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Direct analysis of *JV*-curves applied to an outdoor-degrading CdTe module

February 26, 2014 | C. Ulbrich[1], S. Kurtz[2], D. Jordan[2], A. Gerber[1], U. Rau[1]

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Motivation

Measured *JV* curves of outdoor exposed modules hold accessible information on module efficiency and its degradation.

Yet, the dependence on irradiance, temperature and the resistances complicates the analysis. Note that these dependencies might change with outdoor exposure.

We take a critical look at the information in *JV* curves and extract a minimum parameter set that we test for its physical meaning.

Approach – Applying the KH formalism[1]

3 step process:

1) Individual *JV*-curves (raw data) are **determine**d by 4 independent **parameters**.

2) **Analyze** the **dependence** of the parameters on T_{meas}, ϕ_{meas}.

3) **Reconstruct** *JV*-curves **at** chosen **reference conditions**, analyze parameters and degradation.

1) Determine 4 parameters

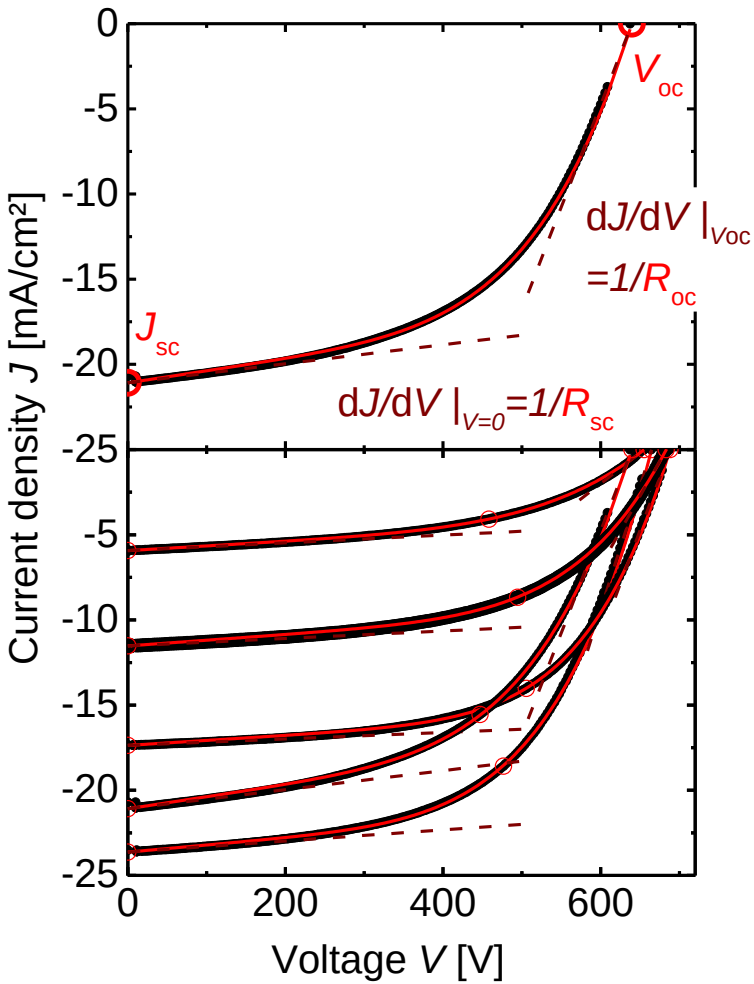
Phenomenological equation[1] is fitted to the measured data

$$J(V) = J_{sc}\left[(1-\gamma)\frac{V}{V_{oc}} + \gamma\left(\frac{V}{V_{oc}}\right)^{m} - 1\right]$$

where

$$\gamma = 1 - 1/R_{sc}\frac{V_{oc}}{J_{sc}}$$

$$m = \frac{V_{oc}\left(1/R_{oc} - 1/R_{sc}\right)}{J_{sc} - V_{oc}/R_{sc}} \quad .$$

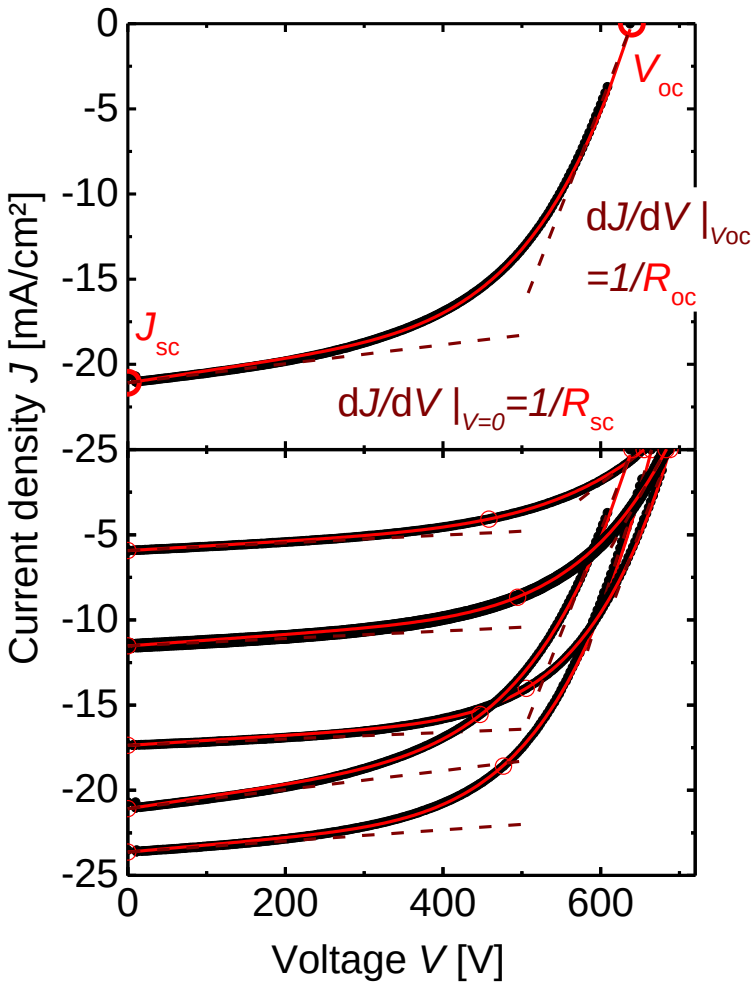


1) Determine 4 parameters

Phenomenological equation is fitted to the measured data

$$J(V) = J_{sc}\left[(1-\gamma)\frac{V}{V_{oc}} + \gamma\left(\frac{V}{V_{oc}}\right)^{m} - 1\right].$$

The equation by itself has no physical meaning but various, more complex, physically motivated solar cell models are compatible with it[2].

