Solar Spectrum and Intensity Analysis Under Venus Atmosphere Conditions for Photovoltaics Operation

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Jonathan Grandidier PhD, Technologist, 8th November 2018
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California Institute of Technology

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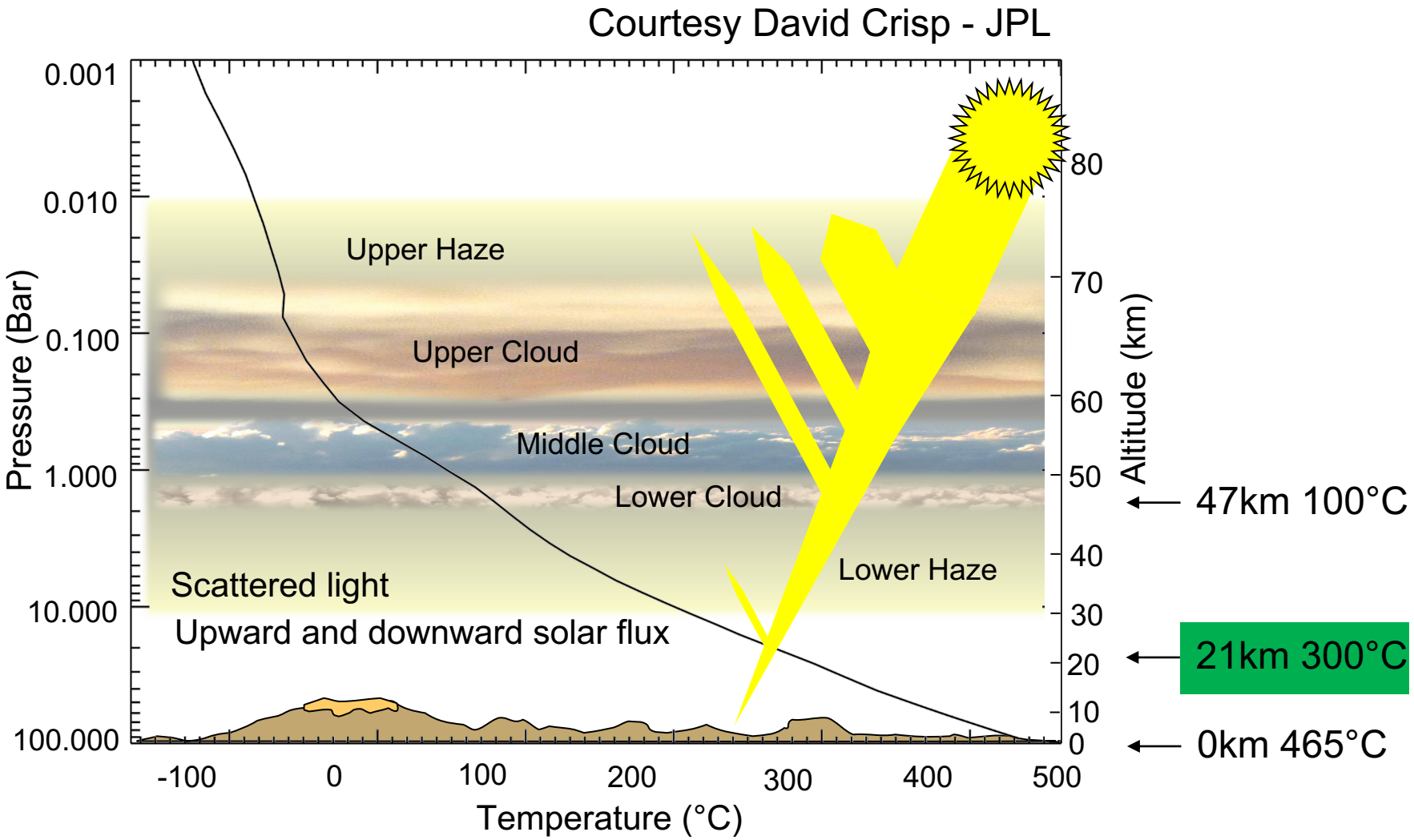
Outline

- Venus atmosphere and solar illumination
- Solar cell performance under Venus temperature and solar spectrum
- Lifetime testing for survivability at Venus
- Solar cell modelling and optimization
- Conclusion

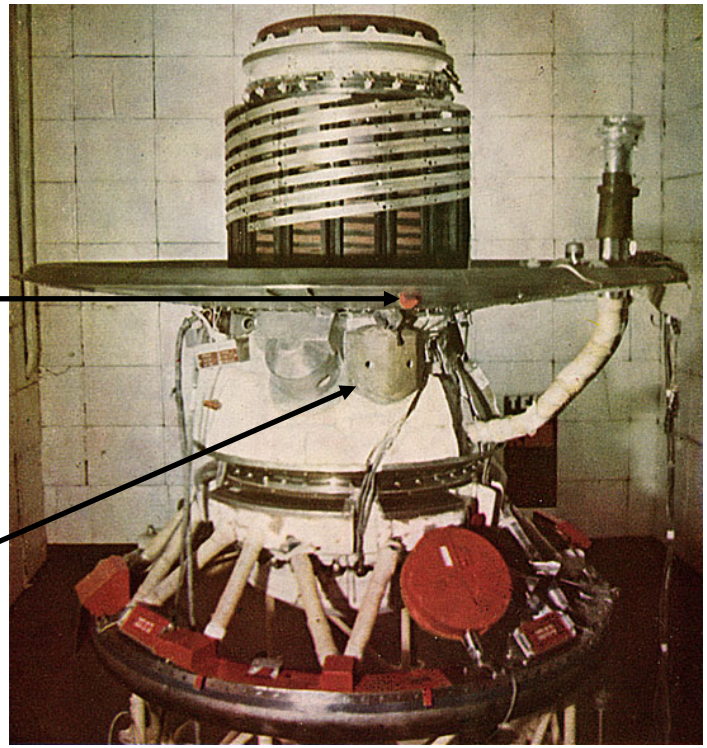
Venus atmosphere and solar illumination



Goal: Solar cell operates optimally at 21km altitude and survives at the surface during limited time excursions

Venus atmosphere and solar illumination

Venera-11 descent module



View of a plain near Phoebe Regio from Venera 13, taken on 1 March 1982.

Photometer measurements from Venera 11 and Venera 13 are used to estimate available solar power.

