Solar Cell Power Analysis Under Venus Atmosphere

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Jonathan Grandidier PhD, Technologist, 24th April 2018

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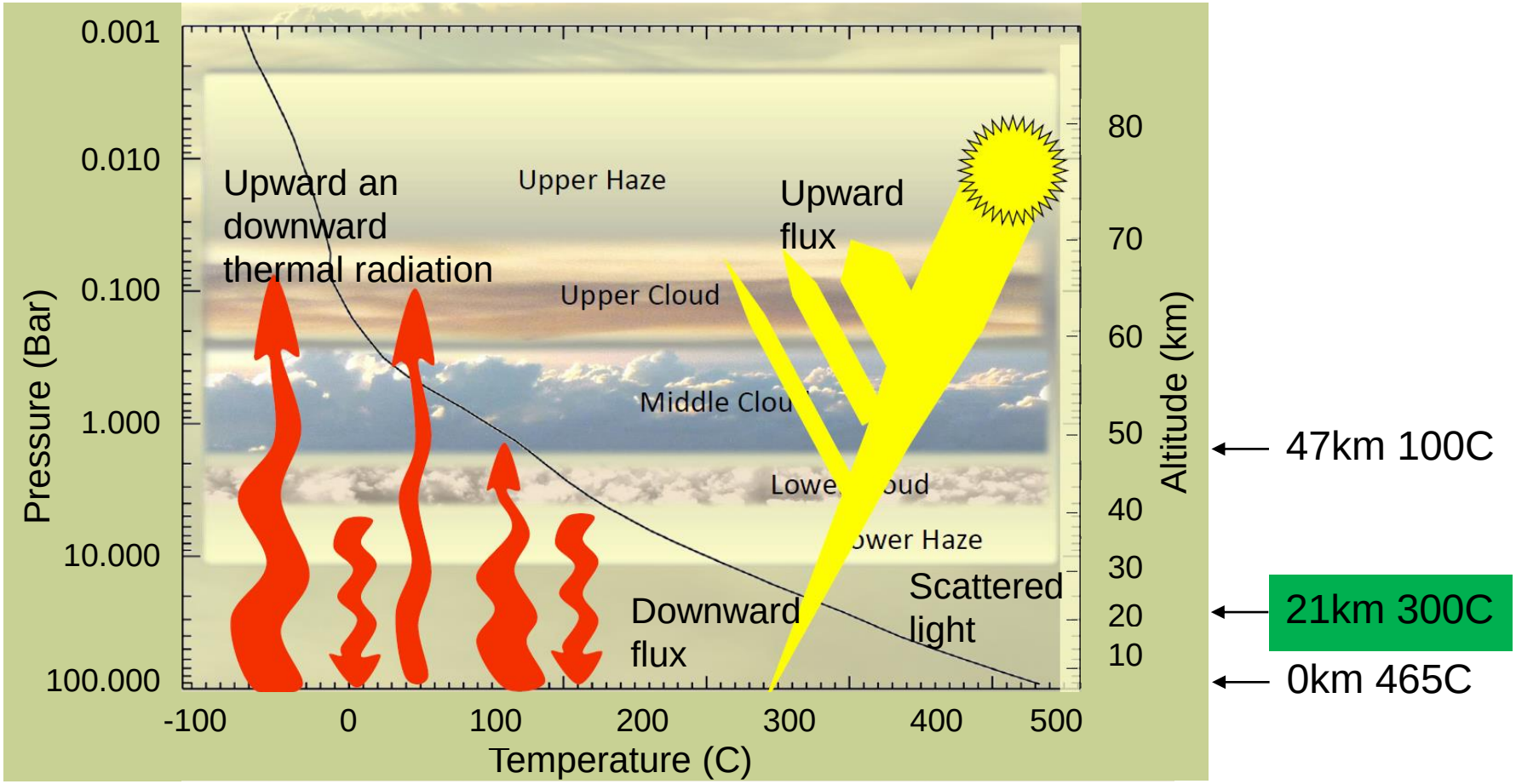
Outline

- 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

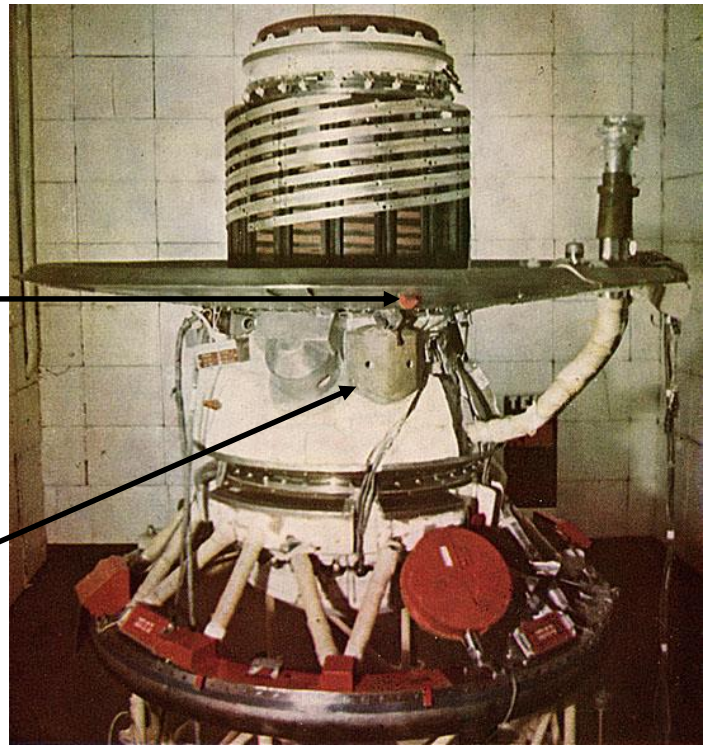
Image David Crisp



Goal: Solar cell operates optimally at 21km altitude and survives at the surface

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.

