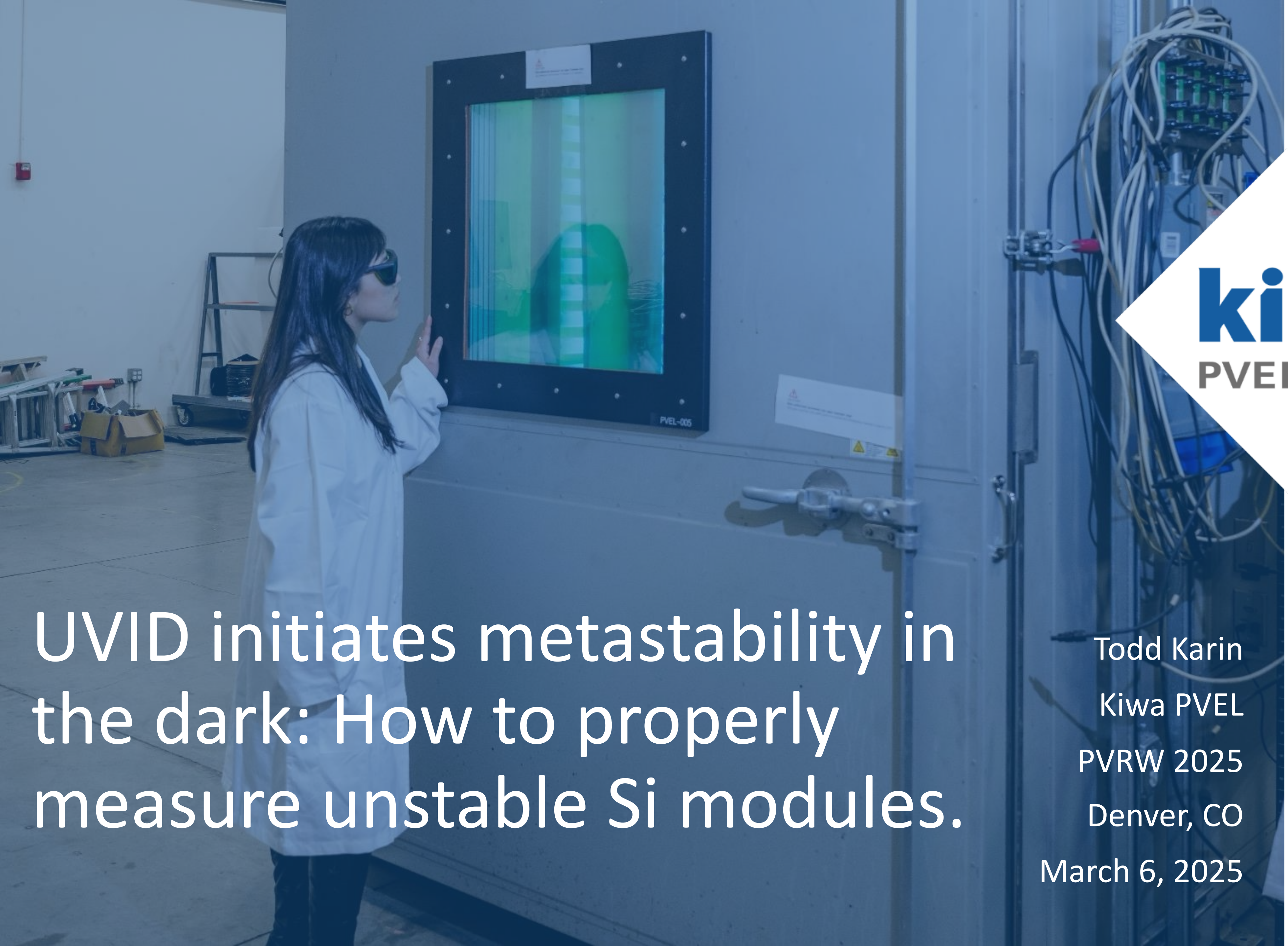


UVID initiates metastability in the dark: How to properly measure unstable Si modules.

Todd Karin

Kiwa PVEL

PVRW 2025

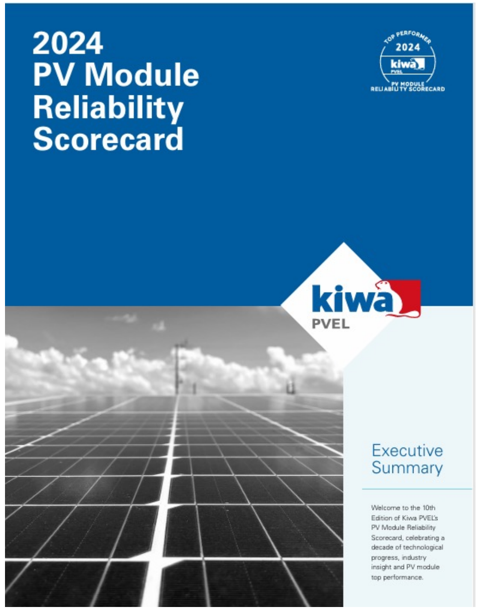
Denver, CO

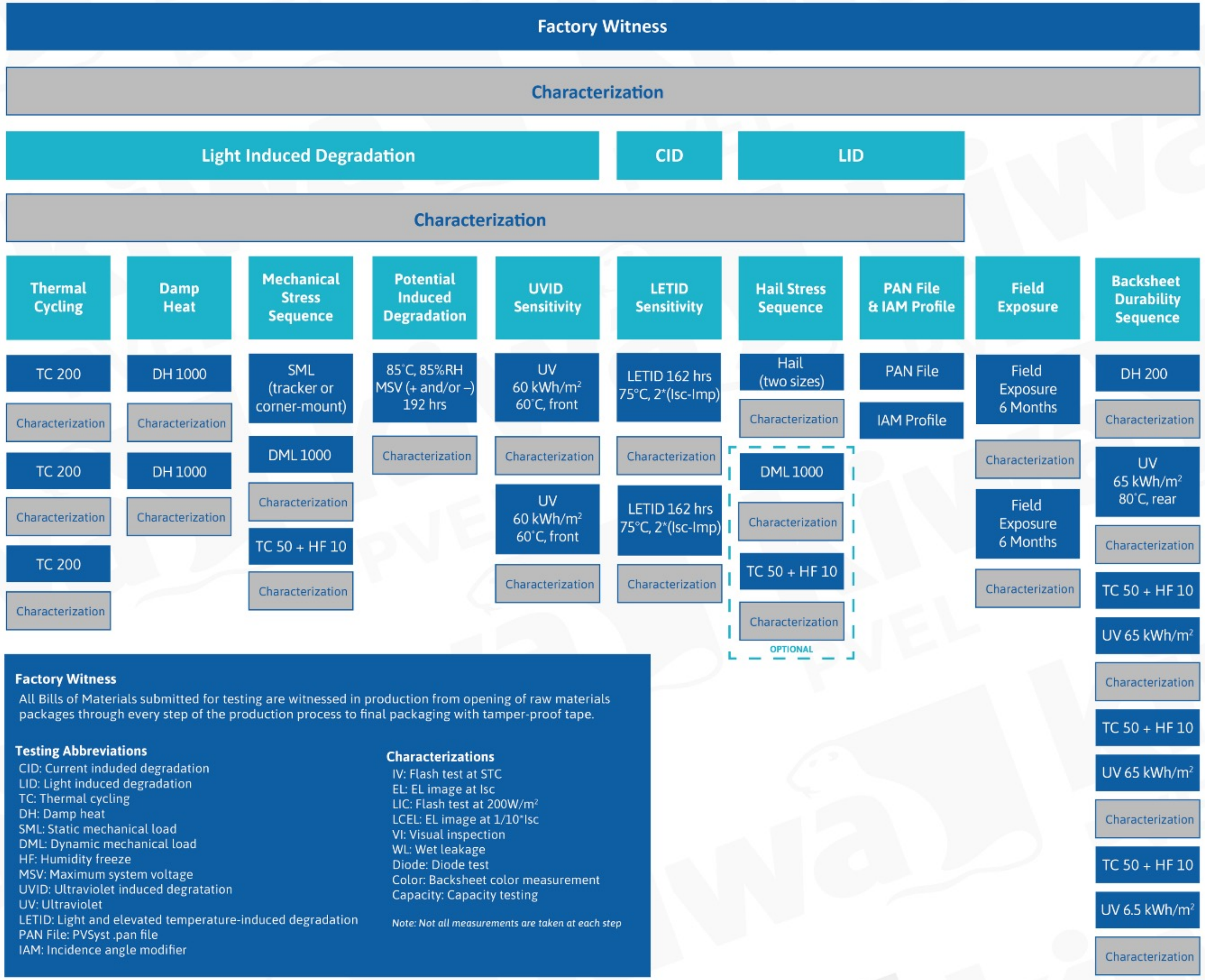
March 6, 2025

We Create Trust

Kiwa PVEL

- Independent lab for PV Module **Performance and Reliability Testing**
- Product Qualification Program (PQP)
- Regularly updated
- Often ahead of the IEC standards group
    - Added UVID before standard is finished.
    - Implementing UVID stabilization procedure





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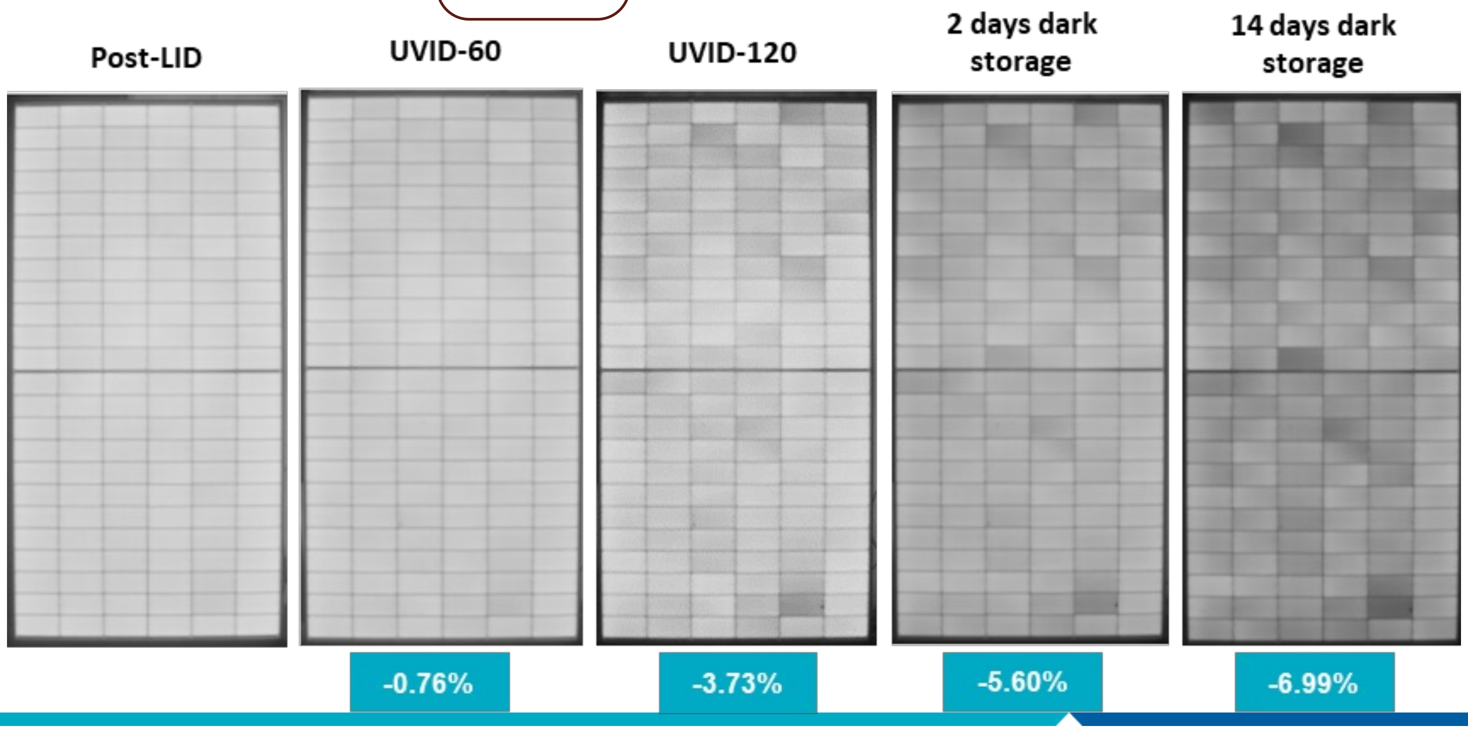
UVID Induces Metastability

- We are all used to treating silicon modules as stable in storage…
  - **Not anymore!**

This talk: what's going on and how to properly measure unstable modules

Industrial Topcon module.