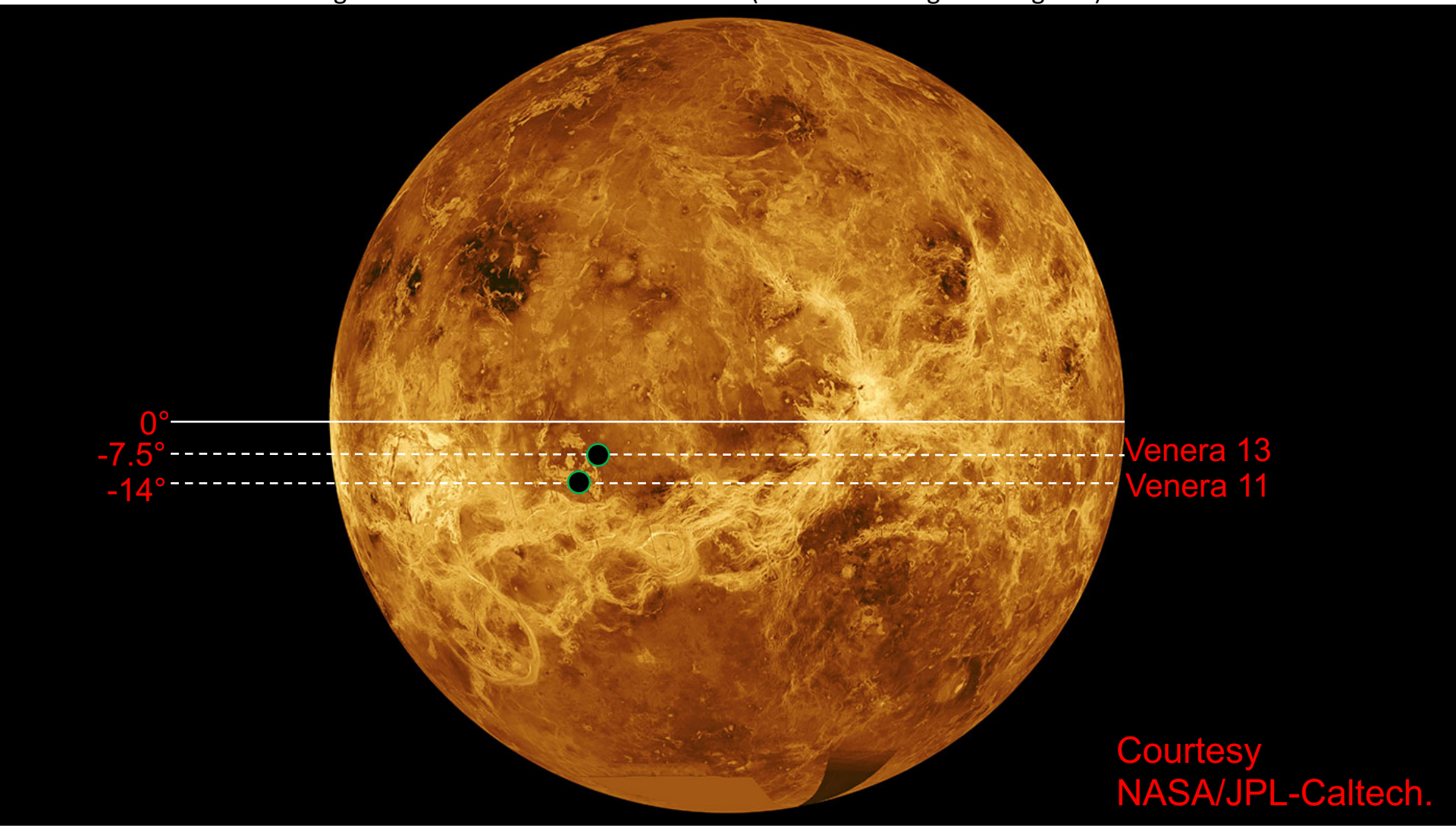
Courtesy Don P. Mitchell

Venus atmosphere and solar illumination

Venus (Hunten, Colin, Donahue, and Moroz, Eds., 1983) - Table II of Larry Colin's chapter (Chapter 2)

Venera 11 entered at -14 degrees latitude at 11:10 AM local solar time (solar zenith angle 17 degrees) on December 25th 1978.

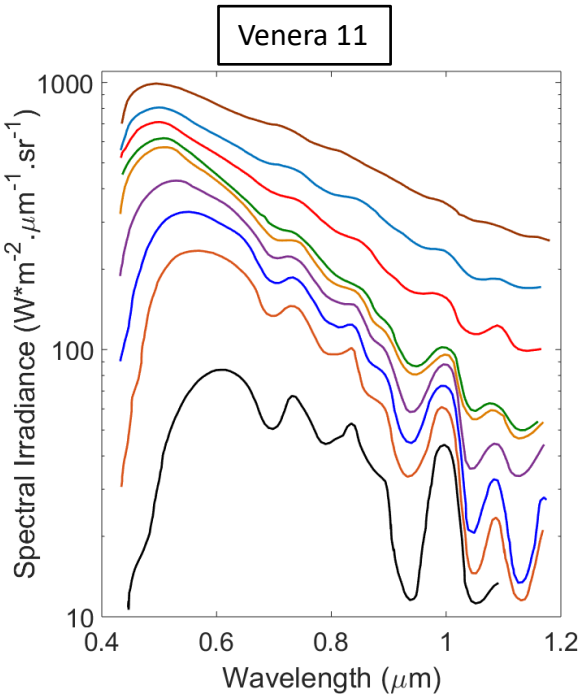
Venera 13 entered at -7.5 degrees latitude at 9:27 AM local time (solar zenith angle 38 degrees) on March 1st 1982.

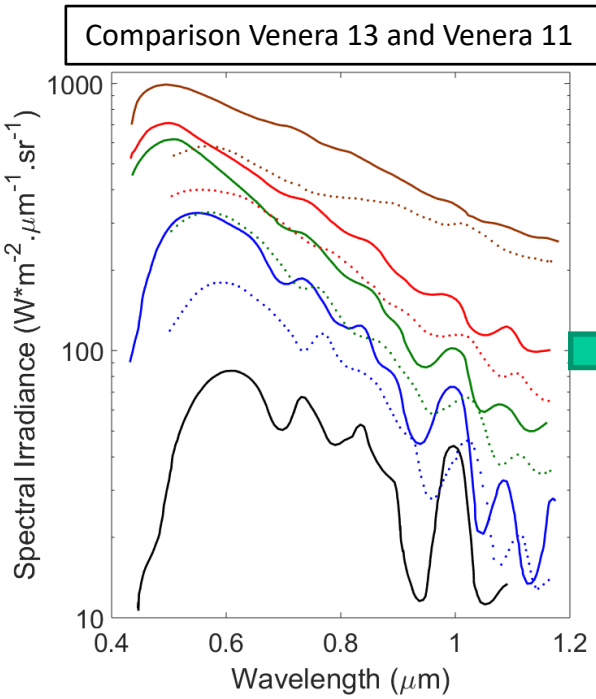


Venus atmosphere and solar illumination

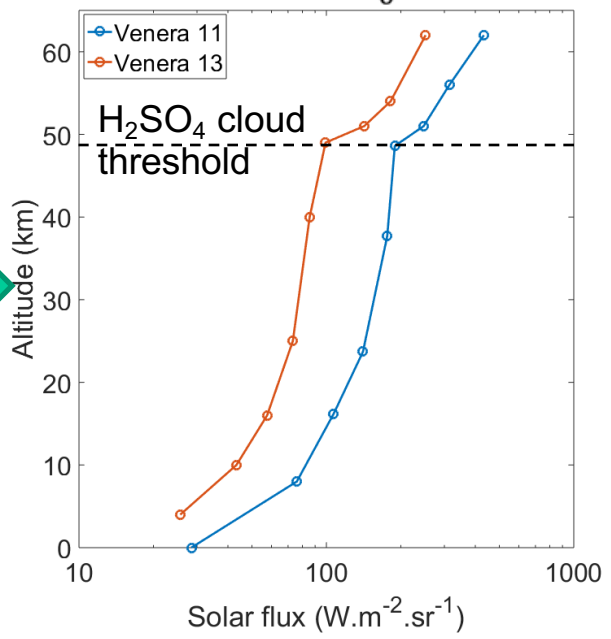
Venus spectrum is very different from Earth and altitude dependent

Solar zenith angle 17 degrees (Venera 11) and solar zenith angle 38 degrees (Venera 13) changes the path length by ~20%, but there is an optical depth 25-40 H_2SO_4 that accounts for a factor of 1.8 in radiance.





$$H(W/m^2/sr) = \int_0^\infty F(\lambda)\, d\lambda$$



0 km, 8 km, 16.2 km, 23.7 km, 37.7 km, 48.6 km, 51 km, 56 km, 62 km

Plain line: Venera 11
Dash line: Venera 13

Venus solar spectrum at various altitudes of Venus measured by Venera 11 and Venera 13 descent probes.

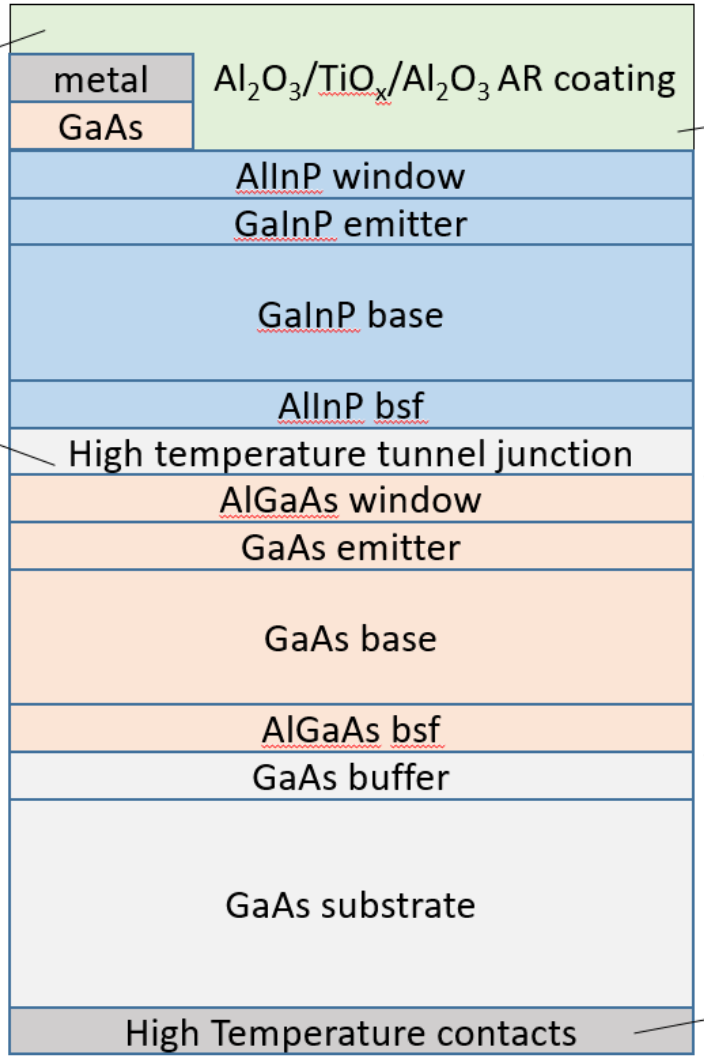
Downward Solar flux calculated by Integrating solar spectrum for Venera 11 and Venera 13 descent probes.

