
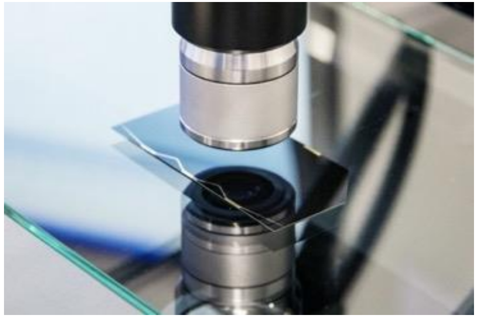


Optimized Space Solar cells for Mars Missions - OptimisM

ESTEC Contract No.: 4000138511/22/NL/MGu

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Fraunhofer ISE

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Table of content

Motivation & Objective

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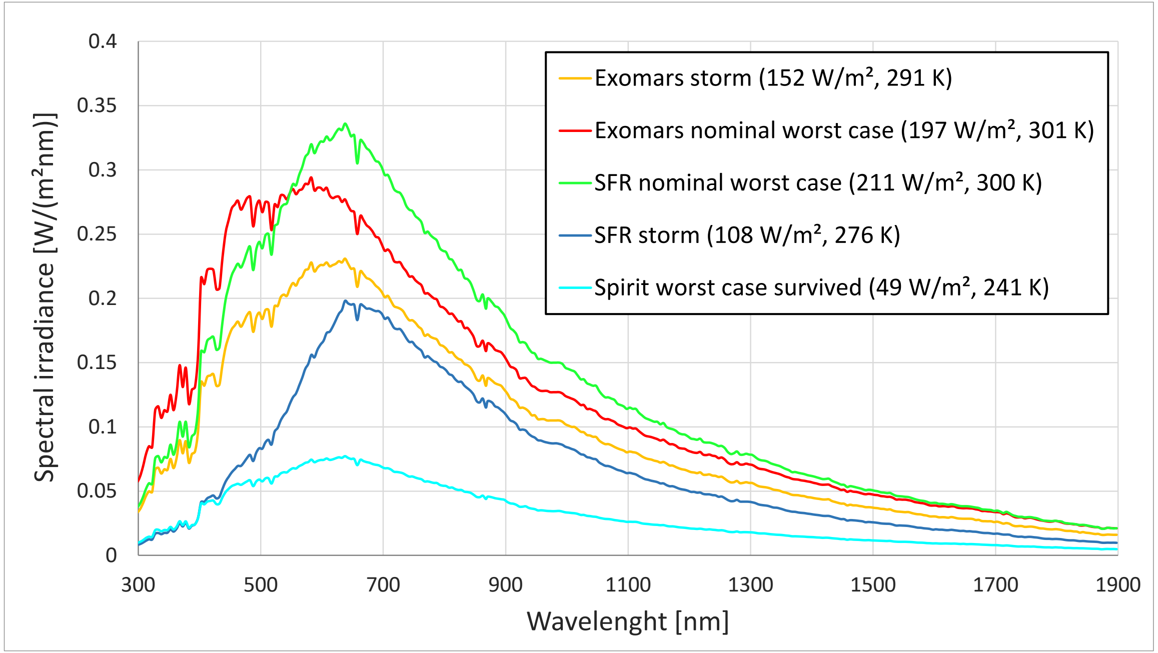
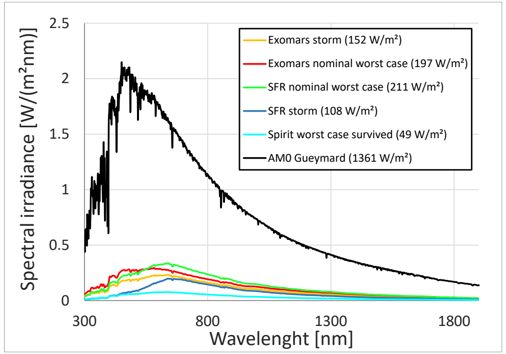
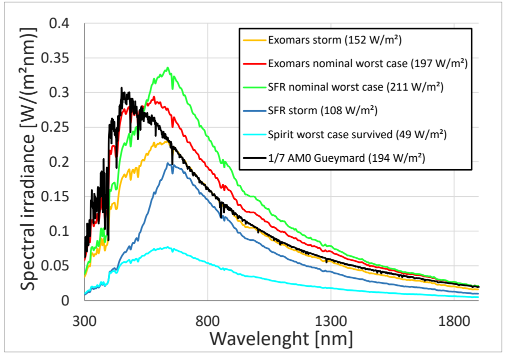
Motivation & Objective

Overall goal of development project: Optimize solar cell for Mars surface







Motivation & Goal

Objectives of the development project

- At least a +10% higher power output under the pre-defined “Exomars nominal worst case” spectrum at 197 W/m² and at 301 K compared to the performance of a standard 3G30 cell.

- Manufacturing of hardware sample cells inclusive measurements under AM0 as well as covering the given five Martian conditions plus derivation of input parameters for a two-diode solar cell model.

- Furthermore, temperature coefficients measurements between -150 °C and +50 °C at minimal five points in this range including spectral responsivity and dark-IV measurements.

- Principle compatibility with flexible solar array concepts.

Identification of best performing cell under Mars conditions

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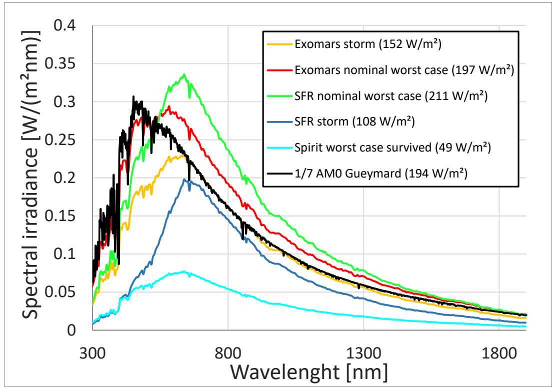
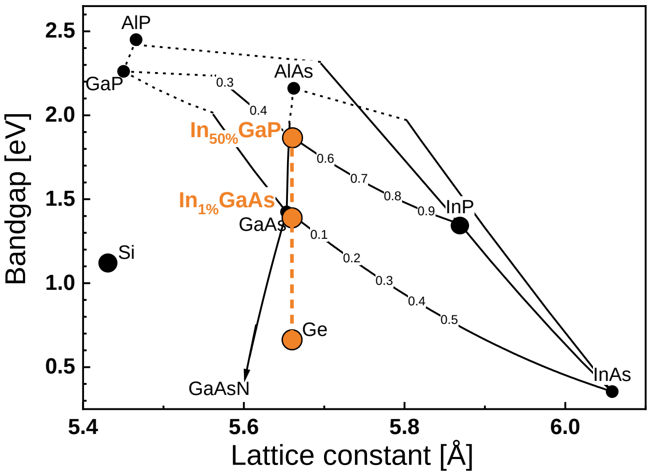
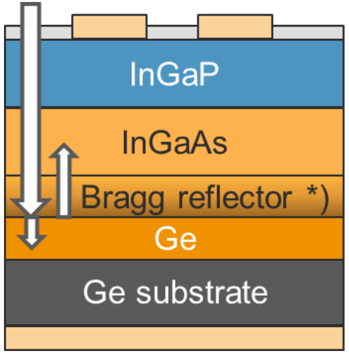
Identification of best performing cell under Mars conditions

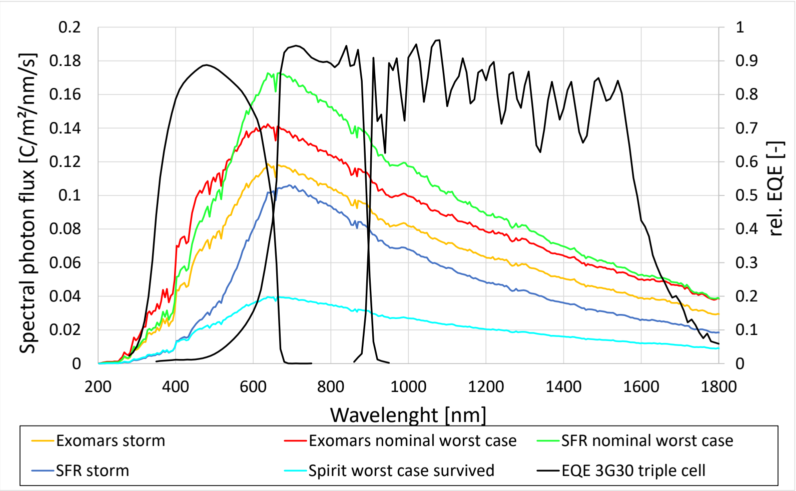
- Principal cell designs at AZUR are 3G30 TJ, the UMM 4J-cell 4G32adv, and a terrestrial 5J cell
- Since target spectra exhibit a red-shift with respect to the AM0 Gueymard spectrum, 3G30 and 4G32adv will be considerably current-mismatched on the Mars surface.
- More precisely, the built-in top/J1 cell current limitation, which is part of the 3G30's and 4G32adv's end-of-life design, are even more limiting the efficiency.