Step#	Pmp%	Voc%	Vmp%	Isc%	Imp%	FF%
Post-LID						
UVID-60	-0.76	-0.84	-1.02	0.60	0.31	-0.52
UVID-120	-3.73	-2.31	-3.24	-0.17	-0.45	-1.29
After 2 days dark storage	-5.60	-3.39	-4.98	-0.47	-0.60	-1.83
After 14 days dark storage	-6.99	-4.18	-5.66	-1.28	-1.42	-1.68



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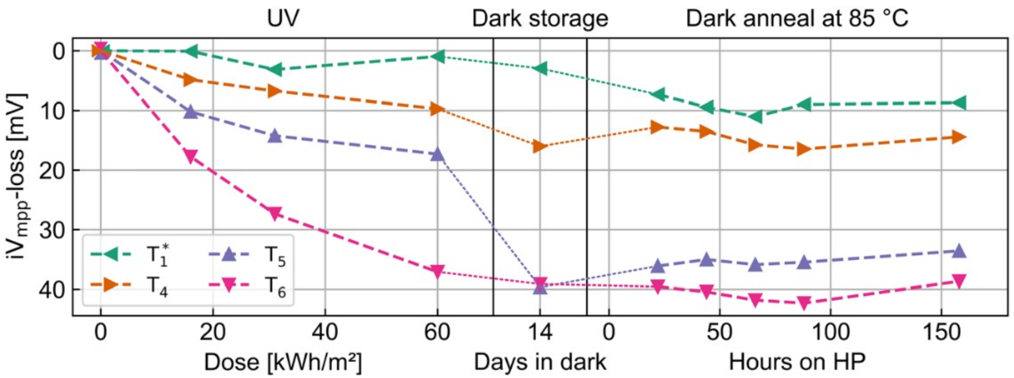
Prior work

Prior work has recognized the dark storage issue.

Cells:
0.5%-3.0% degradation in dark



[1]

Hydrogen diffuses away from the passivation layer in the dark

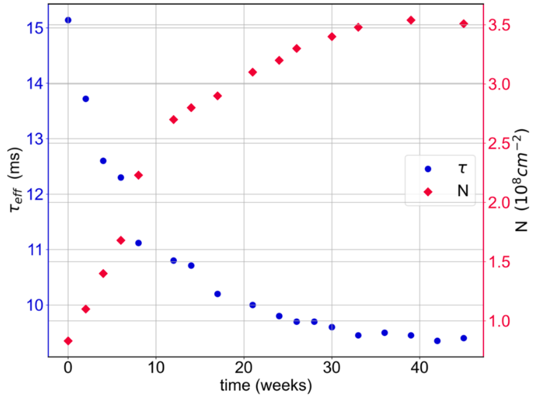
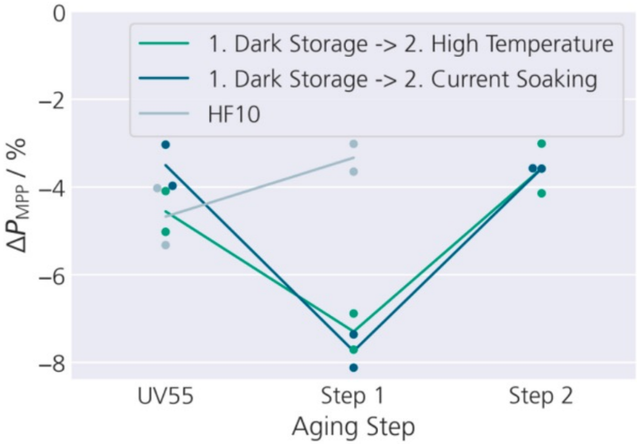


Fig. 1 Degradation of the surface passivation of silicon heterojunction solar cells. The quality of the surface passivation of four silicon heterojunction cells with varying thickness was tracked over the course of a year by monitoring the effective minority carrier lifetime τ_{eff} (blue circles). From analyzing these measurements at different temperatures and different injection levels, we determined the time-dependent defect density at the c-Si/a-Si:H interface N(*t*) (red diamonds).

[2]

Dark storage reversed by high T or current injection.



[3]

[1] Thome et. al. Solar RRL 2024, 8, 2400628
[2] Diggs, A., Zhao, Z., Meidanshahi, R.V. *et al.* Hydrogen-induced degradation dynamics in silicon heterojunction solar cells via machine learning. *Commun Mater* **4**, 24 (2023).
[3] Gebhardt, P., Kräling, U., Fokuhl, E., Hädrich, I. and Philipp, D. (2024), Reliability of Commercial TOPCon PV Modules—An Extensive Comparative Study. Prog Photovolt Res Appl.

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Meta-stability during dark storage after UVID-120

- What happens during repeated flashing of a TOPCon module?
  - Recovers just from the light of the flash tester.

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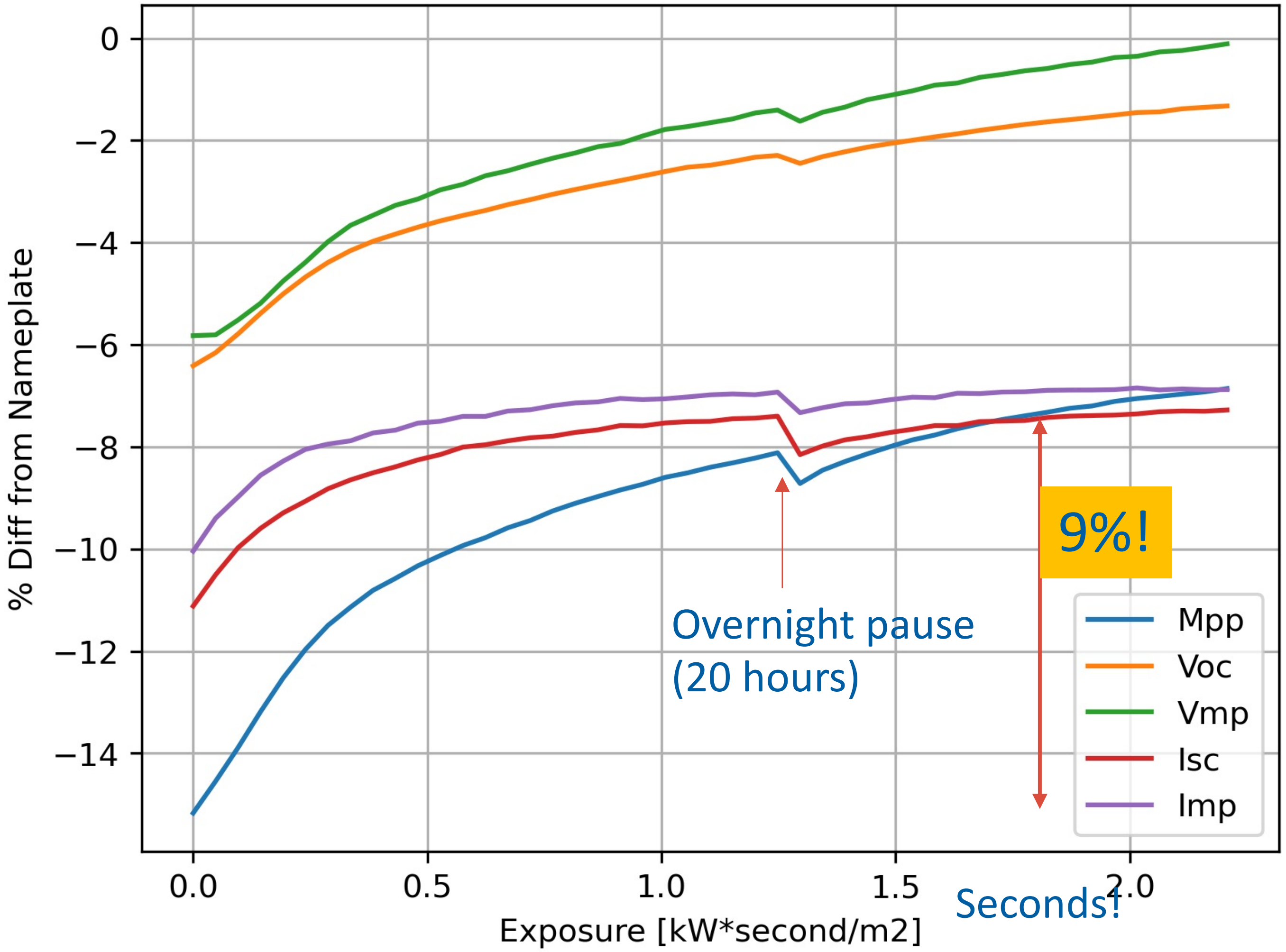
Meta-stability during dark storage after UVID-120

- What happens during repeated flashing of a TOPCon module?
    - Recovers just from the light of the flash tester.

- Module is TOPCon, Post UVID-120 i.e. “1 year equivalent” and left in dark storage for 3 months.
- **Module Pmp recovered by 7% after around 1 second of accumulated exposure.**
- After leaving in dark for 20 hours, MPP dipped again by 0.6%!
- Dark storage degradation is large enough to be relevant and adds a very large uncertainty.



Dark storage degradation for TOPCon happens on the timescale of days and is reversed within **seconds** of full-spectrum 1 sun light.

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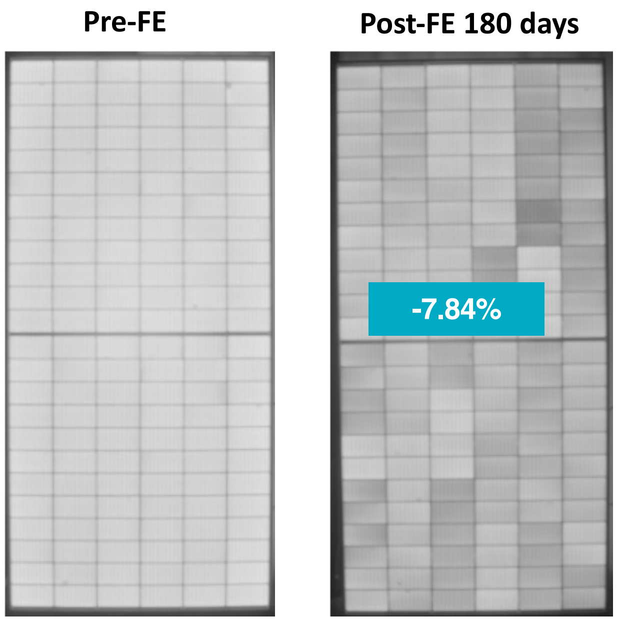
Does the metastability exist for fielded modules?

- **Metastability not just created in a UVID test chamber, it's also created in outdoor-aged modules.**
- Fielded modules have all the signatures of UVID:
  - Checkerboard EL
  - Mostly Voc loss
  - UVID metastability.
- Two TOPCon modules deployed in Davis, CA for 6 months
  - Modules showed an average of -6.3% power loss.
  - Power loss increased up to -7.8% after 11 days of storage in dark.
  - Module recovered power loss after 2 hours of light soaking.

Fielded modules also show the metastability.



	Pmp(%)	Voc(%)	Isc(%)	FF(%)
Pre-FE				
Post FE 180 days (+7 days dark storage)	-6.26	-3.46	-1.12	-1.83
After 11 days of dark storage	-7.84	-4.72	-1.12	-2.18
After 2 hrs of LS indoor	-2.08	-1.28	-0.45	-0.37

*All measurements are with respect to pre-FE

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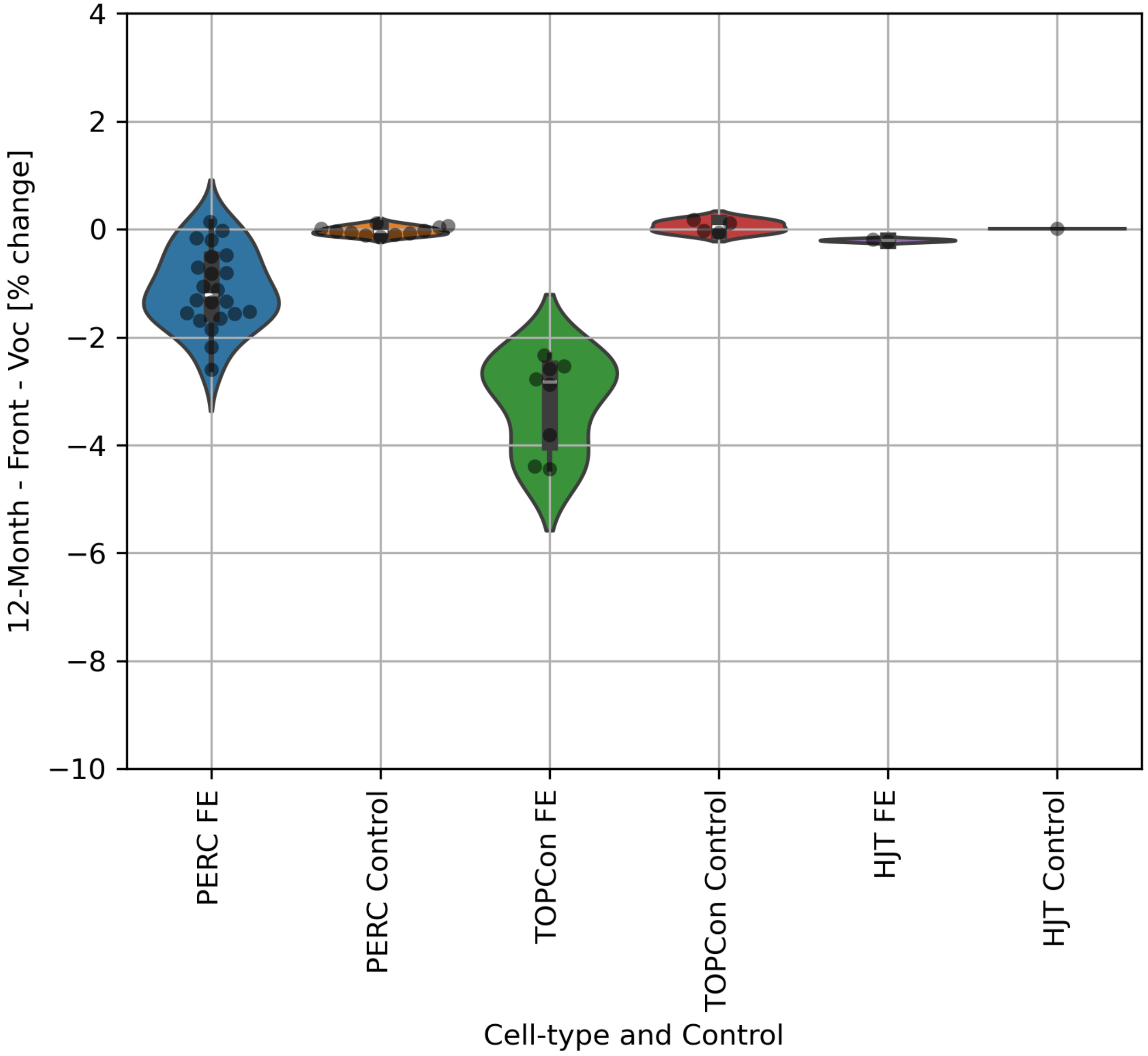
Are unexposed modules stable?