Solar cell performance under Venus temperature and solar spectrum

Corrosion protection. The cell is coated with an Al_2O_3 layer to prevent corrosion from sulfuric acid.

Tunnel junction demonstrated to yield stable operation at 400°C

Optimized bandgap. The top and bottom subcell bandgaps and thicknesses are adjusted to optimize efficiency at Venus.



Anti-reflection coating (ARC). Window layer coated with $Al_2O_3/TiOx$ ARC stable at 450°C

Top subcell

Bottom subcell

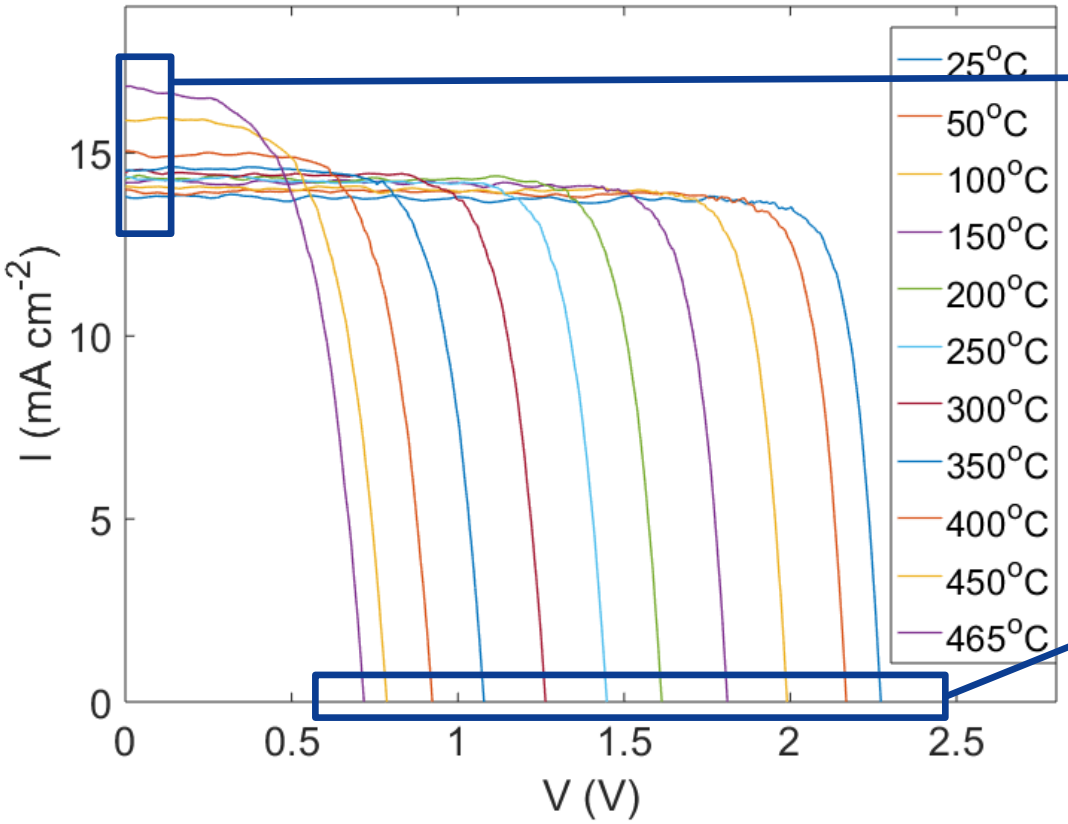
High temperature contacts. Ohmic contact (top and bottom) designs that are thermally stable up to 450°C

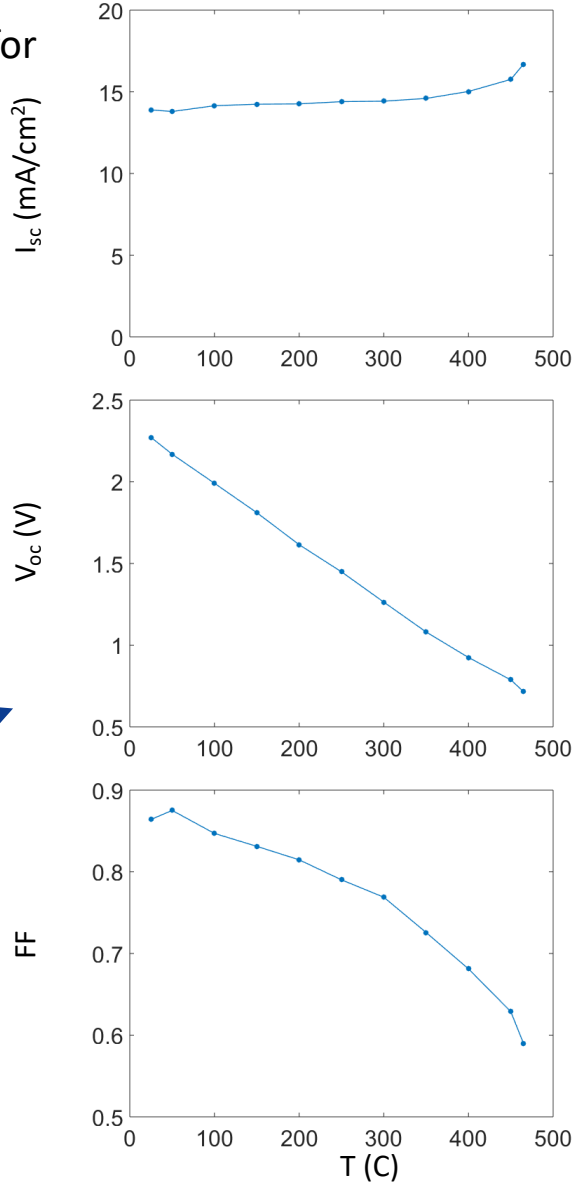
Not to scale

Y. Sun et al., "*Thermal stability of GaAs solar cells for high temperature applications*," 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, 2016, pp. 2385-2388.

Solar cell performance under Venus temperature and solar spectrum

I_{sc} at room temperature is 15.66 mA/cm^2 which is close to 15.60 mA/cm^2 for the current limiting EQE junction weighted by the AM0 solar spectrum

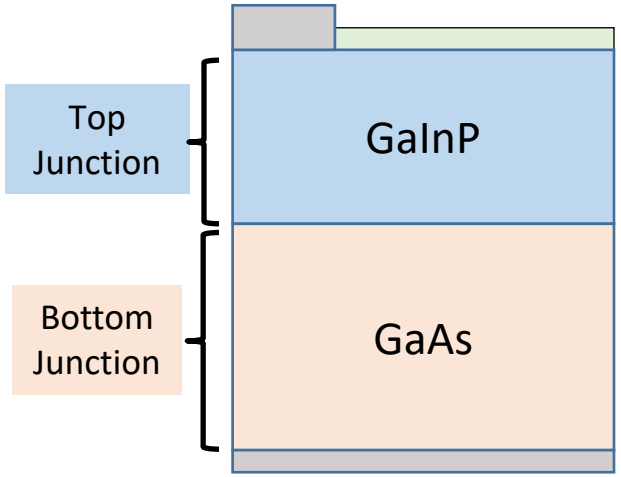




Temperature dependence of the solar cell between room temperature and 465C (Venus Surface)

JPL test capability simulates Venus temperature conditions

Solar cell performance under Venus temperature and solar spectrum



Current:

$$J_{\text{solar}}(\lambda) = N_0(\lambda) * e^-$$

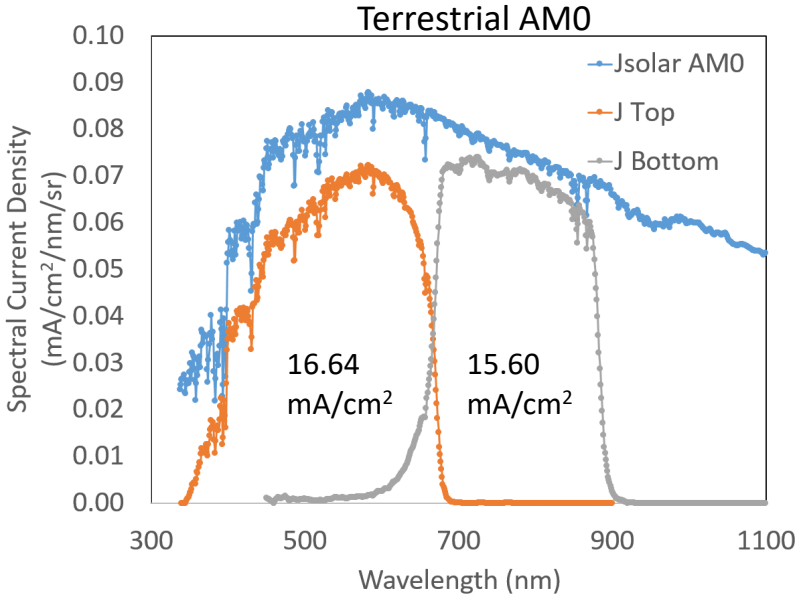
$$J_{ph} = \text{EQE} * J_{solar}(\lambda)$$