Evaluation of 3G30 epitaxy structure

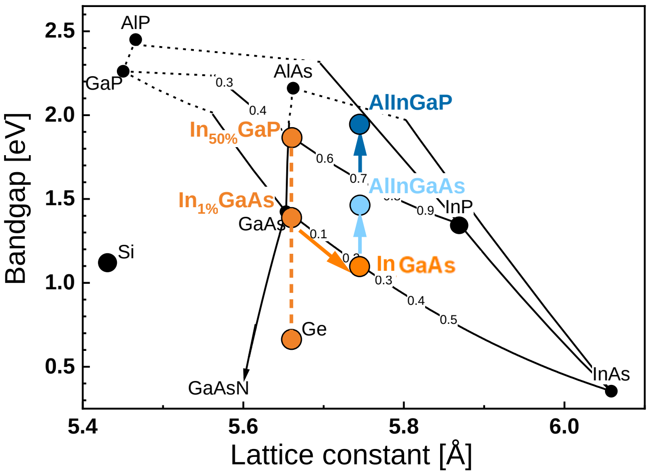


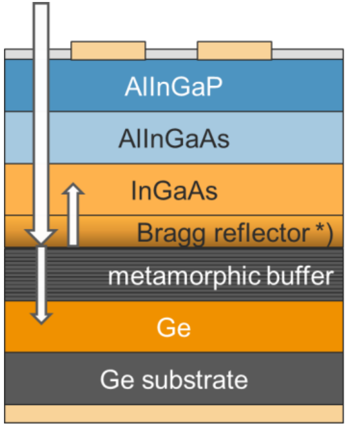


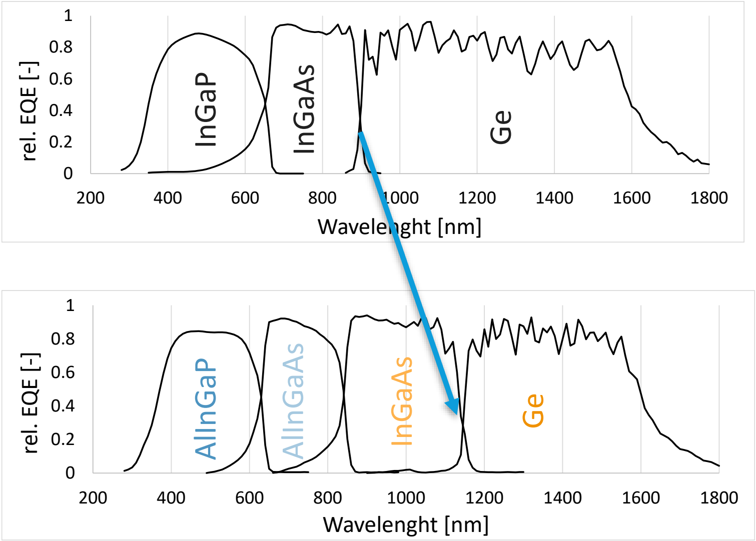


- Simulations/calculations with different epitaxy designs were conducted.
- Lattice matched 3G30 can only be adapted in Top/Mid layer thickness without major epitactical changes.
- Top/Mid current balance could be improved, but rich IR spectrum can not be utilized fully.

Evaluation of 4G32adv epitaxy structure







- Change from triple junction to four junction epitaxy design.
- More Indium in InGaAs subcell causes lower bandgap -> Surplus of current in Ge subcell is reduced.
- Additional subcell adds 0.7 V for 2% more absolute power.

Identification of best performing cell under Mars conditions

Using typical measured spectral response (SR) data of existing 3G30 and 4G32adv solar cells and the “Exomars nominal worst case” spectrum as well as the AM0 Gueymard spectrum, the following performance parameters have been calculated.

3G30	Top cell	Mid cell	Bot cell
Current density under AM0 spectrum (mA/cm²)	17.25	18.09	27.45
Current density under “Exomars nominal worst case” (mA/cm²)	2.52	3.04	4.55
Current density under “Exomars nominal worst case” normalized to one	1.00	1.21	1.81

4G32adv	J1	J2	J3	J4
Current density under AM0 spectrum (mA/cm²)	14.99	15.8	15.64	15.23
Current density under “Exomars nominal worst case” (mA/cm²)	2.16	2.53	2.78	2.59
Current density under “Exomars nominal worst case” normalized to one	1.00	1.17	1.29	1.20
Evenly distributed	1.16	1.16	1.16	1.16

Identification of best performing cell under Mars conditions

- Adaptation of triple-junction solar cell by current matching Top and Mid junction is possible; however, estimated current gain is 10.5 %.
- To adapt the four-junction cell to the "Exomars nominal worst case" spectrum, the aluminum content of junction one and junction two can be adjusted without changing the lattice constant of the sub-cell material.
- The calculations show that a current increase of up to 16 % is possible. However, this can only be achieved by reducing the band gaps of the two sub-cells J1 and J2. A voltage drop of approximately 150 mV must be taken onto account, which will reduce the overall power slightly.

→ **Decision to optimizes the four junction solar cell design.**

Measurements on reference cells under Mars conditions

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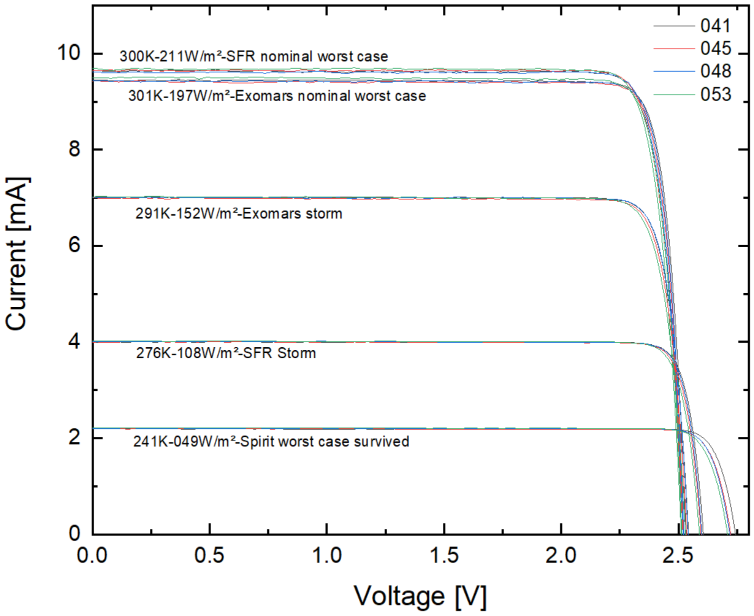
Measurements on reference cells under Mars conditions

Four representative 3G30 solar cells were measured by Fraunhofer ISE under the five different Martian spectra.

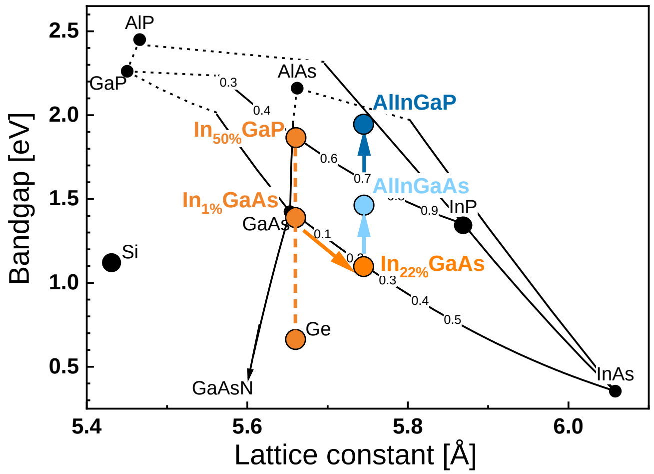


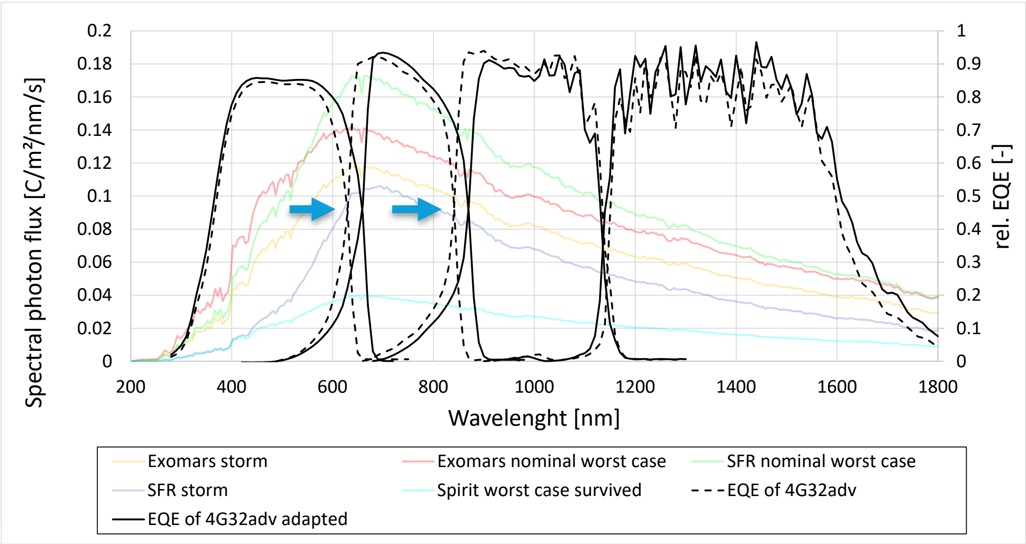
301K-197W-Exomars nominal worst case					
Cell ID	Voc [V]	Eff [%]	Vmpp [V]	Impp [mA]	FF [%]
041_301	2.519	27.3	2.27	9.465	88.47
045_301	2.519	27.3	2.27	9.492	88.52
048_301	2.522	27.3	2.28	9.448	88.82
053_301	2.513	27.2	2.26	9.499	88.14
Average	2.518	27.3	2.27	9.476	88.49

The efficiency of a 3G30 cell under “Exomars nominal worst case” conditions is on average **27.3 %**. This will be the basis for the improvement calculations later.

