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p-type TBC cell and module pilot running in Tongwei

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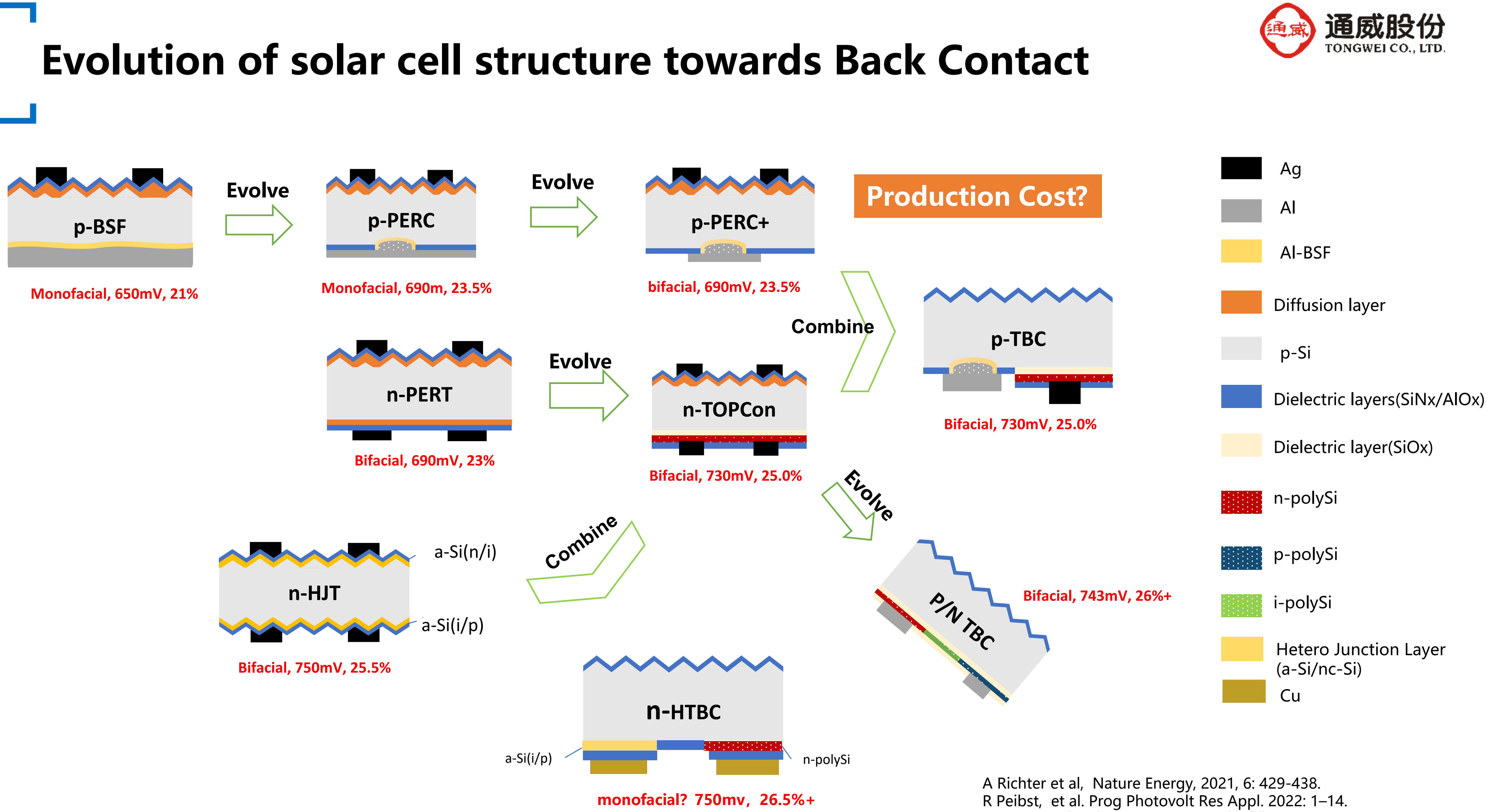
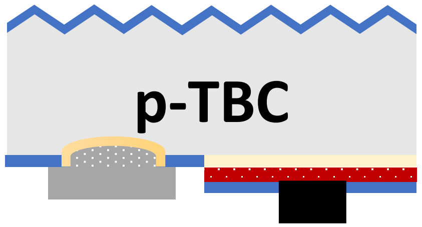
Evolution of solar cell structure towards Back Contact



A Richter et al, Nature Energy, 2021, 6: 429-438.
R Peibst, et al. Prog Photovolt Res Appl. 2022: 1–14.
F Haase et al. Sol. Energy Mater. Sol. Cells, 2018, 186: 184-193.