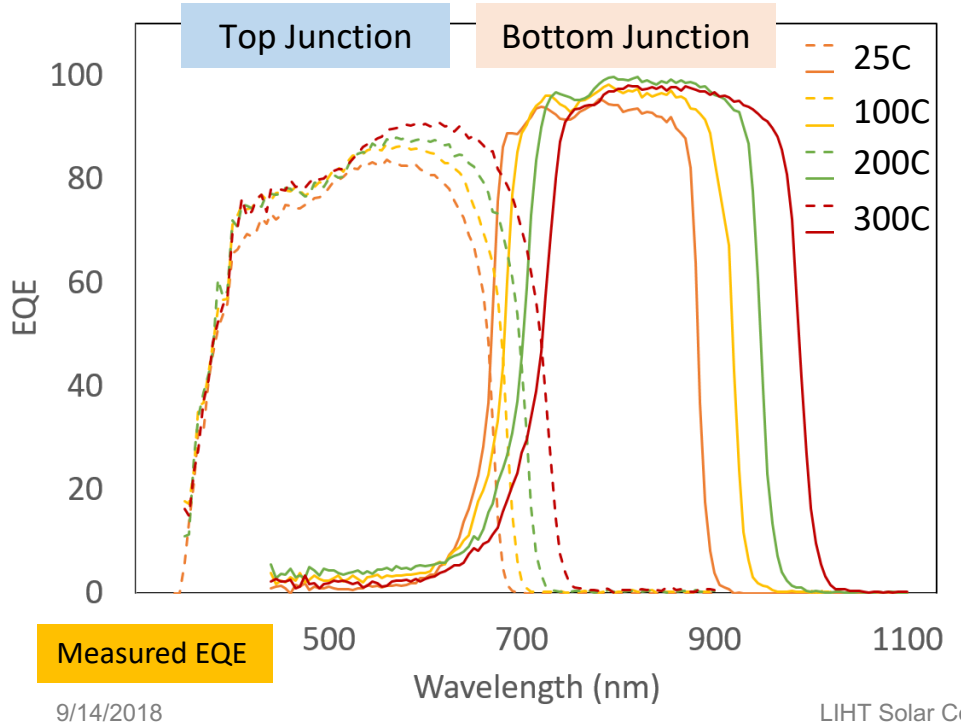
With Incident photon flux:

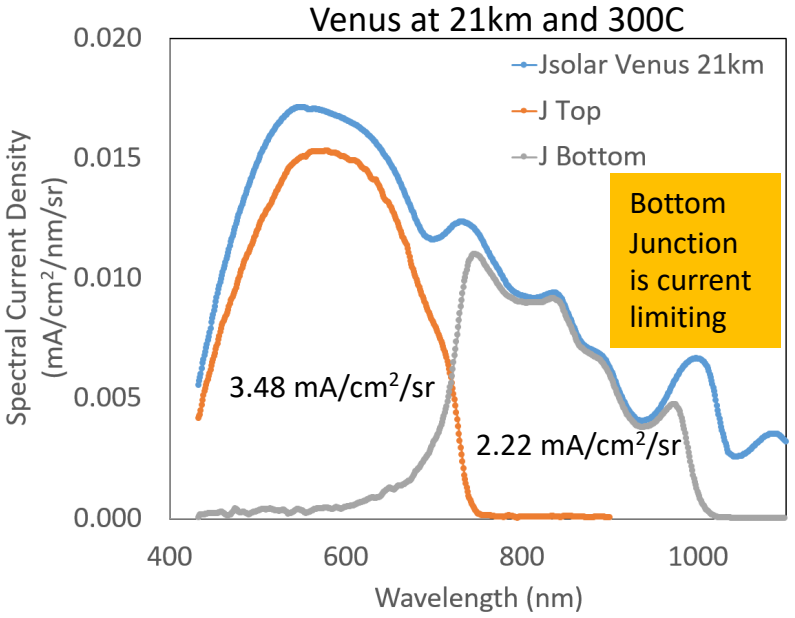
$$N_0(\lambda) = \frac{P_{\text{solar}}(\lambda)}{E_{\text{ph}}(\lambda)}$$

And photon energy:

$$E_{\text{ph}}(\lambda) = \text{hc}/\lambda$$







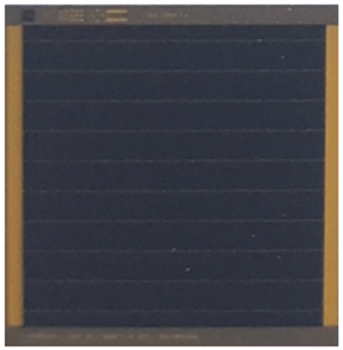
Lifetime testing for survivability at Venus

Ag based Metallization 1
Al based Metallization 2
} Gen 1 (1st year)

Ag based Metallization 3
Al based Metallization 4
} Gen 2 (2nd year – on-going)

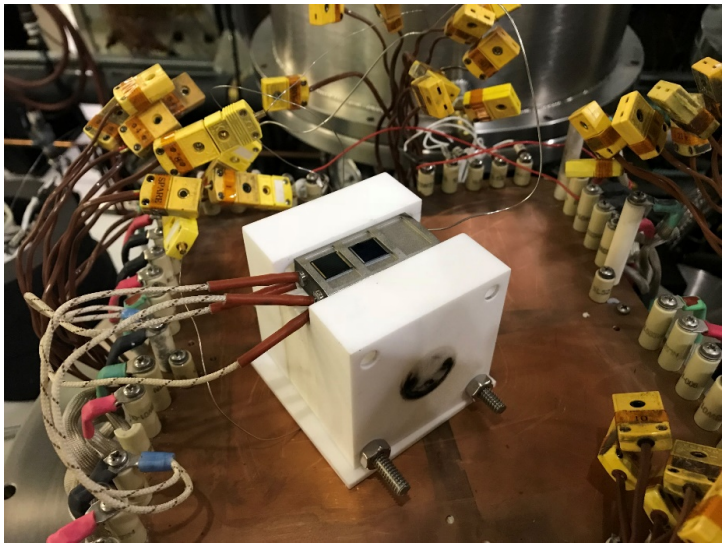
Gen 2 solar cells were improved based on Gen 1 degradation mechanism analysis

