Radiation hardness study using SiPMs with single-cell readout

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Radiation hardness of SiPM

- SiPM radiation damage is a major concern when operating in harsh radiation environment
- main effect – increase of dark current/dark count rate proportionally to fluence that leads to:
  - loss of single photoelectron resolution
  - decrease in response, which could be attributed to either:
    - decrease of gain (G)
    - decrease of photon detection efficiency (PDE)
    - SiPM self-heating effect due to high power dissipation (see talk C. Villalba)
- unclear which effect dominates or if all three are relevant

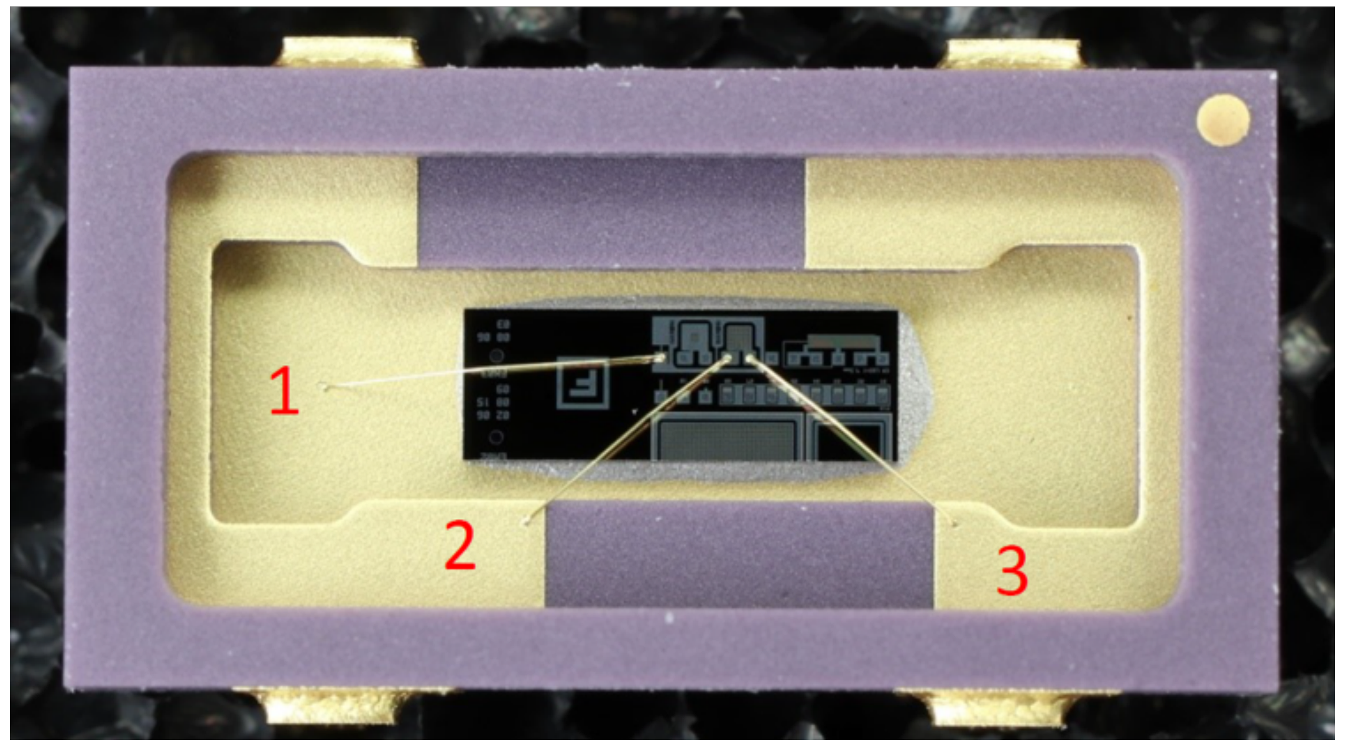
Solution:

- study separately the effects on the dedicated test structures
- gain and PDE of irradiated SiPM are best investigated on the test structure that enables the readout of one single-cell separately from the others in a SiPM

Hamamatsu S14160-15UM-SMPTS

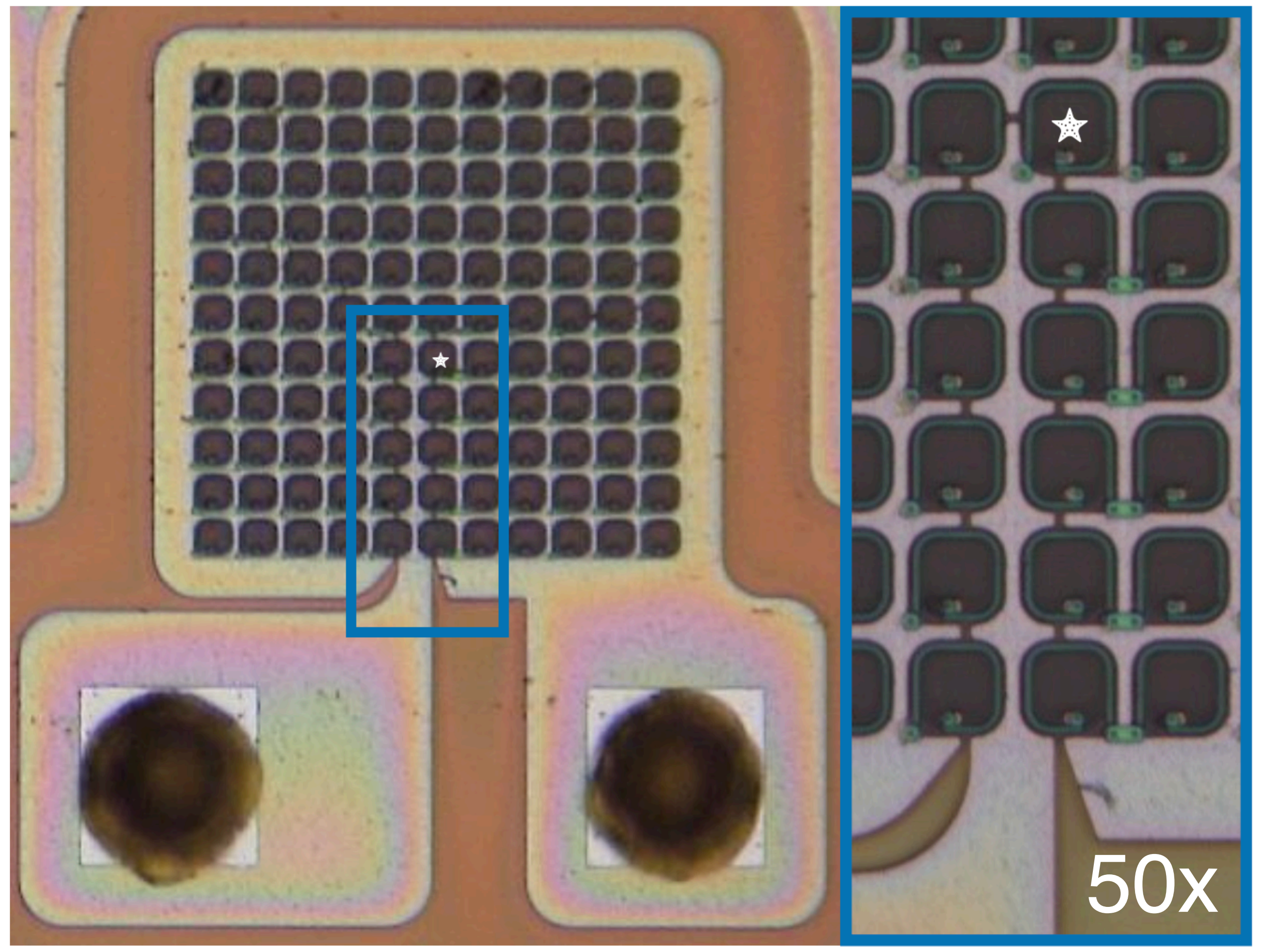
Device under test (DUT) – test structure Hamamatsu S14160-15UM-SMPTS in the ceramic package