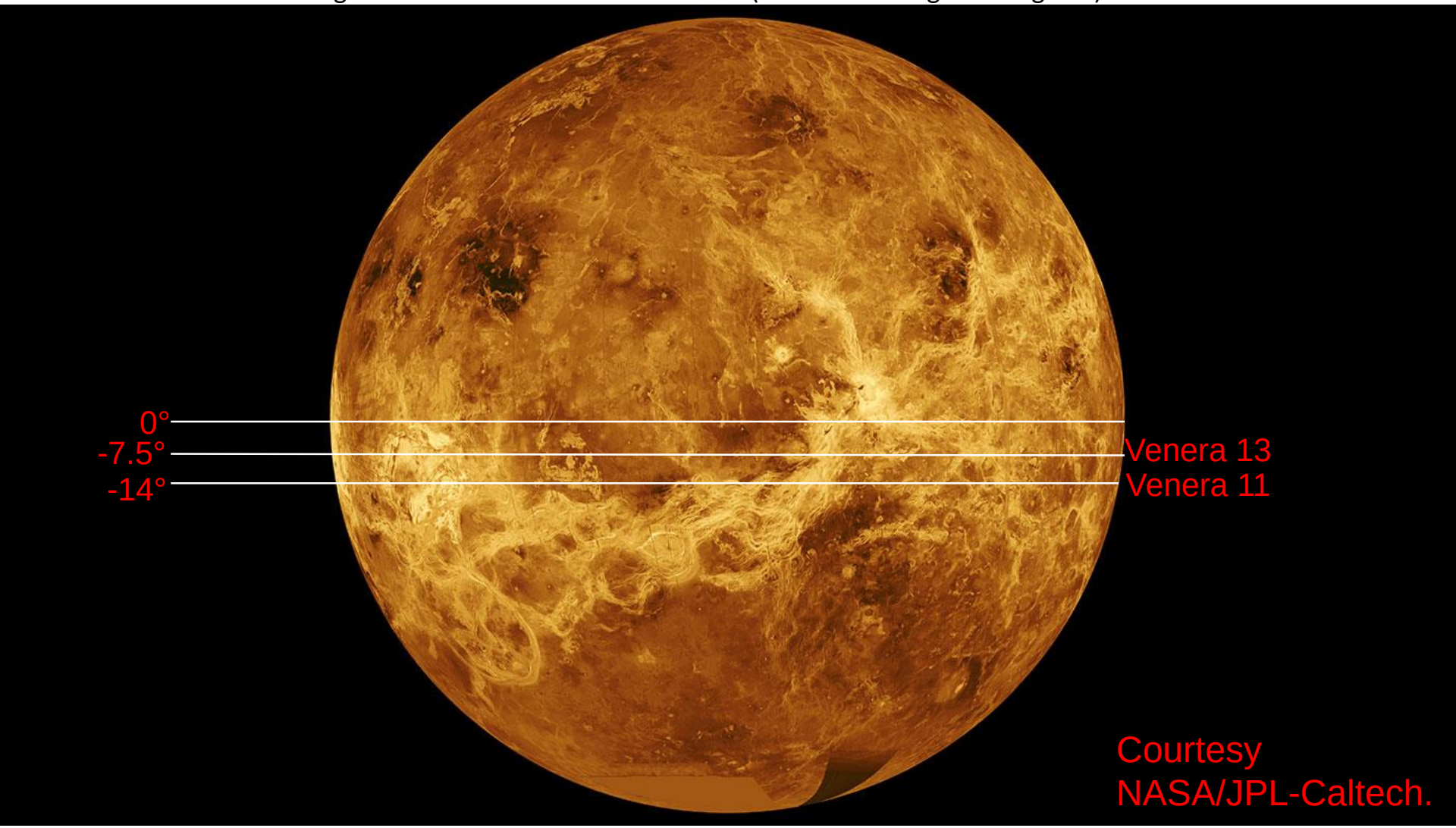
Courtesy Don P. Mitchell

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.

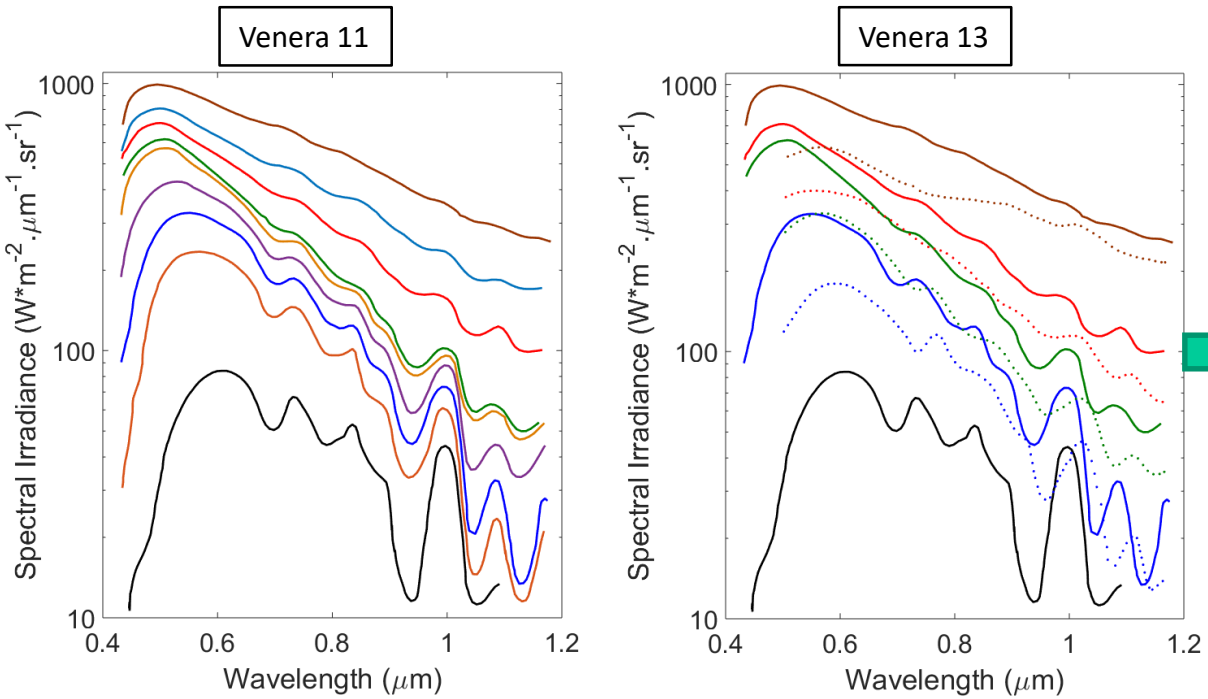


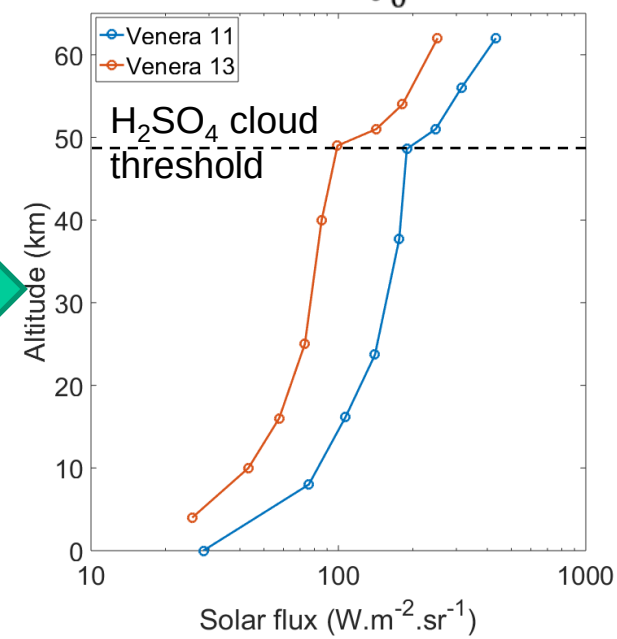
Venus atmosphere and solar illumination

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 2 in radiance.