	300°C Venus 21km	465°C Venus Surface
24h	Lifetime testing	
1 week		
1 month		



1 cm^2 fabricated solar cell

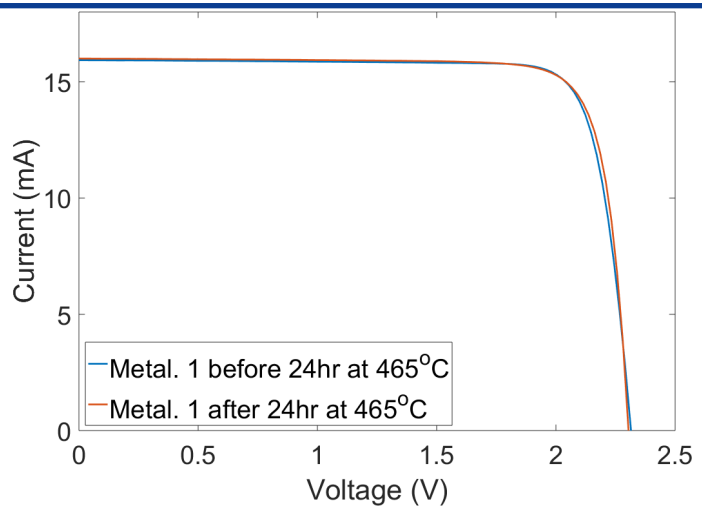
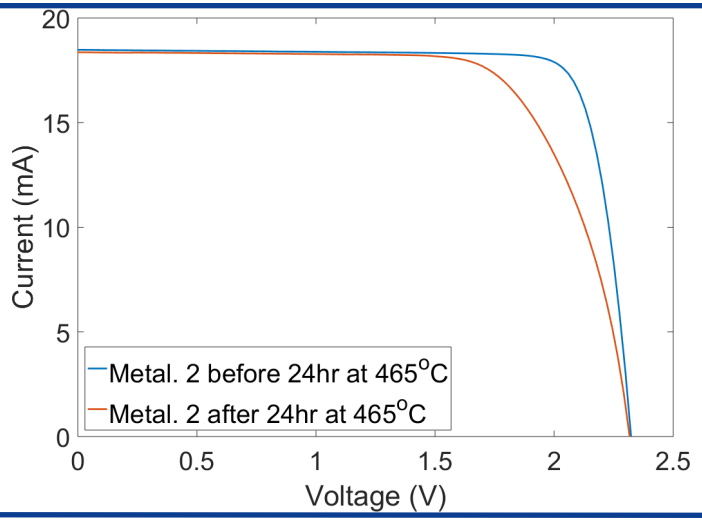
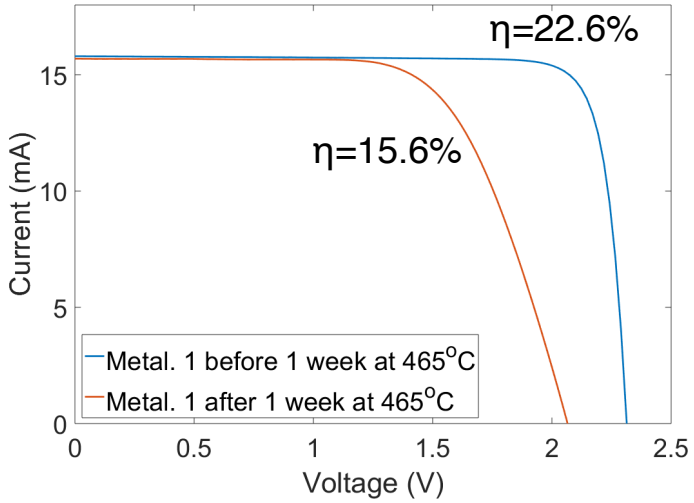
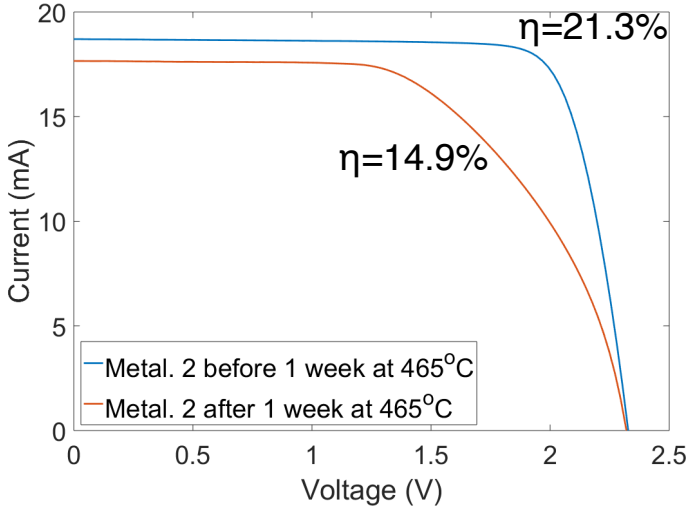
Lifetime Testing setup.
Developed and designed at JPL



Bare solar cells were heated at 300°C (Venus temperature at 21 km altitude) and 465°C (Venus surface temperature) under high vacuum 10^{-7} Torr.

Lifetime testing for survivability at Venus

I-V Before and After exposure at 465°C AM0 1-Sun Light I-V Measurements at MLD

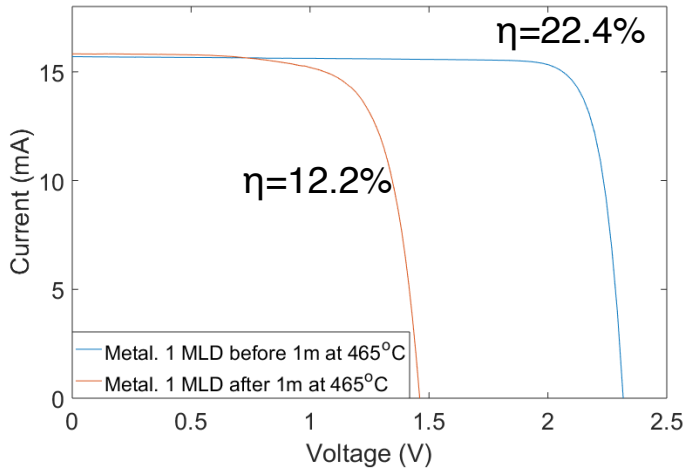
	Metallization 1 (Gen 1)	Metallization 2 (Gen 1)
24 hours		
1 week		

Lifetime testing for survivability at Venus

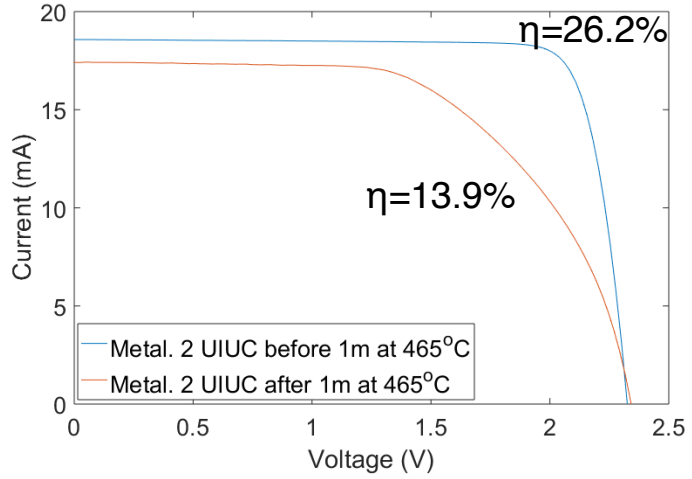
I-V Before and After exposure at 465°C AM0 1-Sun Light I-V Measurements at MLD

1 month

Metallization 1 (Gen 1)

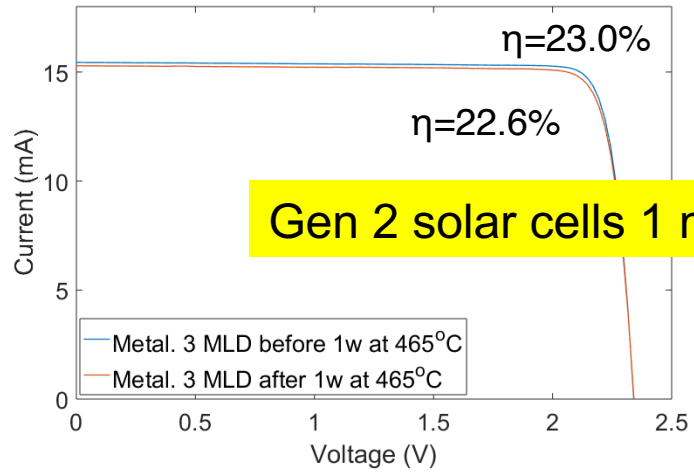


Metallization 2 (Gen 1)

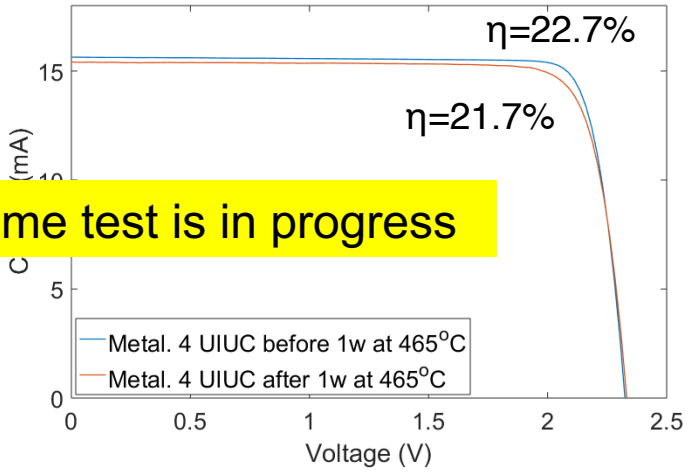


1 week

Metallization 3 (Gen 2)



Metallization 4 (Gen 2)