- array of 11x11 cells with 15 um pitch
- one cell in the centre of array disconnected from the others
  - 1 – common cathode
  - 2 – anode of 1 cell
  - 3 – anode of 120 cells



Hamamatsu SiPM test structure of S14160 series

Test samples	
#	ϕ [cm^{-2}]
10, 11, 13	0E+00
5	2E+12
6	1E+13
7	5E+13



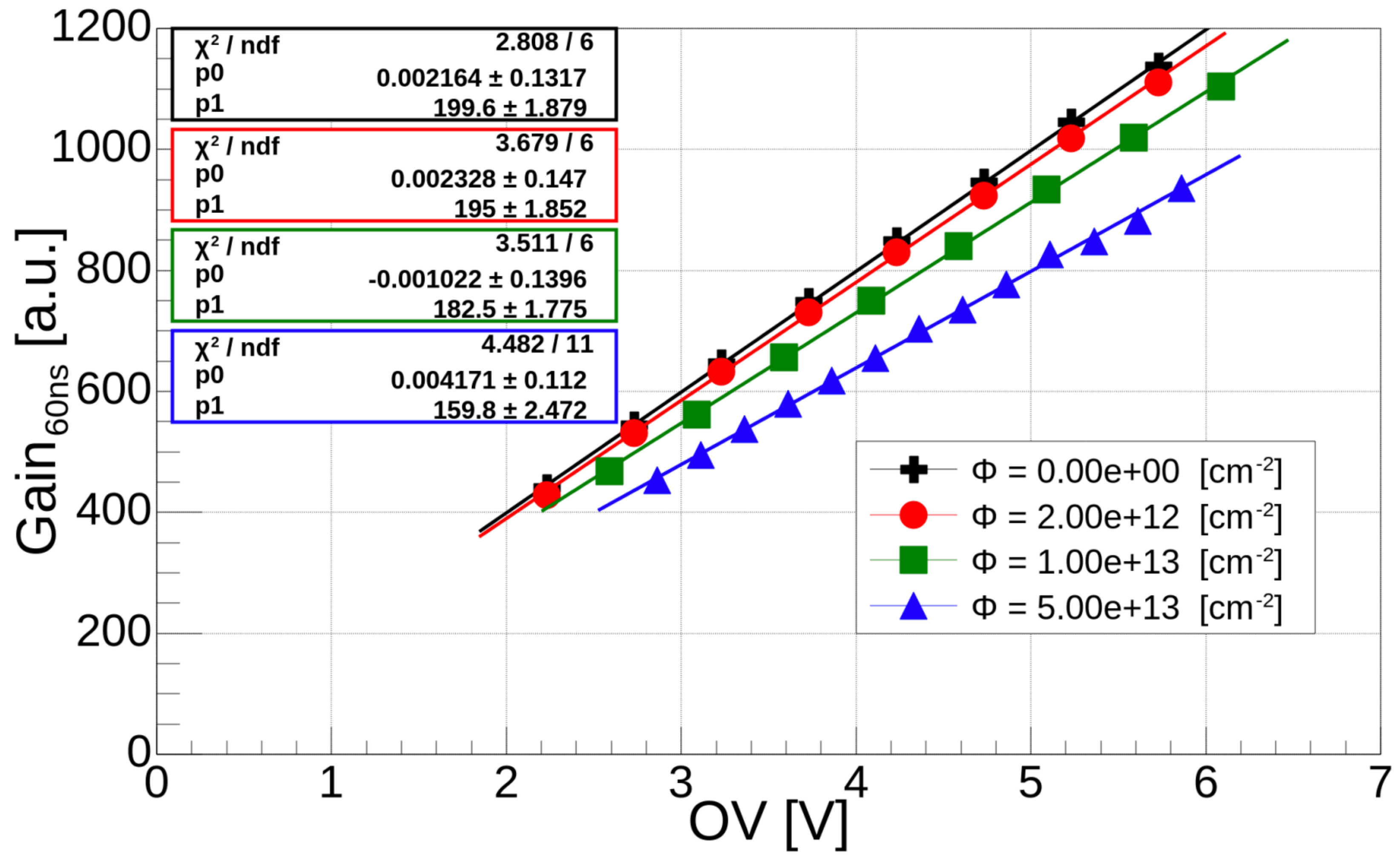
11x11-cell array; ☆ - disconnected cell

Motivation

First results of radiation hardness study using SiPMs with single-cell readout are presented in [1].

For fluence ϕ = 5e13 cm^{-2} we observed:

- gain reduction of 19%
- increase of V_{off} by ~0.5 V



Gain vs V_{ov} for the studied test structures [1]

Open questions:

- self-heating effect
- fluence dependence of the difference between V_{off} and V_{bd}^{IV}, where
  - $V_{off} = V_{bd}^{G}$ – breakdown voltage from G-measurements, so called turn-off voltage that indicates voltage at which Geiger discharge stops
  - V_{bd}^{IV} – breakdown voltage from IV-measurements
    - in this talk the overvoltage is $V_{ov} = V_{bias} - V_{bd}^{IV}$
- radiation damage uniformity of 1 cell and 120 cells