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





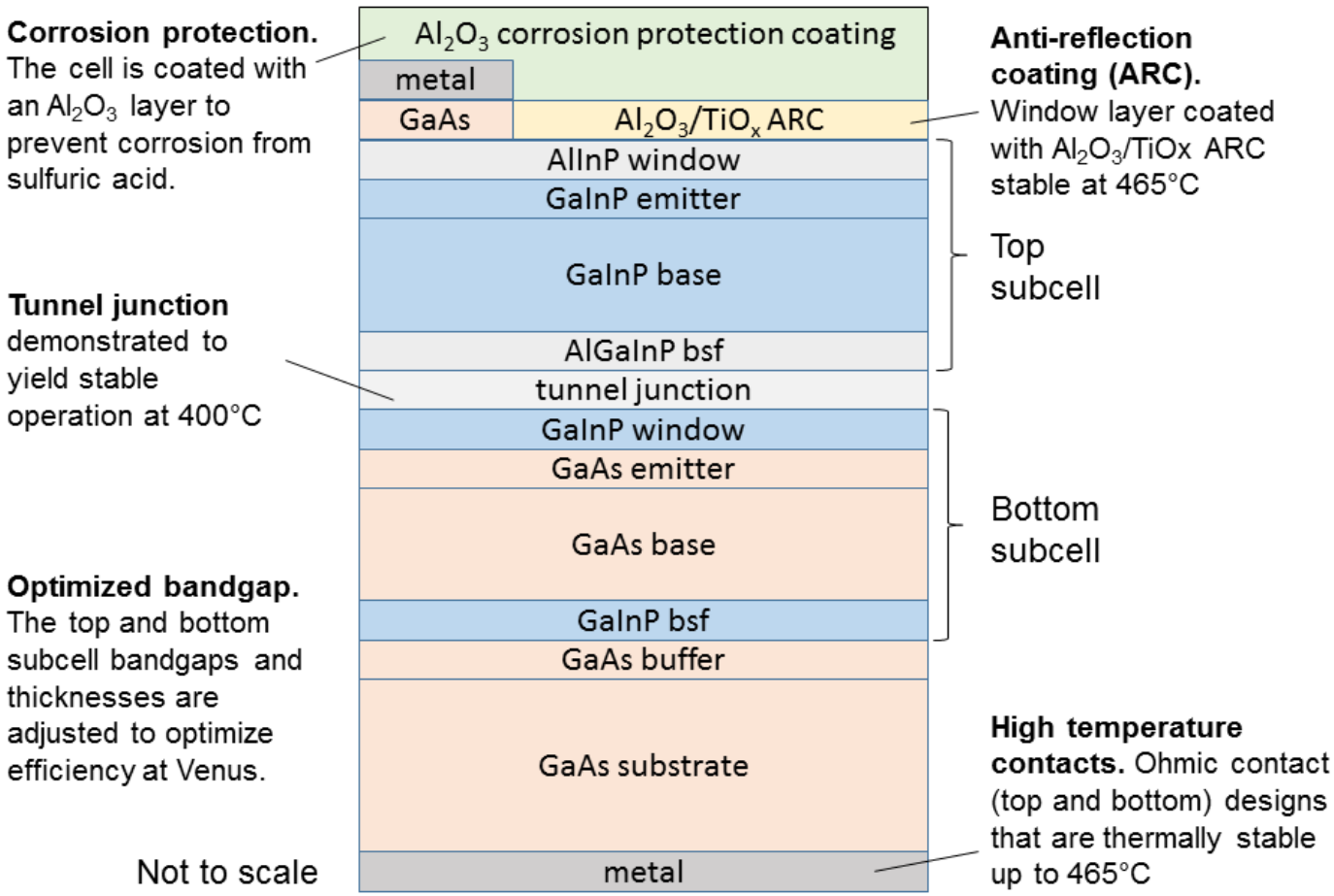
0 km	23.7 km	51 km
8 km	37.7 km	56 km
16.2 km	48.6 km	62 km

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.

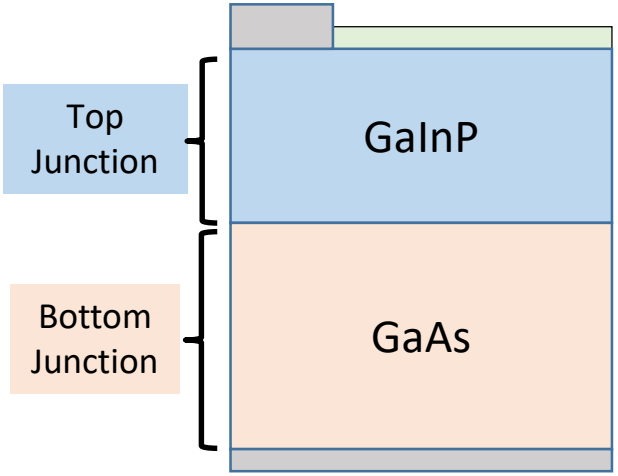
Solar flux calculated by Integrating solar spectrum for Venera 11 and Venera 13 descent probes.

Solar cell performance under Venus temperature and solar spectrum



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



Current:

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

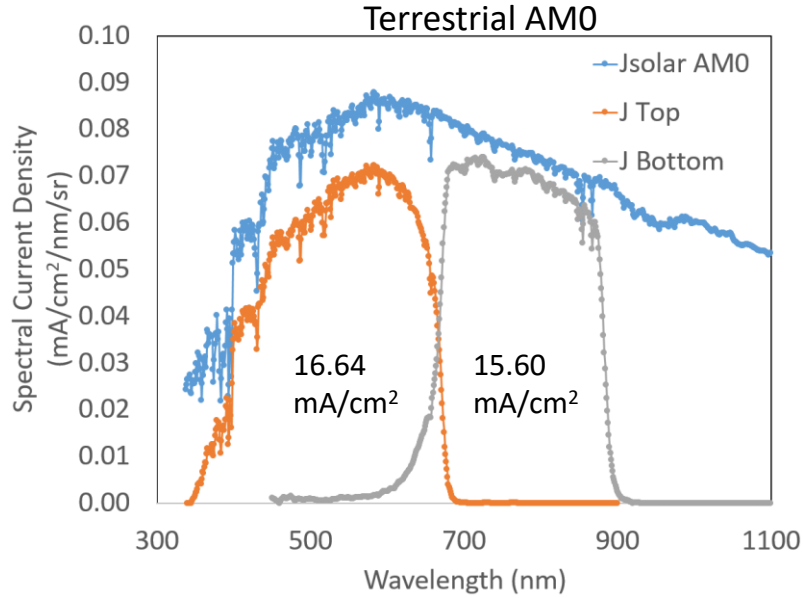
$$J_{ph} = \text{EQE} * J_{solar}(\lambda)$$

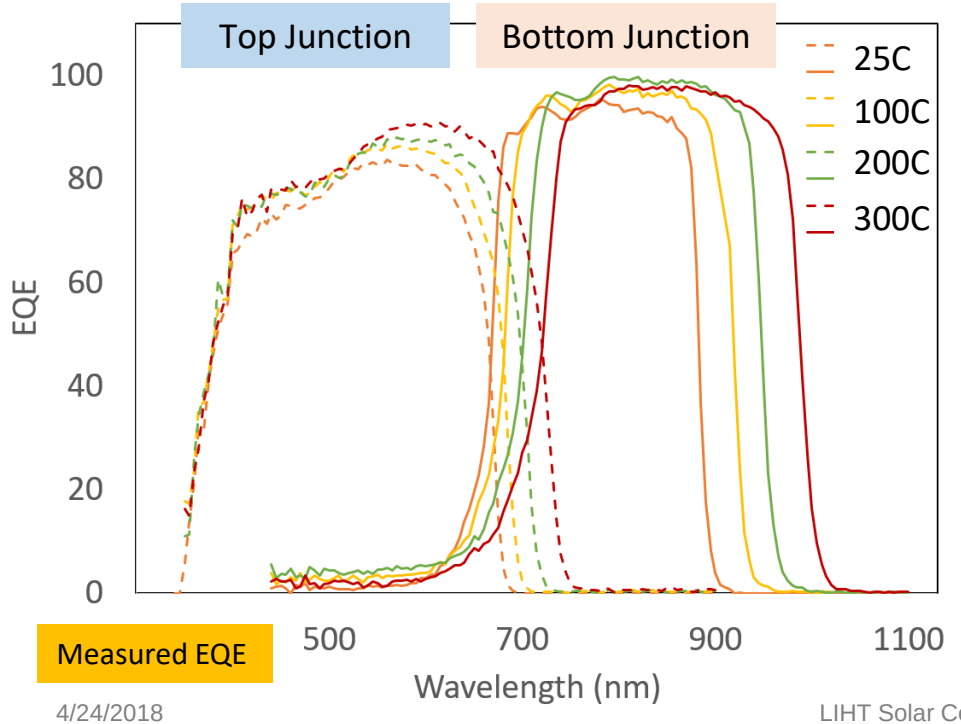
With Incident photon flux:

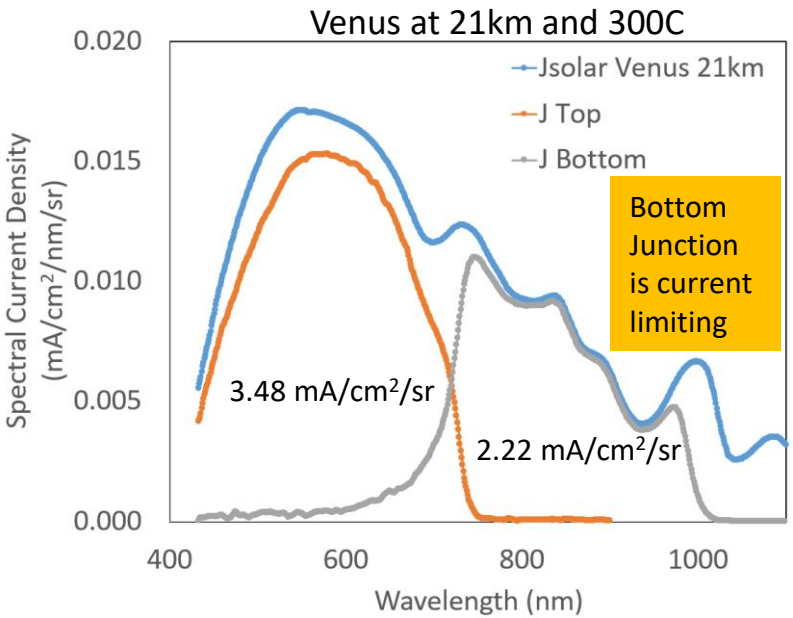
$$N_0(\lambda) = \frac{P_{\text{solar}}(\lambda)}{E_{\text{ph}}(\lambda)}$$

And photon energy:

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

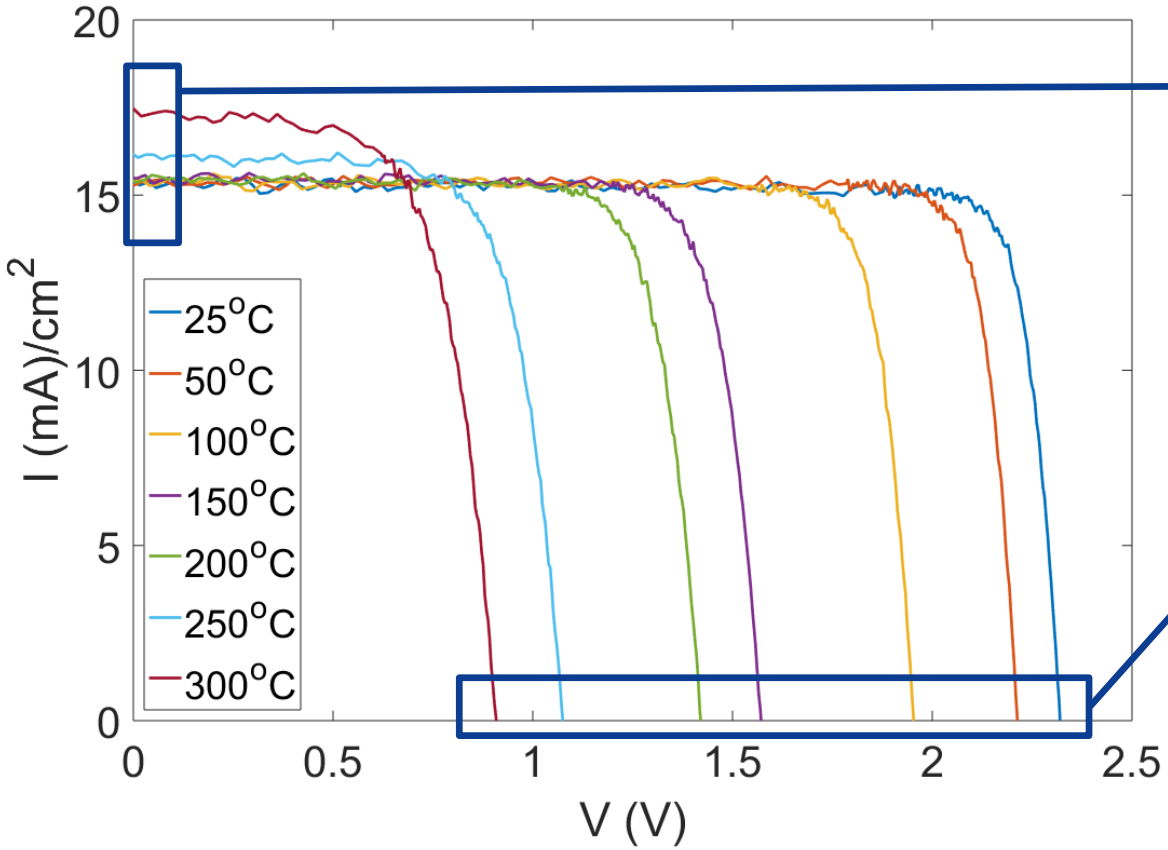


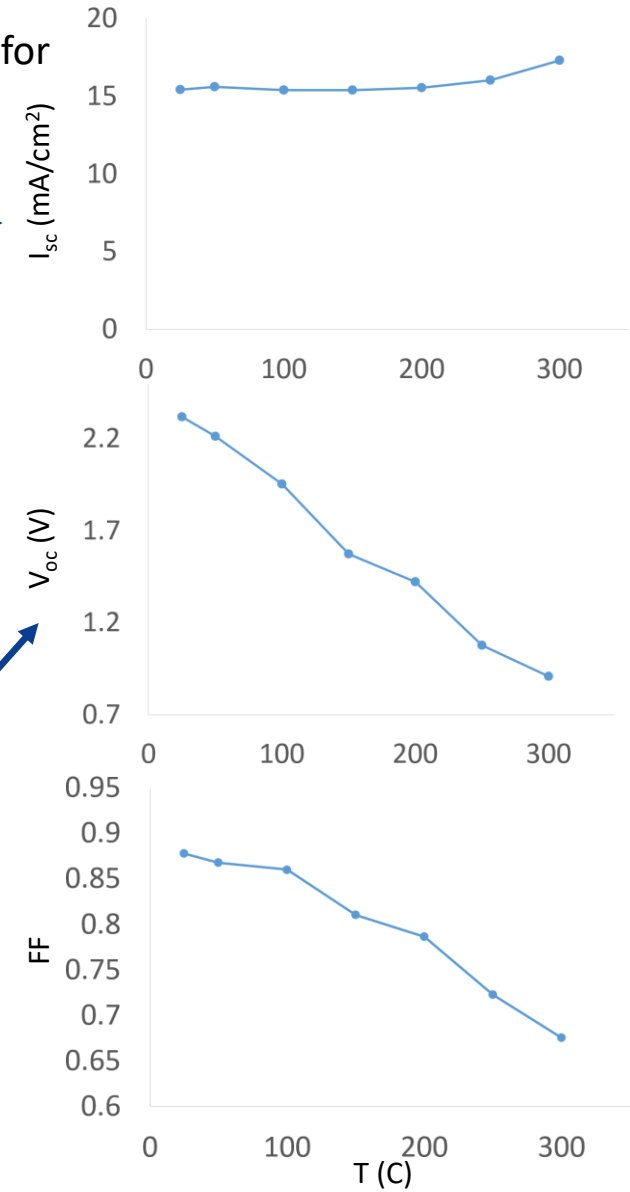




Solar cell performance under Venus temperature and solar spectrum

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

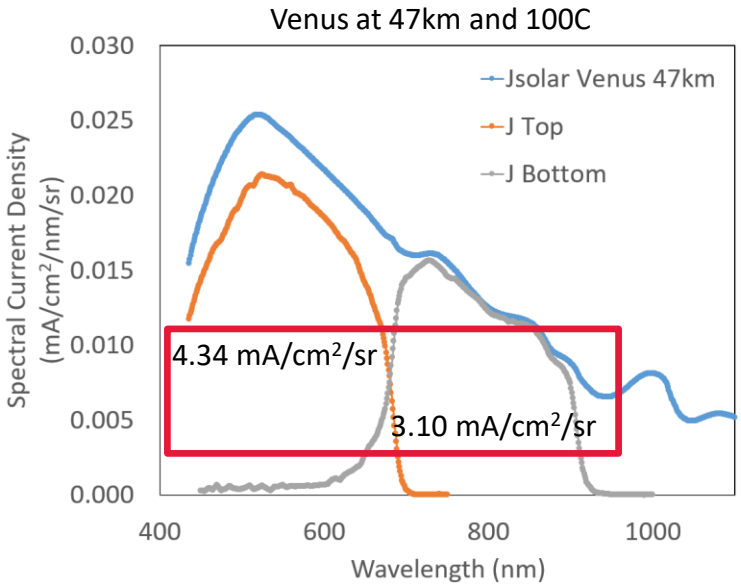


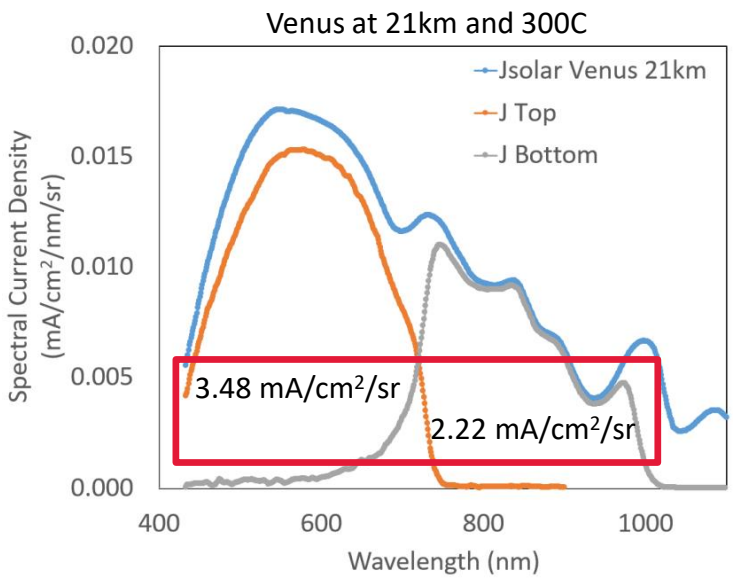


Temperature dependence of the solar cell between room temperature and 300C (21 km altitude at Venus)

JPL test capability simulates Venus temperature conditions

Solar cell performance under Venus temperature and solar spectrum



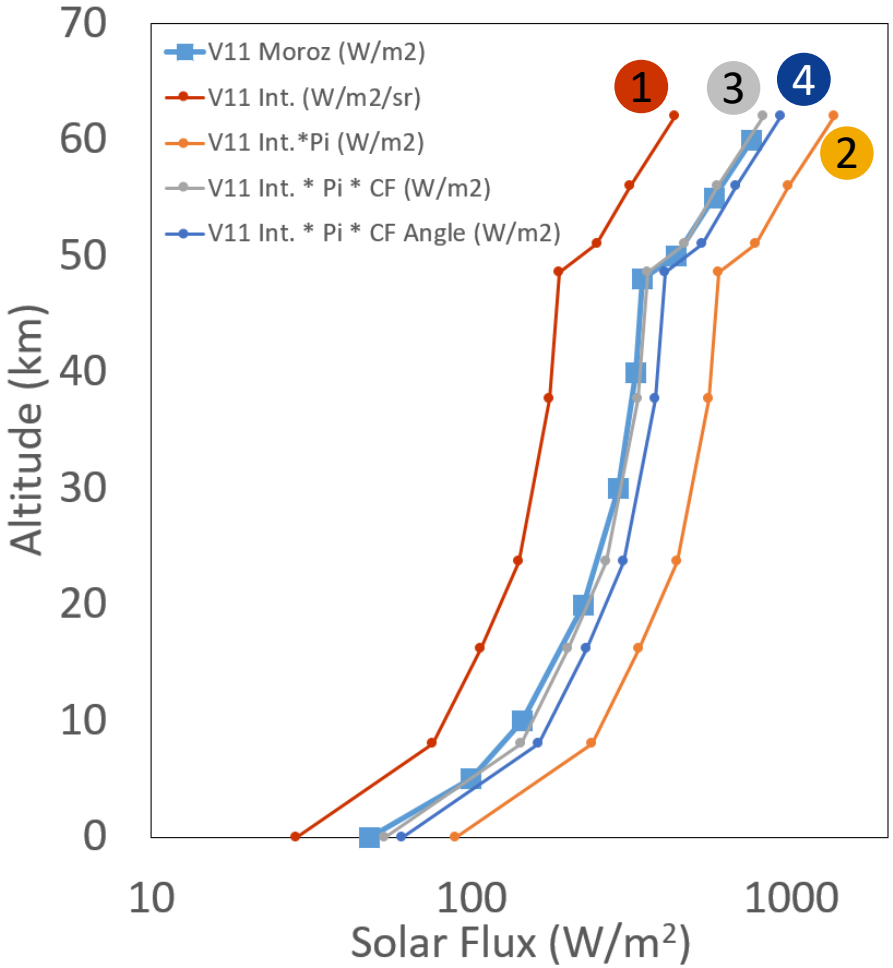


Assumptions made for Efficiency and Power estimation:

- Solar power input at Venus was integrated from Venera 11 solar spectrum.
- Solar cell is optimized by equilibrating current density in both junction from the EQE measurement weighted by Venus solar spectrum.
- V_{oc} and fill factor (FF) at Venus assumed equal to V_{oc} under AM0 for a given temperature.

	AM0 Earth	V 47 km Venus	V 21 km Venus
Temp (°C)	25	100	300
J_{sc} (mA/cm²/sr)	15.53	3.72	2.85
V_{oc} (V)	2.3	1.95	0.91
FF	87.8	86.0	67.6
η	22.8	33.4	13.7
P_{in} (W/m²/sr)	1353	187	128
P_{ele} (W/m²/sr)	310	62	19

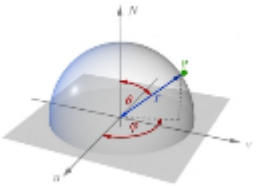
Solar cell performance under Venus temperature and solar spectrum



$$H = \int_0^{\infty} F(\lambda)\, d\lambda$$ 1

Initial Calculation

Downward Flux in W/m² assuming isotropic irradiance:



$$D = H * \int_0^{2\pi} \int_0^{\frac{\pi}{2}} \cos\theta \sin\varphi \, d\theta \, d\varphi = H * \pi$$ 2

Downward Flux in W/m² assuming isotropic irradiance and correction factor:

$$D_{corr} = D * \eta$$

with η=0.6 3

with η=0.68 4

Angular acceptance characteristics for a typical high efficiency solar cell.

Solar cell performance under Venus temperature and solar spectrum

For ① Jsc is in mA/cm^2/sr , P_{in} and P_{ele} are in W/m^2/sr

		①	④	①	④
	AM0	V 47 km (J_{sc} P /sr)	V 47 km	V 21 km (J_{sc} P /sr)	V 21 km
Temp (°C)	25	100		300	
J_{sc} (mA/cm^2)	15.53	3.72	7.95	2.85	6.09
V_{oc} (V)	2.3	1.95		0.91	
FF	87.8	86.0		67.6	
η	22.8	33.4		13.7	
P_{in} (W/m^2)	1353	187	399	128	273
P_{ele} (W/m^2)	310	62	133	18	37

Accounting for upward flux:

P_{ele} (W/m^2)			253		69

Potential improvement by using bi-facial solar cells to take advantage of upward flux.
Planetary science analysis suggest that at a given altitude under the clouds:
Downward Flux = Upward Flux - 40W, for example at Downward Flux(47km)=399-40=359 W/m^2