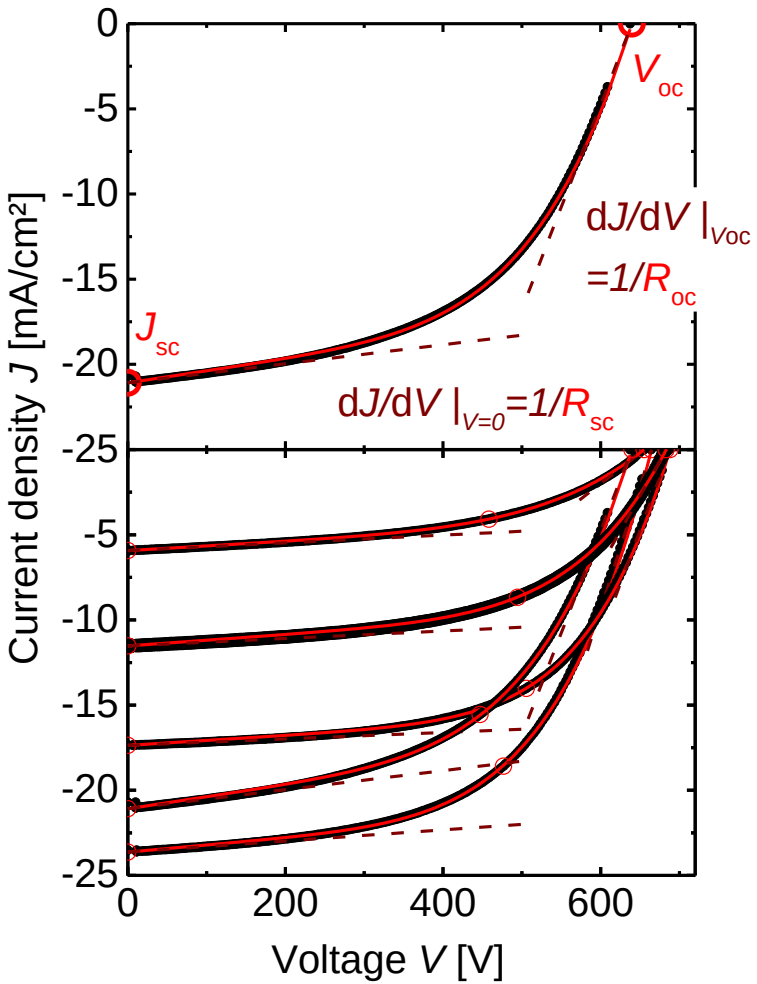


1) Determine 4 parameters

The four parameters

- short circuit current J_{sc}
- open circuit voltage V_{oc}
- differential resistance R_{sc}
- differential resistance R_{oc}

are physically meaningful.



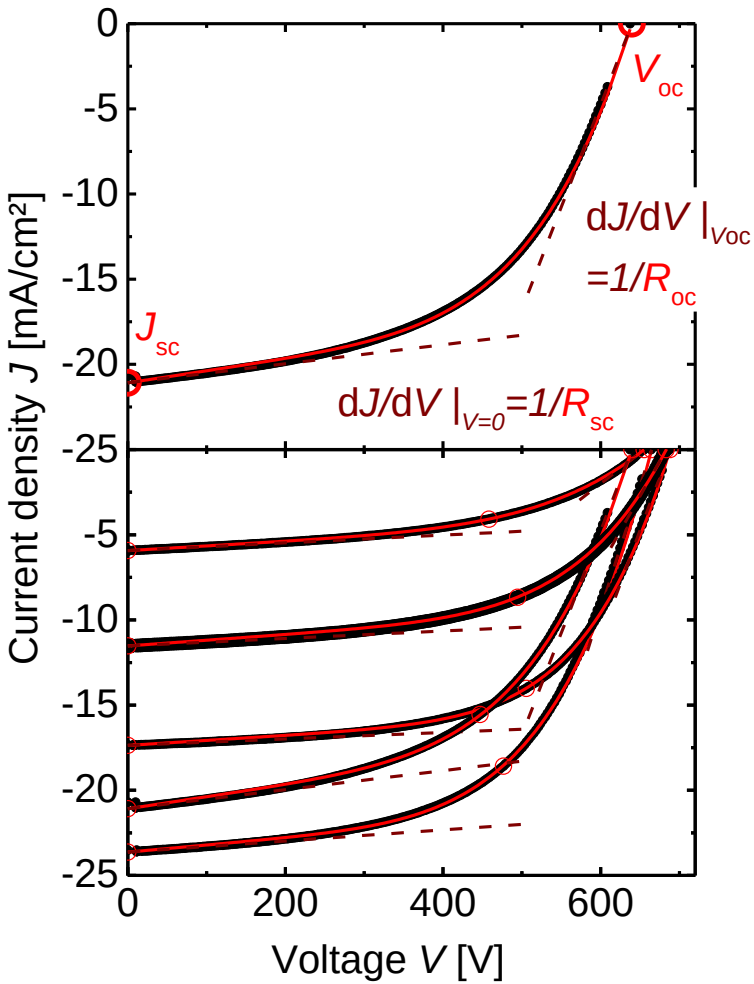
1) Determine 4 parameters

The four parameters

- short circuit current J_{sc}
- open circuit voltage V_{oc}
- differential resistance R_{sc}
- differential resistance R_{oc}

are physically meaningful.

The equation fits the *JV* curves reliably in all irradiance ranges and at all stages of degradation.



2) Analyze T_{meas}, ϕ_{meas} dependence

Parameter: J_{sc}

Assumed dependence: $J_{sc}(\phi_{meas}, T_{meas}) = \{\alpha_{Jsc} T_{meas} + \kappa_{Jsc}\}\phi_{meas}$

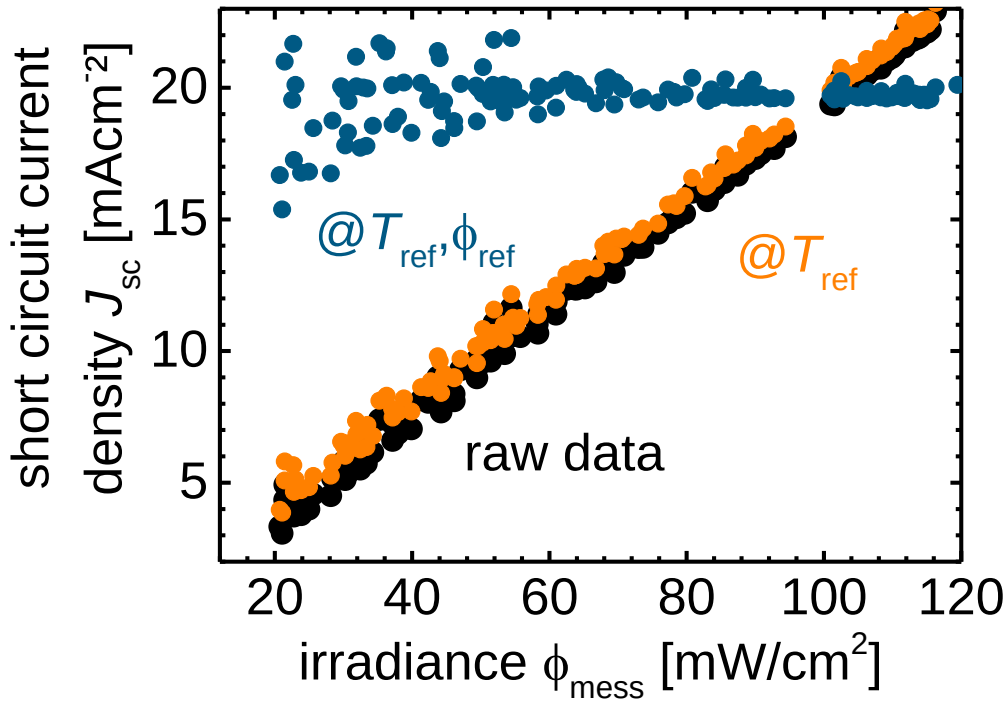
Value at reference conditions: $J_{sc@ref} = J_{sc}(\phi_{ref}, T_{ref}) = \{\alpha_{Jsc} T_{ref} + \kappa_{Jsc}\}\phi_{ref}$

