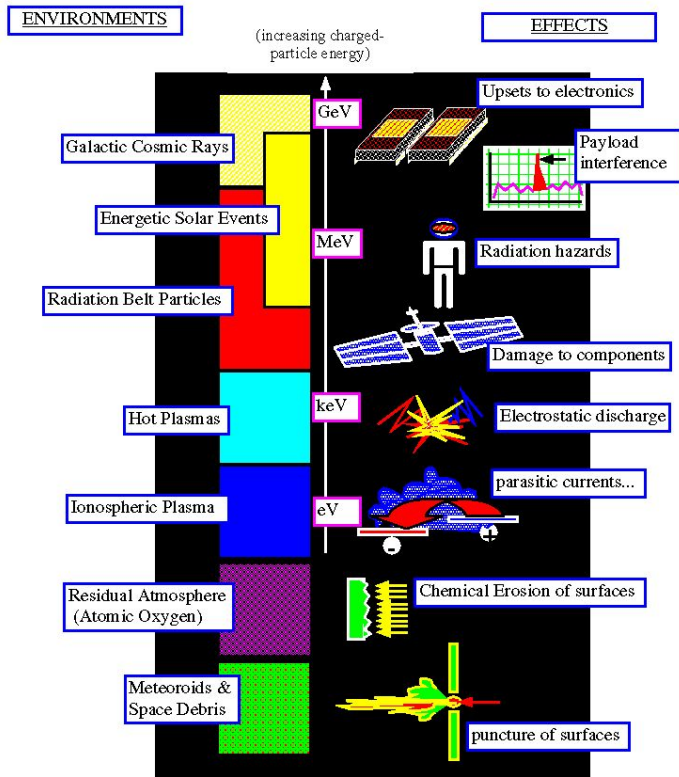
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Successful operation in Space requires :

- extensive qualification tests;
- radiation testing of components;
- understanding of the mechanisms that cause degradation.

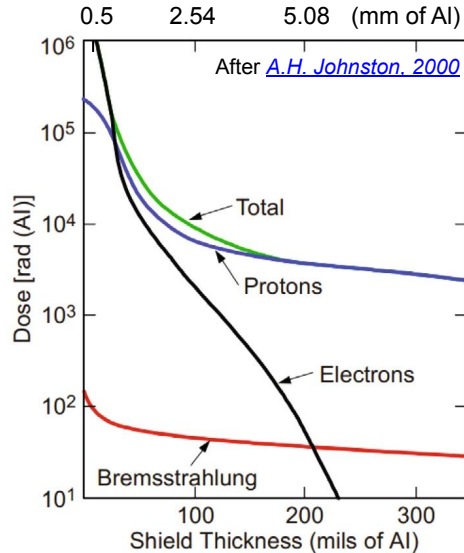


Space environment and typical effects on space systems

Radiation effects on Si solar cells

- In space e and p irradiation \Rightarrow atomic displacements (PKA) in Si bulk \Rightarrow lattice defects (V, I, complexes: V-D, I-A, etc.)
- SRH statistics: highly active recombination/trapping centers generated \Rightarrow \downarrow output power (EOL efficiency)

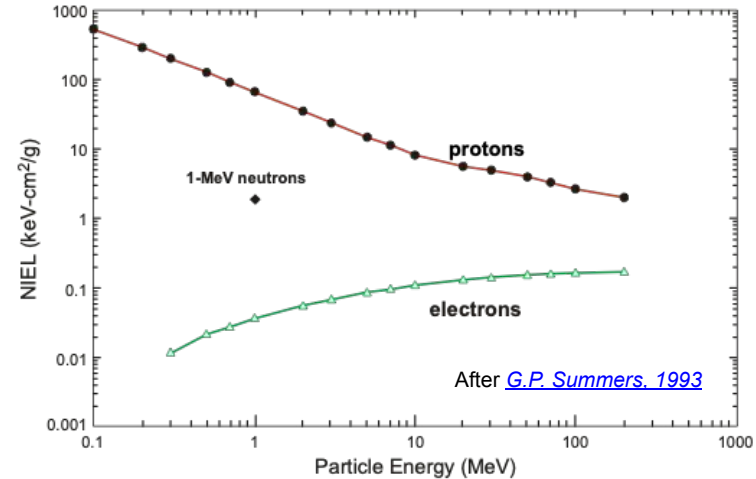
\Rightarrow **appropriate shielding** (coverglass \leftarrow changes in the transmission of light in the visible and near IR region)



