Investigation of GaInNAs and Cu(In,Ga)Se_2 Solar Cells for Space Applications

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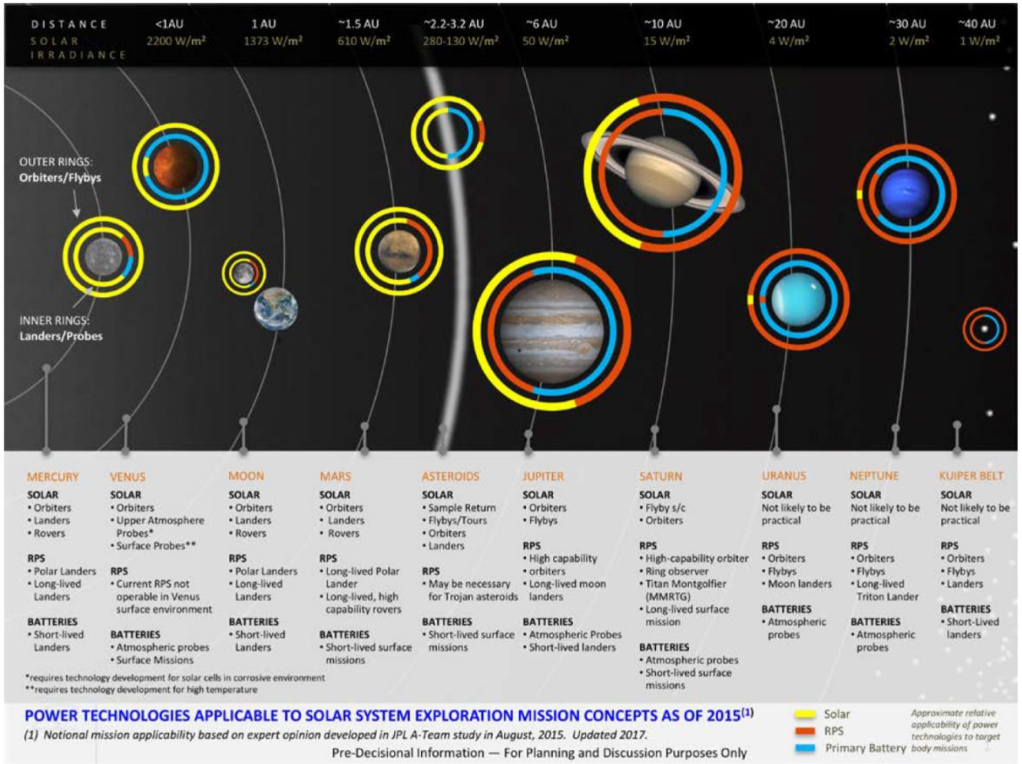
Photovoltaics Materials & Device Group, University of Oklahoma: http://www.nhn.ou.edu/~sellers/group/index.html

Photovoltaics for Next Generation Space Missions: Deep Space/Outer Planetary Missions



	MERCURY	VENUS	MOON	MARS	ASTEROIDS	JUPITER	SATURN	URANUS	NEPTUNE	KUIPER BELT
SOLAR	• Orbiters • Landers • Rovers	• Orbiters • Upper Atmosphere Probes* • Surface Probes**	• Orbiters • Landers • Rovers	• Orbiters • Landers • Rovers	• Sample Return • Flybys/Tours • Orbiters • Landers	• Orbiters • Flybys	• Flyby s/c • Orbiters	Not likely to be practical	Not likely to be practical	Not likely to be practical
RPS	• Polar Landers • Long-lived Landers	• Current RPS not operable in Venus surface environment	• Polar Landers • Long-lived Landers	• Long-lived Polar Lander • Long-lived, high capability rovers	• May be necessary for Trojan asteroids	• High capability • orbiters • Long-lived moon landers	• High-capability orbiter • Ring observer • Titan Montgolfier (MMRTG) • Long-lived surface mission	• Orbiters • Flybys • Moon landers	• Orbiters • Flybys • Long-lived Triton Lander	• Orbiters • Flybys • Landers
BATTERIES	• Short-lived Landers	• Atmospheric probes • Surface Missions	• Short-lived Landers	• Short-lived surface missions	• Short-lived surface missions	• Atmospheric Probes • Short-lived landers	• Atmospheric probes • Short-lived surface missions	• Atmospheric probes	• Atmospheric probes	• Short-Lived landers

*requires technology development for solar cells in corrosive environment
**requires technology development for high temperature

POWER TECHNOLOGIES APPLICABLE TO SOLAR SYSTEM EXPLORATION MISSION CONCEPTS AS OF 2015[1]

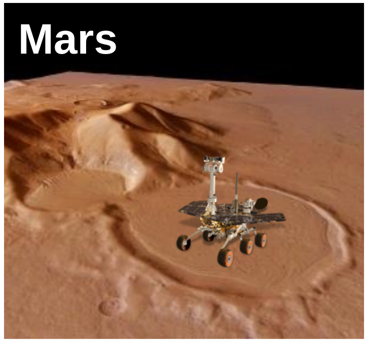
(1) Notional mission applicability based on expert opinion developed in JPL A-Team study in August, 2015. Updated 2017.

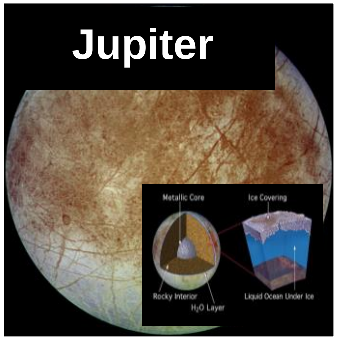
Pre-Decisional Information — For Planning and Discussion Purposes Only