Epitaxy development and cell design adaptation

4G32adv epitaxy adaptation



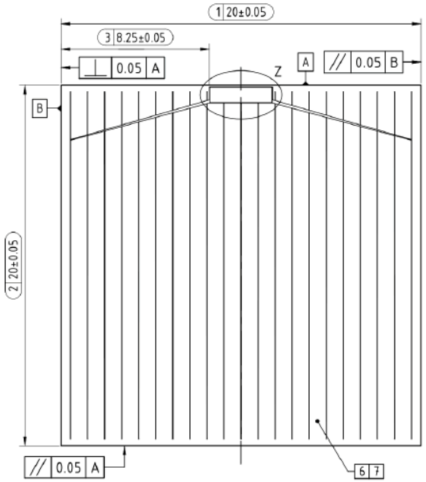


- Aluminum content reduction of upper two junctions to increase absorption wavelenght by 30 nm.
- Slight reduction in subcell voltage, but significant improvement in current matching.
- Radiation hardness of standard design is conserved.

4G32adv grid adaptation

Grid finger spacing was optimized for lower intensity

560 µm to 1100 µm



4G32 adv

4G32adv low intensity adapted

→ 156 optimized solar cells from 13 wafers were manufactured to 2x2 cm^2 solar cells

Characterization of optimized full structure solar cells

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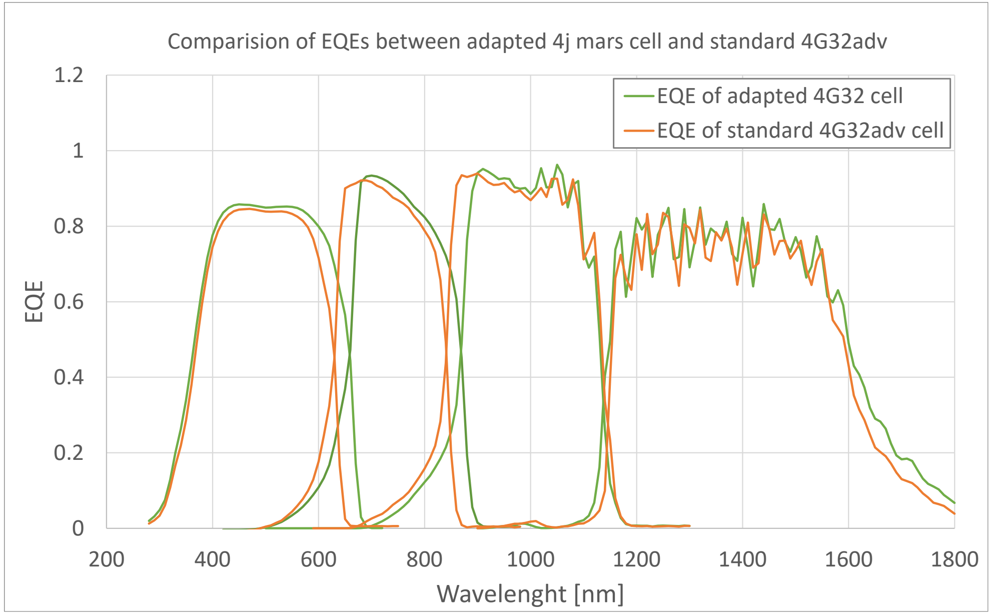
EQE Characterization at AZUR SPACE

Initial external quantum efficiency measurement to verify general success of adaptation:



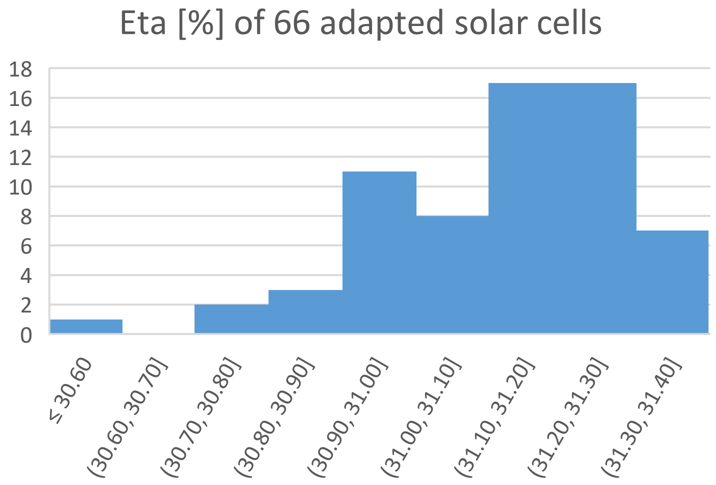
→ Absorption wavelengths of J1 and J2 sub-cells were increased by 30 nm as planned.

Light IV Characterization at AZUR SPACE

More than sixty adapted solar cells were randomly selected and measured under the proposed "Exomars nominal worst case" spectrum at AZUR.

In addition, sixteen reference solar cells were measured.

	Median Isc [mA]	**Median Voc [V]**	**Median FF**	**Median Eta [%]**
4G32 Mars adapted (n = 66)	9.92	3.066	0.8074	31.1
4G32adv reference cells (n = 16)	8.79	3.182	0.8330	29.7
relative delta adapted vs reference	12.8%	-3.7%	-3.1%	4.9%



Light IV Characterization at AZUR SPACE

Goal of adaptation was current matching → Subcell currents were determined for 15 solar cells.

	J1	J2	J3	J4
Median Isc (Iop @1.8 V for J4) [mA]	10.28	10.08	9.94	10.33
Median Jsc [mA/cm²]	2.57	2.52	2.48	2.58
relative distribution to average current	1.18%	-0.80%	-2.23%	1.66%

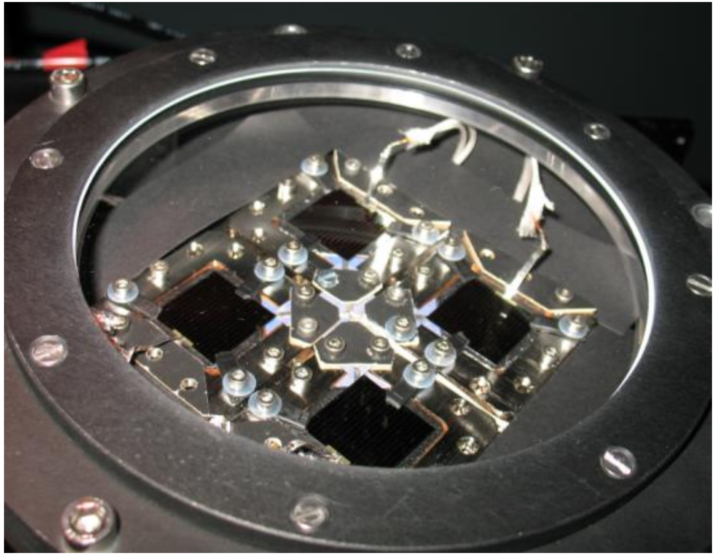
- For adapted cell design, the J3 sub-cell is current limiting.
- Overall current matching is within +/- 2.5 %.

→ Since performance seemed promising, four solar cells were selected and sent to Fraunhofer ISE.

Measurements at Fraunhofer ISE: Cryostat

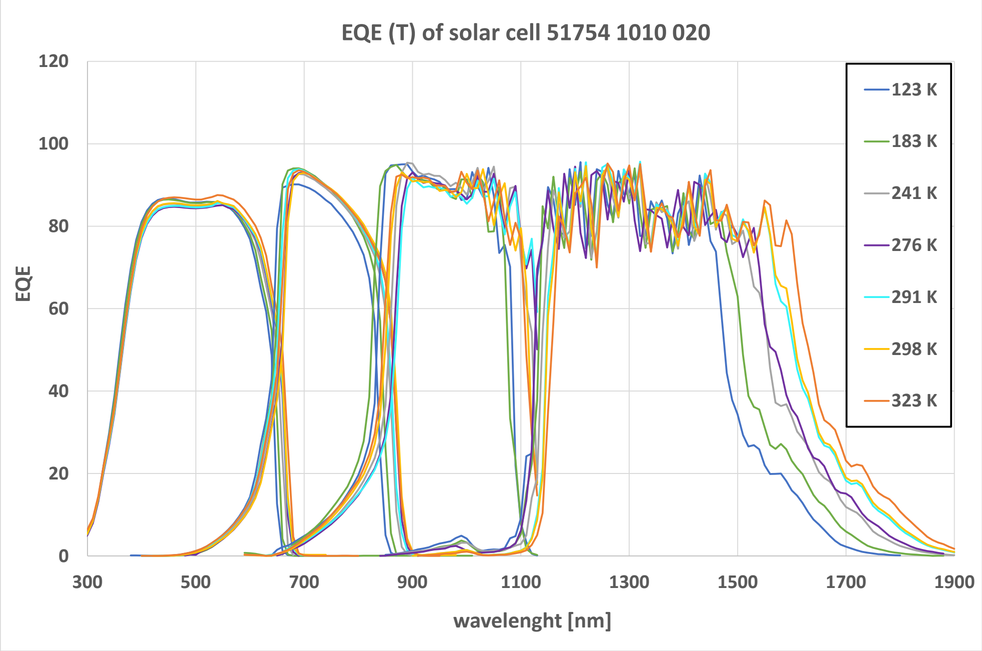
Cryostat at ISE enables measurements with liquid Nitrogen cooling for low temperature measurements.