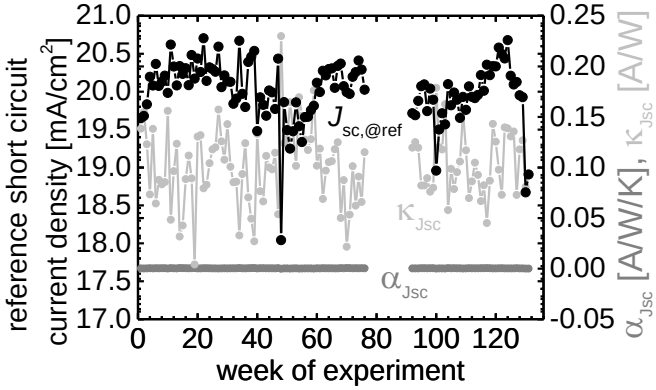
Translation of raw data: $J_{sc,meas@ref} = \{\alpha_{Jsc}(T_{ref} - T_{meas})\}\phi_{ref} + J_{sc}(\phi_{ref} / \phi_{meas})$

2) Analyse T_{meas}, ϕ_{meas} dependence

Exemplary parameter: J_{sc}

Assumed dependence: $J_{sc}(\phi_{meas}, T_{meas}) = \{\alpha_{Jsc} T_{meas} + \kappa_{Jsc}\}\phi_{meas}$



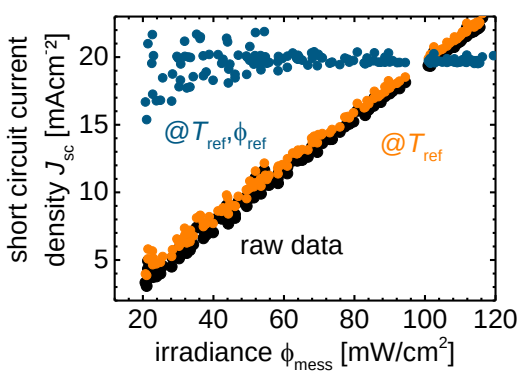


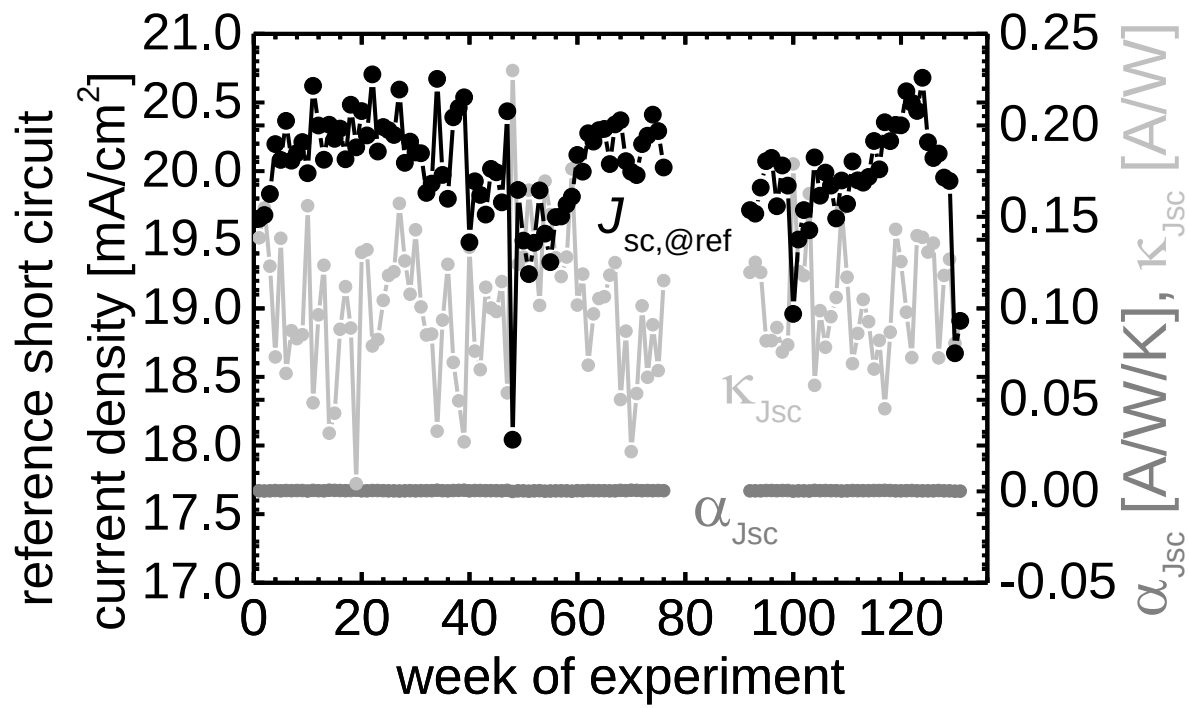
data from 1 week

2) Analyse T_{meas}, ϕ_{meas} dependence

Exemplary parameter: J_{sc}

Assumed dependence: $J_{sc}(\phi_{meas}, T_{meas}) = \{\alpha_{Jsc} T_{meas} + \kappa_{Jsc}\}\phi_{meas}$