🟨 Solar
🟧 RPS
🟦 Primary Battery

Approximate relative applicability of power technologies to target body missions

- **NASA**
- **ESA**
- **JAXA**
- **Space X**

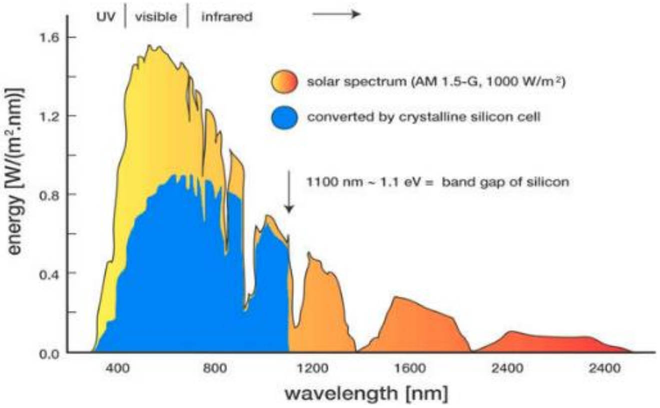


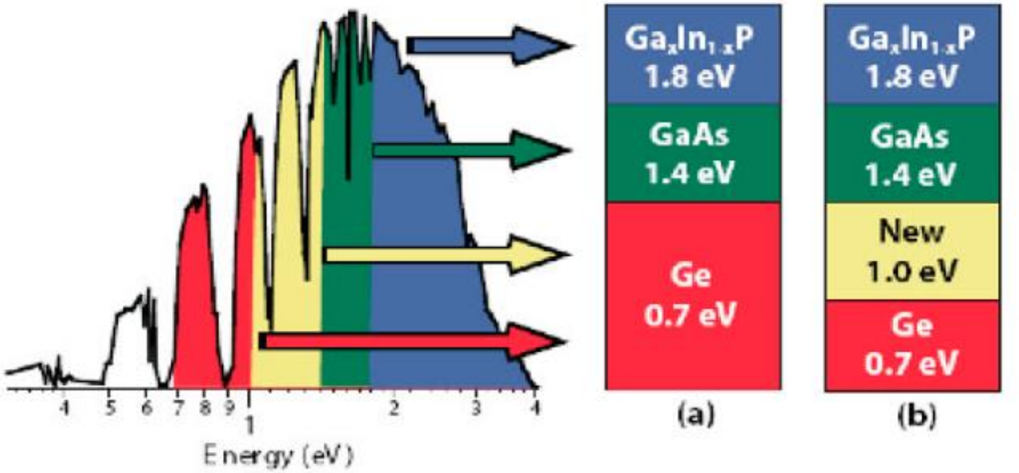


- Higher power requirements for outer planet exploration
  - Beyond power for most radioisotope thermoelectric generators (RTG)
- Outer planets have low temperature compared to Low Earth Orbit (LEO) and some missions, like those near Jupiter, will encounter intense radiation belts.
- Flexible radiation hard thin films solar cells may be competitive if packing ratio/specific power is high compared to multijunction
  - Particularly for low cost satellites (CubeSat and SmallSat, 6U and 24U)

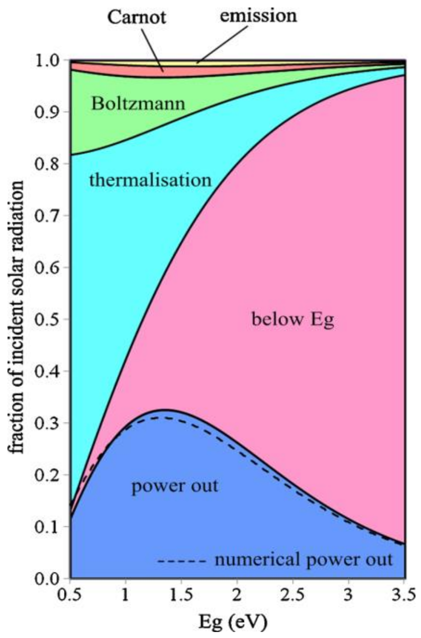
G. A. Landis and J. Fincannon, *IEEE 42nd (PVSC)*,

Single Bandgap Limit and Multijunction Solar Cells: GaInNAs





J.F. Geisz and D.J.Freidman, Semicond. Sci. Technol. 17, 769 (2002)

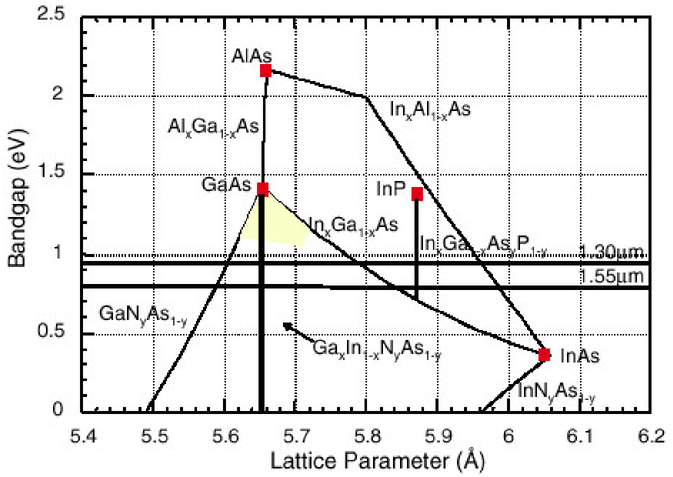


- Three junctions: 44.4% efficient
- Four junctions: Up to 52% efficient
- Power wasted by Ge due to poor current matching

We need a material with 1 eV band gap, correct lattice spacing

L. C. Hirst & N. J. Ekins-Daukes, Prog. PV. **19**, 286 (2010)

GaInNAs is Promising but Problematic - Passivation Techniques



J. S. Harris, Semicond. Sci. Technol. 17, 880 (2002)

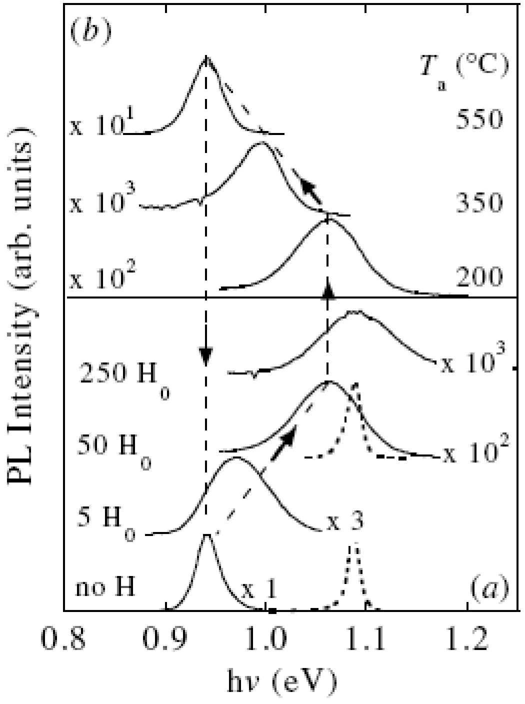
Growth Problems:

- High temperature → phase separation, clustering
- Low temperature → defect formation,

  low nitrogen inclusion,

  alloy fluctuations

Brown *et al*. *RSC Advances* 7, 25353 (2017)



Polimeni *et* a*l*. Semi. Sci Tech. **797,** (2002)

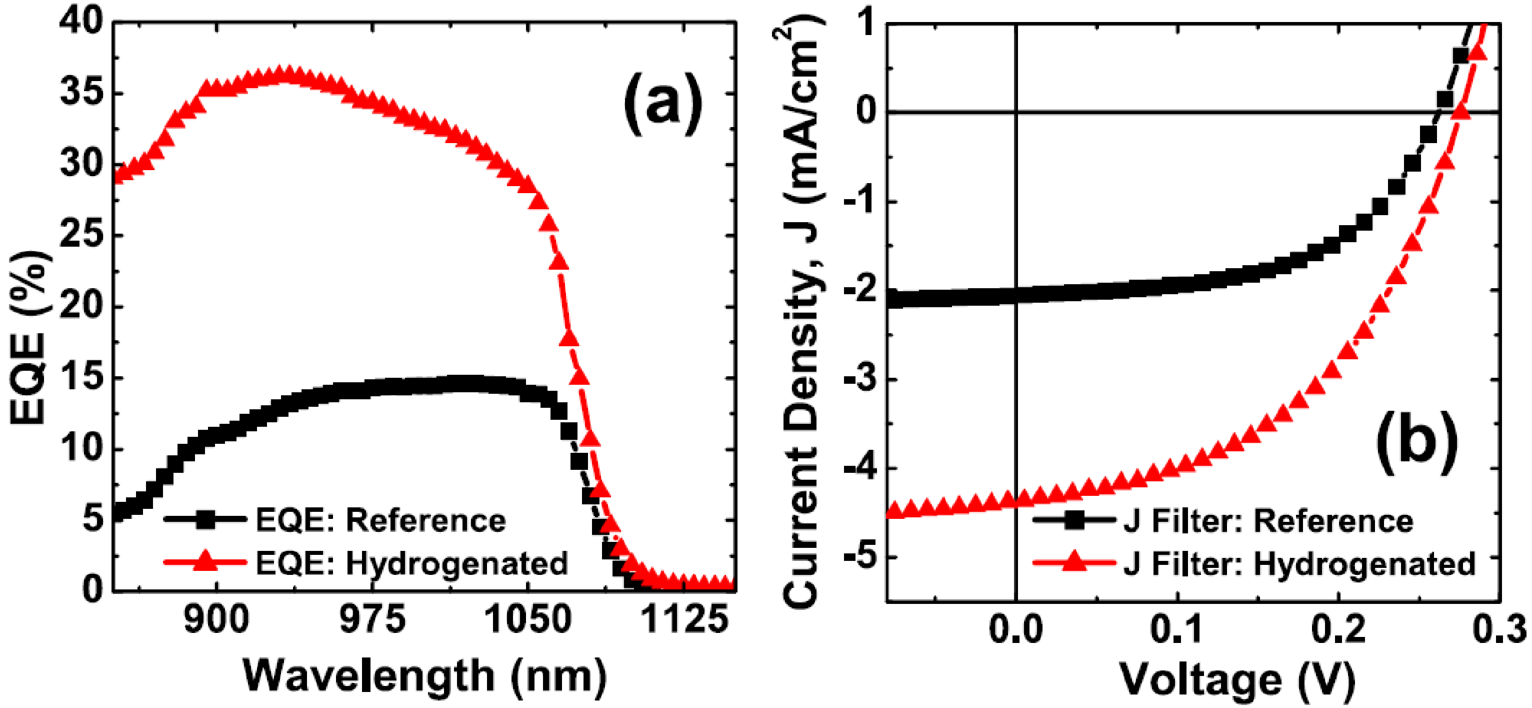
Previous hydrogenation work:

- Removes effect of substitutional nitrogen
- selective passivation of certain defects with increasing hydrogen

AMETHYST RESEARCH INCORPORATED

- UV-activated hydrogenation – Deuterium based
- Typical 100 °C – 350 °C
- Pressures ranging from 10^{-6} – 10^5 Torr

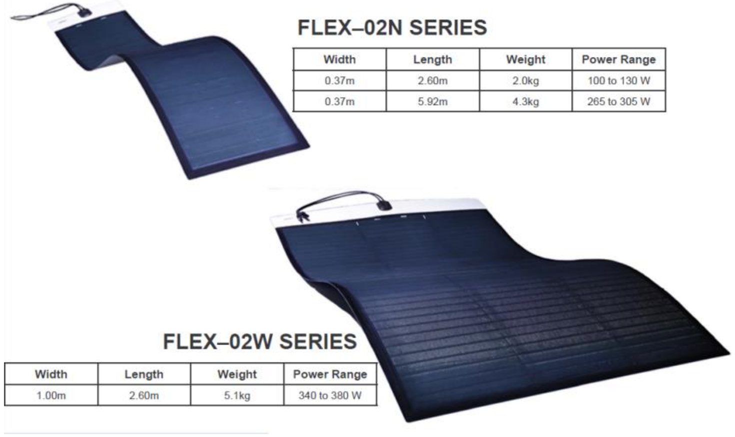
Passivation and Solar Cell Characterization



- **Increase in performance of the solar cell after hydrogenation**
- **No visible effect on the substitutional Nitrogen – *selective passivation***
- **Understanding of doping change necessary, especially for PIN structure**

Fukuda *et al*. *Applied Physics Letters* **106**, 141904 (2015)