Gen 2 solar cells 1 month lifetime test is in progress

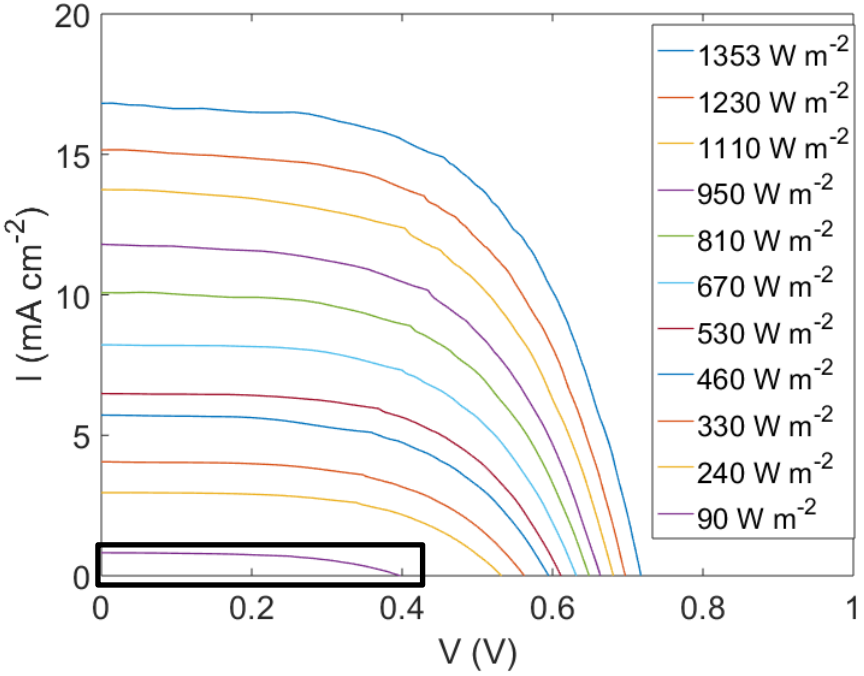
Solar cell measurements under Venus conditions

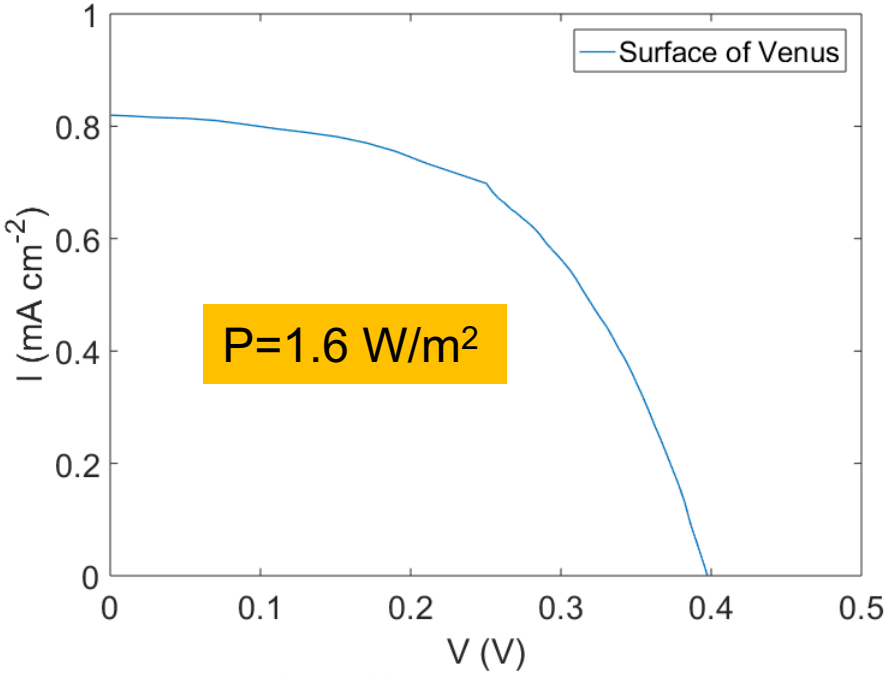
Light I-V at 465°C between 1-Sun and 90 W/m^2 (Surface of Venus)

465°C (surface of Venus)

Measurement between 1353 W/m^2 and 90 W/m^2 (surface of Venus)

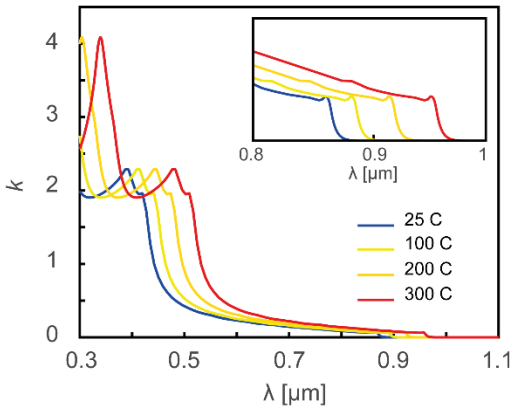
GaInP/GaAs 2J solar cell
Voc=394 mV
Jsc= 0.83 mA/cm^2
FF=54%
η= 2.64%





Accounts for diffused light incidence angle
Could be increased by taking advantage of downward flux.

Solar cell modelling and optimization (Caltech)

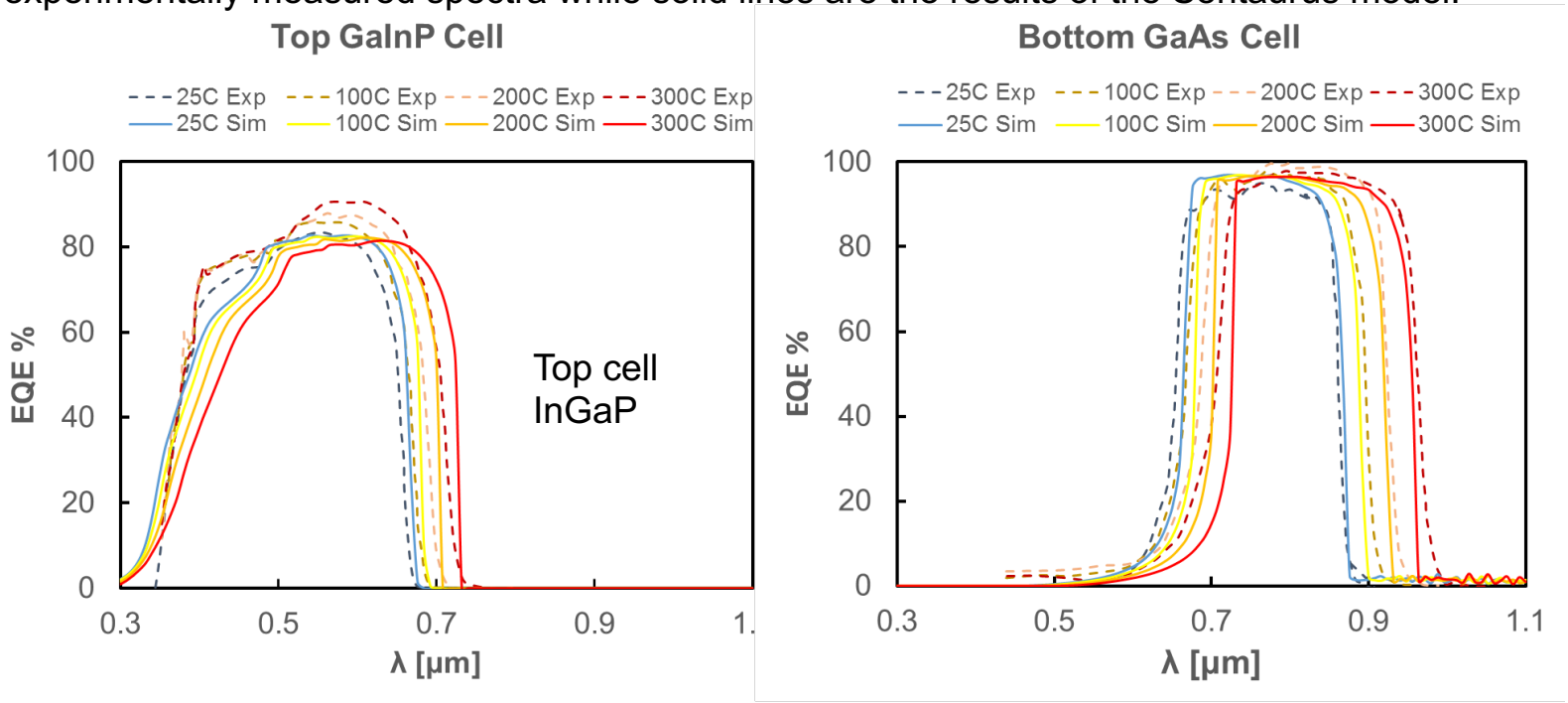


temperature dependence of the material bandgap, $E_g(T)$ is described by:

$$E_g(T) = E_{g0} - \frac{\alpha T^2}{\beta + T}$$

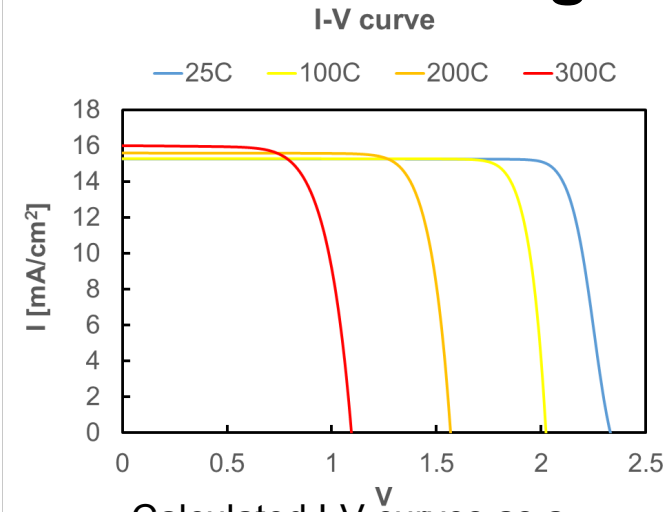
GaAs temperature-dependent imaginary refractive index, k.