Comparison of TOPCon and p-TBC to PERC

Finally, They reached similar Voc and Module Power

	Non-ideal efficiency loss	Extra production cost @M10 size	Module performance
	Boron Diffusion Junction Recombination	• Ag consumption@100mg M10 • Electricity bill of >1000℃ Boron Juction formation	585W High bifaciality
	Contact recombination and resistence of Al-Si BSF	• Ag consumption@80mg M10 • Strict wet chemicals standard • Packaging papers of cells • Lower class A yield	585W Excellent aesthetics (Low bifaciality)

Voc=730mV

Industrial Processes of TOPCon and p-TBC

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TOPCon

- Texturing
- BSG Dep.
- Laser induce B drive
- Oxidation
- Alkaline polish
- PECVD polySi Dep.
- Annealing
- RCA
- Al_2O_3 / SiN_x
- Screen printing
- Sinter + Intense light assisted refire
- Test & sorting

p-TBC

- Alkaline Polish
- LPCVD i-poly
- P diffusion
- Laser pattern
- Texturing by PSG mask?
- AlOx
- SiNx
- Screen printing
- Sinter & Dark Anneal
- Test & sorting

- TOPCon cells in mass production have achieved open circuit voltage (V_{oc}) of 730 mV, owing to the successful implementation of boron diffusion, laser induced boron doping, LP/PE polySi deposition and intense light assisted refire.
- p-TBC loses > 1% efficiency due to recombination caused by Al-BSF.
- No room for further improvement on passivation quality.
- Only if upgrade the cell to bi-polar polySi passivated contact.
- Eventually TOPCon and p-TBC have achieved identical V_{oc} (730mV) and module power (585W@M10-72module)

Typical IV data of p-TBC（M10)

Batch (2023.9.11)	Quantity (PCS)	Eff (%)	Max Eff (%)	Voc (V)	Isc (A)	Jsc_ (A/cm2)	FF (%)	Rsh (Ω)	Rs_ (Ω-cm2)	RserLfDf IEC	Irev2 (A)	SunsVoc_FF (%)	Jo1_ (fA/cm2)	Jo2 (nA/cm2)	pFF (%)	Yield (%)
RUN247	3362	25.24	25.62	0.7297	14.031*	42.14*	82.11	1660	0.56	0.0017	0.75	84.58	19.6	-0.1	84.75	/

* Jsc Internally measured, defined and tracked from module power according TUV certification.
* A

Batch (2023.9.11)	Max hot spot Temp Diff. (℃)	Quantity	Ratio	Bias
1	<5	3387	99.7%	-13V
2	5~7	4	0.1%	
3	7~10	3	0.1%	
4	>10	2	0.1%	

Batch (2023.9.11)	Binning by Irev2	Quantity	Ratio
1	<0.5A	2013	59.0%
2	0.5-1A	479	14.1%
3	1-3A	794	23.3%
4	>3A	123	3.6%

Hot spot on p-TBC cells

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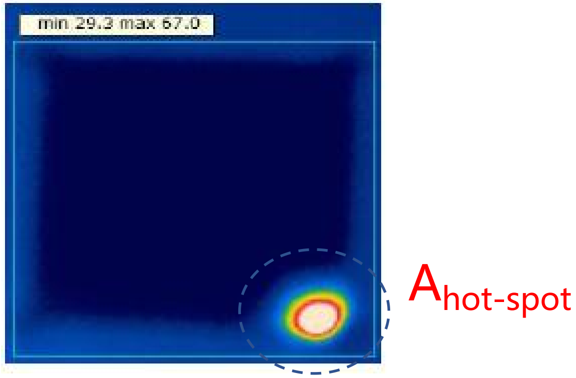
Hot spot is the red-line for module reliability

- For p-TBC cells with low leakage current, the hot spot temperature and knee-point current of the module is similar to those of a PERC module with the same configuration.
- The shading fraction of individual cell when bypass diodes activated are higher than shading fraction of PERC modules.