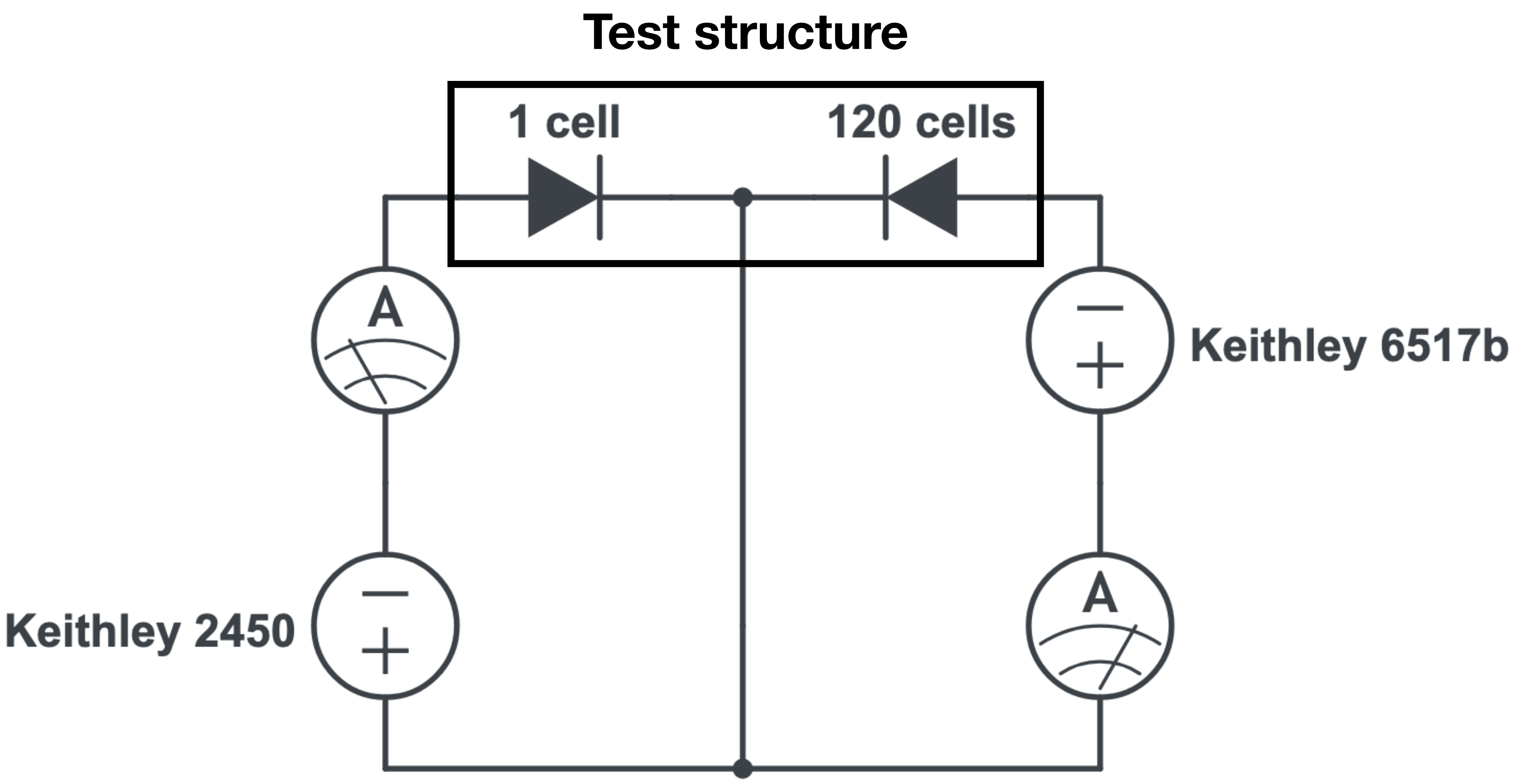
To address these questions IV-measurements were carried out on the same test structure.

[1] E.Garutti et al. Radiation hardness study using SiPMs with single-cell readout. (2021) arXiv:2111.00483

Bias and readout board

The dedicated board was produced:

- specially for IV-measurements
- with independent bias and readout for 1 cell and 120 cells
  - channels are identical



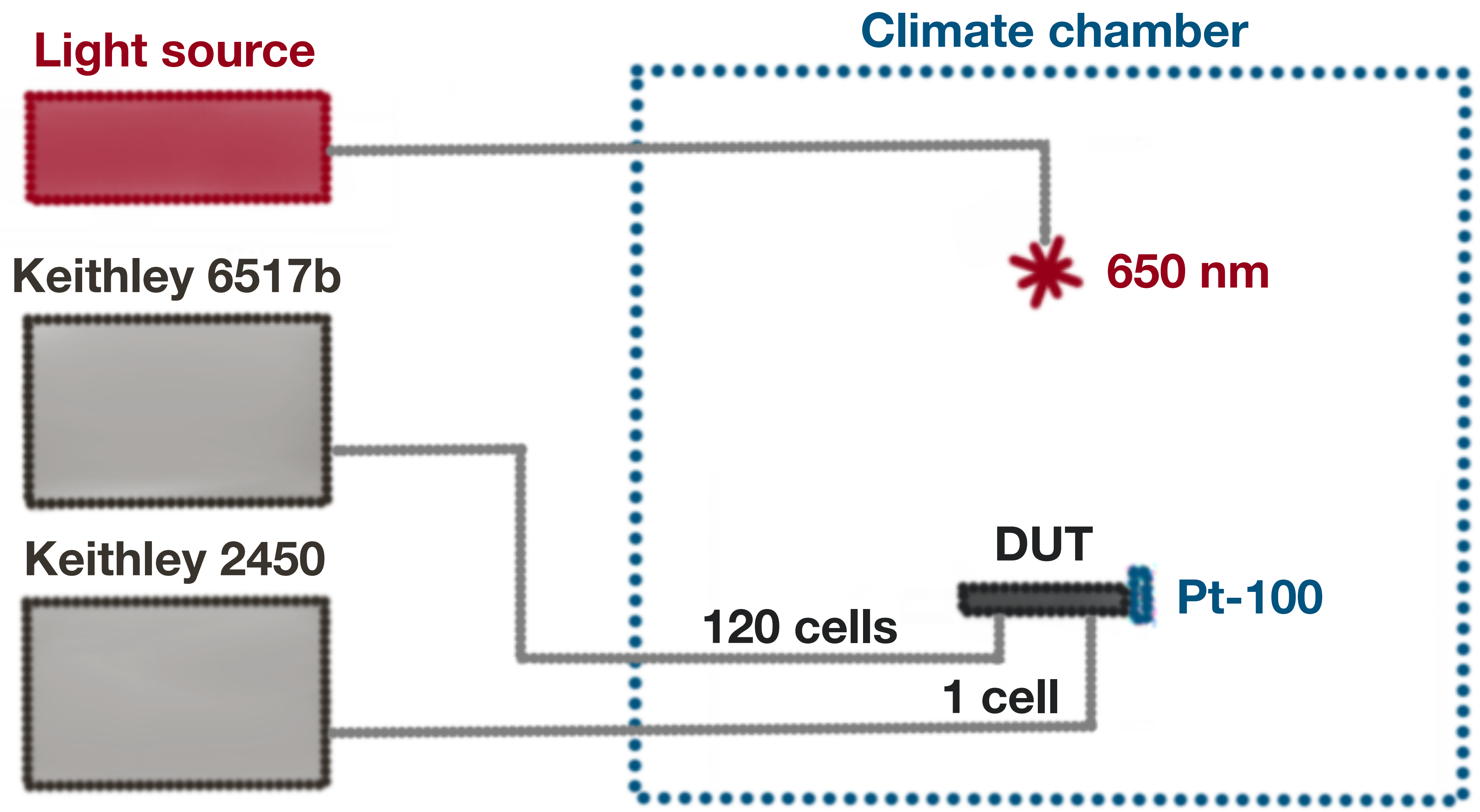
Circuit schematic

Experimental setup

Experimental setup for IV-measurements consists of:

- stabilised broadband light source SLS201L/M
- SourceMeters:
  - Keithley 2450 (for currents > 0.1 nA)*
  - Keithley 6517B (for currents > 1 nA)*
- climate chamber
  - at +20 °C ± 0.1 °C
  - at -30 °C ± 0.7 °C
- Pt100 attached to the side of ceramic package

*The setup has accuracy limitations on low current measurements.