- Only space for four samples with area of 2x2 cm^2.
- Low temperature IV and EQE measurements were conducted by Fraunhofer ISE.



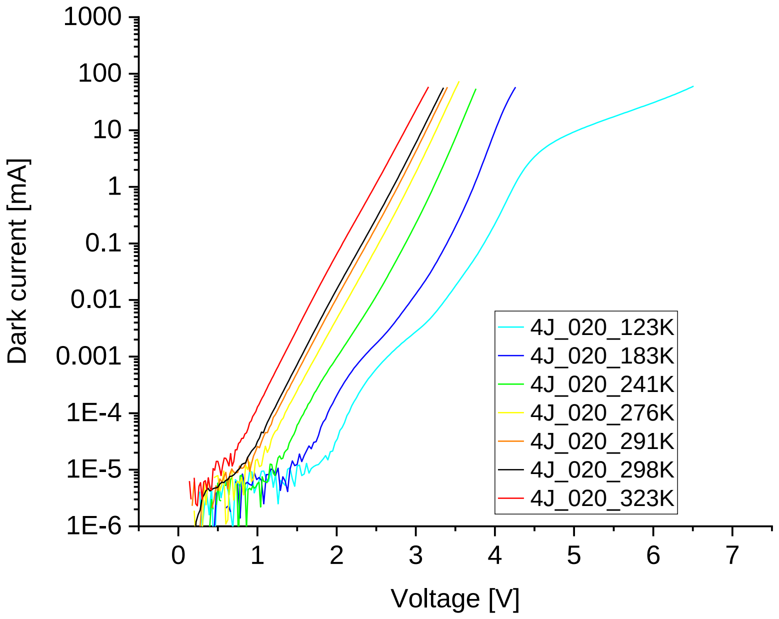
EQE (T) characterization at Fraunhofer ISE

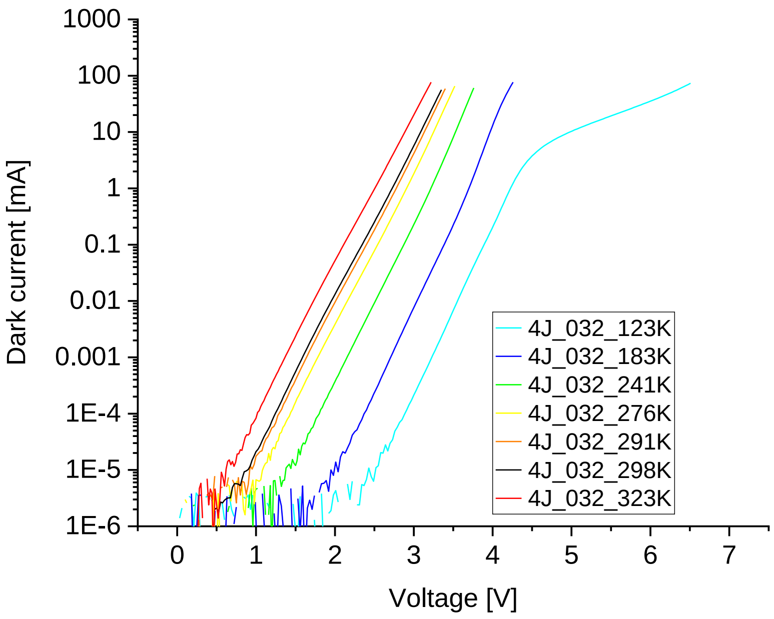
EQE (T) Measurements by Fraunhofer ISE from -150 °C up to 50 °C



Dark IV characterization at Fraunhofer ISE

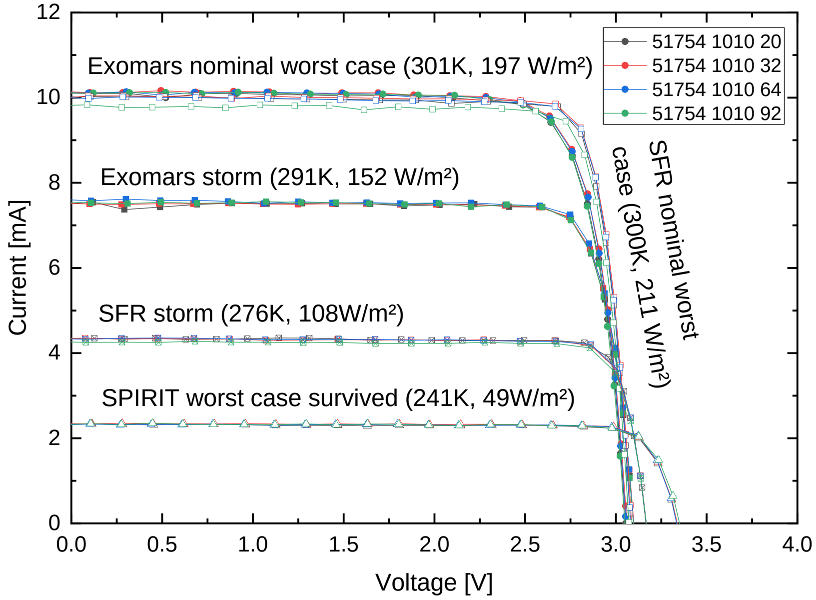
Dark IV (T) measurements from Fraunhofer ISE





Light IV characterization at Fraunhofer ISE

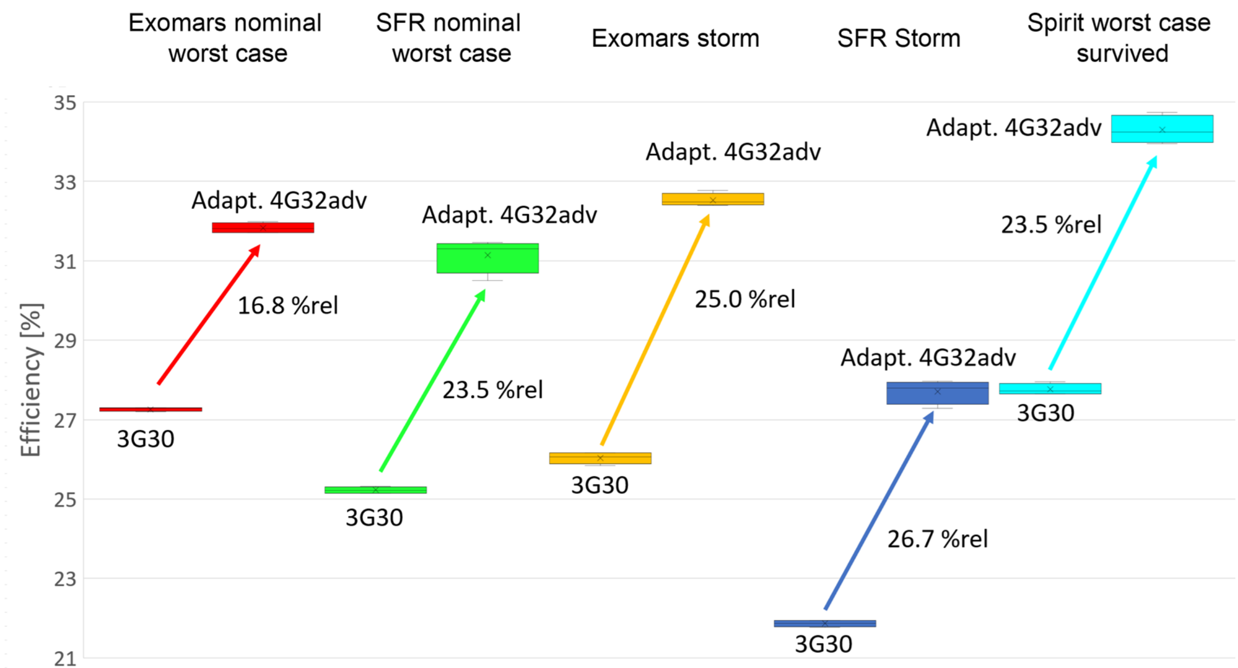
Light IV measurements from Fraunhofer ISE

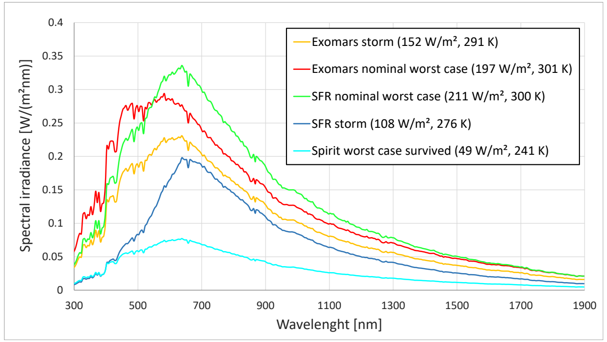


Exomars nominal worst case (301 K, 197 W/m²)							
Cell ID	Isc [mA]	Voc [V]	Pmpp [mW]	Vmpp [V]	Impp [mA]	Eta [%]	FF
51754 1010 20	10.10	3.052	25.00	2.613	9.57	31.7	0.8111
51754 1010 32	10.14	3.058	25.21	2.622	9.61	32.0	0.8129
51754 1010 64	10.12	3.055	25.13	2.621	9.59	31.9	0.8132
51754 1010 92	10.11	3.047	24.99	2.617	9.55	31.7	0.8109

→ Average efficiency of 31.8 %

Effiency comparison of adapted 4G32 vs 3G30 reference





→ The adapted 4G32 solar cell has between 16.8 % and 26.7 % relative more efficiency!

