Faculty of Engineering
School of Photovoltaic and Renewable Energy Engineering
Advanced Hydrogenation Group

SPREE Alumni End of Year Event, 30th November 2017
UNSW Sydney

"PV module degradation: the impact of light induced degradation (LID) and how to fix it!"

Dr. Alison Ciesla

Other contributors: Catherine Chan, Ran Chen, Tsun Fung, Daniel Chen, Moonyong Kim, Brett Hallam, Chendany Sen, Utkarshaa Varshney, Carlos Vargas, Ziv Hameiri, Kyung Kim, Shaoyang Liu, Aref Samadi, Bruno Stefani, Iskra Zafirovska, Malcolm Abbott, CheeMun Chong, Stuart Wenham

Background & Outline

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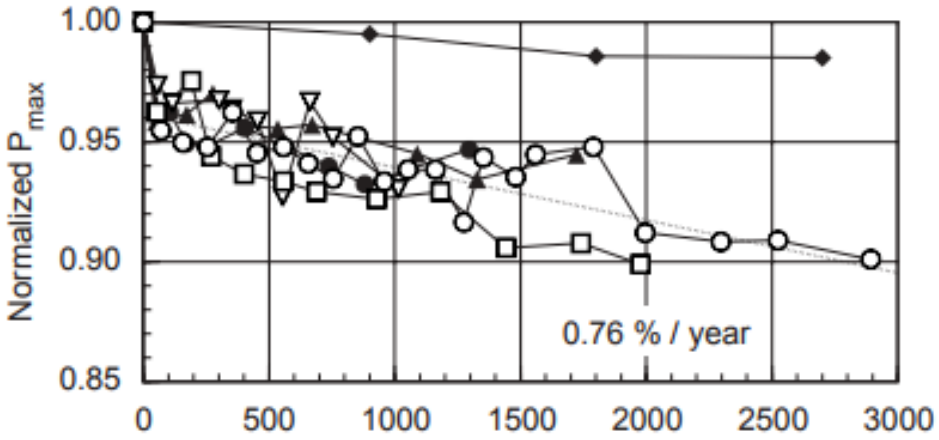
- LID in Cz mono modules due to BO defect



C.R. Osterwald, A. Anderberg, S. Rummel, & L. Ottoson, 'Degradation Analysis of Weathered Crystalline-Silicon PV Modules' PVSC 2002

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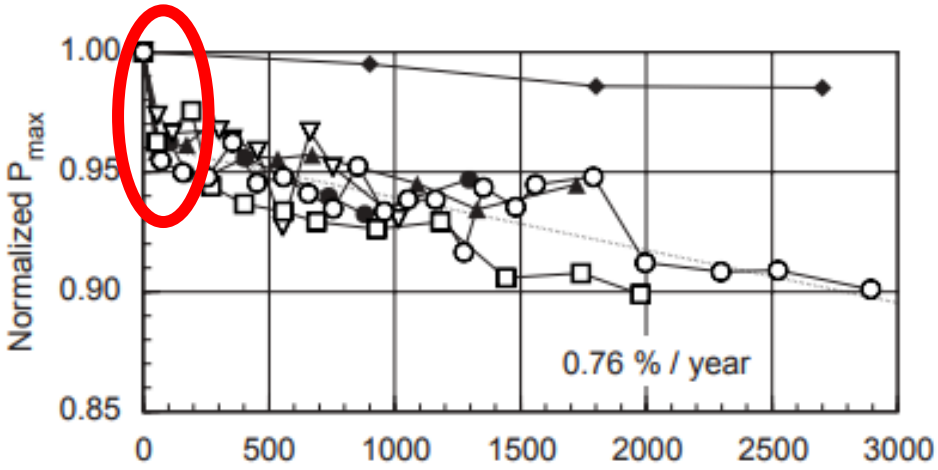

Typically 2-5% absolute power loss in the first 50 h in the sun!

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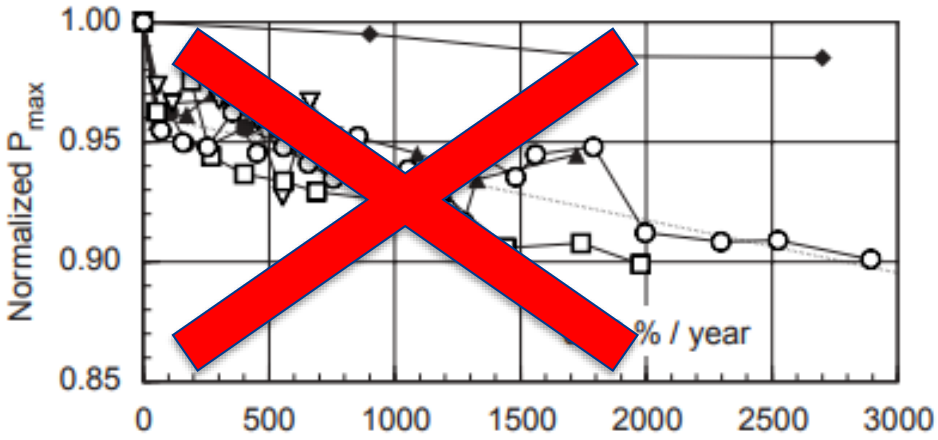
Hydrogen is the solution!



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- LID in multi-PERC ??

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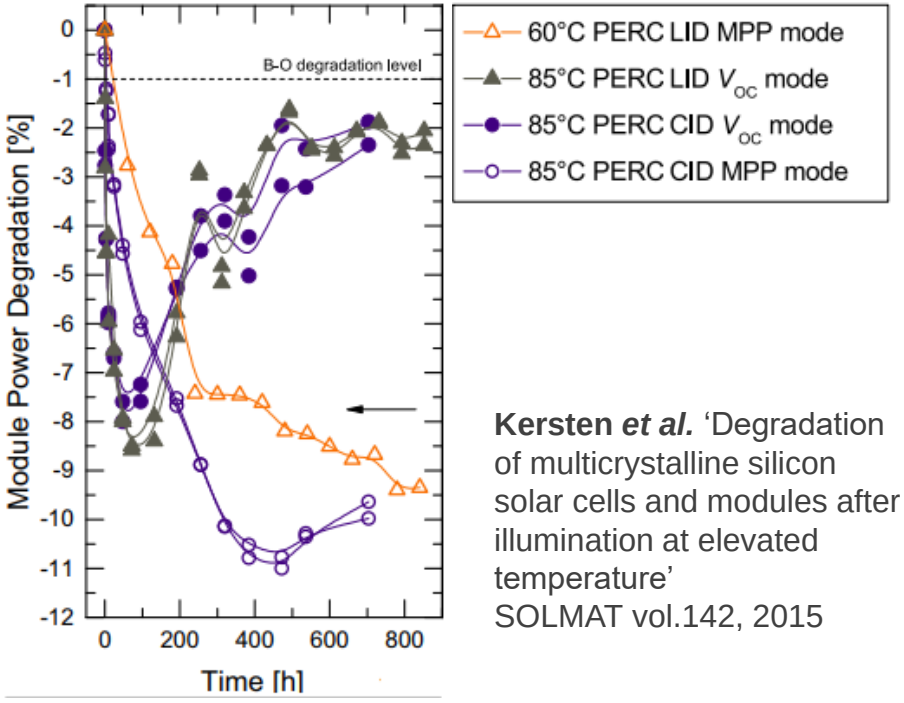
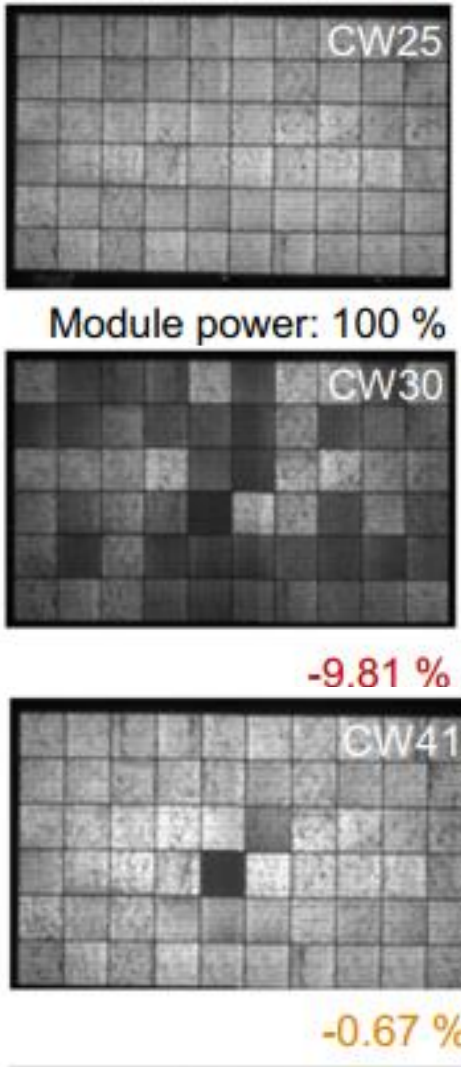


Kersten *et al.* 'Degradation of multicrystalline silicon solar cells and modules after illumination at elevated temperature' SOLMAT vol.142, 2015



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K. Petter et al. (Hanwha Q-Cells) presented at 9th International Workshop on Crystalline Silicon for Solar Cell, Tempe Arizona, October 2016

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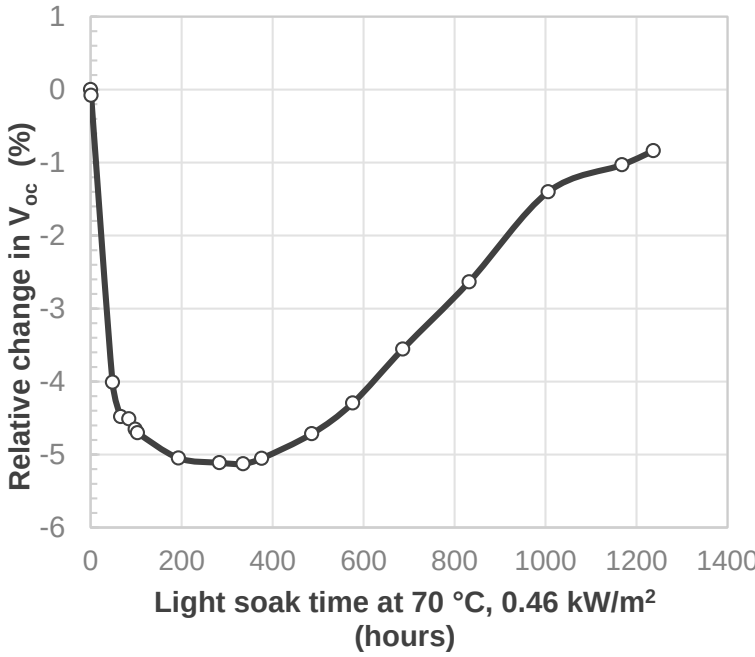

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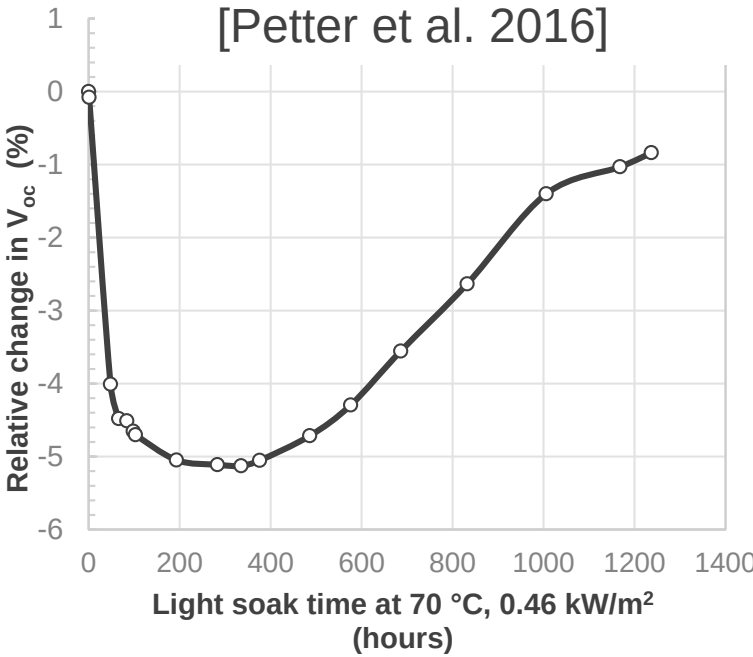
Up to 16% relative efficiency loss!

[Petter et al. 2016]



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Advanced Hydrogenation

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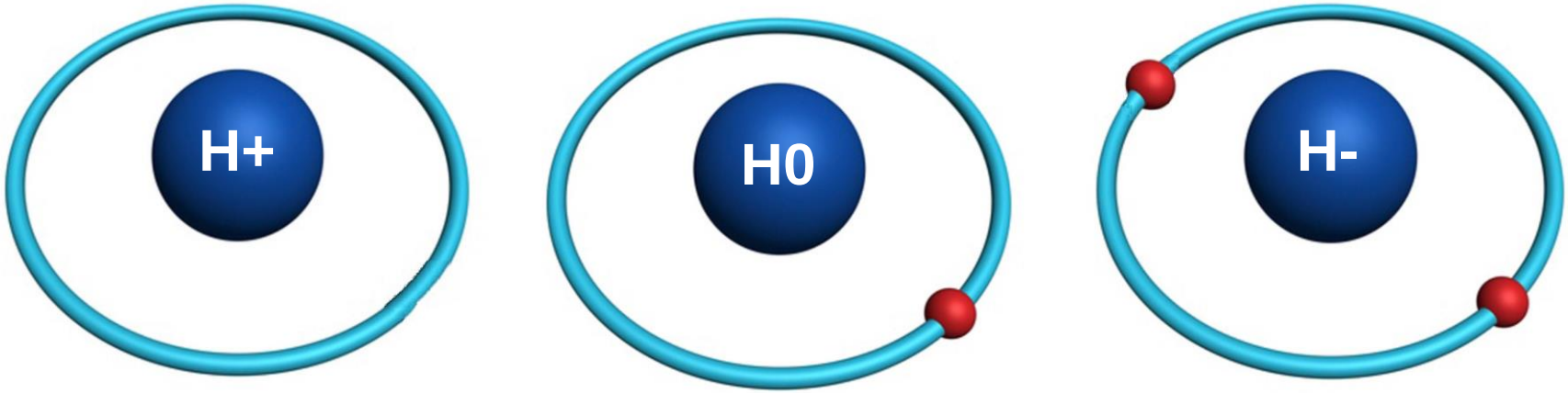
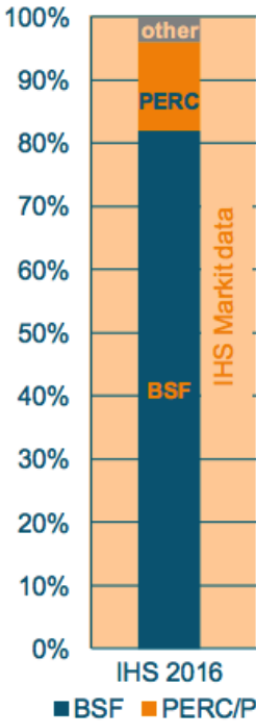
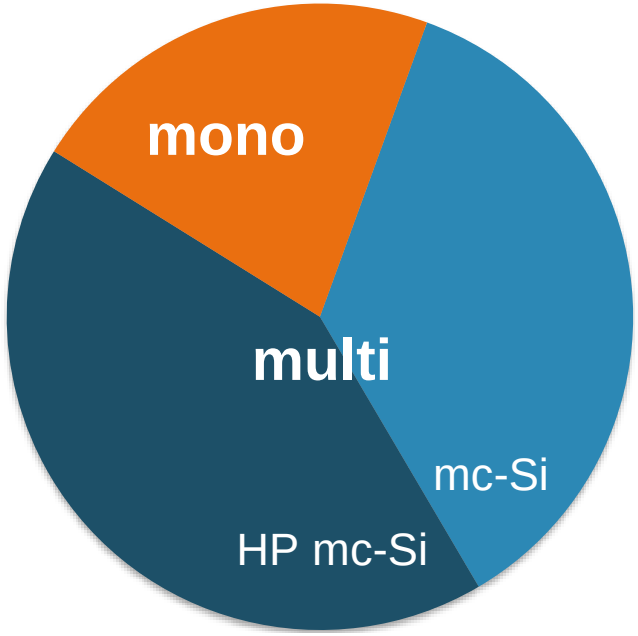


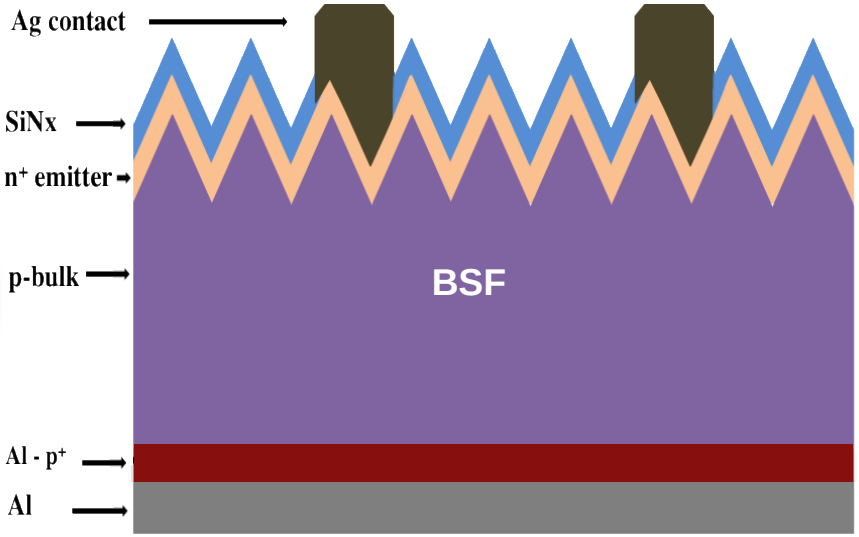
Current Modules Market Share

Cell Type:



p-type crystalline silicon wafers:





Currently dominated by multi-crystalline BSF cells

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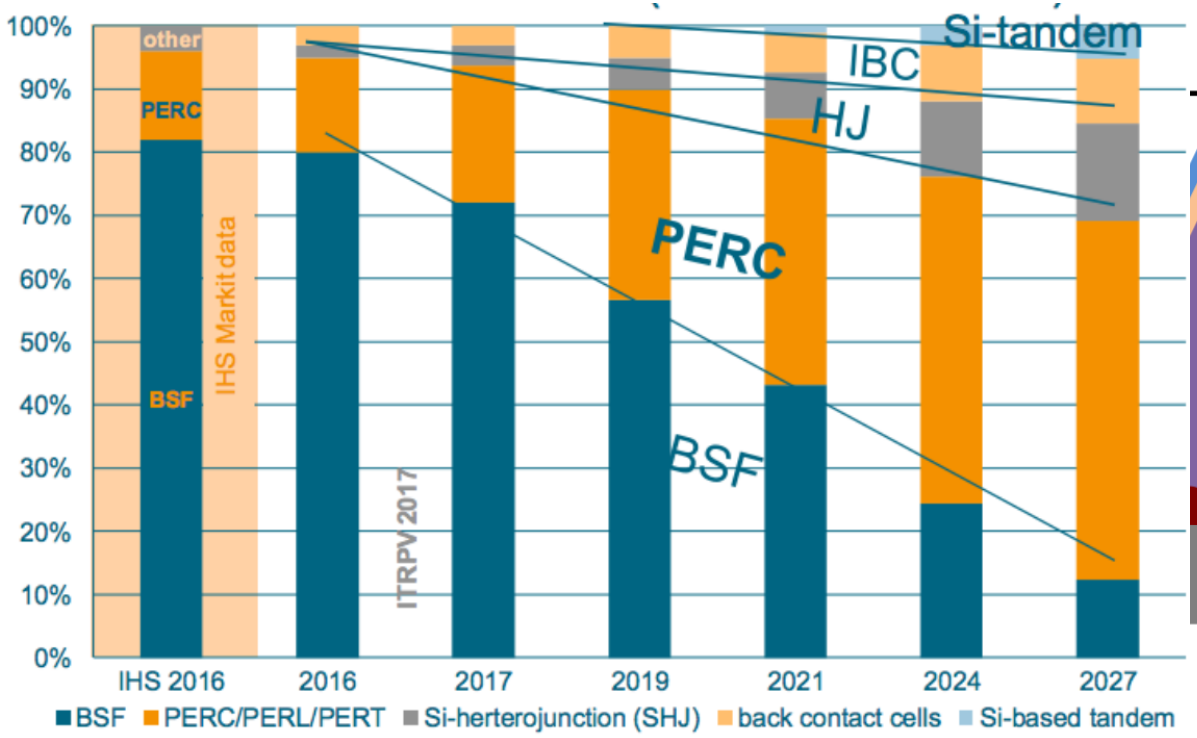
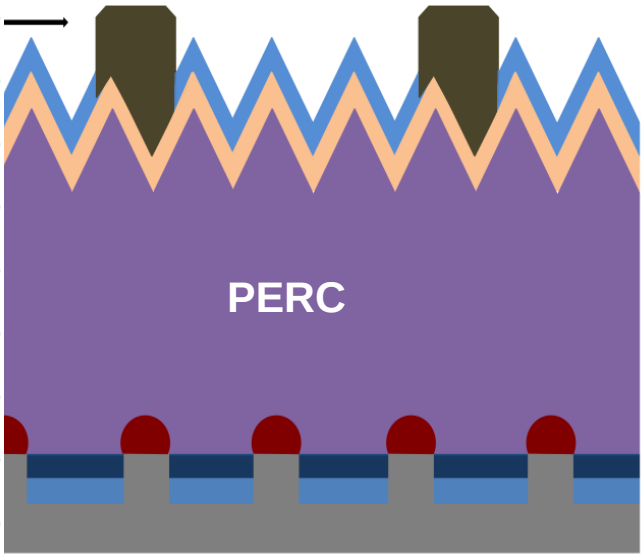
Shift to PERC





Multi ~75% - - - - - - - - - - - - - - - < 50%

Mono ~25% - - - - - - - - - - - - - - - > 50%

Shift to mono predicted

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Our Solutions - Mono

Industry Partners for Advanced Hydrogenation

tindo solar

LONGi 隆基

TW SOLAR

CanadianSolar

LERRI Solar

SAS Sunrise

GCL New Energy

CECENERGY PTE LTD

ADANI

LG

SolarWorld

ARENA

Australian Government
Australian Renewable Energy Agency

ACAP

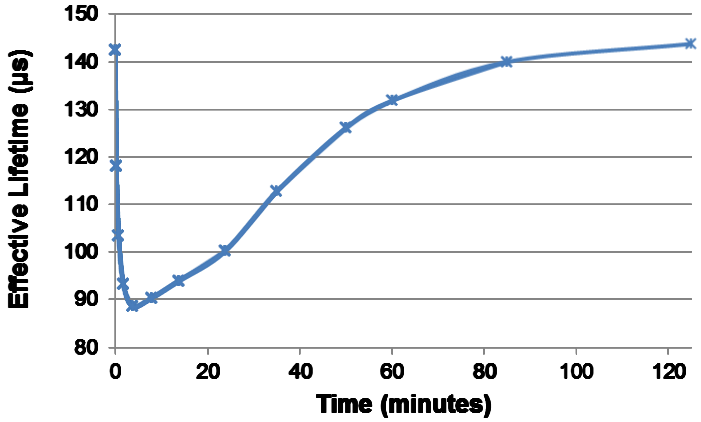
Sunport

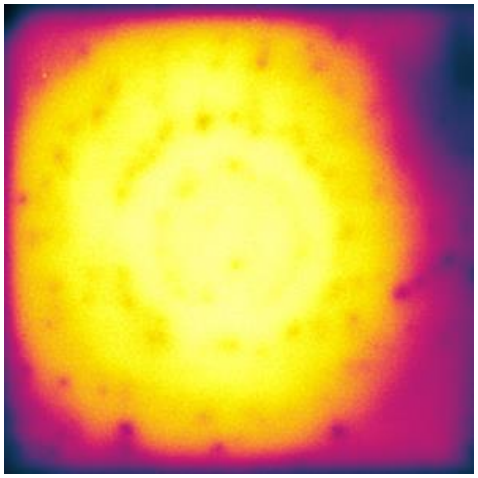
CSUN
energy for the future

Phono® Solar
SHARE THE SUN, POWER THE FUTURE!

SUNTECH
BE UNLIMITED

LID in mono





Sequential Photoluminescence Images

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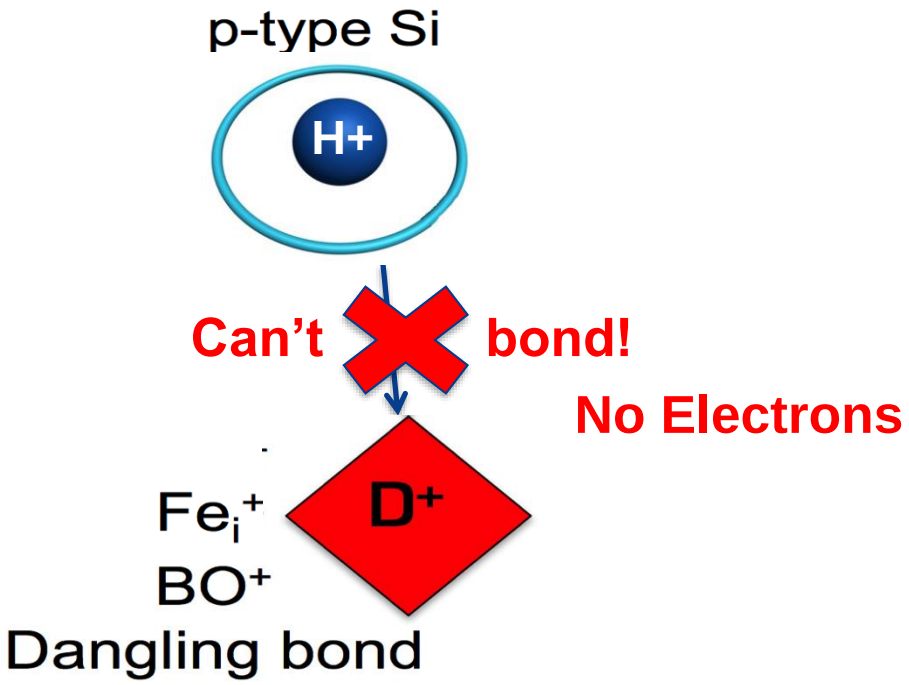
Advanced hydrogenation

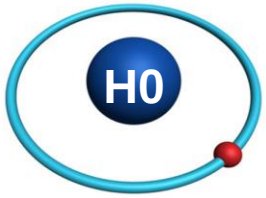


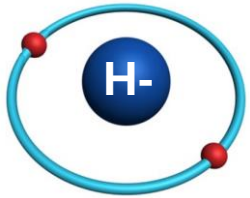
Advanced hydrogenation

p-type Si

High mobility/reactivity

n-type Si

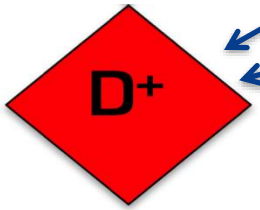


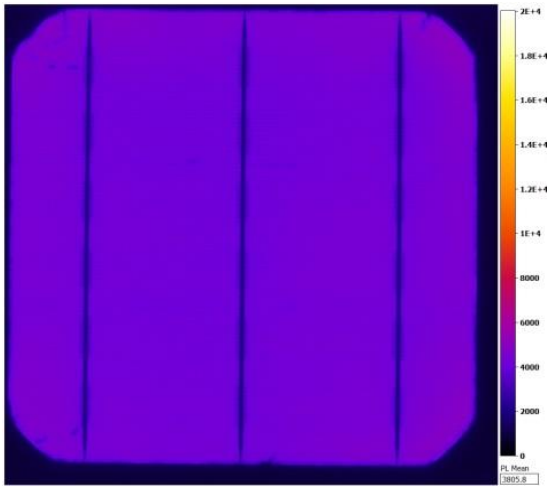


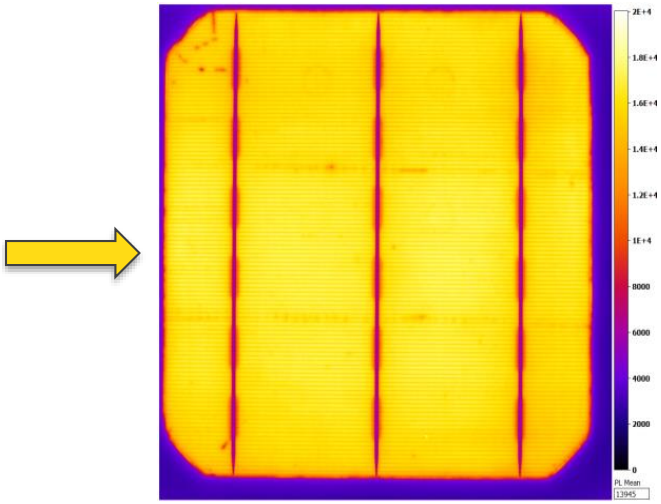
Fe_i^+

BO^+

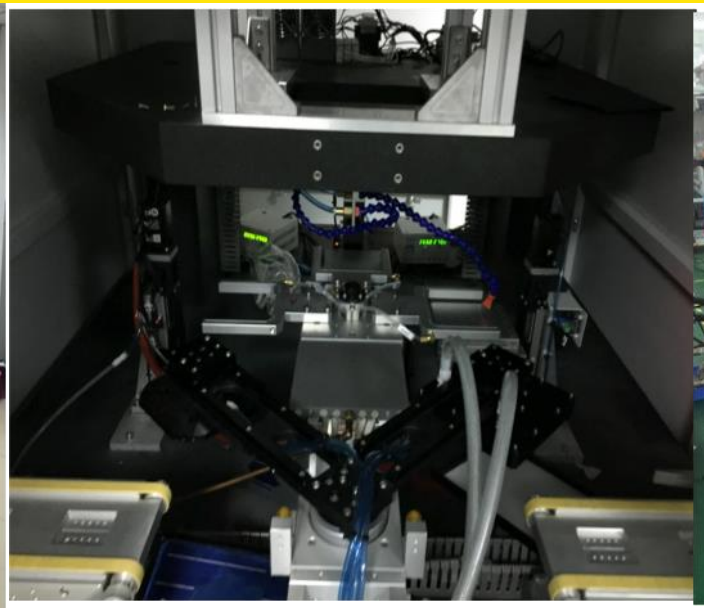
Dangling bond

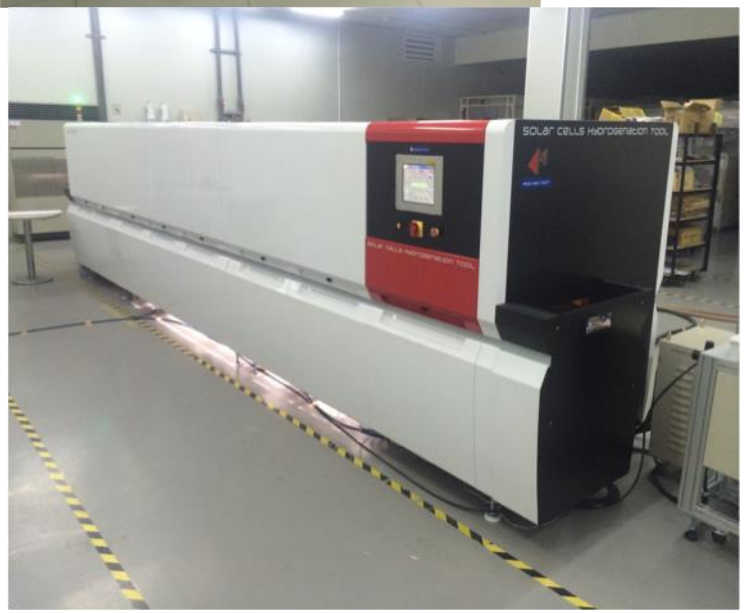






Commercialisation of Advanced Hydrogenation for Cz





- Provide control of the hydrogen charge state
- New tools implementing UNSW hydrogenation
  - Asia Neo Tech (Taiwan – LED based tool)
  - Ke Long Wei (China – Broad spectrum tool)
  - Schmid (Germany)
  - DR Laser (China – Laser-based tool)
  - Meyer Berger (Switzerland)
- New generation of tools in 2018 with solution for multi LID

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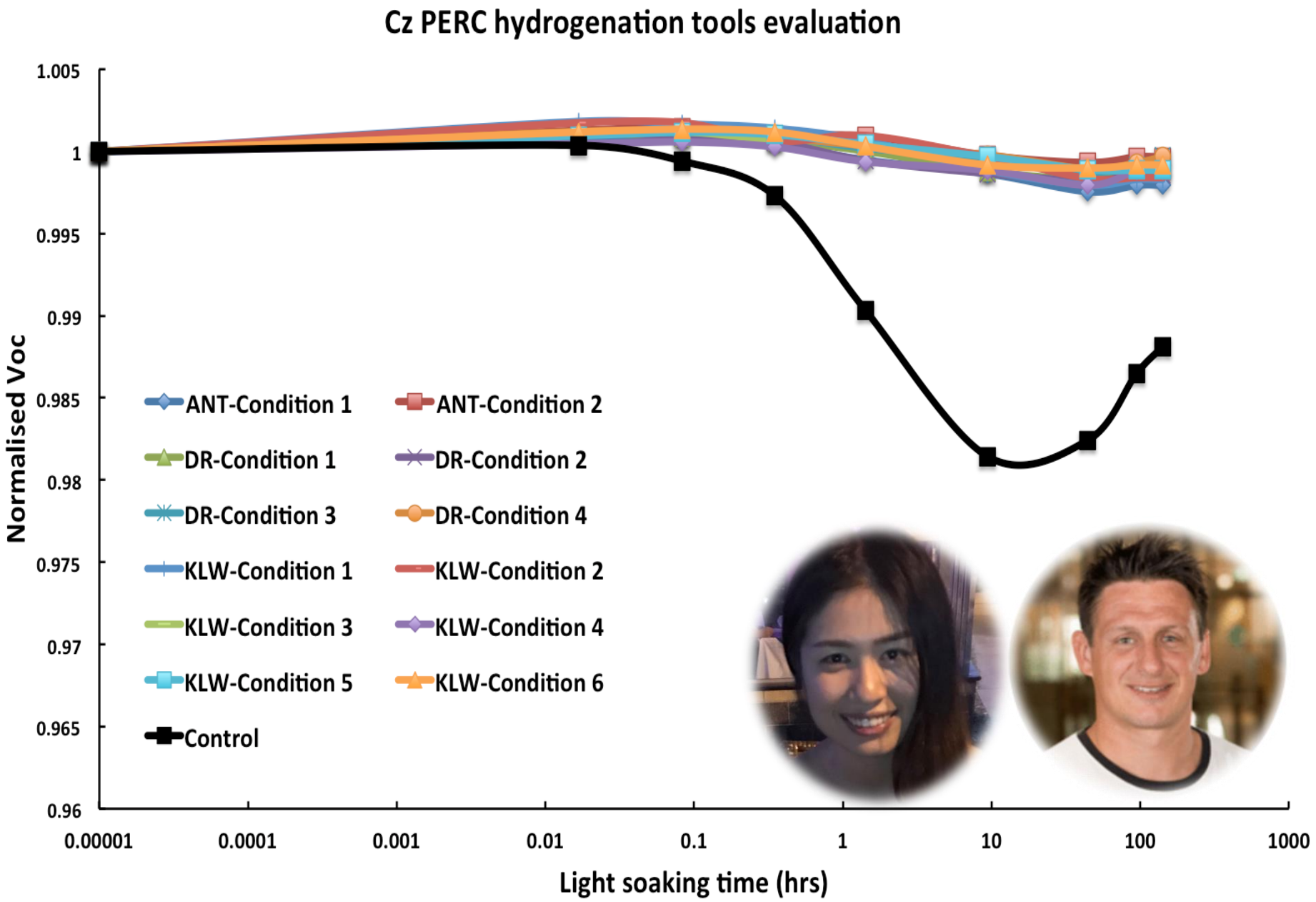
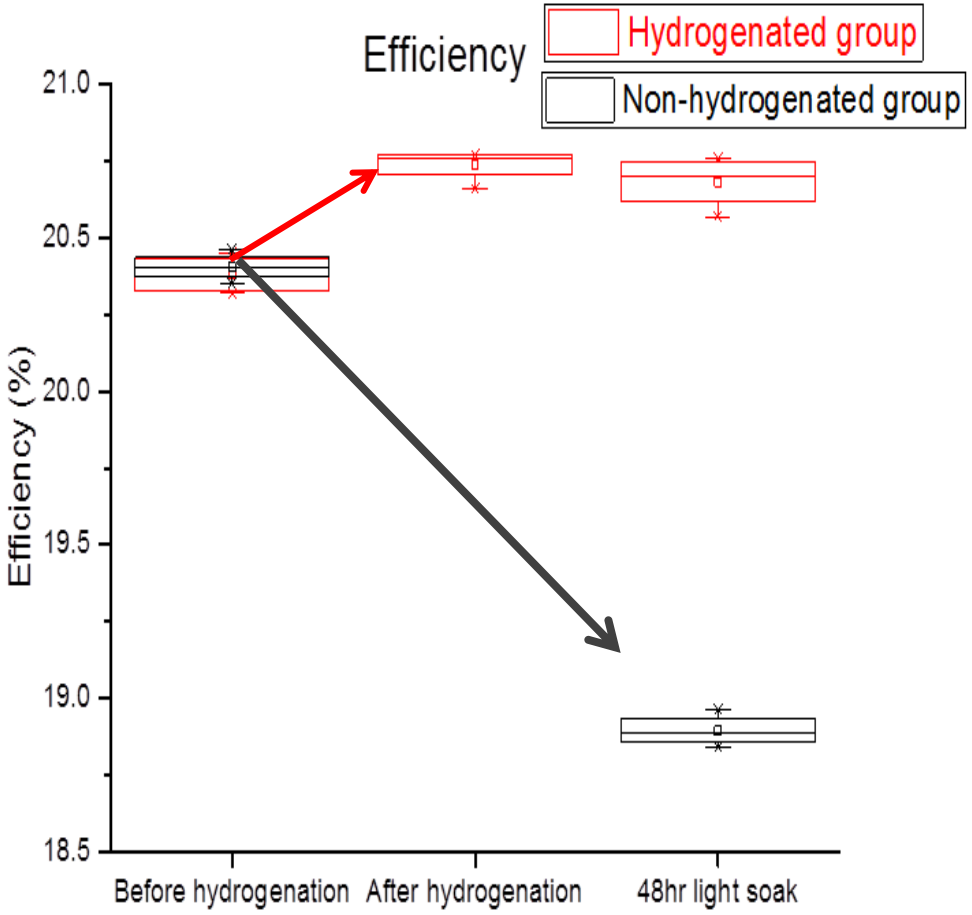
Evaluation of commercial prototypes



Application to production lines of industry partners

PERC cell producers	Stable efficiency increase ($\%_{absolute}$)
Manufacturer A	+0.8%
Manufacturer B	+1.0%
Manufacturer C	+0.7%
Manufacturer D	+0.9%
Manufacturer E	+1.5%
Manufacturer F	+0.8%
Manufacturer G	+1.8%
Manufacturer H	+1.2%
Manufacturer I	+0.7%
Average	+1.0%