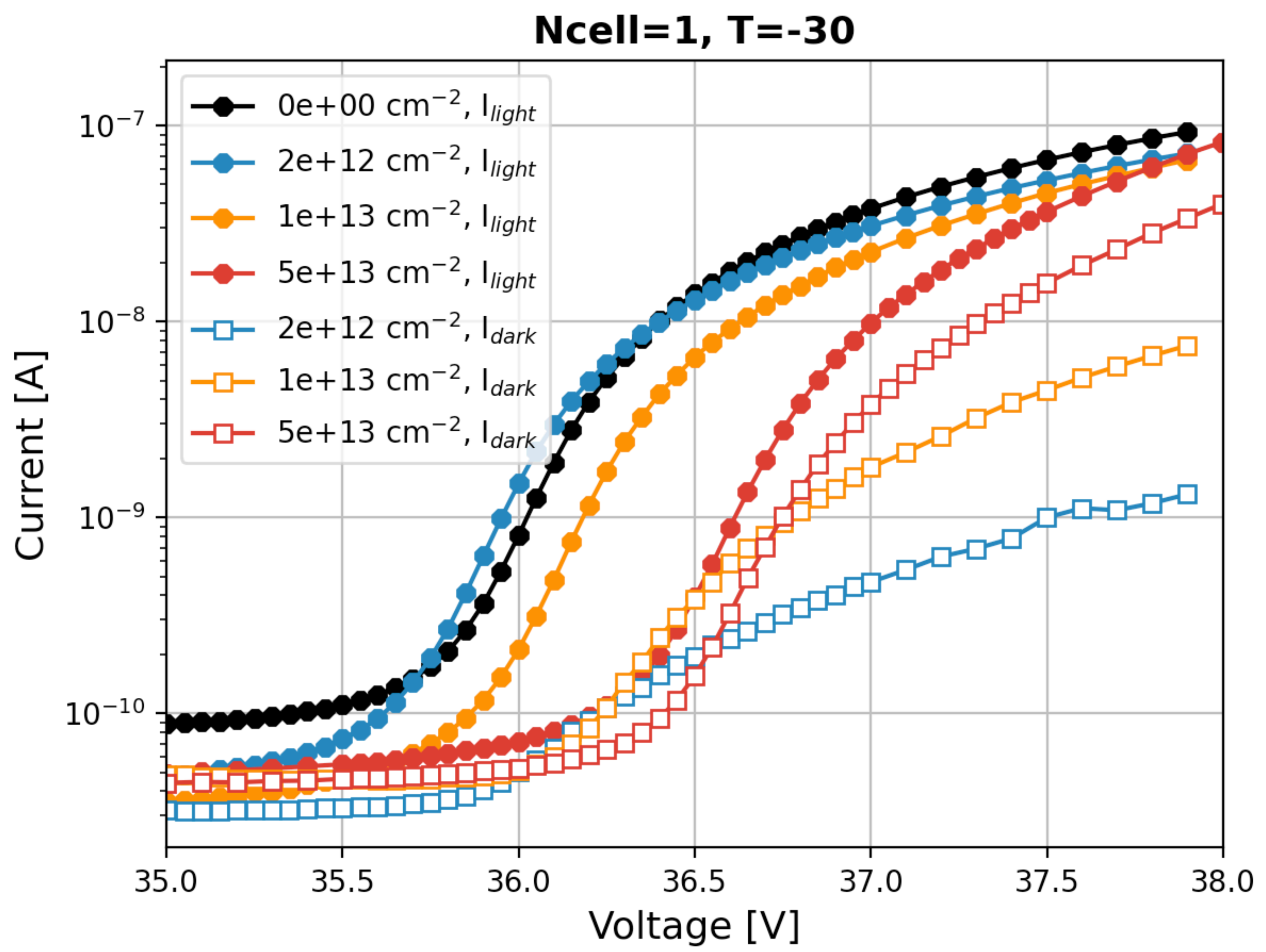
Schematic drawing of experimental setup

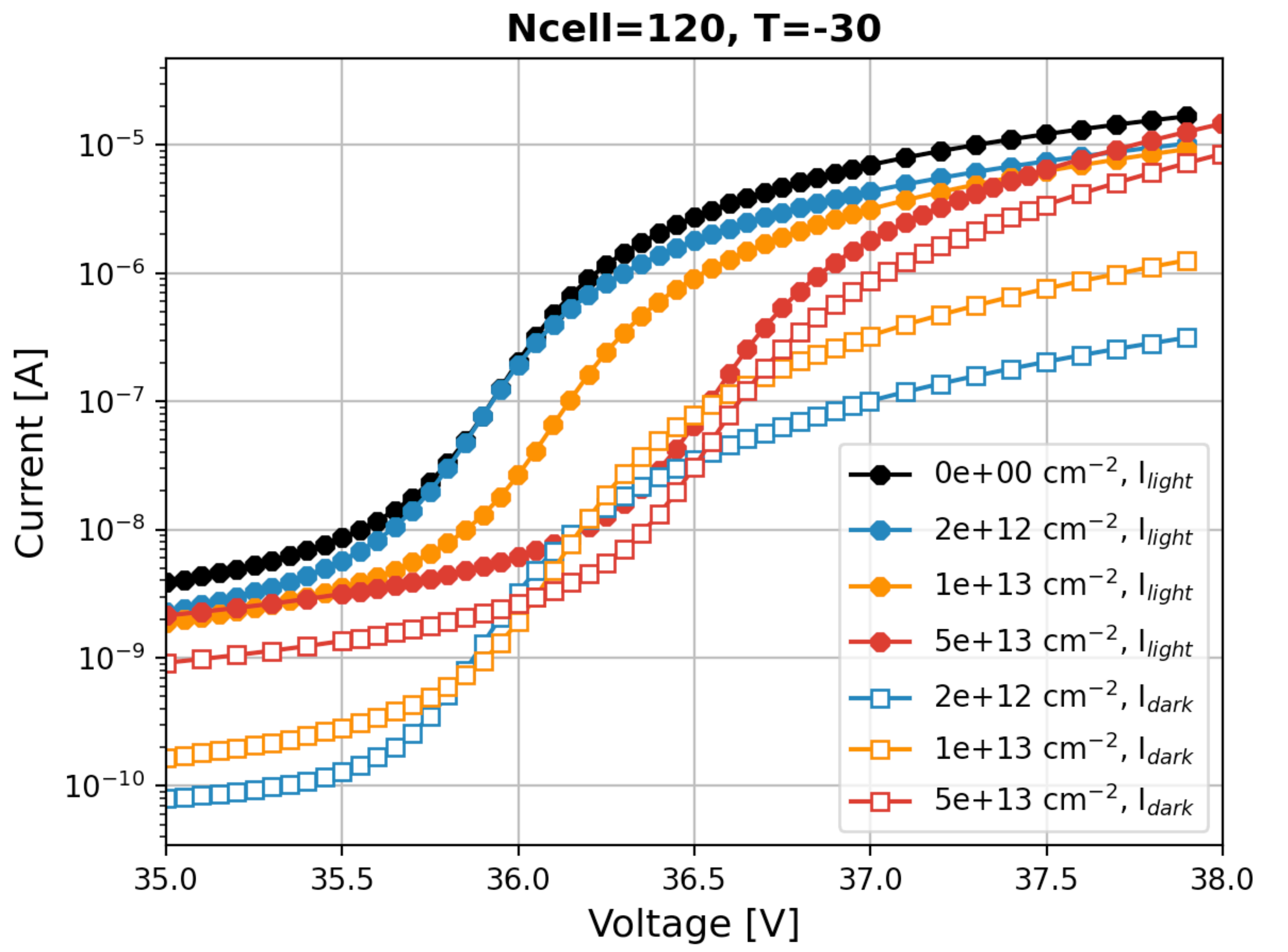
IV-measurements

Measurements of IV-curves for 1 cell and 120 cells:

- at temperature T = -30 °C
- with and without illumination
- in a voltage range V_{bd}^{IV} - 2V < V_{bias} < V_{bd}^{IV} + 2V

I_{dark} — dark current
I_{photo} — photocurrent
$I_{light} = I_{dark} + I_{photo}$ — light current

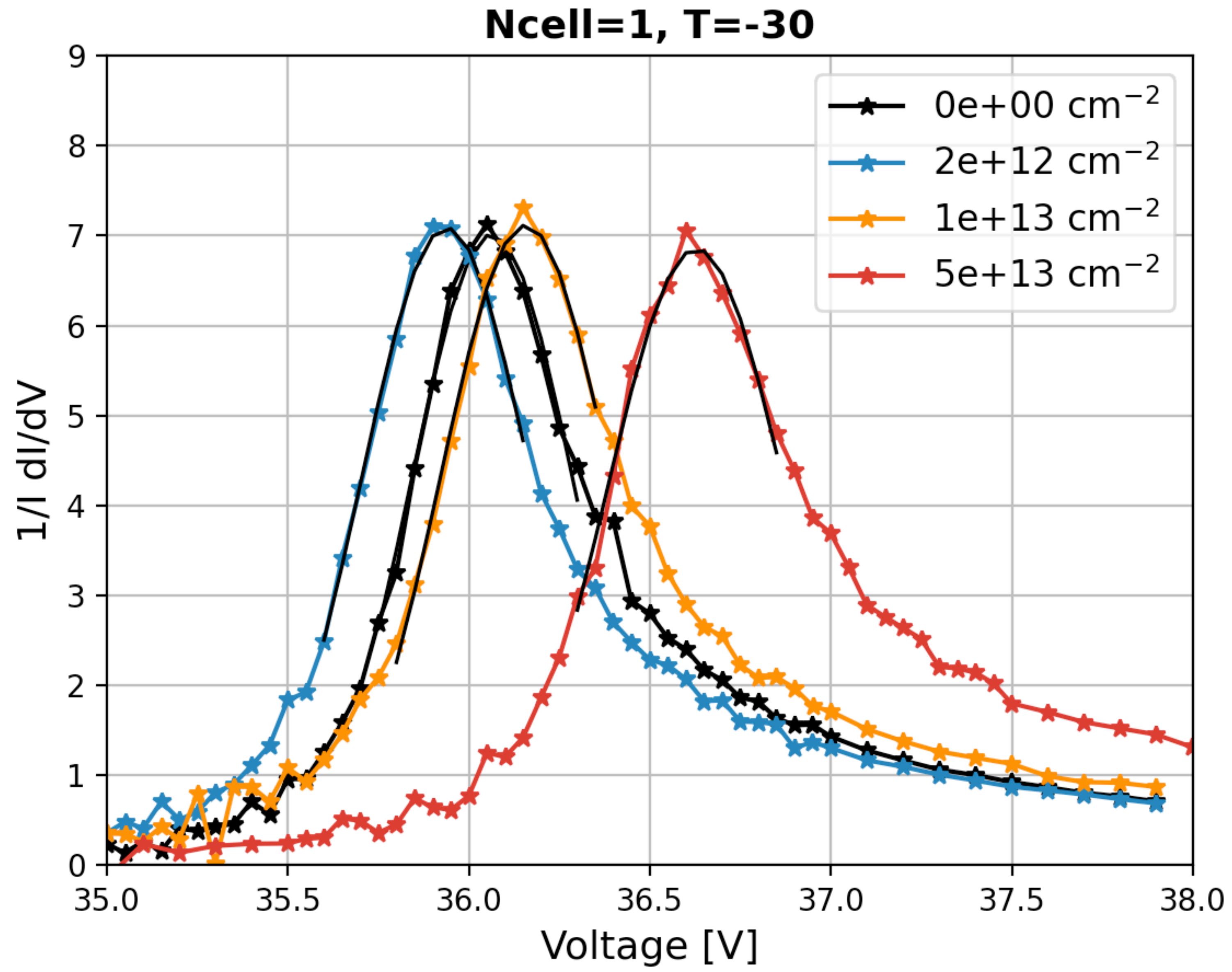


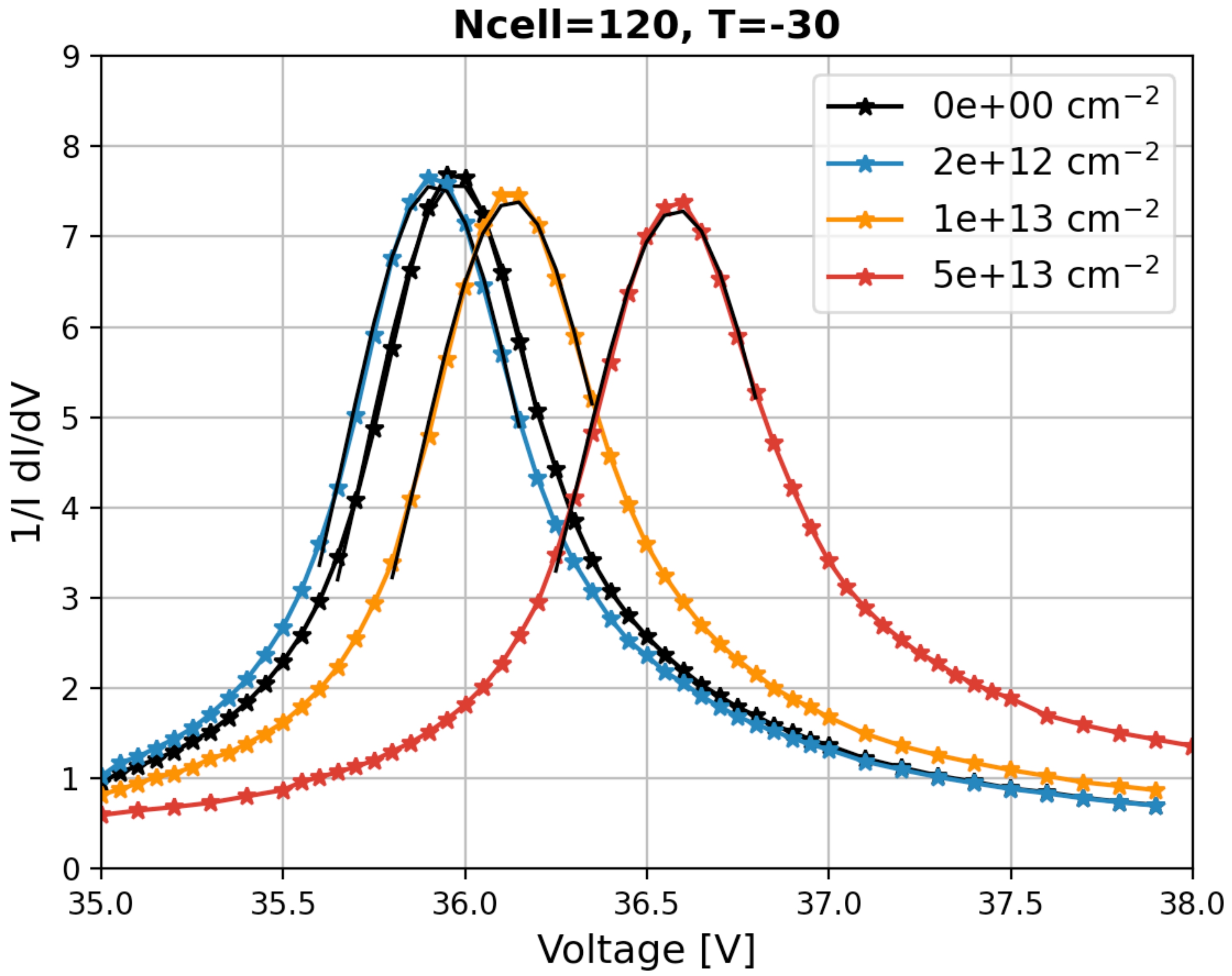


Breakdown voltage V_{bd}^{IV}

LD method [2] was used to determine breakdown voltage:

- as a maximum of logarithmic derivative $LD = \frac{1}{I} \cdot \frac{dI}{dV}$
- approximated with mean from Gauss fit