Purpose	Irev2	Efficiency loss due to hot spot	Hot spot temperature (℃)	Average diode knee point current (A)	Shading Fraction individual cell when bypass diodes activated
Investigating hot spot effect under different leakage current (182-72 module)	< 0.5A	0.16%/-0.4%	153.9	8.41	30%
	0.5-1A	-1.32%	157.4	8.86	48%
	1-3A	-0.88%	159.0	9.27	55%
	> 3A	-0.53%/-0.65%	157.1	7.07	20%
PERC modules as reference (182-72 module)	<0.5A	N.A.	155.8	6.96	8%

Hot spot temperature increases linearly with leakage current density

$$J_{leakage} = \frac{I_{leakage}}{A_{hot-spot}}$$



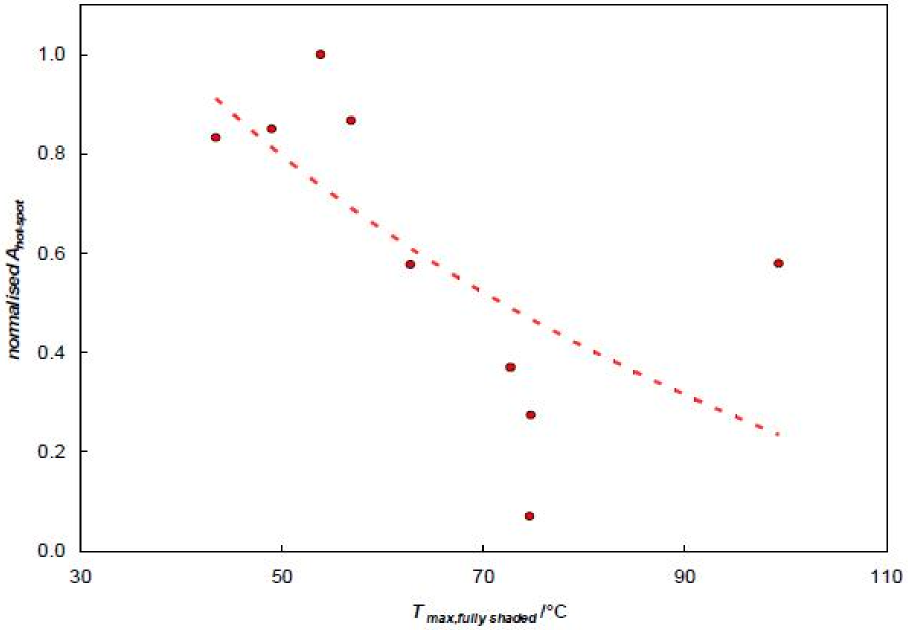


Figure 6: Correlation between the hot spot size and the hot spot temperature.

$J_{leakage}$: leakage current density, $I_{leakage}$: leakage current, $A_{hot\text{-}spot}$: total area of current leakage region

- Hot spot temperature increases linearly with leakage current density. The higher $J_{leakage}$ gets, the higher the hot spot temperature becomes

Wendlandt S, Drobisch A, Buseth T, et al. Hot spot risk analysis on silicon cell modules[C]//25th European Photovoltaic Solar Energy Conference and Exhibition. Valencia, Spain, 2010: 4002-4006.

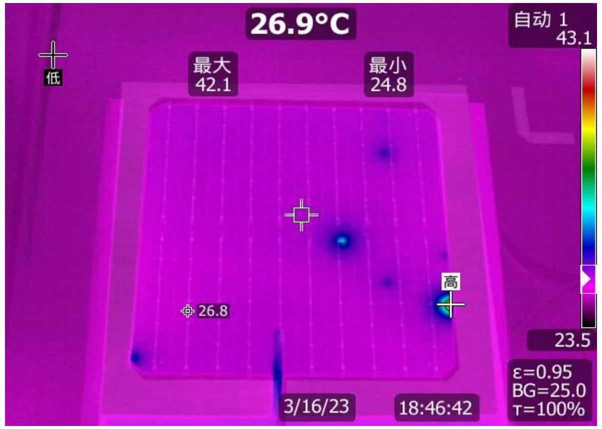
Leakage current densities of PERC and p-TBC cells

Comparison of single cells:

- At 182 mm cell size， **-13V bias**， the p-TBC sample has a leakage current ($I_{leakage}$) of 2A while PERC samples has an $I_{leakage}$ of 0.18A：
- When leakage current is at 2A, the p-TBC cell has lower $J_{leakage}$ (leakage current density) than that of the PERC cell；

Despite of this， p-TBC cells still have limited tolerance for leakage current.

When leakage current is greater than10A, an alternative solution for HOTSPOT is required.



