Faculty of Engineering
School of Photovoltaic and Renewable Energy Engineering

UNSW SYDNEY Australia's Global University

From the Lab to the Field: Decoding Degradation at Cell, Module, and Field Level for SHJ and TOPCon

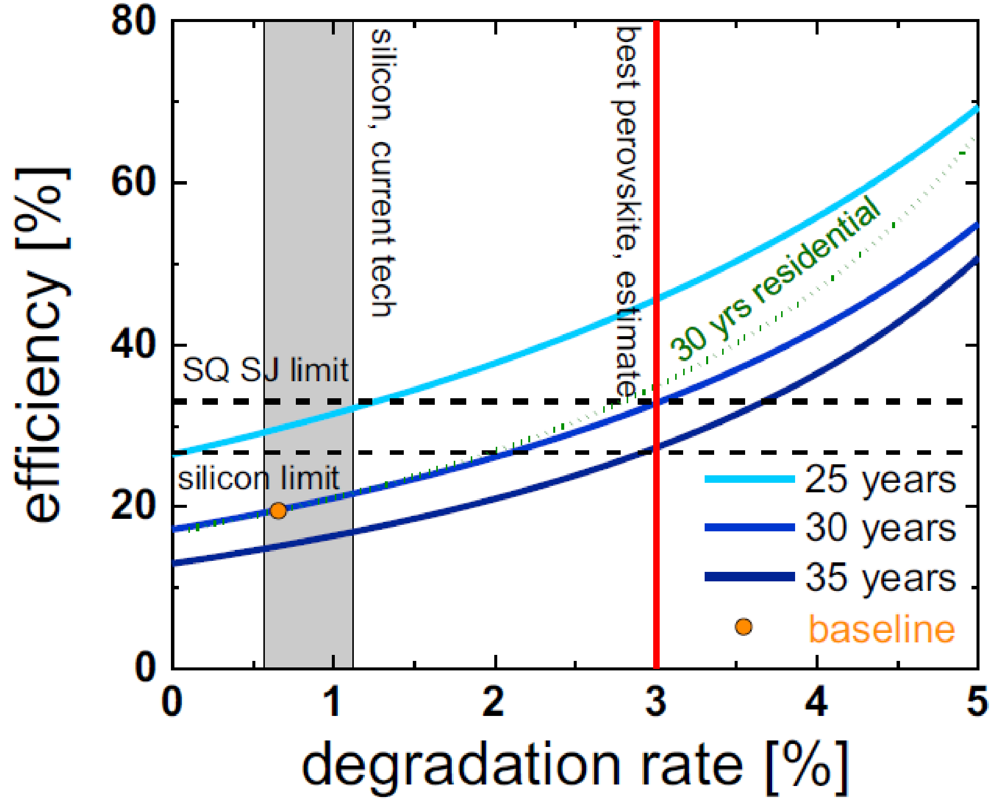
SPREE Seminar, 4 April 2025, Sydney, Australia

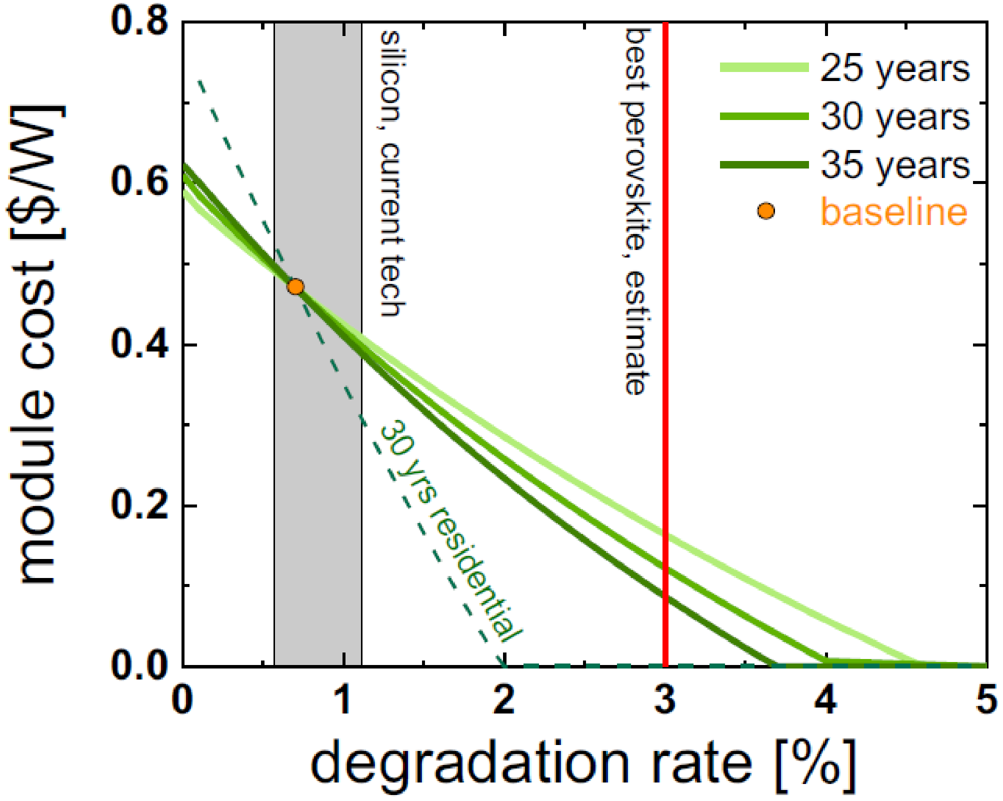
ARENA
Australian Government
Australian Renewable Energy Agency

Bram Hoex, Chandany Sen, Muhammad Umair Khan, Xinyuan Wu, Xutao Wang, Haoran Wang, Jiexi Fu, Shukla Poddar, Phillip Hamer

School of Photovoltaic and Renewable Energy Engineering, UNSW Sydney, Kensington, 2052, Australia

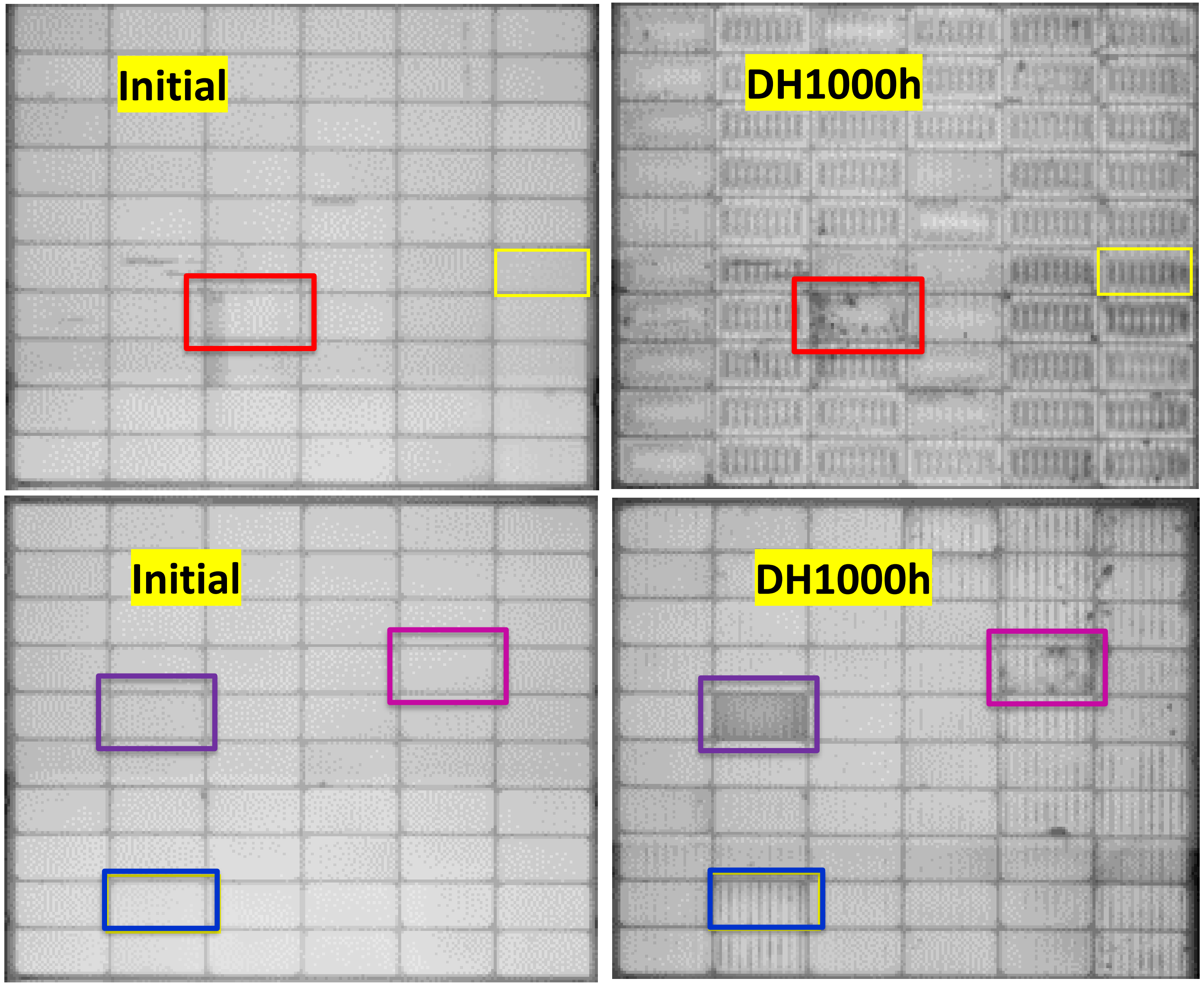
The value of stability vs efficiency





- Peters et al., Joule 3, 1–16, 2019

Failure in HJT glass-backsheet modules



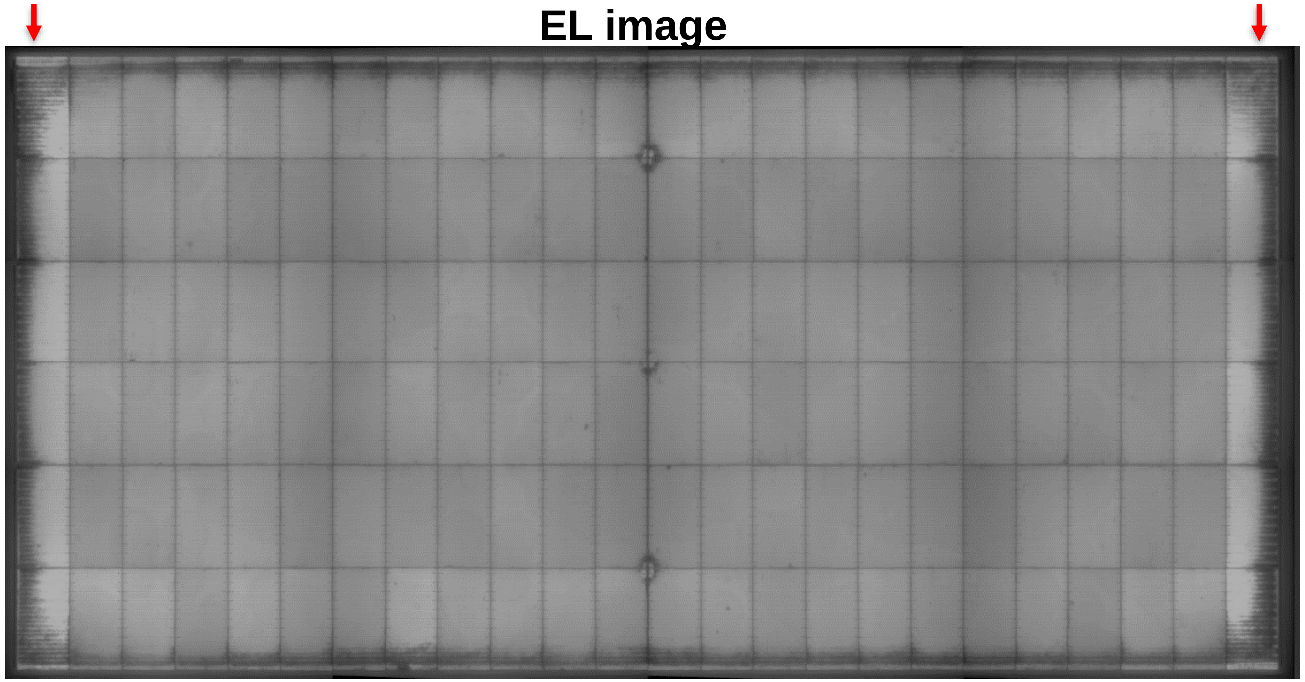
EL images of HJT full modules before and after 1000 h of DH testing

- Several failure modes in the HJT glass-backsheet full modules were detected with losses up to 22.5%$_{rel}$
- The root causes of each failure mode were unclear
- These failure modes occurred randomly in the full-modules
- Some of these failure modes were not observed in PERC modules previously
- Limited/no reports on failure modes in HJT glass-backsheet modules
- Cell-level testing developed for PERC cells (IEC 61215-2:2016) is unable to detect these failure modes

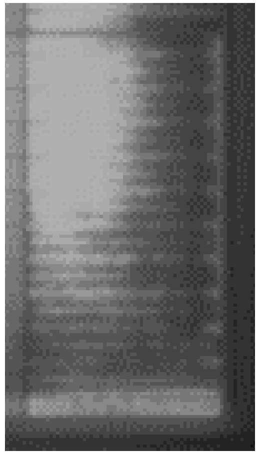
Source: Sen, Khan, Hoex et al., 10.1016/j.solmat.2023.112358

Damp heat-induced degradation in TOPCon glass/glass modules

EL image



G/G: EVA/EVA post DH3000 Loss:8.28%$_{rel}$

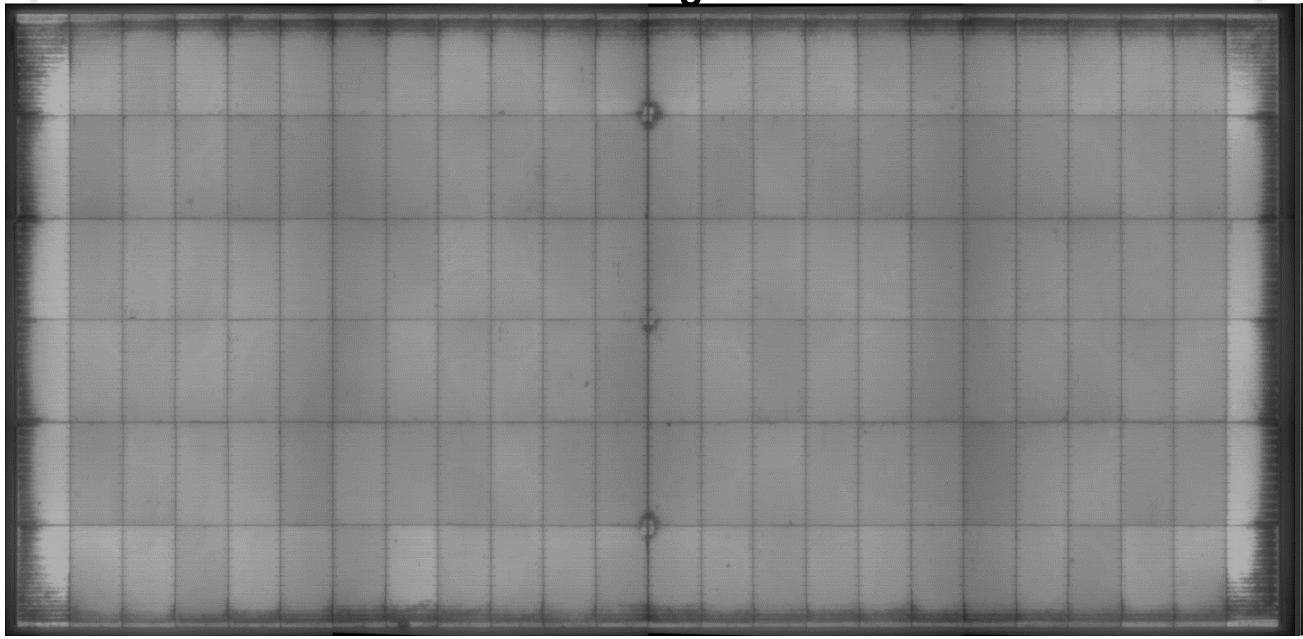


Cell at the edge

→ Speculated root cause of failure: corrosion of front metallization due to a chemical reaction involving **moisture and acetic acid (EVA, EPE) with the front metallization.**

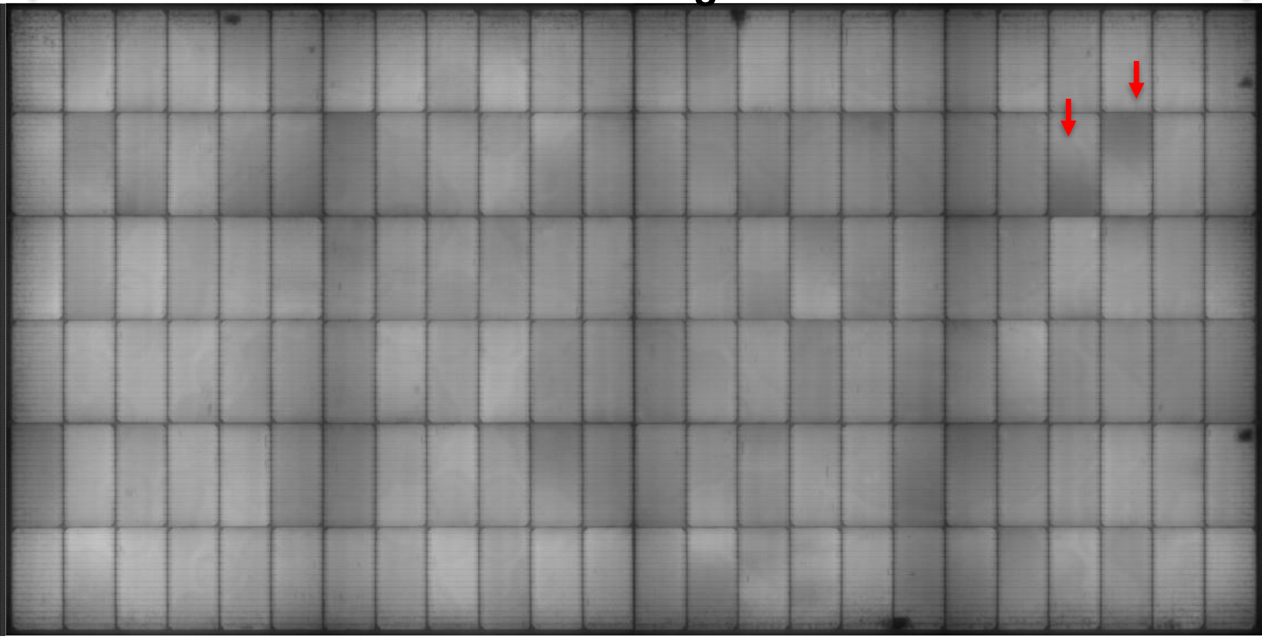
Damp heat-induced degradation in TOPCon glass/glass modules

EL image

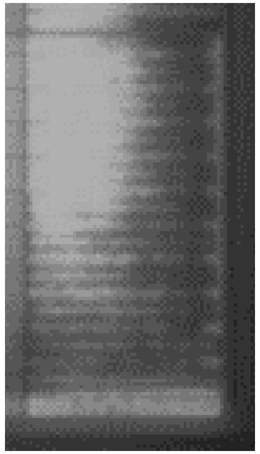


G/G: EVA/EVA post DH3000 Loss:8.28%$_{rel}$

EL image

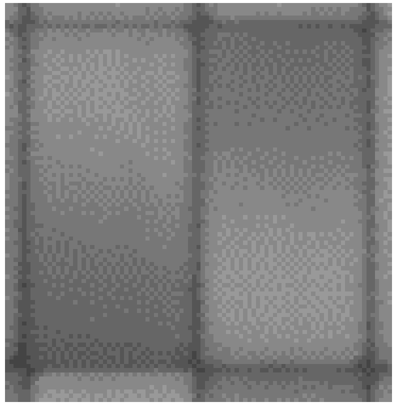


G/G: EPE/EVA post DH3000 Loss (2.8%$_{rel}$)



Cell at the edge

→ Speculated root cause of failure: corrosion of front metallization due to a chemical reaction involving **moisture and acetic acid (EVA, EPE) with the front metallization.**



Cells at the center

Cell at the edge

G: Glass, EVA: Ethylene Vinyl Acetate, POE: PolyOlefin, EPE: EVA-POE-EVA

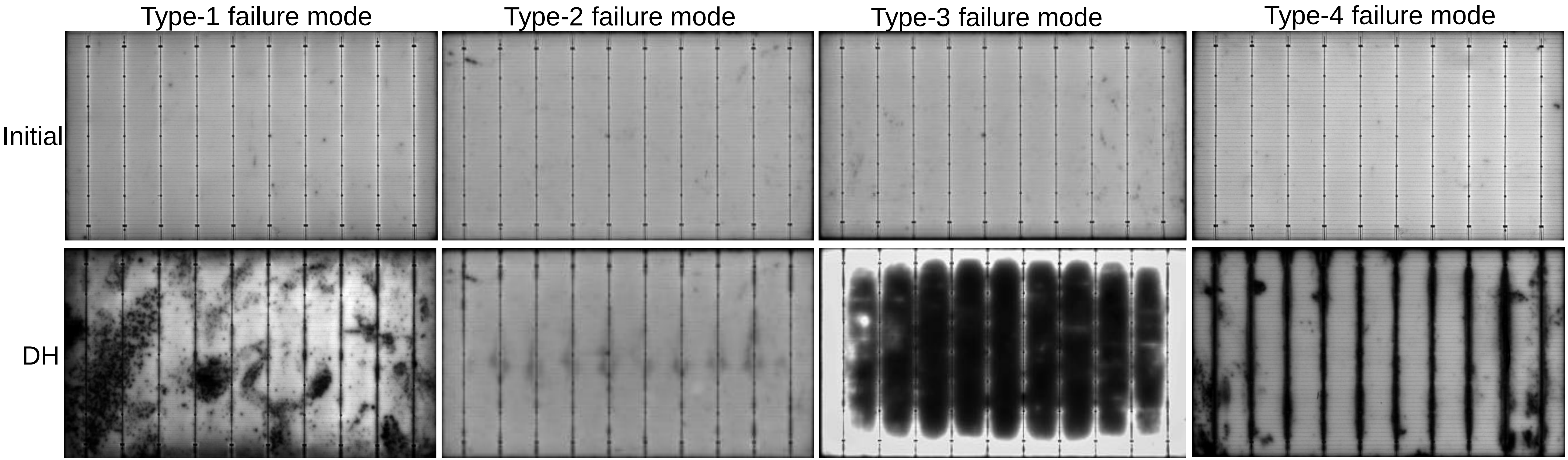
Outline

- Introduction
- Damp-heat failures in HJT and TOPCon solar cells/modules
  - 4 new failure modes in glass-backsheet HJT modules
  - Na^+ induced failures in PERC, TOPCon, and HJT solar cells
  - Flux induced contact failure
- Impact of bill of materials
- UV-induced degradation
- Cell level mitigation of damp-heat failures
- Yield modelling of failure modes
- Conclusions

Outline

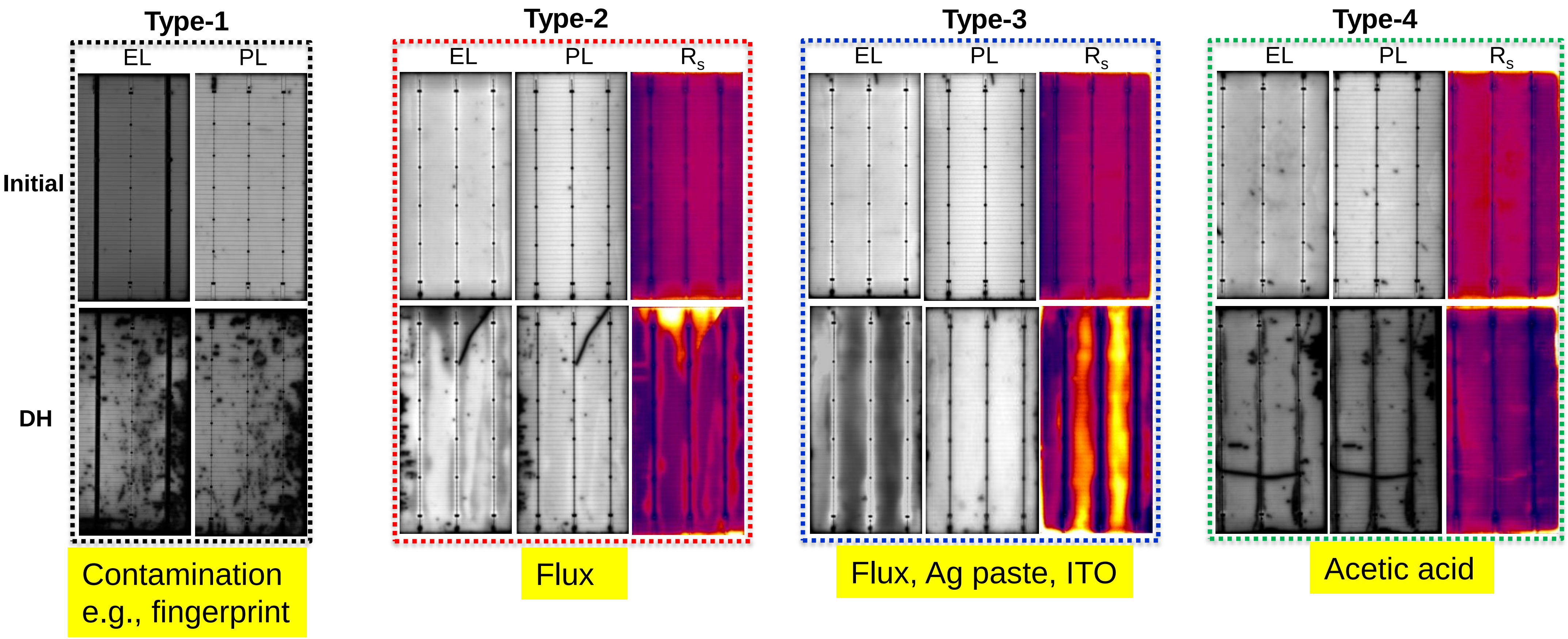
- Introduction
- **Damp-heat failures in HJT and TOPCon solar cells/modules**
  - **4 new failure modes in glass-backsheet HJT modules**
  - Na^+ induced failures in PERC, TOPCon, and HJT solar cells
  - Flux induced contact failure
- Impact of bill of materials
- UV-induced degradation
- Cell level mitigation of damp-heat failures
- Yield modelling of failure modes
- Conclusions

Novel damp-heat failure modes HJT solar cells



- **Four main failure modes found on HJT glass-back sheet modules after the humidity test**
  - Type-1 : **Point** failure (P_{max} loss of up to ~40%$_{rel}$)
  - Type-2 : Failure **around** the interconnection of the busbar and ribbon (P_{max} loss ~5% $_{rel}$)
  - Type-3 : Failure **between** interconnection of busbar and ribbon (P_{max} loss of up to ~50% $_{rel}$)
  - Type-4 : Failure **at/on** the interconnection or busbar and ribbon (P_{max} loss of up to ~16% $_{rel}$)
- **Each failure mode required different approaches to detect and eliminate at the cell level**

Type-1, 2, 3, and 4 failure modes reproduced in non-encapsulated cells



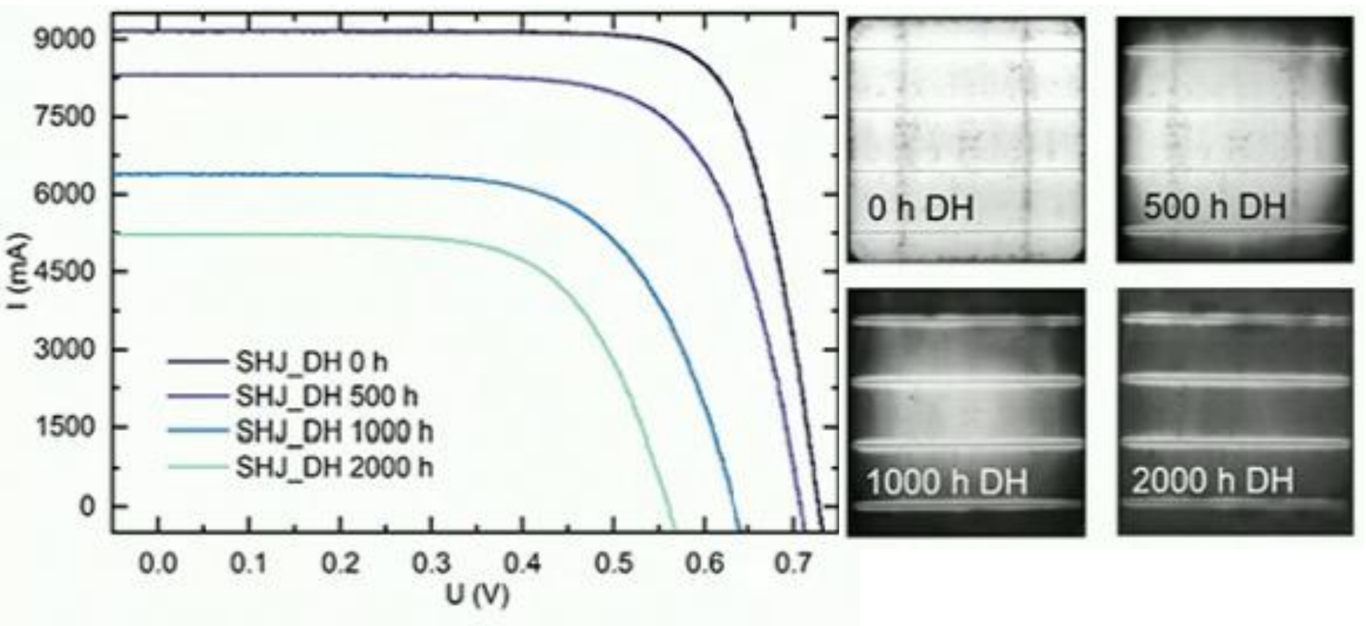
- All four failure modes can be reproduced in the non-encapsulated cells
- Root causes responsible for each failure mode have been identified
- Cell-level testing is one order of magnitude quicker than module-level testing

Outline

- Introduction
- **Damp-heat failures in HJT and TOPCon solar cells/modules**
  - 4 new failure modes in glass-backsheet HJT modules
  - **Na^+ induced failures in PERC, TOPCon, and HJT solar cells**
  - Flux induced contact failure
- Impact of bill of materials
- UV-induced degradation
- Cell level mitigation of damp-heat failures
- Yield modelling of failure modes
- Conclusions

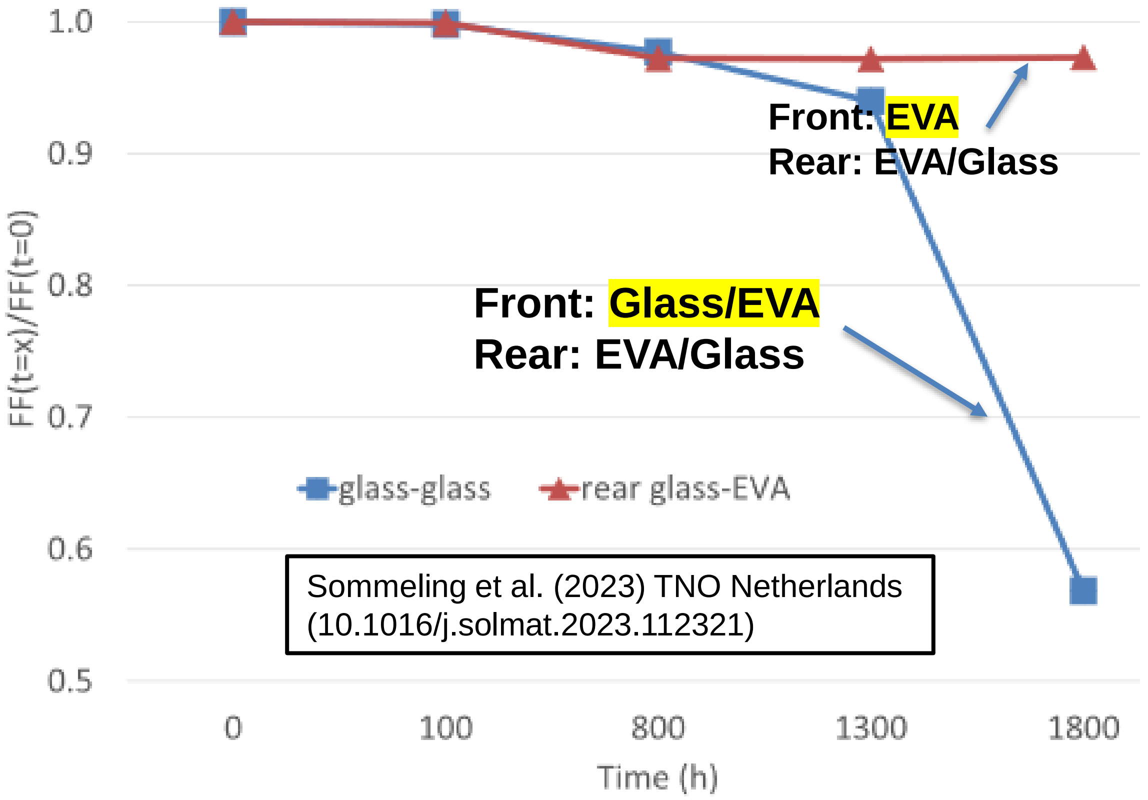
G/G TOPCon and HTJ modules degraded after DH testing