Characterization of optimized component solar cells

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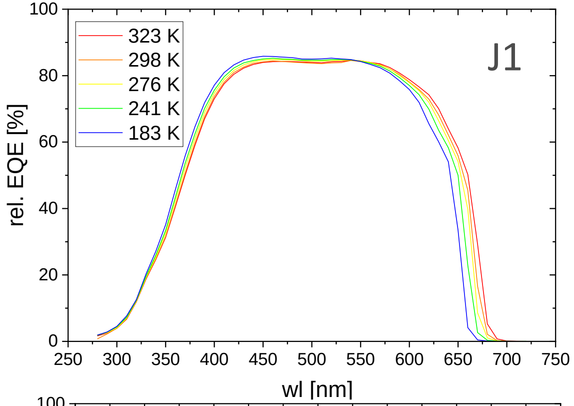
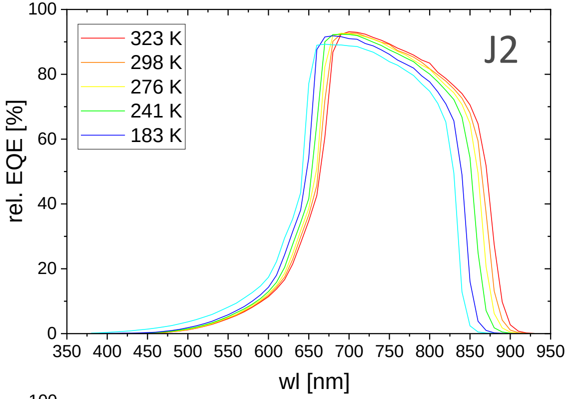
Characterization of optimized component solar cells

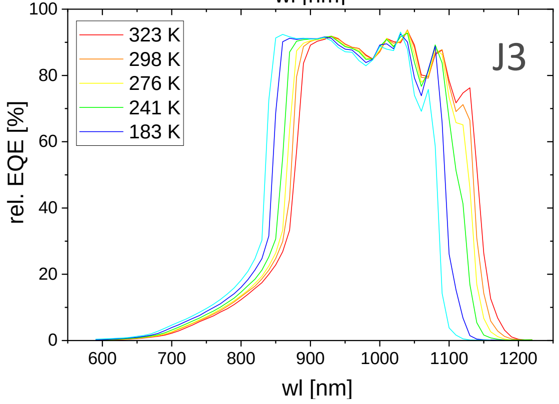
After measurements confirmed adaptation success, component cells of the same epitaxy structure were manufactured.

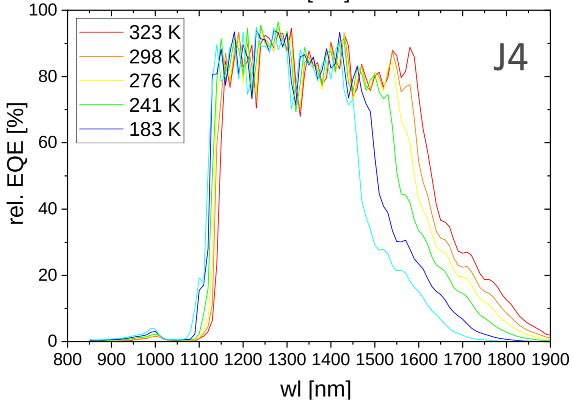
48 component cells for each junction were manufactured with the same 2x2 cm^2 solar cell design as the multi junction solar cells.

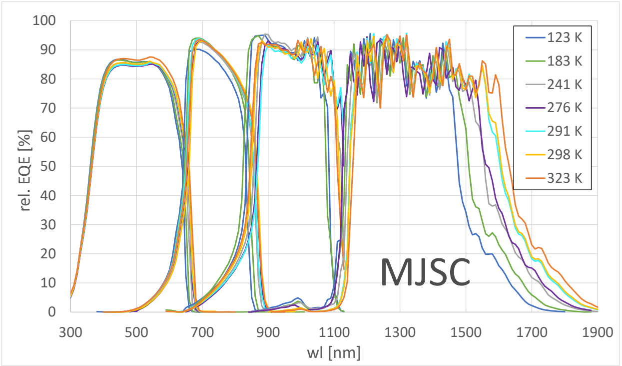
EQE (T) characterization at Fraunhofer ISE



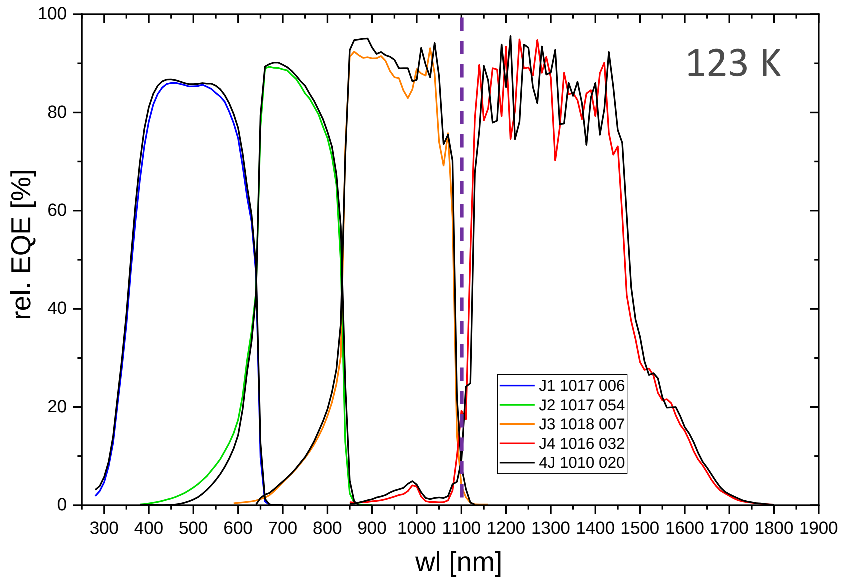


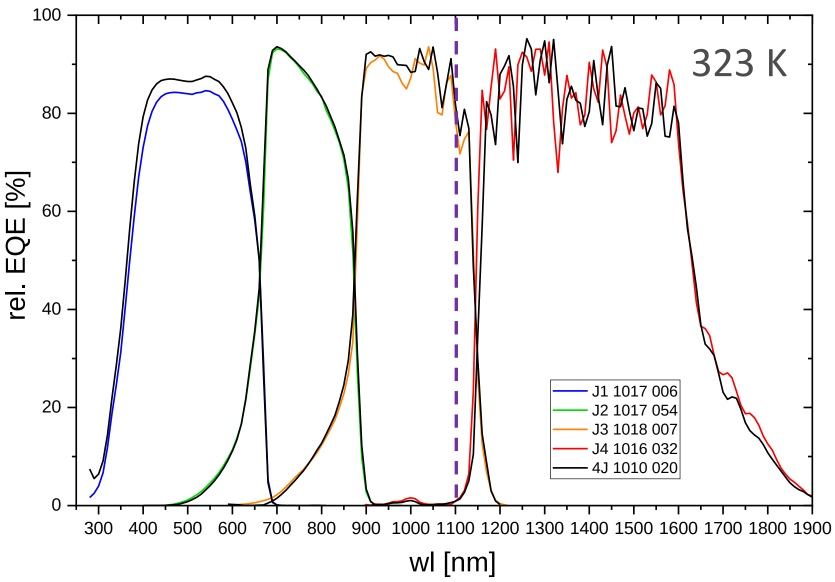




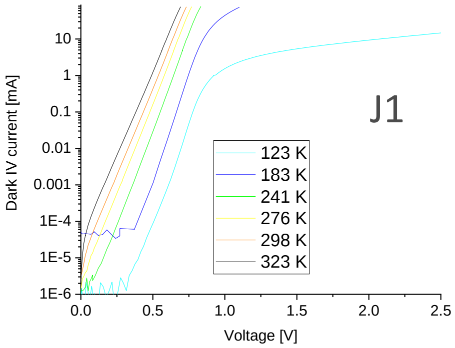


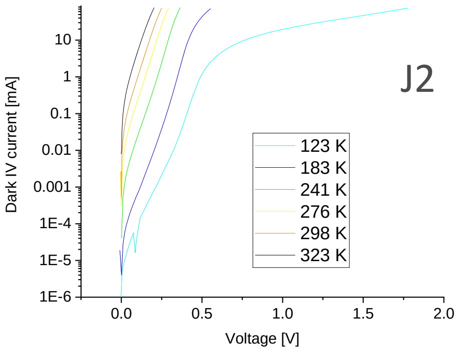
EQE comparison between components and MJSC