Flexible (commercial) CIGS: *MiaSolé product*

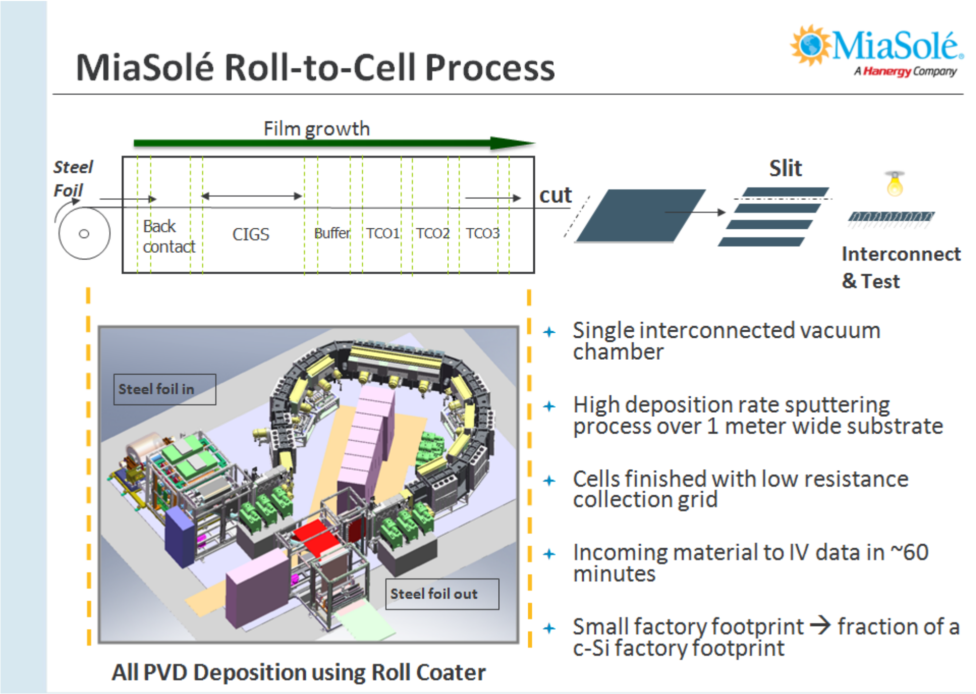


FLEX–02N SERIES

Width	Length	Weight	Power Range
0.37m	2.60m	2.0kg	100 to 130 W
0.37m	5.92m	4.3kg	265 to 305 W

FLEX–02W SERIES

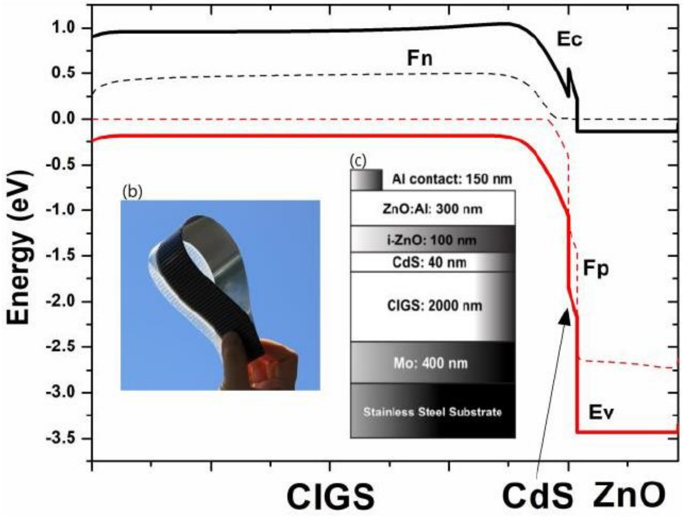
Width	Length	Weight	Power Range
1.00m	2.60m	5.1kg	340 to 380 W



MiaSolé Roll-to-Cell Process

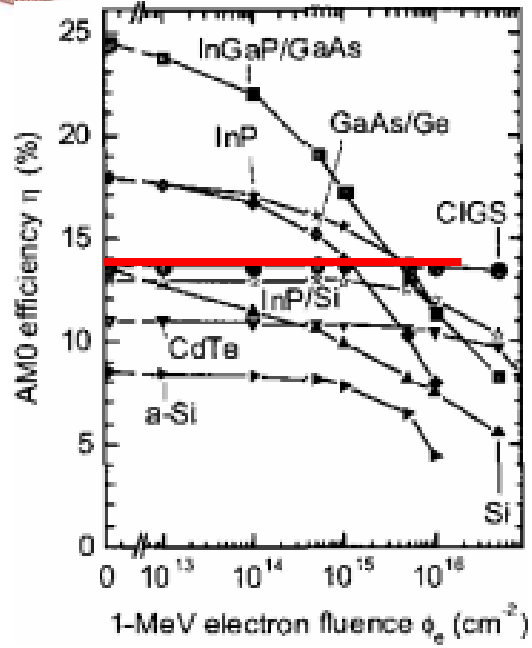
- Single interconnected vacuum chamber
- High deposition rate sputtering process over 1 meter wide substrate
- Cells finished with low resistance collection grid
- Incoming material to IV data in ~60 minutes
- Small factory footprint → fraction of a c-Si factory footprint

All PVD Deposition using Roll Coater

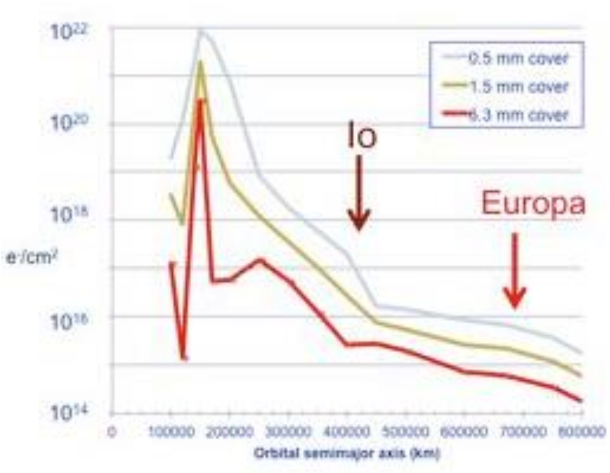


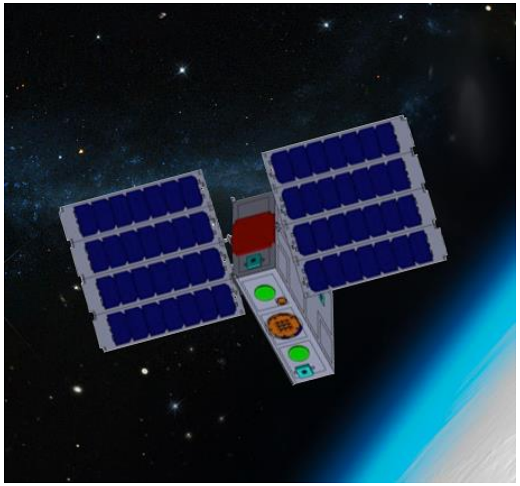
- Commercial grade CIGS with module efficiency of 17 % (20% - 2020)
- PVD Roll-to-Cell process on flexible steel
- Specifications: (for example - *FLEX-02W*) 2.4 Kg/mm / 2598 mm x 1000 mm = 380 W
- Payload (AM1.5G) ~ 61 W/kg