Glass/EVA/Glass HJT



L. Gnocchi et al., EPFL 8th WCPEC 2022

Glass/EVA/Glass TOPCon



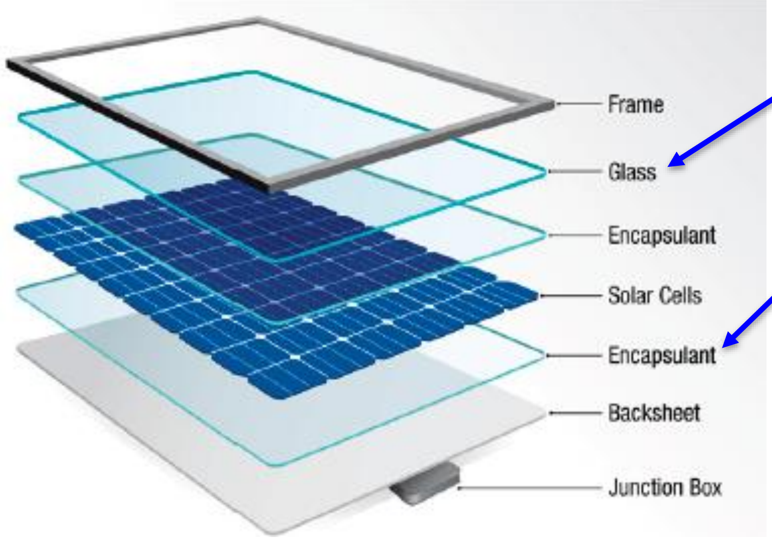
Sommeling et al. (2023) TNO Netherlands (10.1016/j.solmat.2023.112321)

→ Both HJT and TOPCon modules with Glass/EVA/Glass structure severely failed after DH testing

- In the case of HTJ modules, it was speculated that Na^+ might play a role in causing failure
- In the case of TOPCon modules, it was speculated that acetic acid may play a role

→ **However, it is highly likely that Na^+ might be involved in the degradation of both HJT and TOPCon modules**

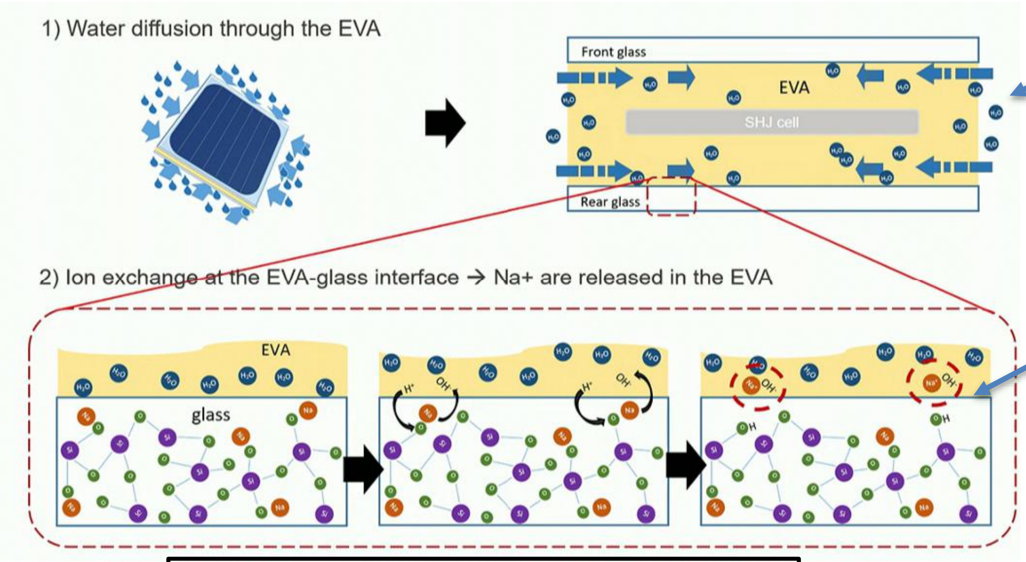
Na$^+$ contained in the module encapsulated material



Na$^+$ (8200mg/kg), double-figure for glass-glass module

White EVA (Na$^+$ ~85 mg/kg)

POE: (Na$^+$ ~32mg/kg)



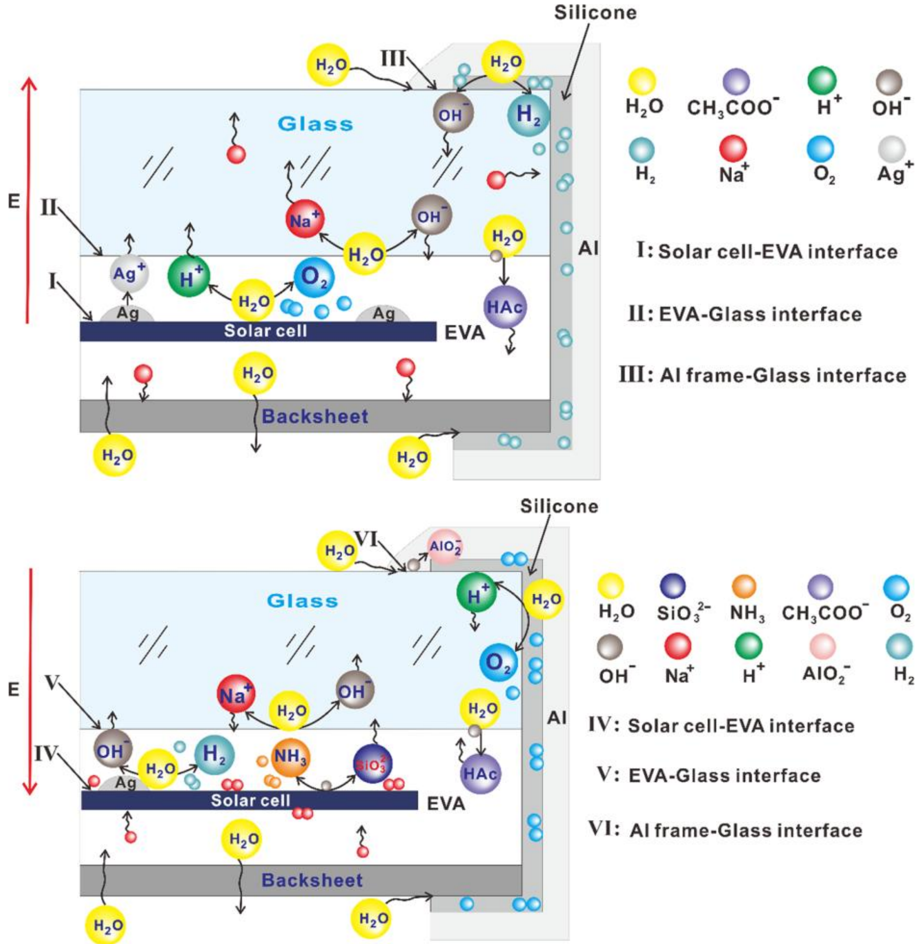
Water diffuses through the EVA

Ion exchange at the EVA-glass interface

→ Na$^+$ released in the EVA

L. Gnocchi et al., 8th WCPEC 2022

High voltage operating conditions → release Na$^+$ from glass

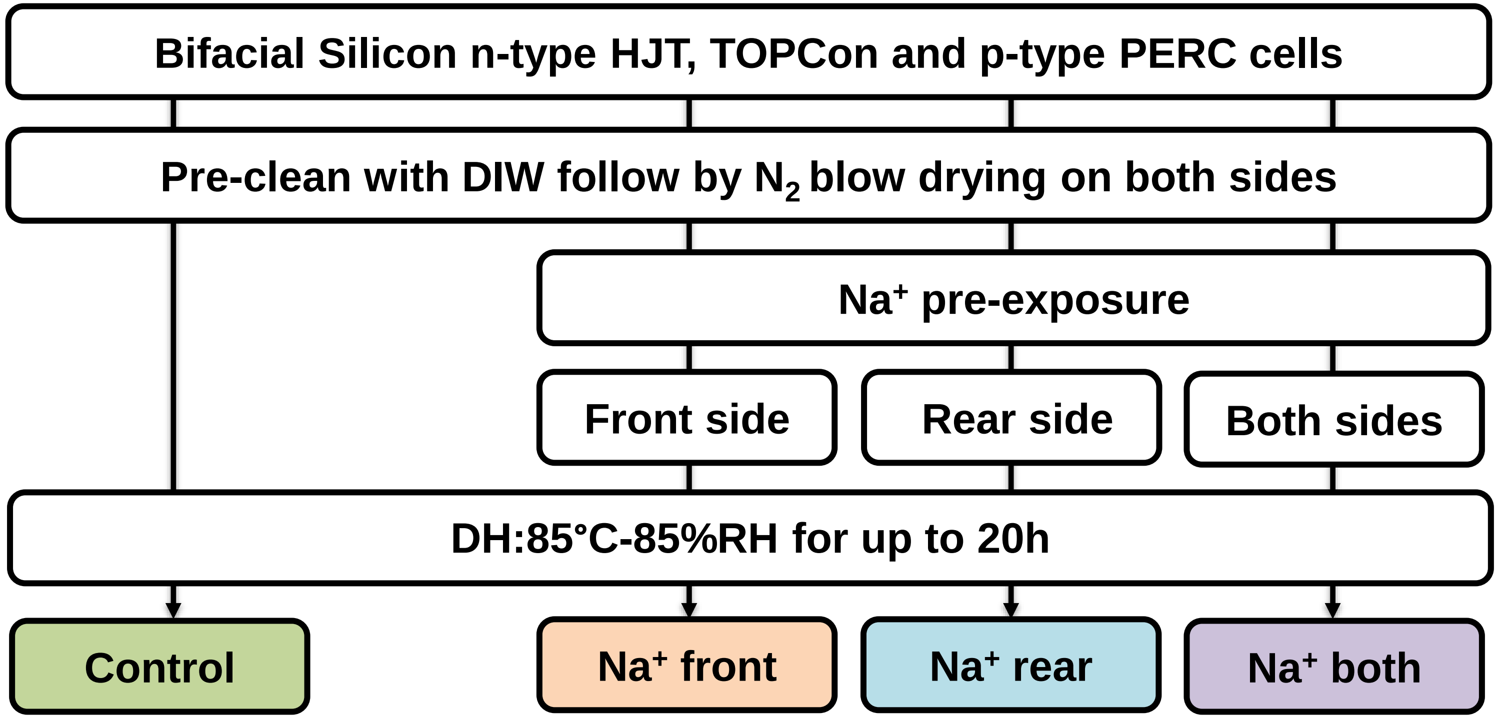


Bai et al. Solar Energy 225 (2021) 718–725

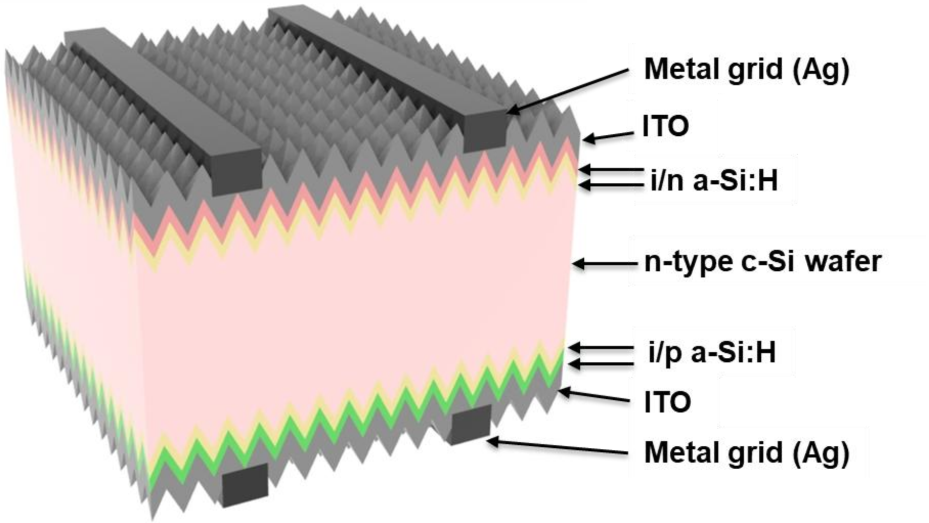
→ How does Na$^+$ impact the HJT, TOPCon and PERC cells during damp heat testing?

UNSW SYDNEY

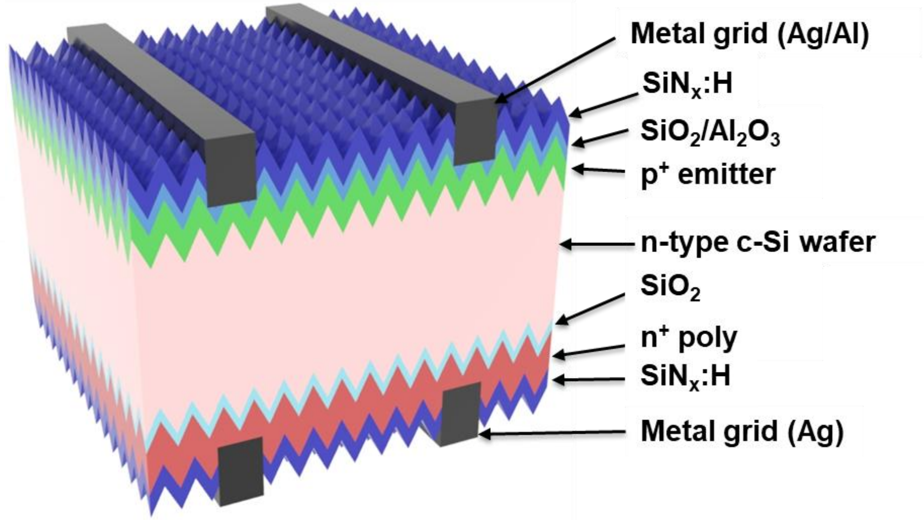
Role of Na^+ in damp heat-induced failure in silicon HJT, TOPCON PERC



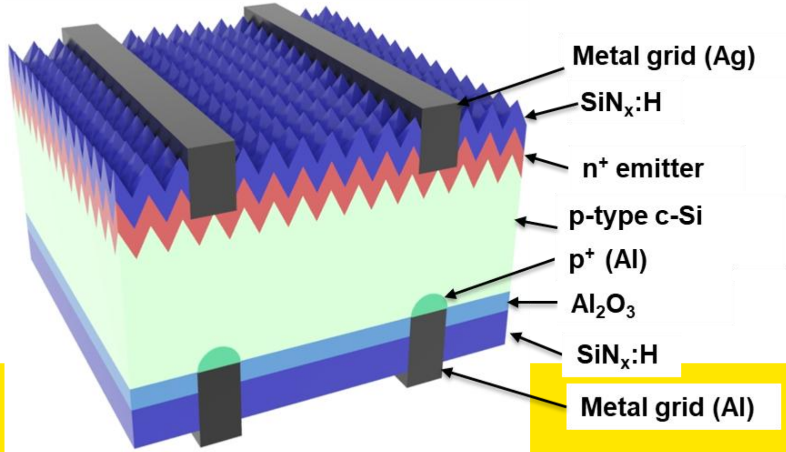
Schematic of the HJT cell



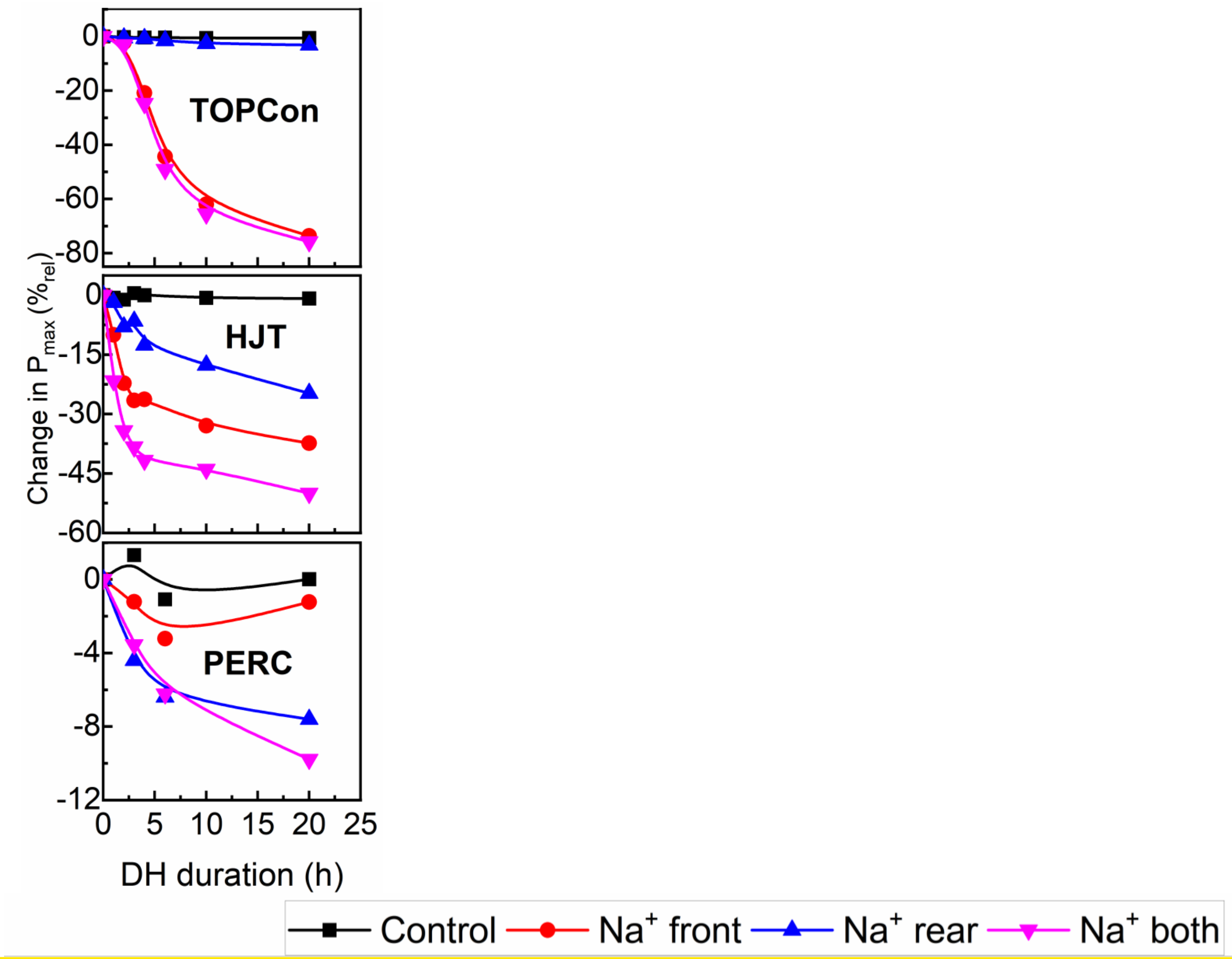
Schematic of the TOPCon cell



Schematic of the PERC cell



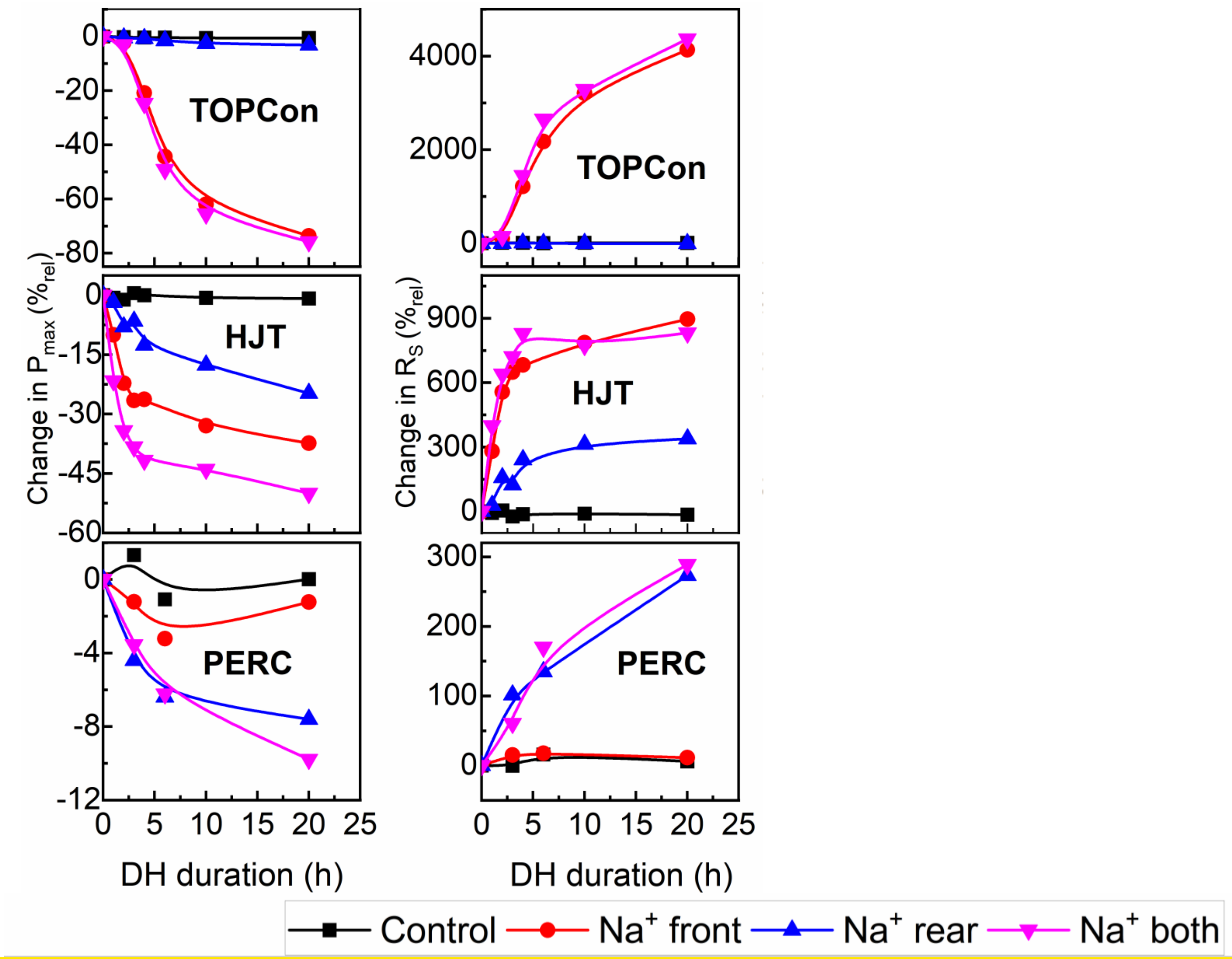
Change in I-V parameters after damp heat testing



- TOPCon cells degrade ~75%$_{rel}$ (mainly on the front side).
- HJT cells degrade ~50%$_{rel}$ (both sides).
- PERC cells degrade ~10%$_{rel}$ (mainly on the rear side).

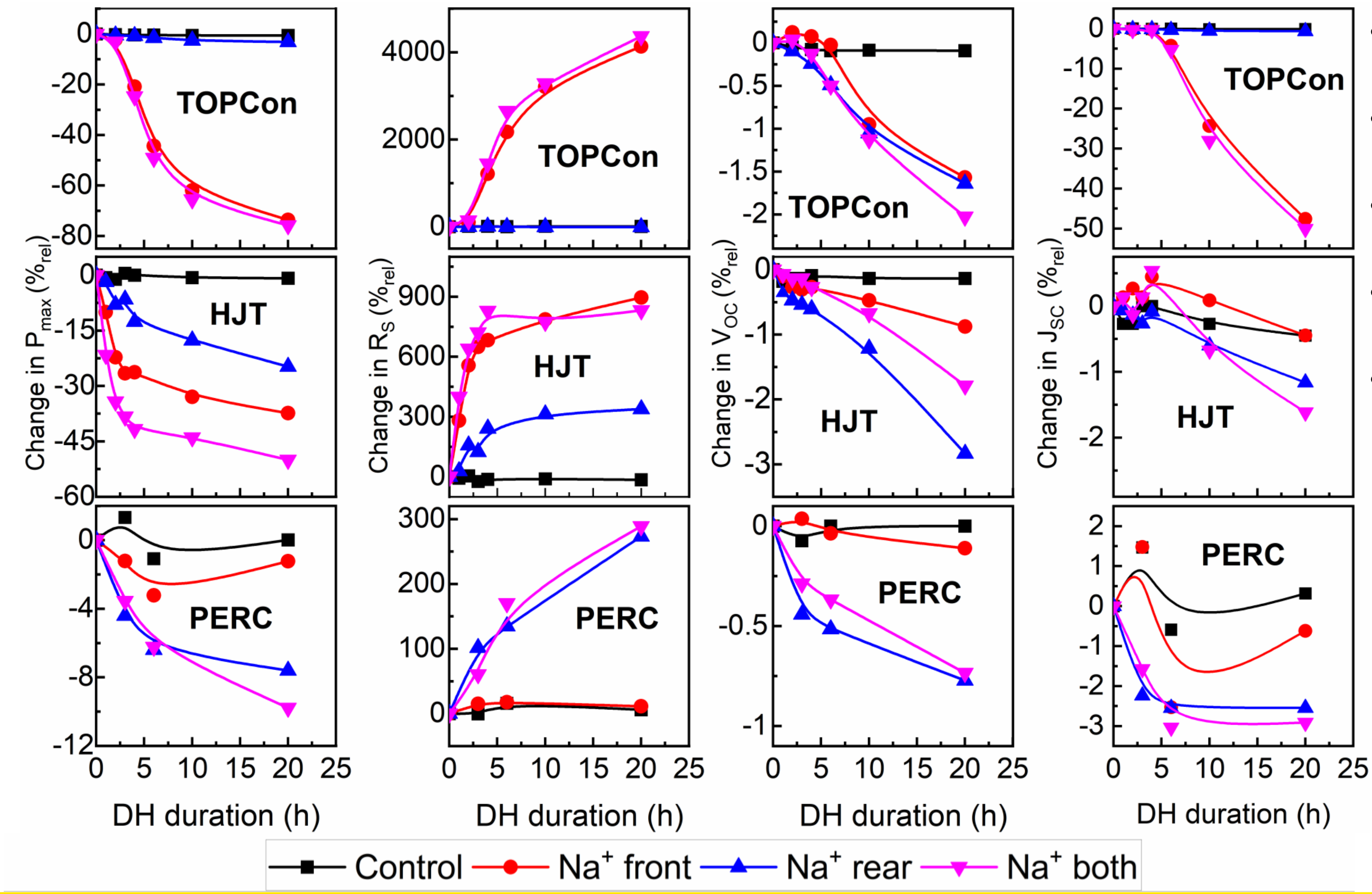
Sen, Wu, Khan, Hoex et al., 10.1016/j.solmat.2023.112554

Change in I-V parameters after damp heat testing



- TOPCon cells degrade ~75%$_{rel}$ (mainly on the front side).
- HJT cells degrade ~50%$_{rel}$ (both sides).
- PERC cells degrade ~10%$_{rel}$ (mainly on the rear side).
- Main loss is due to a severe increase in R_s.

Change in I-V parameters after damp heat testing

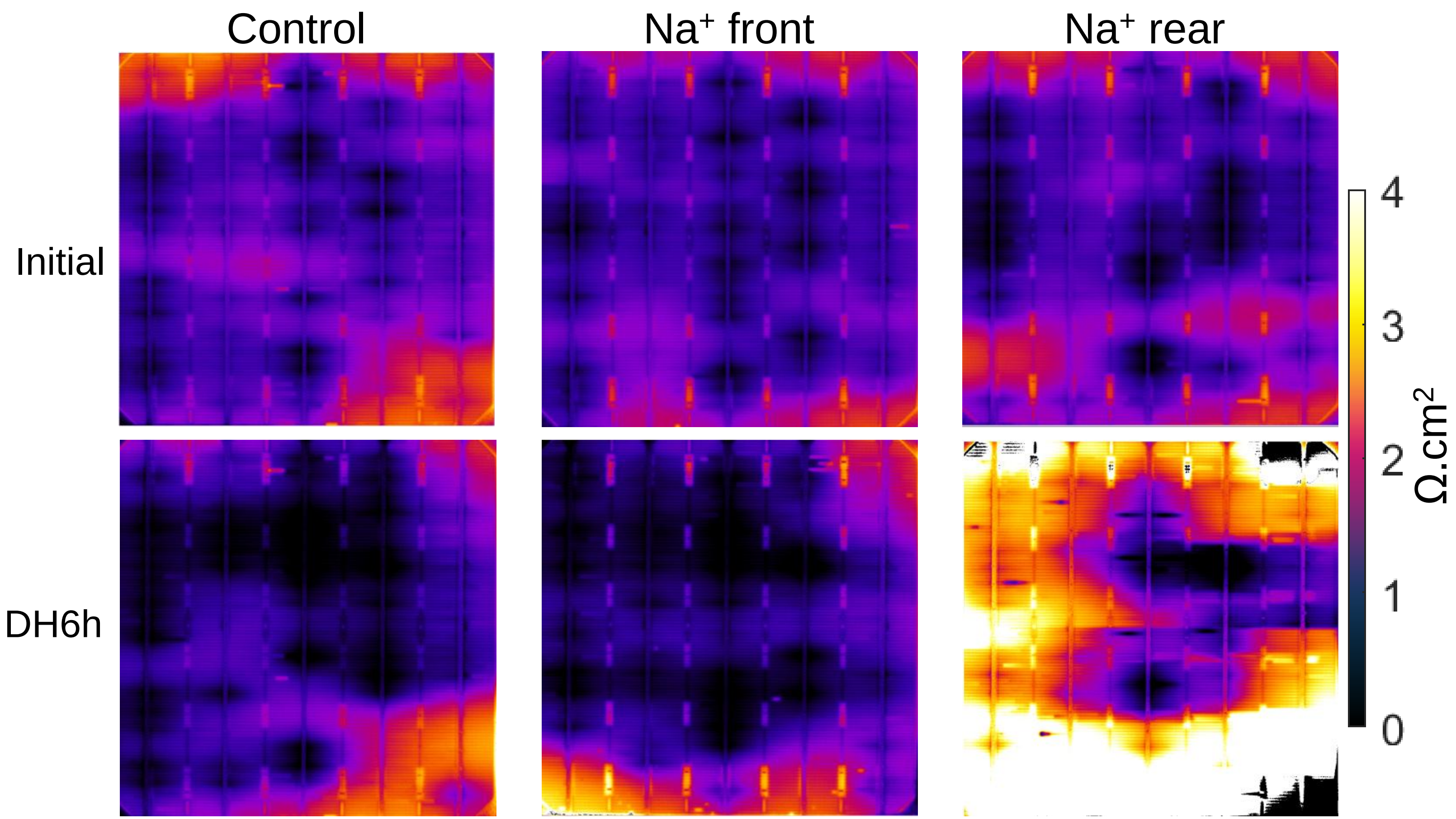


- TOPCon cells degrade ~75$\%_{rel}$ (mainly on the front side).
- HJT cells degrade ~50$\%_{rel}$ (both sides).
- PERC cells degrade ~10$\%_{rel}$ (mainly on the rear side).
- Main loss is due to a severe increase in R_s.
- Slight recombination loss is also observed on both sides of TOPCon and the rear side of HJT and PERC solar cells.
  → V_{OC} and J_{SC} losses

→ Note: a severe drop of J_{SC} (~50$\%_{rel}$) in TOPCon is due to very bad R_s in these cells.