DDD can be correlated analytically by NIEL

$$DDD = \int (d\varphi(E) / dE) S(E) dE,$$

$\varphi(E)$ - irradiation fluence,
 $S(E)$ - NIEL value



Dependence of NIEL on proton energy in silicon

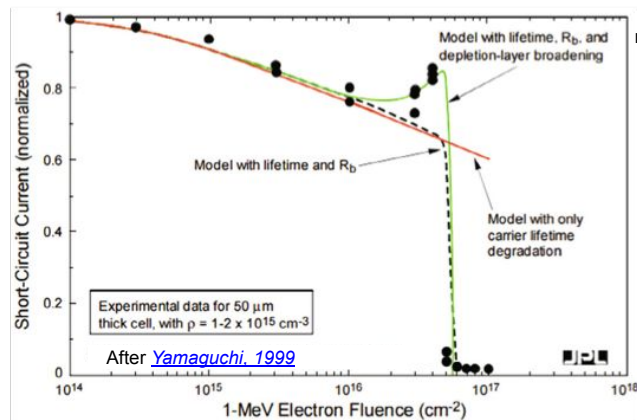
Shielding effect on total dose for 5-years mission at 98°, 705 km

Please, see next talk given by Vendula Subert

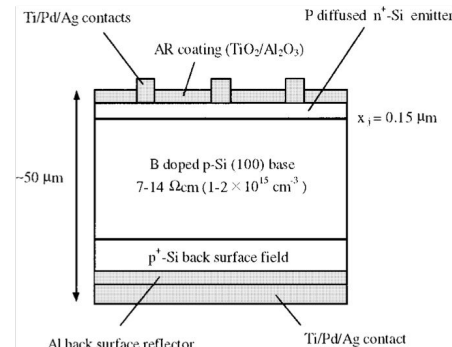
Radiation effects on Si solar cells

⇒ n^+p configuration is a preferred choice over p^+n (more Rad-Hard)

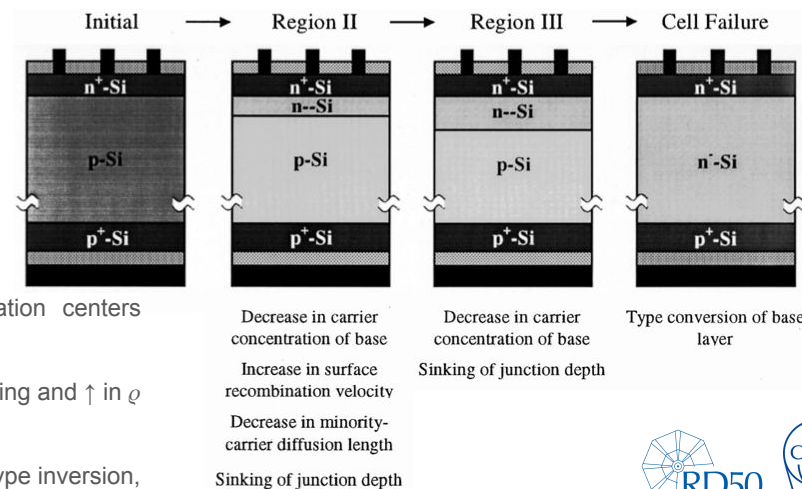
Model with lifetime, R_b and depletion layer broadening



reported by [Hisamatsu, 1998](#)



Back-surface field and reflector (BSFR)
 n^+p - p^+ test structure, $A=2 \times 2 \text{ cm}^2$

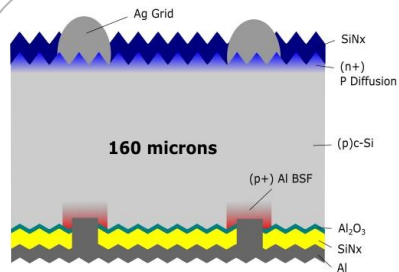


I: $<1E+16 \text{ e/cm}^2$ - the gradual degradation is observed: radiation-induced recombination centers contribute to the reduction of the minority carrier diffusion length

II: $1E+16 < 5E+16 \text{ e/cm}^2$ - the anomalous increase is observed: depletion layer width broadening and \uparrow in ρ due to AR effect (\uparrow photo-current contribution)

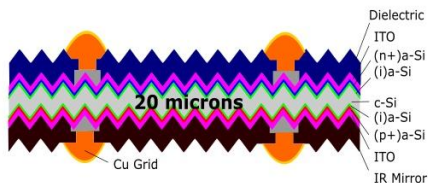
III: $>5E+16 \text{ e/cm}^2$ - abrupt decrease: \downarrow in carrier concentration; and subsequent cell failure: type inversion, donors dominate due to 'super-diffusion' enhanced by high-fluence electron irradiation, emitter = P source, generation of Vs and vacancy-mediated diffusion of P into the bulk