→ **8 second process**

→ **Final efficiency higher**

→ **Final efficiency stable**

B. Hallam *et al.* 33rd EUPVSEC (2017).

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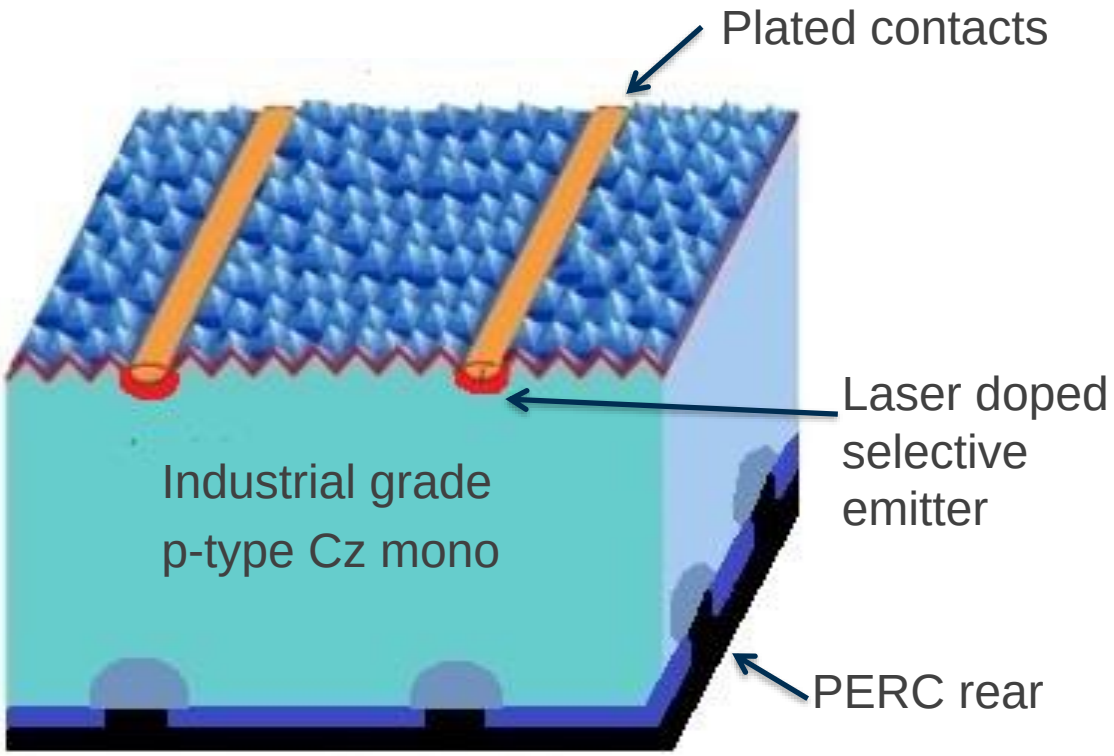
High voltage commercial PERC cells

Using only industrial tools:



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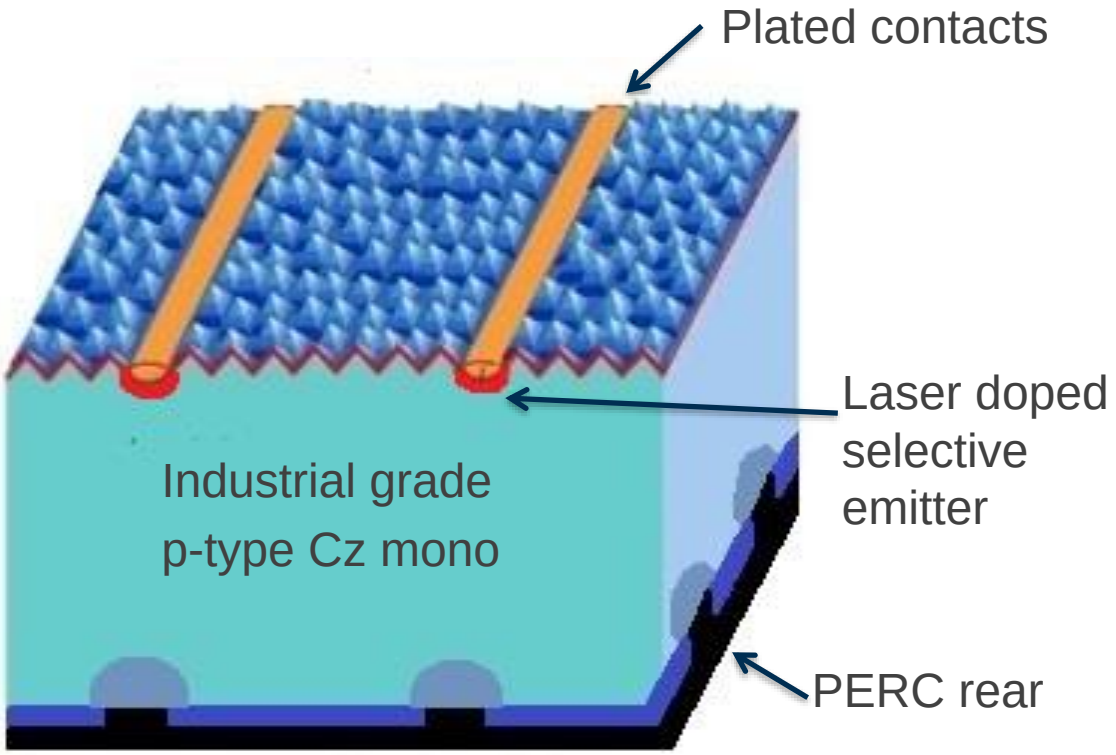

Average performance with hydrogenation	
Jsc	40.3 mA/cm^2
Voc	**696 mV**
FF	72.4 %
Eff	20.3 %

*20 cell batch

Highest recorded!

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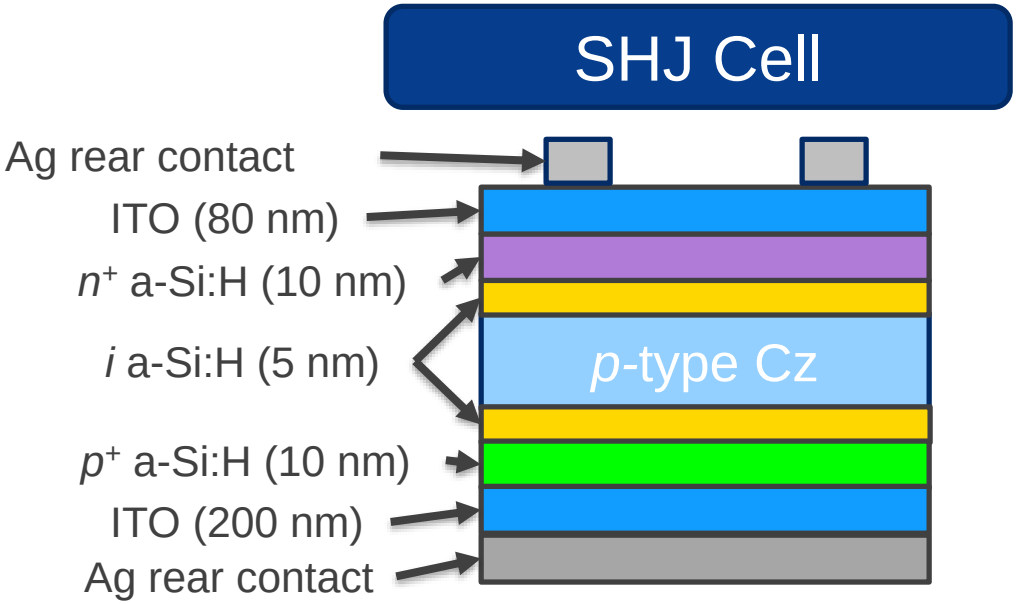
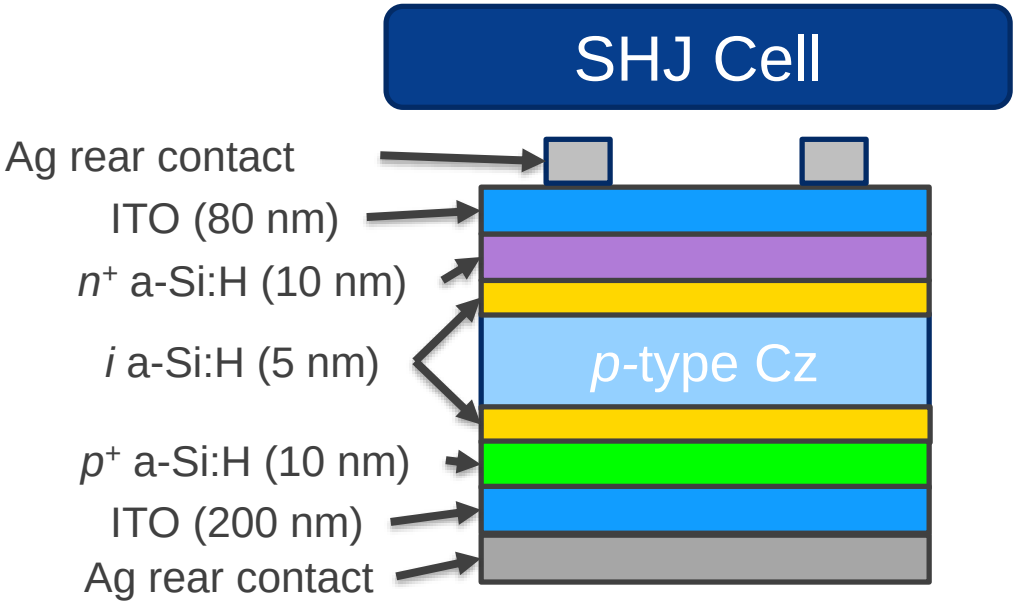
SHJ Fabrication at Arizona State University

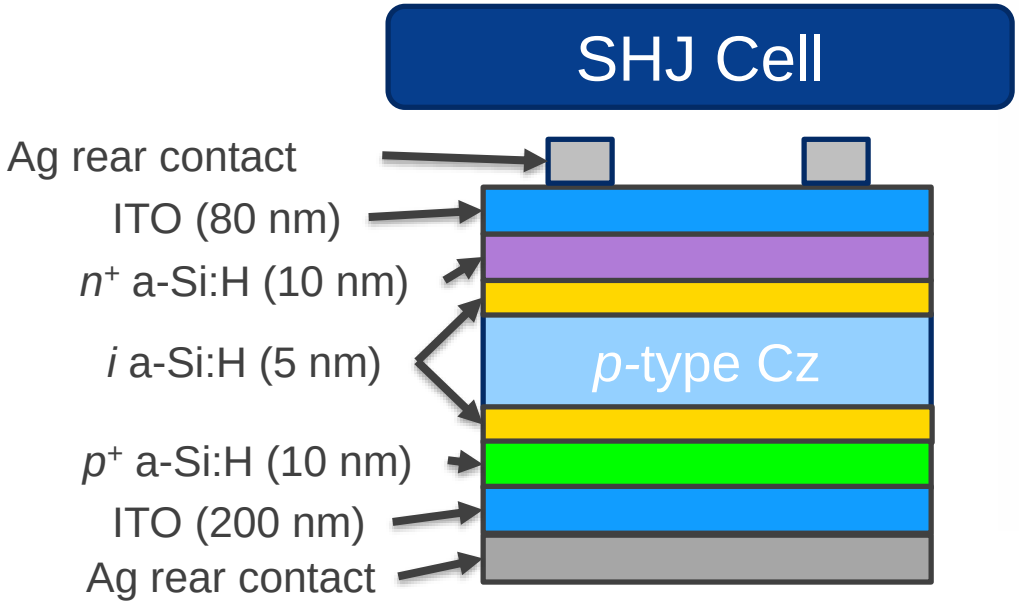


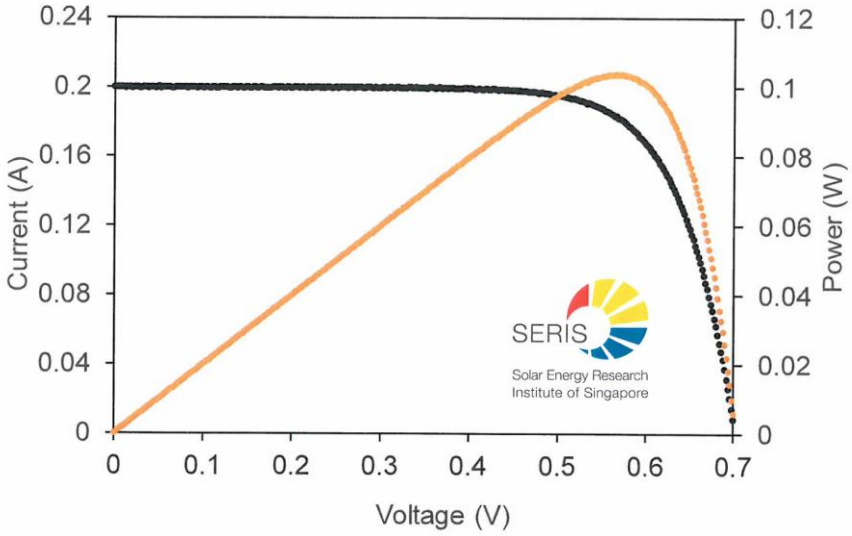
SHJ Fabrication at Arizona State University



With Advanced Hydrogenation	
Jsc	39.5 mA/cm^2
Voc	**707 mV**
FF	72.1 %
Eff	20.2 %

SHJ Fabrication at Arizona State University

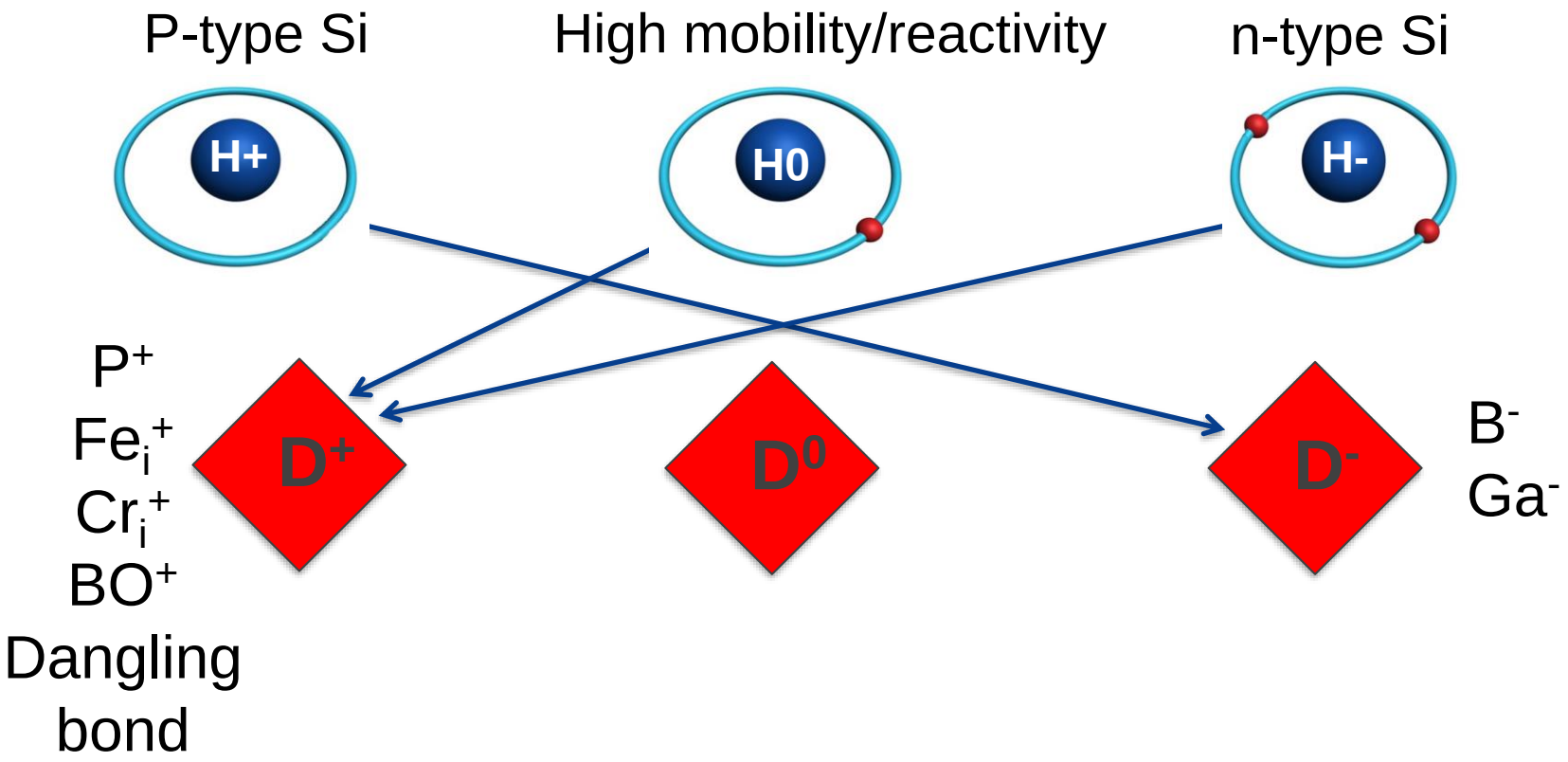




Cell area: 5.63 cm^2	
Jsc	35.5 mA/cm^2
Voc	**702.7 mV**
FF	73.8 %
Eff	18.4 %

Multi: New Problems Require New Solutions

Charge of Hydrogen and Defects



mc-Si much more complicated:

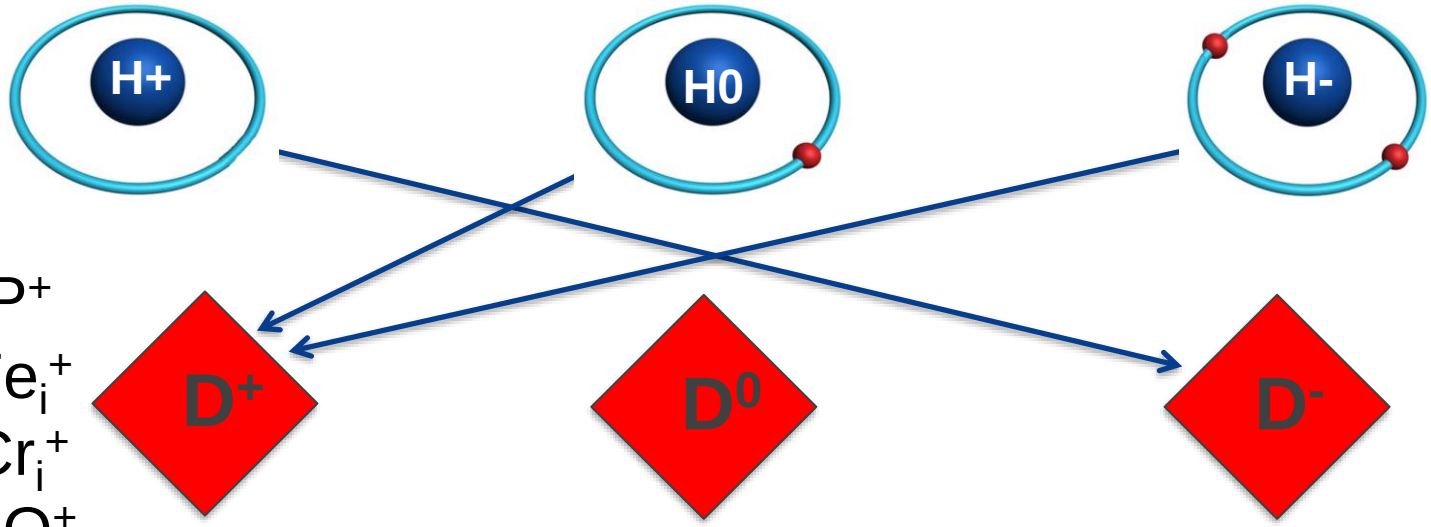
- defects of all charges
- varying concentrations
- different LID (longer timescales)