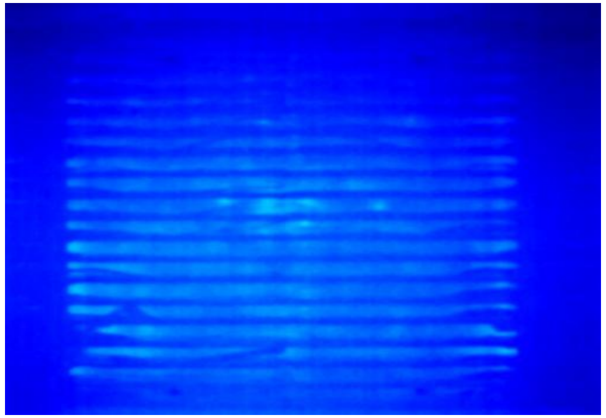
T_{MAX}=42.1℃

$I_{leakage}$=0.18A

$A_{hot\text{-}spot}$=60mm^2

$J_{leakage}$=0.003A/mm^2

PERC cell



T_{MAX}=30.22℃

$I_{leakage}$=2A

$A_{hot\text{-}spot}$=3926mm^2

$J_{leakage}$=0.0005A/mm^2

p-TBC cell

- The leakage current of TBC cells is uniform across the entire cell.
- Mass produced TBC cells have larger leakage current than mass produced PERC cells

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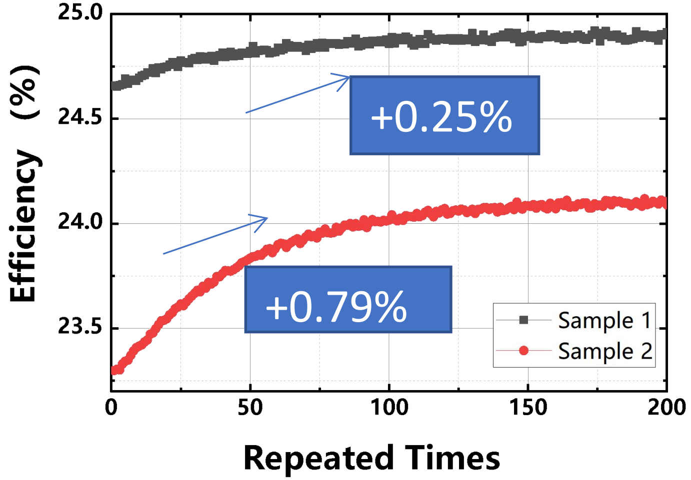
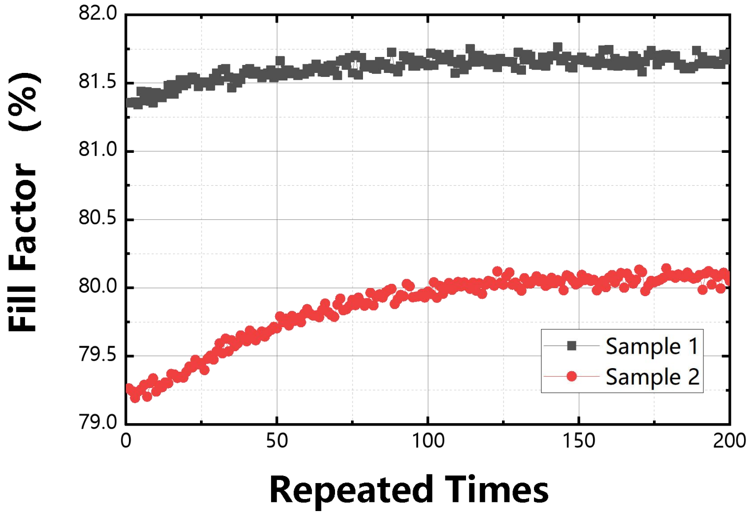
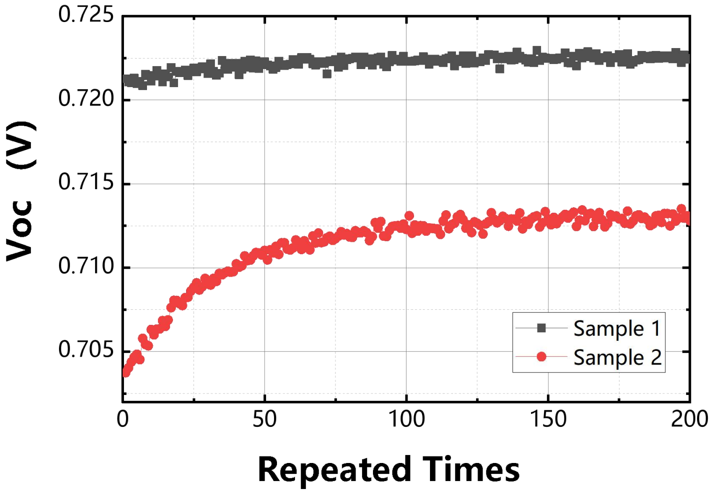
Instability of p-TBC cell efficiency