- **Field Exposure (FE)**: Modules fielded for 12 months.
- Control modules (left inside for 1 year) do not degrade in voltage.
- Also, Voltage loss in TOPCon is worse than PERC/HJT (attributed to UVID).



Modules have good stability (<1%) before exposure to outdoor conditions.

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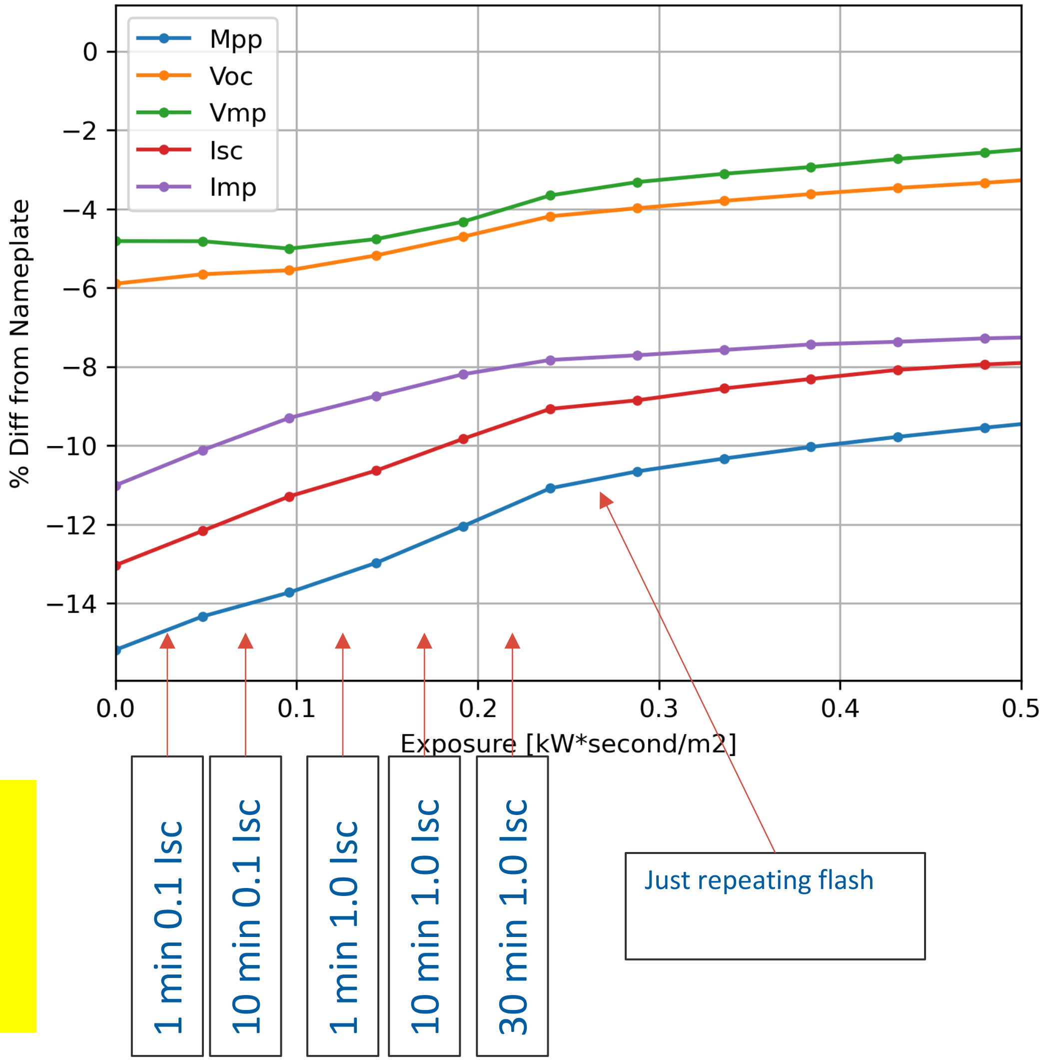
Methods for recovery

- **Current injection is not a good candidate for dark-storage recovery.**
- Even 30 minutes of charge injection at 1.0 Isc is approximately equal to the recovery achieved in just 0.05 seconds of light.



Light is necessary for recovery process: voltage alone does not cause recovery at the same rate.

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Full spectrum light causes recovery, but what wavelengths are most important?

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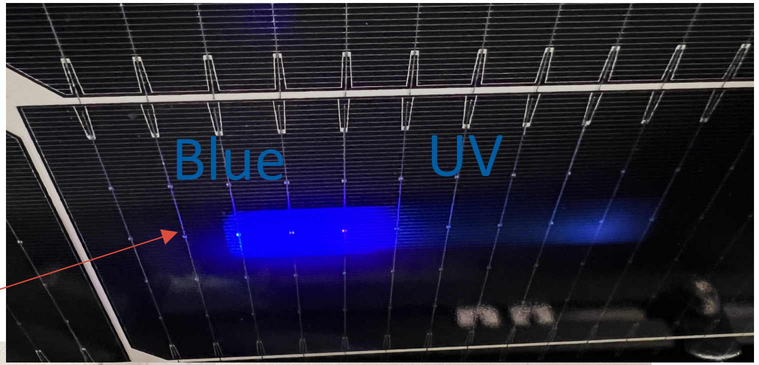
51.1 14.9
POWER
BK PRECISION

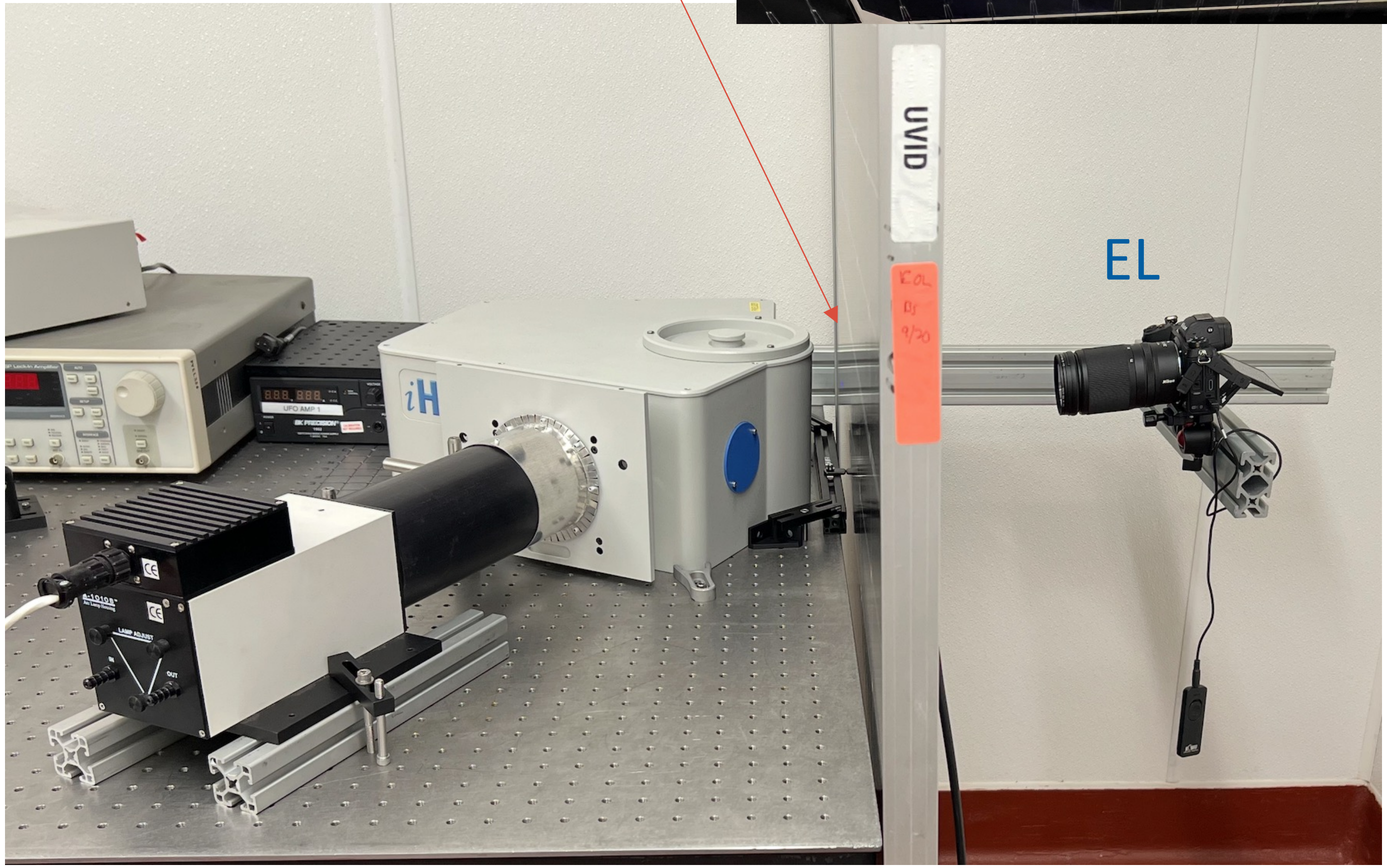
UVID Recovery wavelength dependence

- Used a xenon arc lamp and a spectrometer to send a UV-Blue rainbow to the module.
- Took EL images from the back.
- Input light is blocked when taking the EL image.

Front of mod



Blu-V (?)
Rain-blue (?)



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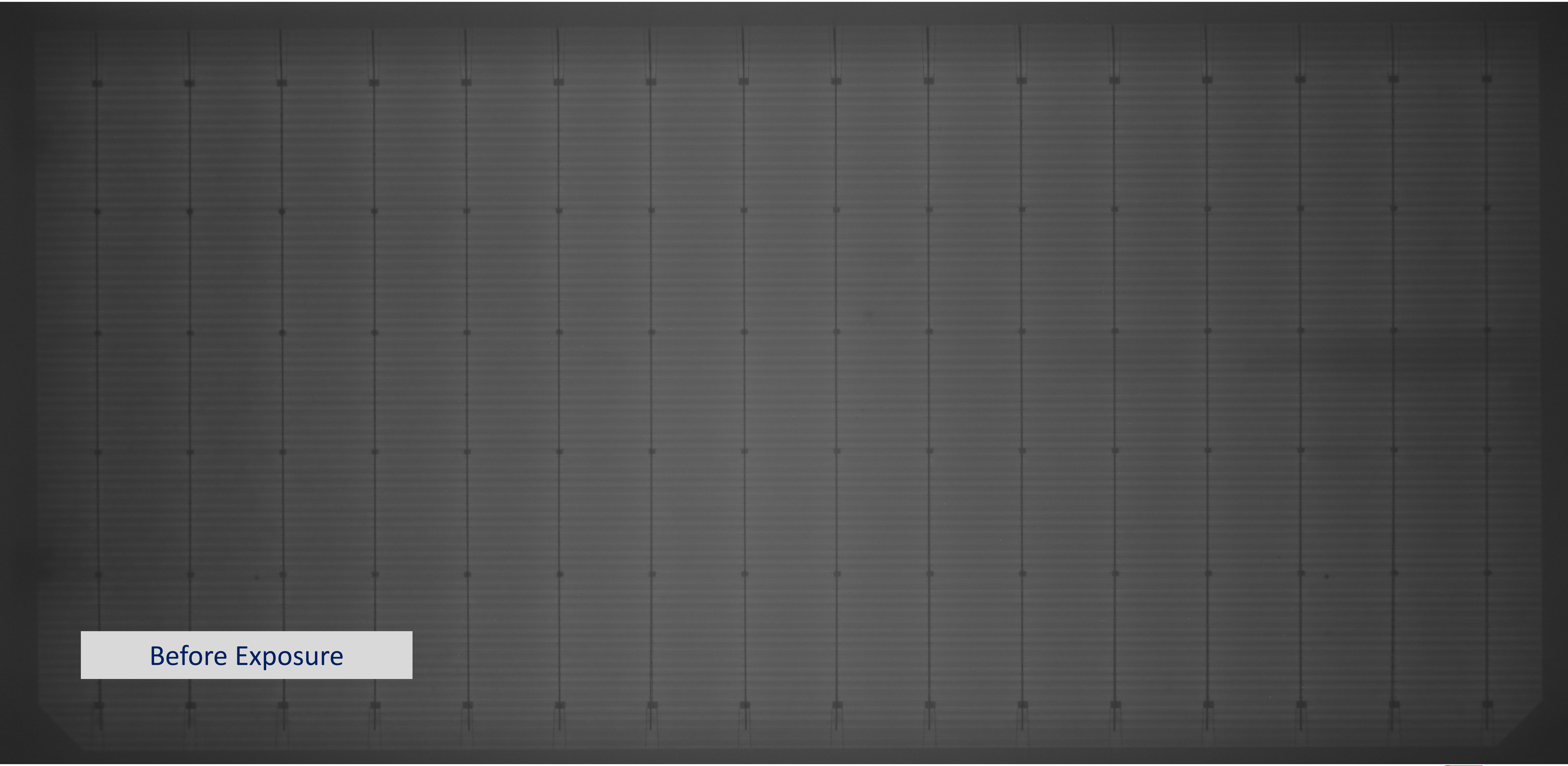