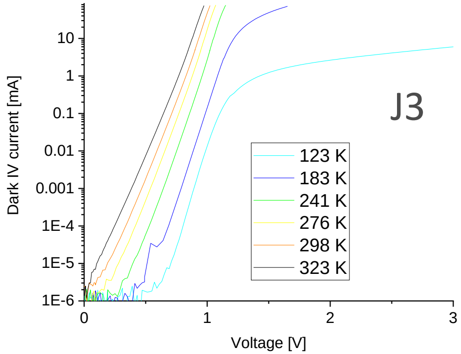


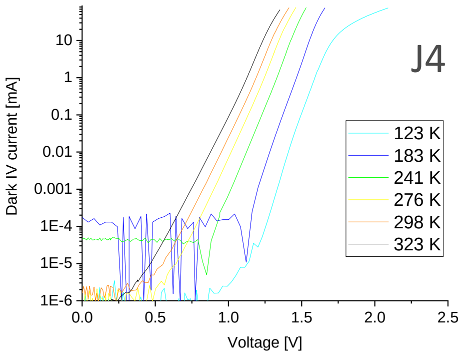


Dark IV characterization at Fraunhofer ISE



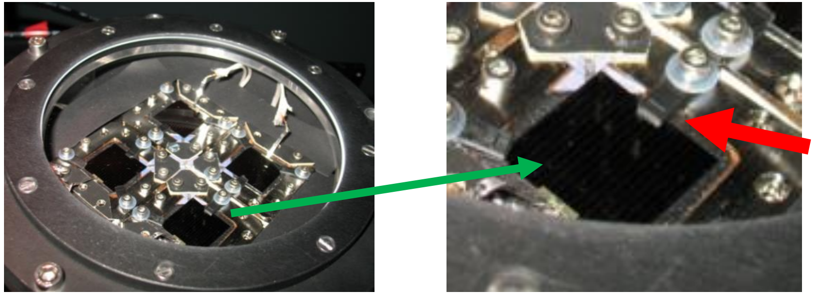


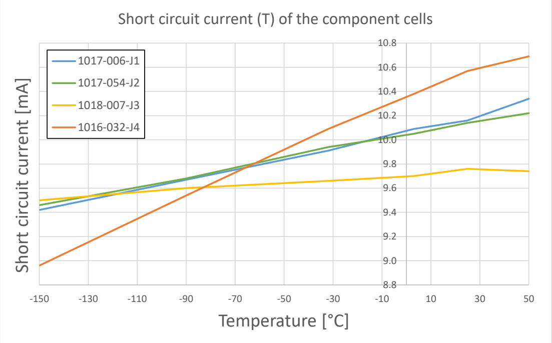




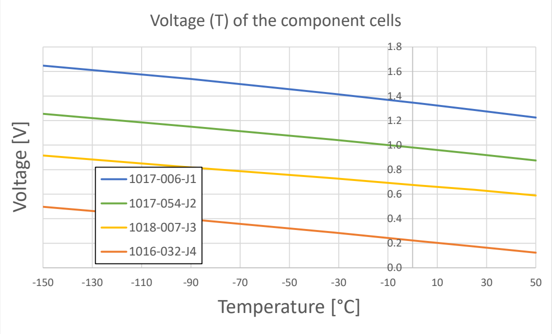
Light IV characterization at Fraunhofer ISE

- Temperature dependent light IV measurements from -150 °C to 50 °C





Junction	ΔmV/Δ°C	ΔµA/Δ°C
J1	-2.1	4.6
J2	-1.9	3.8
J3	-1.6	1.2
J4	-1.9	8.65



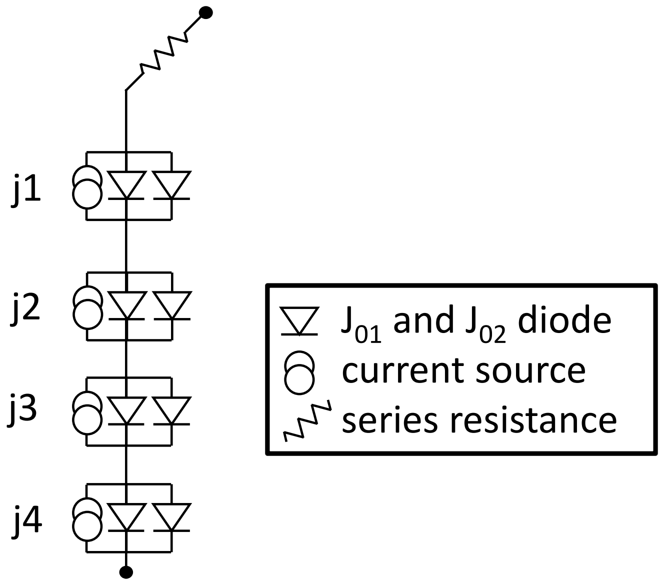
Derivation of cell model parameters

Derivation of cell model parameters

A 2-diode model is used to calculate the current voltage characteristic of the optimized solar cell under Martian spectral conditions.

Each of the four sub cells is modeled via two diodes, one current source, one series resistance and one parallel resistance.

The series and the parallel resistance are neglected in this work, leaving short circuit current densities (J_{SC}) and dark saturations current densities J_{01} and J_{02} as required input parameter per sub cell.



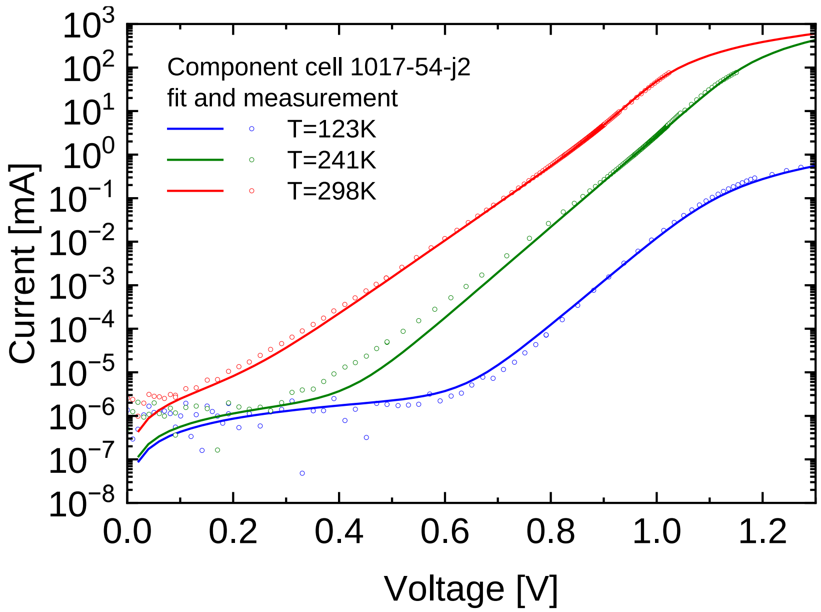
Derivation of cell model parameters

Determine J_{SC}: The subcell J_{SC} are calculated from measured subcell EQE and given Martian spectra.

Scenario	J_{SC1}	J_{SC2}	J_{SC3}	J_{SC4}	T	Irradiance
[-]	[mA/cm²]	[mA/cm²]	[mA/cm²]	[mA/cm²]	[K]	[W/m²]
Mars1	1.90	2.17	2.17	2.23	291	152
Mars2	2.56	2.53	2.57	2.72	298	197
Mars3	2.50	3.09	3.04	2.97	298	211
Mars4	1.09	1.90	1.82	1.58	276	108
Mars5	0.58	0.70	0.72	0.67	241	49

Derivation of cell model parameters

Determine J_{01}, J_{02}: To determine J_{01}, J_{02} of each sub cell, the 2-diode equation is fitted to the dark IV curves from the component cells for known, temperature depending measurement data points.



Sub cell	T	J_{01}	J_{02}	n1	n2
[-]	[K]	[A/cm²]	[A/cm²]	[-]	[-]
j1	241	3.15E-34	3.01E-18	1	2
	276	2.42E-28	1.04E-15	1	2
	298	1.55E-25	2.08E-14	1	2
	323	9.31E-23	3.54E-13	1	2
j2	241	1.66E-26	2.37E-14	1	2
	276	9.35E-22	2.26E-12	1	2
	298	2.07E-19	2.26E-11	1	2
	323	1.72E-17	2.42E-10	1	2
j3	241	2.43E-19	4.59E-11	1	2
	276	4.89E-16	1.21E-09	1	2
	298	2.54E-14	6.10E-09	1	2
	323	7.69E-13	3.23E-08	1	2
j4	241	1.45E-09	8.69E-07	1	2
	276	1.61E-07	8.47E-06	1	2
	298	1.84E-06	2.72E-05	1	2
	323	1.16E-05	1.61E-04	1	2

Derivation of cell model parameters

Determine J_{01}, J_{02} (T): To consider the temperature dependency of J_{01}, J_{02} the following equations are used:

$$J_{01}(T) = A_{01} \cdot \exp\left(B_{01} \cdot E_g(T)\right) \cdot T^3 exp\left(-\frac{E_g(T)}{k_b T}\right) \qquad (1)$$