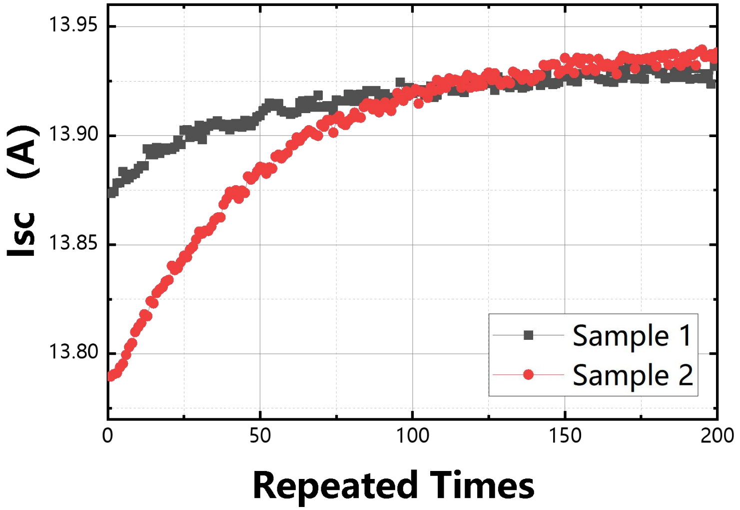
--Repeated I-V tests

Under exposure to flashing during repeated I-V tests, p-TBC cell efficiency temporarily increases until a plateau due to the limit by passivation









Equipment manufacturer: Halm

Luminance: 1000W/m2

Interval between tests: 2s

Xiajie Meng et al, presented in SiliconPV 2023

Instability of p-TBC cell efficiency

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Cell efficiencies increase after exposure to repeated flashing (200 times), but drops when stored in dark overnight

Possible causes：

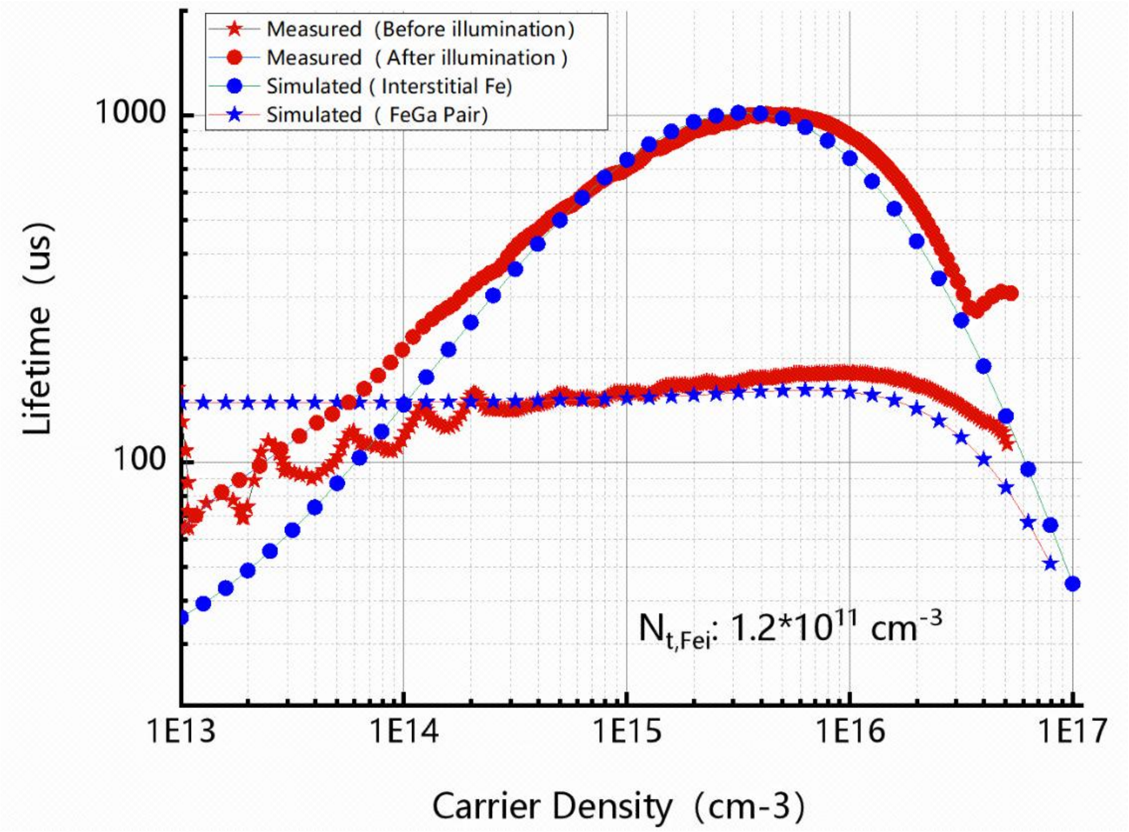
FeGa decomposition in p-type silicon wafers①②; passivation quality of AlOx improves when exposed to repeated flashing③