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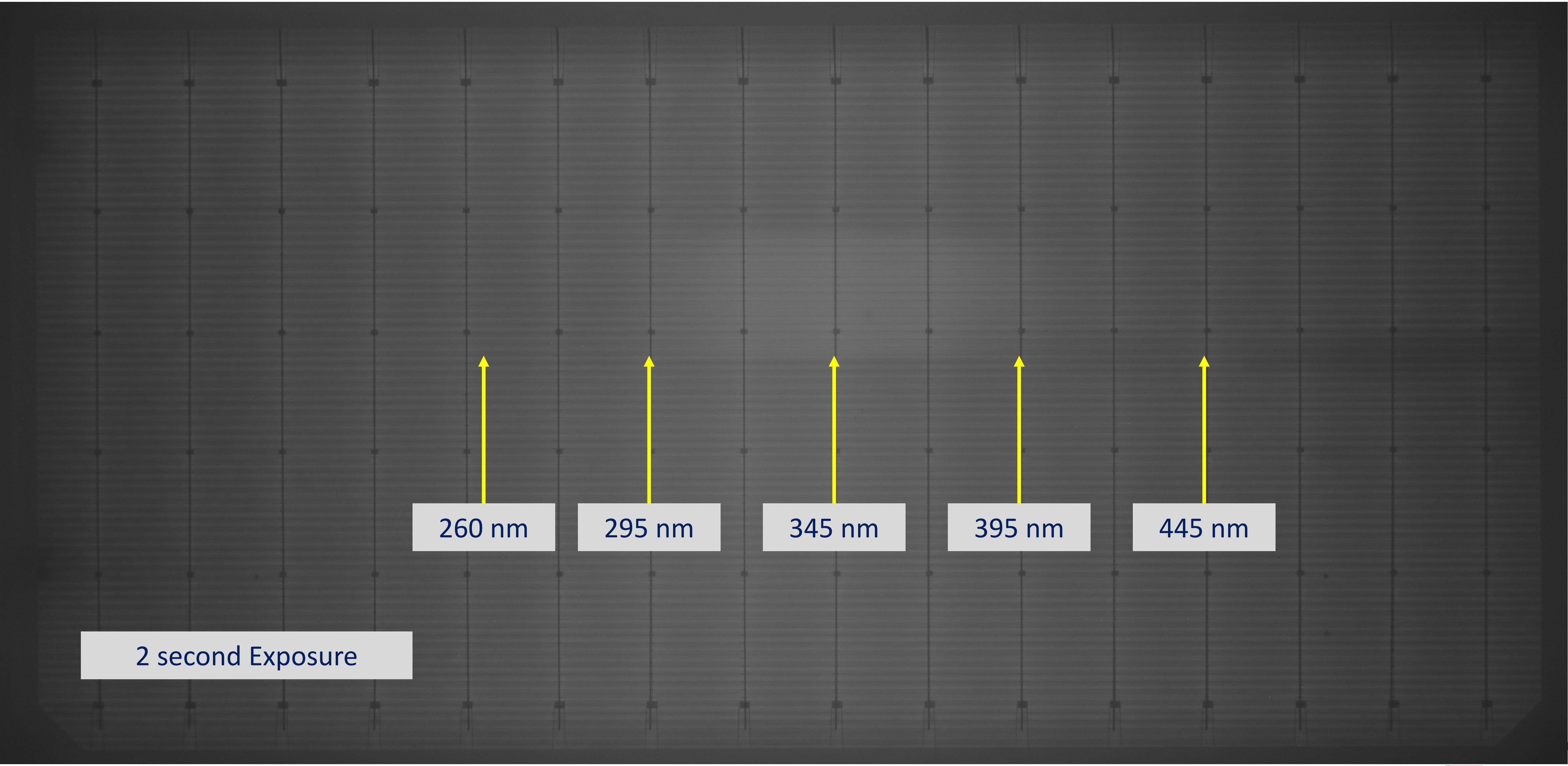

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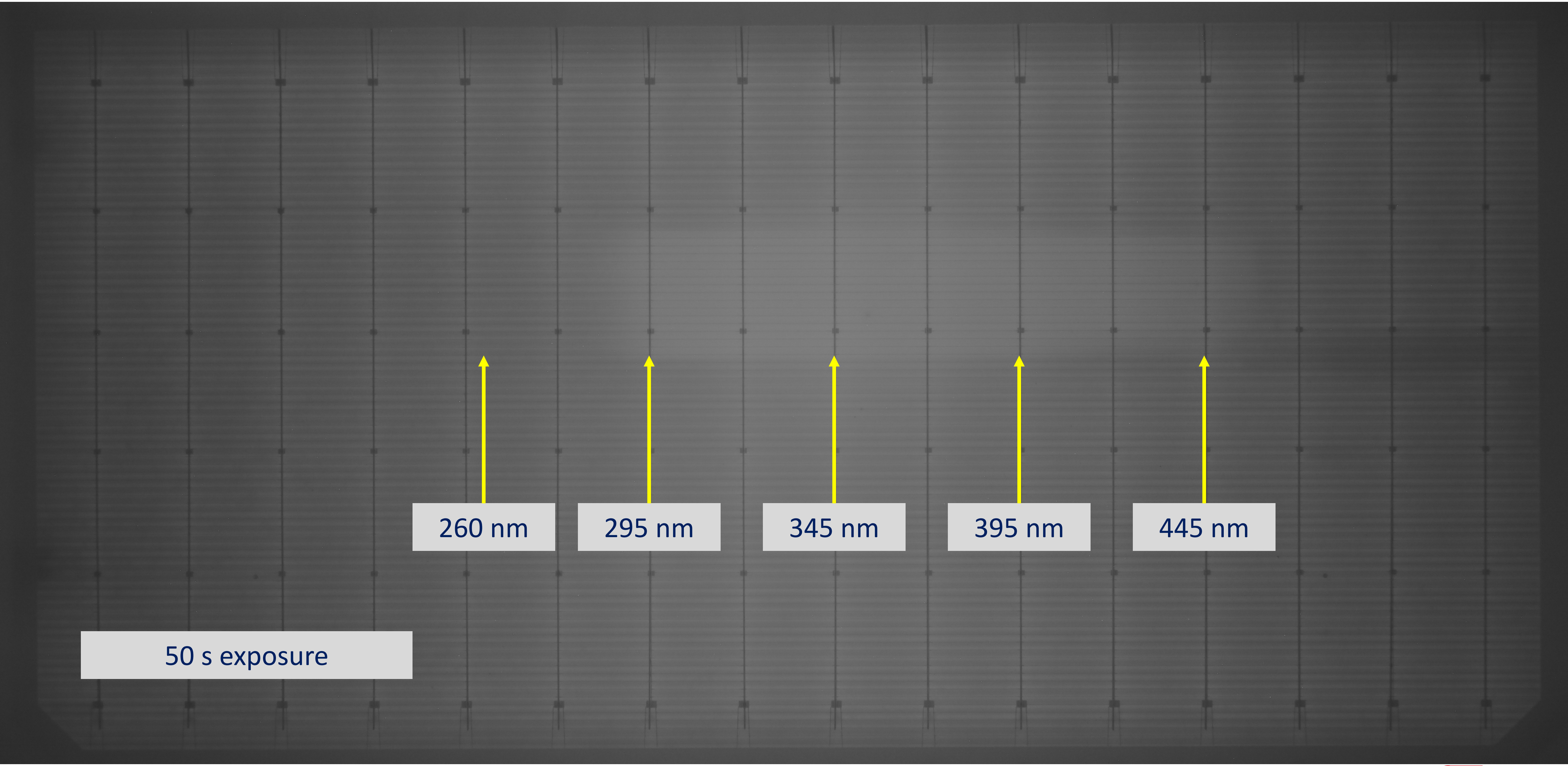

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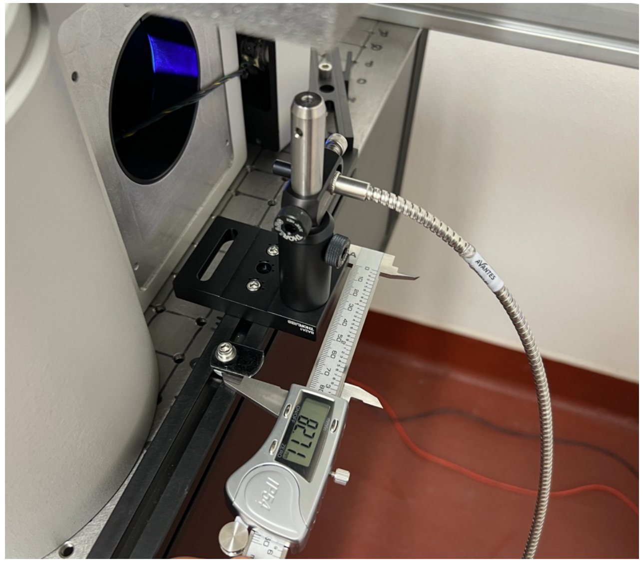
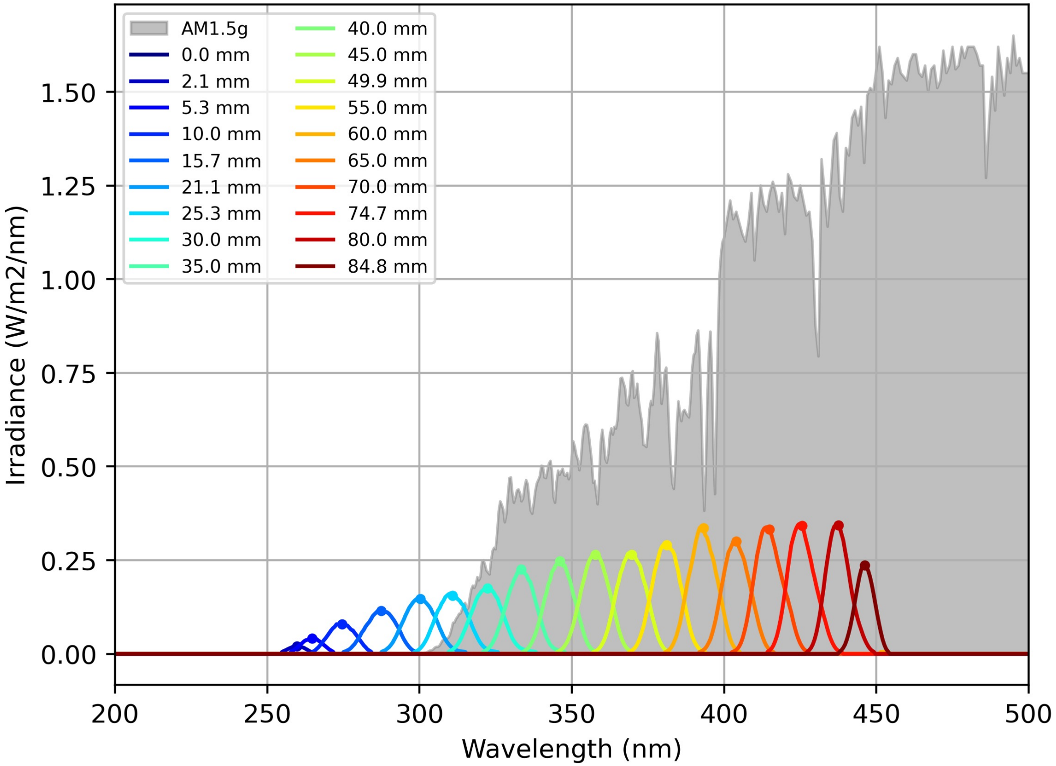
Spectrum vs. position

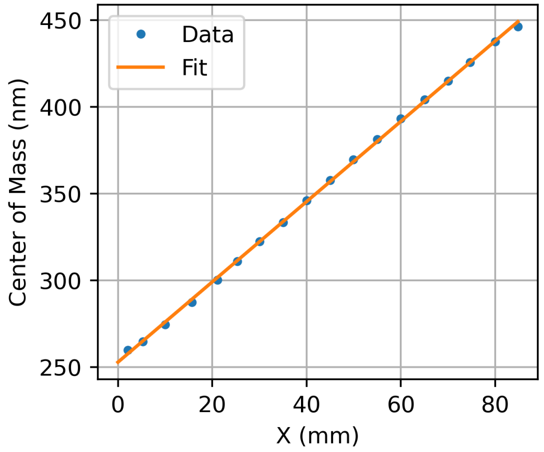
Found the dependence of spectrum on position using a spectrometer.