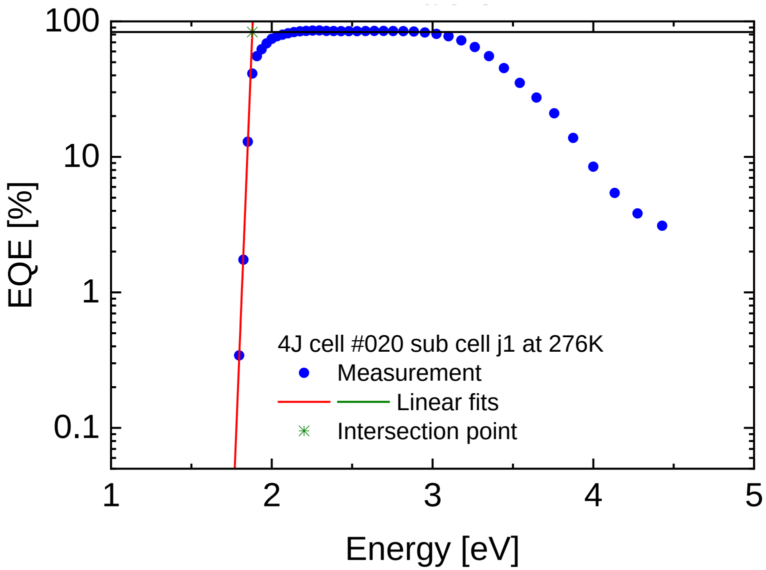
$$J_{02}(T) = A_{02} \cdot T^{2.5} exp\left(-\frac{E_g(T)}{2k_b T}\right) \qquad (2)$$

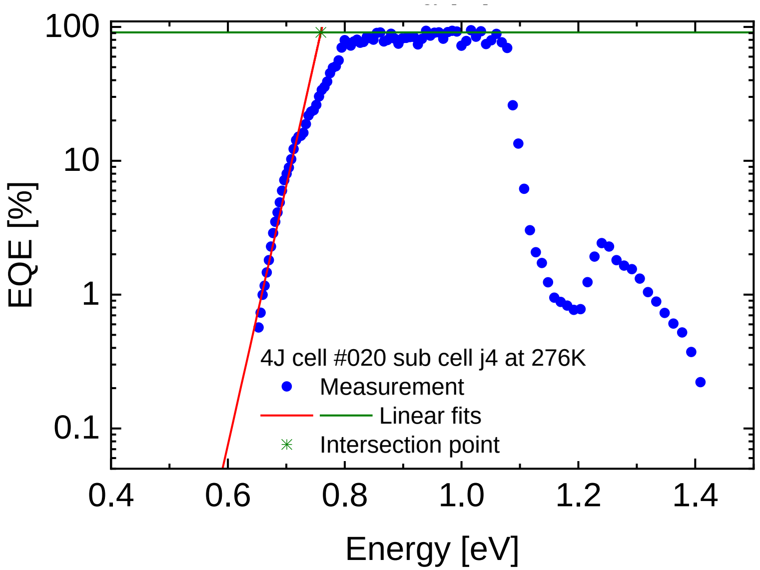
Where A_{01}, B_{01}, A_{02} are fit parameters, T is temperature, k_b Boltzmann's constant and $E_g(T)$ is the sub cell band gap at a given temperature T calculated using the following equation:

$$Eg(T) = a - b \cdot (T)^2/(T + c) \qquad (3)$$

Derivation of cell model parameters

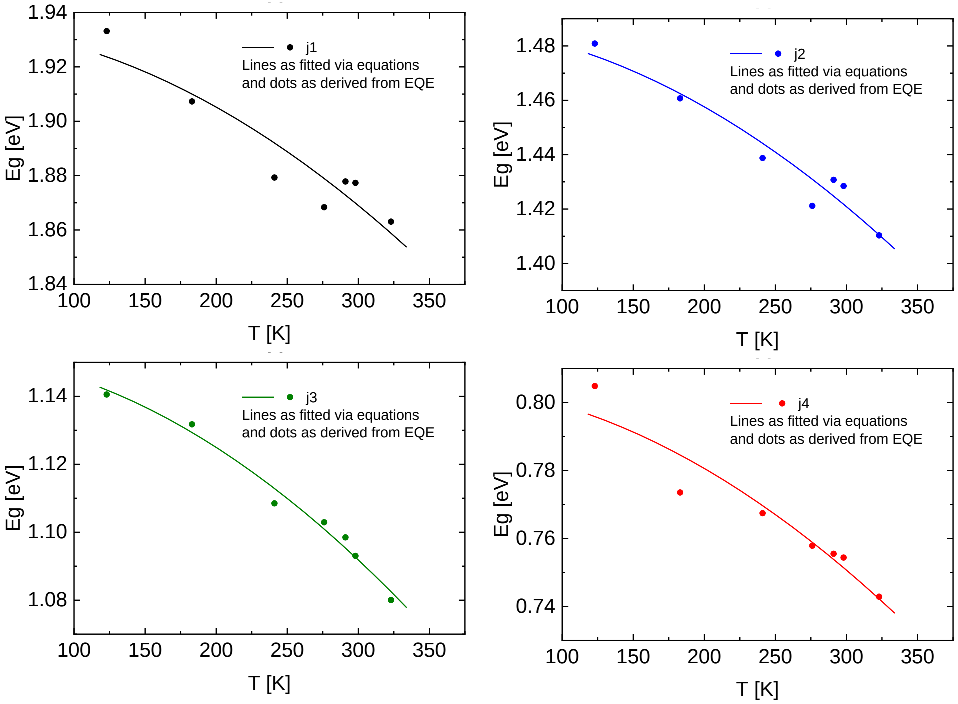
The necessary subcell band gaps are derived from 4J EQE measurements at different temperatures:





Derivation of cell model parameters

Using these bandgaps and fitting parameters a, b and c:

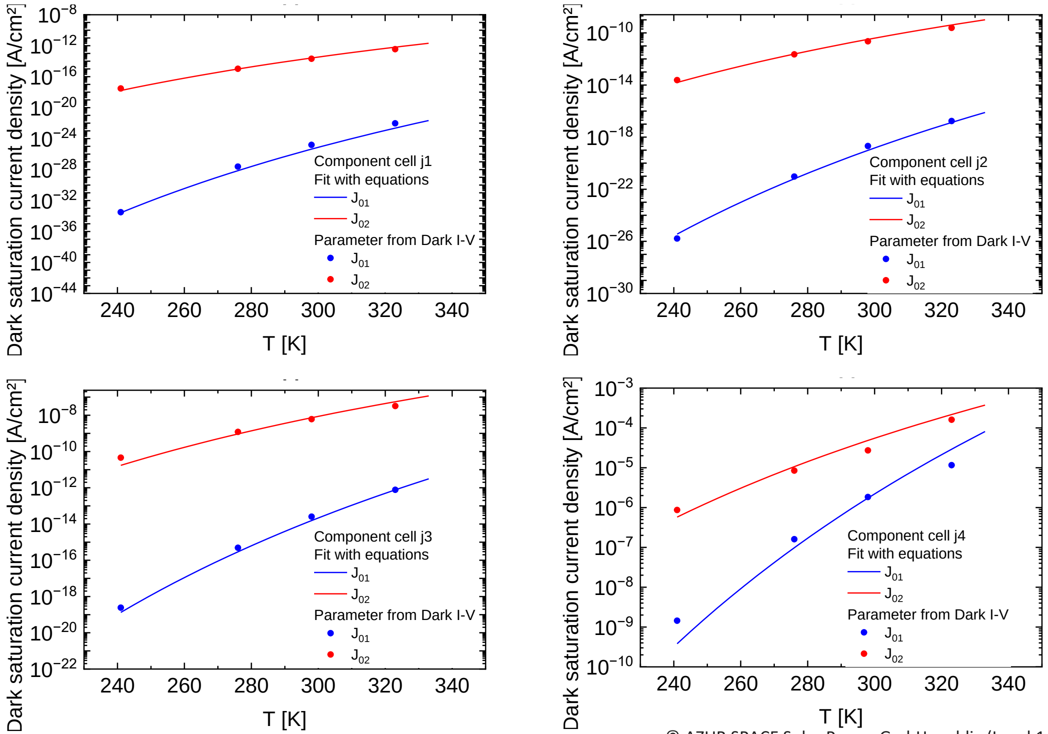


Sub cell	a	b	c	Eg@298K
[-]	[eV]	[eV/K]	[K]	[eV]
j1	1.9352	3.99E-03	5125	1.87
j2	1.488	4.03E-03	5104	1.42
j3	1.1524	3.60E-03	5049	1.09
j4	0.8054	3.19E-03	4945	0.75

$$Eg(T) = a - b \cdot (T)^2/(T + c) \quad (3)$$

Derivation of cell model parameters

With J_{01}, J_{02} (T) it is now possible to fit the 2-diode model for the individual subcells.