Charge of Hydrogen and Defects

P-type Si

High mobility/reactivity

n-type Si



P^+

Fe_i^+

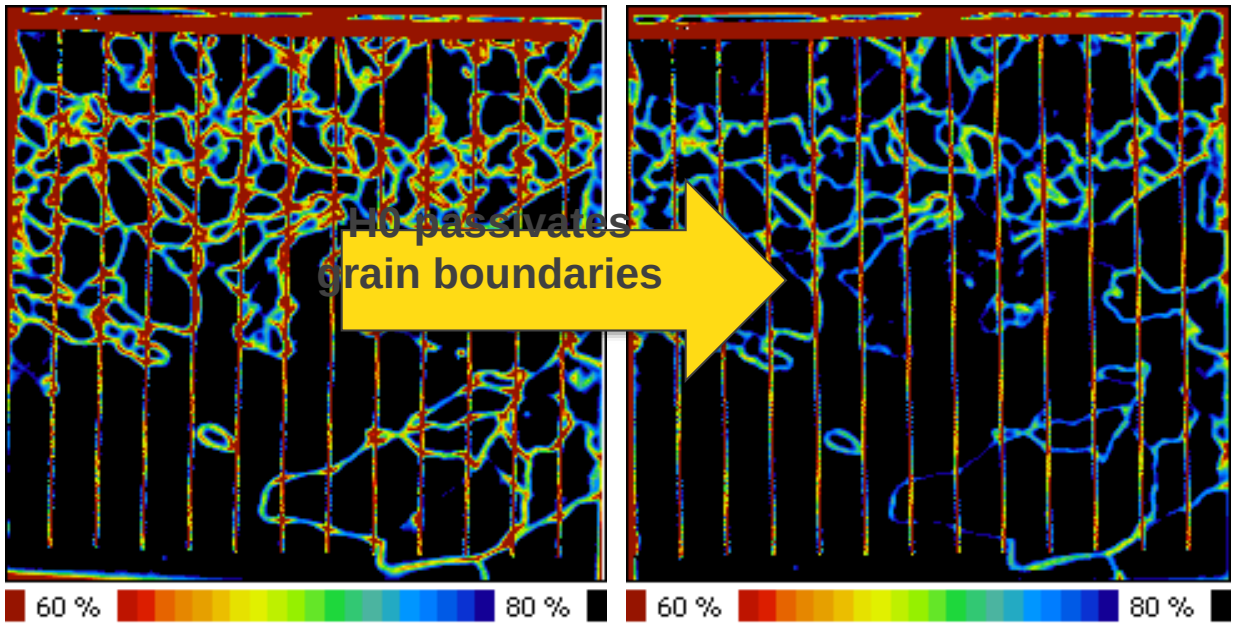
Cr_i^+

BO^+

Dangling bond

B^-

Ga^-



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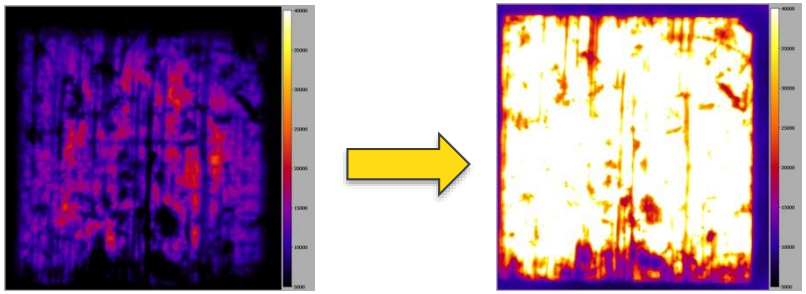
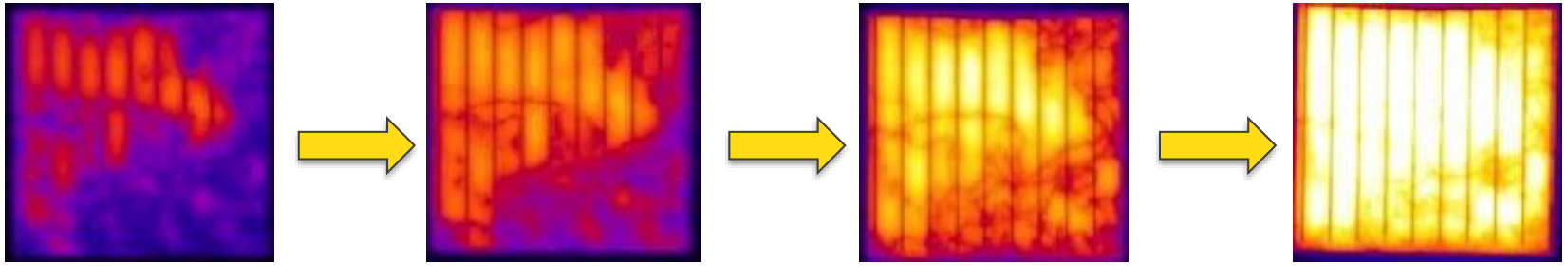
Crystallographic defects need H charge-state control

- H+ for trapping
- H0 for dispersion
- H- for bonding
- Multi-step process for multi!

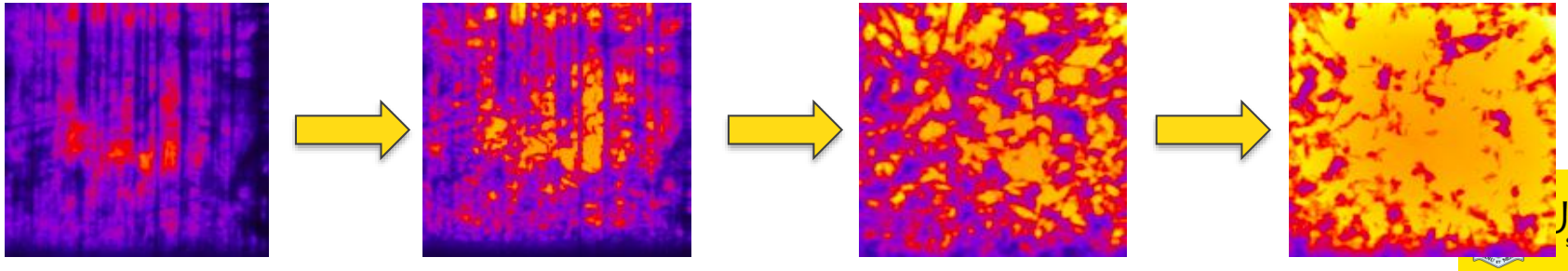
Conventional multi



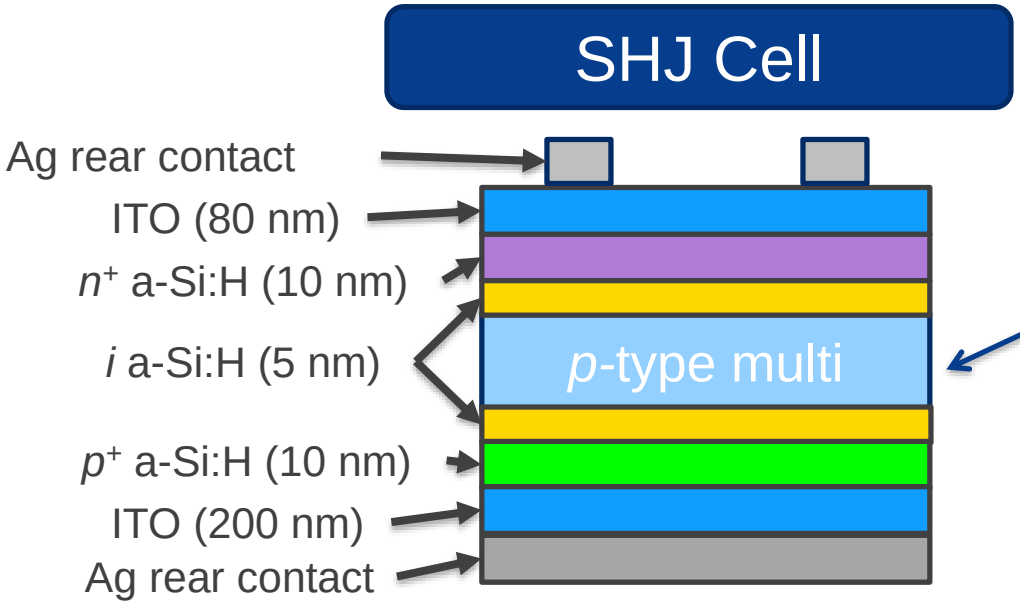
Reject cast material

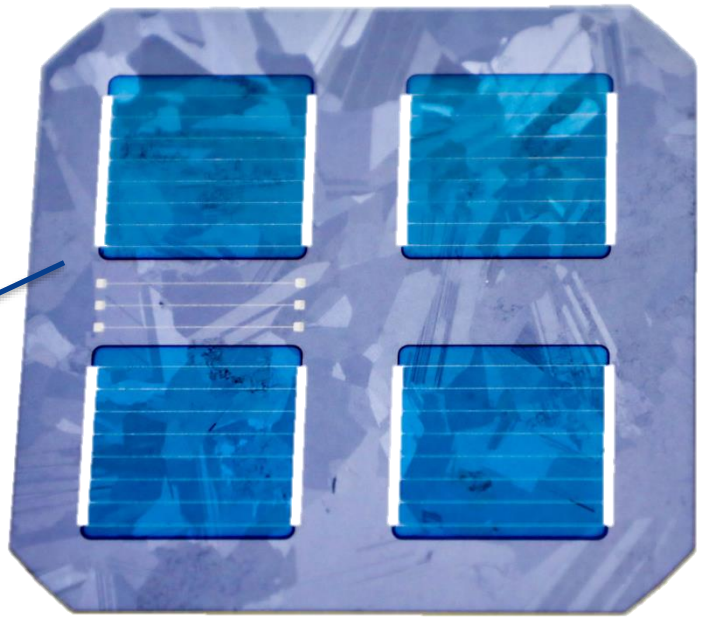


UMG multi wafers



Preliminary results on multi p-type SHJ Solar Cells





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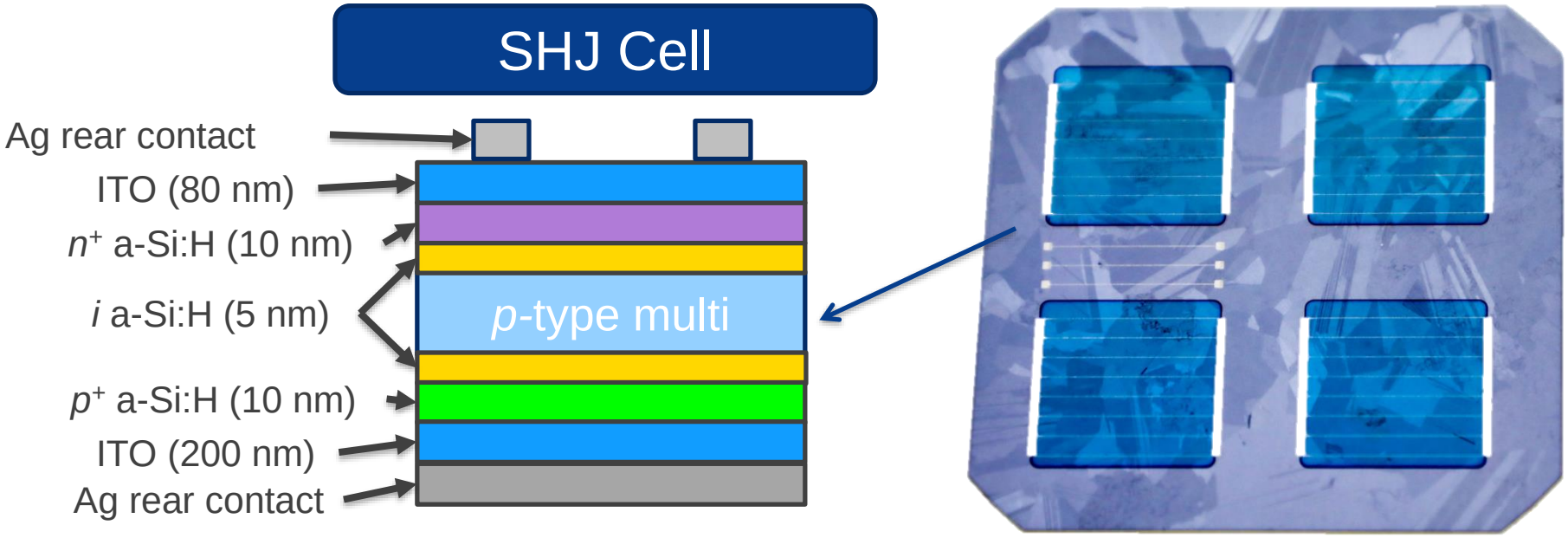

Record V_{OC} of 695 mV for p-type multi-crystalline silicon (pending independent confirmation)

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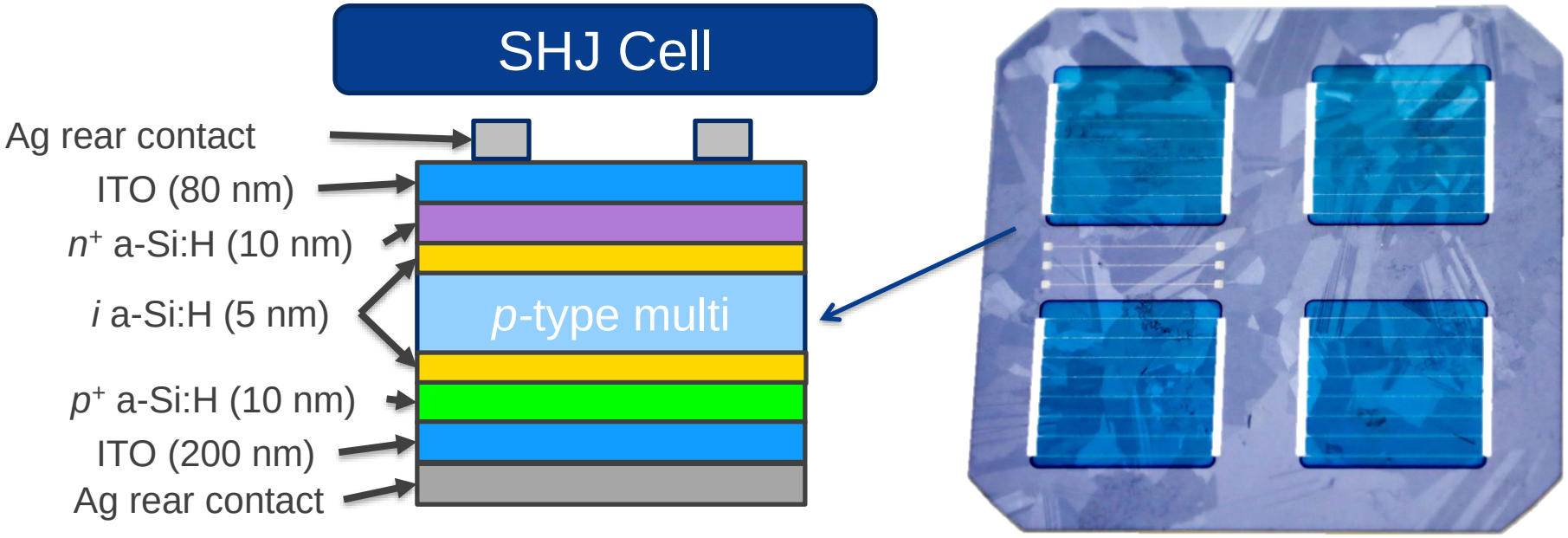

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- 20 mV higher than record multi PERC cell

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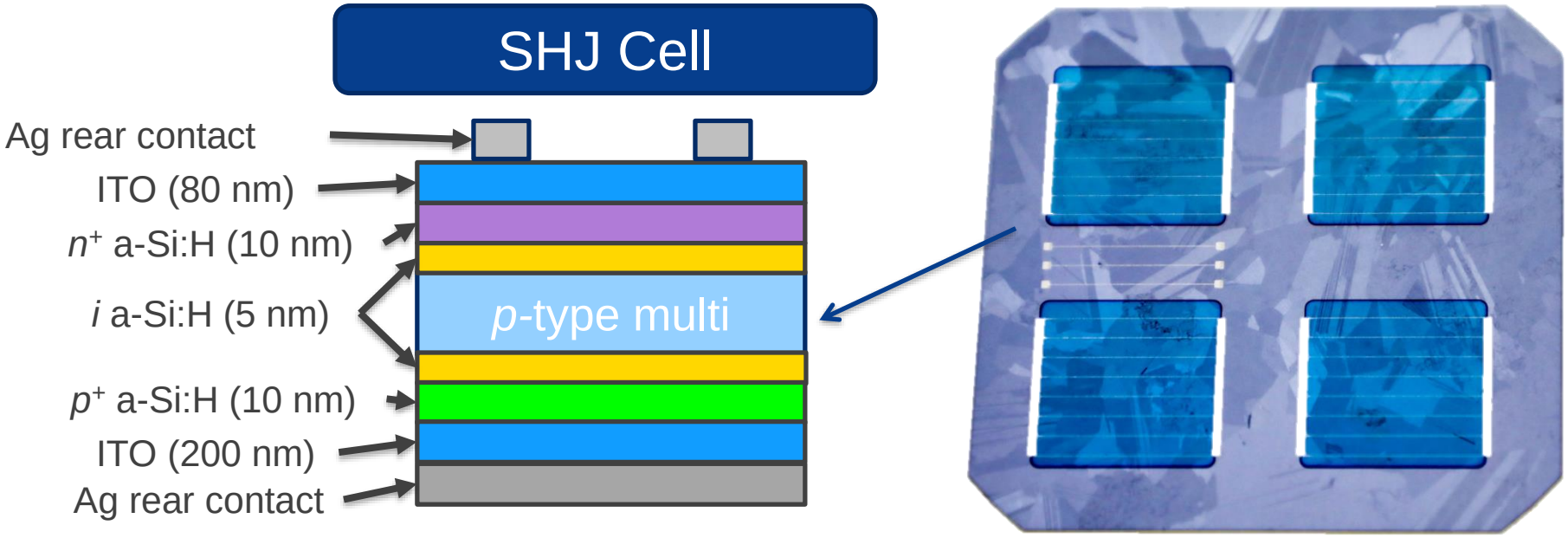

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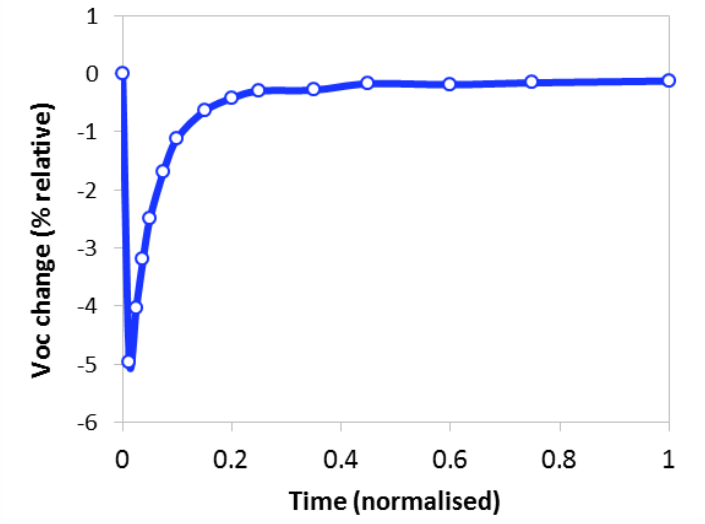
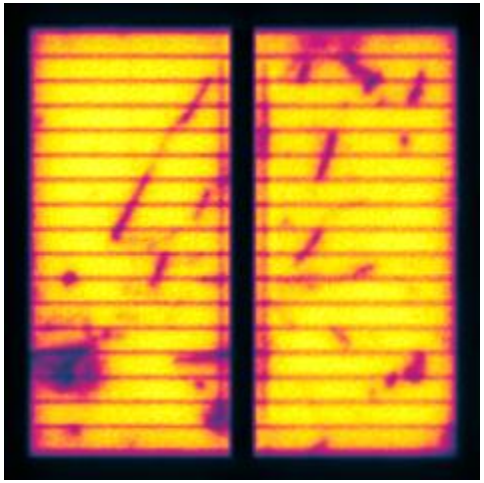
- 20 mV higher than record multi PERC cell
- >700 mV will be achieved soon!