EQE spectra of top and bottom cells as a function of temperature. The dashed lines are the experimentally measured spectra while solid lines are the results of the Sentaurus model:

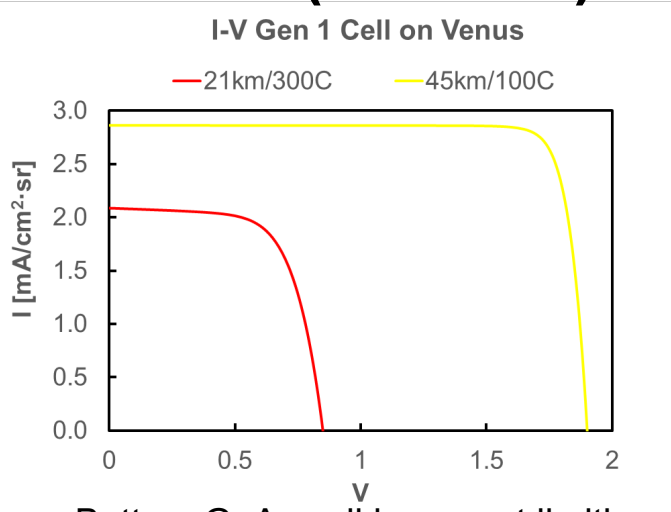


Solar cell modelling and optimization (Caltech)

Before Optimization

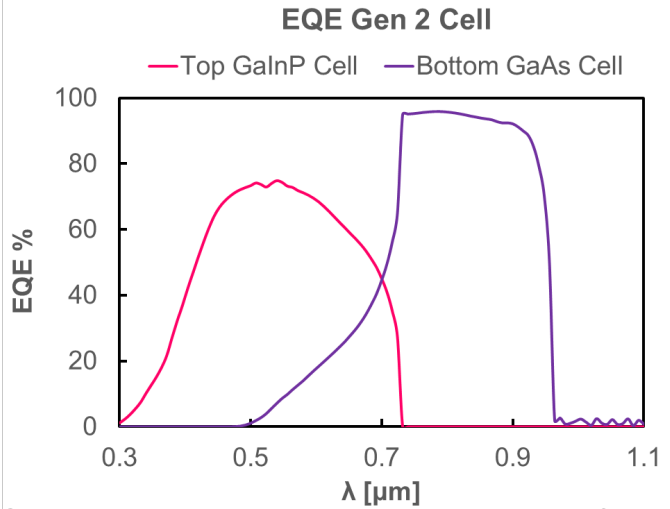


Calculated I-V curves as a function of temperature – AM0

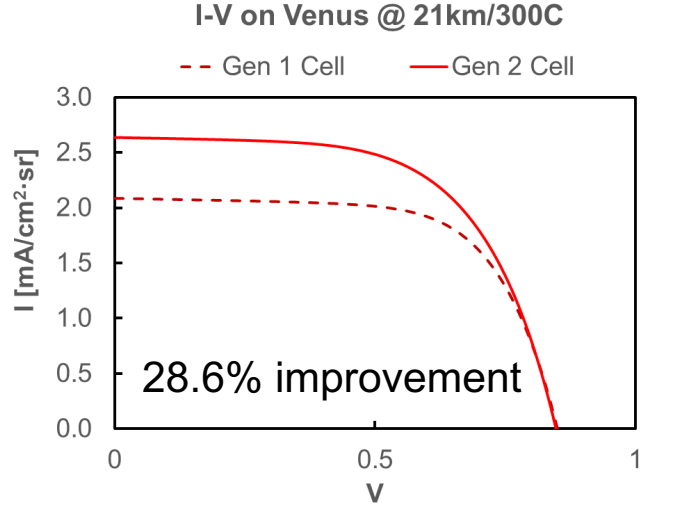


Bottom GaAs cell is current limiting Venus solar spectrum

After Optimization



Gen2 cell has a reduced thickness of the top GaInP cell to ensure current matching



The Short circuit current at design conditions of 21km/300C is increased from 2.1 to 2.7 mA/cm²/sr

Conclusion

- Venus solar spectrum and temperature vary significantly with altitude.
- Solar cell needs to be designed for a particular spectrum and temperature – therefore particular altitude conditions.
- Gen 1 solar cells showed 13.9% efficiency after 1 month exposure at 465˚C. Gen 2 solar cells showed no degradation after 1 week exposure at 465˚C.
- Modelling shows an optimal design for a dual junction InGaP/GaAs solar cell at 21km Venus altitude where temperature is 300˚C.

Future work:

- Finalize 1 month at 465˚C lifetime testing for Gen 2 solar cells.
- Fabricate optimized InGaP/GaAs solar cell at 21km Venus altitude/300˚C.
- Modelling of solar cell performance at the surface of Venus, 465C – 90 W/m^2.

J. Grandidier, et al., "Low-Intensity High-Temperature (LIHT) Solar Cells for Venus Atmosphere," *IEEE Journal of Photovoltaics*: 1-6, **8**, 2018. https://doi.org/10.1109/JPHOTOV.2018.2871333