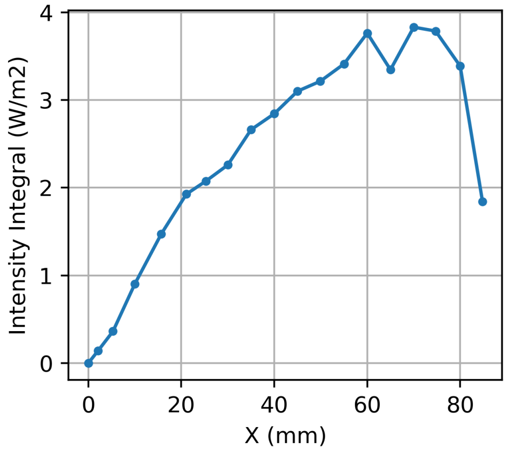


Note: intensity in UV to blue region is comparable to AM1.5G



Find center and integral





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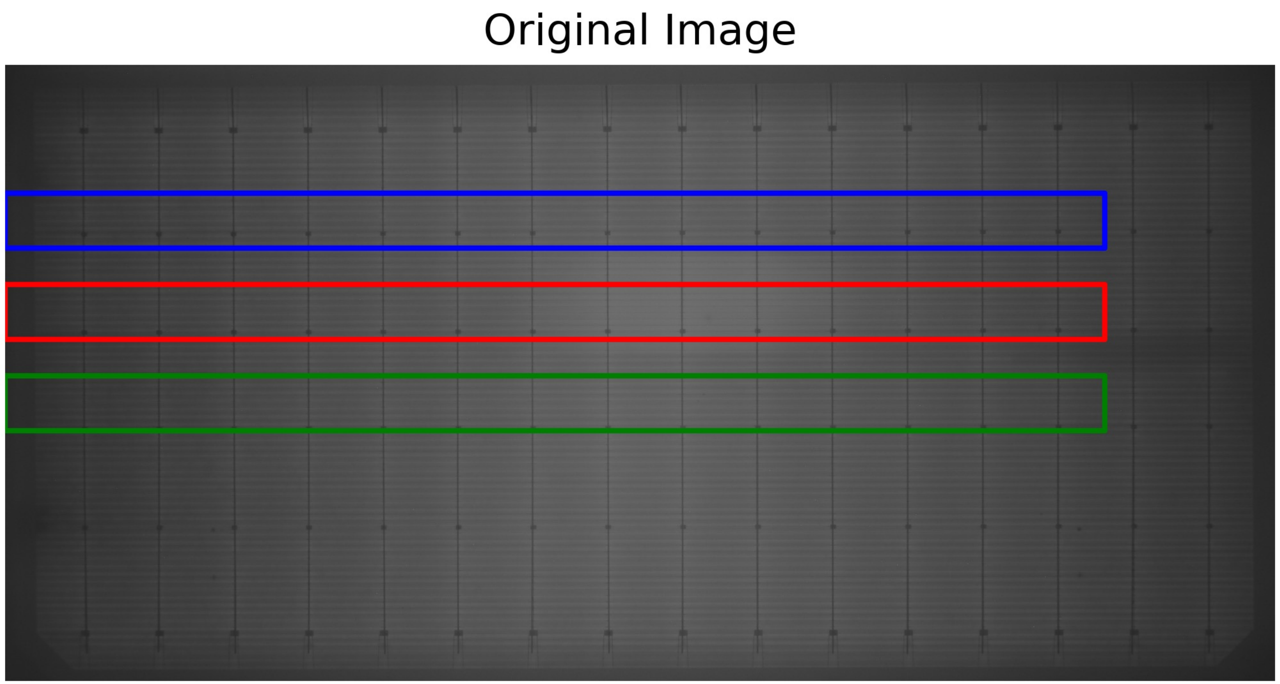
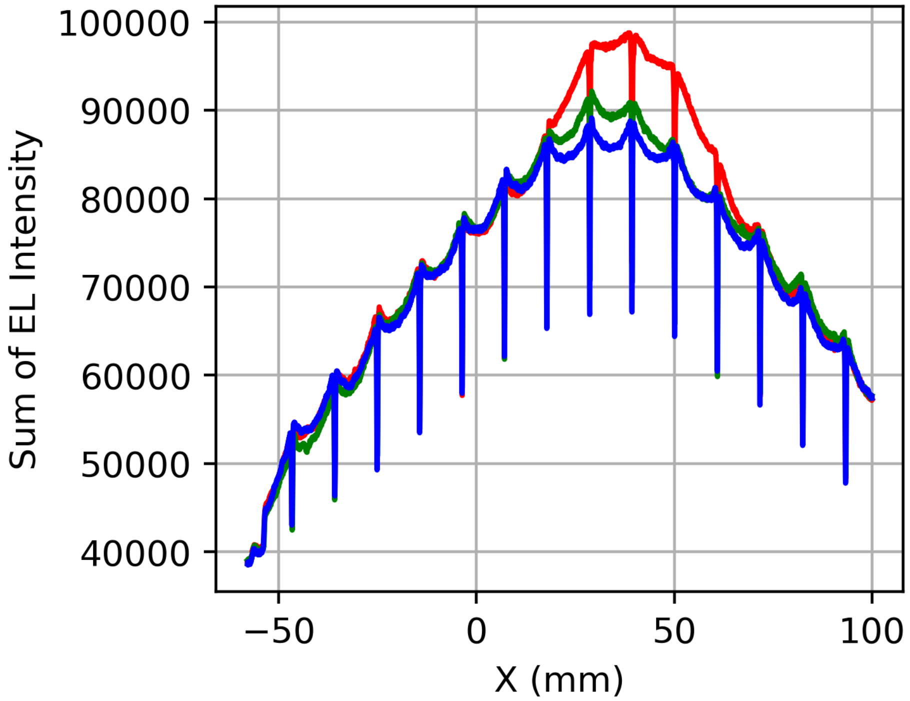
EL Image analysis





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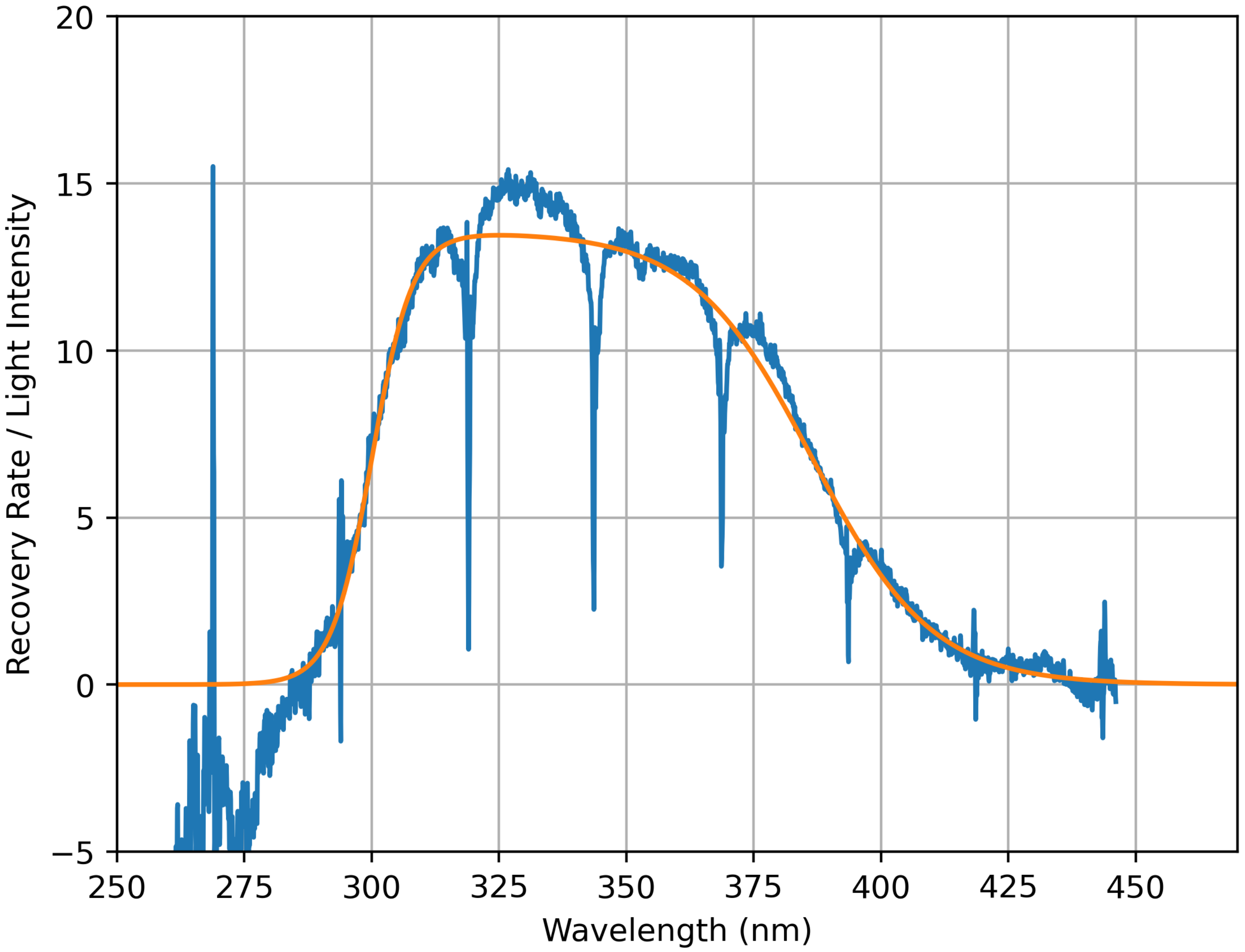
Put it together

- Combine the wavelength + power at each location with the amount of EL brightening to get the recovery rate normalized by light intensity.
- Note: glass cuts off around 300 nm.

UV light causes recovery of UV-induced dark metastability.



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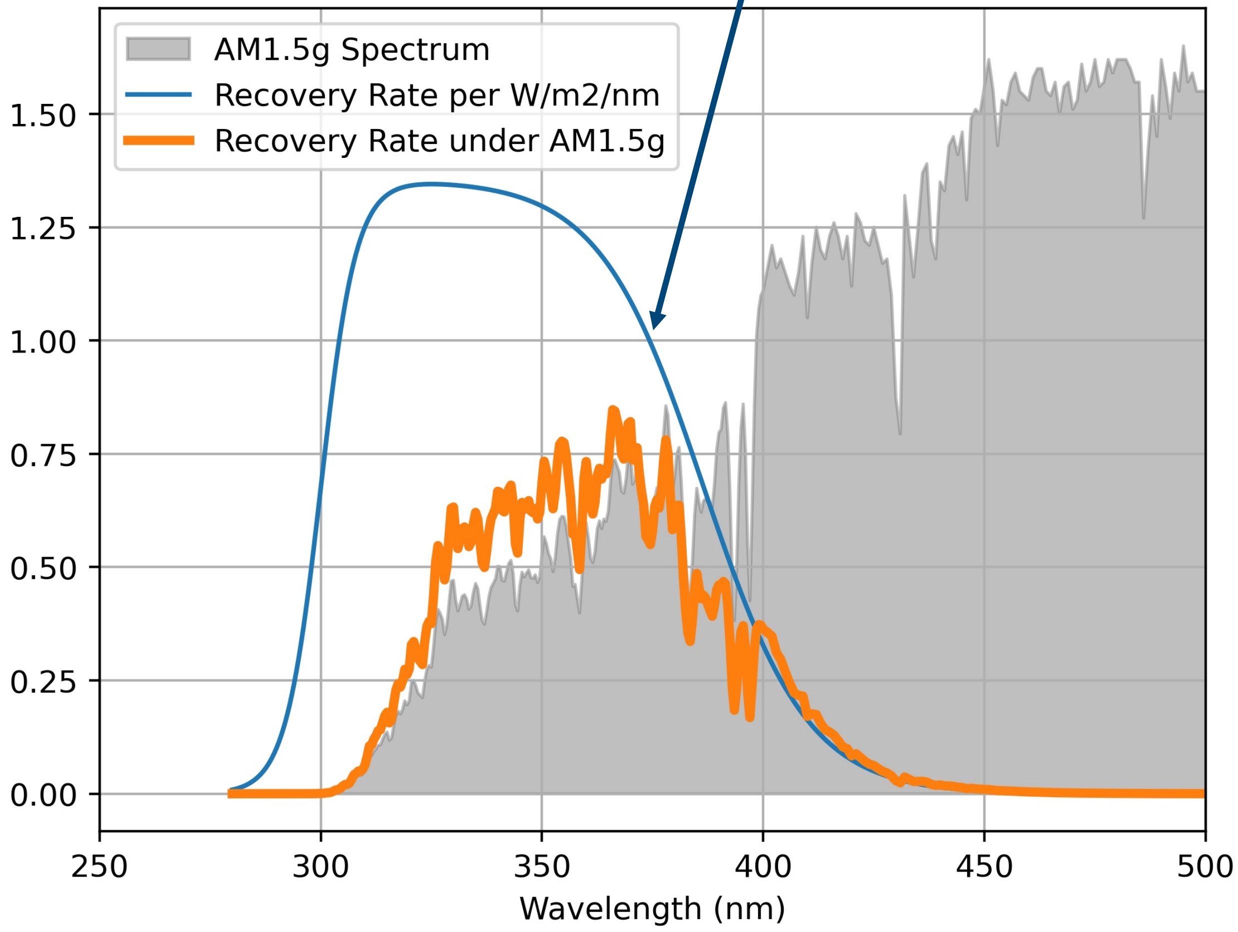
Spectral dependence of recovery

Recovery under full spectrum light almost completely due to UVA exposure in range of 320 – 400 nm (for TOPCon).