CIGS for Deep Space: a *unique application*

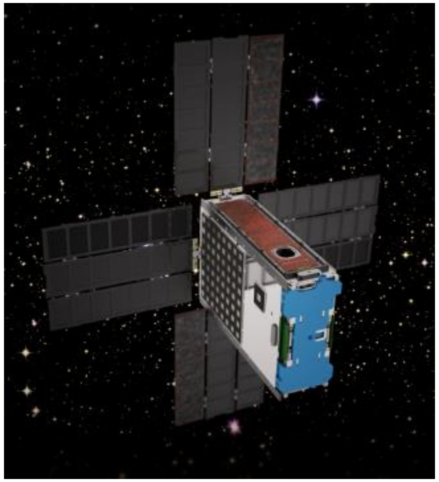


A. Jasenek et al., Proc. WCPEC-3, 2003.





www.nasa.gov/mission_pages/smallsats



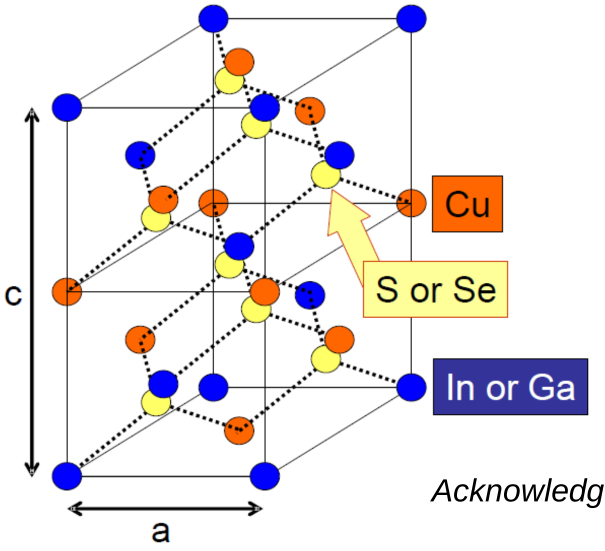
BioSentinel - www.nasa.gov

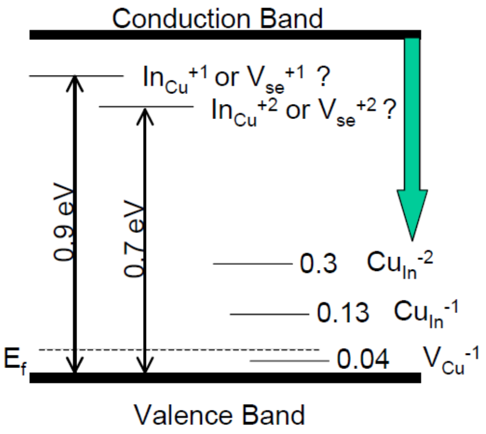
	I (AM0 suns)	I (W/m^2)	T_{eq} (K)
Saturn	0.011	14.82	100
Jupiter	0.037	50.26	135
Mars	0.431	586.2	263

G. A. Landis and J. Fincannon, *IEEE 42nd (PVSC)*,

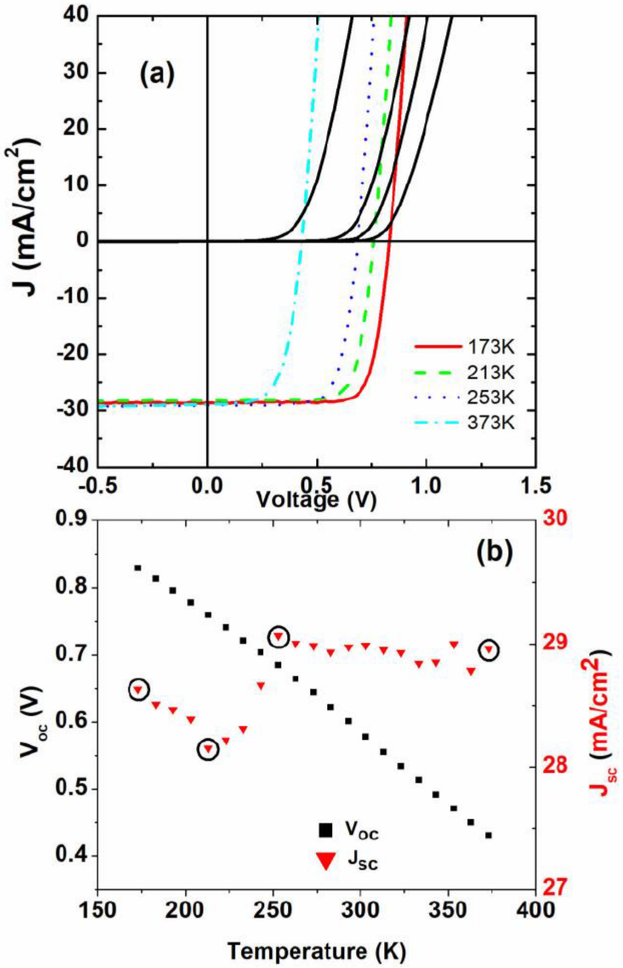
- Low cost, deployable technology
- (At least) equivalent payload
- Higher packing volume
- Radiation hard

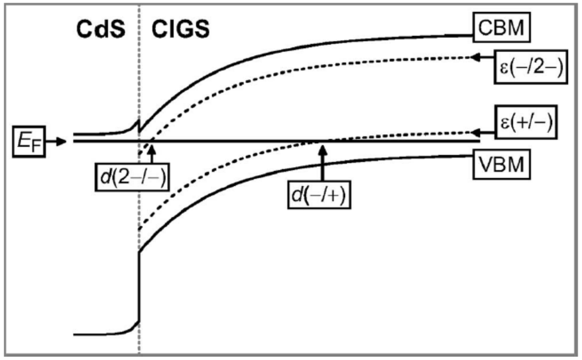
CIGS: Materials Properties: *Metastability*