Acknowledgements

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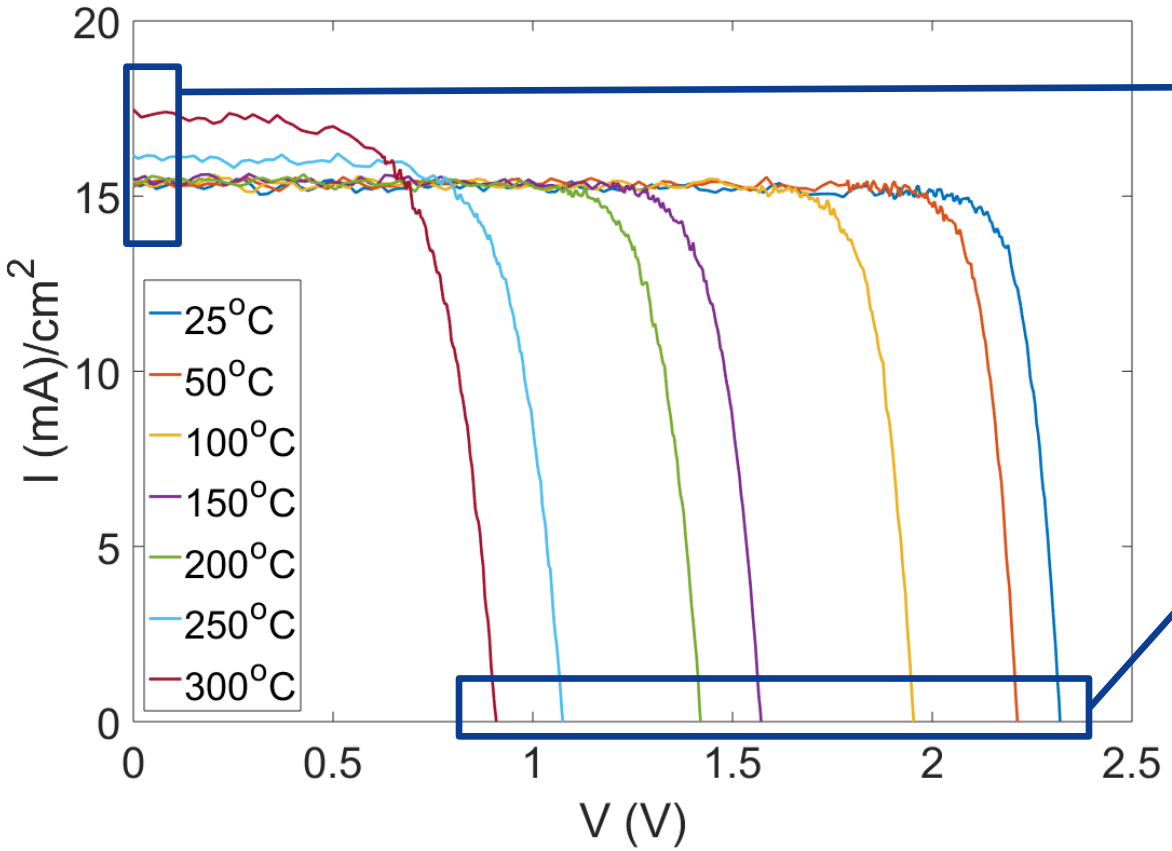
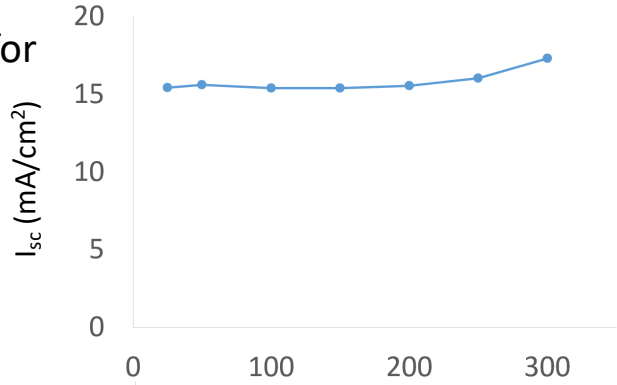
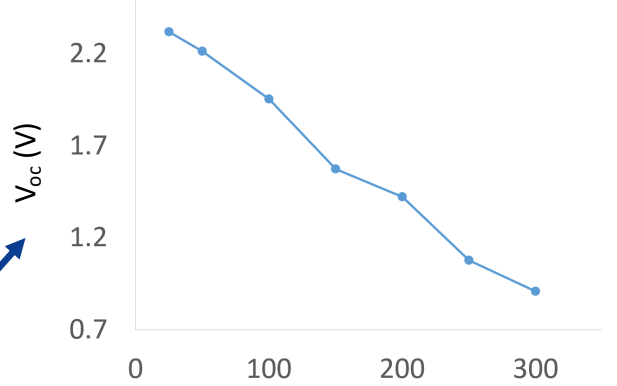
BACKUP SLIDES

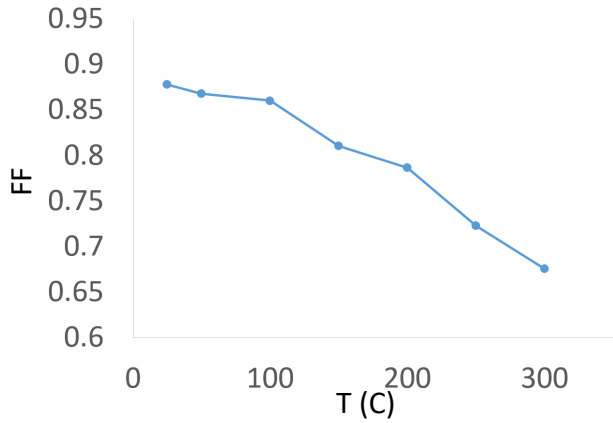
Solar cell performance under Venus temperature and solar spectrum

I_{sc} at room temperature is 15.66 mA/cm^2 which is close to 15.60 mA/cm^2 for the current limiting EQE junction weighted by the AM0 solar spectrum







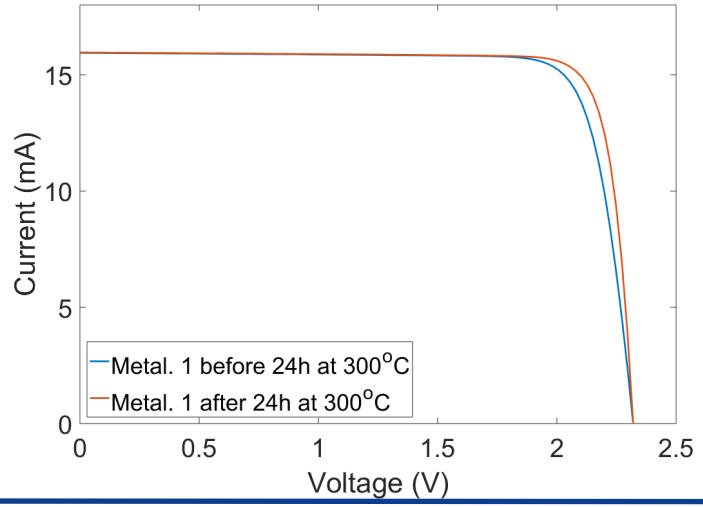
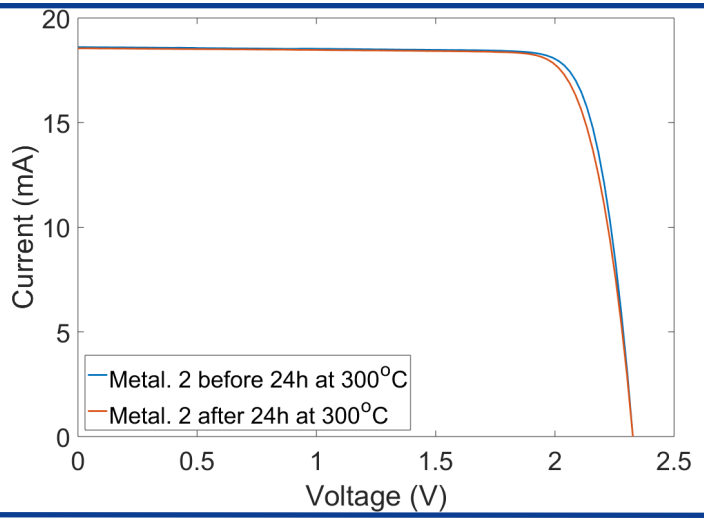
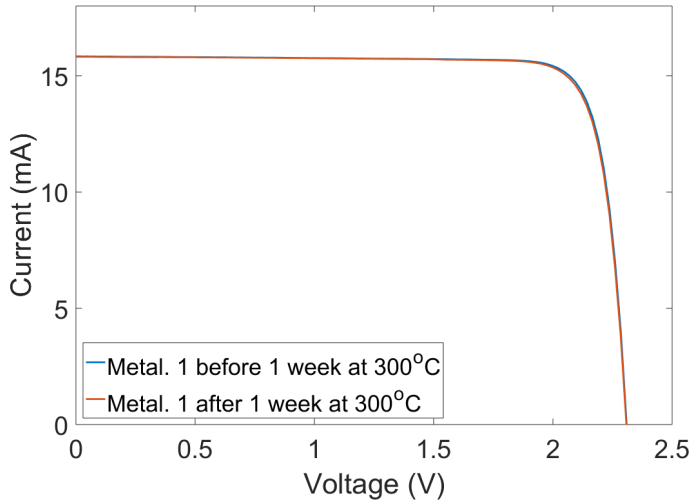
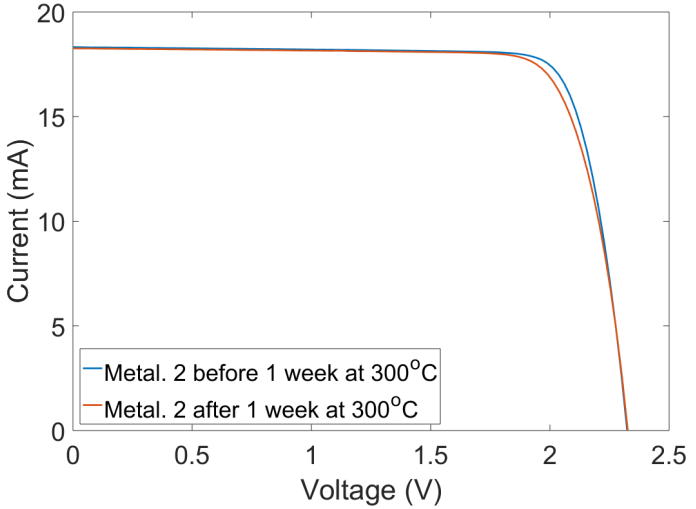


Temperature dependence of the solar cell between room temperature and 300C (21 km altitude at Venus)

JPL test capability simulates Venus temperature conditions

Lifetime testing for survivability at Venus

I-V Before and After exposure at 300°C AM0 1-Sun Light I-V Measurements at MLD

	Metallization 1 (Gen 1)	Metallization 2 (Gen 1)
24 hours		
1 week