DUT	V^{IV}_{bd} [V] at -30C	
ϕ [cm^{-2}]	1 cell	120 cells
0E+00	35.98 ± 0.03	35.94 ± 0.03
2E+12	35.93 ± 0.02	35.91 ± 0.03
1E+13	36.16 ± 0.03	36.13 ± 0.03
5E+13	36.62 ± 0.02	36.58 ± 0.03

- V_{bd}^{IV} of 1 cell = V_{bd}^{IV} of 120 cells within the errors

[2] R. Klanner, Characterisation of SiPMs, Nucl. Instrum. Methods Phys. Res. A 926 (2019) 36–56

Self-heating effect

The highest heat power we observed in our study — P_{heat} = 1.9 mW for:

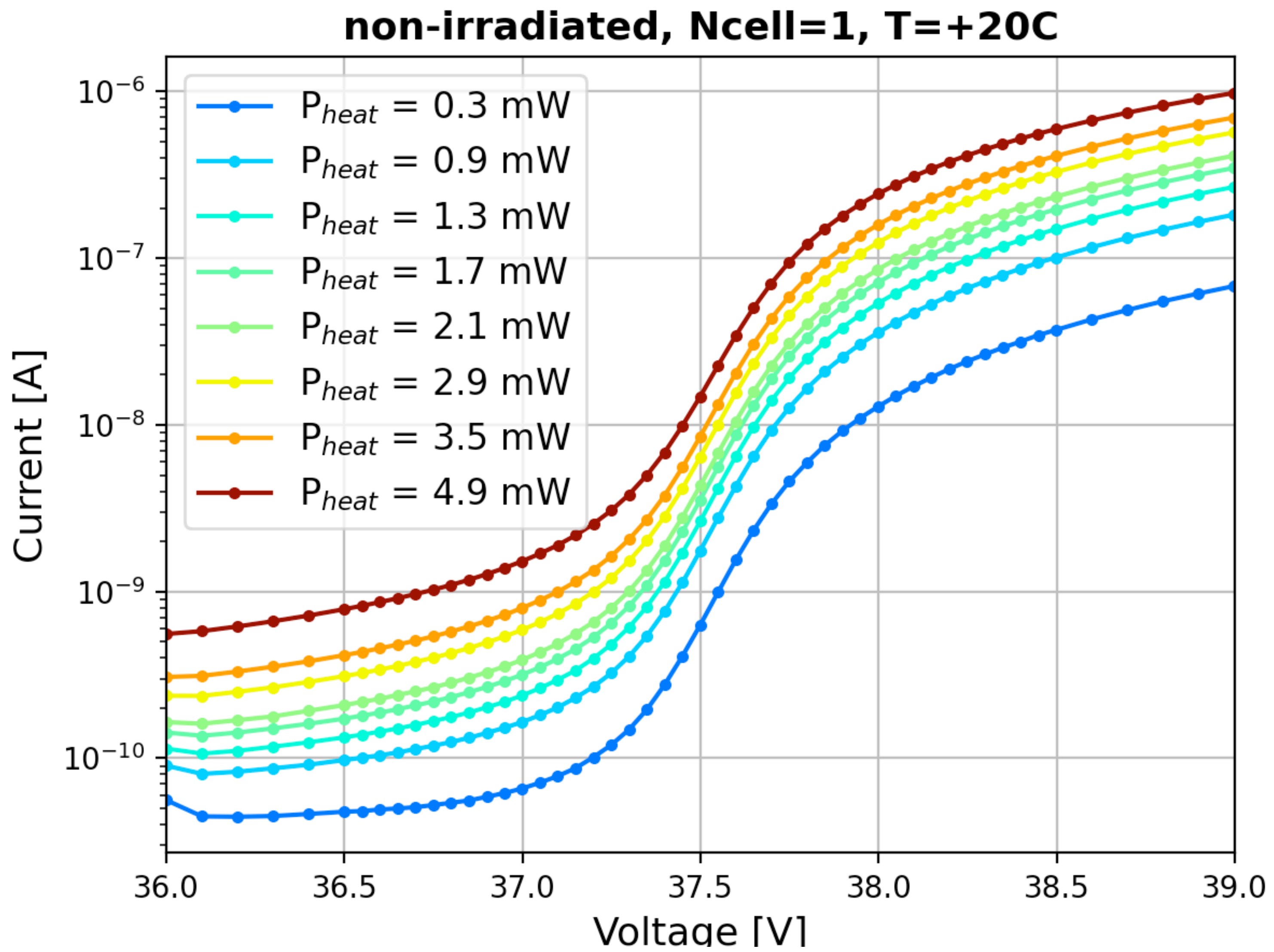
- 120 cells, ϕ = 5e13 cm^{-2}, T = -30 °C and V_{ov} = +4 V