LID in multi PERC cells





Left: Relative voltage
Right: PL images

C. Chan et. al, “Rapid stabilization of HP mc-Si PERC cells” JPV 2016

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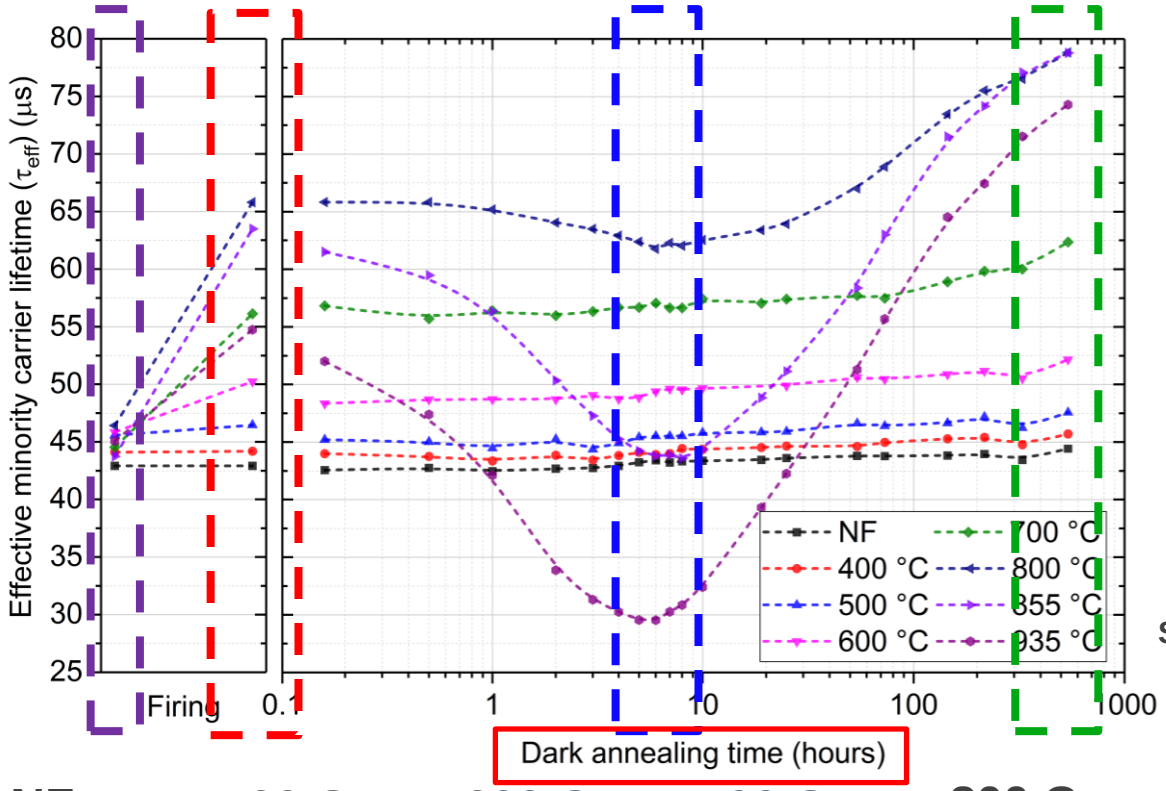
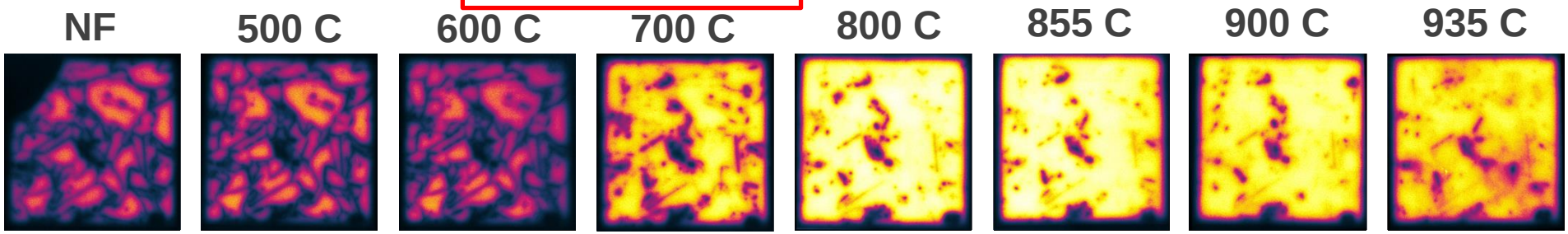
Effect of peak firing temperature on thermal degradation



Defect induced in the dark has the same firing dependence as the defect induced by light soaking

Set T (actual T ~ 100C lower)



1. Before Firing 2. After Firing 3. Degraded **4. Recovered**

D. Chen et al, Evidence of an identical firing-activated carrier induced degradation in multicrystalline and monocrystalline silicon, 2017, Sol. Energy Mat. & Sol. Cells 172 (293-300)

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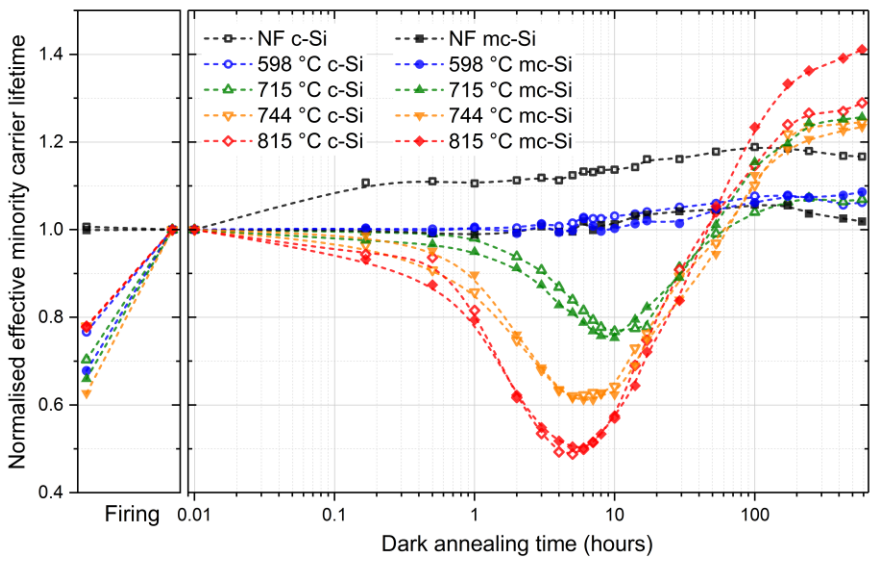
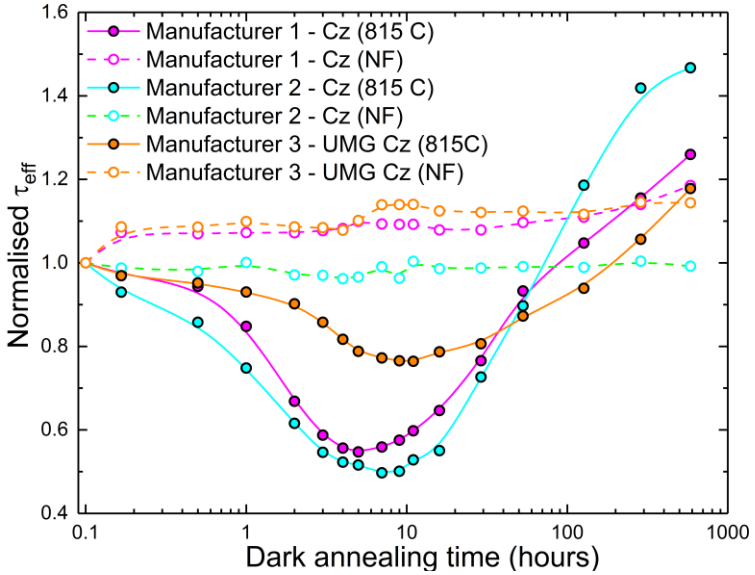
Same defect present in Cz





D. Chen et al, Evidence of an identical firing-activated carrier induced degradation in multicrystalline and monocrystalline silicon, 2017, Sol. Energy Mat. & Sol. Cells 172 (293-300)

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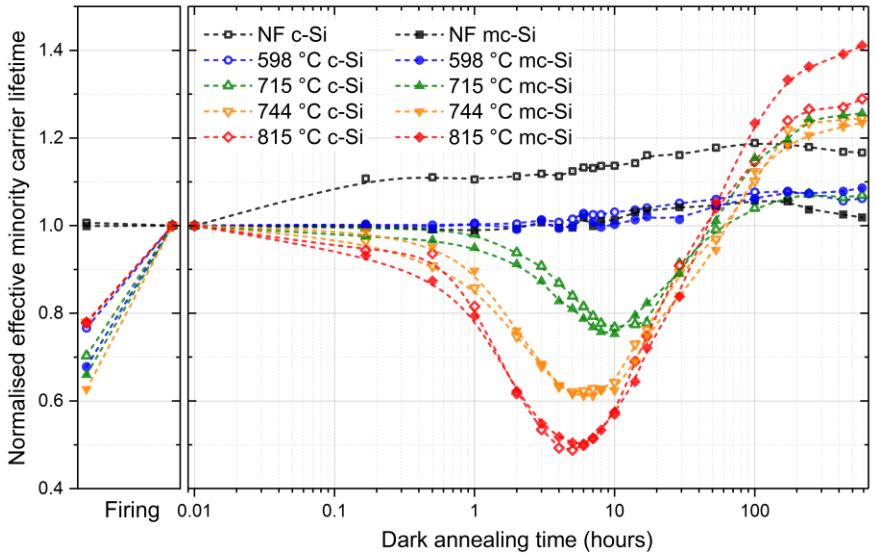
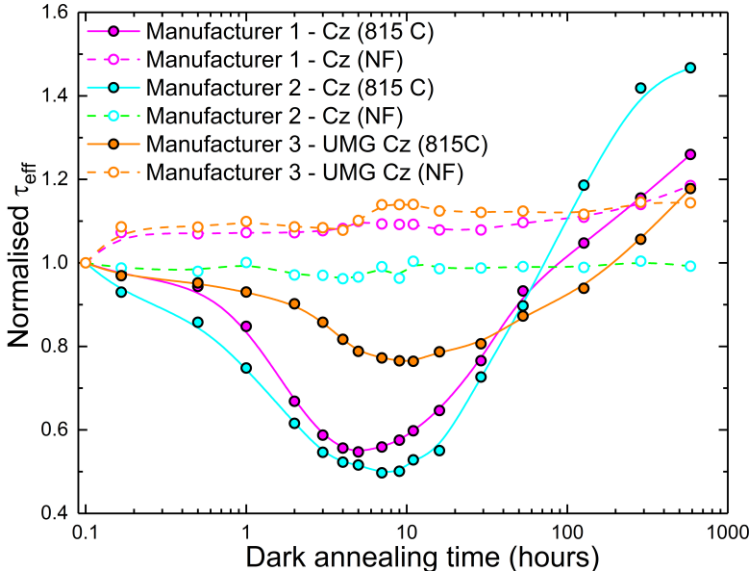
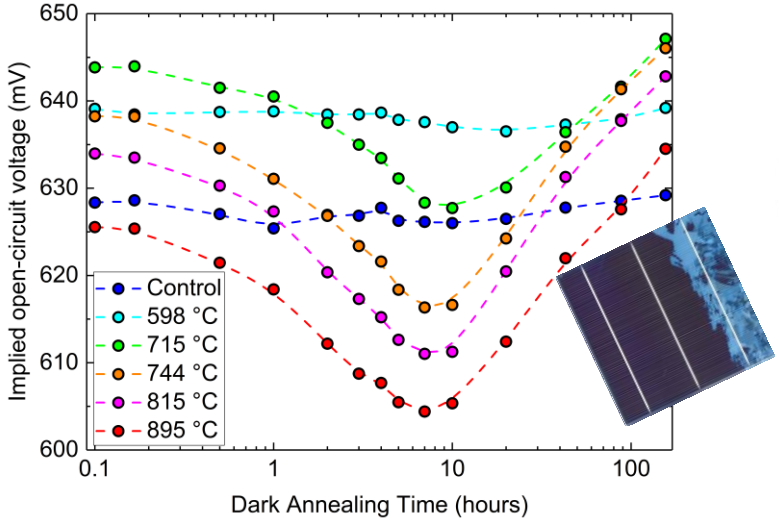
Same defect present in Cz, cast-mono







D. Chen et al, Evidence of an identical firing-activated carrier induced degradation in multicrystalline and monocrystalline silicon, 2017, Sol. Energy Mat. & Sol. Cells 172 (293-300)

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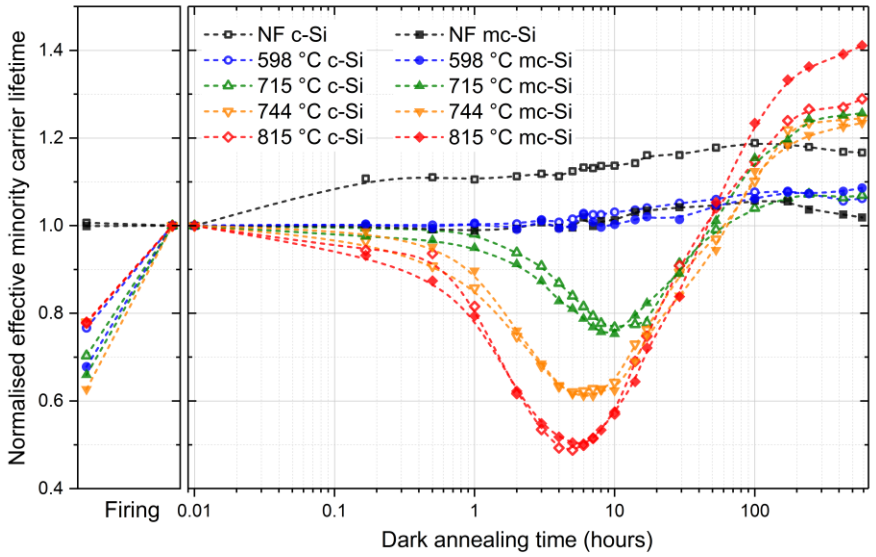
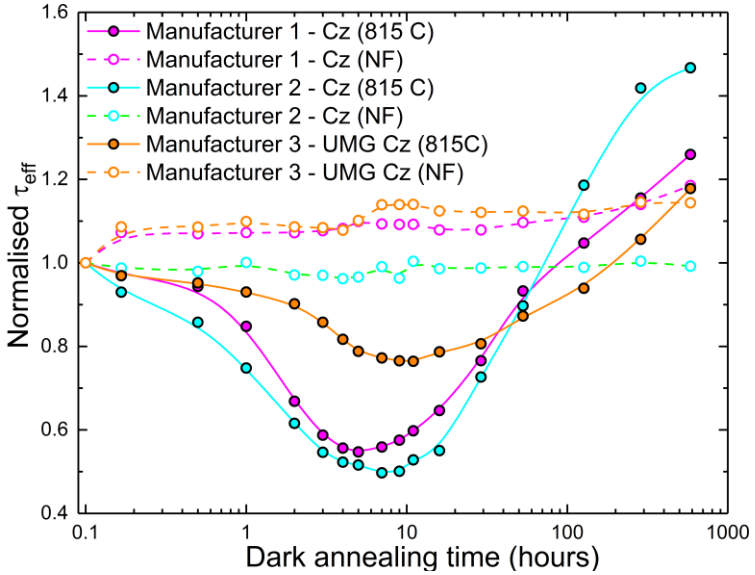
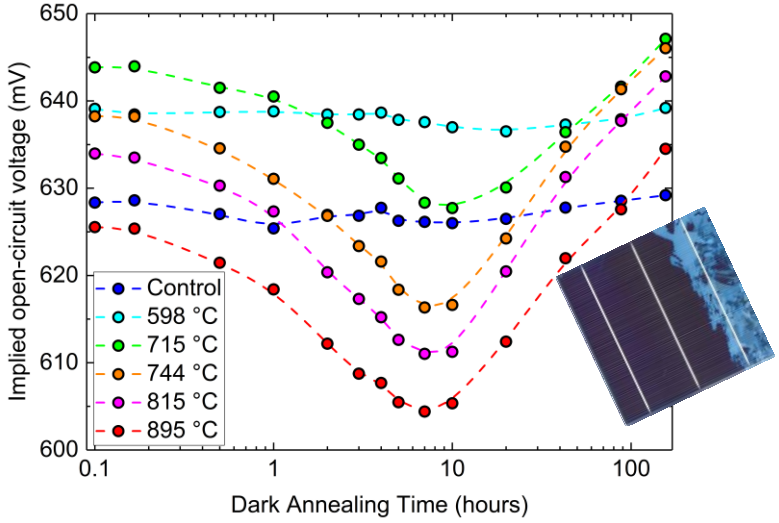
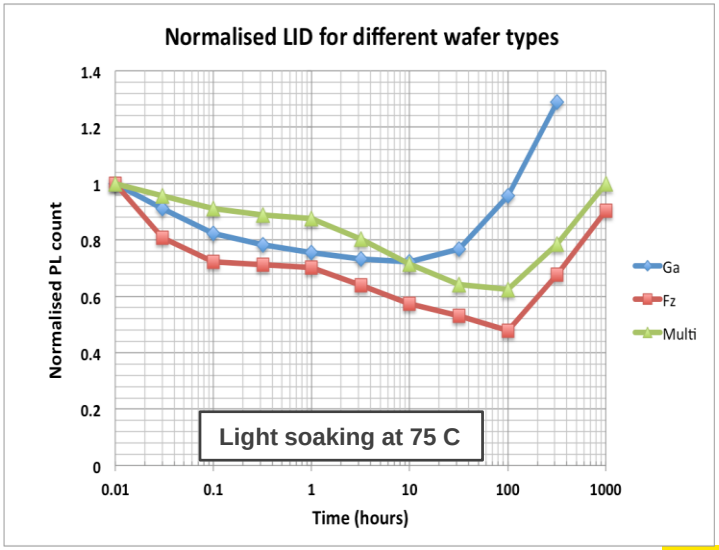
Same defect present in Cz, cast-mono and FZ!