- Note glass cuts off below 300 nm.
- (Note: this is a tricky measurement – exact shape should be verified with further measurements.)

Spectral dependence of the recovery rate



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What is happening in the cell during dark degradation and recovery?

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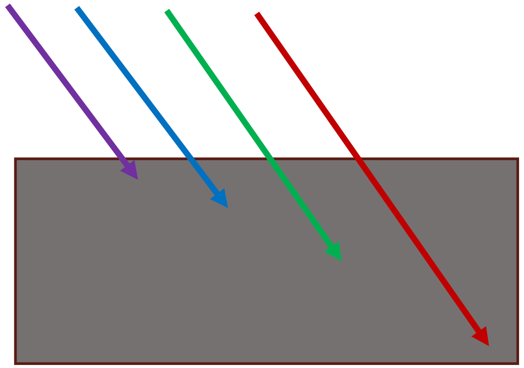
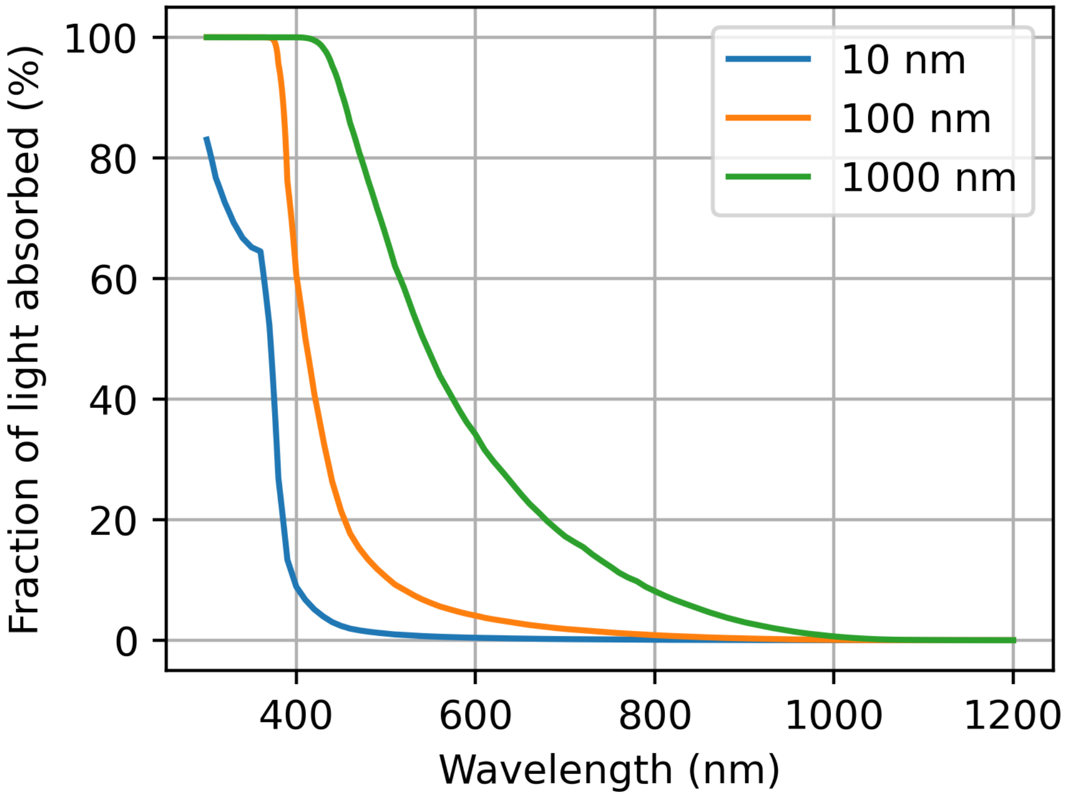
External Quantum Efficiency (EQE) primer



- Nearly 100% of UV light is absorbed in the top 100 nm of the cell, longer wavelength light is absorbed deeper into the cell.

- **The quantum efficiency in the UV region probes the quality (passivation) of the front surface.**



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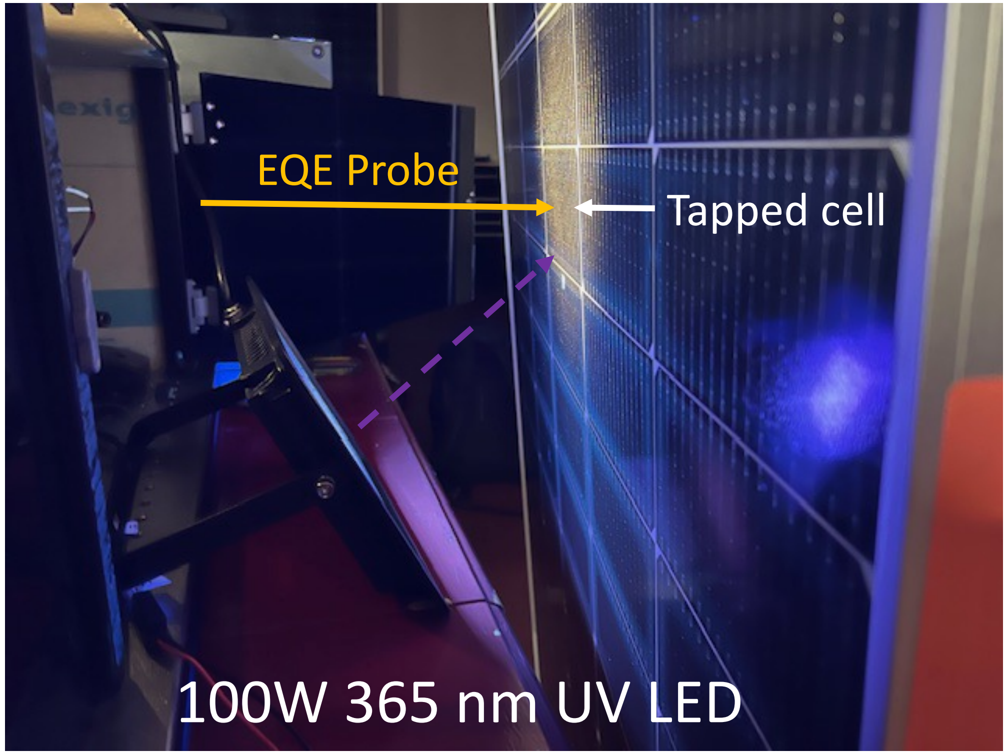
EQE change during recovery

- TOPCon module experienced UVID followed by several months of dark storage.
- Acquired EQE before and after a 2 minutes dose from UV LED at 365 nm.



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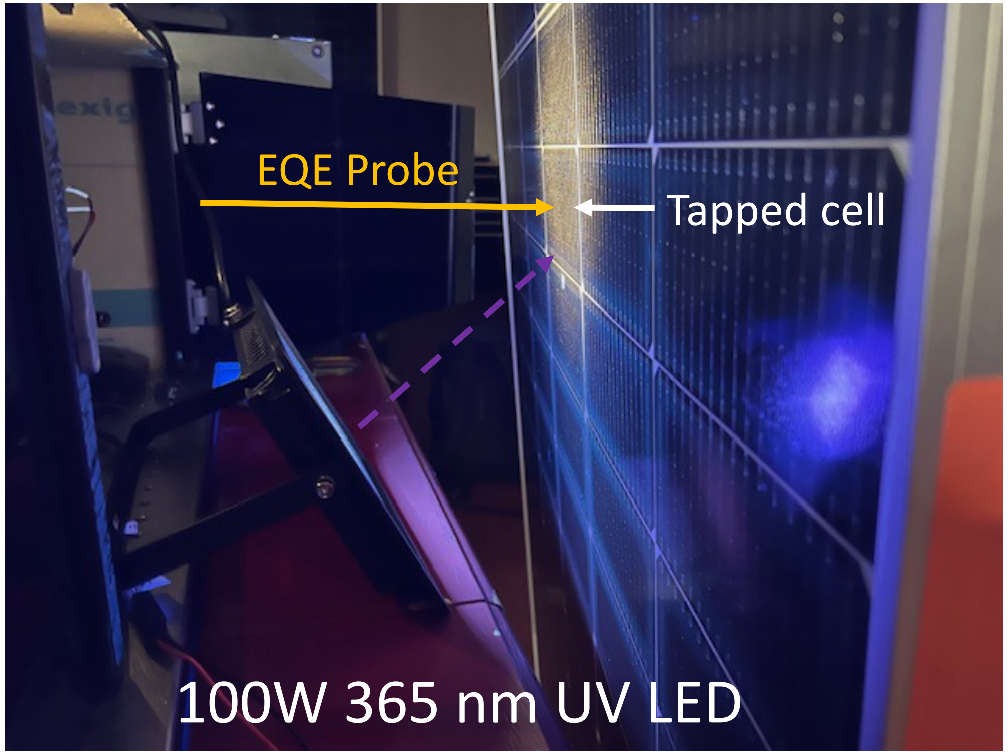
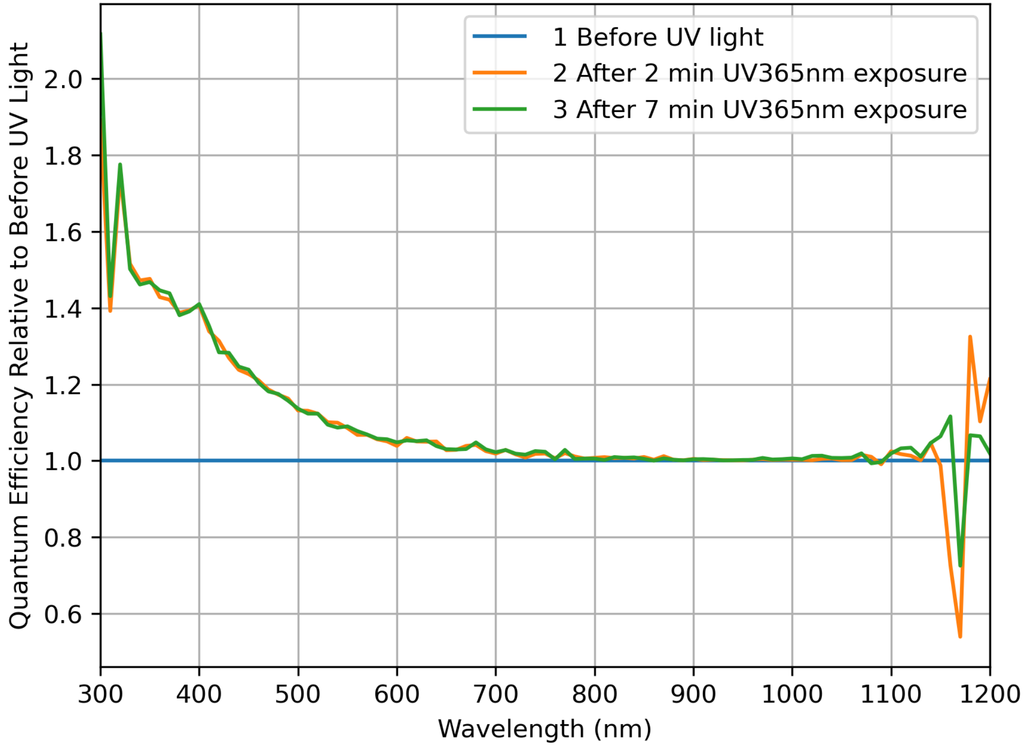


- Change in EQE during recovery shows power gain is greatest in the blue/UV region.