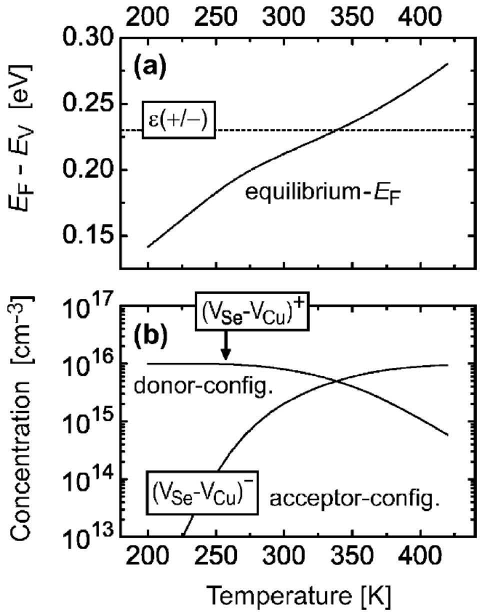


Acknowledgement - Angus Rockett (CSM)



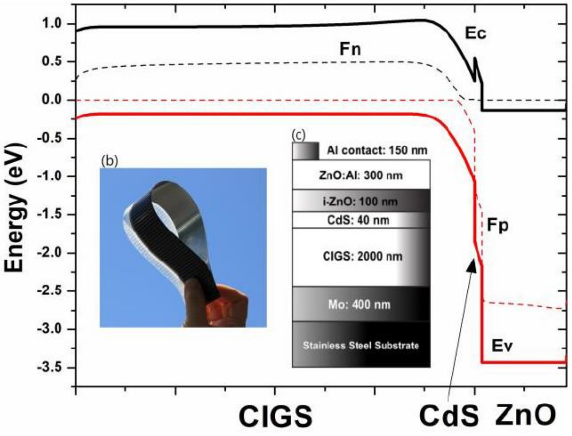


Lany and Zunger, JAP 100, 113725 (2006)



Reversible metastability under PV operating conditions

Effects of Metastability: *LILT Effect*



- *Relaxed – dark 330 K for 1 hour*
- *Metastable – light soaked at RT for 1 hour (AM-0)*

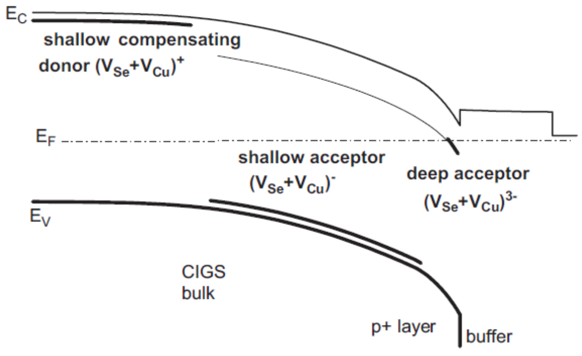
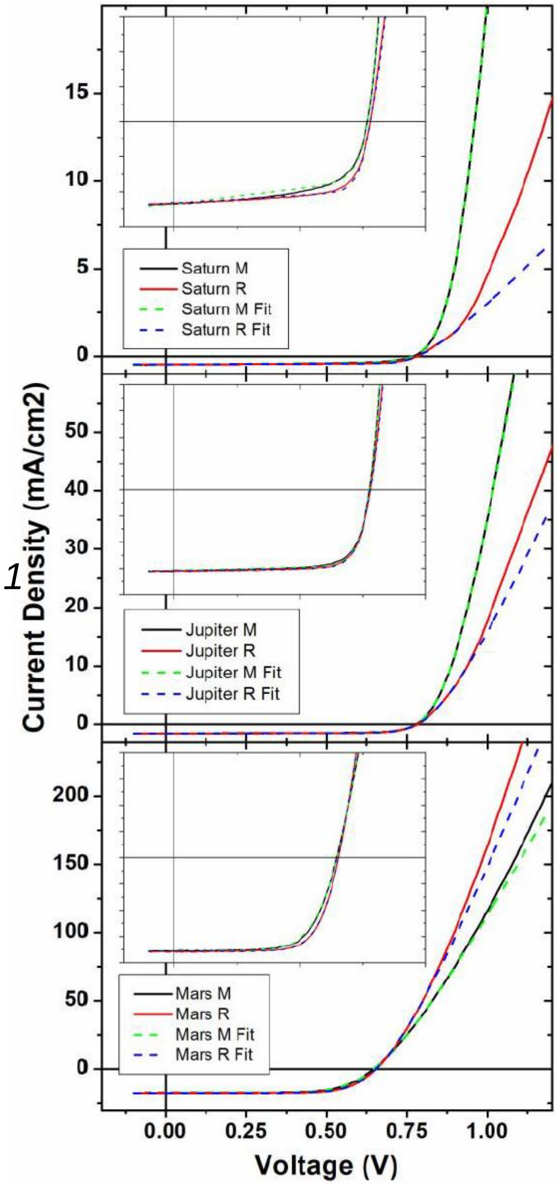


Fig. 1. Distribution of charged defects within the junction according to the Lany–Zunger model of V_{Se}–V_{Cu} divacancy [9,10].

M. Igalson et al., SOLMAT 93, 1290 (2009)



$$I = I_0\left(\exp\left(\frac{q(V-R_sI)}{nk_BT}\right)-1\right)+\frac{(V-R_sI)}{R_{sh}}-I_{ph}$$

Saturn: T = 100 K; I = 0.01 suns
- Loss of Fill factor in R-state
- Evidence of parasitic barrier

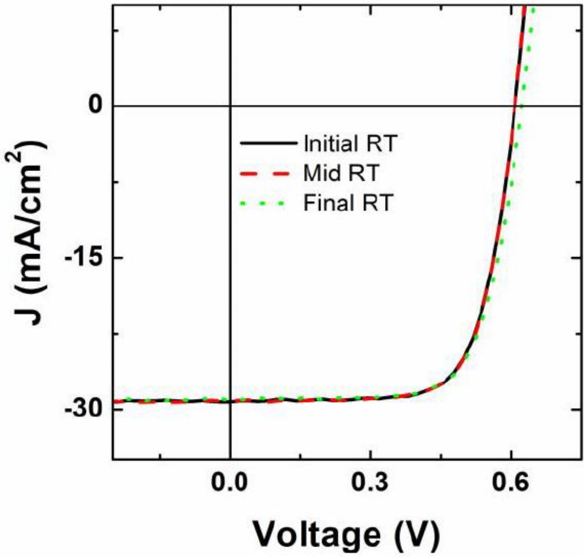
Jupiter: T = 135 K; I = 0.04 suns
- Loss of Fill factor in R-state (less than observed in Saturn)
- Higher thermal energy