data from 2.5 years

Approach – Applying the KH formalism

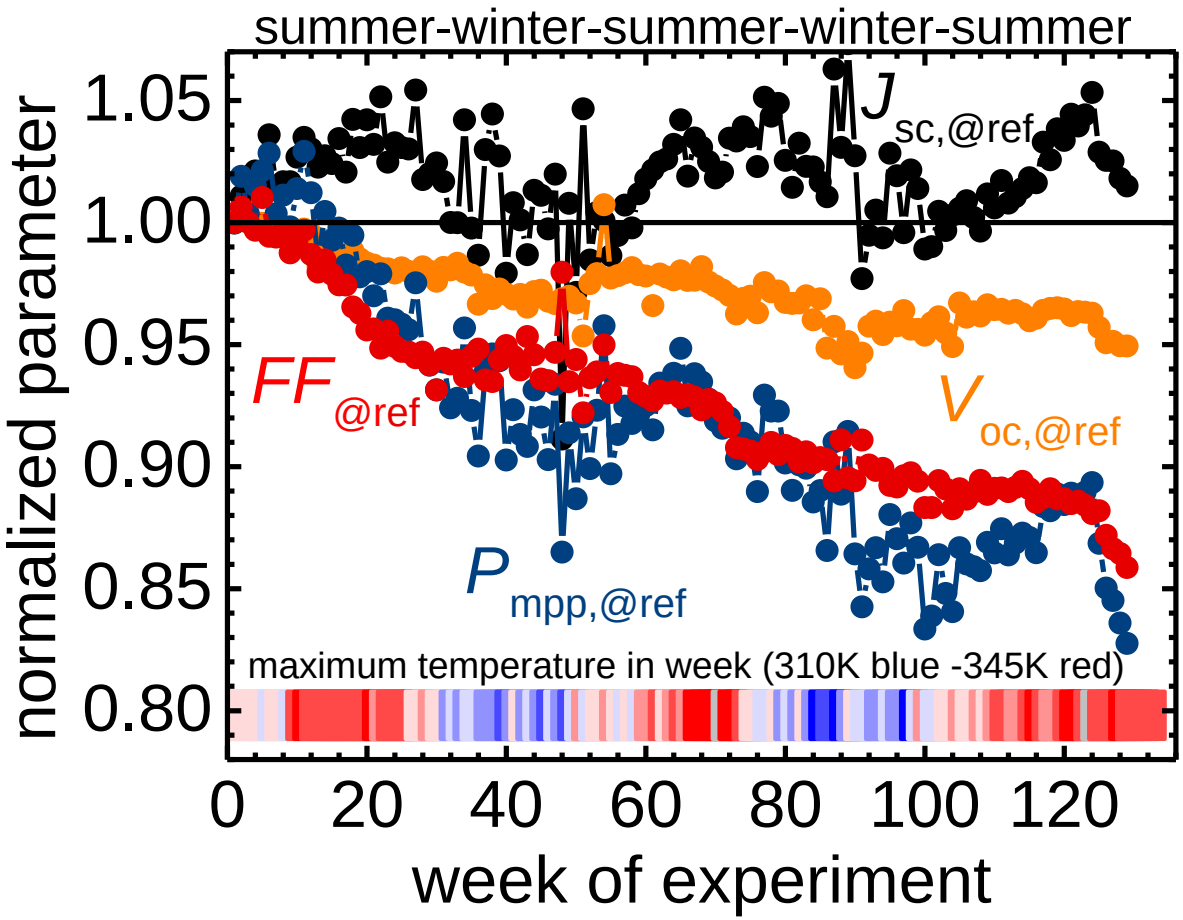
3 step process:

1) Determined individual *JV*-curve parameters.

2) Analyzed T_{meas}, ϕ_{meas} dependence
(Analysis of V_{oc}, R_{sc}, R_{oc} follows)

3) Reconstruct *JV*-curves at chosen reference conditions

3) Reconstruct at reference conditions



Findings

Analyses of V_{oc}, R_{sc}, and, R_{oc} hint at voltage dependent charge carrier collection in CdTe (has been observed before [3])

→ Let‘s go back to step 2)

2) Analyze T_{meas}, ϕ_{meas} dependence

Parameter: V_{oc}

Assumed dependence:

$$V_{oc}(J_{sc,meas}, T_{meas}) = V_{oc}^{0} - \{\alpha_{Voc} - \varepsilon_{Voc} \log(J_{sc,meas})\} T_{meas}$$

standard diode equation of an illuminated solar cell [4]:

$$V_{OC} = E_a / q - \{nk / q \log(J_{00}) + nk / q \log(J_{SC})\} T$$

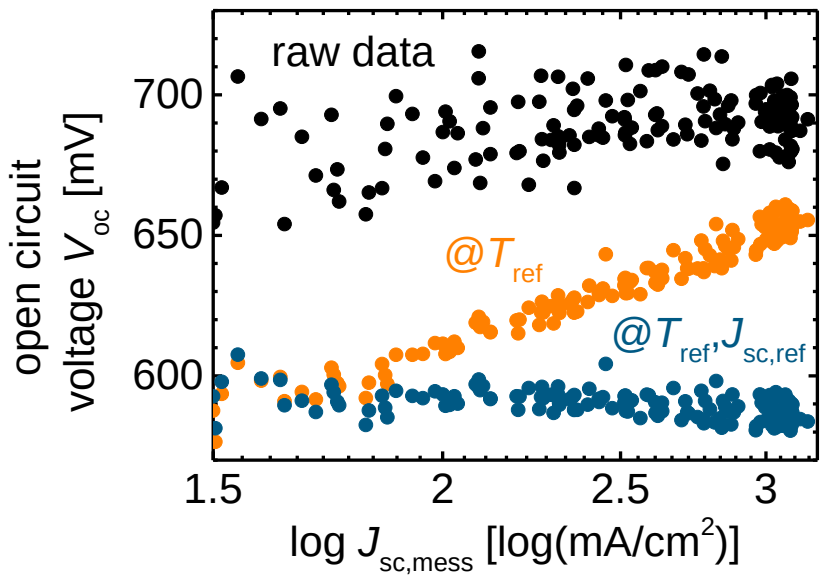
ε_{Voc} ➔ n

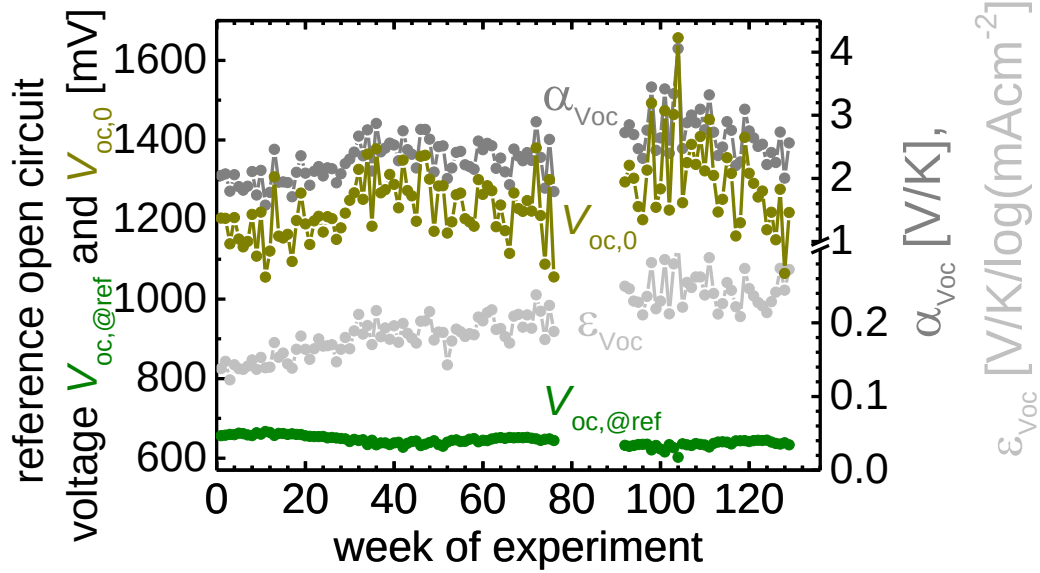
2) Analyze T_{meas}, ϕ_{meas} dependence