Clear evidence that:

The dark-storage defect causes front-side passivation loss



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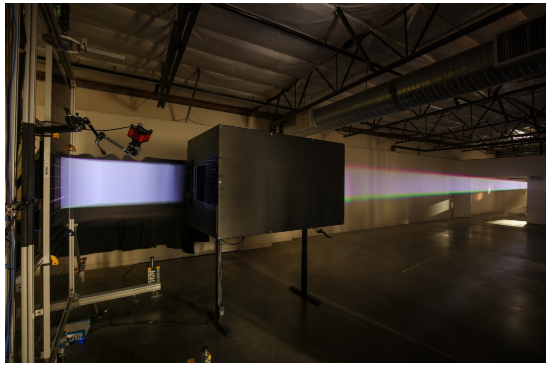
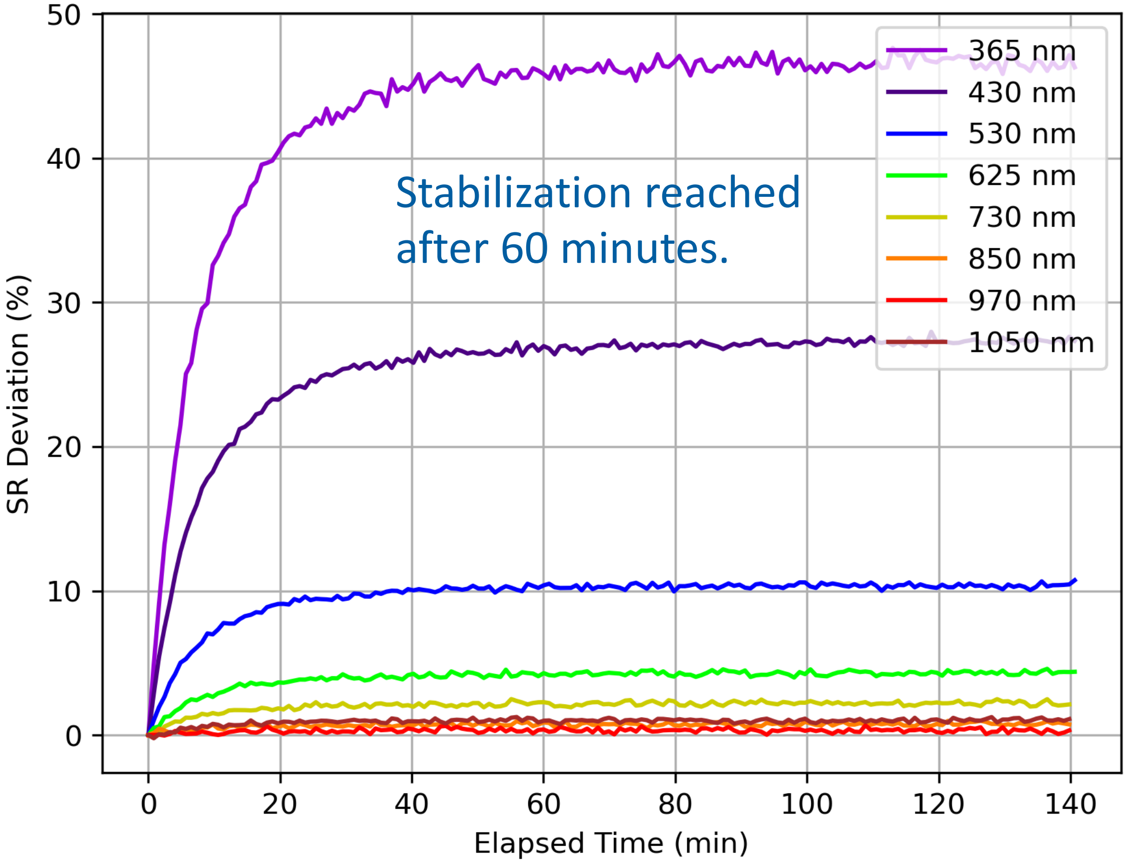
Metastability measured with EQE vs. time

- Module: Commercial TOPCon module. UVID-120 + 3 months of dark storage. Tapped out single cell.
- Plotting change in SR vs. time using an LED EQE setup. Plot is relative to SR measured at t=0. Bias light turned on at t=0.
- Bias irradiance ~100 W/m2 of 630nm light.
- Overall, getting huge 0% to 45% increase in responsivity depending on wavelength.
- DUT temperature only changes by 3 C during test, and cannot explain the huge increase in blue response.
- How much light needed?
  - This experiment used ~0.01 W/m2 of UV 365 nm.
  - Causes recovery with time constant of 15 minutes.
  - Recovery complete after only a dose of 0.01 Wh/m^2 of UV 365 nm LED.

Recovery is very fast: Even in early morning outdoor conditions of 10 W/m2 (0.4 W/m2 of UV). Expect recovery within 2 minutes





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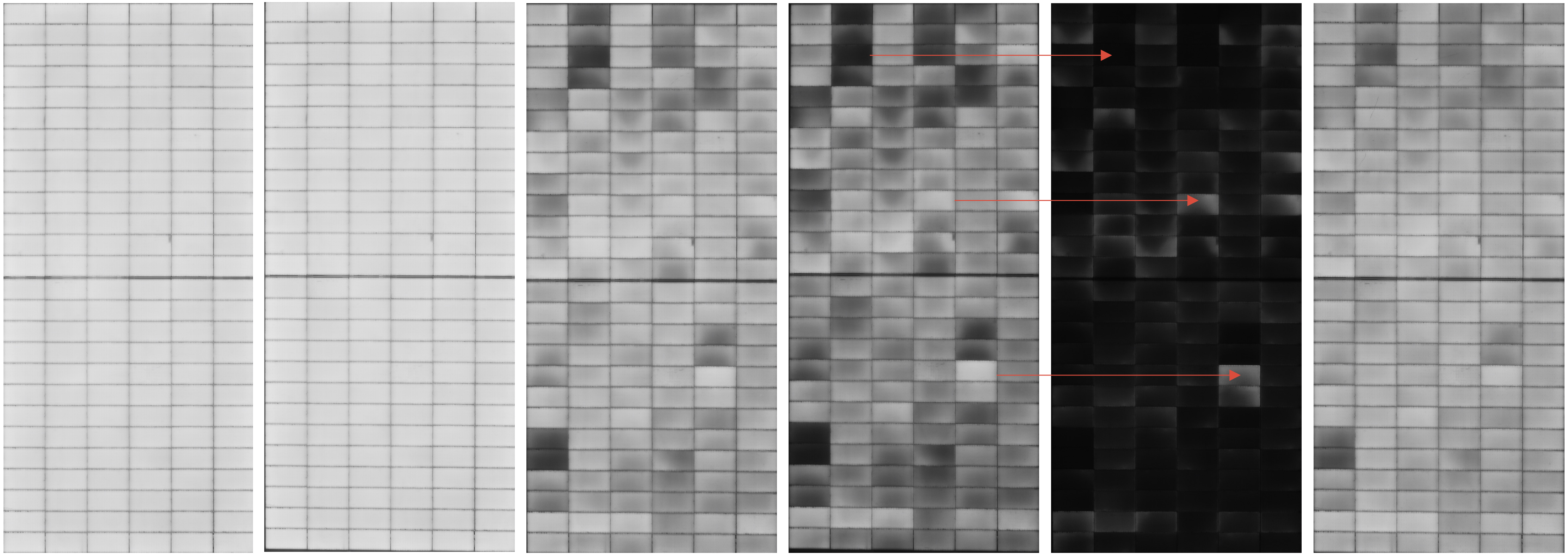
All images taken on same settings.

Correlation between UVID-120 and dark storage EL

- Cells that darken more in UVID also darken more in dark storage.
- Full recovery is not achieved.

Pre-LID | LID 40 kWh/m2 Pmp: +0.3% | UVID-60 Pmp: -3.7% | UVID-120 Pmp: -6.2% | Dark storage 13D | Light Soak 2 kWh/m2



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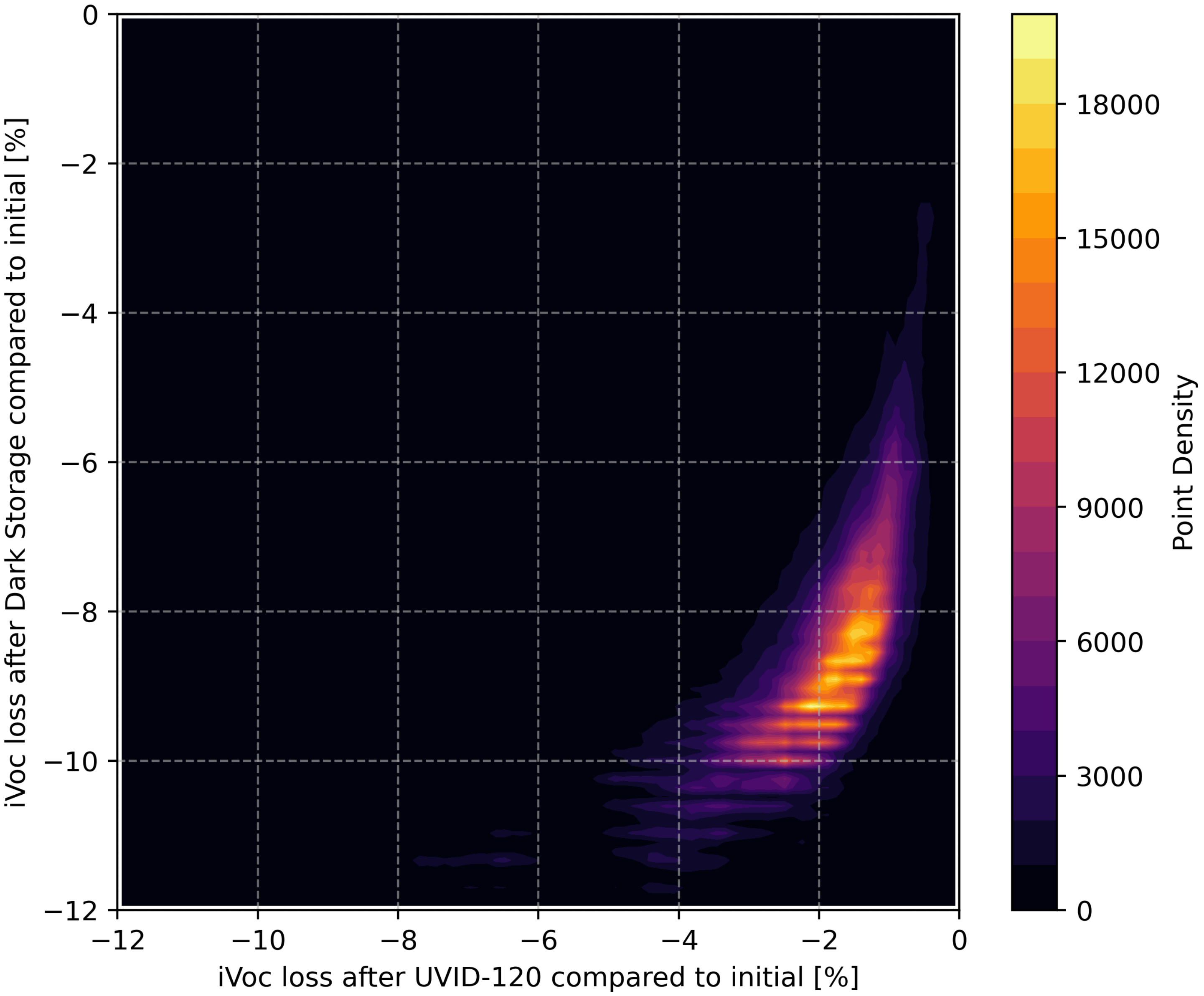
Susceptibility to UVID correlated to dark degradation

- **The areas of cells that degrade more in UV also degrade more in dark storage.**
- Starting to see saturation of dark storage loss.