Change in R_s images after damp heat testing of PERC cells

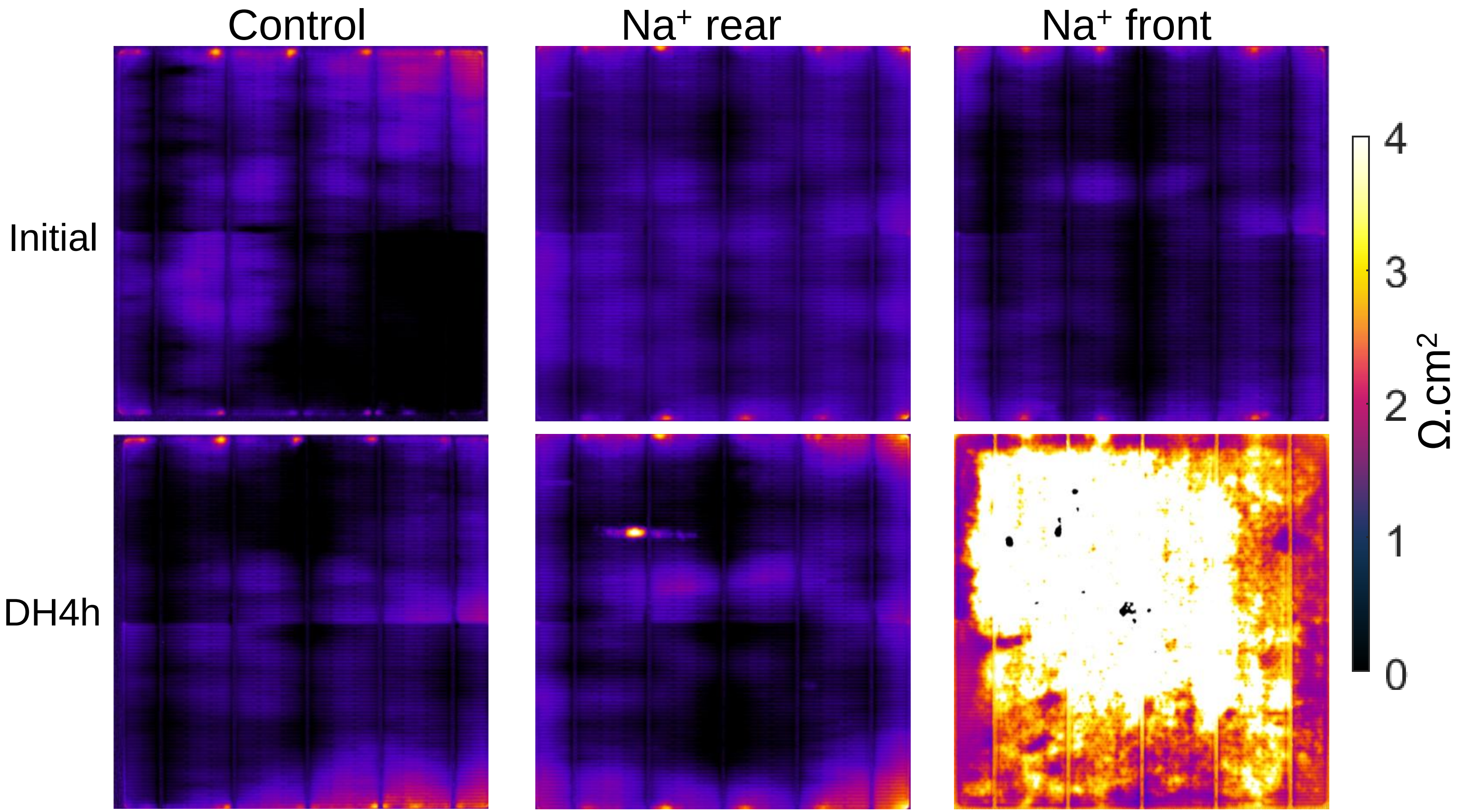
- No R_s change was observed on the control cell, and the cell with Na^+ was exposed only on the front side after damp heat (DH) testing.
- R_s of cells with Na^+ pre-exposed to the rear side substantially increased after DH testing.



Sen, Wu, Khan, Hoex et al., 10.1016/j.solmat.2023.112554

Change in R_s images after damp heat testing of TOPCon cells

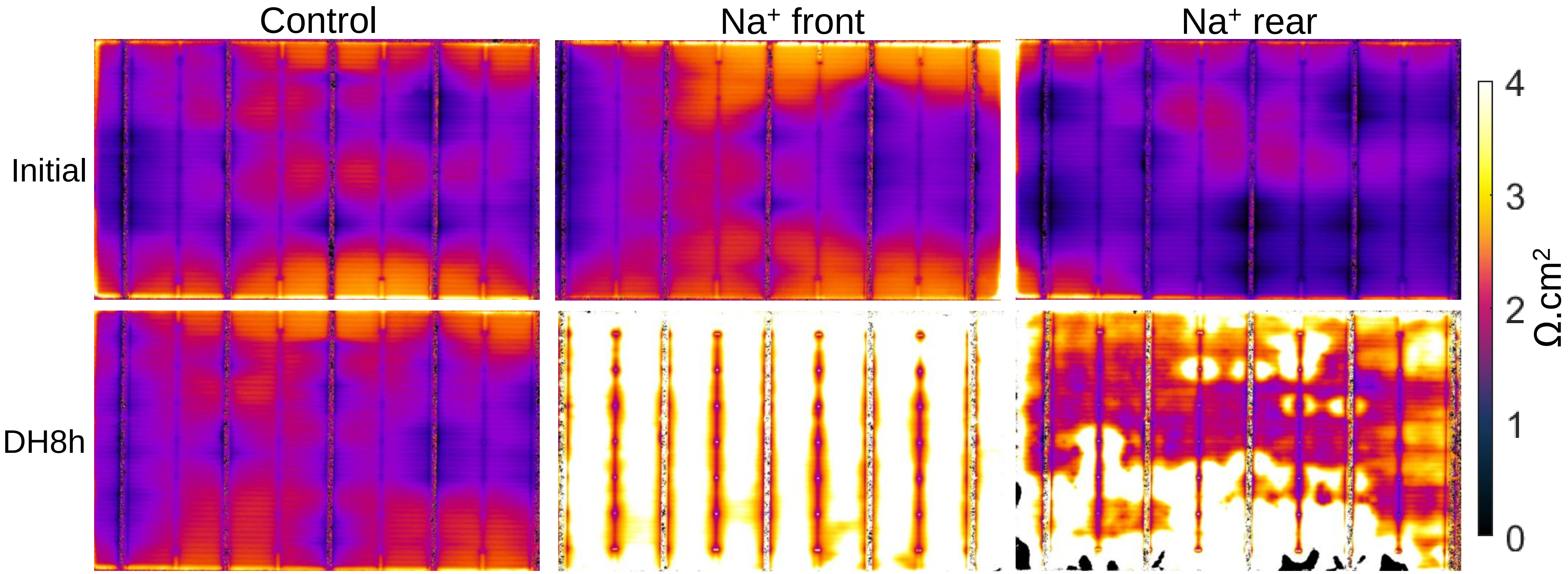
- No R_s change was observed on the control cell, and the cell with Na^+ was exposed only on the rear side after damp heat (DH) testing.
- R_s of cells with Na^+ pre-exposed to the front side substantially increased after DH testing.



Sen, Wu, Khan, Hoex et al., 10.1016/j.solmat.2023.112554

Change in R_s images after damp heat testing of HJT cells

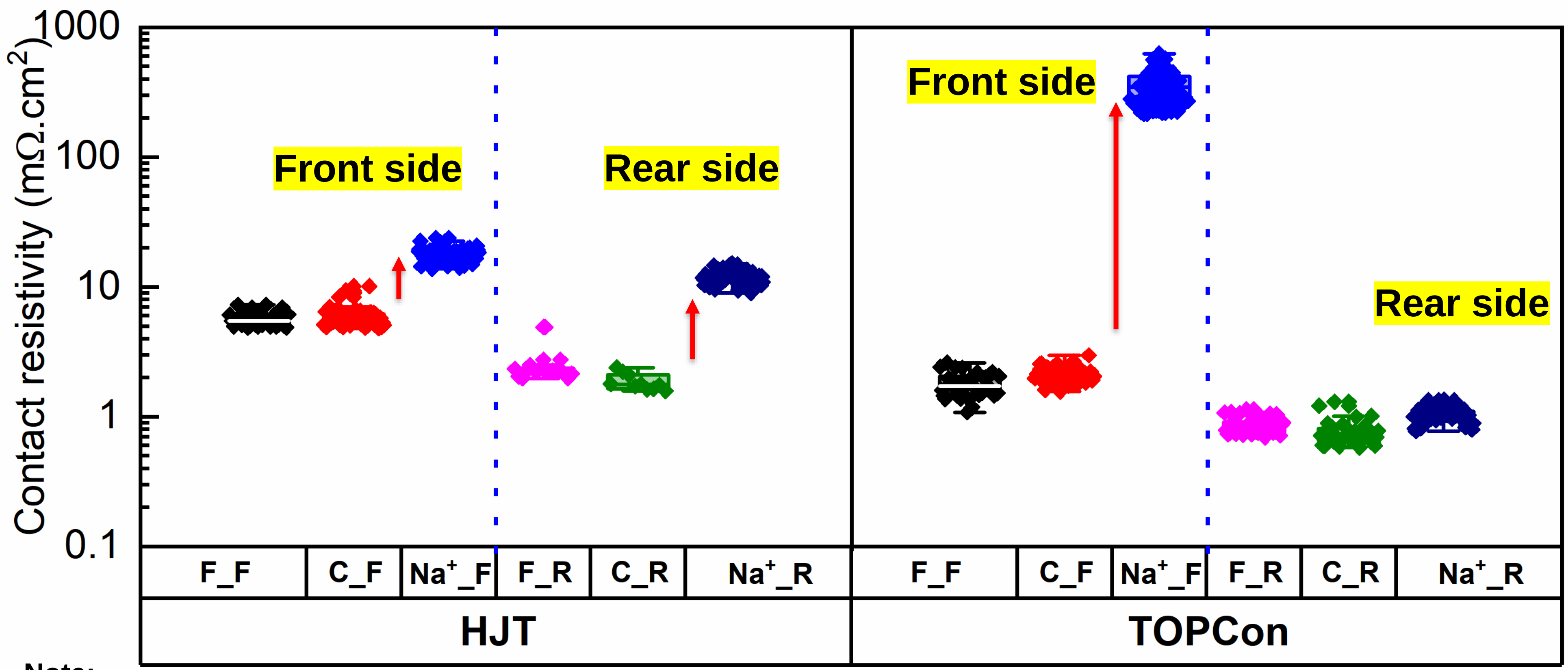
- No R_s change was observed on the control cell.
- R_s of cells with Na^+ pre-exposed to the front or rear side substantially increased after DH testing.



Sen, Wu, Khan, Hoex et al., 10.1016/j.solmat.2023.112554

Increase in contact resistivity after damp heat testing

- No change in contact resistivity of the control cells (values are the same as the fresh cell that did not undergo DH testing).
- Contact resistivity of HJT cells with Na^+ exposed only on the front or rear sides increased substantially after DH testing.
- Contact resistivity of TOPCon cells with Na^+ exposed only on the front side significantly increased.

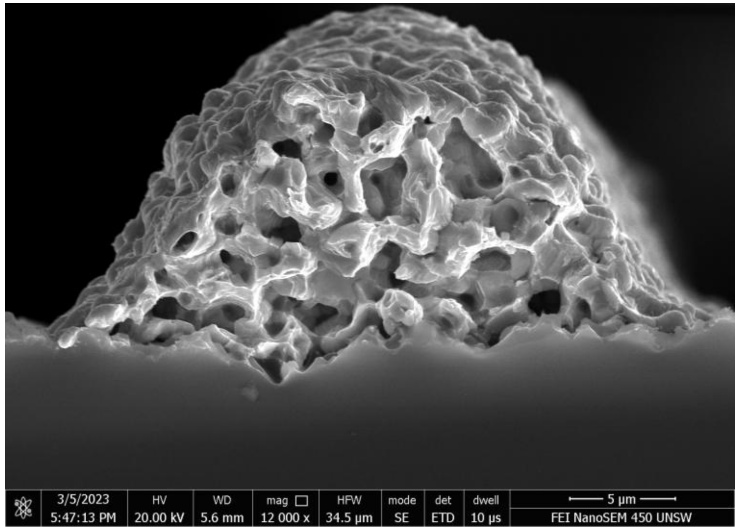


Na^+_F : Na^+ front
C_F: Control, front side
F_F: Fresh, front side
Na^+_R: Na^+ rear
C_R: Control, rear side
F_R: Fresh, rear side

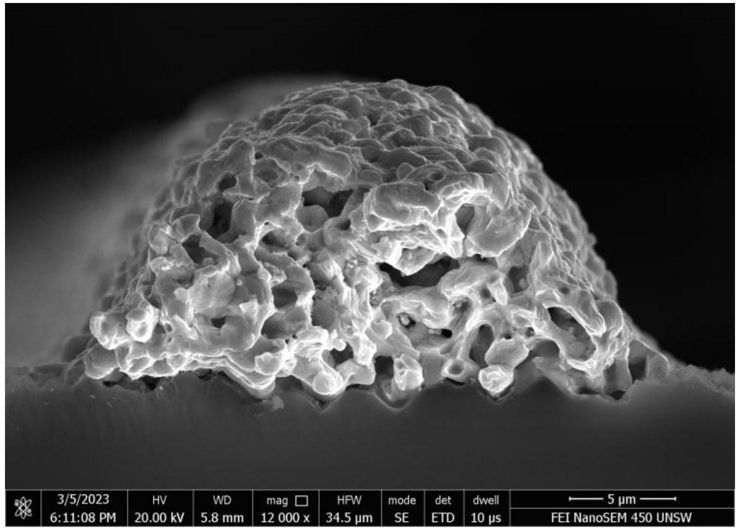
Note:
1. Contact resistivity on the rear side of the PERC cell was unable to measure as rear contact was completely compromised after 20h of DH testing.
2. No change in sheet resistance of all cells was observed after the DH test (data not shown here).

PERC contact: SEM cross-section and top-view images

Control front

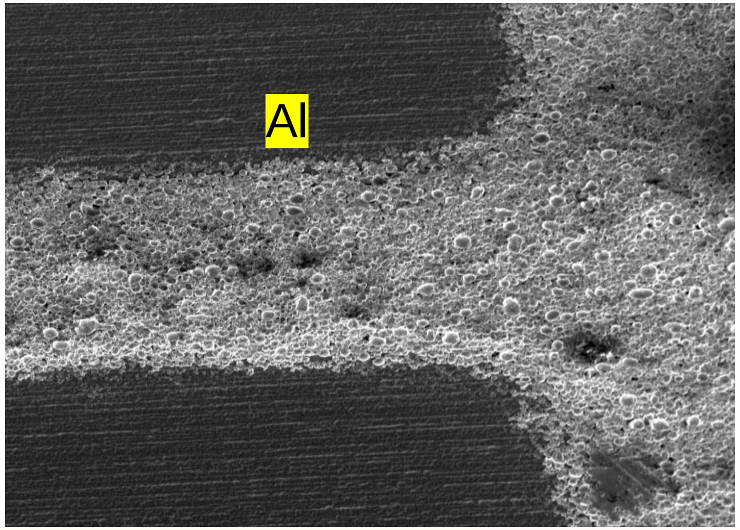


Na+ front

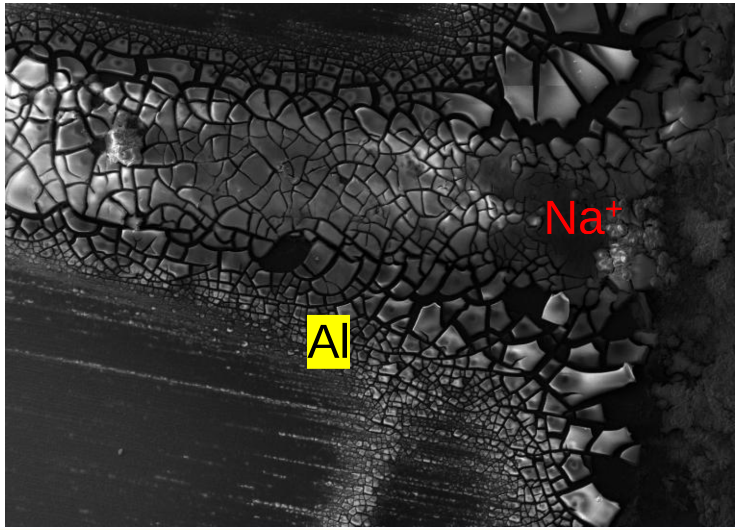


No significant change

Control rear



Na^+ rear



Completely damaged

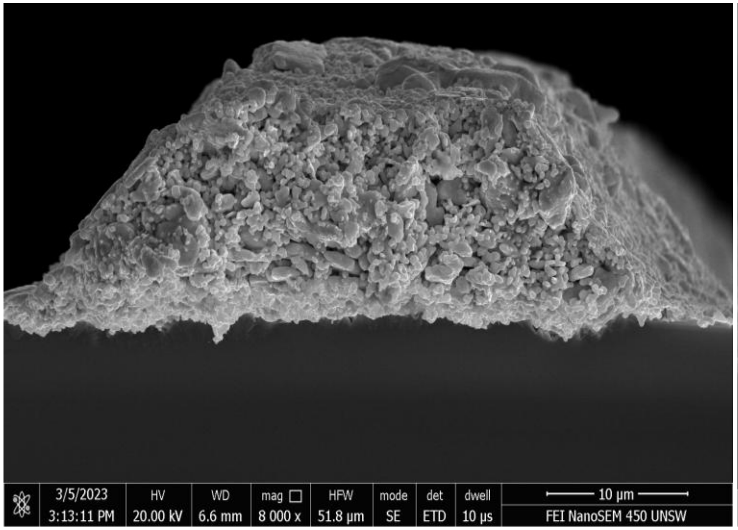
→ **Chemically reaction between Al contact, Na^+ and moisture, leading to corrosion of the contact electrode**

Sen, Wu, Khan, Hoex et al., 10.1016/j.solmat.2023.112554

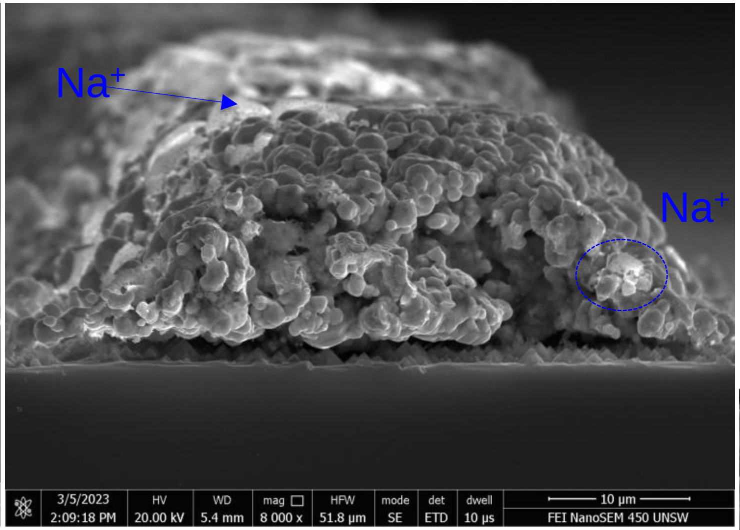
UNSW SYDNEY

HJT contact: SEM-cross section images

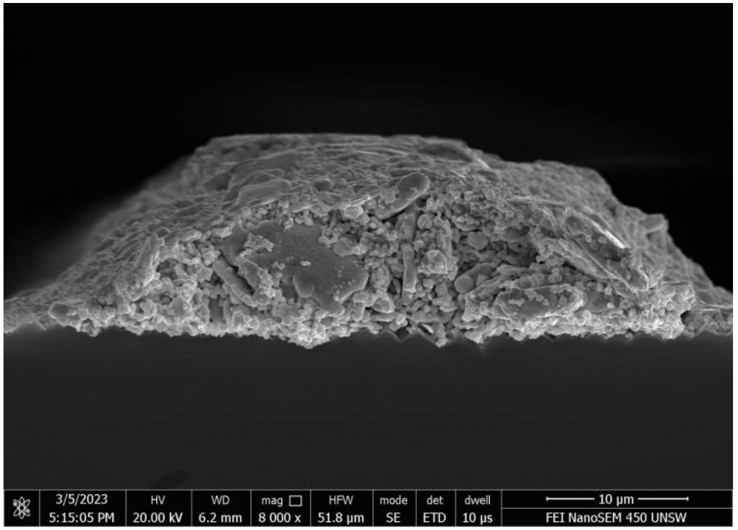
Control front



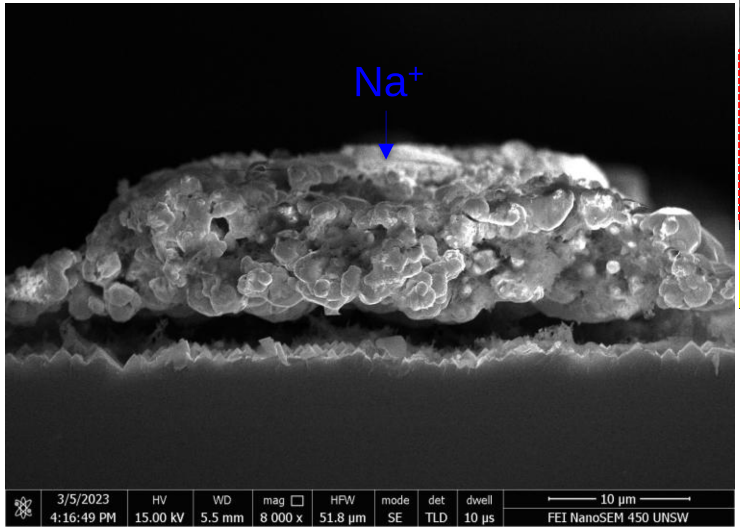
Na$^+$ front



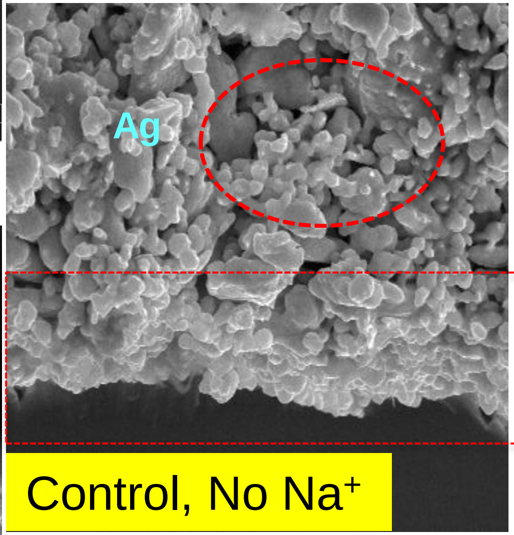
Control rear

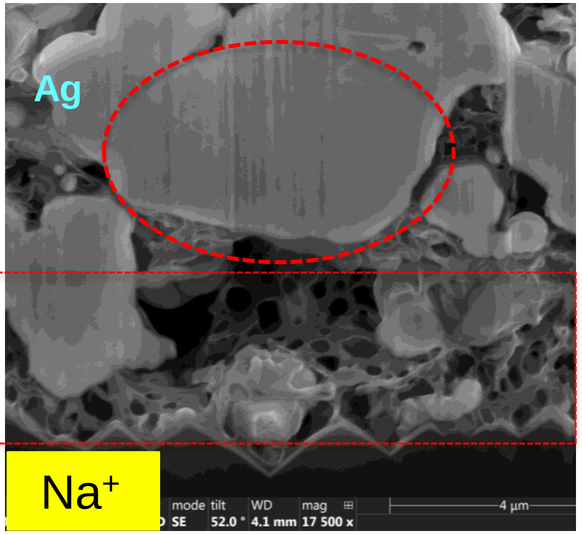


Na$^+$ rear



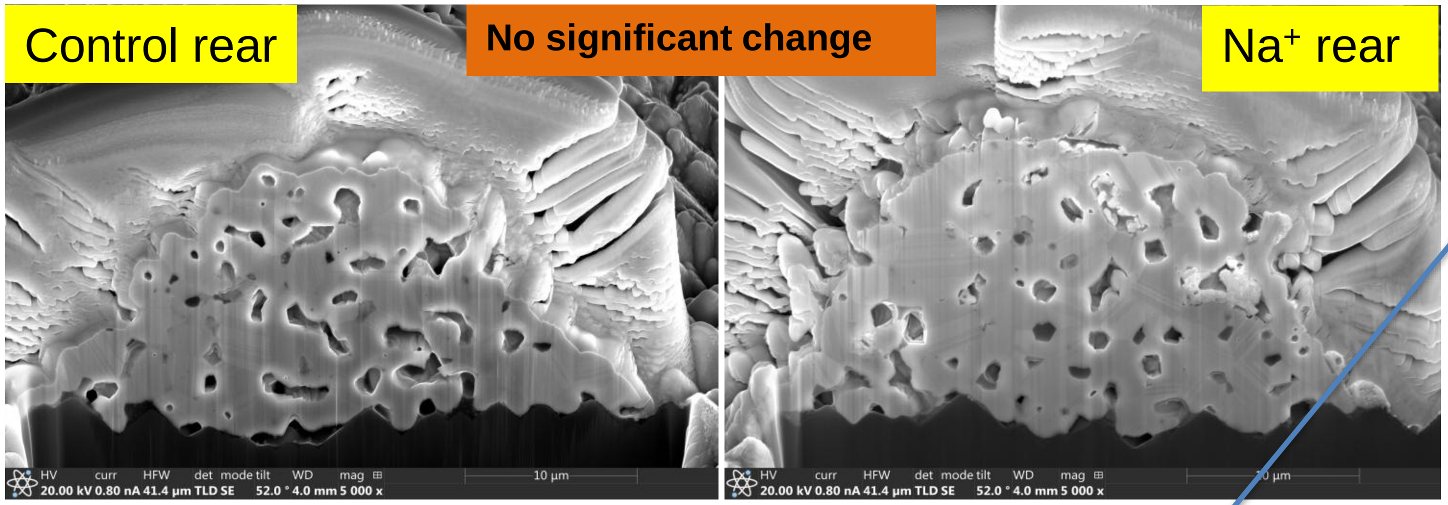
→ **Chemical reaction between Na$^+$, moisture, Ag, and binder resin**
- → **Degradation of binder resin**
- → **Delamination of finger electrode and change in particle size (small to big) for both front and rear contacts**



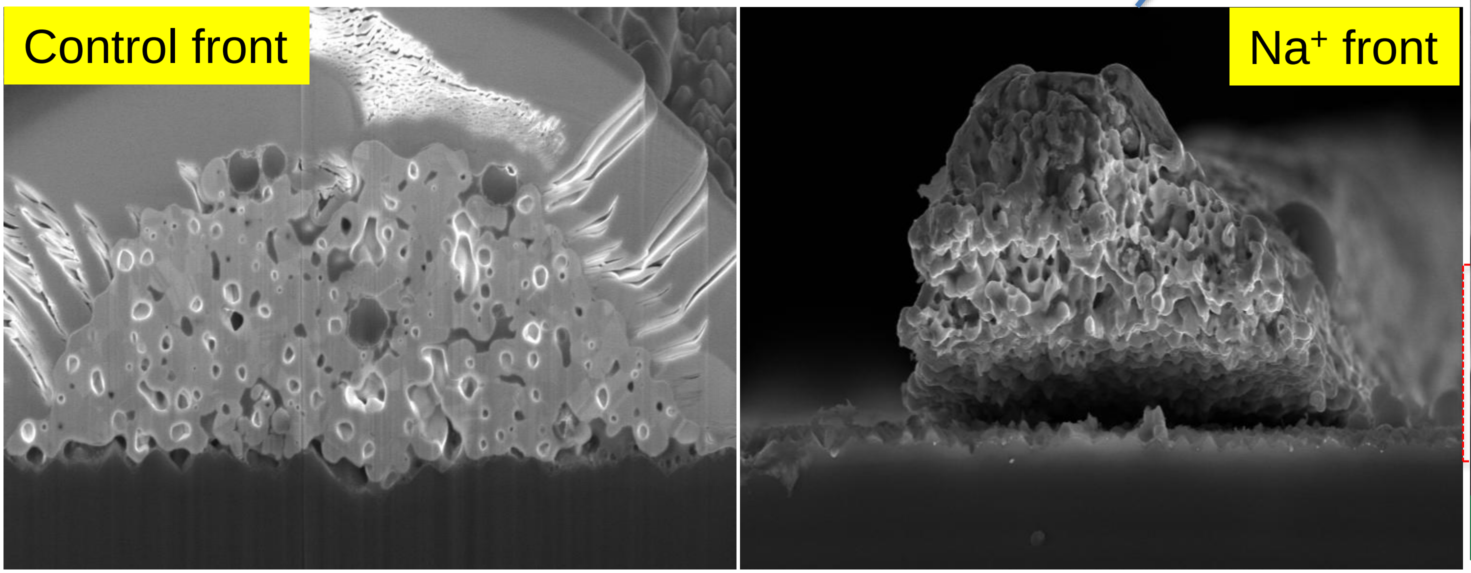


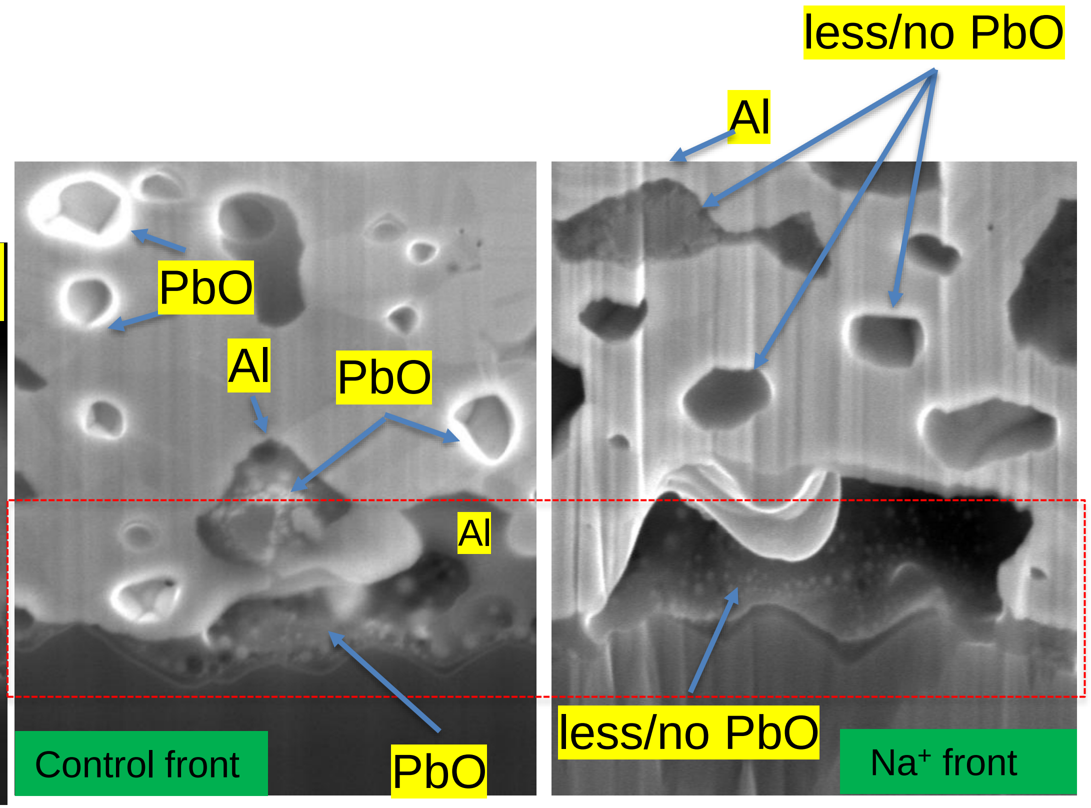
Sen, Wu, Khan, Hoex et al., 10.1016/j.solmat.2023.112554

TOPCon contact: SEM-cross section images



- → **Chemical reaction between Na^+, moisture, Al, and glass frit layer (PbO)**
  - → **degradation of the glass layer (PbO), increased porosity, and delaminate of finger electrode (weak adhesive)**





Sen, Wu, Khan, Hoex et al., 10.1016/j.solmat.2023.112554

Outline

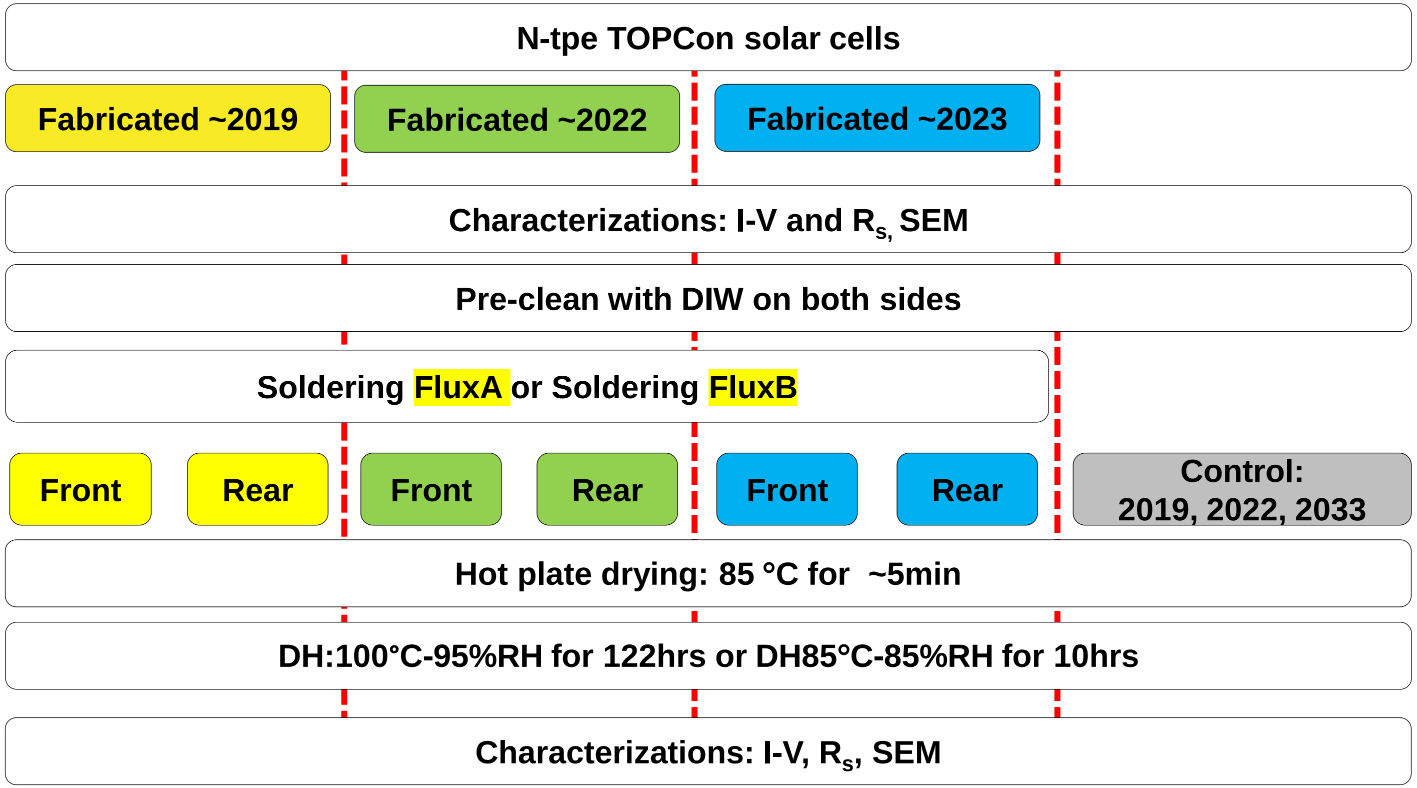
- Introduction
- **Damp-heat failures in HJT and TOPCon solar cells/modules**
  - 4 new failure modes in glass-backsheet HJT modules
  - Na^+ induced failures in PERC, TOPCon, and HJT solar cells
  - **Flux induced contact failure**
- Impact of bill of materials
- UV-induced degradation
- Cell level mitigation of damp-heat failures
- Yield modelling of failure modes
- Conclusions

Experimental detail

Aim

- Investigating soldering flux-induced corrosion in TOPCon solar cells.
- Evaluating key properties of soldering flux that impact solar cell performance.
- Comparing corrosion sensitivity of metal contacts in TOPCon cells across manufacturers.