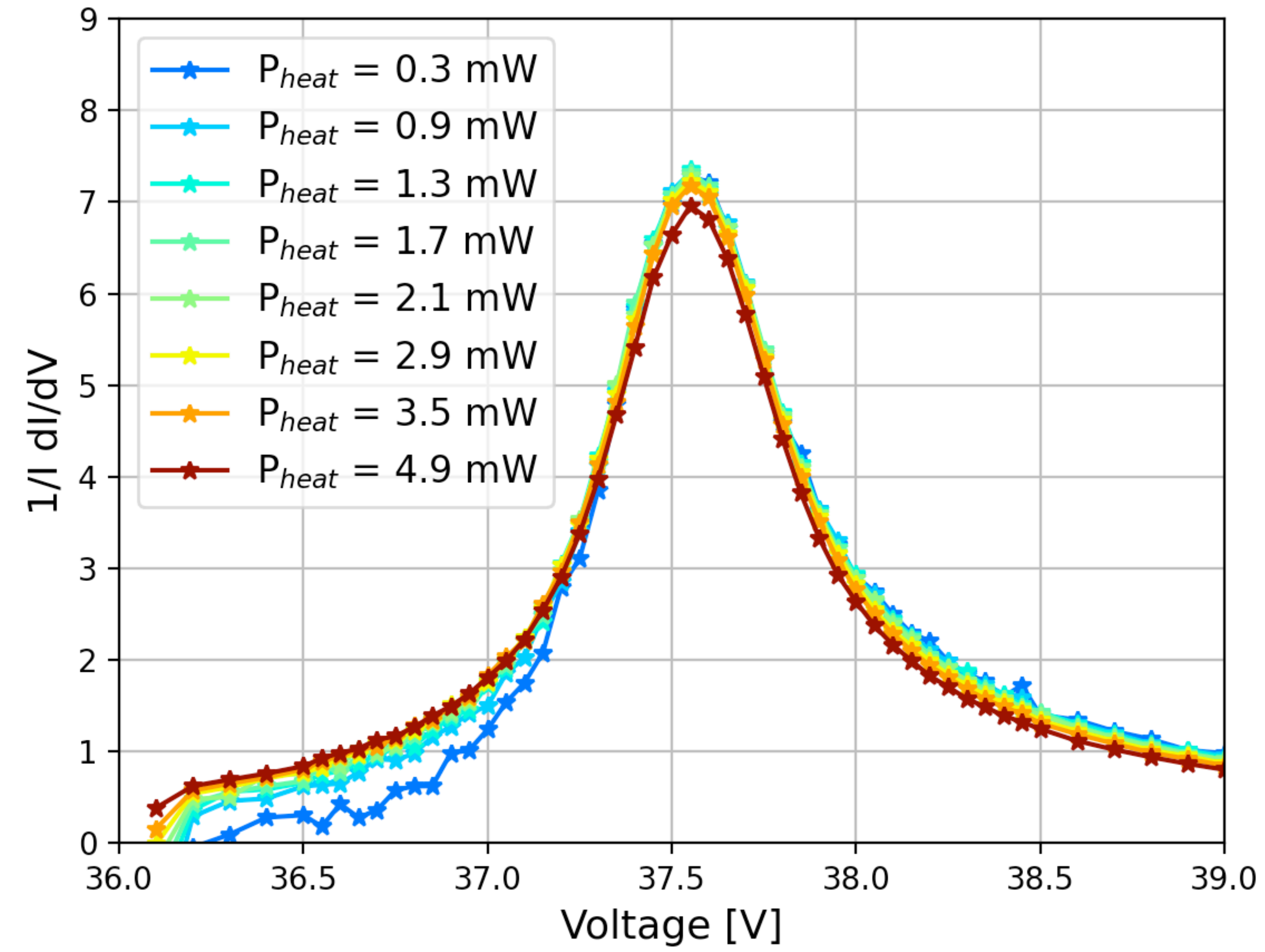
To check if the measurements are affected by self-heating effect the following test was carried out:

- operate 120 cells at the fixed voltage above the breakdown (V_{bias} = 39.1 V, V_{ov} = +1.5 V)
- change light intensity to generate different heat power
  - ▸ 120 cells serve as a heater
- measure IV-curve of 1 cell and calculate V_{bd}^{IV}
  - ▸ 1 cell serves as a temperature sensor since V_{bd} strongly depends on SiPM temperature

Result:

- no shift in V_{bd}^{IV} is observed up to 4.9 mW
- ▸ self-heating effect is negligible in this study





For more information about self-heating effect in SiPMs see dedicated talk by C. Villalba.

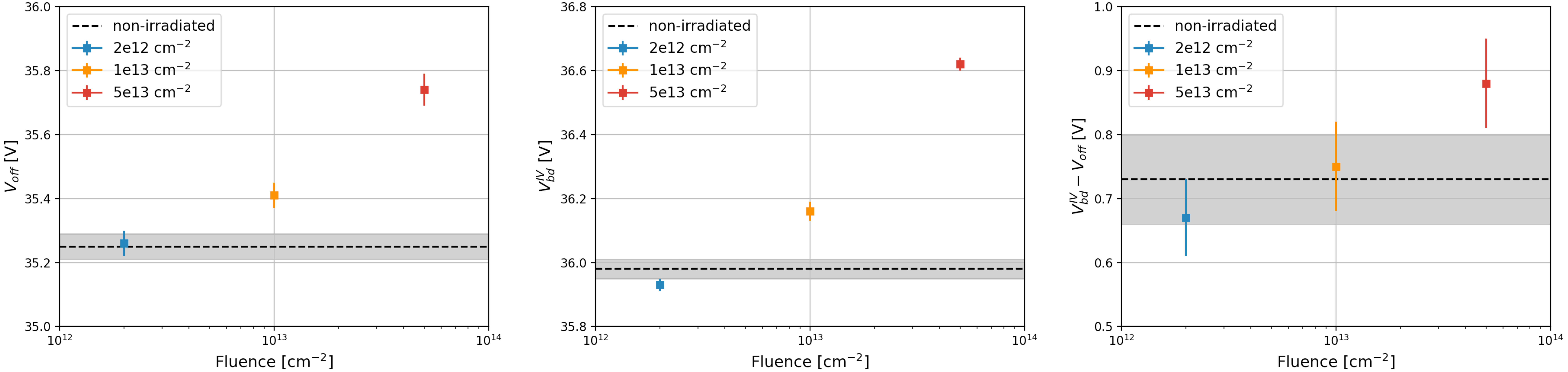
V_{off} and V_{bd}^{IV} vs fluence

- Is the value of V_{off} changing with fluence, and if so, is the change correlated to that of V_{bd}^{IV}?

For fluence ϕ = 5e13 cm^{-2} we observed:

- increase of V_{off} by ~0.5 V
- increase of V_{bd}^{IV} by ~0.6 V
- difference between V_{bd}^{IV} and V_{off} ~0.9 V

DUT	V_{off} [V]	V^{IV}_{bd} [V]
ϕ [cm^{-2}]	1 cell at -30C	
0E+00	35.25 ± 0.04	35.98 ± 0.03
2E+12	35.26 ± 0.04	35.93 ± 0.02
1E+13	35.41 ± 0.04	36.16 ± 0.03
5E+13	35.74 ± 0.05	36.62 ± 0.02



Radiation damage uniformity

Radiation damage may produce local "hot spots" with size smaller than or similar to a cell [3].