Mars: T = 263 K; I = 0.4 suns
- Comparable fill factor (R and M)
- Reversal observed/ higher R_s in M-state

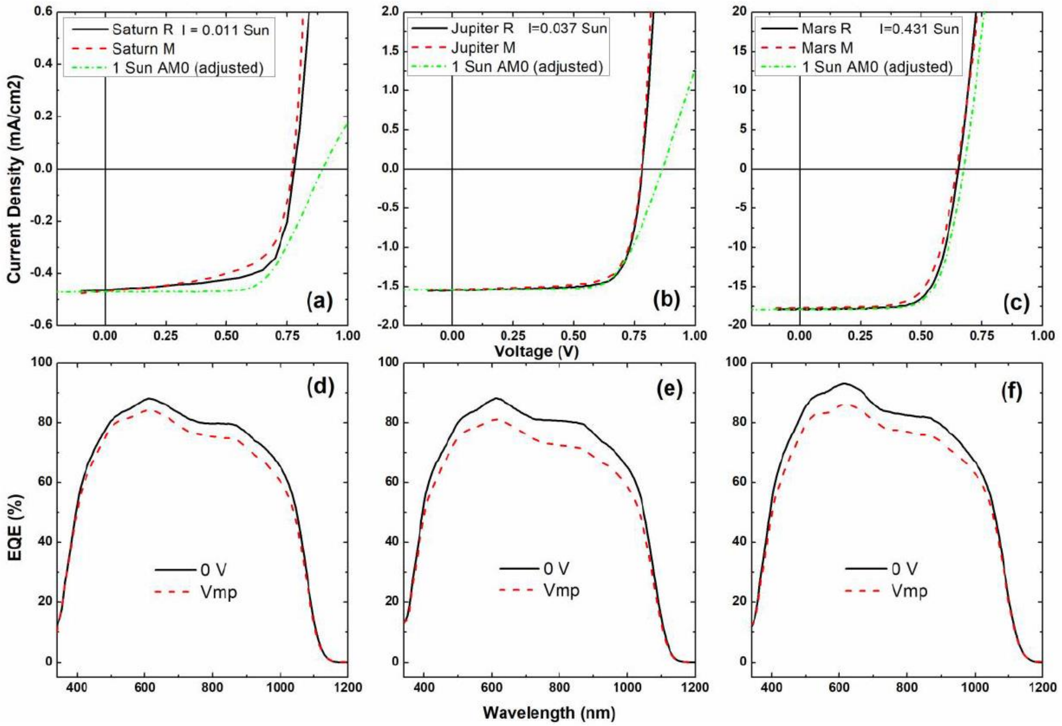
- Evidence of generation recombination losses in the bulk.

Brown *et al. in preparation*

Thermal Cycling and LILT Analysis



Brown *et al*. *in preparation*

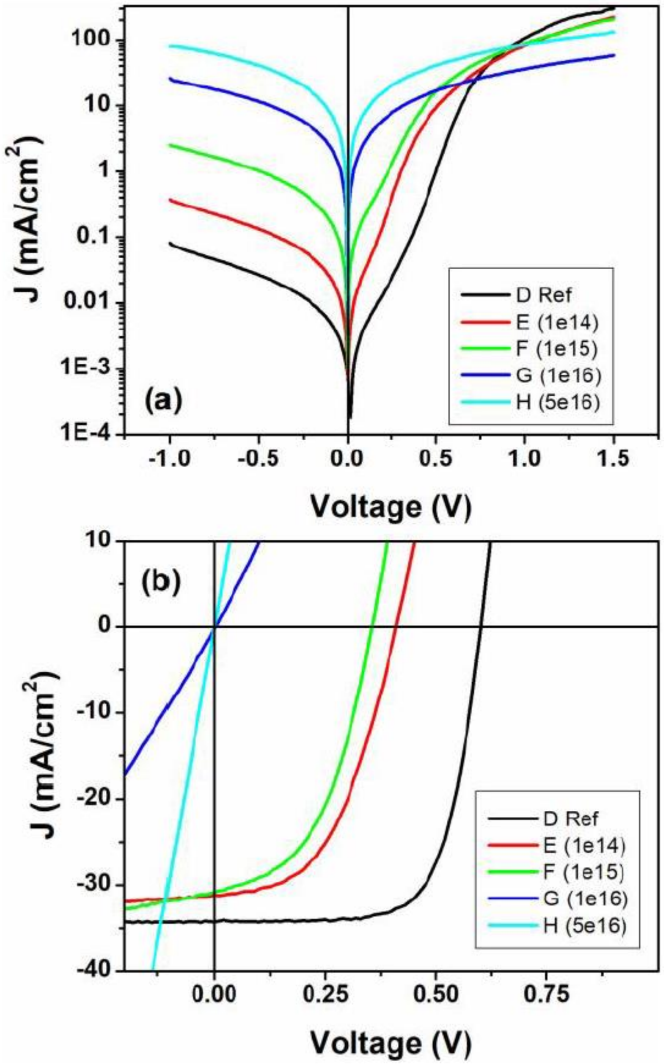


- Initial – AM0 300 K
- Mid RT – after 12 hour at -100 ˚C
- Final RT – after 12 hour at 100 ˚C

No significant degradation – some improvement after high temperatures!