Ultra-Thin (UT) *Solestial* Silicon Solar Cells



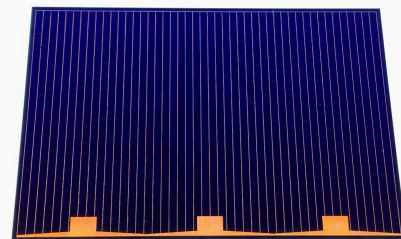
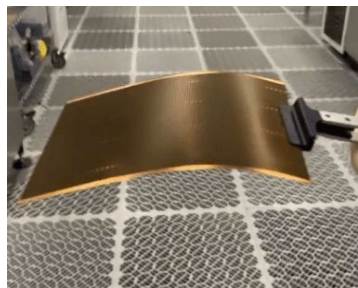
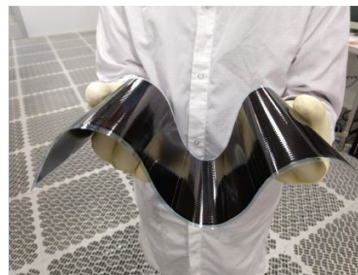
Commercial single-Si Cell

- 160 μm thick
- Diffused Junction
- Screen printed Ag and Al
- Degrade fast under irradiation
- Rigid



Solestial Ultra-Thin Si Cell

- 20 μm thick
- a-Si/c-Si Heterojunction
- Electroplated Cu
- Potentially more radiation hard
- Light-weight and flexible



Different flavours of UT-Si PV cells developed and produced by *Solestial, Inc.*

Novel UT-Si PV cell technology is in development by *Solestial, Inc.*

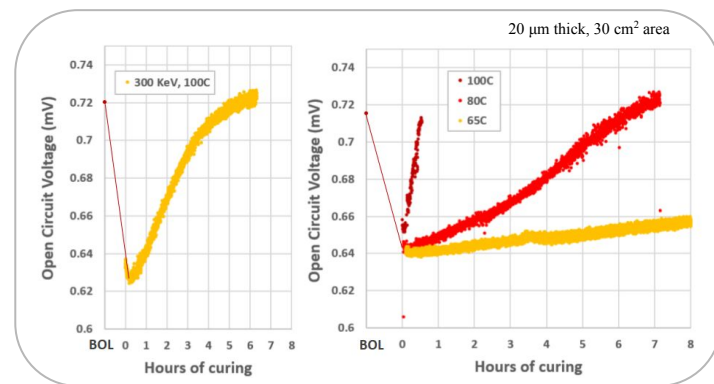
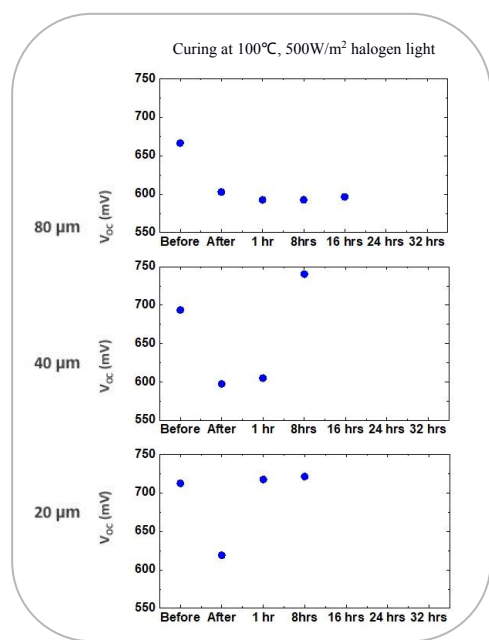
Such solar cells have a potential to achieve efficiencies of >40% in emerging technologies (present >20%), being Rad-Hard, light-weight, flexible and low-cost because of high volume manufacturing process available.

Self-curing capabilities of *Solestial* Solar Cells

- Comparison of open-circuit voltage V_{oc} vs annealing time/cell thickness/annealing T
- Irradiation: 1 MeV electrons: $1E+15$ e/cm²; 300 keV protons: $1E+10$ p/cm²
- Curing: 65, 80, 100°C; under illumination: 500 W/m² halogen lamp
- 2nd round of e-irradiation - third-party validation (90°C → 96% recovery)