- the probability to find a hot spot in the single cell depends on the fluence and the cell size
- our study is based on the measurements of four single cells → results could be subject to large fluctuations due to the presence of "hot spots”
- one has to compare the 1 cell results to the average results of few cells

To check radiation damage uniformity, we calculate the ratio of:

- I_{dark} of 120 cells to I_{dark} of 1 cell
- I_{photo} of 120 cells to I_{photo} of 1 cell
- for non-irradiated sample I_{dark} could not be measured → only ratio of I_{light} were calculated

- for all IV-curves V_{bd}^{IV} was corrected as shown on the slide #14

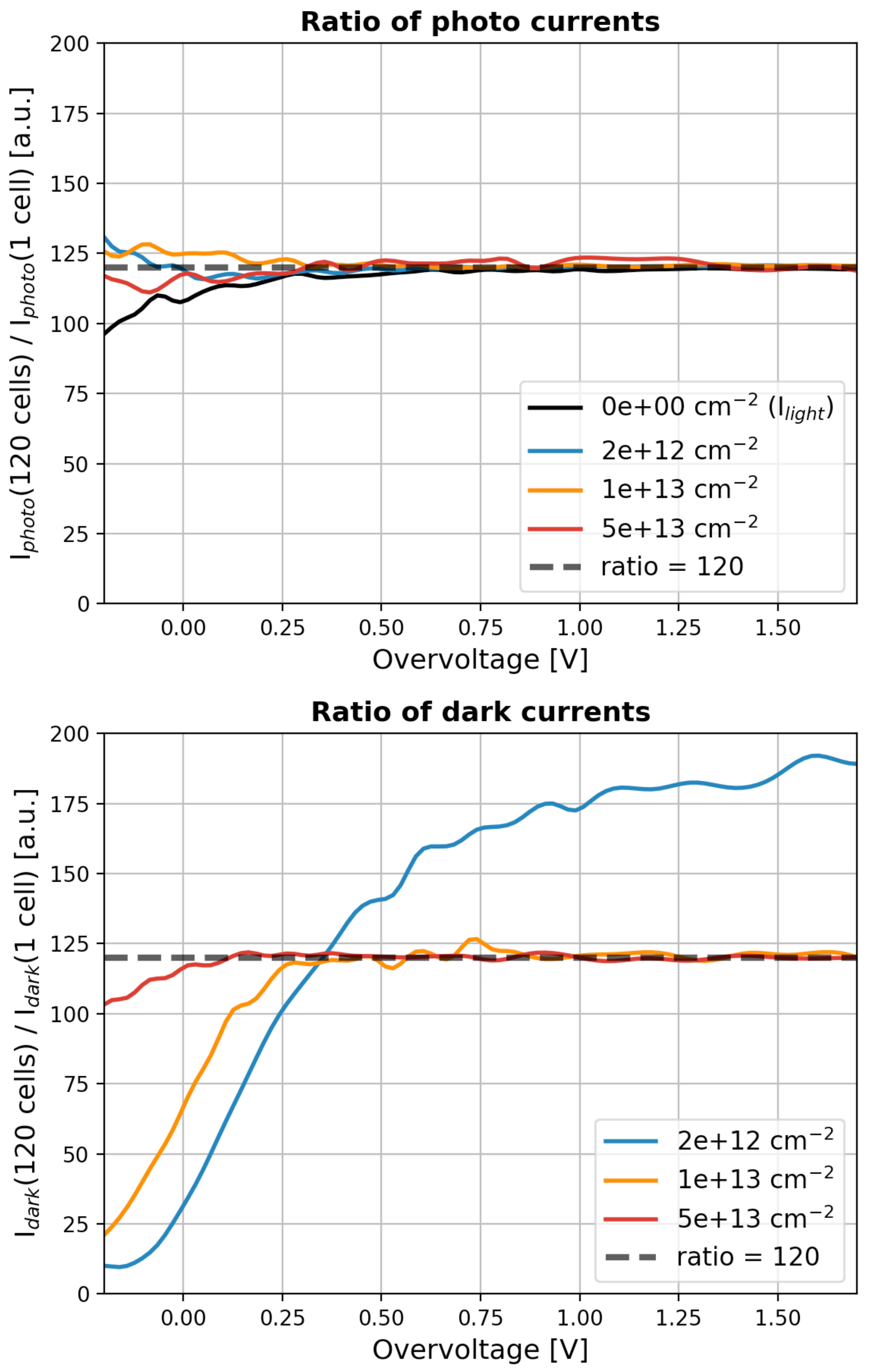
[3] E. Engelmann, E. Popova, S. Vinogradov, Spatially resolved dark count rate of SiPMs (2018). arXiv:1807.04113

Radiation damage uniformity

Result:

- expected value of the current ratio was obtained for:
  - I_{photo} for all fluences and I_{light} of non-irradiated sample
  - I_{dark} of ϕ = [1e13, 5e13] cm^{-2}
- ratio does not reach a plateau and exceeds the value of 120 for I_{dark} of ϕ = 2e12 cm^{-2}, the reason could be:
  - radiation damage non-uniformity
  - limited accuracy of low current measurements

▸ for most of the studied samples the radiation damage of the single cell is comparable to the average of the surrounding 120 cells, indicating good damage uniformity both in terms of dark current change, and of PDE*G*(1+CN) change



Summary

- The radiation hardness study using SiPMs with single-cell readout is ongoing.
- First observations from waveform measurements and analysis:
  - gain reduction of 19% for ϕ = 5e13 cm^{-2}
  - increase of V_{off} by ~0.5 V for ϕ = 5e13 cm^{-2}
- IV-measurements were carried out for the same test samples to address the questions:
  - self-heating effect
    - negligible in this study
  - fluence dependence of the difference between V_{off} and V_{bd}^{IV}
    - no visible dependence within the uncertainties for ϕ = [2e12, 1e13] cm^{-2}
    - ~0.9 V for ϕ = 5e13 cm^{-2}
  - radiation damage uniformity of 1 cell and 120 cells
    - for most of the studied samples the radiation damage of the single cell is comparable to the average of the surrounding 120 cells, indicating good damage uniformity both in terms of dark current change, and of PDE*G*(1+CN) change
- method for extraction of IV-curves ratio was proposed

Backup: Extraction of IV curves ratio

- determine breakdown voltage for each IV curve
- scale IV curves x-axis to overvoltage
- perform spline interpolation
- compute the ratio
- evaluate the effect of V_{bd}^{IV} uncertainty (± 50-60 mV) on the ratio:
  - for 120 cells curve — fix V_{bd}^{IV} value → V_{bd}^{IV} = 36.58 V
  - for 1 cell curve — vary V_{bd}^{IV} with 10 mV step within the errors → V_{bd}^{IV} = [36.57..36.67] V
  - take the ratios and evaluate the result
    - plateau is expected above the breakdown → violet curve V_{bd}^{IV} = 36.63 V (10 mV difference with measured one)
    - extrema at V_{ov} = 0 V mean that the IV-curves are inconsistent → yellow and greenish curves