D. Chen et al, Evidence of an identical firing-activated carrier induced degradation in multicrystalline and monocrystalline silicon, 2017, Sol. Energy Mat. & Sol. Cells 172 (293-300)

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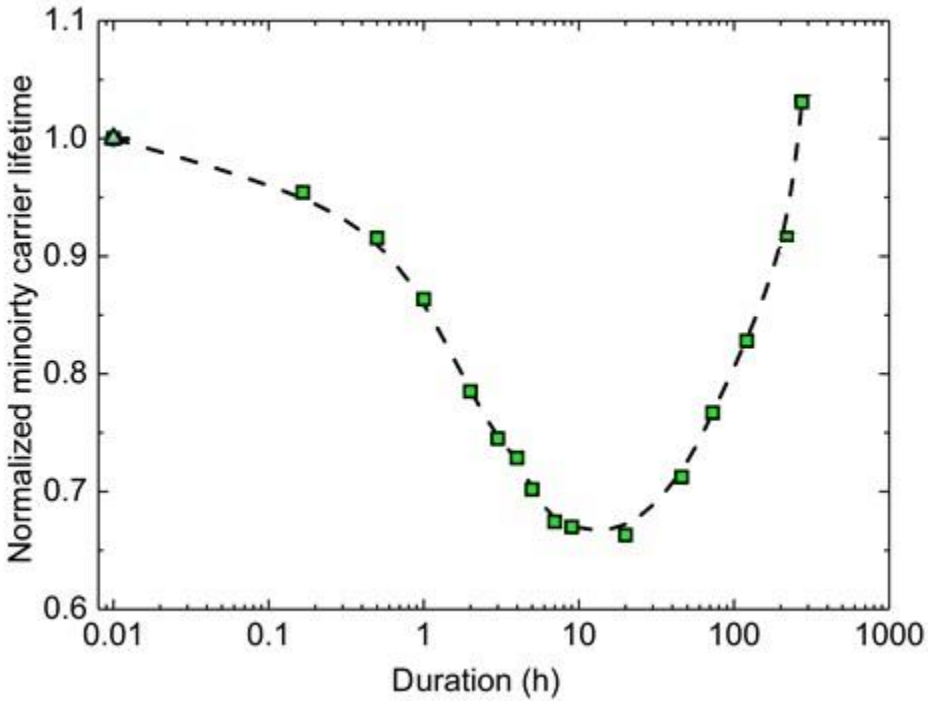
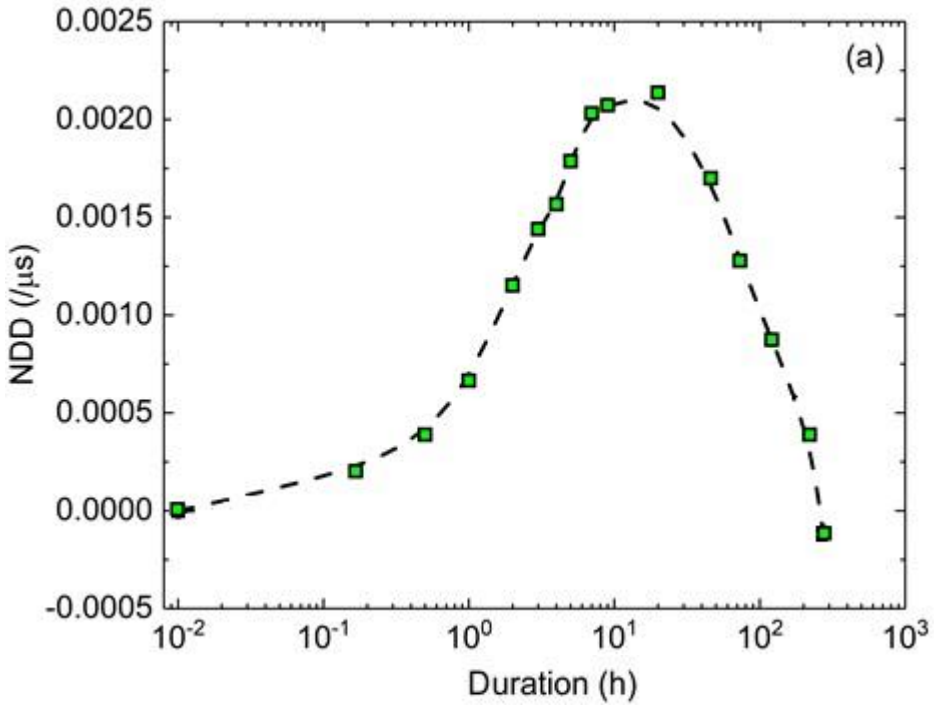
N-type is not immune!





Will be presented at Silicon PV and published next year!

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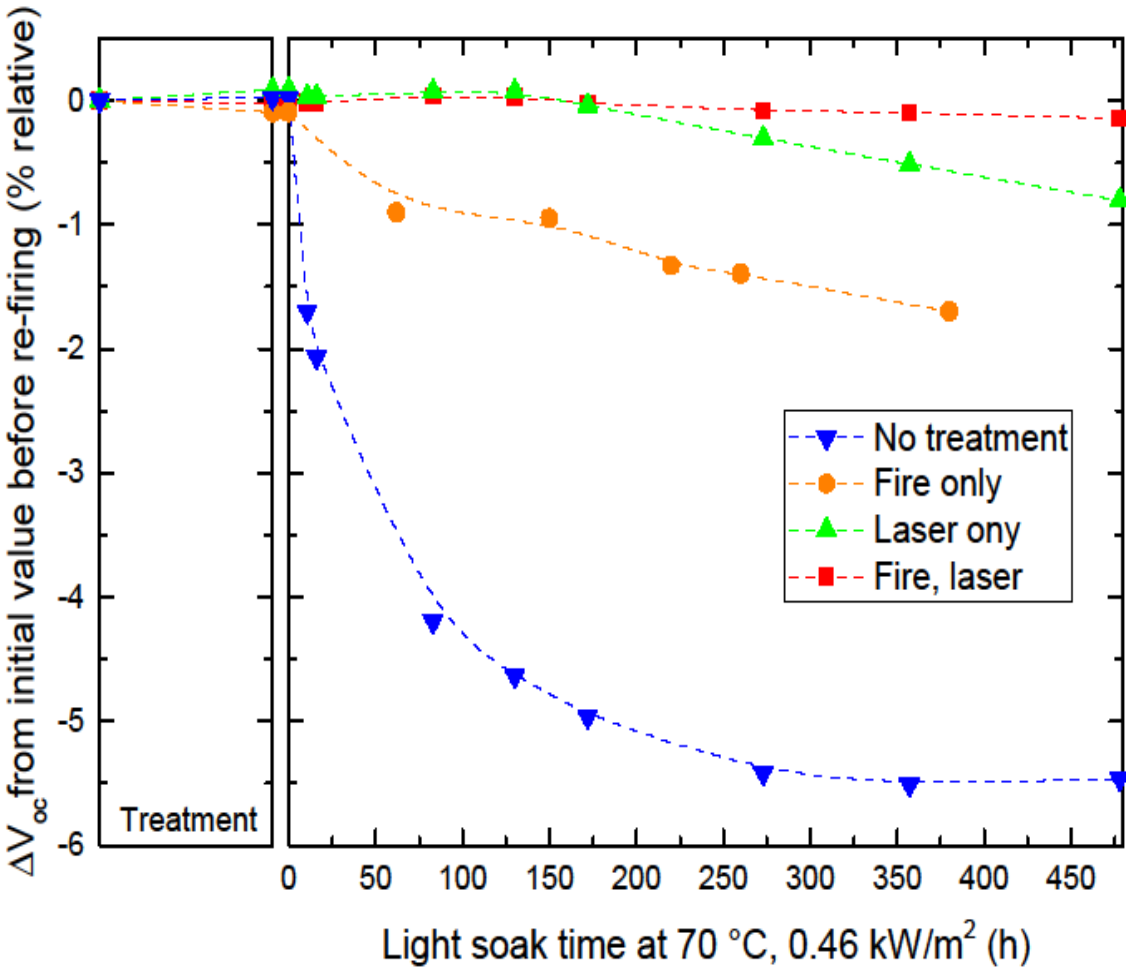
Green Curve– Process used for Cz



C.E. Chan et al. Rapid Stabilization of High-Performance Multicrystalline P-type Silicon PERC Cells. *IEEE Journal of PV,* 2016

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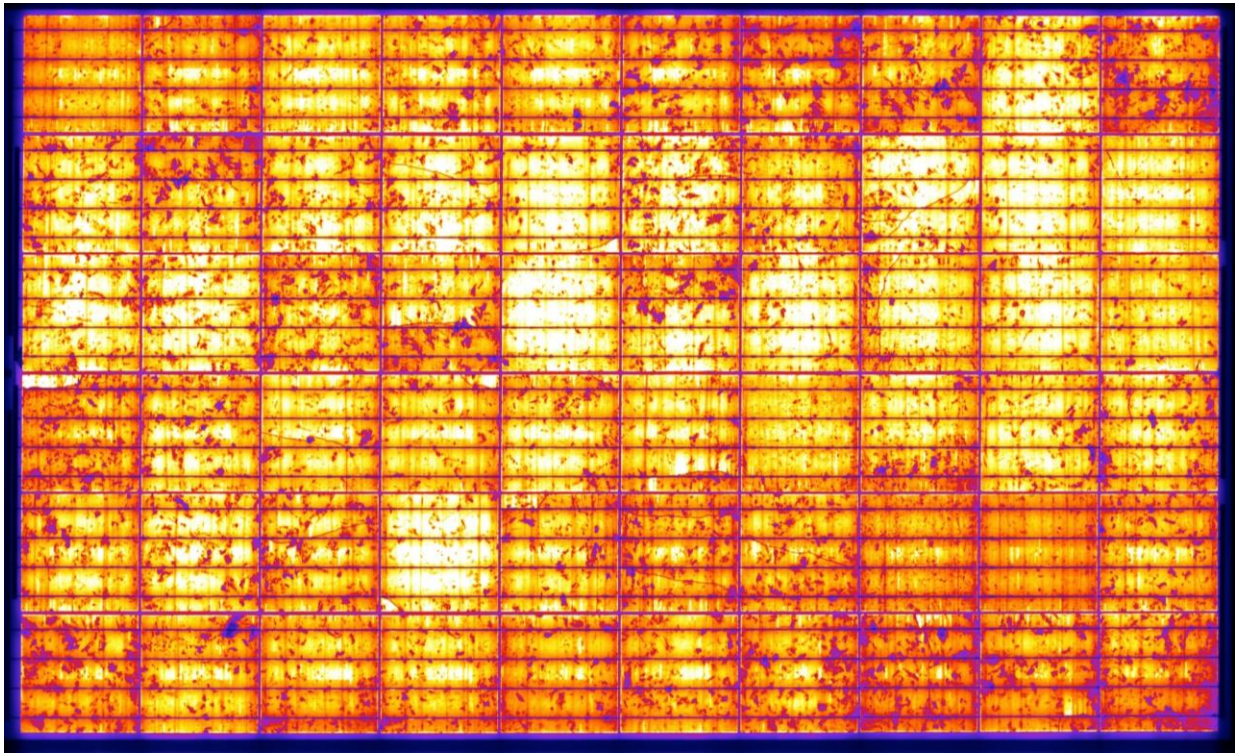
LID of commercial multi-PERC modules

- Mc-Si PERC modules acquired from the market
- Including LID solutions and linear degradation warranty
- Light soaked ≥70 ° C, ~1 sun (halogen source)
- Module PL characterisation (Zafirovska *et al*.)



I. Zafirovska et al. Module Inspection Using Line Scanning Photoluminescence Imaging, 32nd Eu PVSEC, 2016
I. Zafirovska et al. Detection of finger interruptions in silicon solar using line scan photoluminescence imaging, IEEE JPV 2017

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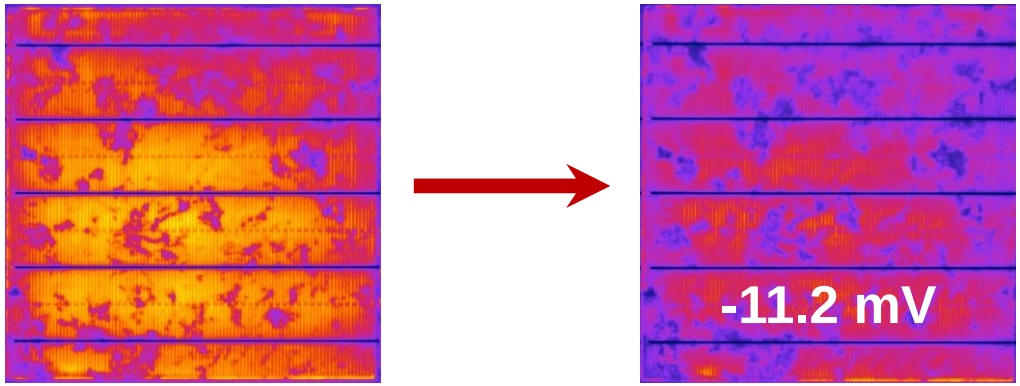
- $$\Delta Voc(V) = \frac{kT}{q} \cdot ln\left(\frac{PL_{new}}{PL_{initial}}\right)$$



10,000 mins

(167 hours)

I. Zafirovska et al. Module Inspection Using Line Scanning Photoluminescence Imaging, 32nd Eu PVSEC, 2016
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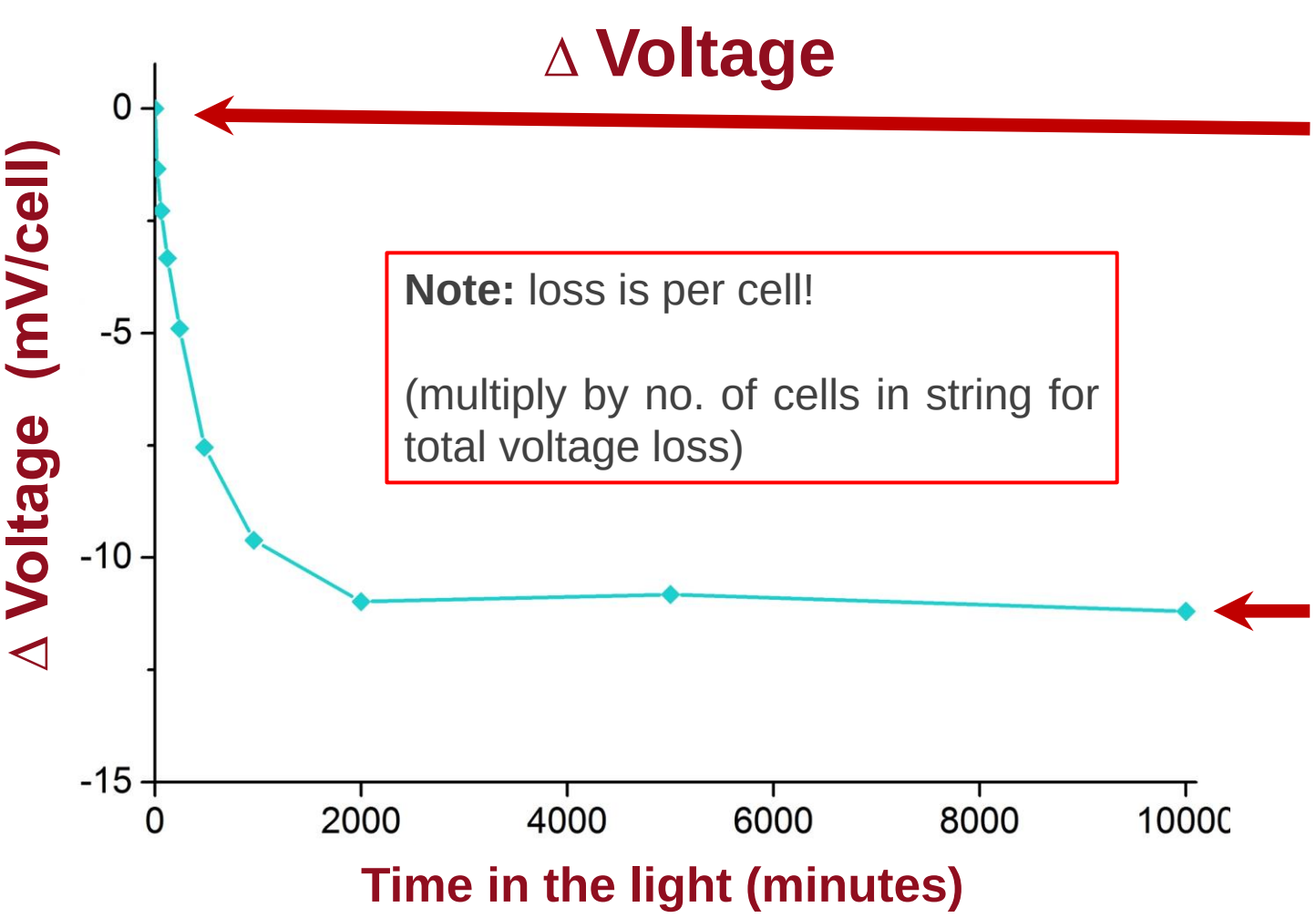
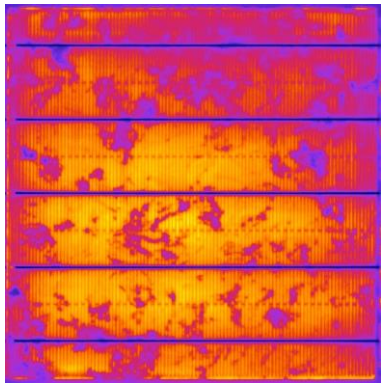
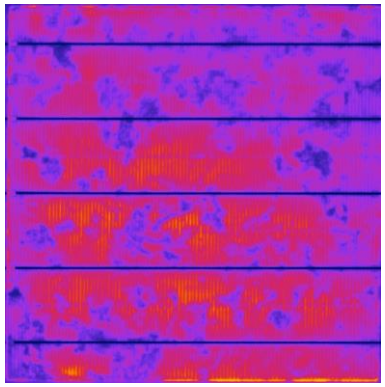
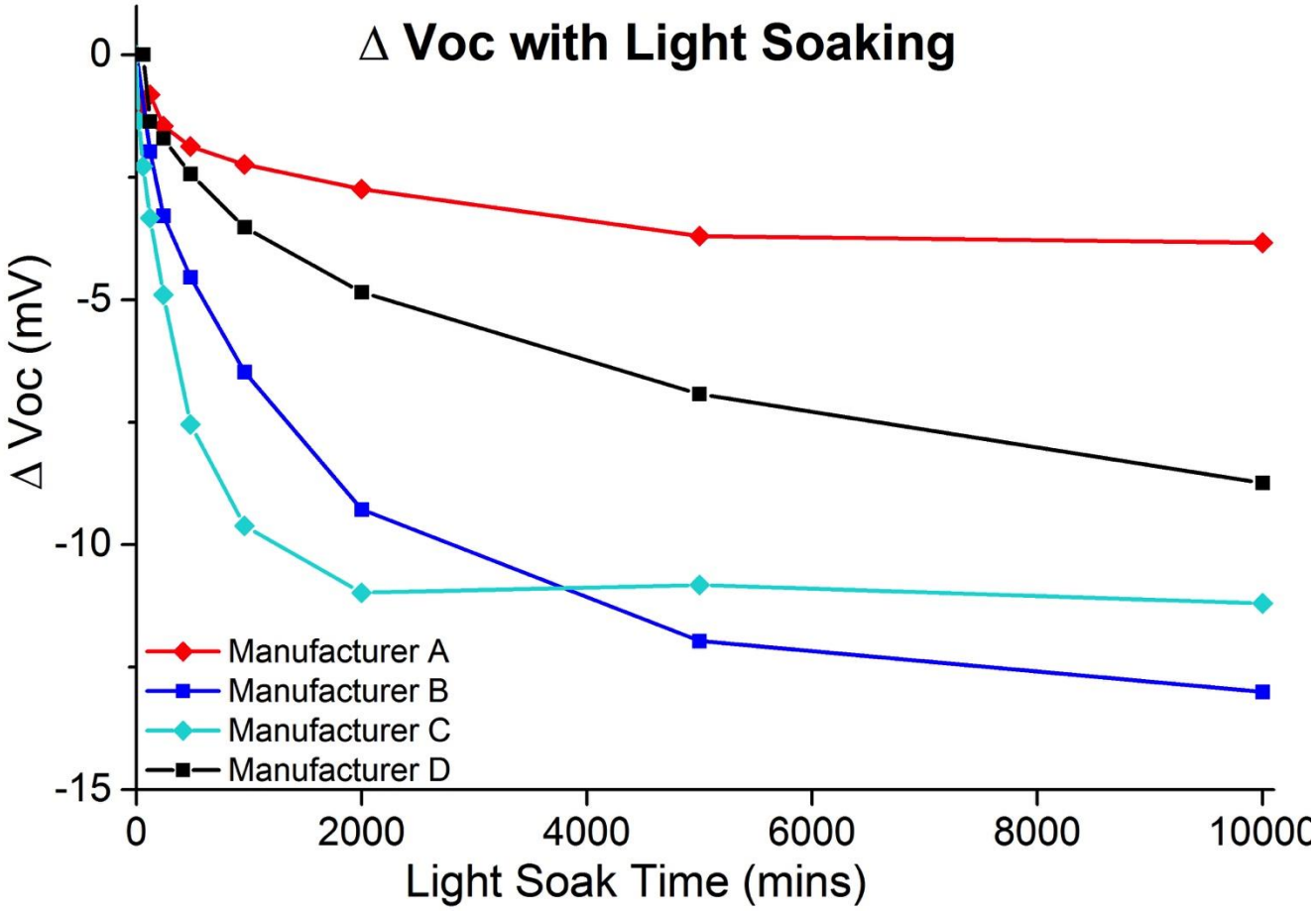