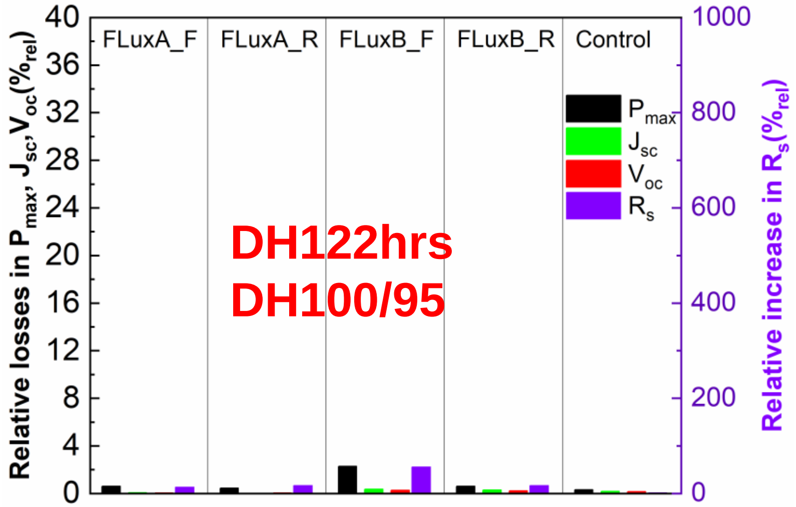
Detail experimental flow diagram



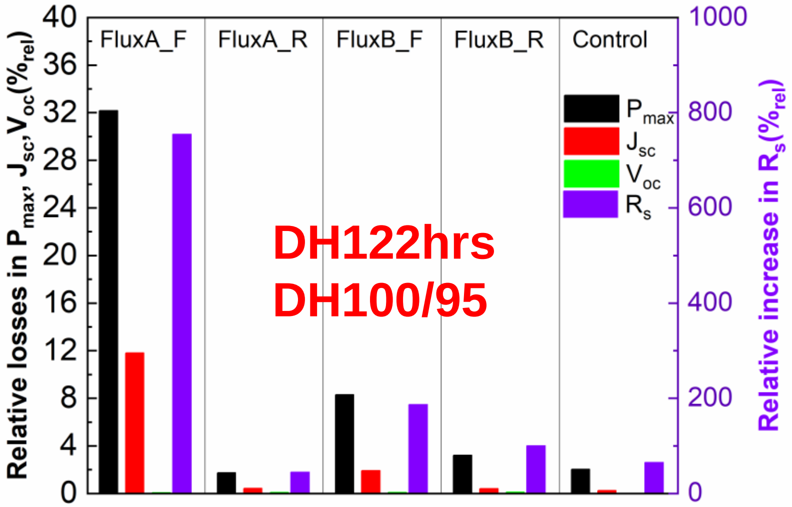
→Note: All cells were sourced from various PV manufacturers and not directly from CSI Solar.

Changes in I-V results after damp heat (DH) testing

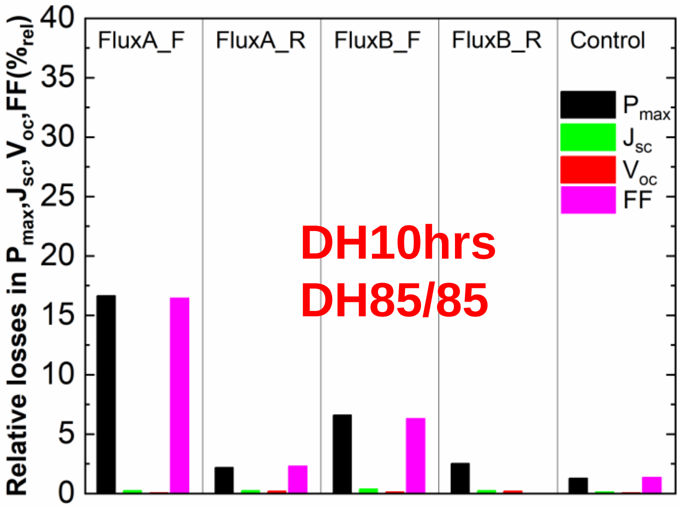
TOPCon cells ~2019



TOPCon cells ~2022



TOPCon cells ~2023



- TOPCon cells fabricated ~2019 remained stable after DH testing.
- However, cells fabricated ~2022 showed significant degradation after DH testing.
- TOPCon cells fabricated in ~2023 showed even higher degradation extent compared to those made in 2022.
    - Flux A had a more detrimental effect compared to Flux B.
    - Front side was more affected than the rear side.

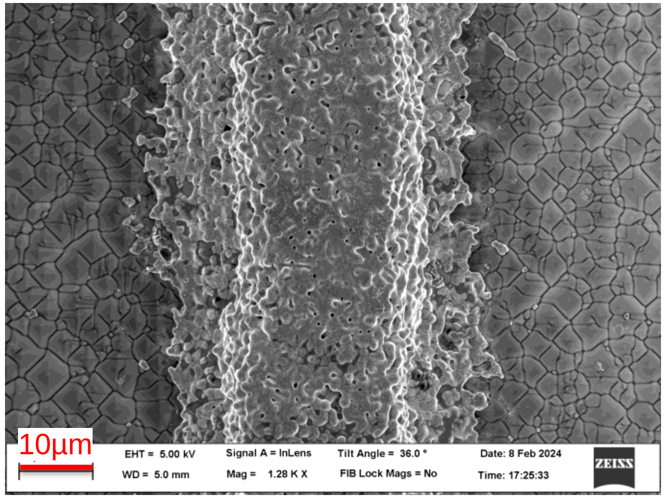
DH100/95: damp heat at 100 °C/95%RH, **DH85/85:** damp heat at 85°C/85%RH

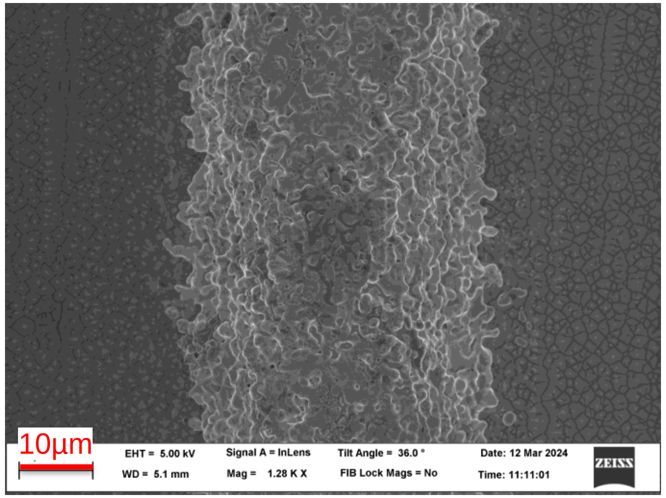
FluxA_F: **Front** side exposed to **soldering flux A** before damp heat testing; **FluxA_R**: **Rear** side exposed to **soldering flux A** before damp heat testing
FluxB_F: **Front** side exposed to **soldering flux B** before damp heat testing: **FluxB_R: Rear** side exposed to **soldering flux B** before damp heat testing
Control: No soldering exposure before damp heat testing

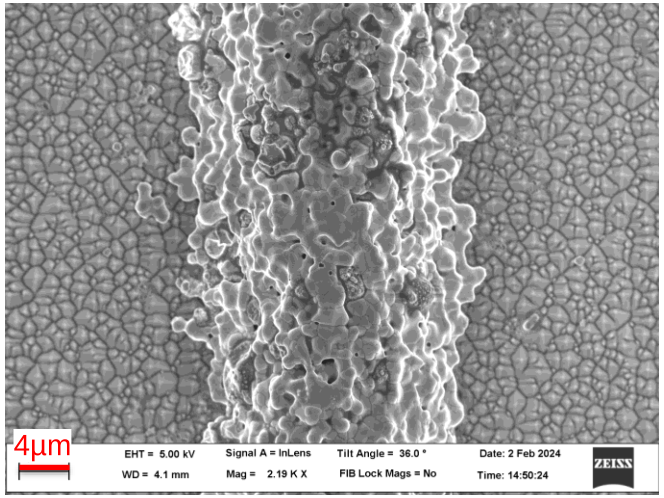
Front contact of fresh TOPCon cells

Top view SEM images

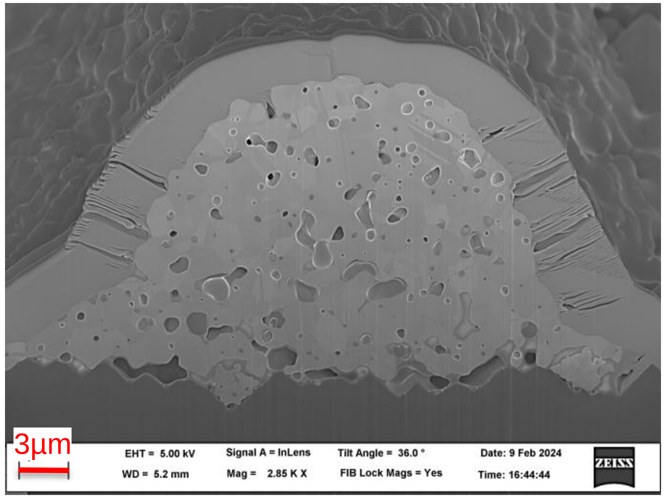
~2019	~2022	~2023

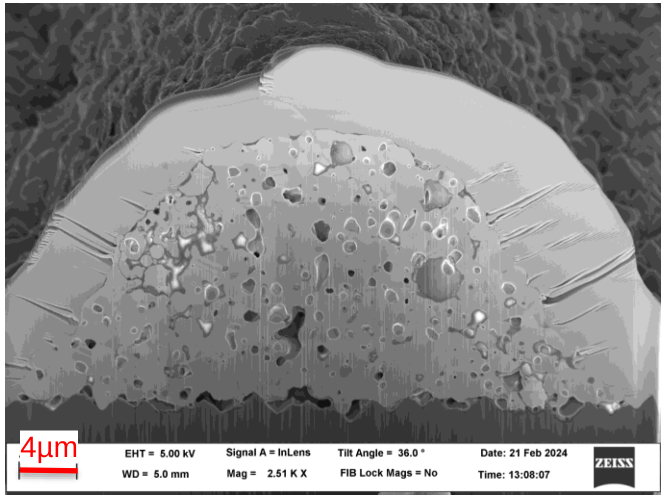


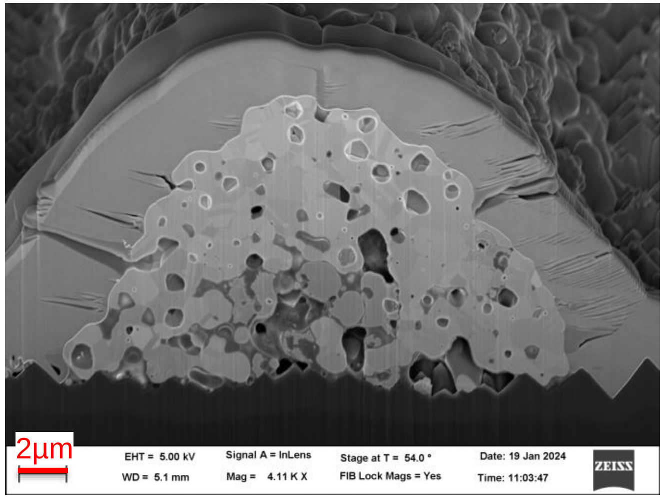




Cross-section SEM images







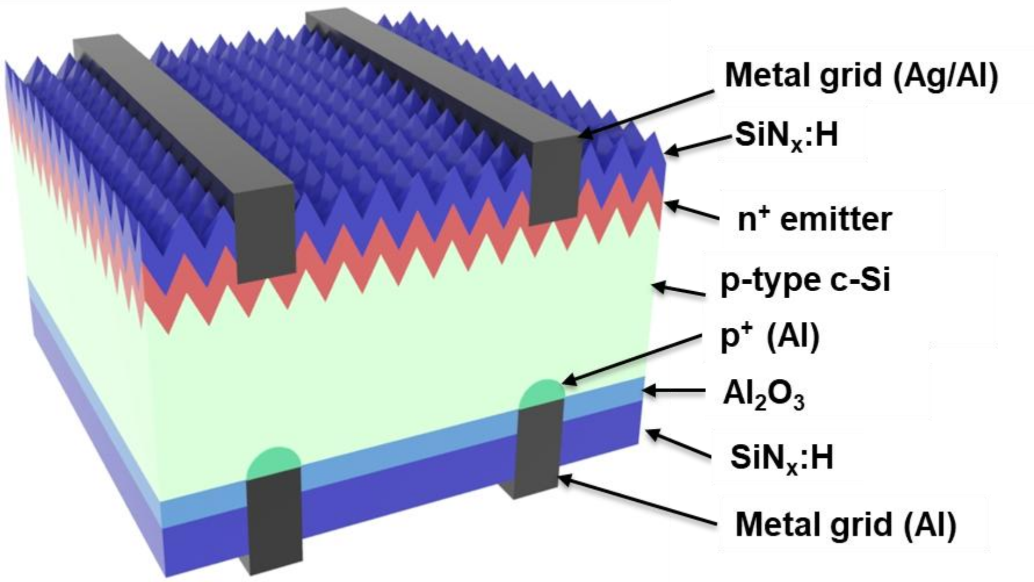
UNSW SYDNEY

Outline

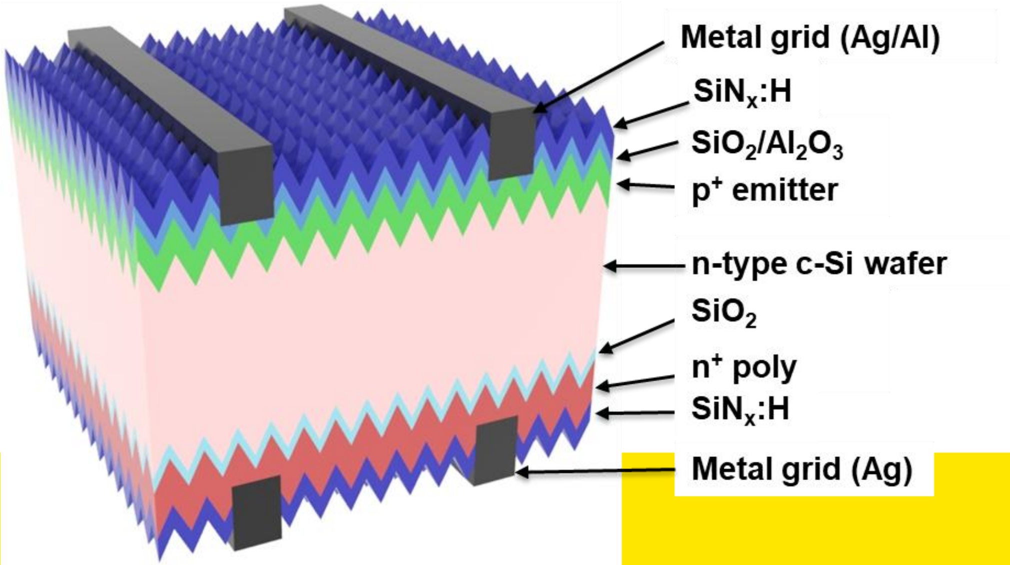
- Introduction
- Damp-heat failures in HJT and TOPCon solar cells/modules
  - 4 new failure modes in glass-backsheet HJT modules
  - Na^+ induced failures in PERC, TOPCon, and HJT solar cells
  - Flux induced contact failure
- **Impact of bill of materials**
- UV-induced degradation
- Cell level mitigation of damp-heat failures
- Yield modelling of failure modes
- Conclusions

Experimental plan

a) Schematic of the PERC cell



b) Schematic of the TOPCon cell



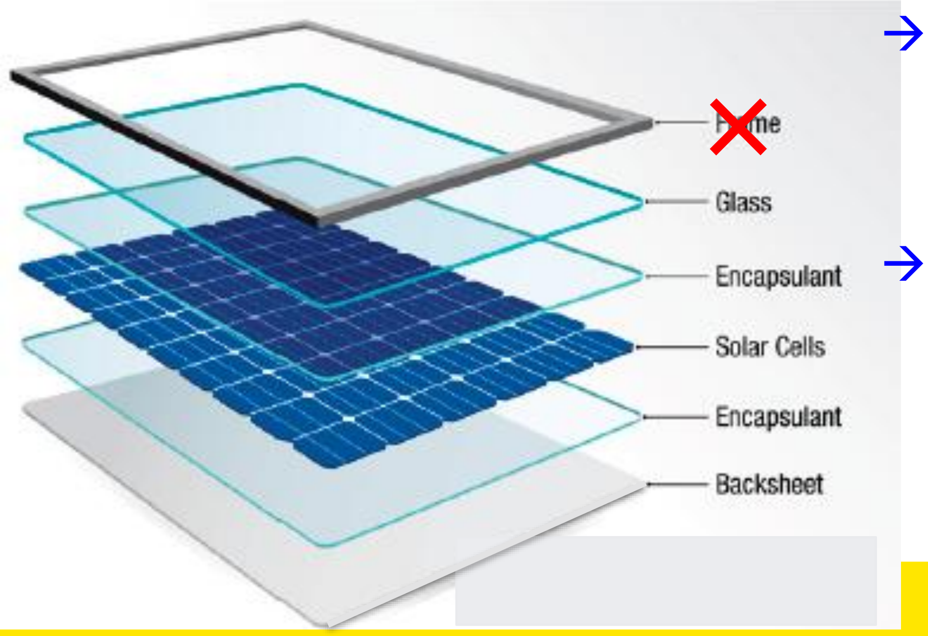
Experimental flow diagram

P-type PERC and n-type TOPCon cells

Group 1	Group 2
Glass	Glass
EVA or POE (A)	EVA or POE (A, B, C)
PERC cells	TOPCon cells
EVA or POE (A)	EVA or POE (A, B, C)
Backsheet (W, WT)	Backsheet (W, WT, B)

DH:85°C-85% room humidity for 1000hrs

Group1: PERC Module	**Group 2: TOPCon Module**

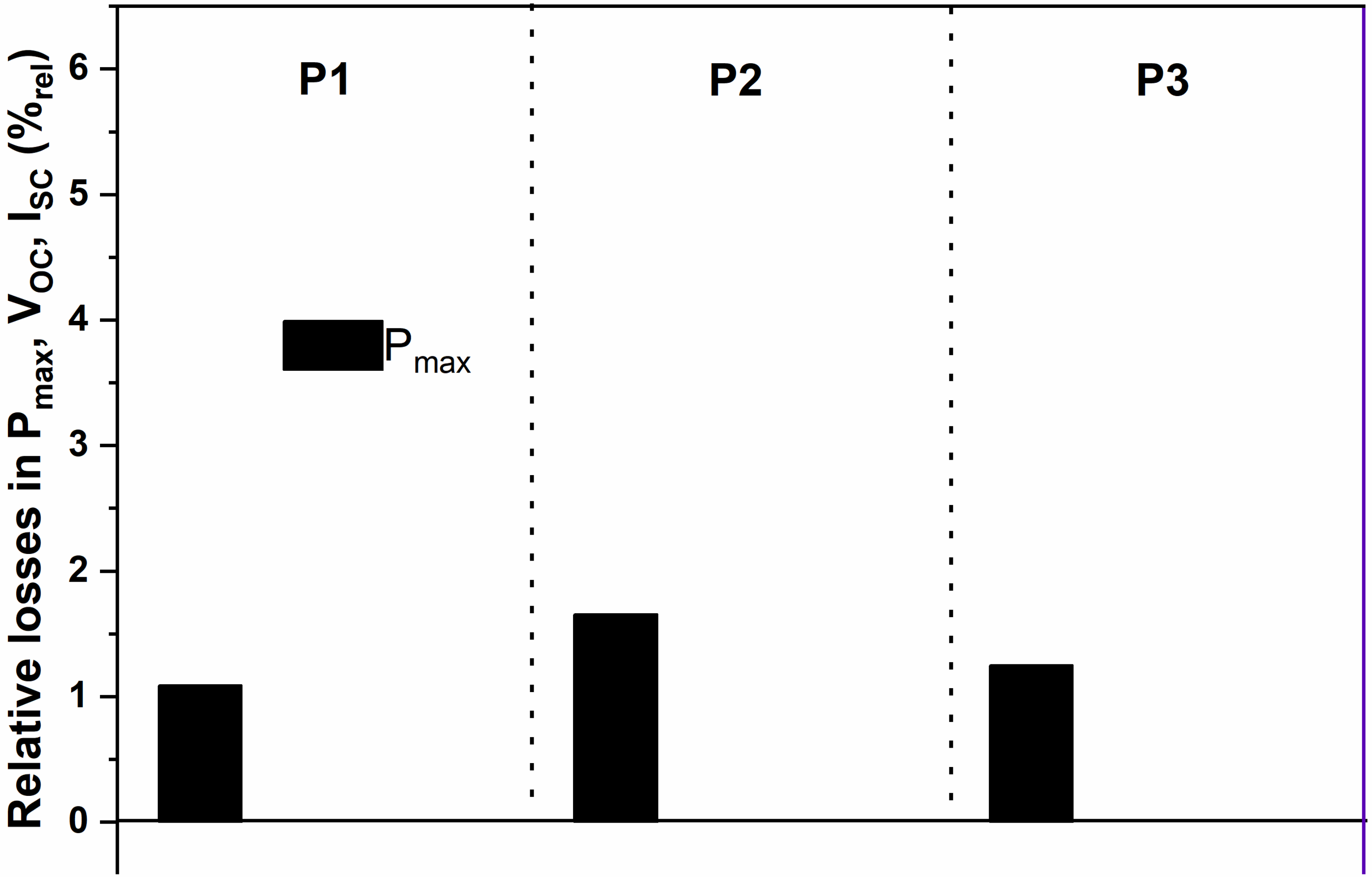


→ **Module encapsulation processes were done at an industrial production line**

→ **DH testing and characterisation were done at UNSW**

UNSW SYDNEY

Changes in I-V parameters of modules with PERC cells after DH1000hrs



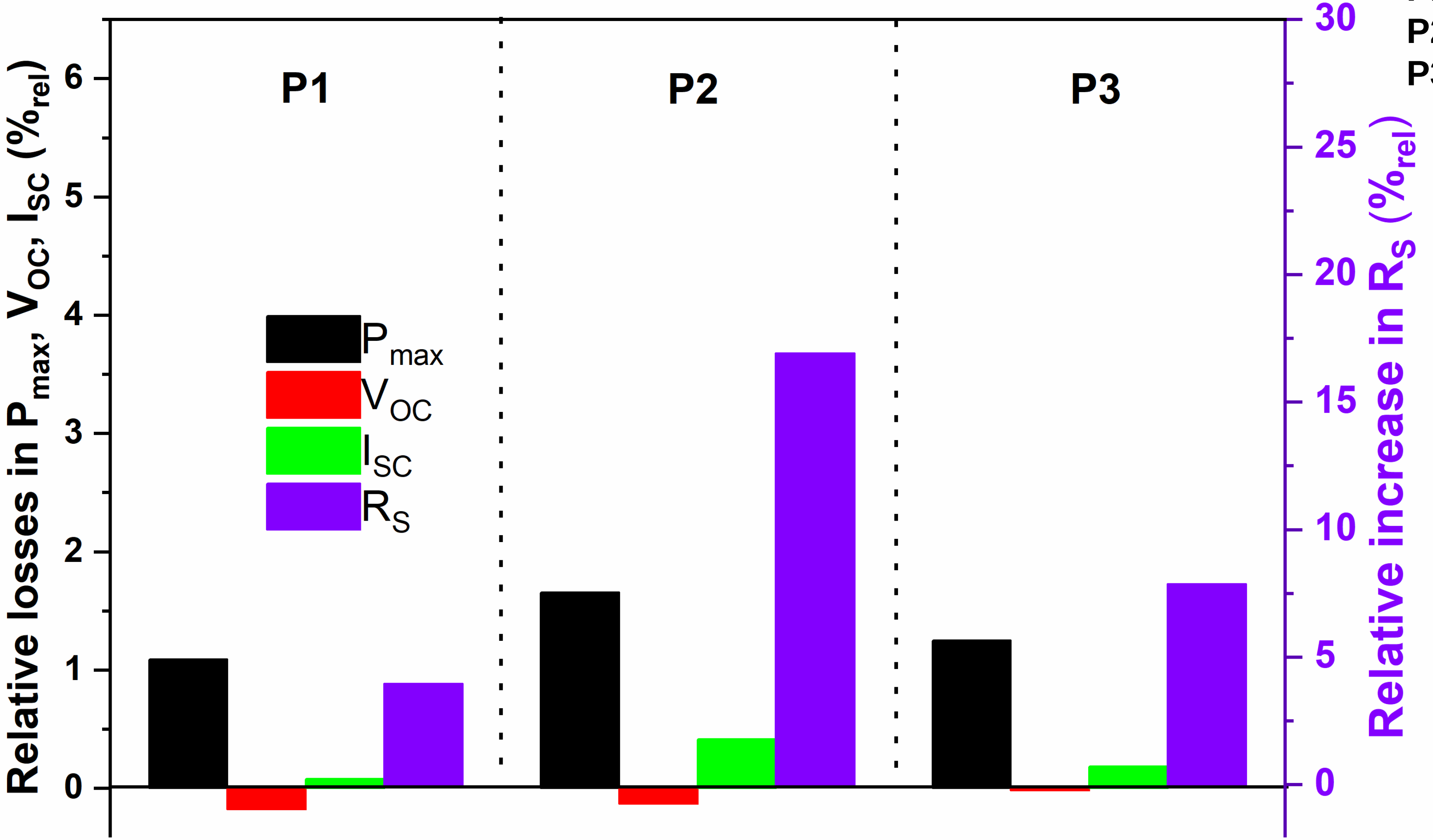
P1: p-G/EVA/BS-W
P2: p-G/POE-A/BS-WT
P3: p-G/POE-A/BS-W

DH: damp heat,
p: p-type PERC cells
G: Glass
EVA: Ethylene Vinyl Acetate
POE: PolyOlefin,
BS: Backsheet

→ **All modules degrade less than 2%$_{rel}$.**

Changes in I-V parameters of modules with PERC cells after DH1000hrs

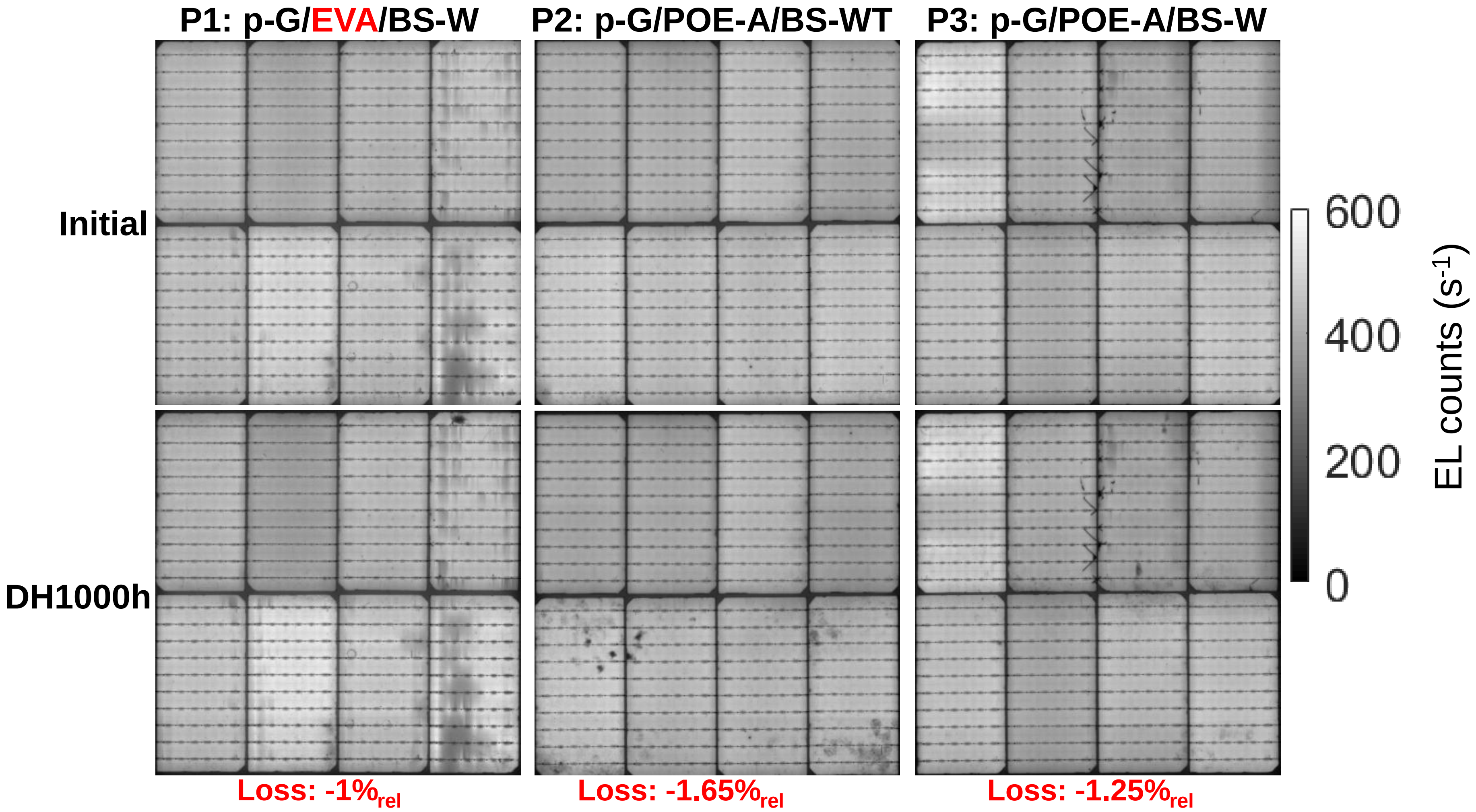
P1: p-G/EVA/BS-W
P2: p-G/POE-A/BS-WT
P3: p-G/POE-A/BS-W



DH: damp heat,
p: p-type PERC cells
G: Glass
EVA: Ethylene Vinyl Acetate
POE: PolyOlefin,
BS: Backsheet

→ **All modules degrade less than 2%$_{rel}$.**
→ **Loss mainly driven by the R_s increase.**

Changes in EL images of modules with PERC cells

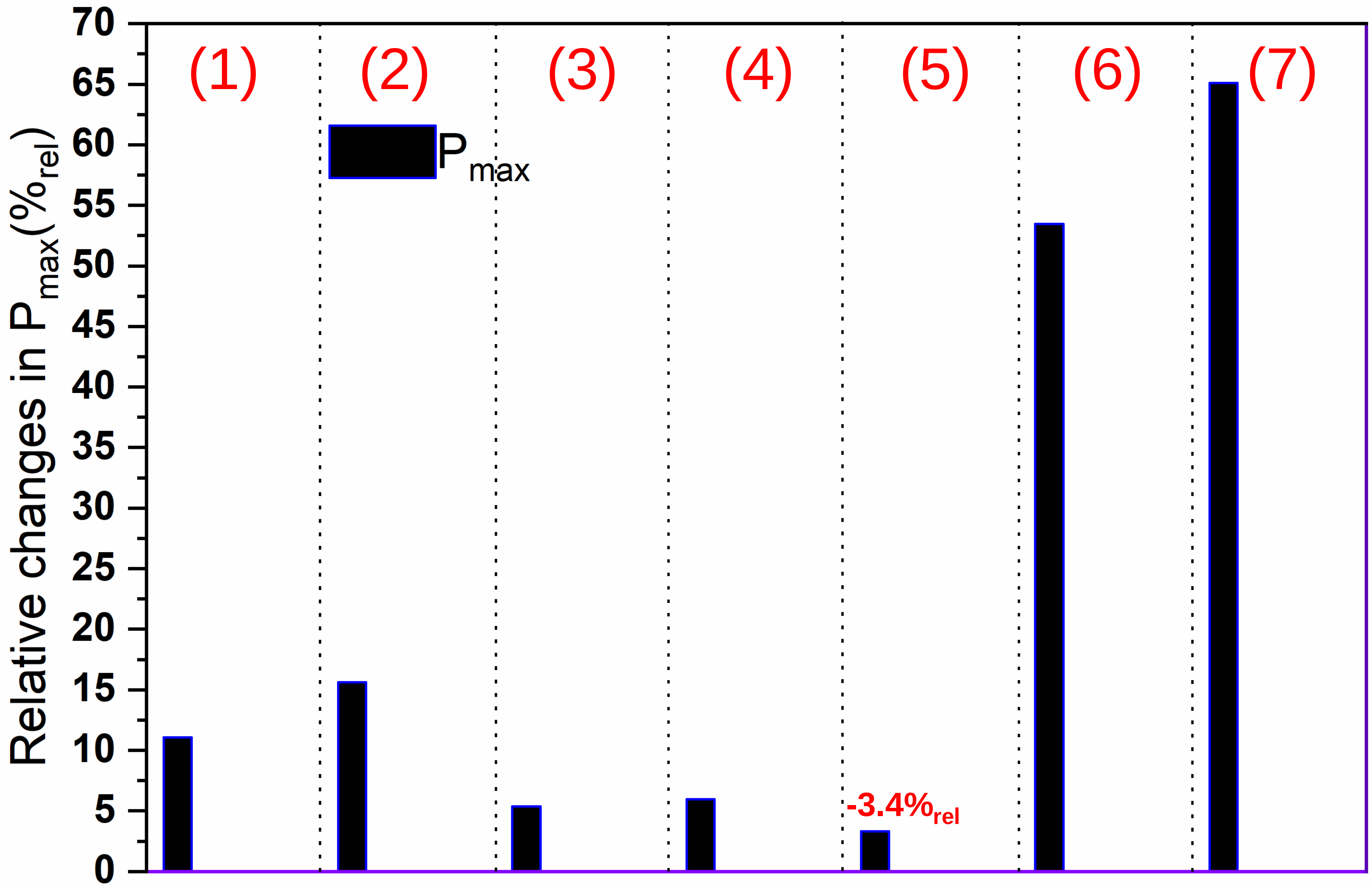


DH: damp heat,
p: p-type PERC cells
G: Glass
EVA: Ethylene Vinyl Acetate
POE: PolyOlefin,
BS: Backsheet

- No significant changes after 1000 hrs of DH testing.
- Changing bill of material (BOM) does not seem to significantly impact loss.