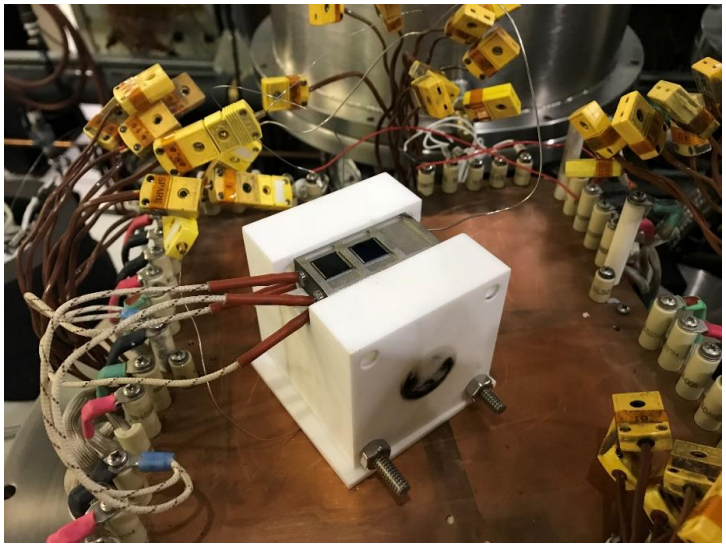
Lifetime testing for survivability at Venus

Ag based Metallization 1
Al based Metallization 2

	300°C Venus 21km	465°C Venus Surface
1h	Metallization 1 and Metallization 2	Metallization 1 and Metallization 2
8h		
24h		
1 week		

1 cm^2 fabricated solar cell

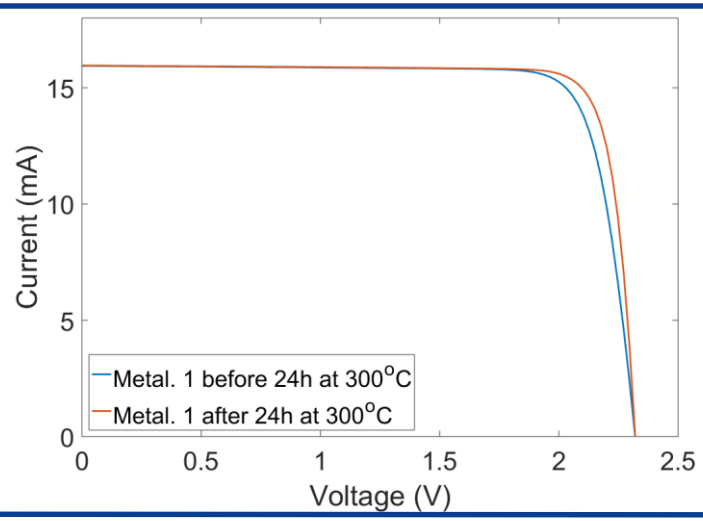
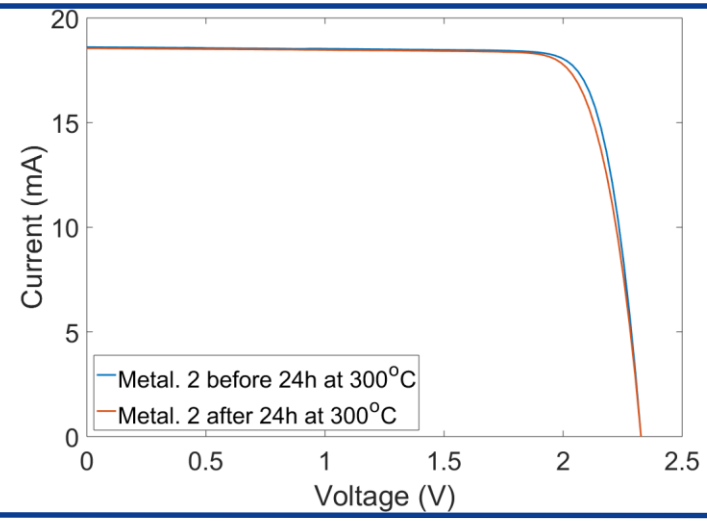
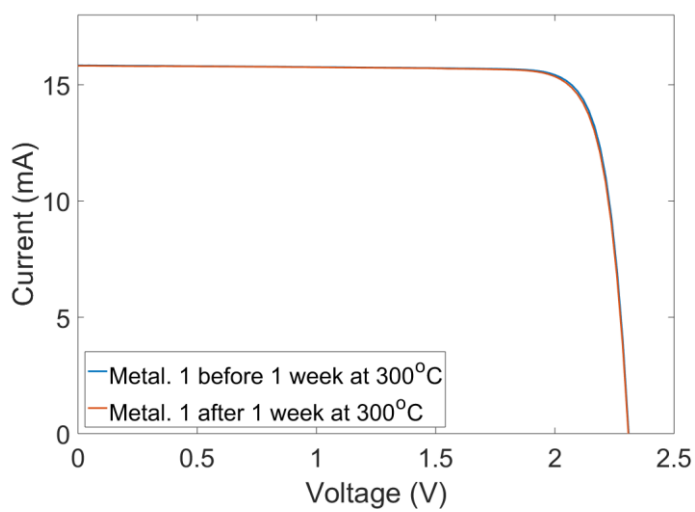
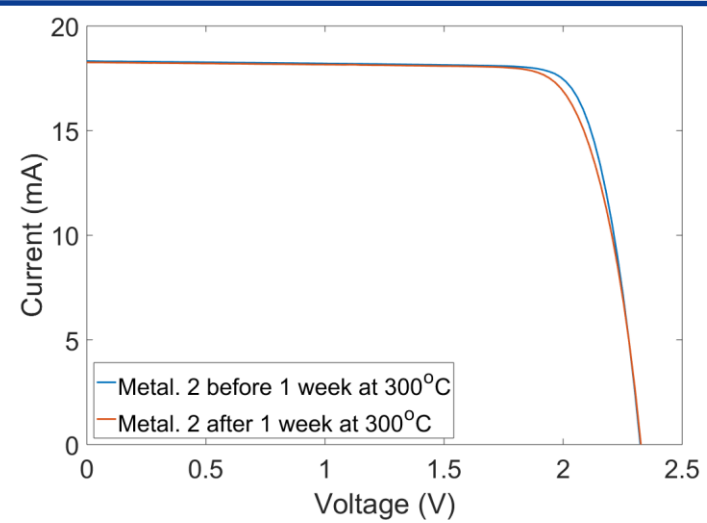
Lifetime Testing setup.
Developed and designed at JPL



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.