Parameter: V_{oc}

Assumed dependence:

$$V_{oc}(J_{sc,meas}, T_{meas}) = V_{oc}^{0} - \{\alpha_{Voc} - \varepsilon_{Voc}\log(J_{sc,meas})\}T_{meas}$$





data from 1 week

data from 2.5 years

2) Analyze T_{meas}, ϕ_{meas} dependence

Parameter: R_{oc}

Assumed dependence:

$$R_{oc}(J_{sc,meas}, T_{meas}) = R_s + \beta_{Roc} T_{meas} / J_{sc,meas}$$

Werner plot[5] equation

$$R_{oc} = R_S + \frac{nkT}{q} \frac{1}{J_{sc,meas}}$$

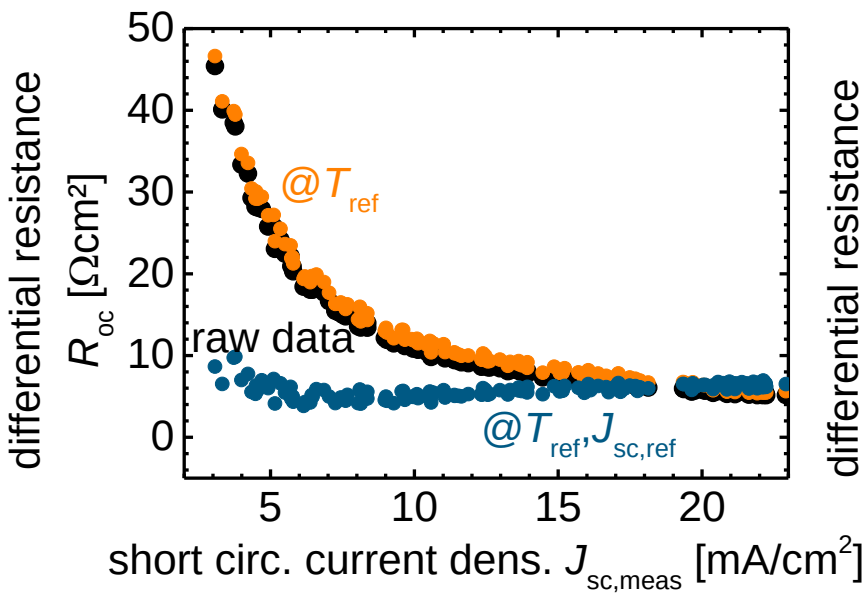
β_{Voc} ➔ n

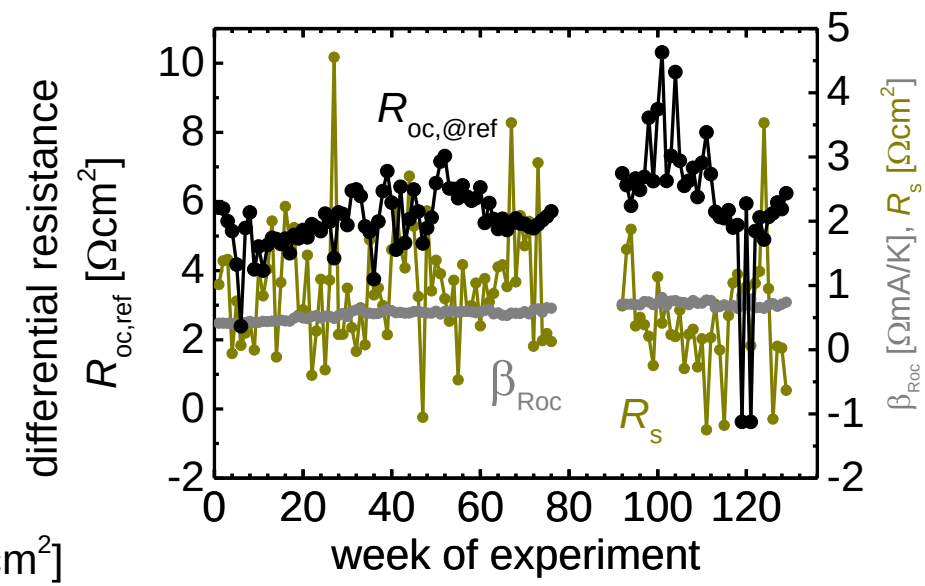
2) Analyze T_{meas}, ϕ_{meas} dependence

Parameter: R_{oc}

Assumed dependence:

$$R_{oc}(J_{sc,meas}, T_{meas}) = R_s + \beta_{Roc} T_{meas} / J_{sc,meas}$$





data from 1 week

data from 2.5 years

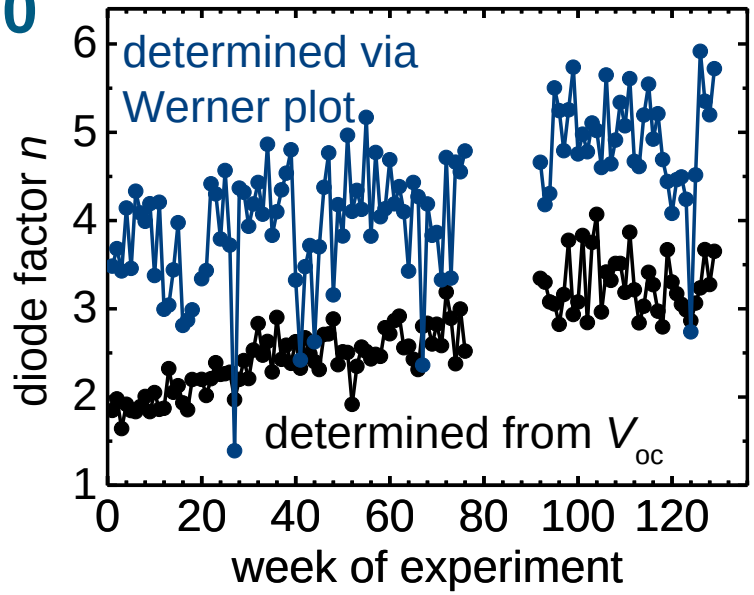
Findings

Diode factor *n* determined from Werner plot[5] **assuming dJ_{sc}/dV=0**

$$R_{oc} = \frac{nkT}{q}\frac{1}{J_{sc,meas}} + R_S$$

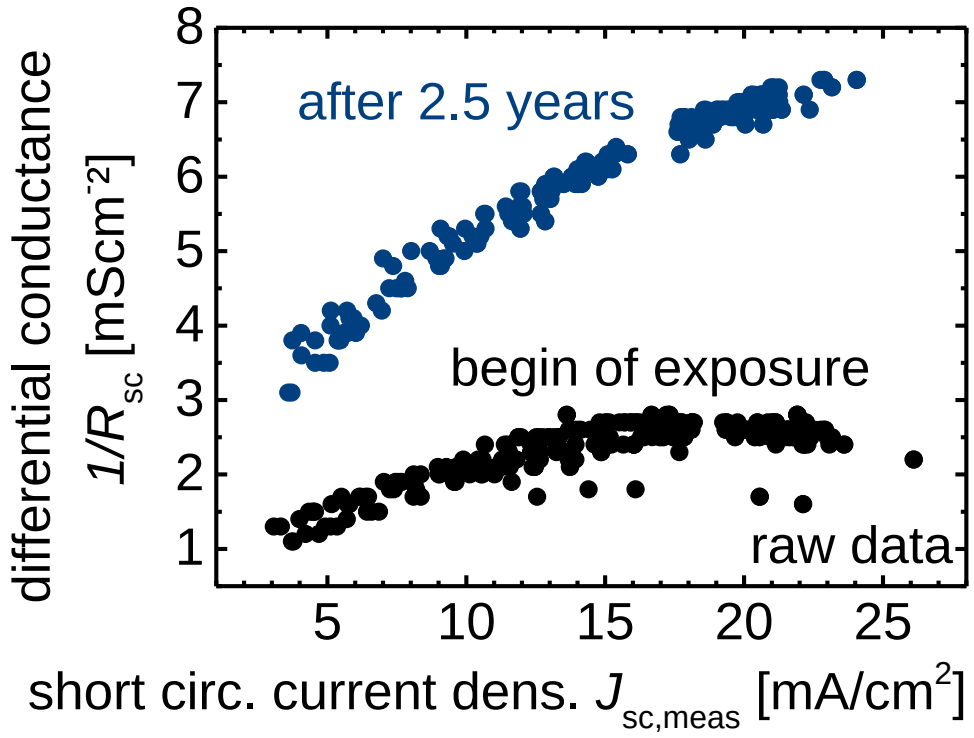
differs from value determined from V_{oc}

$$V_{OC} = E_a / q - nkT / q \log(J_{00}) + nkT / q \log(J_{SC})$$



Findings

R_{sc} raw data hint at a change in voltage dependent charge carrier collection in CdTe over time



Summary and Outlook

Advantages of the Karmalkar-Haneefa formalism

- Only 4 parameters
- Physically meaningful
- Comparison across technologies, interpretation for specific technology and module
- Especially significant in analysis of solar modules with non-negligible resistances
- Easy calculation of effect of losses in energy yield

Thanks

- To the colleagues in Juelich and at the NREL
- To you

Questions and suggestions are very welcome

References:

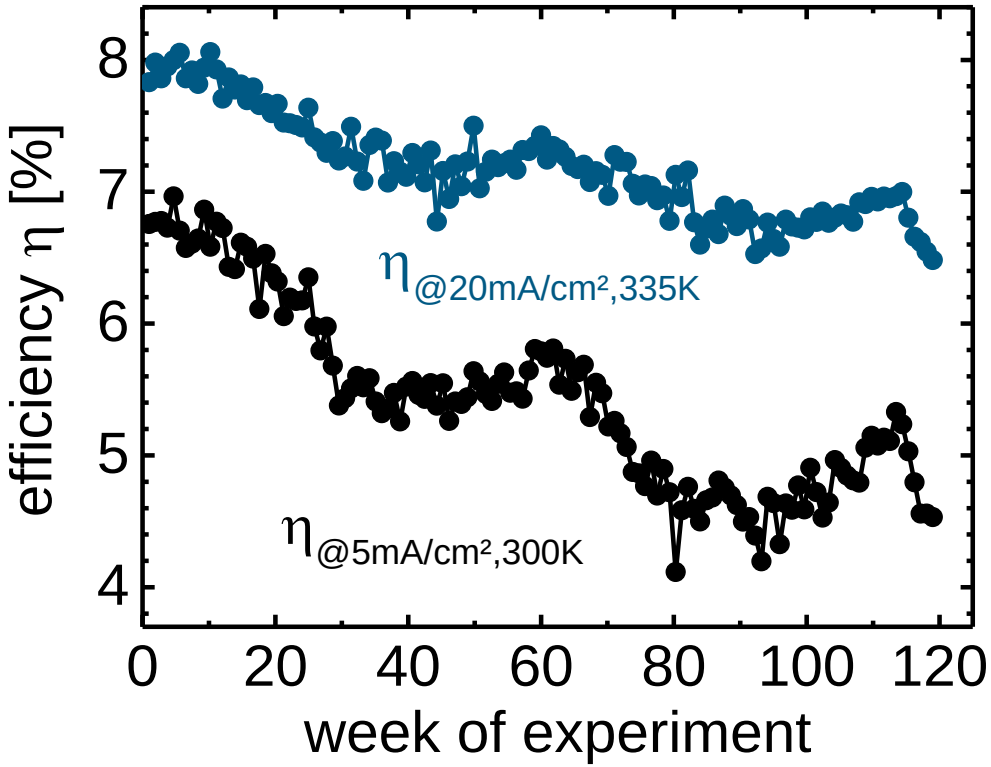
[1] S. Karmalkar, S. Haneefa, “A physically based explicit J–V model of a solar cell for simple design calculations,” *IEEE Electron Device Letters*, vol. 29, pp. 449-451, 2008.

[2] A. K. Das, S. Karmalkar, “Analytical derivation of the closed-form power law J–V model of an illuminated solar cell from the physics based implicit model,” *IEEE Transactions on Electron Devices*, vol. 58, pp. 1176-1181, 2011.

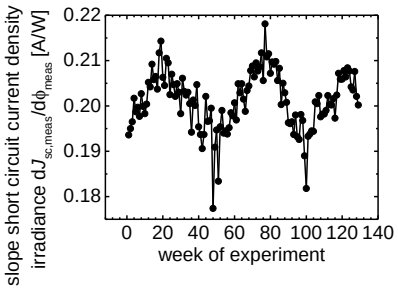
[3] S. Hegedus, D. Desai, C. Thompson, “Voltage dependent photocurrent collection in CdTe/CdS solar cells,” *Prog. Photovolt.: Res. Applic.* 15, 587–602, 2007.

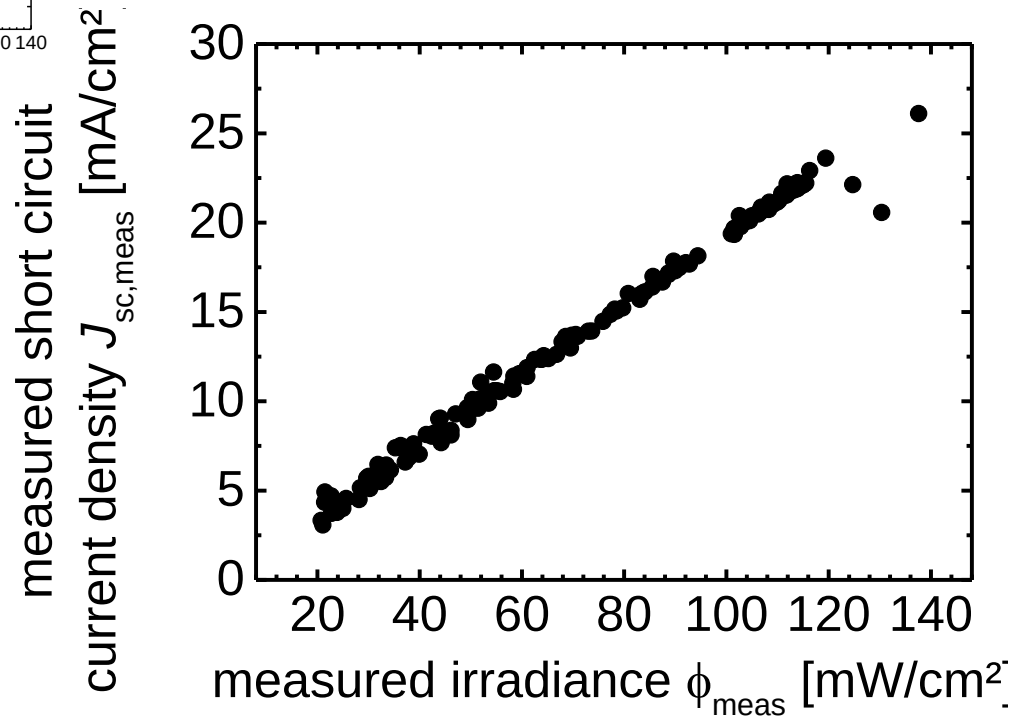
[4] J. Nelson, *The physics of solar cells*, London, Imperial College Press, 2003.