The defects created by UVID are the source material for the dark storage defect



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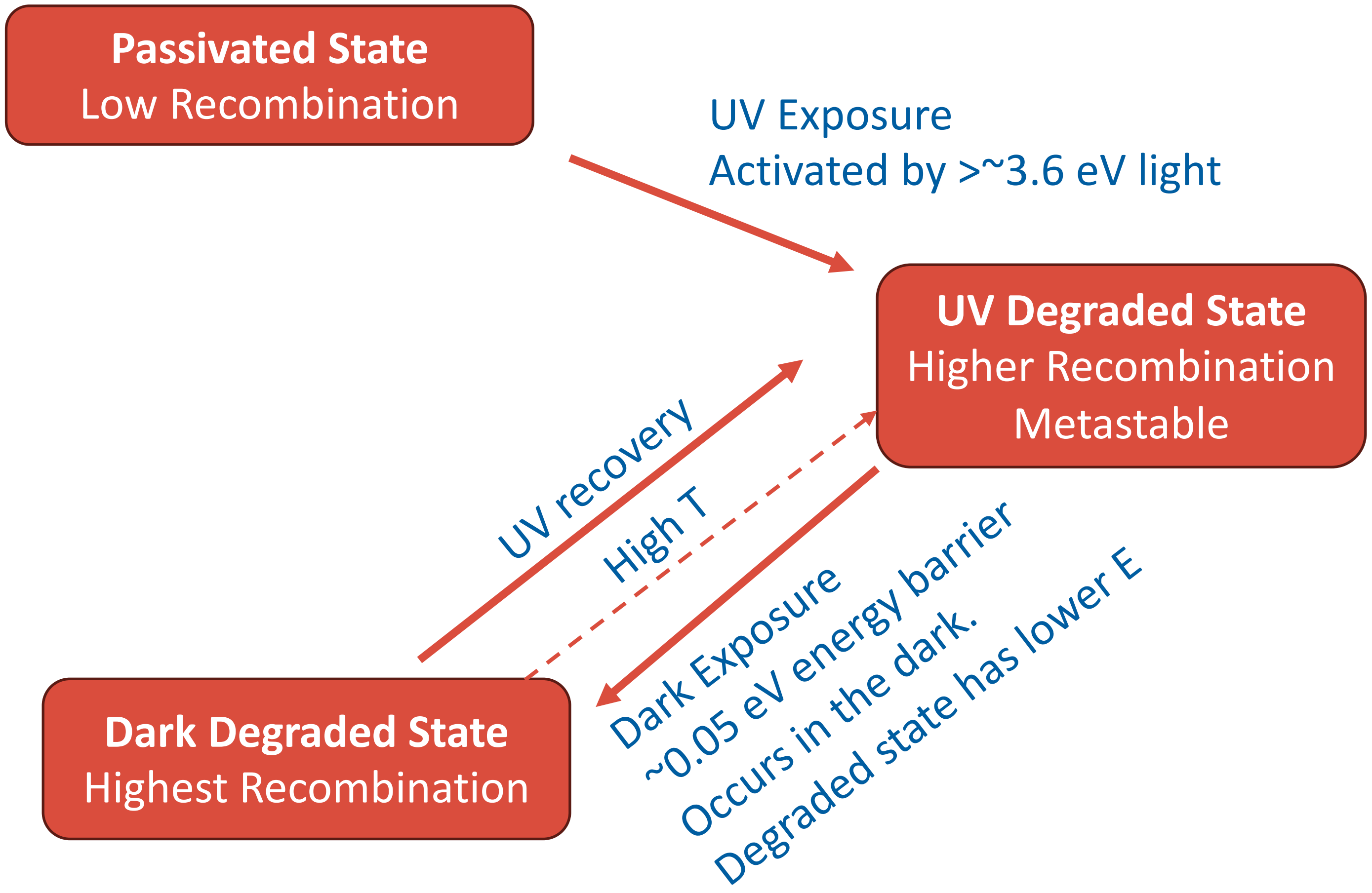
Hypothesis for UVID + Metastability three state model on TOPCon cells

Observations

1. Dark degradation rate low before UVID.
2. UVID damages front-side passivation.
3. Dark degradation occurs quickly (~days) once UV degraded.
4. Rate of dark degradation is correlated to extent of UVID.
5. UV light can reverse dark storage degradation
6. Full recovery to initial state is not achieved.
7. High temperatures can partially recover (prior work)



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UVID Recovery on HJT Module

Conclusion: HJT cells are different, they degrade in Isc and FF during dark storage

(*low sample size)

- Voc is perfectly stable, degradation driven by Isc loss.
- Suspect a different mechanism from TOPCon: contact resistance?

Step#	PMP	VOC	VMP	ISC	IMP	PMP%	VOC%	VMP%	ISC%	IMP%
Post-LID	555.32	53.66	45.73	12.83	12.14					
UVID60#1	550.43	53.66	45.62	12.76	12.07	-0.88	0.00	-0.24	-0.55	-0.58
UVID60#2	549.26	53.67	45.64	12.73	12.04	-1.09	0.02	-0.19	-0.75	-0.83
2-day	546.91	53.67	45.51	12.68	12.02	-1.51	0.02	-0.47	-1.14	-0.99
2-week	546.98	53.64	45.67	12.67	11.98	-1.50	-0.04	-0.13	-1.25	-1.32
Post-LID	554.28	53.68	45.92	12.8	12.07					
UVID60#1	550.66	53.69	45.8	12.76	12.02	-0.65	0.02	-0.26	-0.31	-0.41
UVID60#2	549.03	53.71	45.77	12.71	12.00	-0.95	0.06	-0.32	-0.67	-0.59
2-day	548.60	53.72	45.77	12.71	11.99	-1.02	0.08	-0.32	-0.67	-0.67
2-week	548.06	53.7	45.83	12.68	11.96	-1.12	0.04	-0.20	-0.94	-0.91

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UVID Recovery by technology

Pmax	Bad PERC	Good PERC	HJT	Bad TOPCon	Good TOPCon	Tiers1 TOPCon	Bad TOPCon (outdoor)
Initial	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LID	0.0%	0.0%	0.1%	0.4%	-0.1%	-0.1%	-0.7%
UVID60	-1.9%	-1.3%	-2.7%	-3.7%	-1.0%	-3.1%	-3.5%
UVID120	-3.0%	-1.9%	-4.5%	-5.6%	-1.4%	-4.4%	-11.1%
Dark Storage	-3.8%	-2.3%	-6.3%	-12.3%	-2.6%	-12.1%	-10.1%
LS 50Wh/m^2	-3.8%	-2.4%	-6.0%	-5.7%	-2.4%	-5.0%	-3.4%
LS 1000Wh/m^2	-3.7%	-2.3%	-5.5%	-5.6%	-2.3%	-4.9%	-3.4%

TOPCon/PERC: Short light soak is sufficient

HJT: Short light soak not sufficient, need 0.5 to 1.0 kWh/m2

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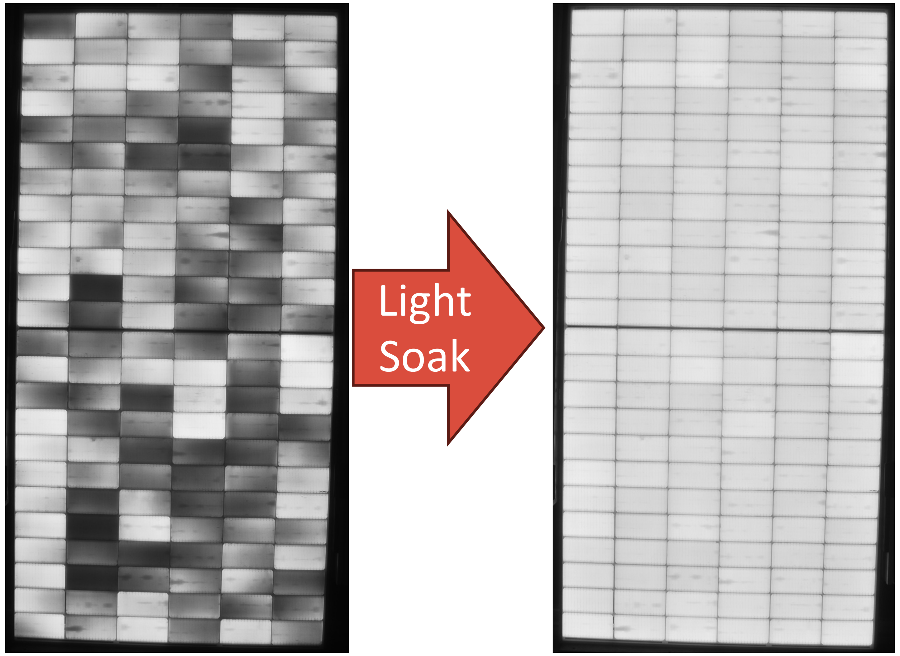
Kiwa PVEL's new stabilization procedure.

- Kiwa PVEL's new stabilization procedure uses a **full spectrum light soak**
  - Light source requirement:
    - Intensity over 500 W/m2, indoors or outdoors.
    - Class CCC light source, with sufficient UVA.
  - <u>TOPCon or PERC</u>: At least 100 Wh/m^2 of light with at least 4 Wh/m^2 of UVA. (320-400 nm)
  - <u>HJT</u>: At least 500 Wh/m^2 of light with at least 20 Wh/m^2 of UVA.
  - CdTe: no light soak requirement (different stabilization procedure)
  - Soak performed at open-circuit.
  - Total dose not to exceed 2000 Wh/m^2
- Module to be flashed within 4 hours of coming off light soaking.



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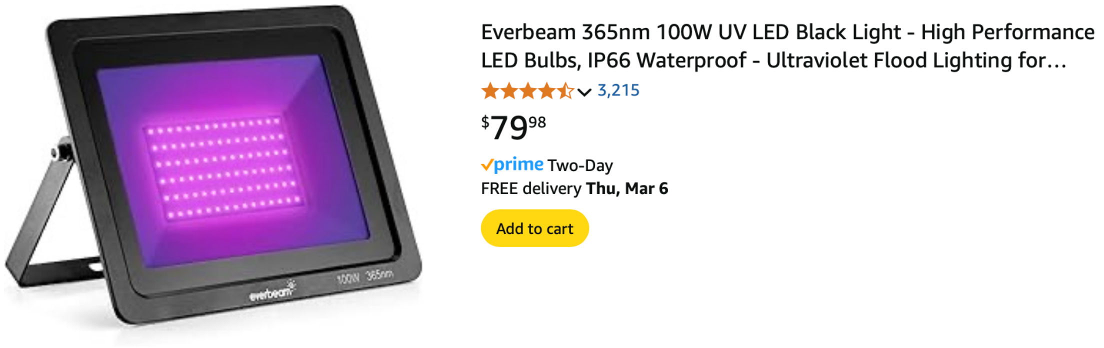
El Cheapo module stabilization

- Kiwa PVEL uses a full spectrum light soak.
- But what if you don't have access?
- **Indoors**: 365 nm LEDs work great for stabilization. They are cheap, easy to use, and don't heat the module (wear safety glasses!)
- **Outdoors:** TOPCon stabilizes completely in 2 minutes of >500 W/m2 sun conditions (probably shorter).

Do try this at home!



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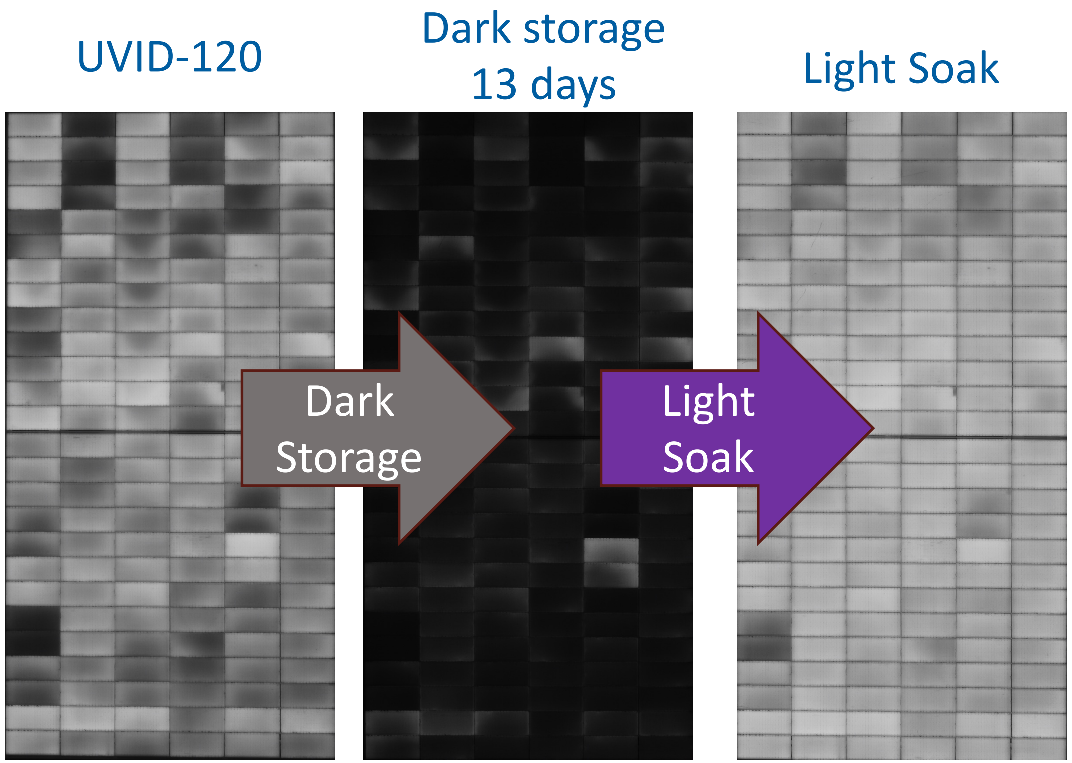
Summary

- **Dark Storage** metastability is a significant problem for test labs:
  - TOPCon (and HJT) modules exposed to UV or outdoors can develop this metastability.
  - Independent test labs and researchers should all **apply light soak** before measurements on UV-exposed modules.
  - A UV-sensitive TOPCon module can degrade in the dark at a rate of 1% power loss per day.
- Dark Storage degradation is <u>not a problem for field performance</u> – it disappears once the sun comes out.

- Mechanism: dark storage degradation on TOPCon is caused by front-side passivation loss and recovery.



Thanks to Duramat Funding

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