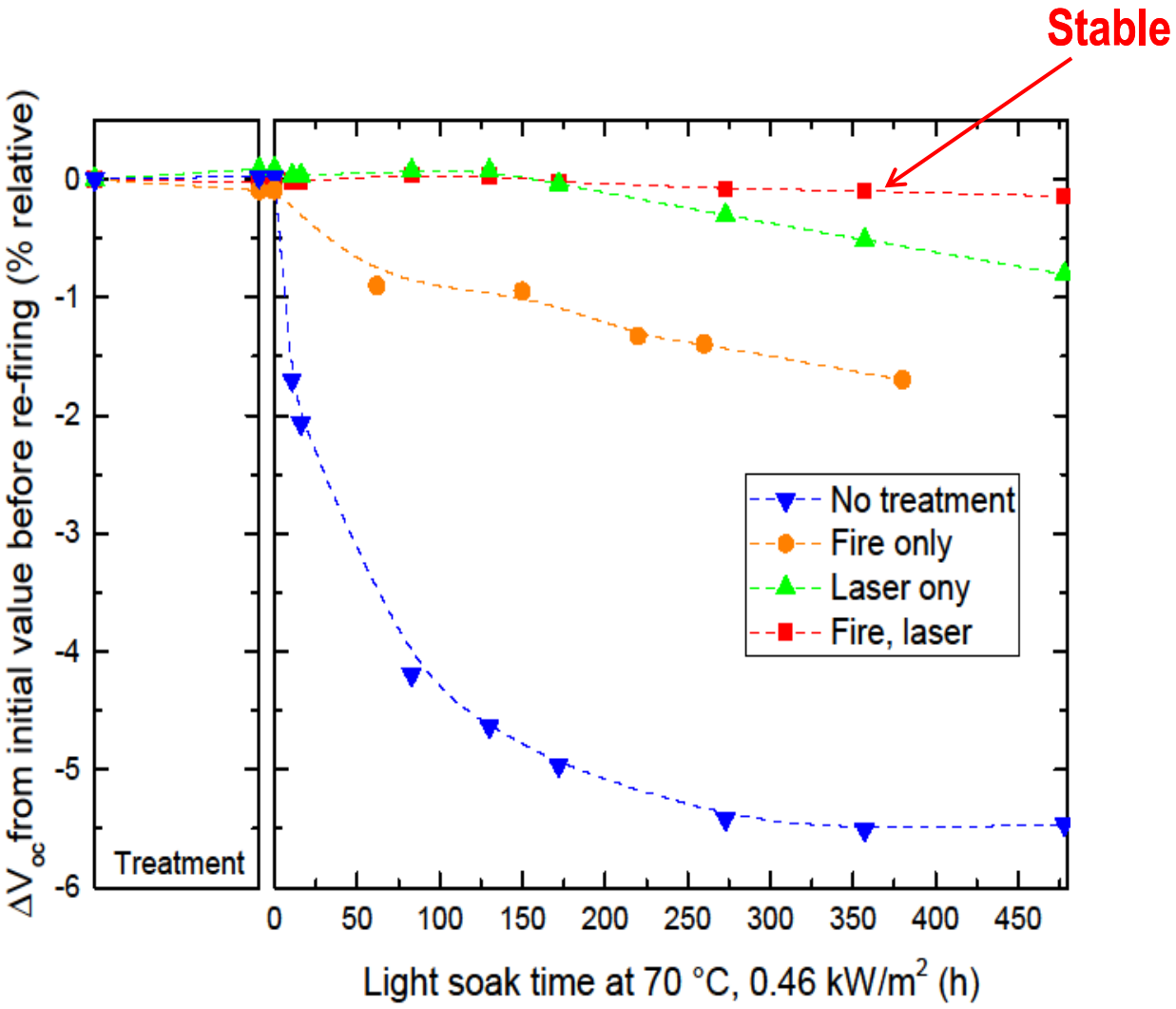




LID of commercial multi-PERC modules



Best published stability –
Re-fire and laser



[2] C.E. Chan et al. Rapid Stabilization of High-Performance Multicrystalline P-type Silicon PERC Cells. *IEEE Journal of PV,* 2016

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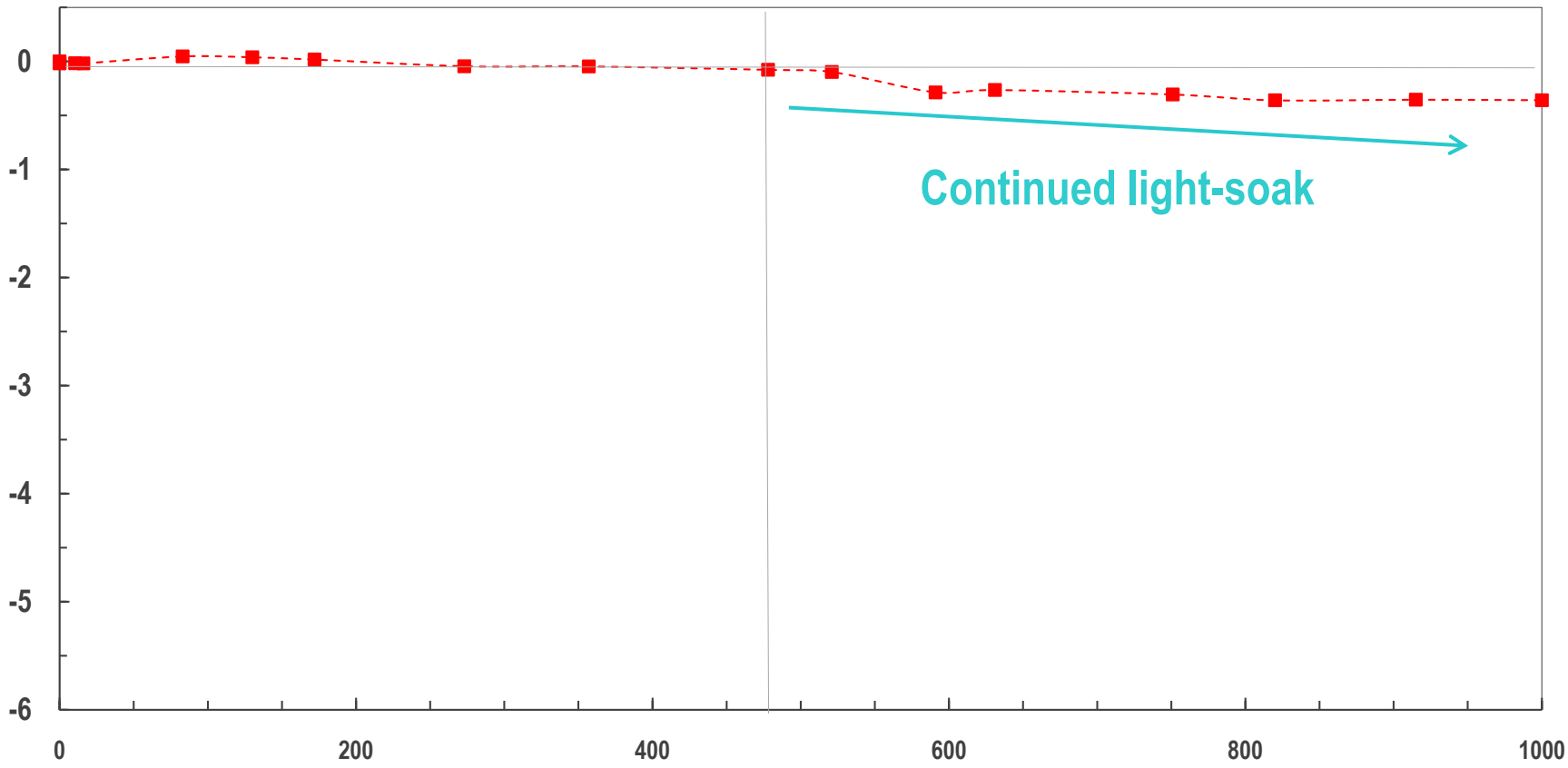
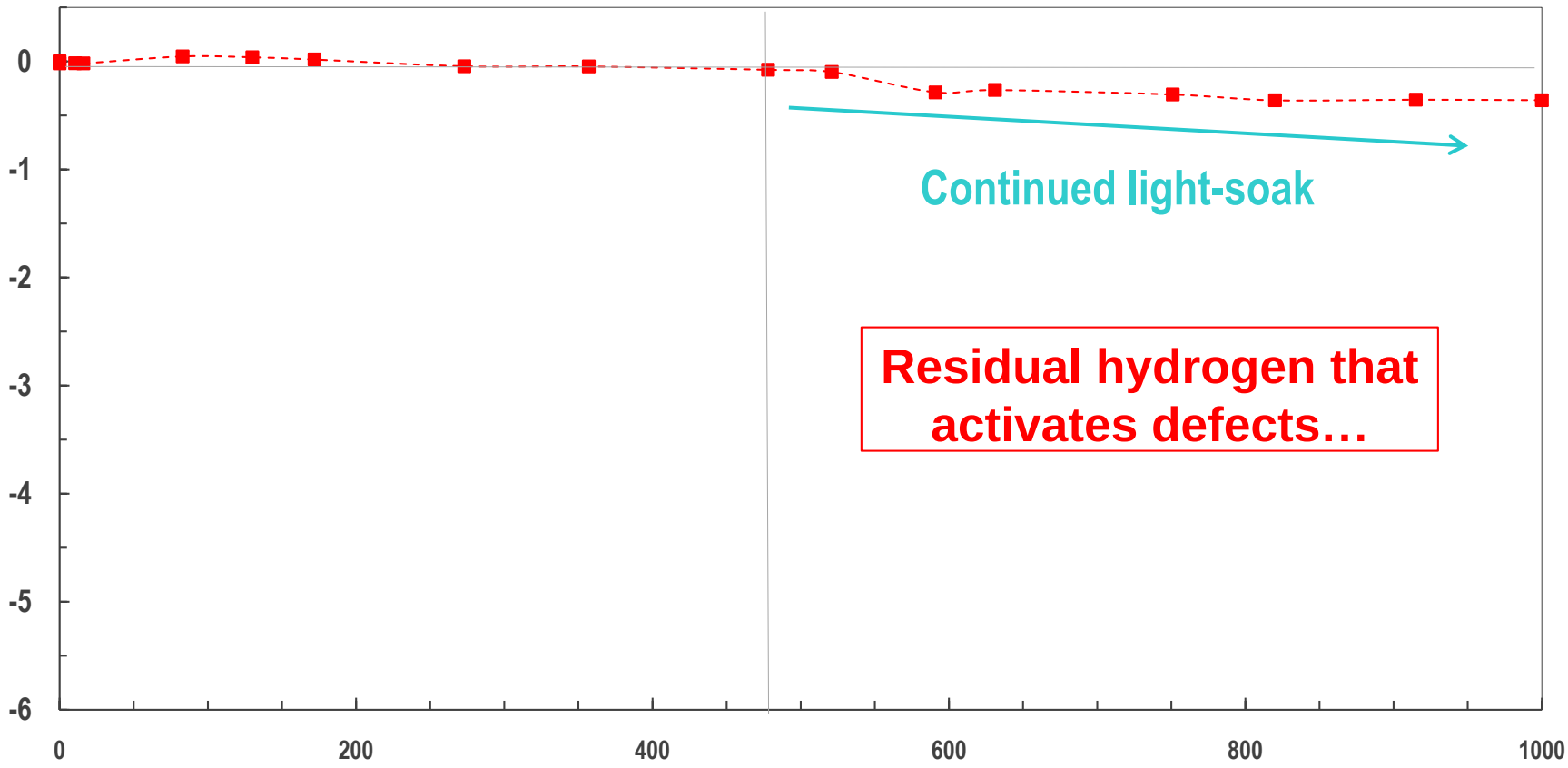
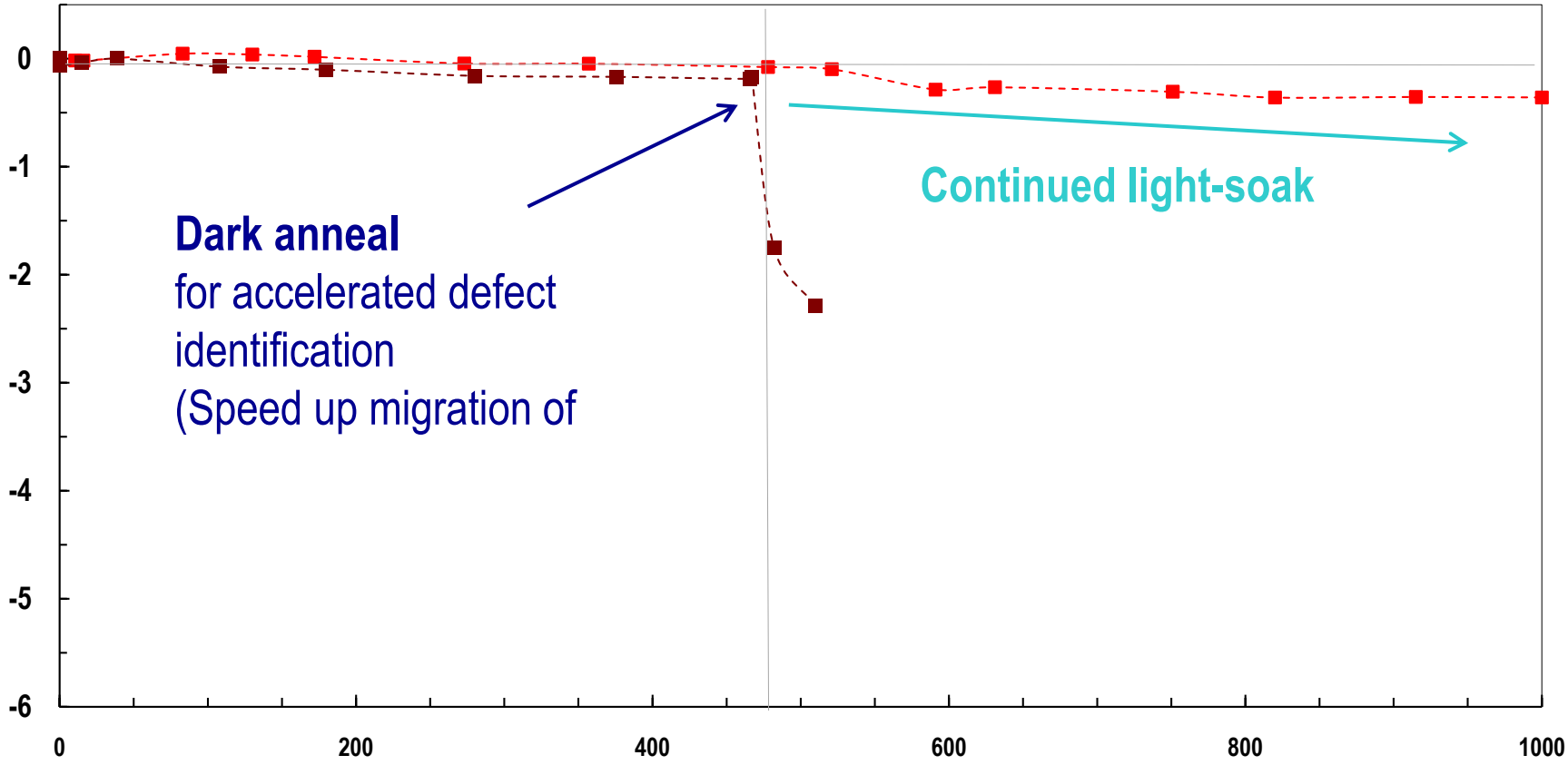
Long term LID



Long term LID

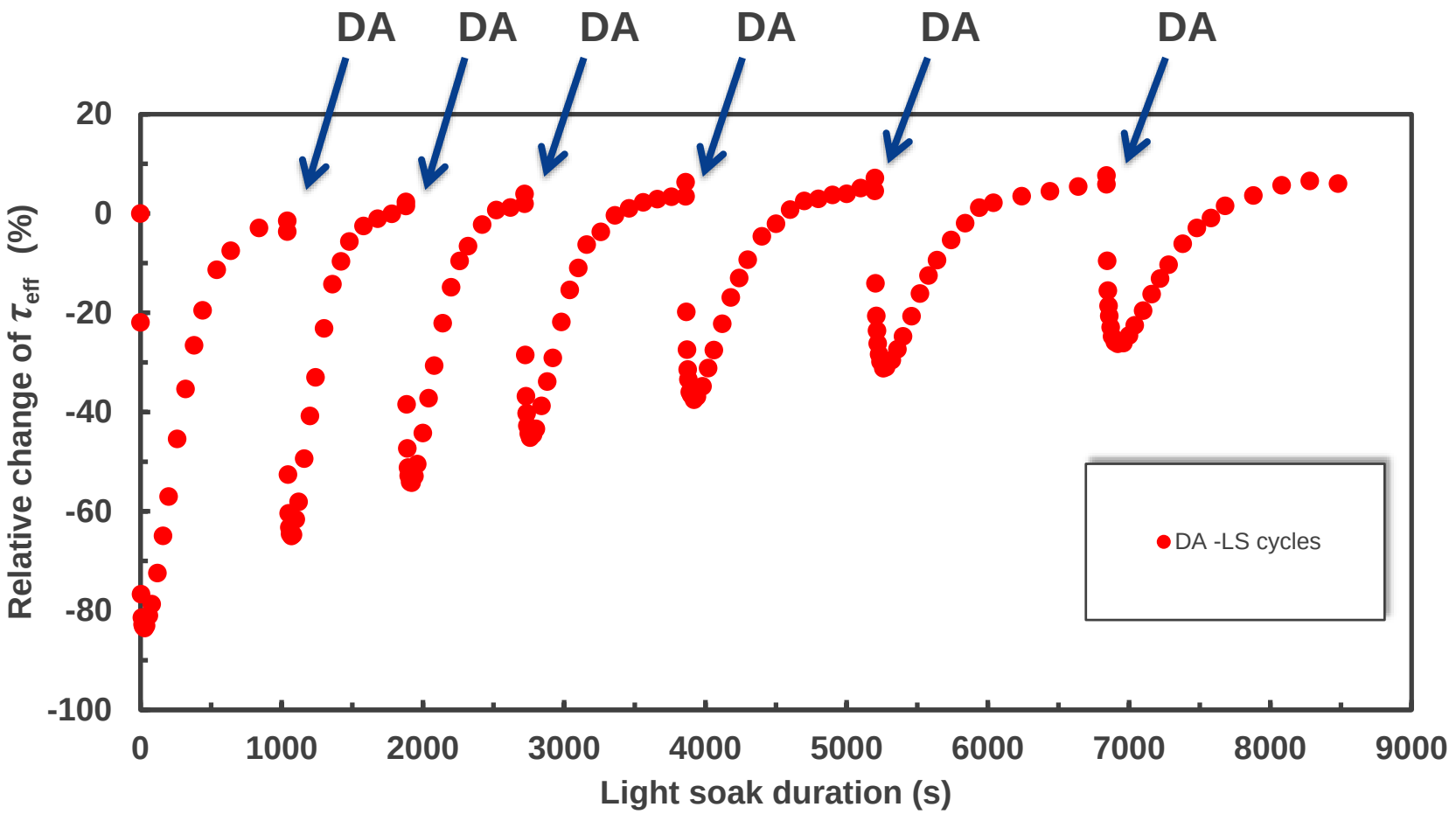


Accelerated identification of long-term issue



Dark anneals accelerate the hydrogen

DA after degradation and regeneration - cycling



Tsun Fung et. al., Impact of Annealing on the Formation and Annihilation of Carrier-Induced Defects in Multi-crystalline Silicon. *Silicon PV* 2017