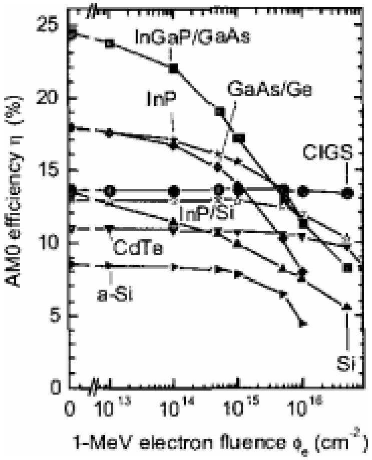
- Solar Cells measured at conditions equivalent to Saturn, Jupiter, and Mars
- Distinct reduction in series resistance in lower LILT conditions – *metastable defects/impurities*
- Evidence of photosensitive barrier at lower temperatures
- EQE suggest losses are Voltage related

Effects of proton irradiation and self healing effects



Brown *et al.* *in preparation*

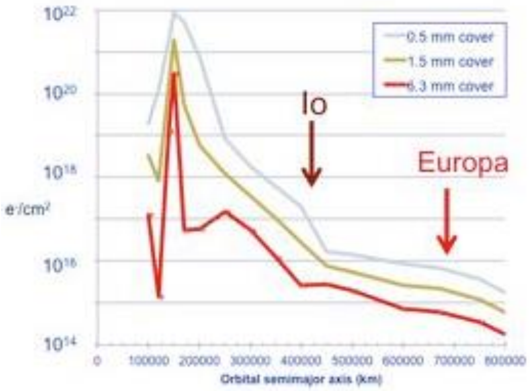
- Solar cells exposed to 1MeV proton irradiation/fluence from 1×10^{12} protons/cm^2 to 1×10^{16} protons/cm^2
- Rapid degradation evident….
- Significantly higher than typically used!



Jasenek *et al*. WCPEC 2003

Fluence (e^-/cm^2)	Efficiency 5AU -125°C	Efficiency 1.58AU -125°C	Efficiency 1AU 28°C
0e00 (Ctrl)	37.6% ± 0.7%	39.0% ± 0.5%	33.0% ± 0.4%
1e15 (Rad)	35.0% ± 0.6%	36.2% ± 0.7%	27.0% ± 0.4%
4e15 (Rad)	27.9% ± 0.4%	29.6% ± 0.7%	20.8% ± 0.2%

JPL (NASA) EESP Base Report 4/26/2017: “Solar Arrays for LILT and High Radiation Environments.”



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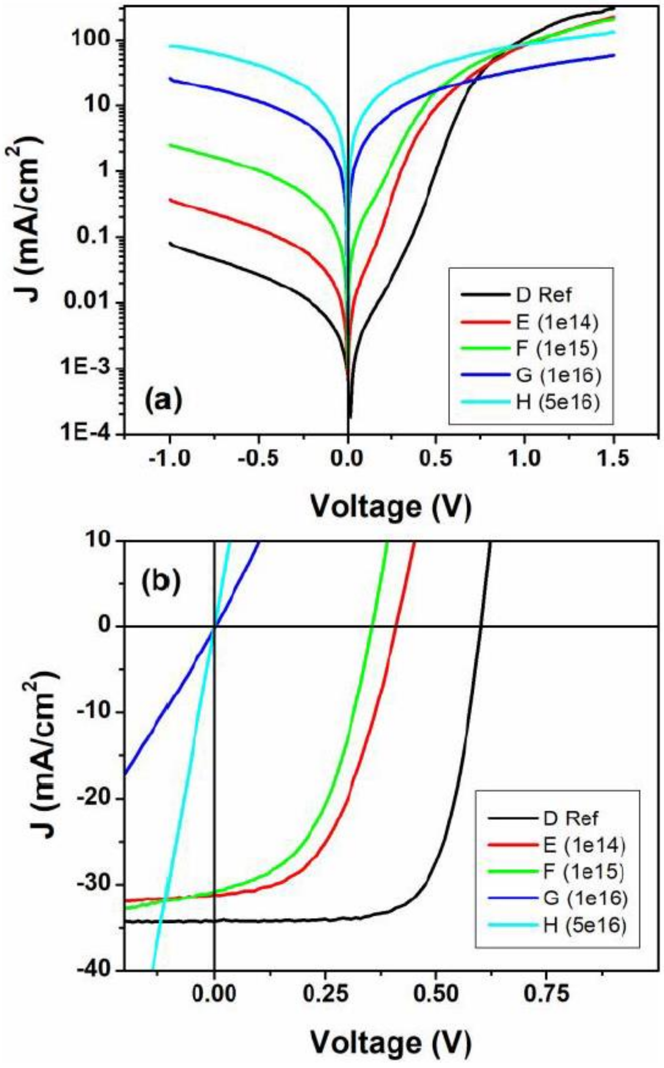
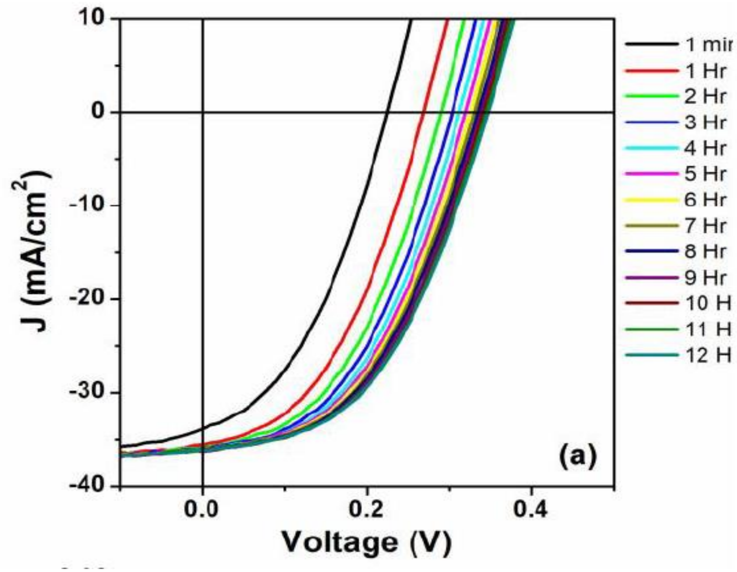


Brown *et al. in preparation*



- **Cells exposed to heat under illuminations**
- **Upon heating strong evidence of “self-healing”**
- **Further studies underway**

Summary and Acknowledgements

- **For future trips to deeper space technologies need developing unique to the rigors of those environments**
- **Both GaInNAs (MJSCs) and CIGS have potential for such applications**
- **GaInNAs requires more work to improve materials quality and hydrogen passivation has potential**
- **CIGS appear to have unique potential for deep space CubeSat and SmallSat applications**

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OCAST OARS 12.2-040 and Oklahoma NASA EPSCoR NNX16AQ97A

NASA

The Oklahoma Photovoltaic Research Institute