[5] J. H. Werner,. ”Schottky barrier and pn-junction I/V plots- small signal evaluation,” *Applied Physics A*, vol. 47, pp. 291-300, 1988.



Taking into account the differential resistances, we find a stronger degradation of the efficiency $\eta_{@ref}$ for low irradiance intensity/short circuit current density conditions.



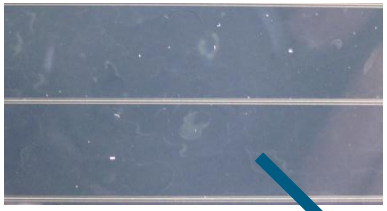


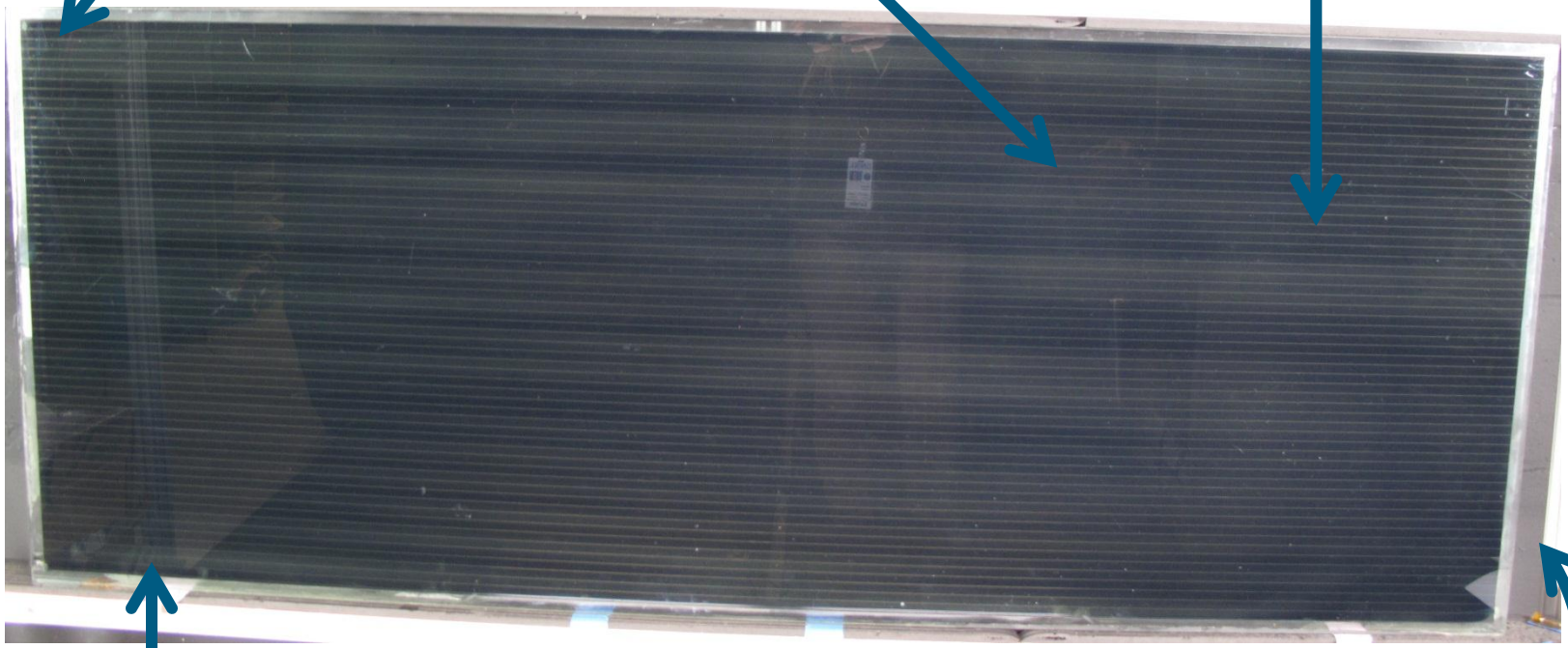
The substitution of irradiance ϕ_{meas} by $J_{sc,meas}$ when calculating the irradiance dependence of the three parameters V_{oc}, R_{sc} and R_{oc} is justified by the linear relation between $J_{sc,meas}$ and ϕ_{meas}.

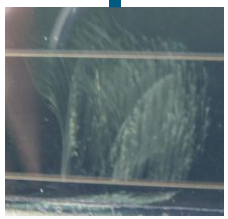
Possible origin of degradation

- Corrosion at junction box (at hot and humid days)
- Ion movement (temperature)
- Applied bias – not temperature
- Bias and temperature combined