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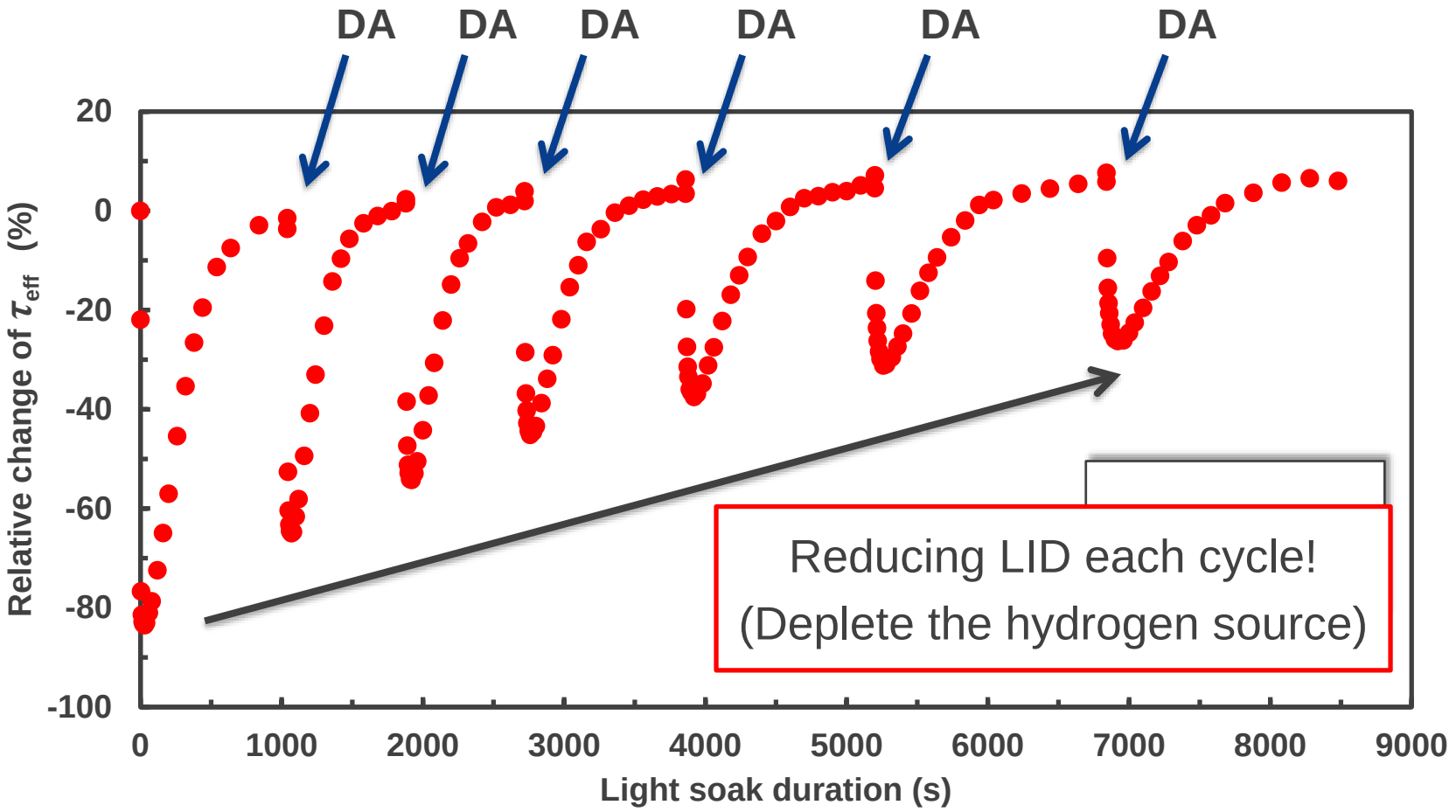

Tsun Fung et. al., Impact of Annealing on the Formation and Annihilation of Carrier-Induced Defects in Multi-crystalline Silicon. *Silicon PV* 2017

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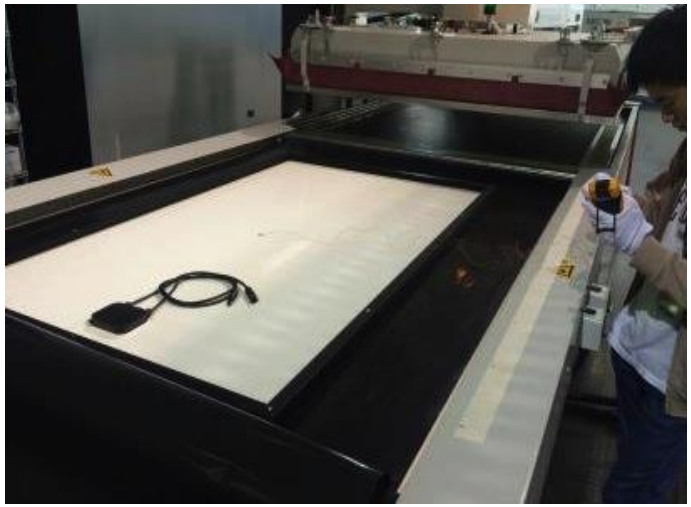
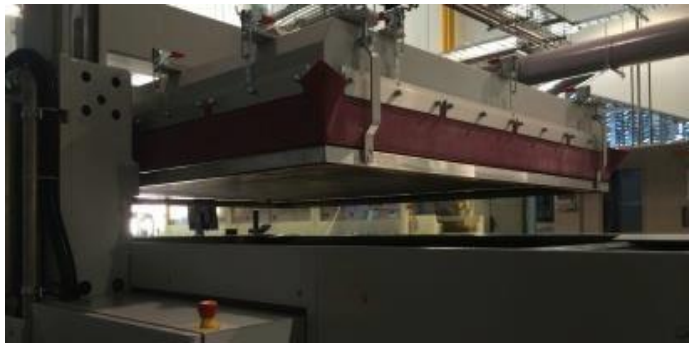
Tests on modules

1. Dark anneal

Inside module laminator at standard lamination temp 150 ° C (10 hours)





2. Light soak

~1 Sun at T≥70 ° C

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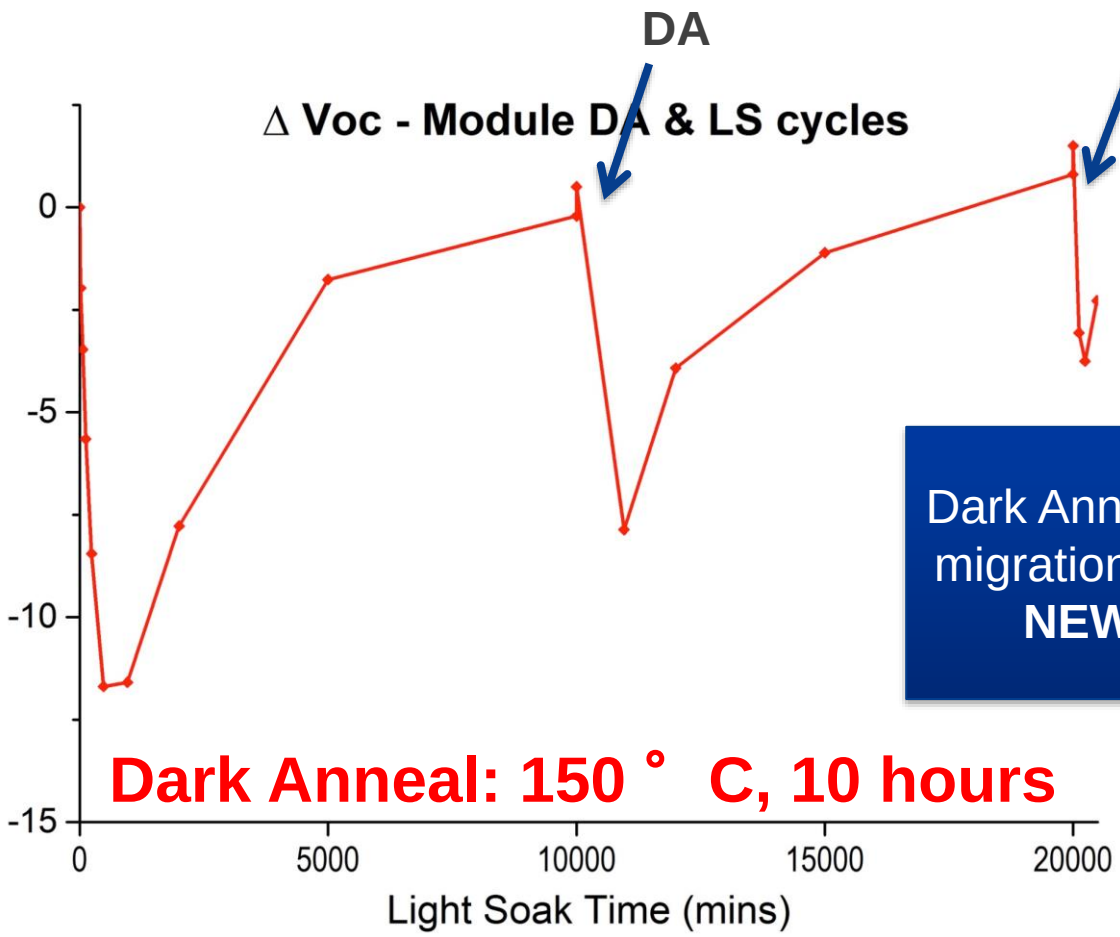
Module dark anneal and light soak cycles



Dark Anneal accelerates migration of reservoir of **NEW** hydrogen

Dark Anneal: 150 ° C, 10 hours

Commercial module – long-term LID testing

- **Dark anneal 10 hours at 150 °C** (can do in laminator)
- Light soak and compare with control module

Commercial module – long-term LID testing

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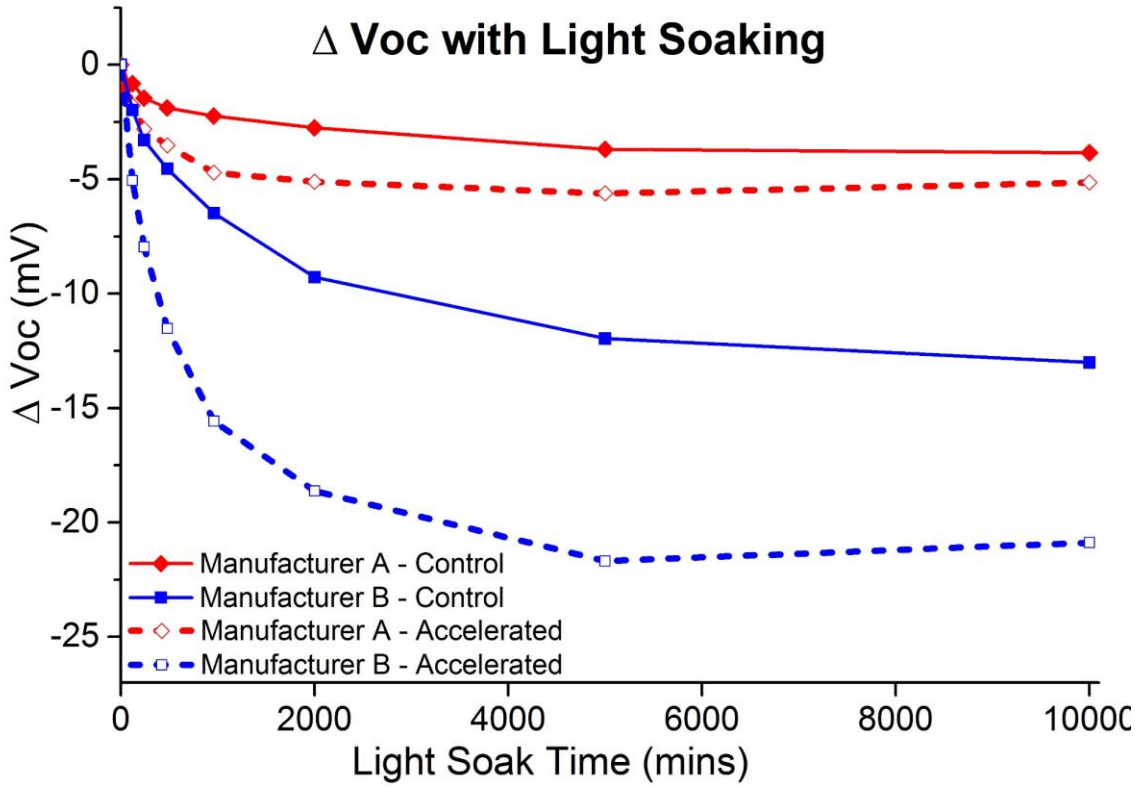

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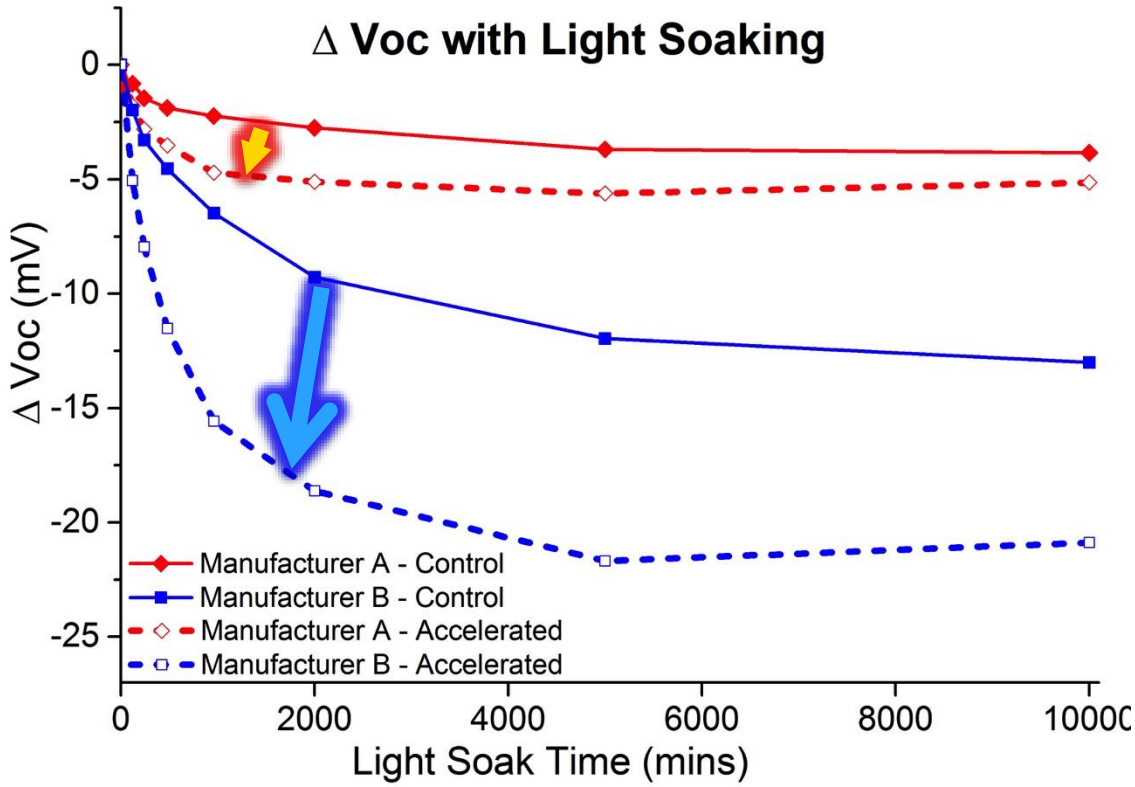
Commercial module – long-term LID testing

- **Dark anneal 10 hours at 150 °C** (can do in laminator)
- Light soak and compare with control module
- Difference => indicator of extent of long-term LID



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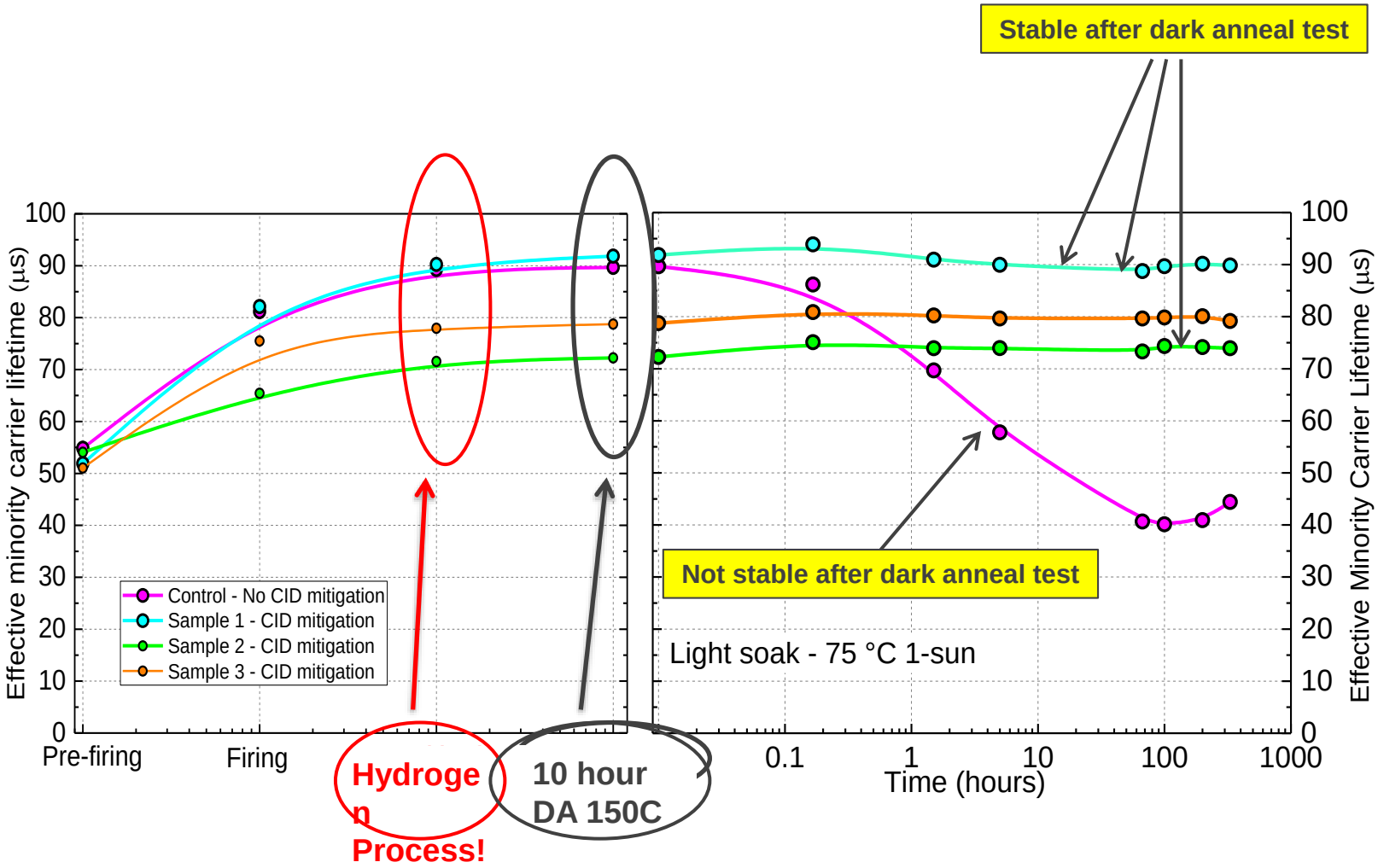
Hydrogen is the problem but also the solution!



8 new patents for manipulating H and the H charge state

- Auto-generation of H^0 for enhanced hydrogen passivation
- Controlling the hydrogen charge state in crystallographic defects
- Controlling the hydrogen location in silicon
- Generation of H^0 in n-type silicon
- Use of photons to control the charge state of hydrogen
- Novel thermal manipulation of hydrogen
- Use of hydrogen sinks to control hydrogen flow
- Solving LID in multi-crystalline silicon wafers

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Thank You!

UNSW Advanced Hydrogenation Tool
(1st Generation)
- Now commercialised

- Improves silicon quality
- Solves light-induced degradation

→ **Cheaper, more efficient and stable solar cells**

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