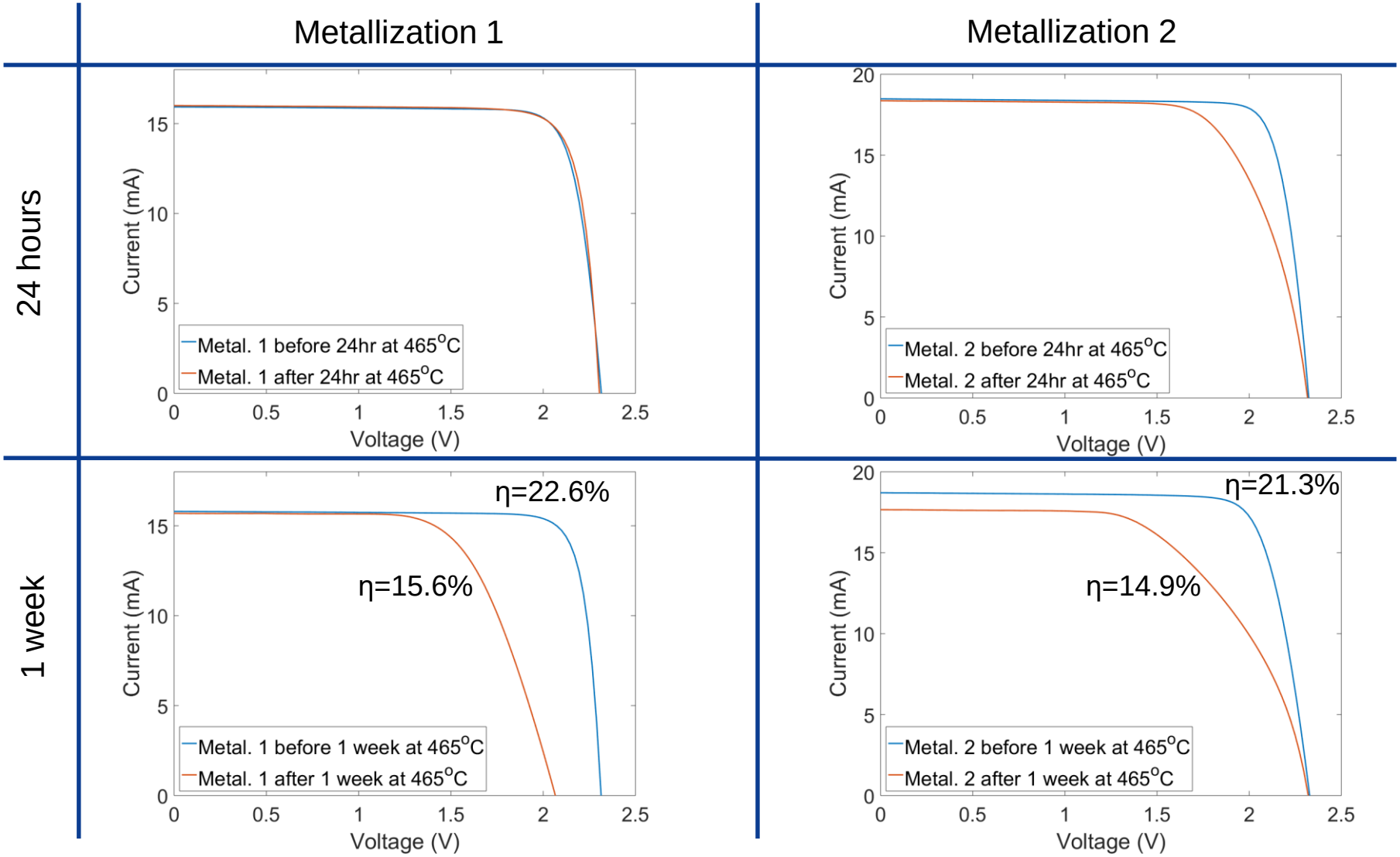
Lifetime testing for survivability at Venus

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

	Metallization 1	Metallization 2
24 hours		
1 week		

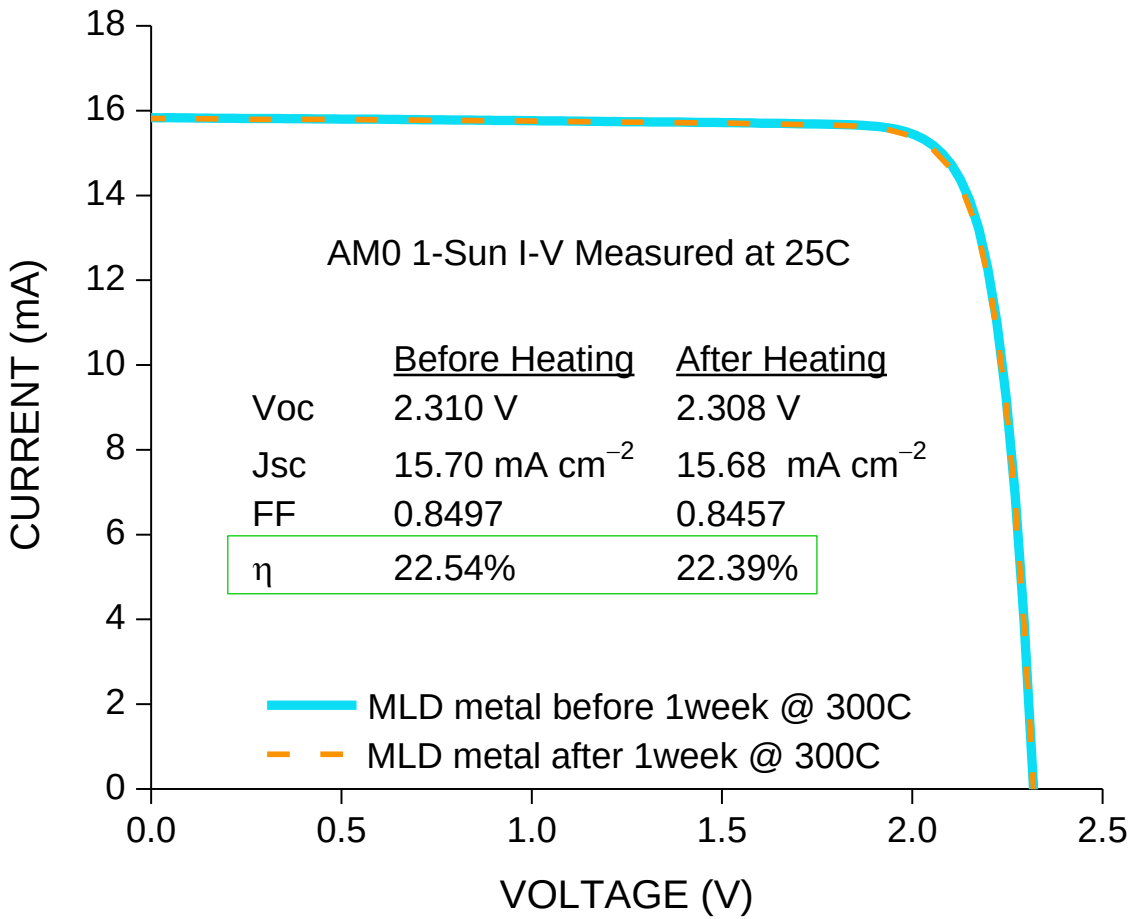
Lifetime testing for survivability at Venus

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

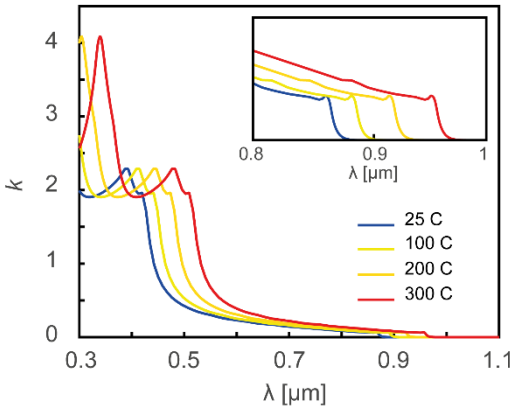


Lifetime testing for survivability at Venus

I-V Before and After 1 Week at 300°C
AM0 1-Sun 25°C Light I-V Measurements at MLD



Solar cell modelling and optimization (Caltech)