UNSW SYDNEY

Changes in I-V parameters of modules with TOPCon cells after DH1000hrs

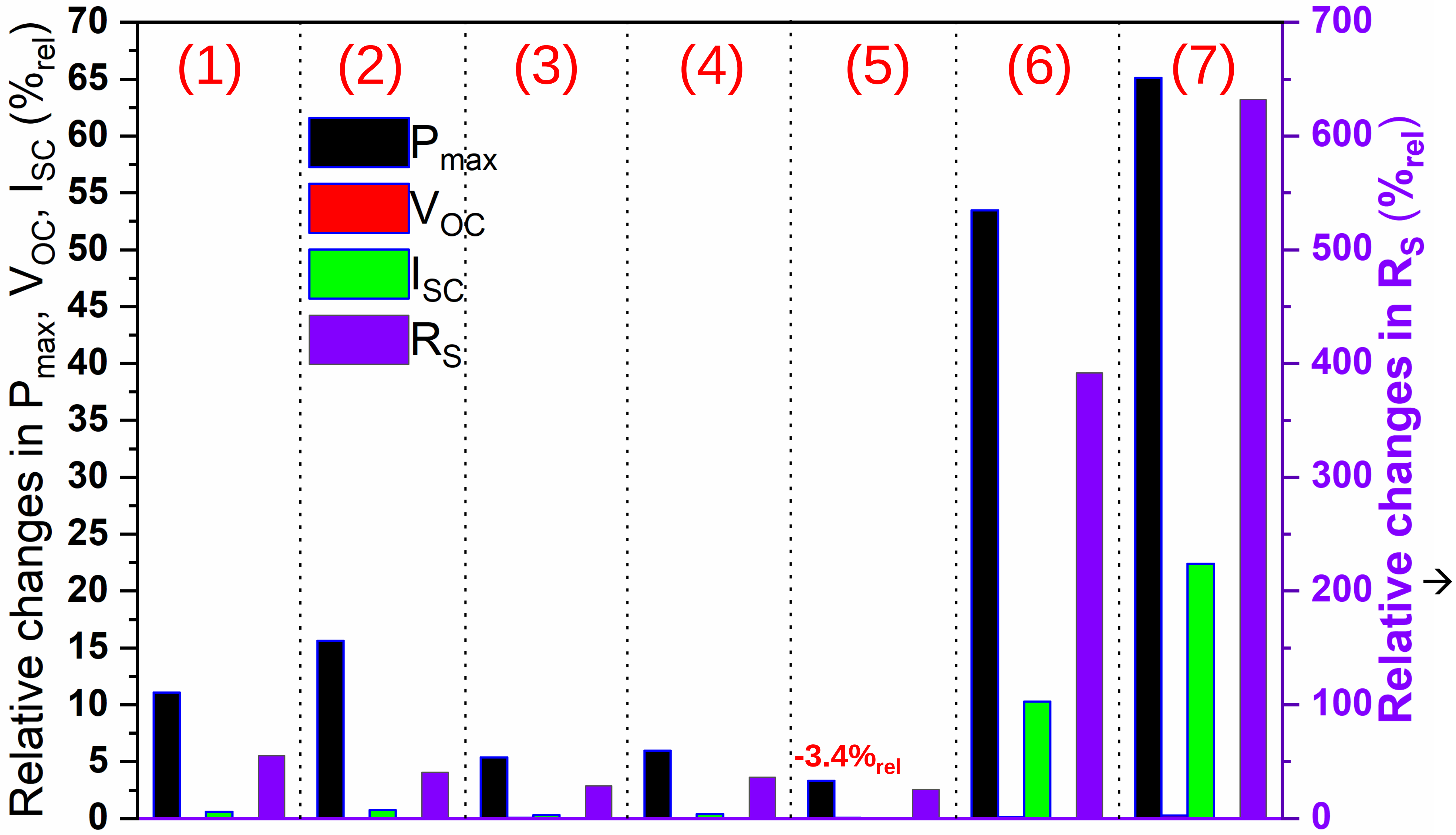


(1) n-G/EVA/BS-W
(2) n-G/POE-A/BS-W
(3) n-G/POE-B/BS-WT
(4) n-G/POE-B/BS-W
(5) n-G/POE-B/BS-B
(6) n-G/POE-C/BS-W
(7) n-G/POE-C/BS-WT

→ **Degradation extent is beyond the minimum loss specified in the IEC standard (≤2% relative after DH2000hrs).**

DH: damp heat, n: n-type TOPCon cells G: Glass, EVA: Ethylene Vinyl Acetate, POE: PolyOlefin, BS: Backsheet

Changes in I-V parameters of modules with TOPCon cells after DH1000hrs



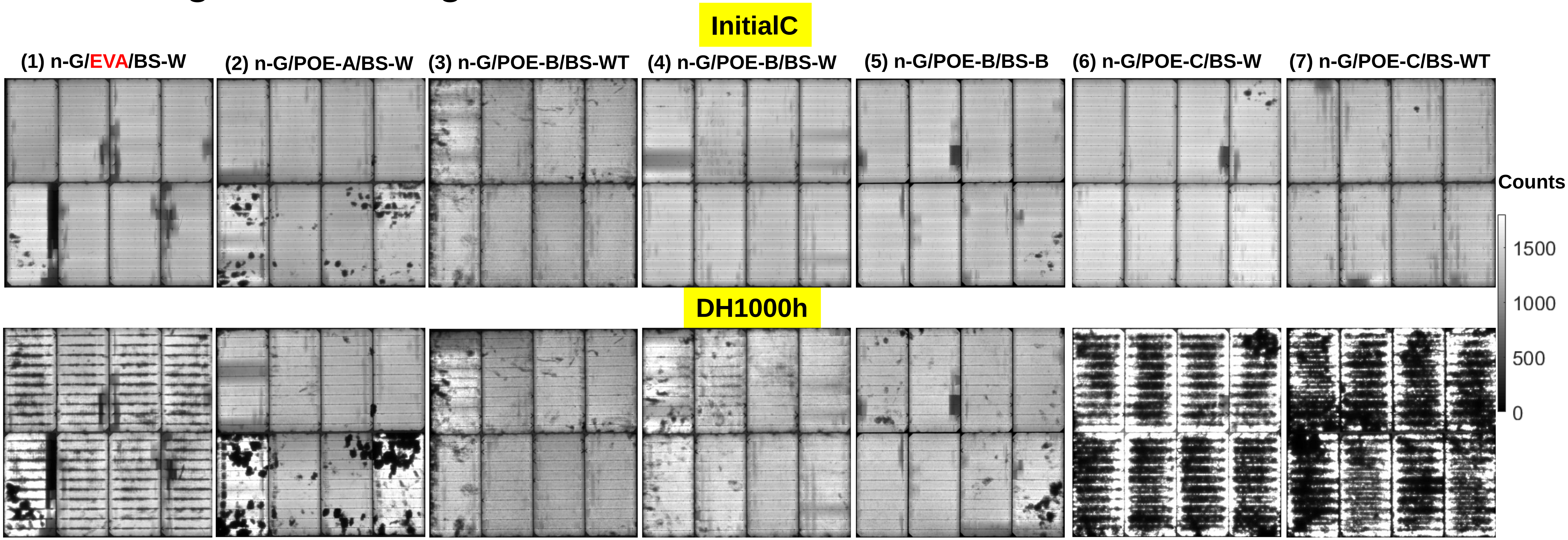
(1) n-G/EVA/BS-W
(2) n-G/POE-A/BS-W
(3) n-G/POE-B/BS-WT
(4) n-G/POE-B/BS-W
(5) n-G/POE-B/BS-B
(6) n-G/POE-C/BS-W
(7) n-G/POE-C/BS-WT

→ **Degradation extent is beyond the minimum loss specified in the IEC standard (≤2% relative after DH2000hrs).**

DH: damp heat, n: n-type TOPCon cells G: Glass, EVA: Ethylene Vinyl Acetate, POE: PolyOlefin, BS: Backsheet

Sen, Wang, Khan, Hoex et al., 10.1016/j.solmat.2024.112877

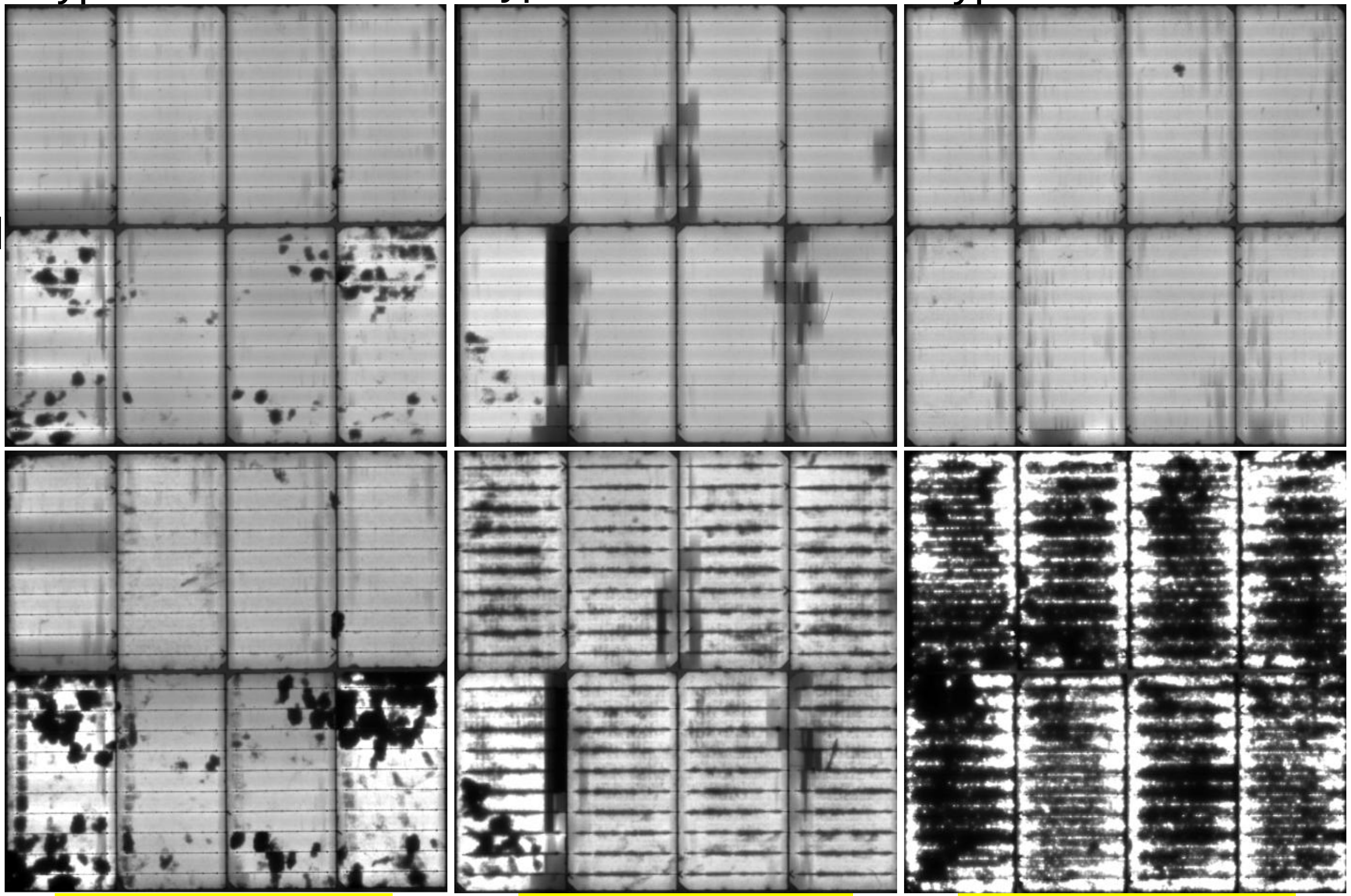
Changes in EL images of modules with TOPCon cells after DH1000hrs



Loss: -11%$_{rel}$ Loss: -16%$_{rel}$ Loss: -5.4%$_{rel}$ Loss: -6%$_{rel}$ Loss: -3.4%$_{rel}$ Loss: -53.5%$_{rel}$ Loss: -65.1%$_{rel}$

- Degradation extent is beyond the minimum loss specified in the IEC standard (≤2% relative after DH2000hrs).
- Failure modes are random
- Modules with EVA degrade less than some modules with POE-C, indicating failure isn't solely related to acetic acid…..

Three failure modes in TOPCon modules



P_{max} loss ~15%$_{rel}$ | P_{max} loss ~11%$_{rel}$ | P_{max} loss ~65%$_{rel}$

Type-1 failure mode: point-localized failure

Type-2 failure mode: failure at/around the interconnection point

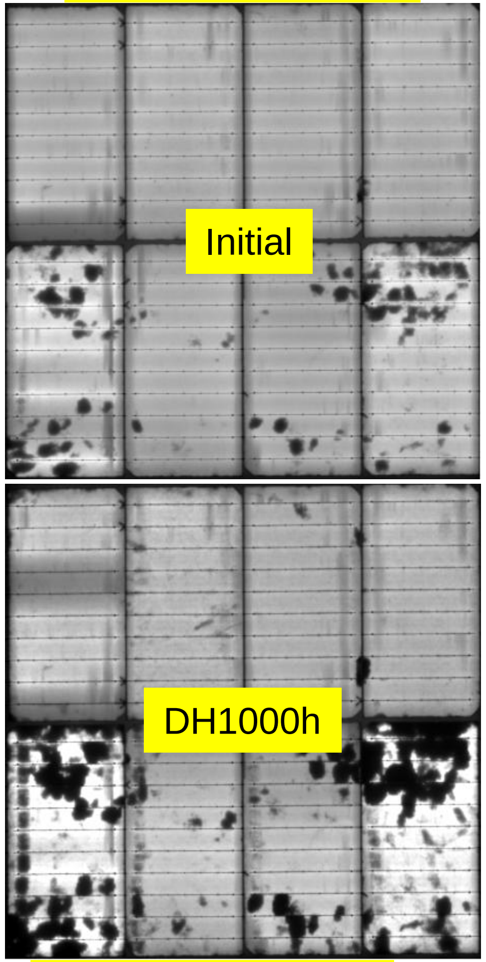
Type-3 failure mode: failure across the entire area of cells/module

- Three failure modes has been realised in TOPCon modules, but absent in PERC modules
- These failure modes are quite similar to HJT modules

Sen, Wang, Khan, Hoex et al., 10.1016/j.solmat.2024.112877

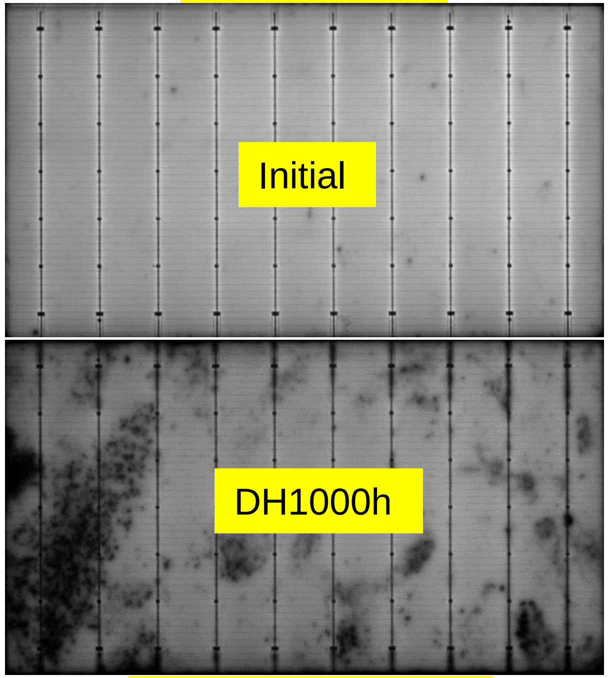
Type-1 failure mode in TOPCon and HJT glass/backsheet modules

Type-1 failure mode
TOPCon modules



P_{max} loss ~15%$_{rel}$
I_{SC} loss ~0.8%$_{rel}$
R_s increase ~55%$_{rel}$
Glass/**POE**/Backsheet

Type-1 failure mode
HJT modules



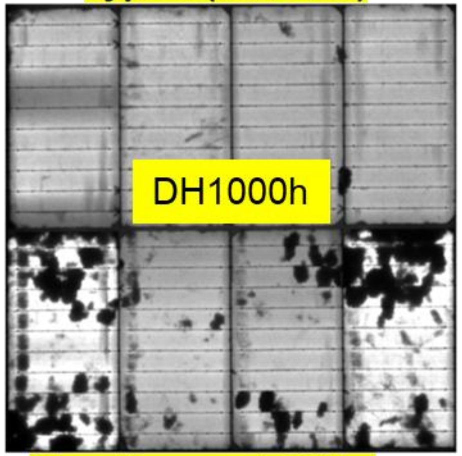
P_{max} loss ~12%$_{rel}$
V_{OC} loss ~2%$_{rel}$
I_{SC} loss ~3%$_{rel}$
Glass/**EVA**/Backsheet

- Similar failure modes were observed in TOPCon and HJT modules, despite the different BOMs being used.
- Note that TOPCon and HJT modules were fabricated on a **different industrial production line.**
- This underscores the possibility of similar contaminants occurring in numerous industrial settings,
  - Emphasizing the need to mitigate their adverse effects during DH testing, especially when dealing with TOPCon and HJT cells.

Source: Sen, Khan, Hoex et al., 10.1016/j.solmat.2023.112358
Sen, Wang, Khan, Hoex et al., 10.1016/j. solmat.2024.112877

Type-1 failure mode: potential root causes: Na, Cl and/or soldering flux

Type-1 (TOPCon)

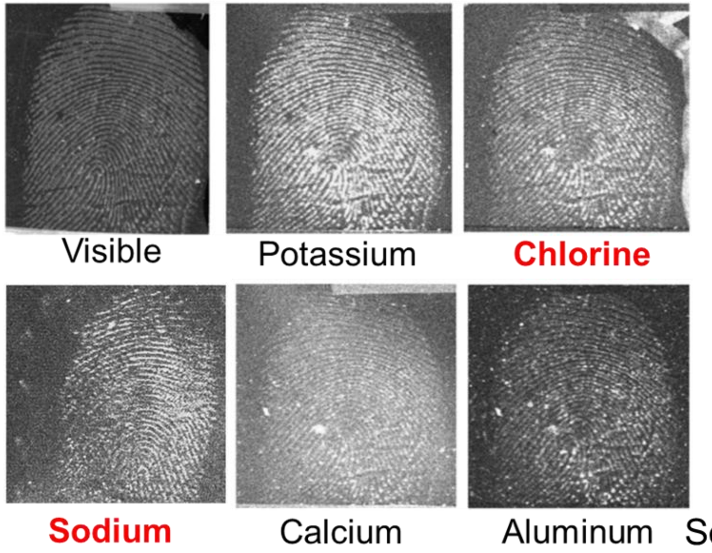


P_{max} loss ~15%$_{rel}$

I_{SC} loss ~0.8%$_{rel}$

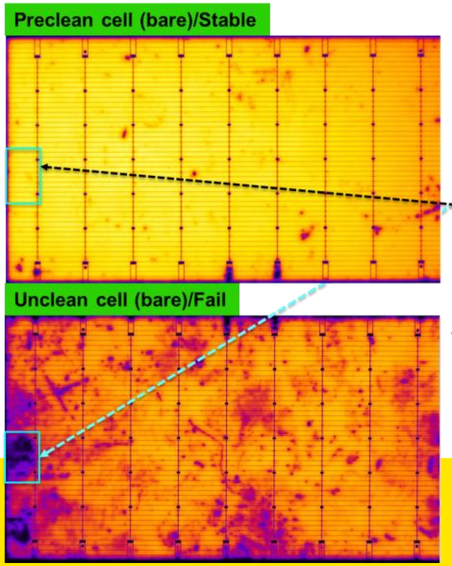
R_s increase ~55%$_{rel}$

Fingerprint

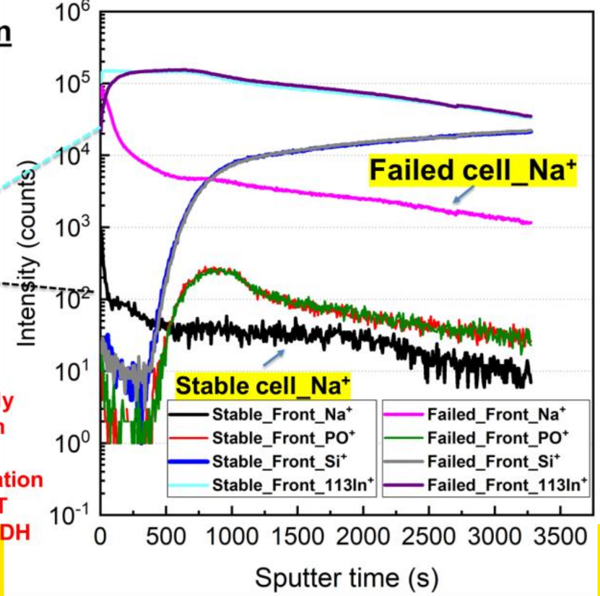


Worley, C. G et al., *Journal of Forensic Sciences*, *51*(1), 57–63 2006

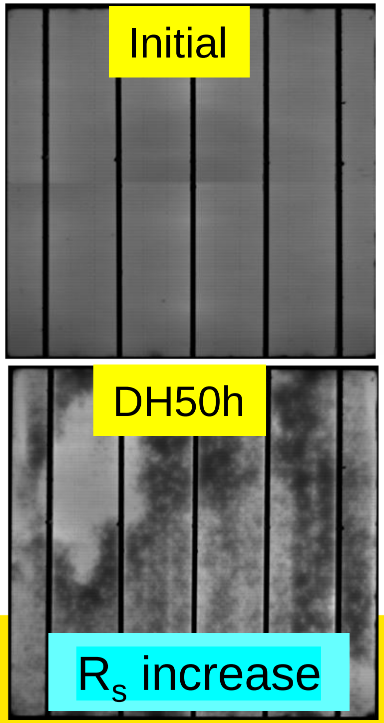
Higher Na^+ ion detect on failed region

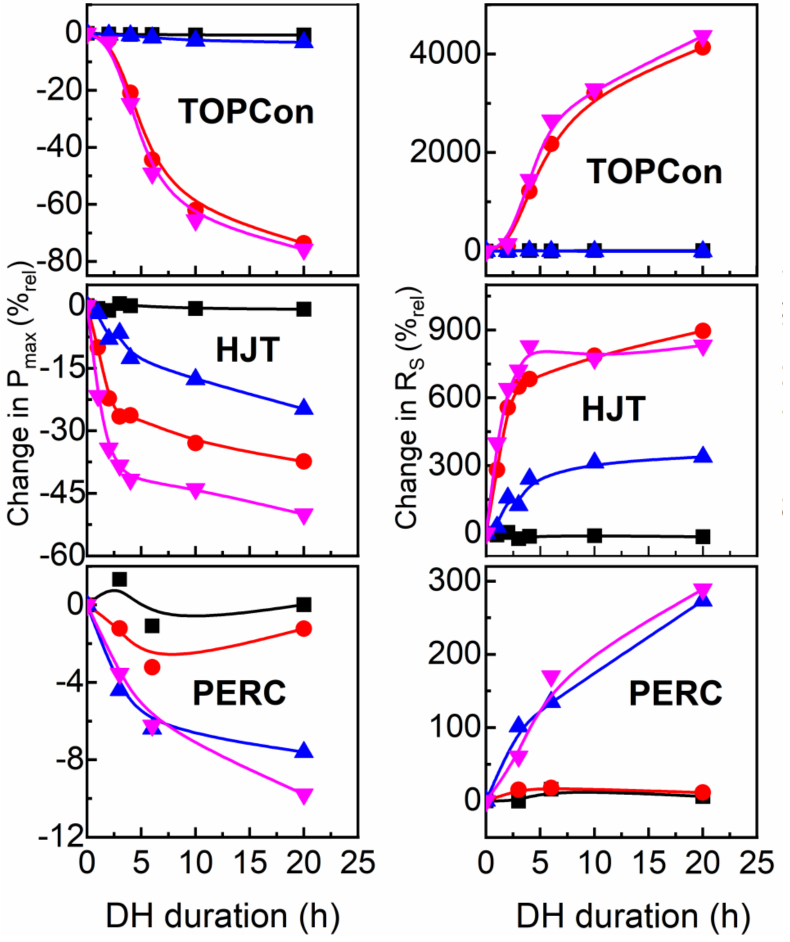


→ Na^+ is likely involved in causing recombination loss in HJT cells after DH testing



Soldering flux B_front



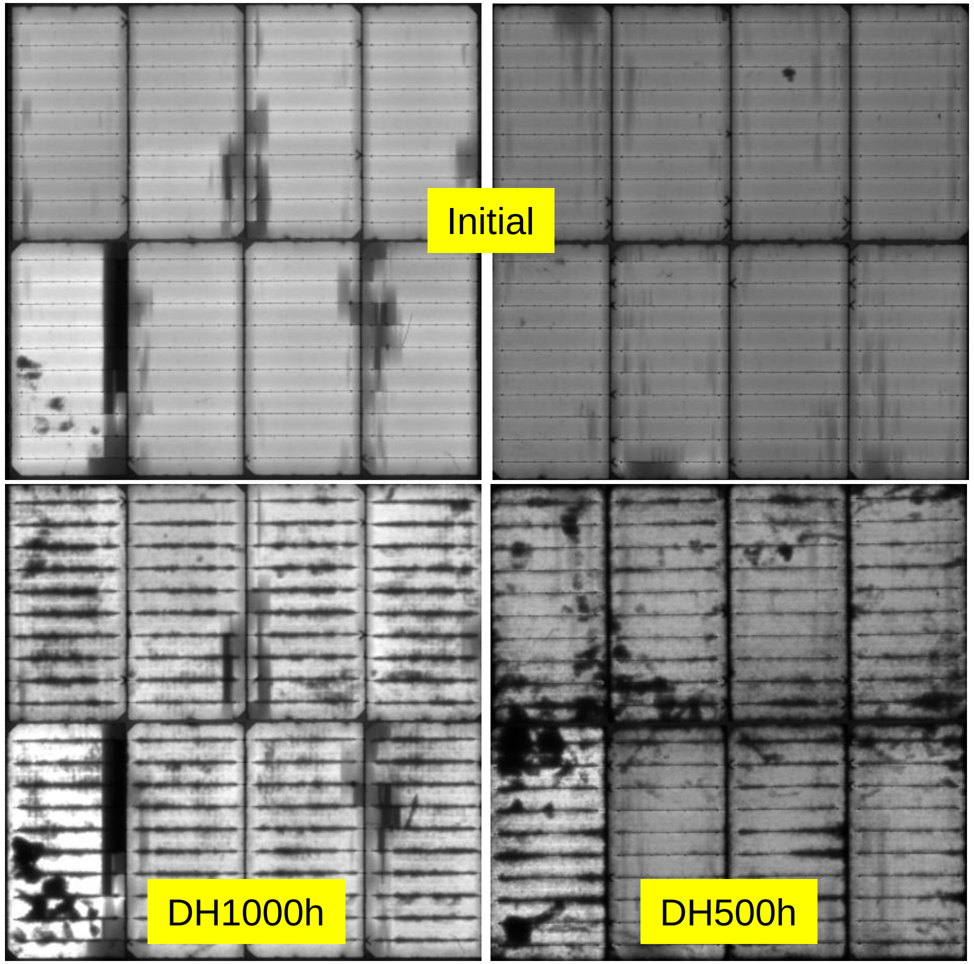


Sen et al., 10.1016/j.solmat.2023.112554

Type-2 failure mode in TOPCon and HJT glass/backsheet modules

EL Images

Type-2 failure mode
TOPCon modules



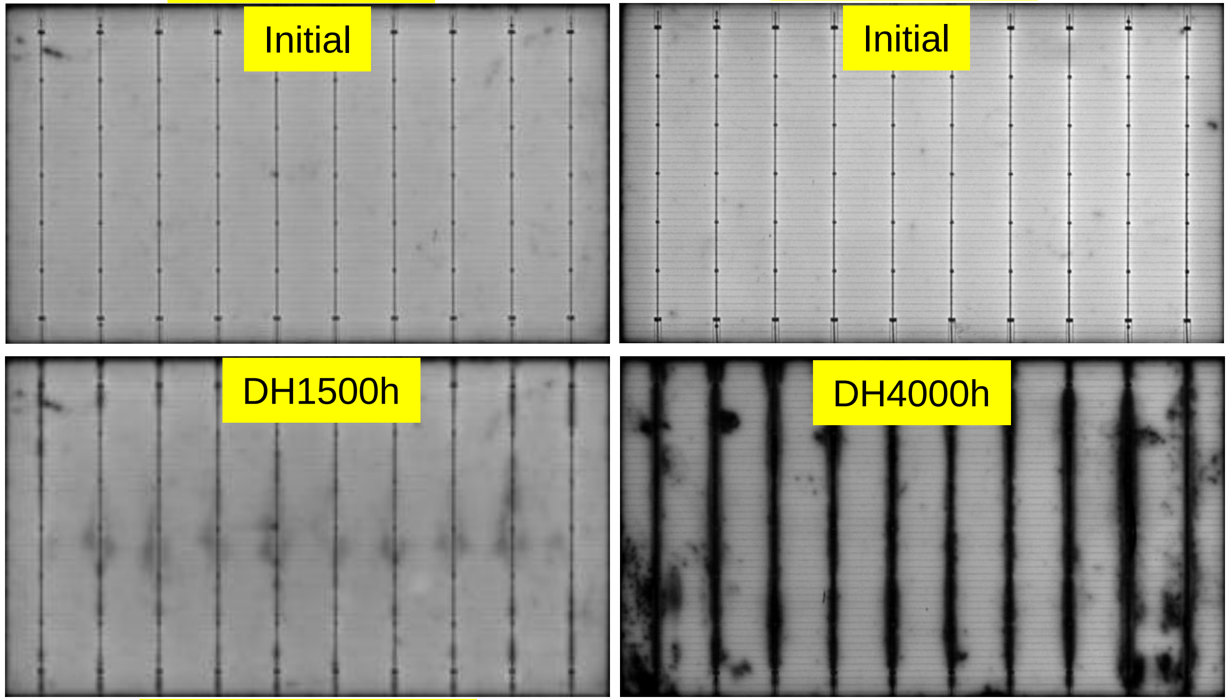
P_{max} loss ~11%$_{rel}$ | P_{max} loss ~16%$_{rel}$