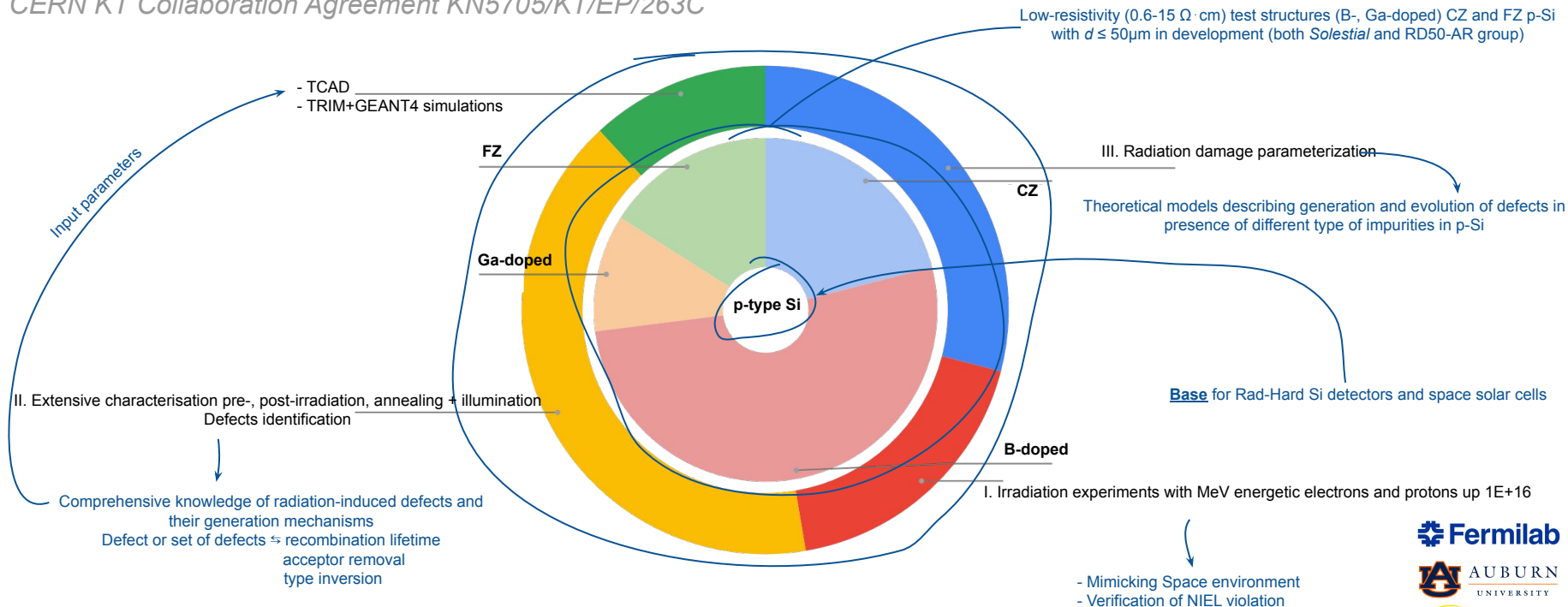
- Curing at low temperatures works
- Curing rate increases with thinning the cell
- Cells with ≤ 40 μm thickness have fully restored the initial V_{oc}
- Validated by the third-party ([CEA-INES](#))
- Additional curing experiments by low temperature annealing, illumination and forward biasing are planned

Several CiS CZ p-Si sensors (please, see presentation by Niels) are sent to 1 MeV electron irradiation to Fermilab



Synergy: KT project for 2022-24

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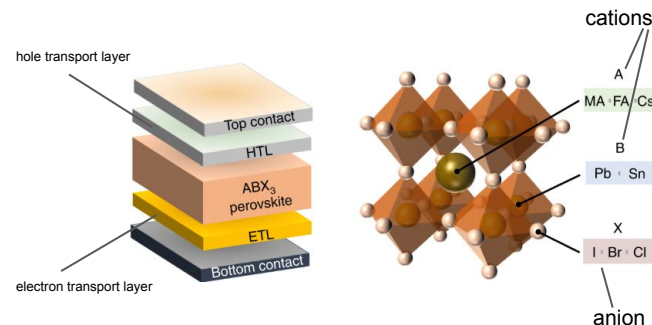


Apply the gained knowledge to improve the **radiation hardness** of **p-type Si**-based devices by **defect engineering** approaches

Perovskites and emerging technologies

Strength:

- fast advancing solar technology
- include perovskite-structured compound as a light-harvesting level
- hybrid organic-inorganic lead or tin halide-based material
- simple to process (low-T solution-based processing - coating, printing, deposition)
- tunable bandgap (1.3-2.2 eV) by altering halide content
- BOL efficiency AM1.5 solar spectrum - 3.8→25.2%, tandem - 33.2%
- [radiation hardness](#) summary available



Frailties:

- toxicity ← replacing lead, encapsulation, coating to reduce lead leakage
- inherent **instability** and can react with moisture and oxygen → drastic **degradation**
- low thermal stability (-80°C; +100°C at best)

Not yet ready to conquest the Space market!

Summary of the talk

- Overview of the silicon solar cell technology and others were presented;
- Space environment has certain damage effect due to radiation == displacements and ionisation due to presence of high-energy electrons and protons;
- Progress in Si solar cells for Space has occurred over time and still ongoing;
- Anomalous degradation at high fluences ($>1\text{E}+16 \text{ e/cm}^2$) were observed and models exist;
- Radiation-hard Si solar cells with self-curing capabilities are under development;
- Synergy to improve radiation hardness by defect engineering approaches for space solar cells development and HEP community via resources and efforts is created.

Thanks for your attention!