Sub cell	A01	B01	A02	J01	J02
[-]	[A/cm²/K³]	[1/eV]	[A/cm²/K$^{2.5}$]	[A/cm²]	[A/cm²]
j1	4.84E-03	1.42	1.10E-04	4.34E-26	2.60E-14
j2	1.70E-03	0.609	2.19E-05	9.65E-20	3.19E-11
j3	1.10E-03	0.433	8.29E-06	1.55E-14	7.33E-09
j4	1.55E-01	1.017	7.13E-05	1.73E-06	4.84E-05

(J_{01}, J_{02} here calculated for 298 K)

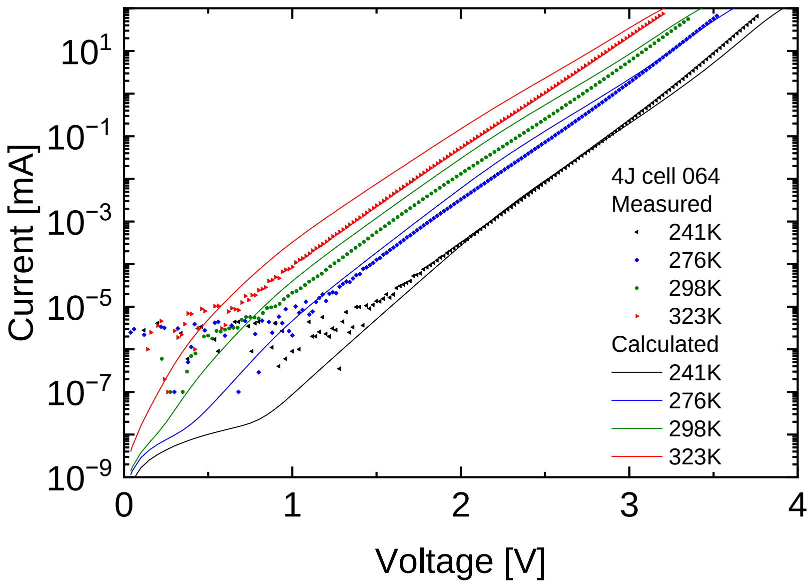
$$J_{01}(T) = A_{01} \cdot \exp\left(B_{01} \cdot E_g(T)\right) \cdot T^3 exp\left(-\frac{E_g(T)}{k_b T}\right) \quad (1)$$

$$J_{02}(T) = A_{02} \cdot T^{2.5} exp\left(-\frac{E_g(T)}{2 k_b T}\right) \quad (2)$$

Validation of cell model parameters

Validation of cell model parameters

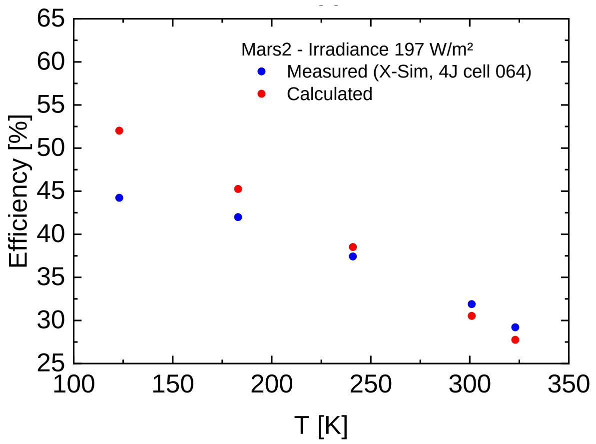
Validation of dark IV measurement: Measurement of cell 064 vs. calculation based on model.

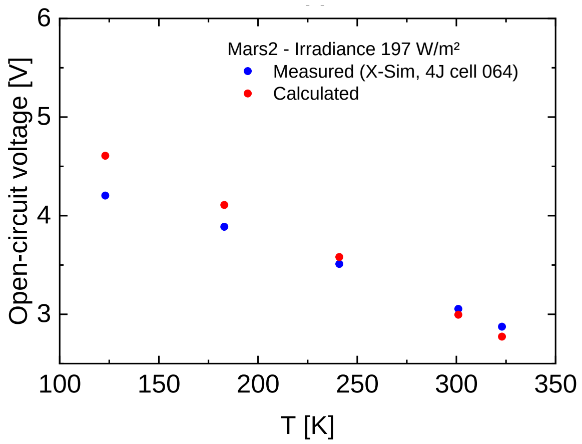


Validation of cell model parameters

Validation of light IV measurement: Measurement of cell 064 vs. calculation based on model.

Effiency and V_{oc} over temperature range.



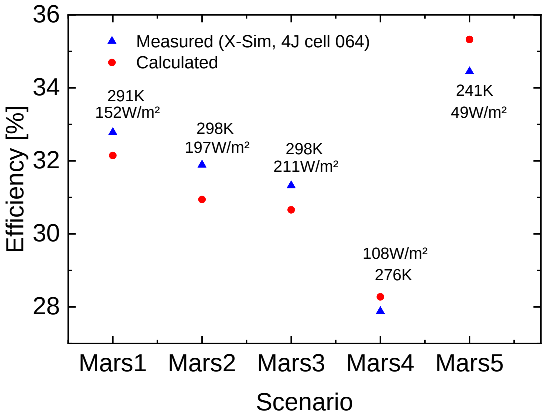


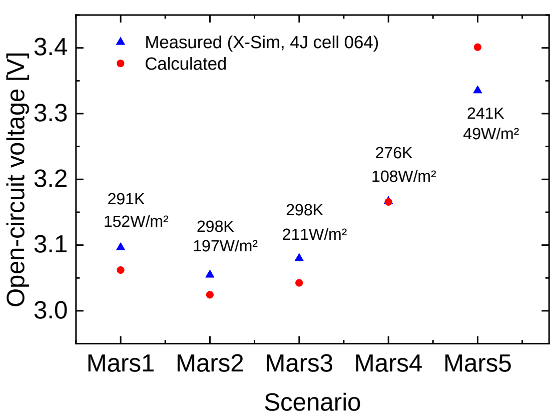
Note: The calculation is based on J_{01} and J_{02} values derived from the equations (1) and (2). Both equations use fit parameters derived in the temperature range between 241 K and 323 K. For this reason, the fit parameters are to be reliably used in this range only.

Validation of cell model parameters

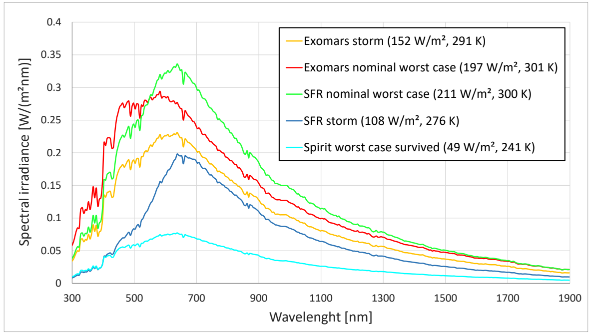
Validation of light IV measurement: Measurement of cell 064 vs. calculation based on model.

Effiency and V_{oc} for the five proposed Martin scenarios:





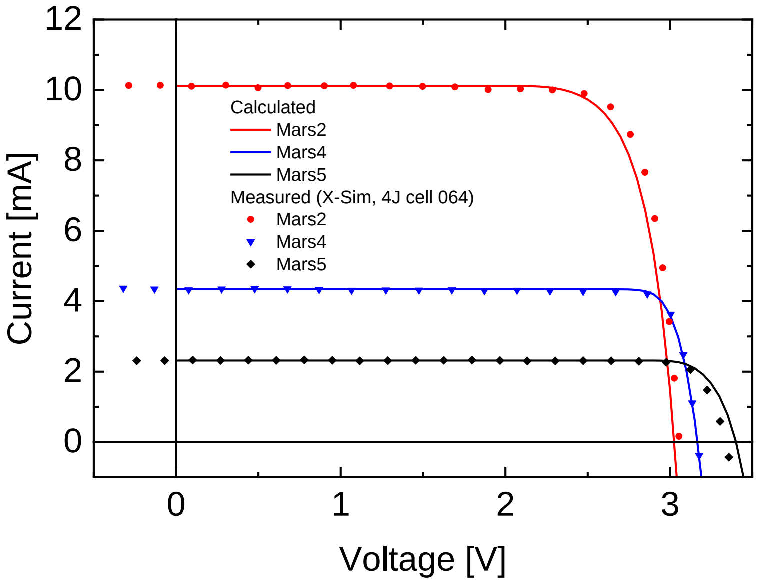
Scenario	I_{SC}	V_{OC}	FF	Eta
[-]	[$\%_{rel.}$]	[$\%_{rel.}$]	[$\%_{rel.}$]	[$\%_{rel.}$]
Mars1	0.00	1.12	0.84	1.97
Mars2	0.00	1.00	2.04	3.06
Mars3	0.00	1.23	0.92	2.16
Mars4	0.00	0.03	-1.44	-1.41
Mars5	0.00	-1.94	-0.56	-2.49

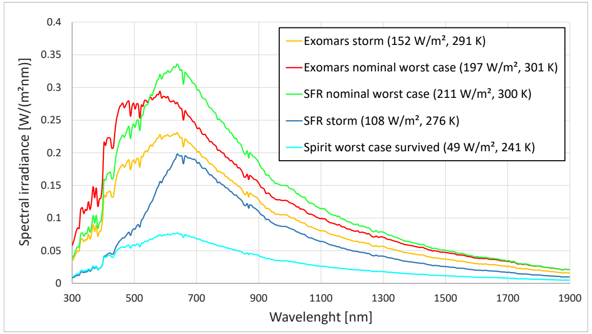


Validation of cell model parameters

Validation of light IV measurement: Measurement of cell 064 vs. calculation based on model.

IV curve comparison for three different scenarios:





Summary

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Summary

- Objective was to develop a solar cell with 10 %+ relative efficiency compared to 3G30 solar cell.
- 3G30 reference cell has an average efficiency of 27.26 % under “Exomars nominal worst case”.
- 4G32adv cell was adapted and optimized with an efficiency of 31.83 % , which is 16.76 % more.
- Component solar cells were manufactured and characterized by Fraunhofer ISE to gain access to two-diode model parameters. These parameters were then used to create a simulation model which was verified by further measurements.
- The model can be used to predict the power for different scenarios in the future, based on spectral conditions and temperature.

Thank you very much for your attention!

Are there any questions?

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