I_{SC} loss ~0.8%$_{rel}$
R_s increases ~50-55%$_{rel}$

Glass/**EVA**/Backsheet | Glass/**POE**/Backsheet

Type-2 failure mode
HJT modules

Type-4 failure mode
HJT modules



Type-2 HJT: P_{max} loss ~5%$_{rel}$
R_s increases ~33%$_{rel}$
Glass/**EVA**/Backsheet

Type-4 HJT: P_{max} loss ~16%$_{rel}$
V_{OC} and I_{SC} loss ~3%$_{rel}$
Glass/**EPE**/Backsheet

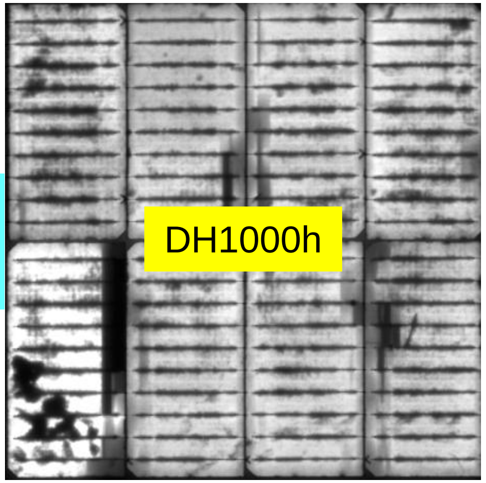
- → Similar failure modes were observed in TOPCon and HJT modules despite the different BOMs being used.
- → Note that TOPCon and HJT modules were fabricated on a **different industrial production line.**

Source: Sen, Khan, Hoex et al., 10.1016/j.solmat.2023.112358
Sen, Wang, Khan, Hoex et al., 10.1016/j. solmat.2024.112877

Type-2 failure mode: potential root causes: Soldering flux with/o acetic acid

Glass/EVA/Backsheet

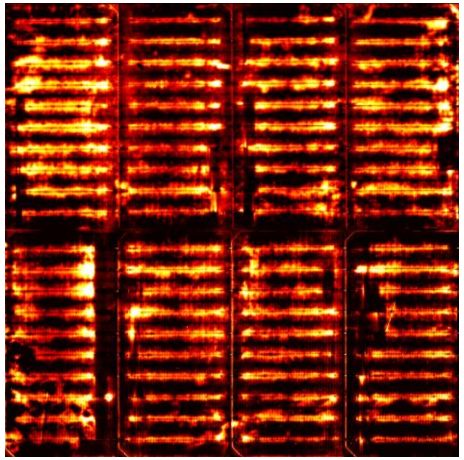
EL images



Pmax loss ~11%$_{rel}$
I_{SC} loss ~0.8%$_{rel}$
R_s increases ~50%$_{rel}$

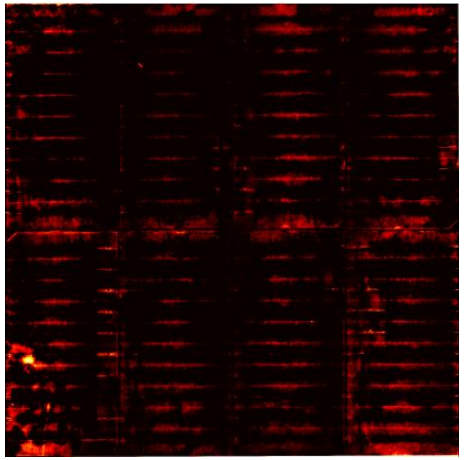
PL_{LS} Ratio images

i) DH1000h divided by Initial



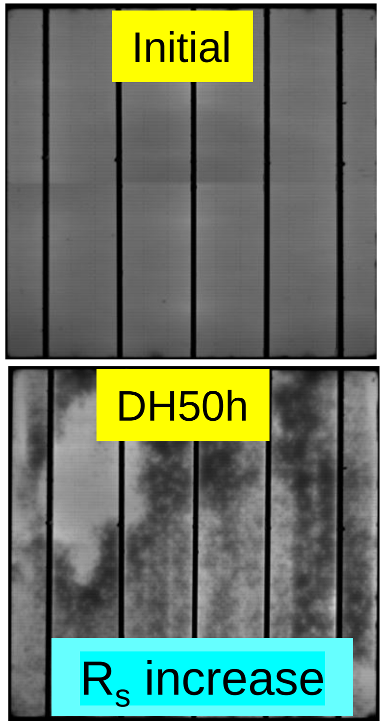
Region with R_s increases

ii) Initial divided by DH1000h

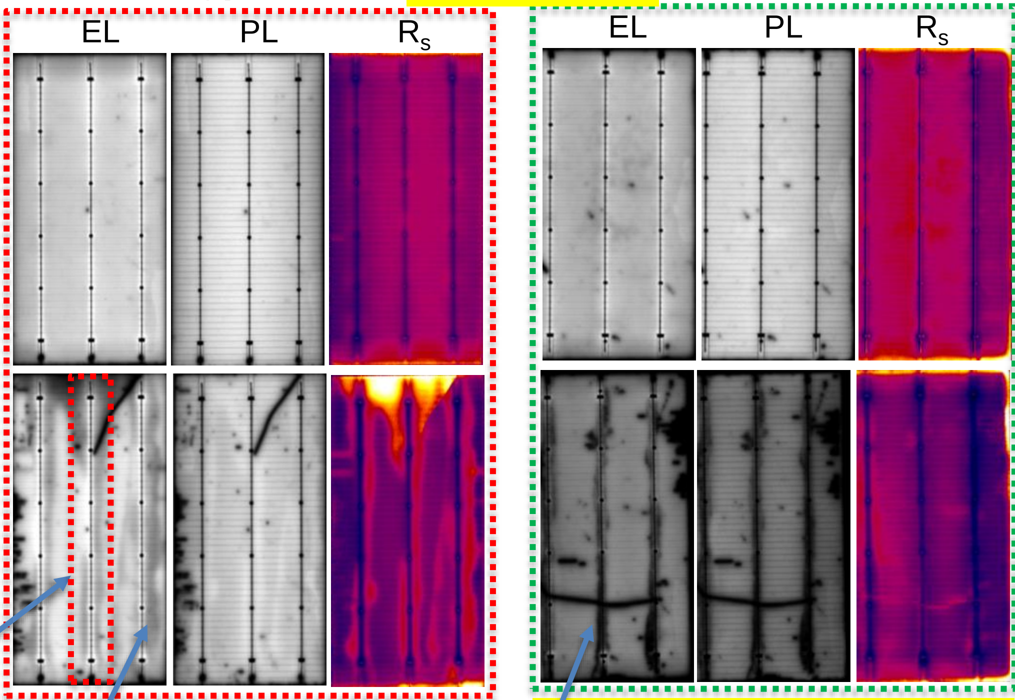


Region with recombination increases

Soldering flux B_front



HJT cells



Region soldering flux applied

Soldering flux
R_s increase

Acetic acid
Recombination increase

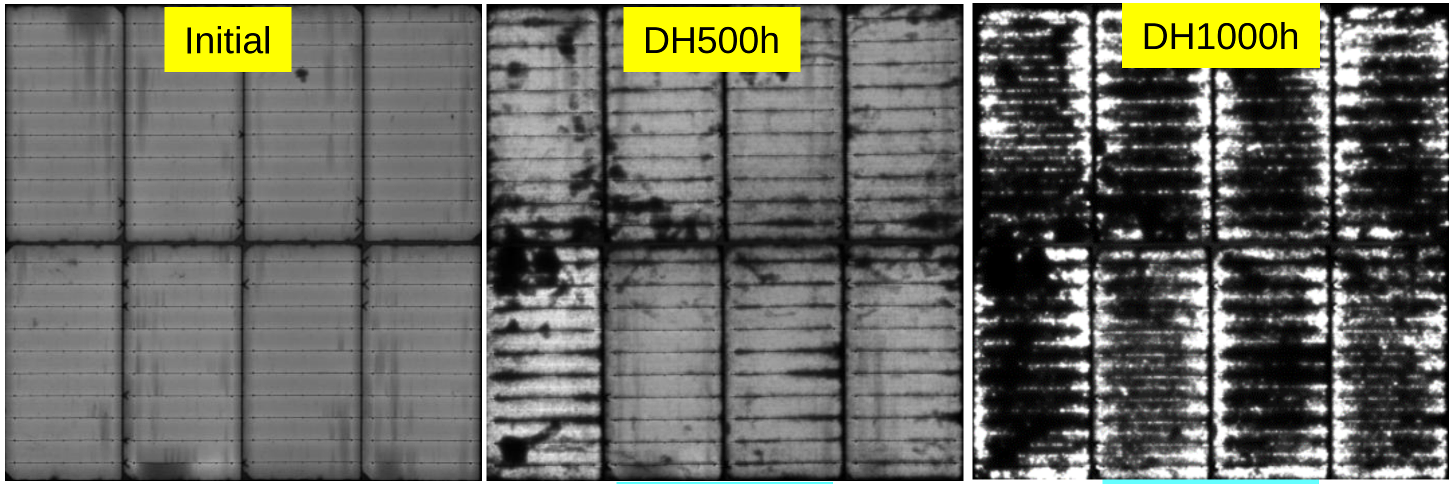
Region with acetic acid apply

Source: Sen, Khan, Hoex et al., 10.1016/j.solmat.2023.112358
Sen, Wang, Khan, Hoex et al., 10.1016/j. solmat.2024.112877

Type-3 failure mode in TOPCon and HJT glass/backsheet modules

EL Images

Type-3 failure mode (TOPCon modules)

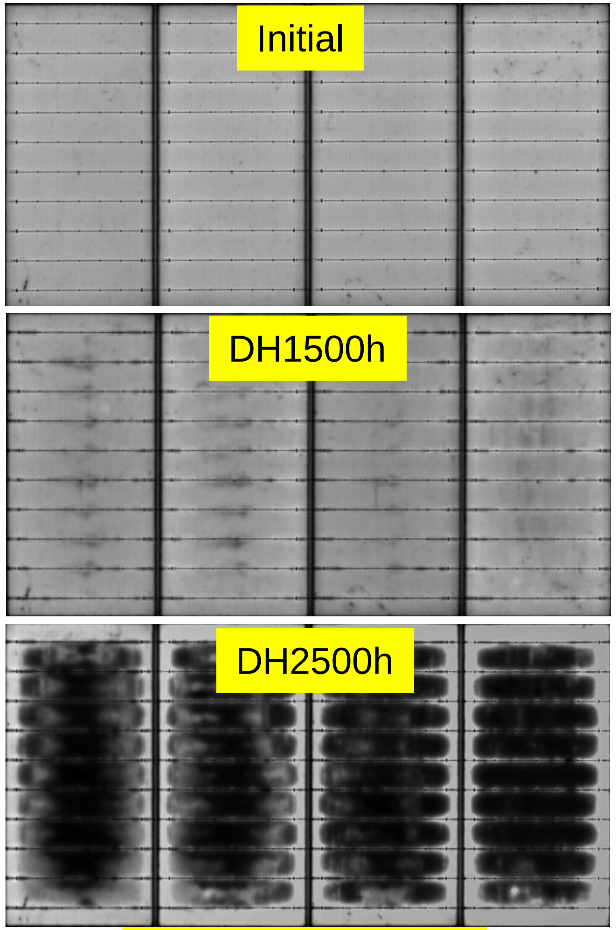


Glass/**POE**/Backsheet

Type-2 → **Type-3**

P_{max} loss ~65%$_{rel}$
R_s increases ~640%$_{rel}$

Type-3 failure mode (HJT modules)



Type-2 → **Type-3**

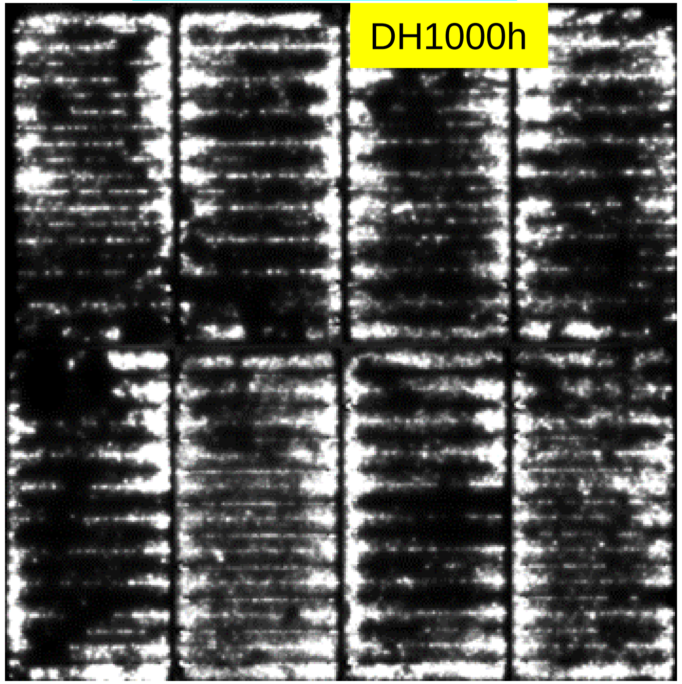
P_{max} loss ~50%$_{rel}$
R_s increases ~300%$_{rel}$

Glass/**EVA**/Backsheet

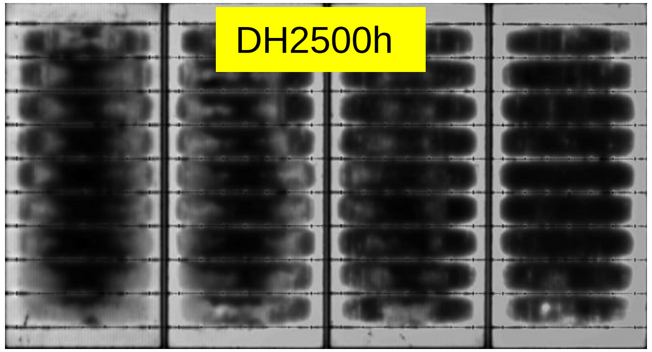
- Similar failure modes were observed in TOPCon and HJT modules, despite different BOMs being used.
- However, the degradation in TOPCon module occurs quicker than HJT module.
- Note that TOPCon and HJT modules were fabricated on a **different industrial production line.**

Type-3 failure mode in TOPCon: potential root causes: Soldering flux and POE

Type-3 failure mode (TOPCon modules)



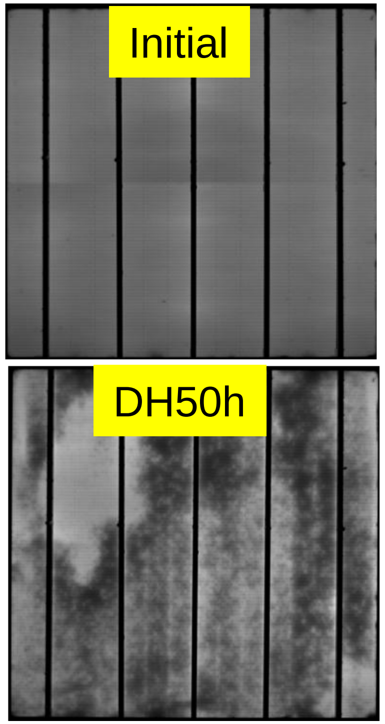
Type-3 failure mode (HJT modules)



Soldering flux

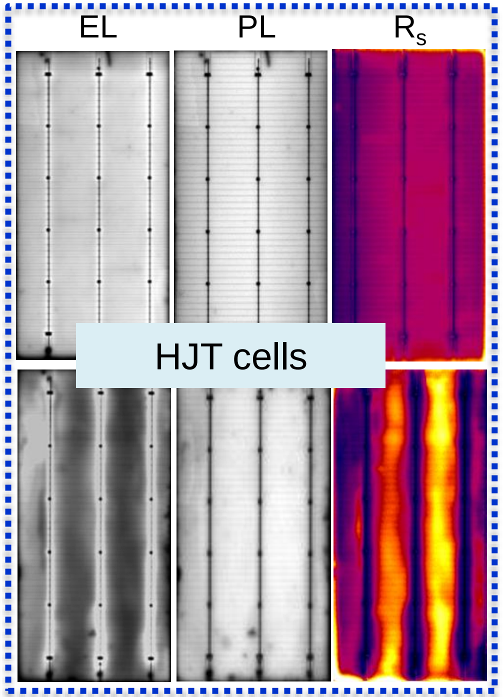
TOPCon cell

TOPCon cell



Soldering flux, metal finger

Type-3- HJT cell



Soldering flux, metal finger, ITO layer

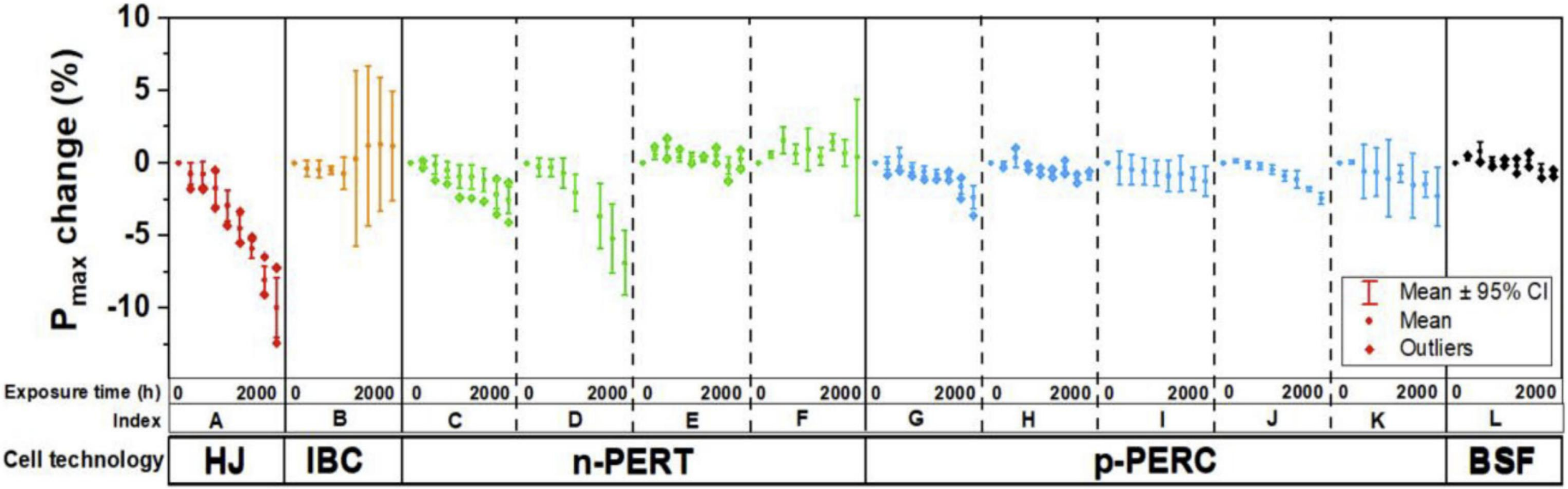
- **Type-3 failure mode in TOPCon module with POE occurs more quickly than that of the HJT module with EVA.**
  - → **Therefore, it is speculated that some additive release from POE is also involved in causing Type-3 failure mode in TOPCon modules.**

Outline

- Introduction
- Damp-heat failures in HJT and TOPCon solar cells/modules
  - 4 new failure modes in glass-backsheet HJT modules
  - Na^+ induced failures in PERC, TOPCon, and HJT solar cells
  - Flux induced contact failure
- Impact of bill of materials
- **UV-induced degradation**
- Cell level mitigation of damp-heat failures
- Yield modelling of failure modes
- Conclusions

UV induced degradation a concern for various technologies

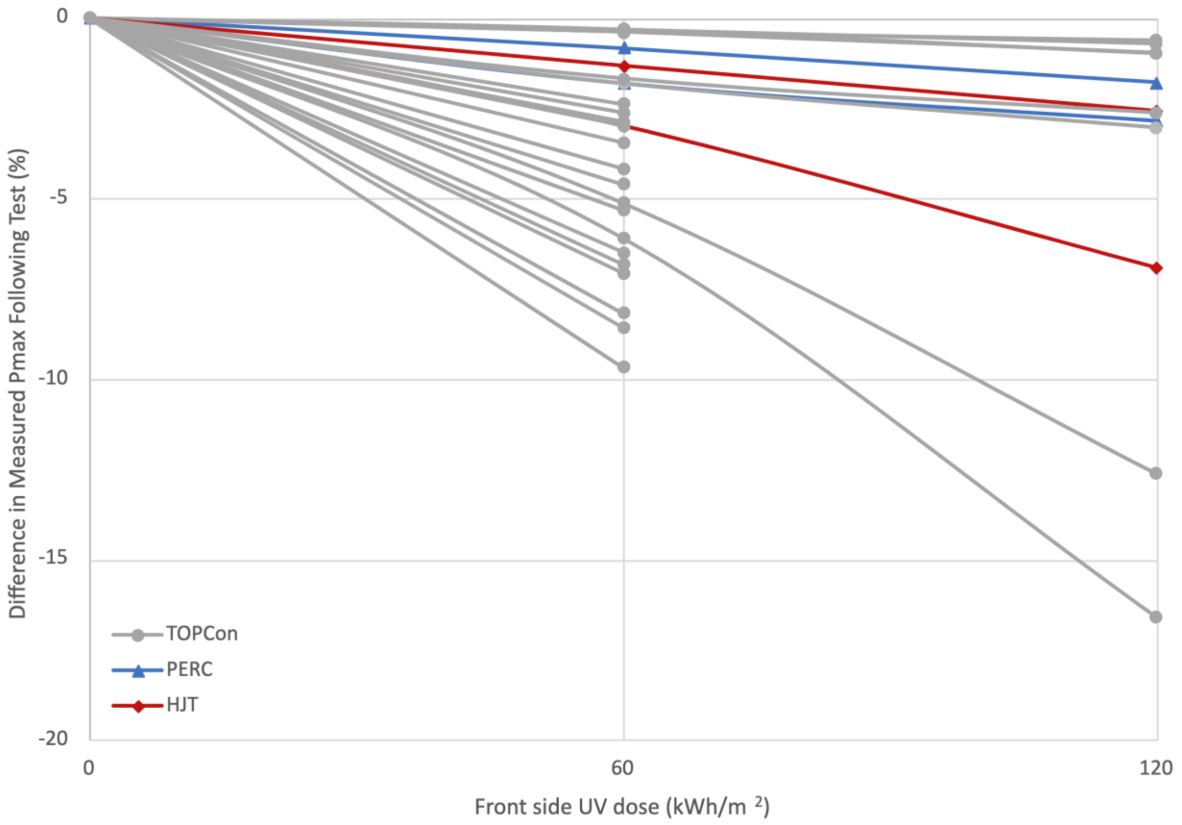
- Various solar cell technologies such as HJT and n-PERT (with the same front as TOPCon) are sensitive to UV induced degradation (UVID)
- UVID typically related to the breaking of Si-H bonds in the front dielectric including the interface with c-Si



Sinha, A., Qian, J., Moffitt, S. L., Hurst, K., Terwilliger, K., Miller, D. C., ... & Hacke, P. (2023). UV-induced degradation of high-efficiency silicon PV modules with different cell architectures. *Progress in Photovoltaics: Research and Applications*, *31*(1), 36-51.

UV induced degradation a concern for various technologies

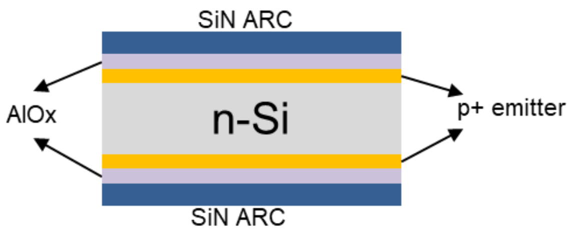
- Various solar cell technologies such as HJT and n-PERT (with the same front as TOPCon) are sensitive to UV induced degradation (UVID)
- UVID typically related to the breaking of Si-H bonds in the front dielectric including the interface with c-Si
- UVID is a serious concern for TOPCon!

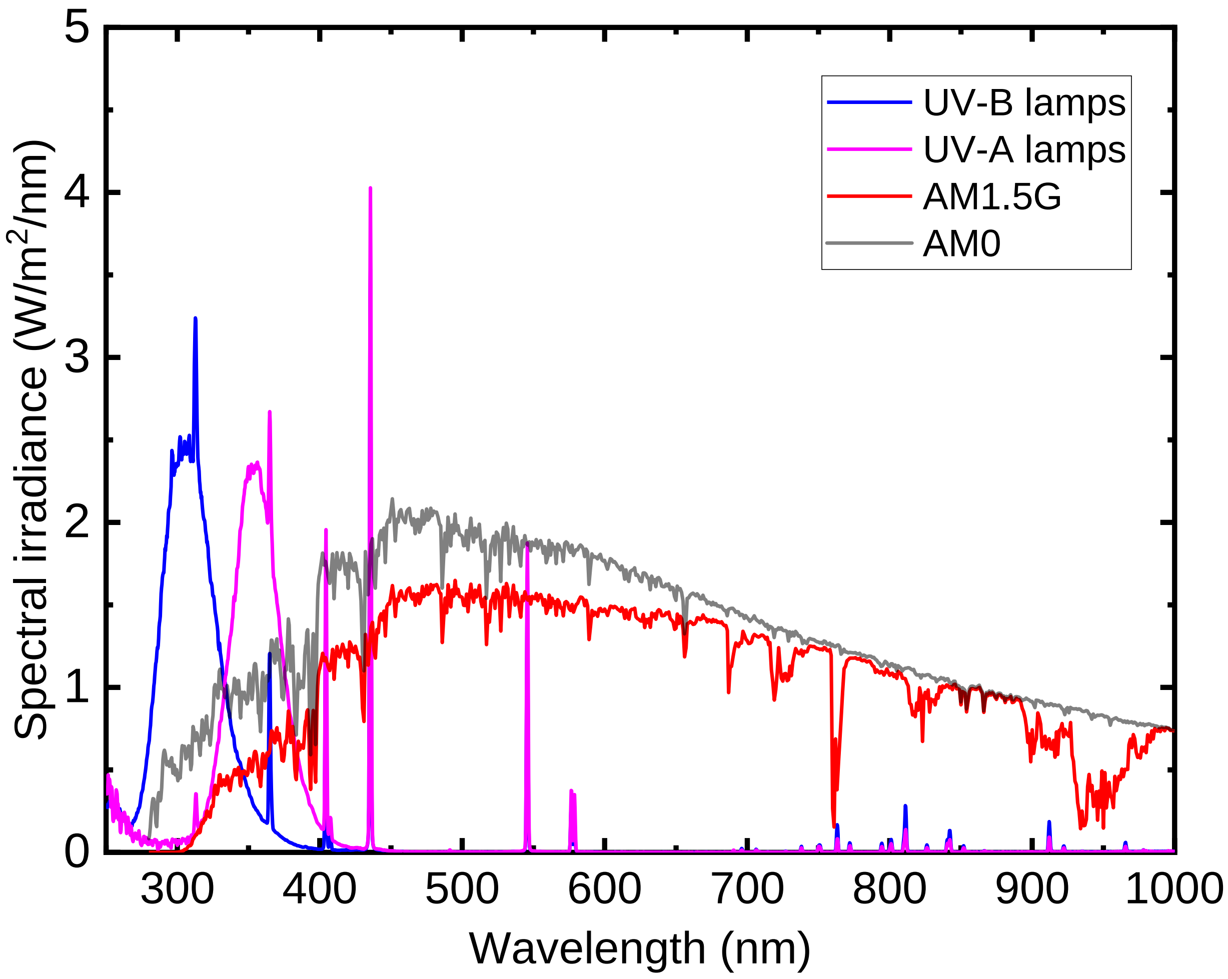


UVID testing setup

- Testing UVID with both UV-A and UV-B
- Integrated irradiance (280-385nm)
  - AM1.5: 35.26 W/m^2
  - AM0: 85.99 W/m^2
  - UV-B: 114.1 W/m^2
  - UV-A: 102.2 W/m^2

Lifetime Structure



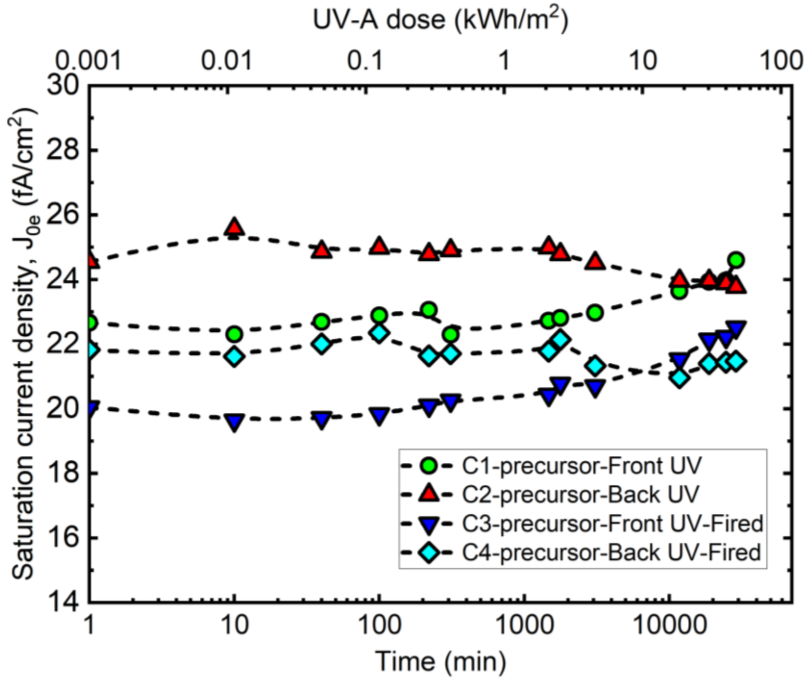


Source: Khan, et al., under review

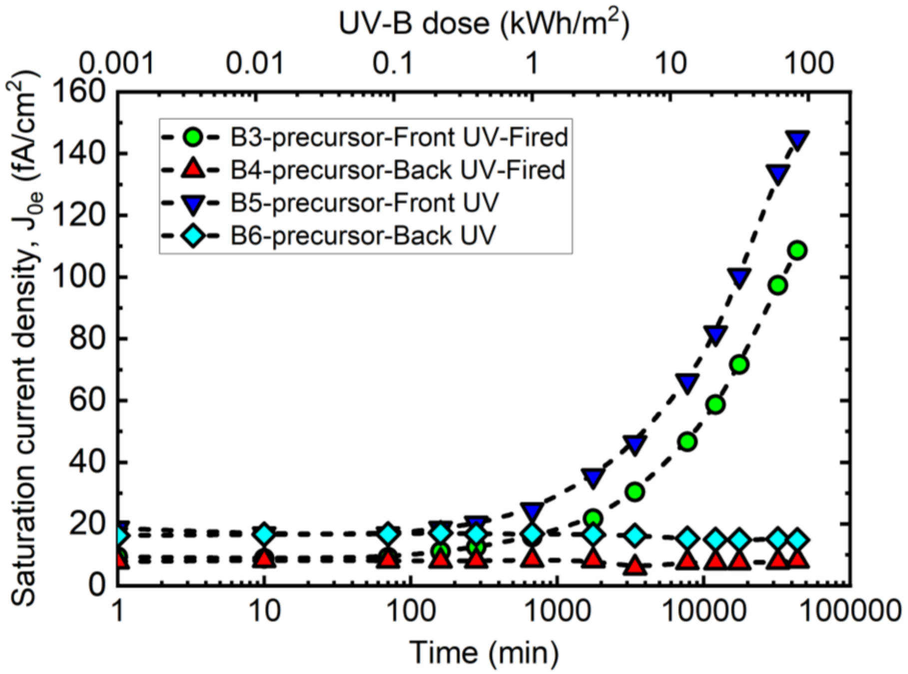
UVID in TOPCon solar cells

- Tested TOPCon solar cells are susceptible to UVID on the front but not at the rear.
- Accelerating UVID testing is crucial for obtaining quick feedback in a fast-paced industry.
- Our research revealed that UV-B wavelengths significantly accelerate degradation compared to UV-A wavelengths without introducing new failure modes.