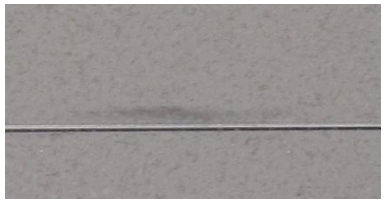
Visual inspection of module



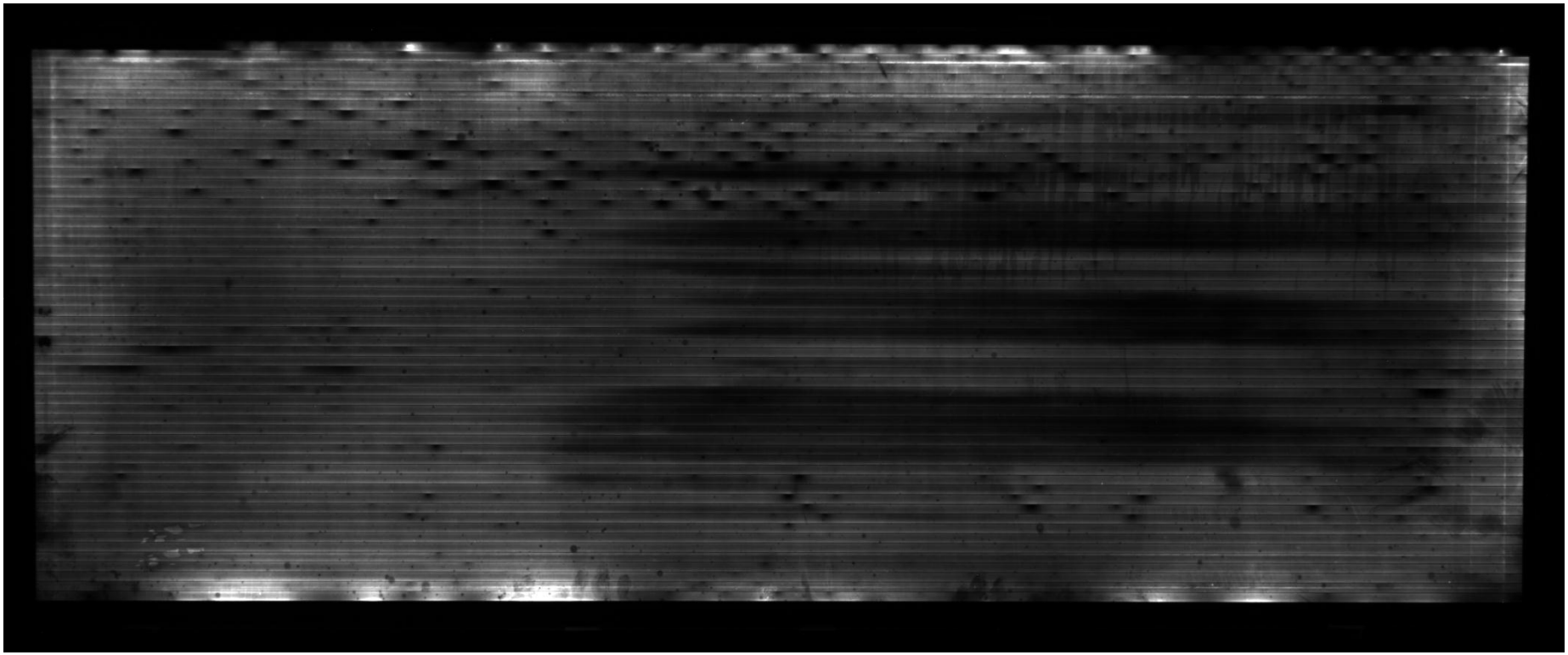




Corrosion of junction box?



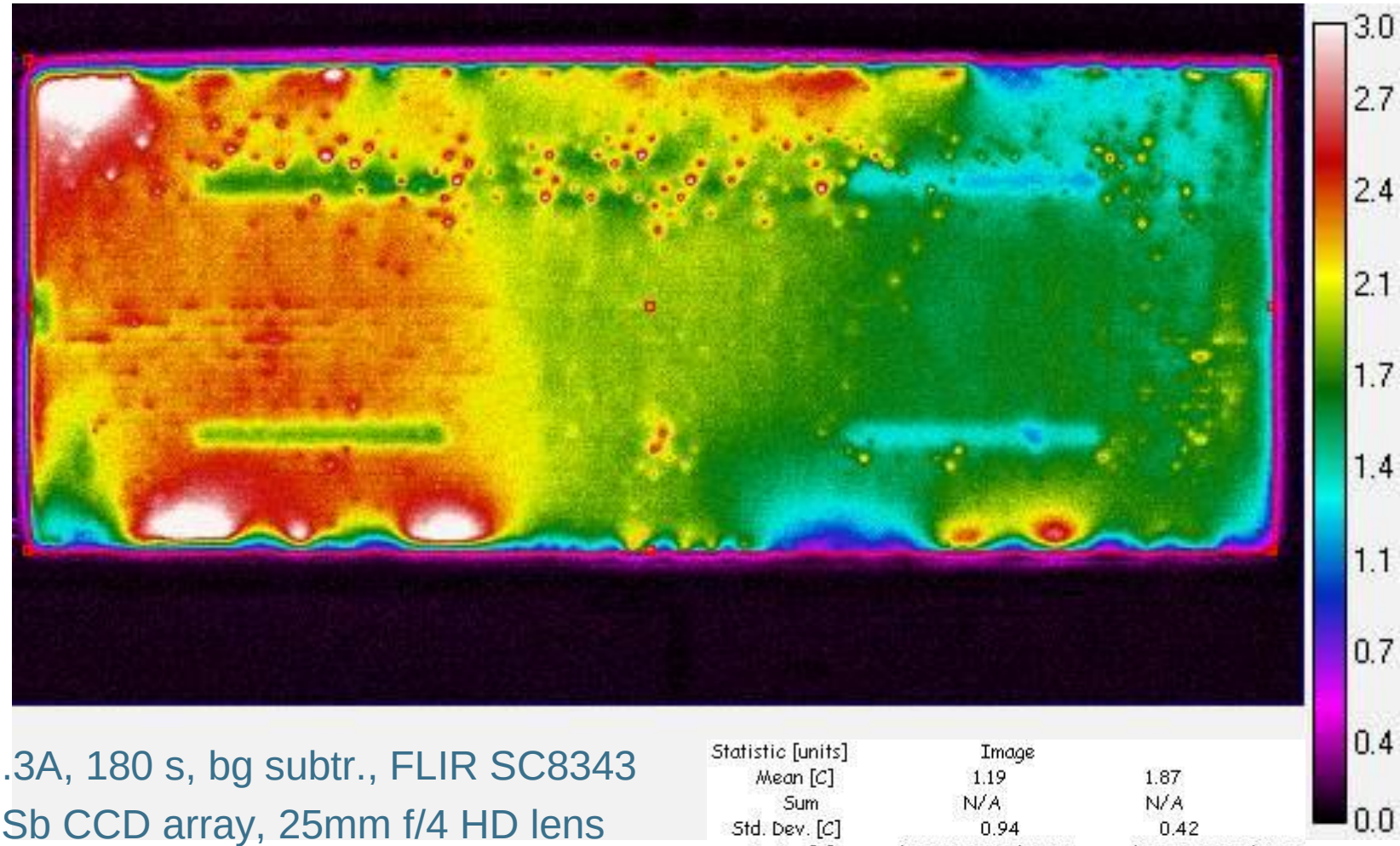
Electroluminescence



54615mV, 2997 mA applied, 1.28min

Si-CCD 16Mpixel (4095x4095) with Zeiss 72mm IR lens, 1.4/85 zoom, no filter

IR image



Statistic [units]	Image	
Mean [C]	1.19	1.87
Sum	N/A	N/A
Std. Dev. [C]	0.94	0.42
Center [C]	(639.5, 359.5) 1.85	(645.0, 333.0) 1.88
Maximum [C]	(93, 126) 3.91	(93, 126) 3.91
Minimum [C]	(958, 697) -0.35	(44, 97) -0.02
Number of Pixels	921600	575225

55V, 4.3A, 180 s, bg subtr., FLIR SC8343 with InSb CCD array, 25mm f/4 HD lens

FLIR 23898-000-0033 cold filter 3-5um