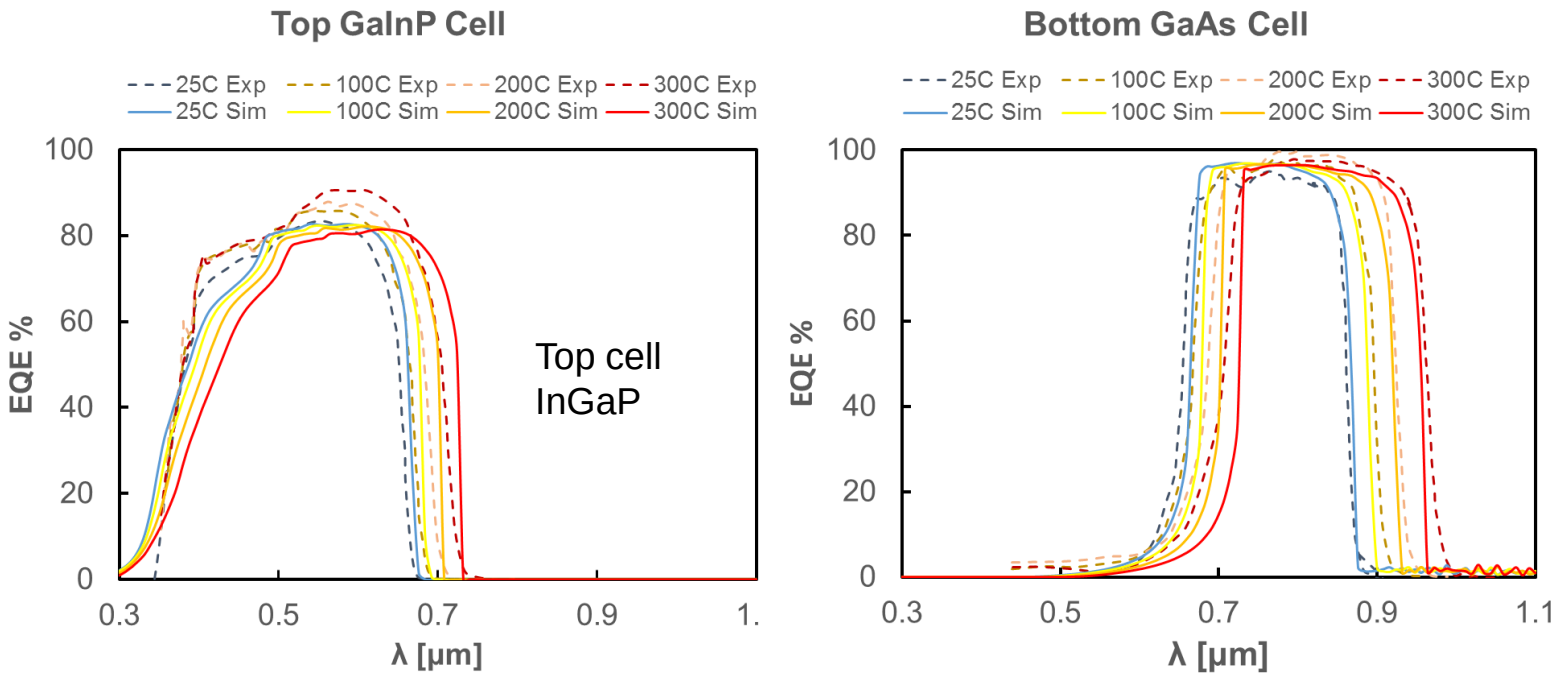


temperature dependence of the material bandgap, $E_g(T)$ is described by:

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

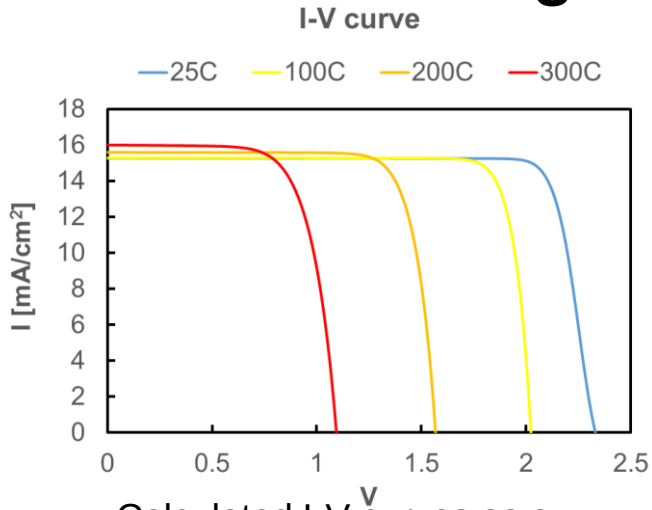
GaAs temperature-dependent imaginary refractive index, k.

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:

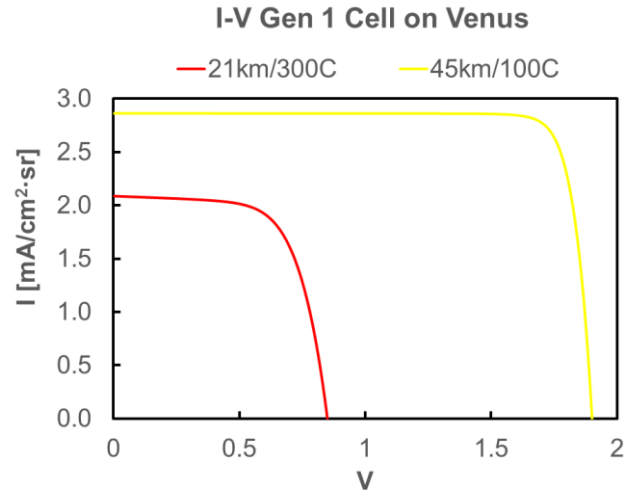


Solar cell modelling and optimization (Caltech)

Before Optimization

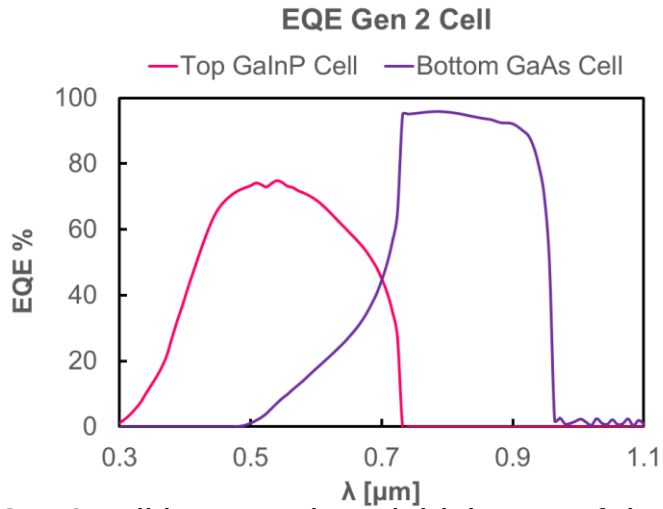


Calculated I-V curves as a function of temperature

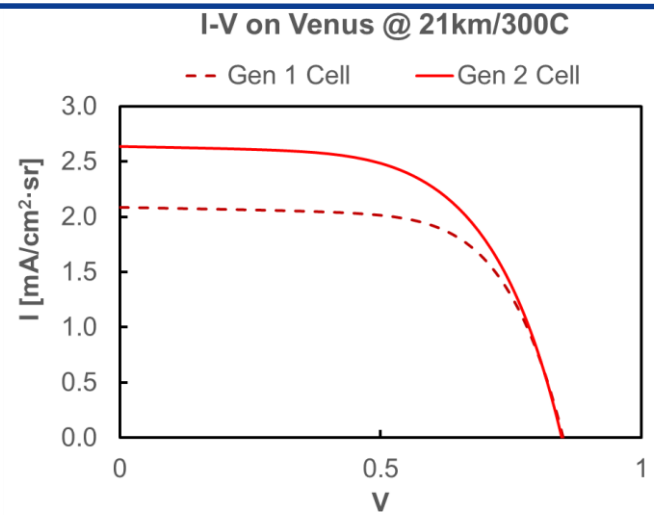


Bottom GaAs cell is current limiting

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/cm^2 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.
- For Metallization 1, no degradation observed after 1 week at 300C. Series resistance appears after 1 week at 465C. For Metallization 2, degradation appears after 24 hours at 465C.
- Modelling shows an optimal design for a dual junction InGaP/GaAs solar cell at 21km Venus altitude where temperature is 300C.

<u>Future work:</u>

- Understanding degradation mechanism at high temperature
- Improve metallization for survivability up to 1 month at 465C
- Fabricate optimized InGaP/GaAs solar cell at 21km Venus altitude/300C

Acknowledgements

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