UV-A exposure



UV-B exposure

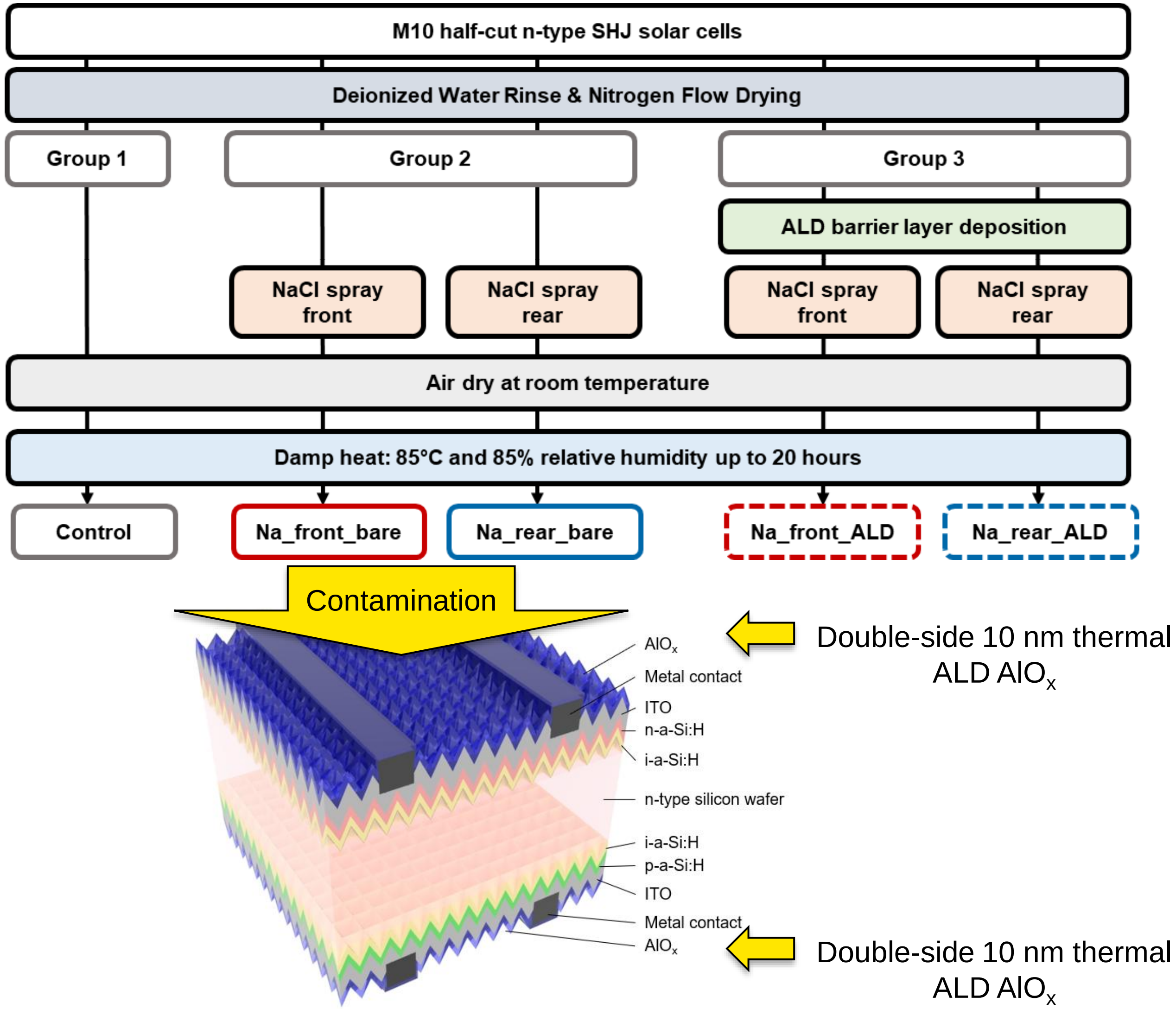


Outline

- Introduction
- Damp-heat failures in HJT and TOPCon solar cells/modules
  - 4 new failure modes in glass-backsheet HJT modules
  - Na^+ induced failures in PERC, TOPCon, and HJT solar cells
  - Flux induced contact failure
- Impact of bill of materials
- UV-induced degradation
- **Cell level mitigation of damp-heat failures**
- Yield modelling of failure modes
- Conclusions

Experiment details

Experimental flow

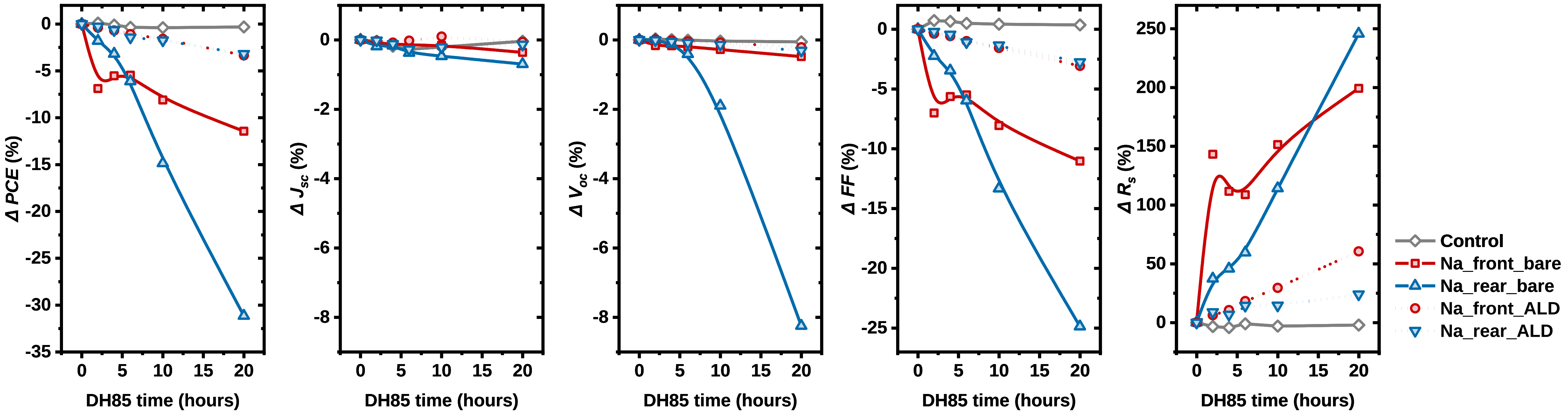


Leadmicro QL200

Wu, et al. "Addressing sodium ion-related degradation in SHJ cells by the application of nano-scale barrier layers." *Solar Energy Materials and Solar Cells* 264 (2024): 112604.
Hoex, B, Sen, C., Wu, X. Australian patent 2023900037

Results Electrical performance characterization

I-V relative variation

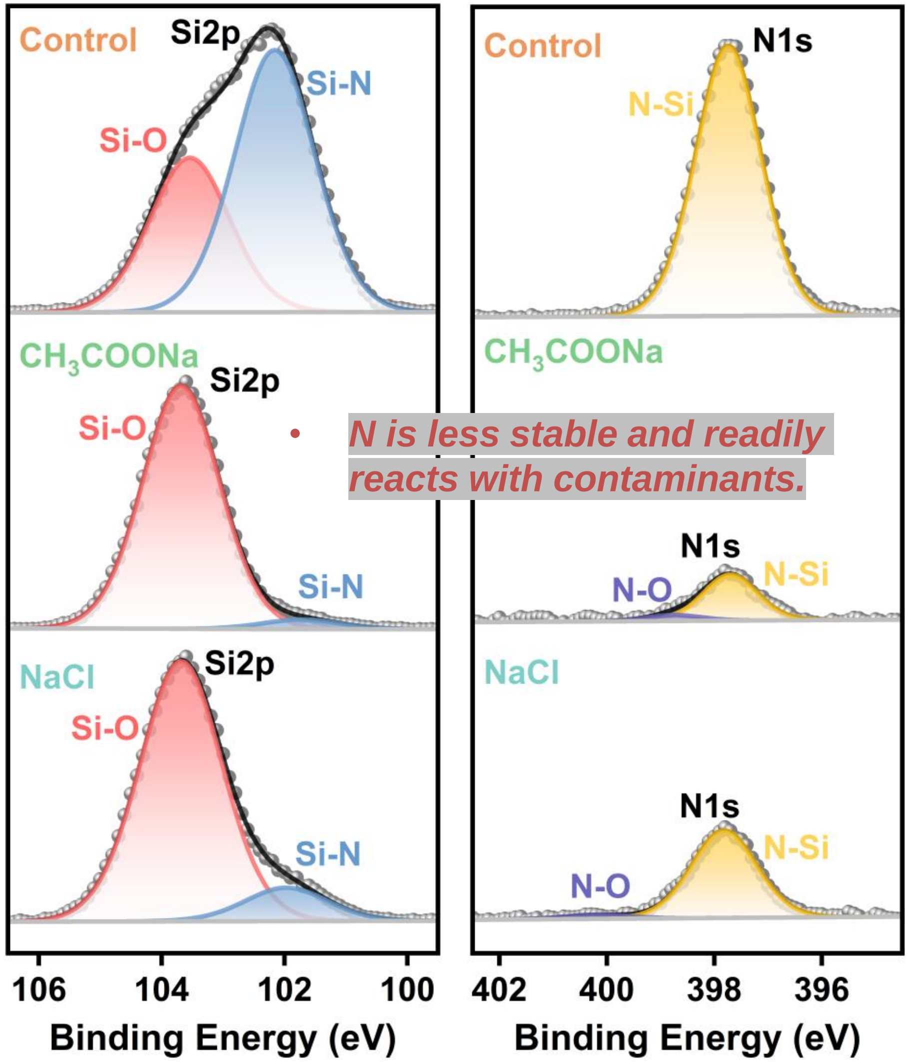


Wu, et al. "Addressing sodium ion-related degradation in SHJ cells by the application of nano-scale barrier layers." *Solar Energy Materials and Solar Cells* 264 (2024): 112604.

Sen, et al. "Accelerated damp-heat testing at the cell-level of bifacial silicon HJT, PERC and TOPCon solar cells using sodium chloride." Solar Energy Materials and Solar Cells 262 (2023): 112554

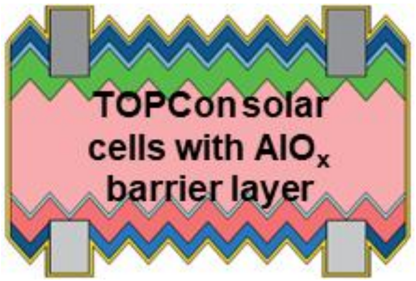
Contaminant impacts on the TOPCon passivation

XPS analysis

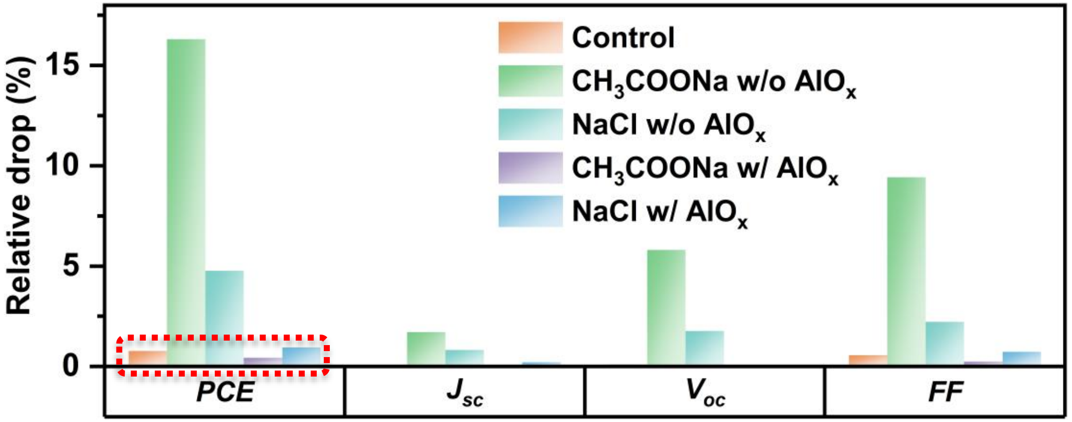


- *N is less stable and readily reacts with contaminants.*

Stability enhancement

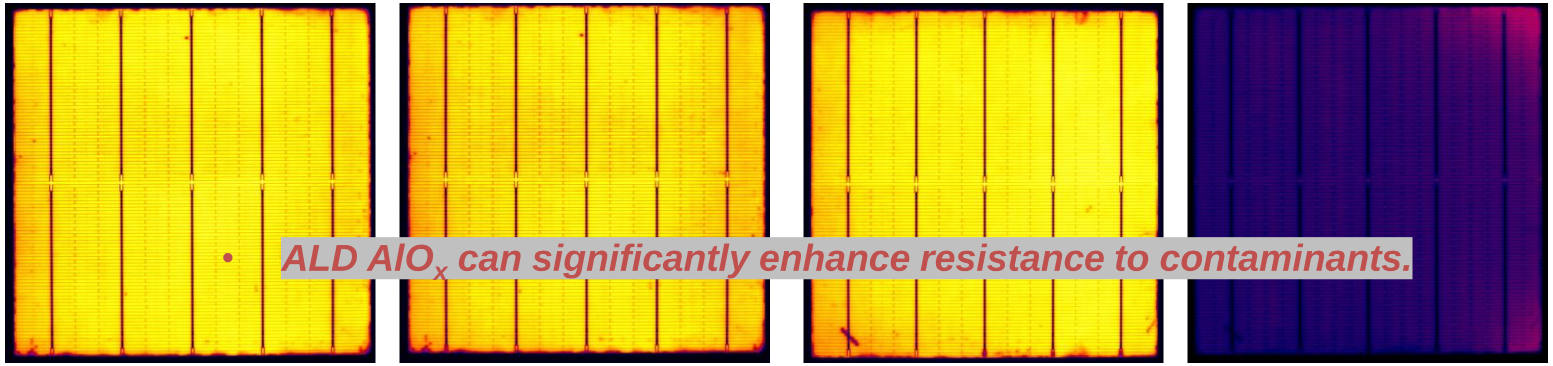


10 nm AlOx by atomic layer deposition (ALD)



PL imaging (samples were sprayed with CH_3COONa on the rear side)

AlO_x group | **Bare cell**



Initial | After 20-hour DH85 | Initial | After 20-hour DH85

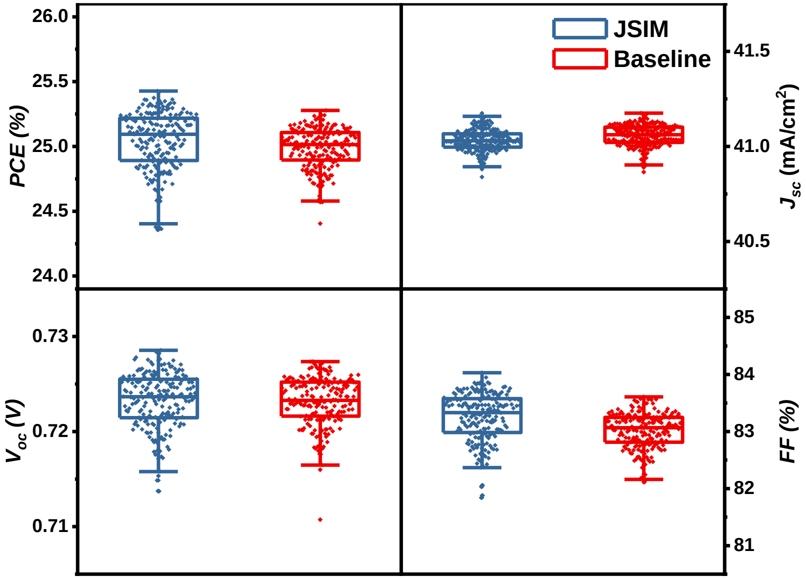
- *ALD AlO_x can significantly enhance resistance to contaminants.*

Tong, H., Wu, X., Wang, X., Hoex, B., et al. Mitigating Contaminant-induced Surface Degradation in TOPCon Solar Cells: Mechanisms, Impacts, and Solutions with Atomic Layer Deposition, submitted to SOLMAT.

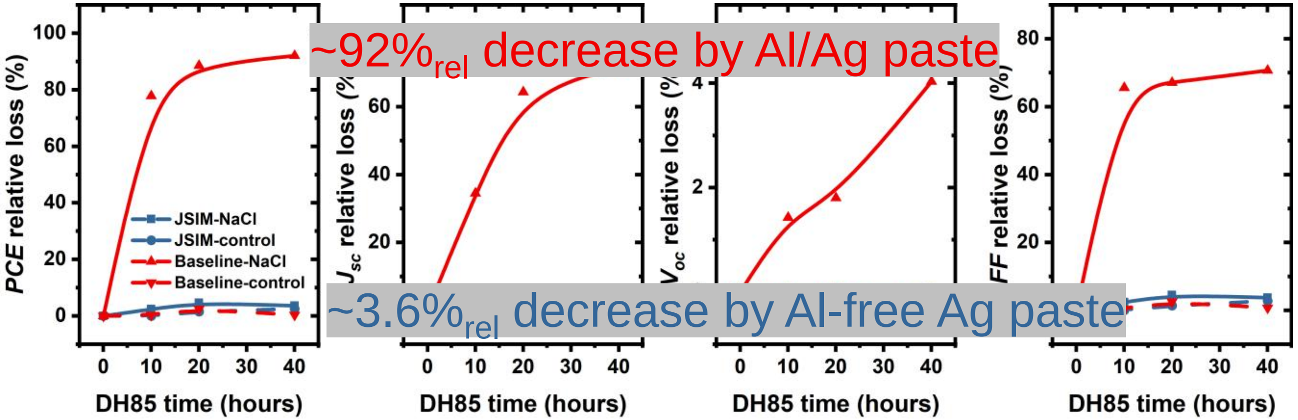
Enhancing DH Stability Through Metallization Optimization

➢ ***Laser-assisted firing process developed by Jolywood***

Jolywood Special Injected Metallization (JSIM)



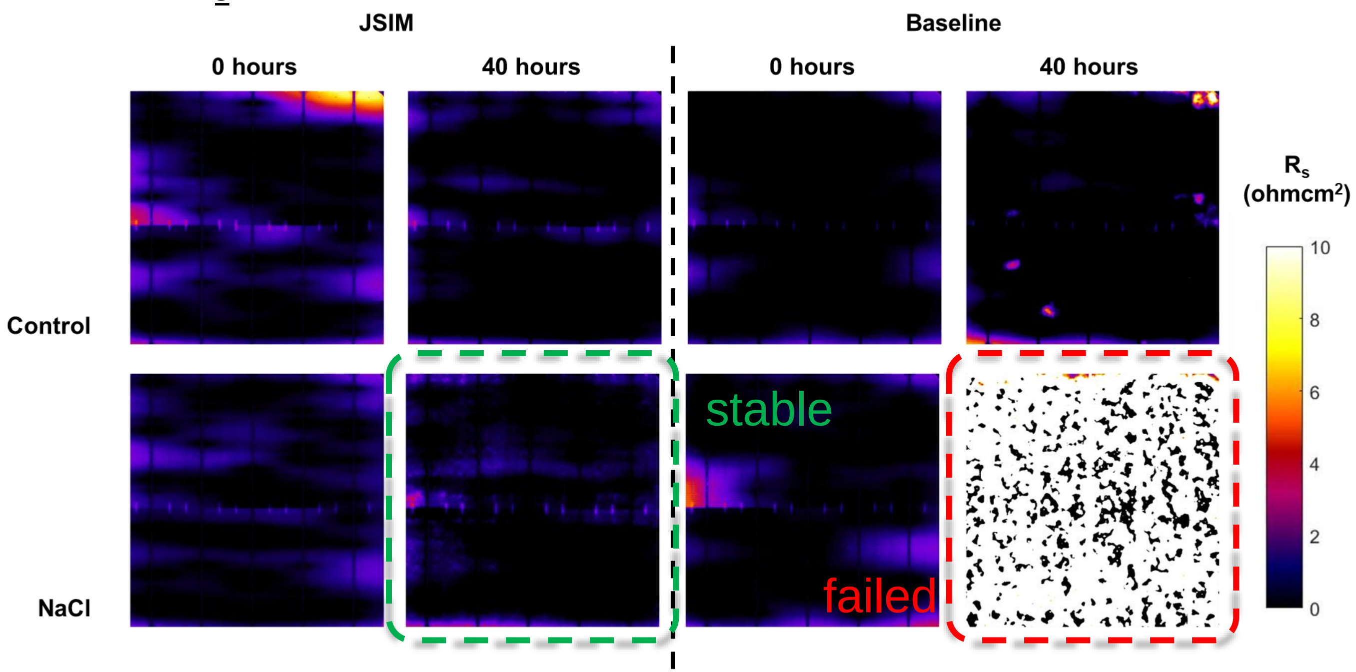
➢ *Cell-level accelerated DH85 test*



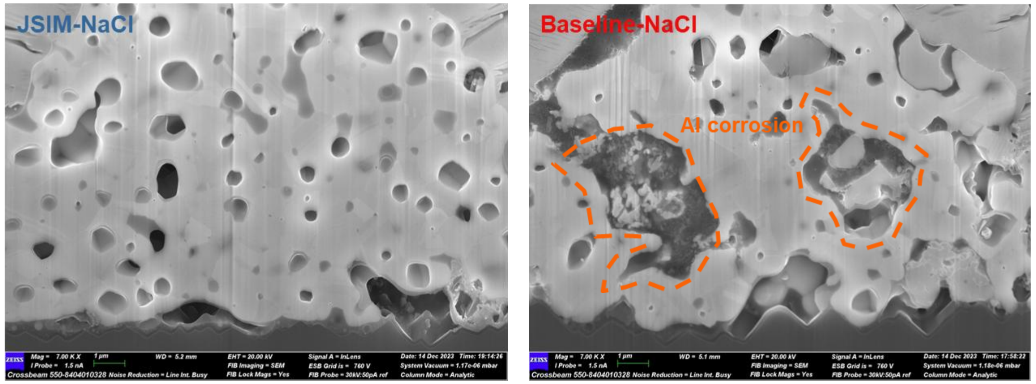
~92%$_{rel}$ decrease by Al/Ag paste

~3.6%$_{rel}$ decrease by Al-free Ag paste

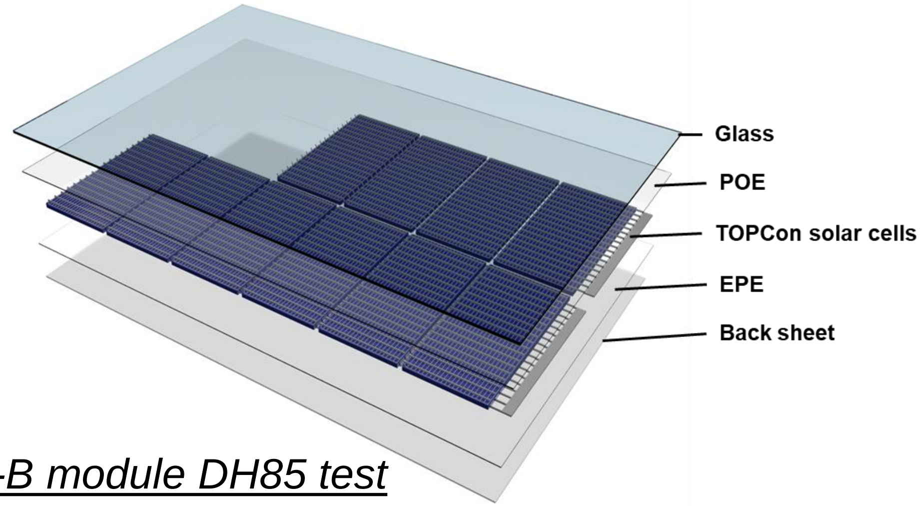
➢ *R_s mapping with DH85*



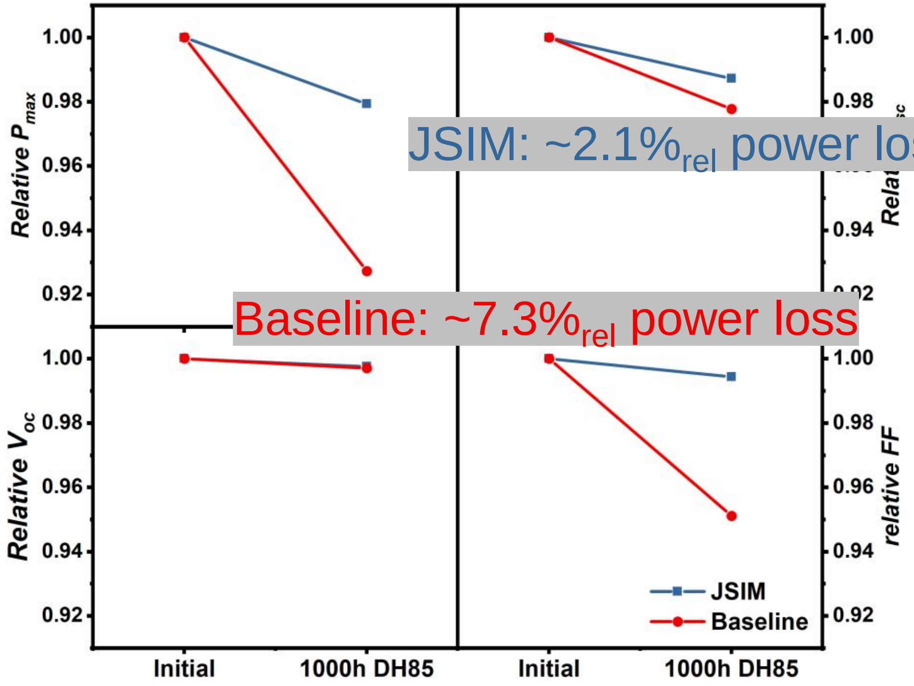
➢ *Cross-sectional analysis*



Assessing Module-Level Stability of JSIM



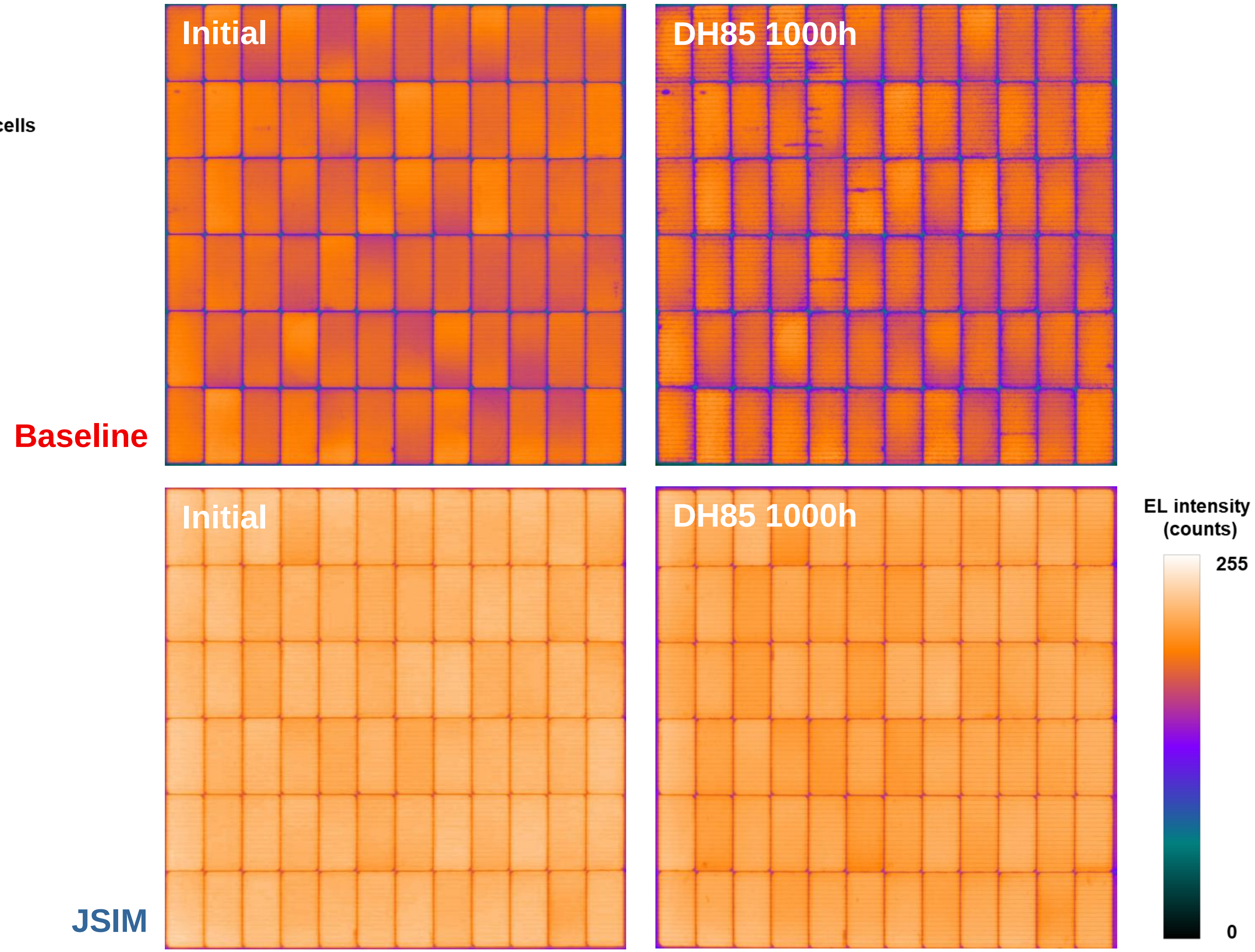
➢ *G-B module DH85 test*



JSIM: ~2.1%$_{rel}$ power loss

Baseline: ~7.3%$_{rel}$ power loss

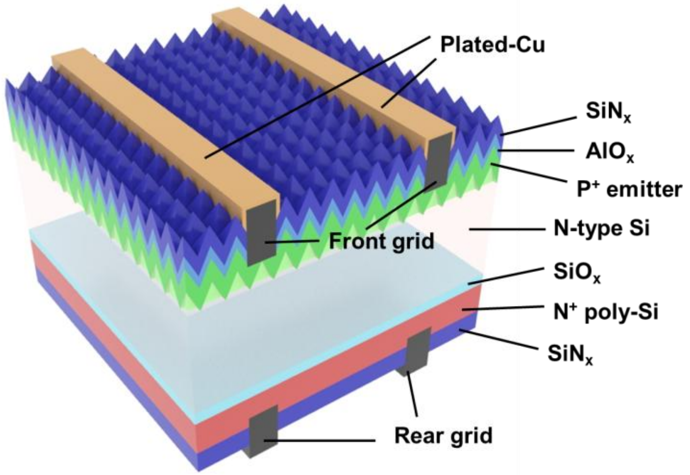
➢ *Electroluminescence images*



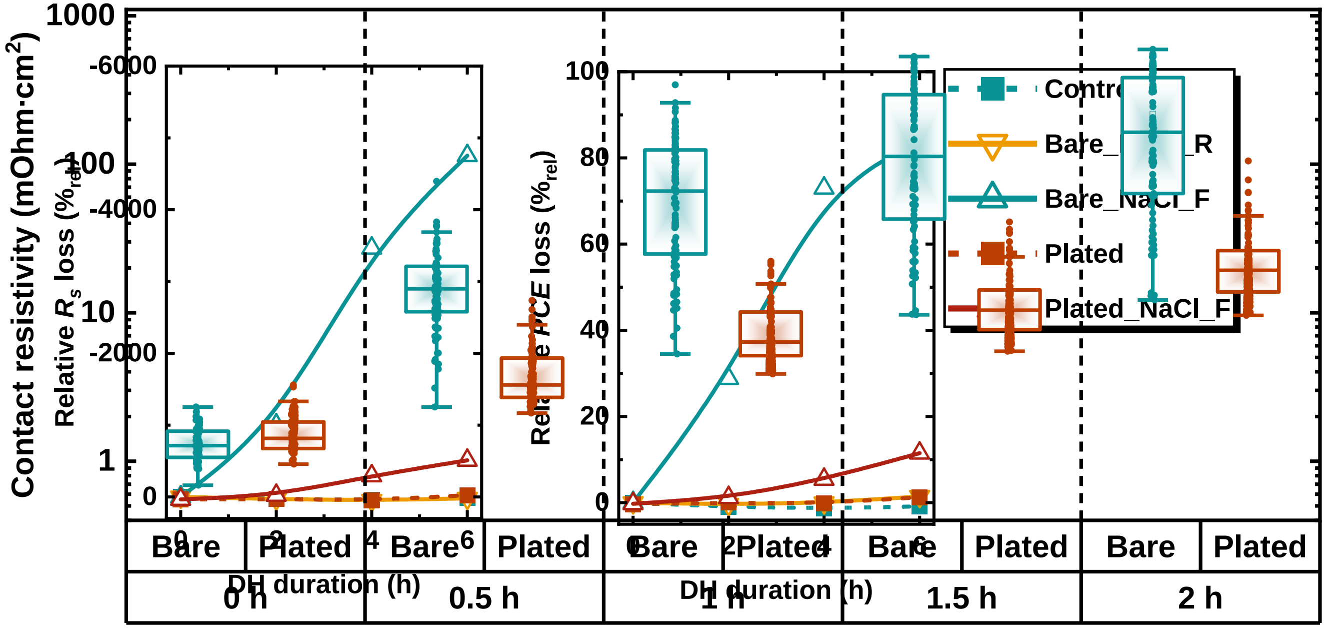
Mitigating contaminant-induced damp-heat degradation via copper plating

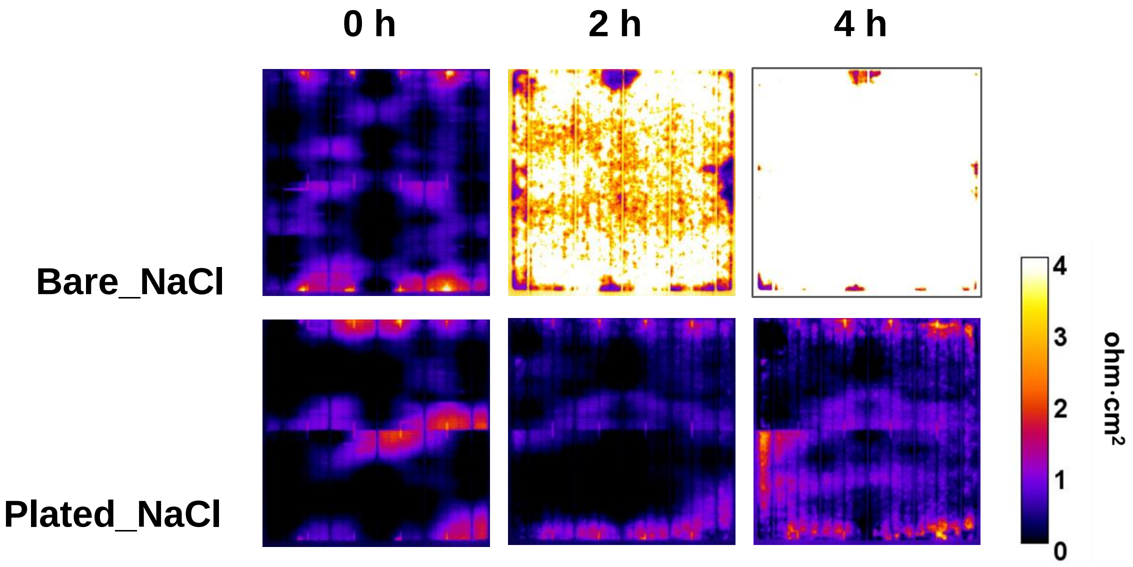
As-plated TOPCon solar cells

	PCE (%)	V_{oc} (mV)	J_{sc} (mA/cm^2)	*FF* (%)
Before Plating	**23.24** ± *0.01*	**706.4** ± *0.7*	**39.79** ± *0.03*	**82.68** ± *0.11*
After Plating	**23.33** ± *0.02*	**706.6** ± 0.7	**39.67** ± *0.04*	**83.23** ± *0.05*
Relative Variation	0.39%	0.02%	-0.29%	0.67%



Enhanced stability with plated-Cu

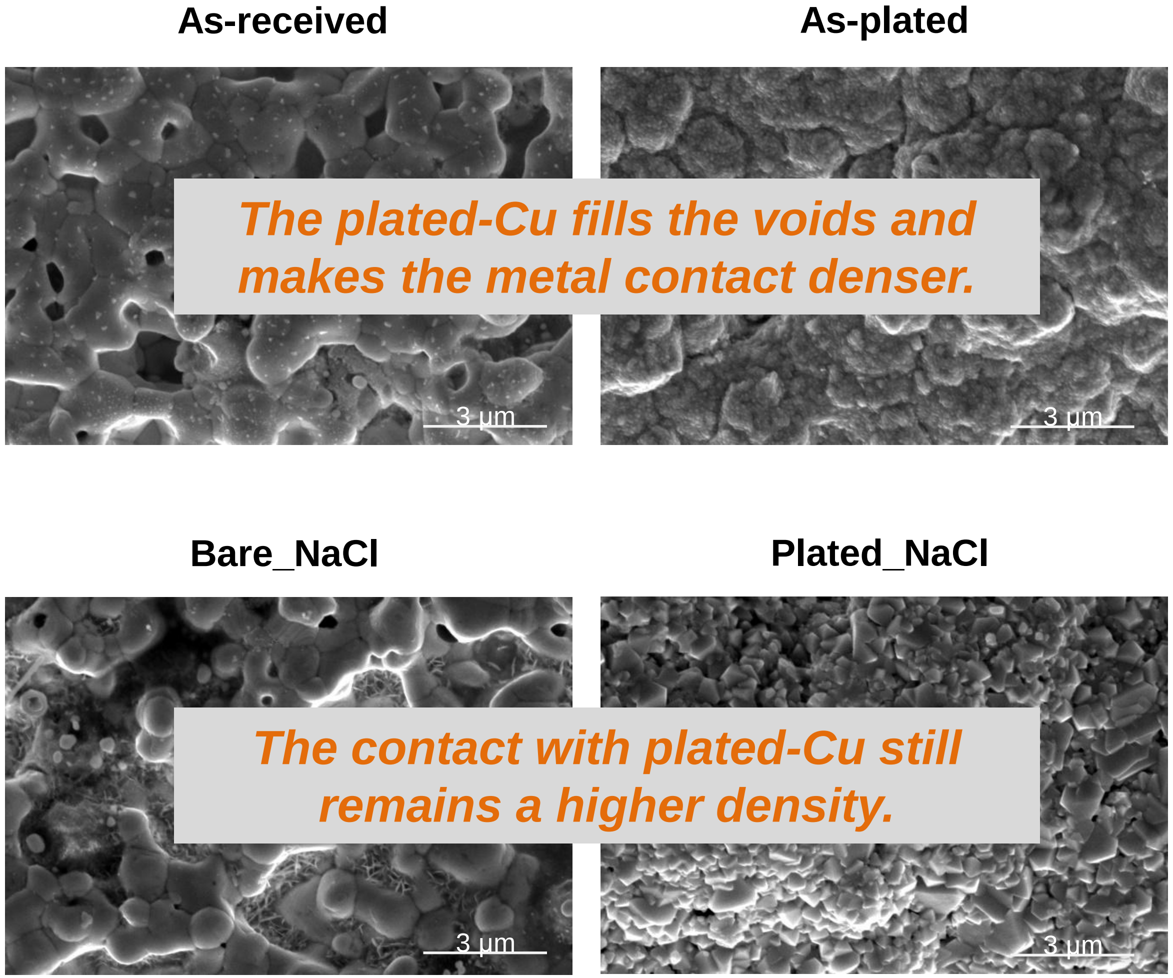




Wang, X., Sen, C., Wu, X., Chang, Y.-C., Wang, H., Khan, M.U., Hoex, B., 2025. Alleviating contaminant-induced degradation of TOPCon solar cells with copper plating. Solar Energy Materials and Solar Cells 282, 113444. https://doi.org/10.1016/j.solmat.2025.113444

Protection mechanism of plated-Cu

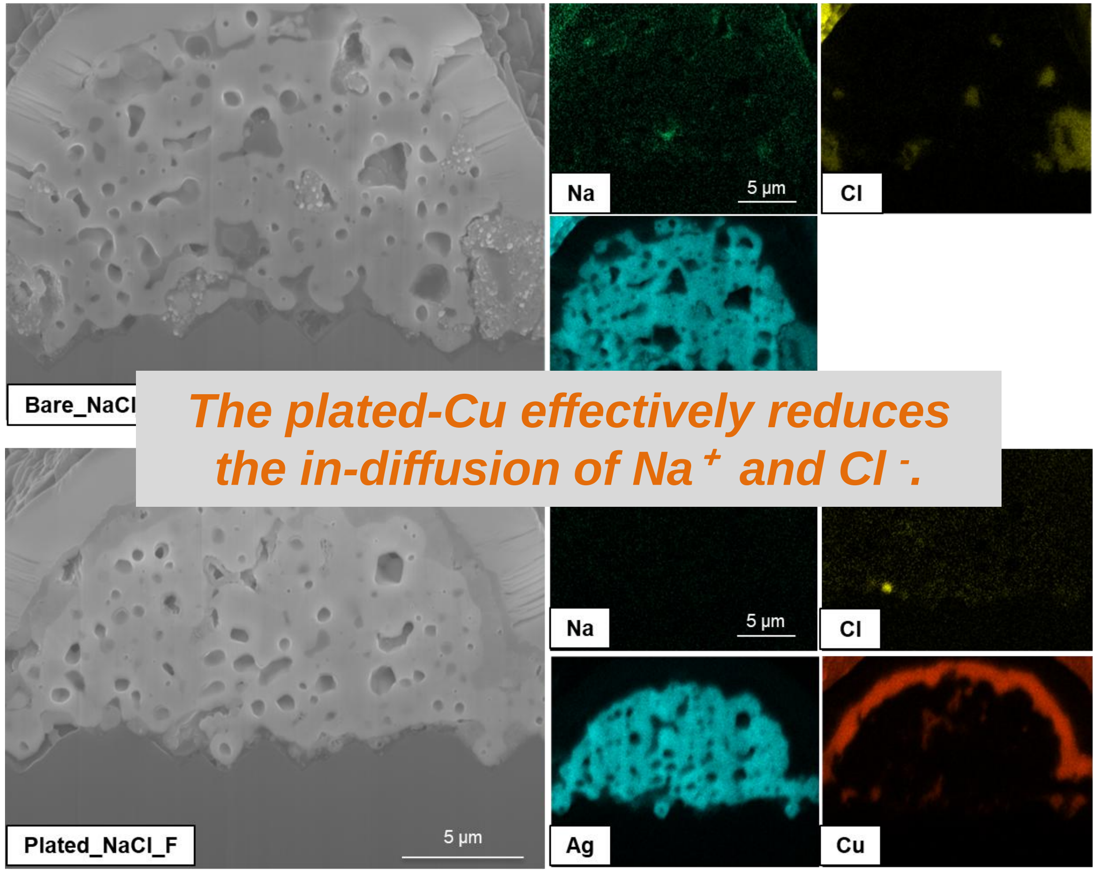
Top-view SEM



The plated-Cu fills the voids and makes the metal contact denser.

The contact with plated-Cu still remains a higher density.

Cross-sectional SEM



The plated-Cu effectively reduces the in-diffusion of Na^+ and Cl^-.

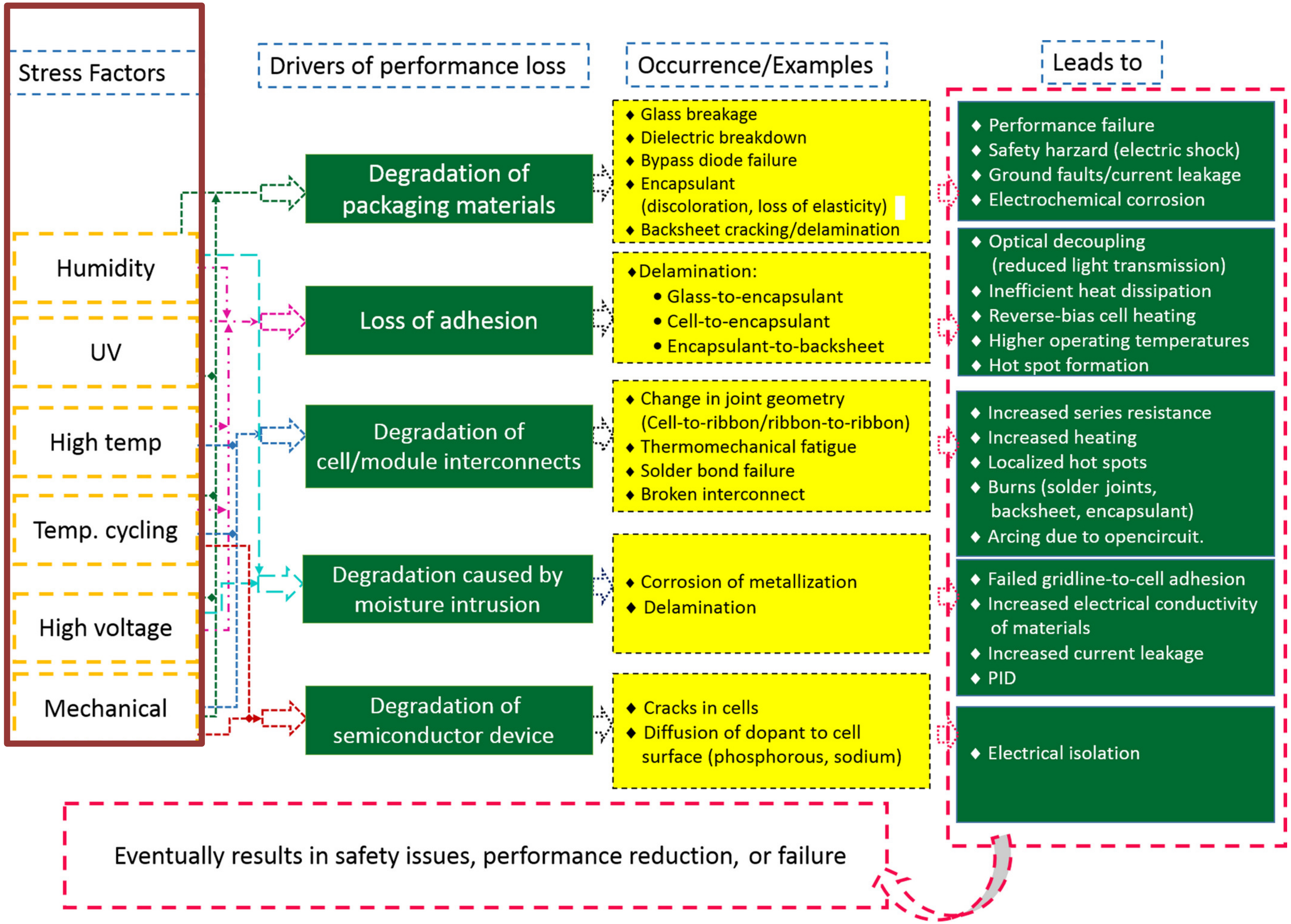
Atomic ratio (%)	Na/Ag	Cl/Ag
Bare_NaCl	1.36	2.33
Plated_NaCl	0.00	0.22

Outline

- Introduction
- Damp-heat failures in HJT and TOPCon solar cells/modules
  - 4 new failure modes in glass-backsheet HJT modules
  - Na^+ induced failures in PERC, TOPCon, and HJT solar cells
  - Flux induced contact failure
- Impact of bill of materials
- UV-induced degradation
- Cell level mitigation of damp-heat failures
- **Yield modelling of failure modes**
- Conclusions

Impacts of Module Degradation

Stresses

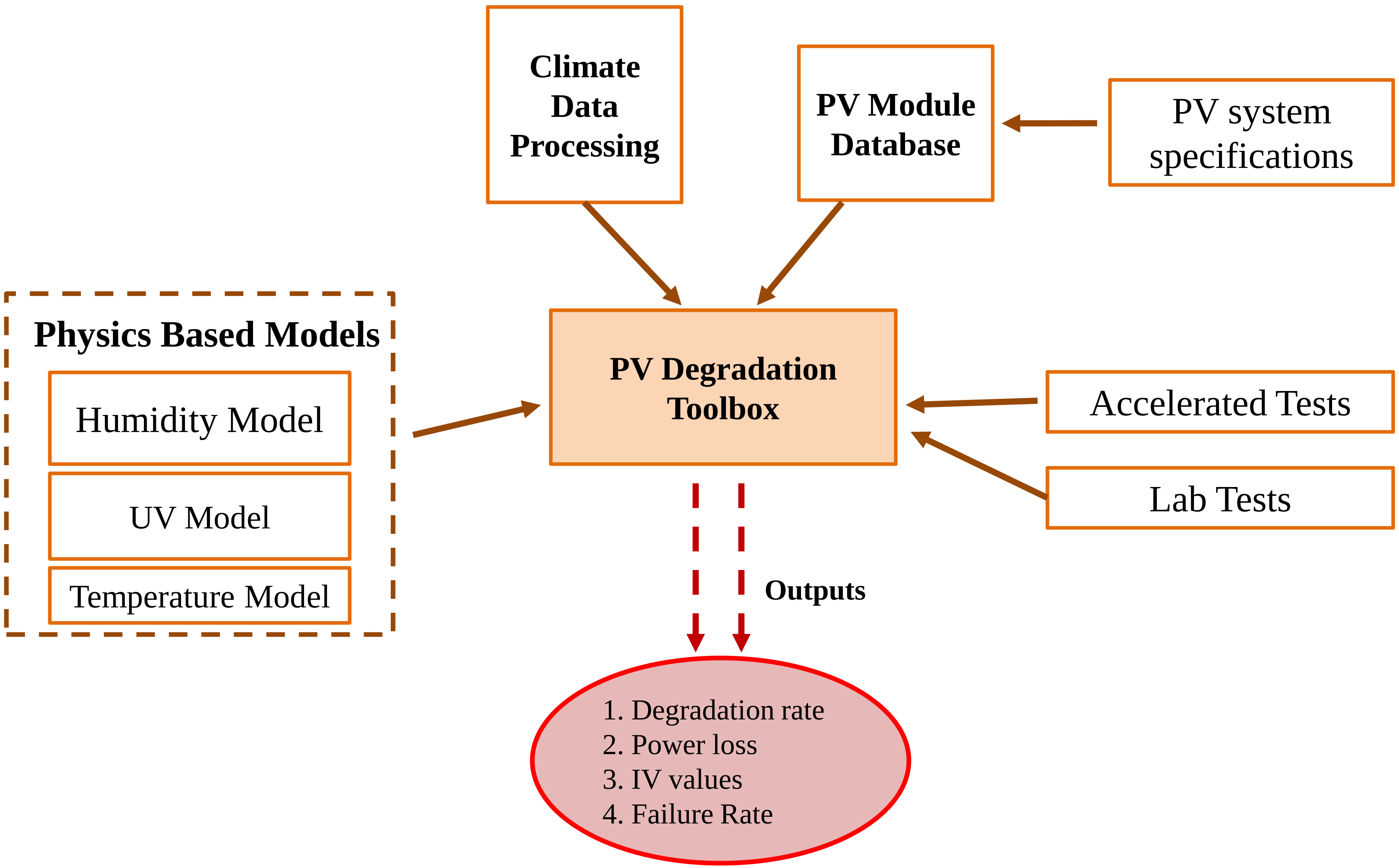


Indicators

I-V Parameters

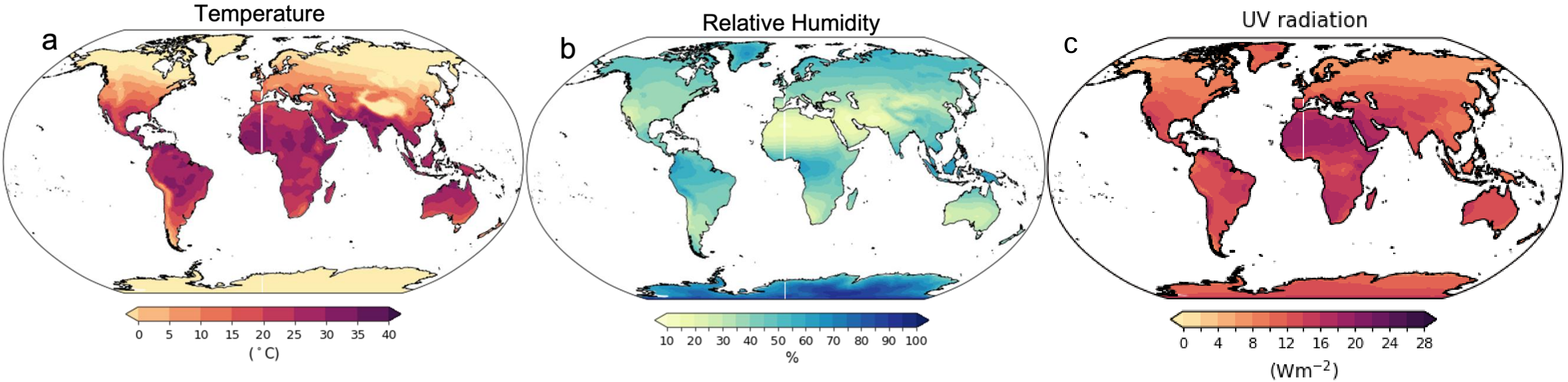
Power

Methods



Climate Data Processing
PV Module Database
PV system specifications
Physics Based Models
Humidity Model
UV Model
Temperature Model
PV Degradation Toolbox
Accelerated Tests
Lab Tests
Outputs
1. Degradation rate
2. Power loss
3. IV values
4. Failure Rate

Climate Stressors



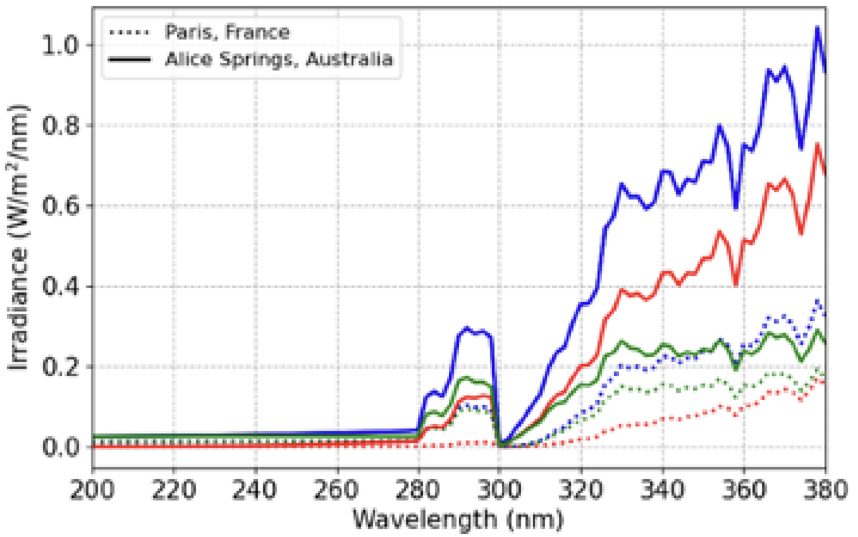
- The main important climate stressors are temp , relative humidity and UV radiation.
- Obtaining global-scale UV radiation data is usually a challenge.
- We use advanced UV radiation modelling to derive UVA and UVB radiation.

Global Scale UV irradiance modelling for accurate estimation of UV-induced degradation

Objective: To assess downward ground-reaching solar irradiance, which varies globally and affects UV levels.

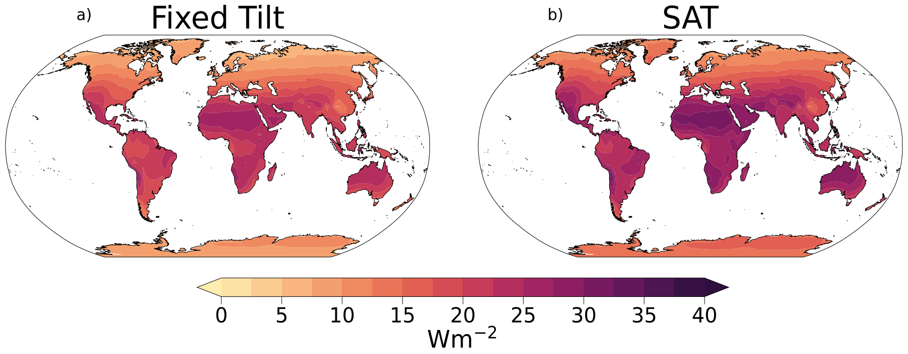
Method: We model global UV exposure using module tilt, azimuth, sun position, activation energy, manufacturer specs, temperature, moisture, and UV on tilted surfaces.

Results: The IEC 61215 UV pre-conditioning test (15 kWh/m²) equals only ~46 days!!! in Arizona, underestimating UV exposure and degradation globally.



Global, direct and diffuse irradiance are shown in blue, red and green colours respectively.

UV radiation on PV systems



UV induced degradation of PV systems

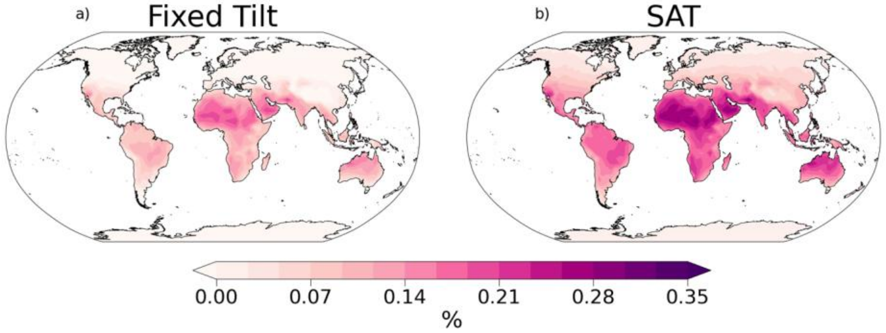
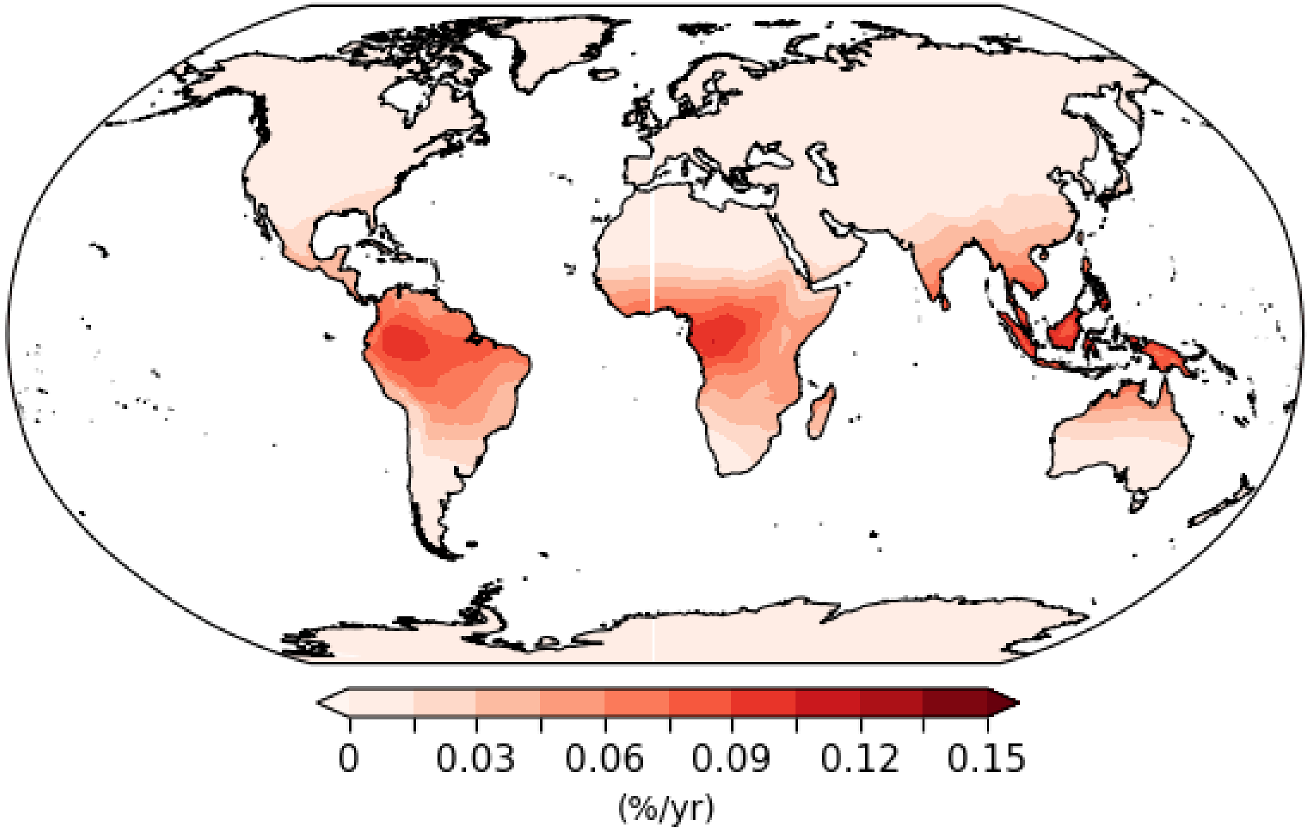


Photo-Degradation Modelling



- Photo-Degradation mainly occurs due to UV radiation
- also dependent on humidity on the surface of the module.

$$k_P = A_P\left((UV)^X\left(1 + rh_{eff}{}^X\right)\exp\left(-\frac{E_P}{k_B \times T_m}\right)\right)$$

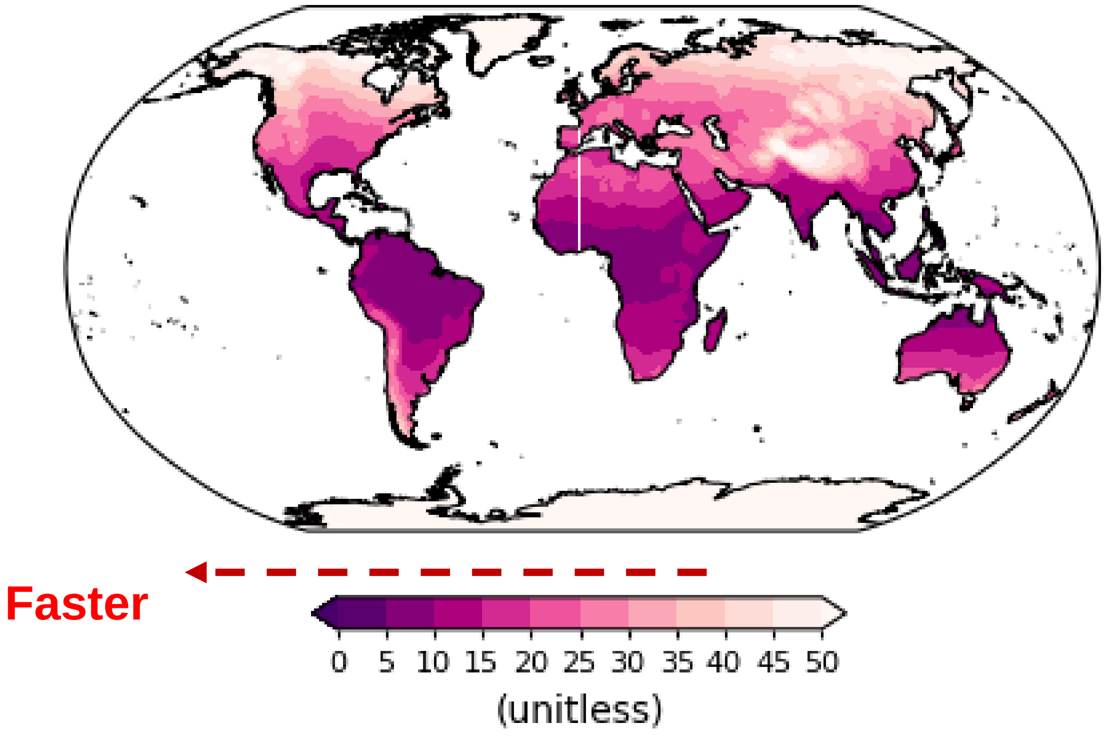
Ap : pre-exponential constant;
Ep : activation energy;
K_B: Boltzmann Constant;
rh_{eff} : effective RH

- Tropical regions are the highest affected by photo-degradation degradation mechanism.
- Desert regions have relatively lower photo-degradation rates due to lower levels of humidity.

Accelerated Test

- Acceleration Factor between the rate of degradation of a modelled environment versus a modelled controlled environment.

- If the AF=25 then 1 year of Controlled Environment exposure is equal to 25 years in the field.



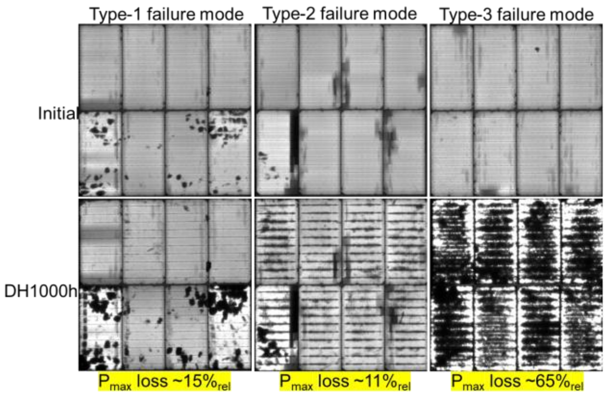
- Higher AF = Longer time to degrade
- Lower AF = **Faster degradation**

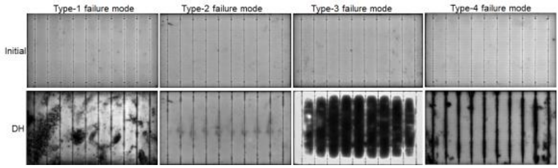
Modelled Control Conditions: UV = 80 W/m^2
Chamber Temp = 80 °C
Chamber RH = 65%

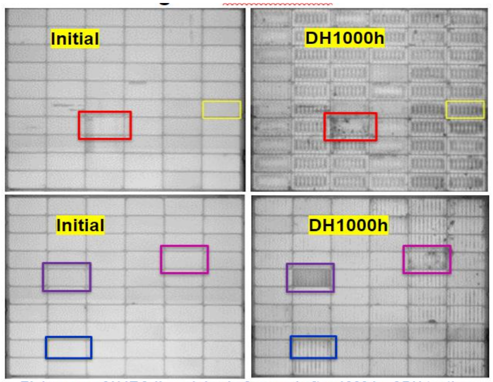
Summary

- We have developed cell-level tests for rapid (10-100 times faster) identification of damp-heat failure modes
- Four new failure modes were detected in glass-backsheet HJT modules, and their root cause was identified
- Three types of failure modes were identified in TOPCon glass-backsheet modules.
- Na^+ and soldering flux can undergo a chemical reaction with TOPCon and HJT metallization, resulting in significant power losses
- Bill of materials can have a significant impact on reliability.
- We have a cell-level solutions for various HJT and TOPCon failures
- We have advanced yield modelling that can assess degradation at the global scale

We are keen to work with **you** to further improve the reliability of solar!







EL images of HJT full modules before and after 1000 h of DH testing

Treated HJT cell: Stable after Na^+ exposure