Efficiency Category	Condition	Eff (%)	Voc (V)	Isc (A)	FF (%)	PFF (%)	Rs_ (Ω-cm2)
24.0%	Initial	24.06	0.7242	13.934	79.41	84.23	0.83
	Flash 200 times	24.50 ↑	0.7268	13.994	80.23	84.89	0.74
	Stored for 12 hrs	24.11 ▬	0.7251	13.931	79.48	84.18	0.80
	ΔEff	0.44	0.0025	0.060	0.82	0.66	-0.09
24.5%	Initial	24.52	0.7247	13.968	80.68	84.94	0.70
	Flash 200 times	24.99 ↑	0.7261	14.021	81.74	85.74	0.62
	Stored for 12 hrs	24.55 ▬	0.7248	13.965	80.77	84.94	0.69
	ΔEff	0.46	0.0014	0.053	1.05	0.80	-0.08
25.0%	Initial	25.02	0.7289	14.050	81.34	85.71	0.67
	Flash 200 times	25.25 ↑	0.7295	14.076	81.86	86.15	0.65
	Stored for 12 hrs	25.05 ▬	0.7294	14.047	81.40	85.78	0.65
	ΔEff	0.23	0.0006	0.026	0.52	0.43	-0.02

① Marwan Dhamrin PhDThesis, Fabrication and Evaluation of Ga-doped Multicrystalline Silicon Wafers and Solar Cells
②Nærland T U, Bernardini S, Haug H, et al. On the recombination centers of iron-gallium pairs in Ga-doped silicon[J]. Journal of Applied Physics, 2017, 122(8): 085703.

FeGa affected minority carrier lifetime fitting

	Dopant level (eV)	Et-Ei	Electron capture cross section σn (cm2)	Hole capture cross section σp (cm2)	Ratio of E/H capture cross section σn/σp	References
Fei	Ev+0.38	-0.18	4.00E-14	7.00E-17	571.4	Istratov
FeGa	Ev+0.2	-0.36	1.20E-14	6.00E-15	2.000	Narland



- Estimated FeGa concentration：1.0~1.3E11cm^{-3}；

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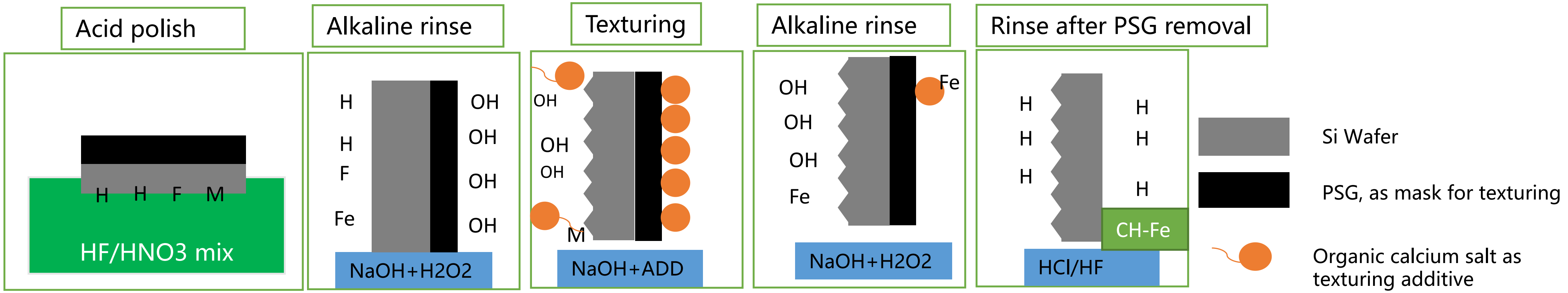
Possible Origins of FeGa in Cells

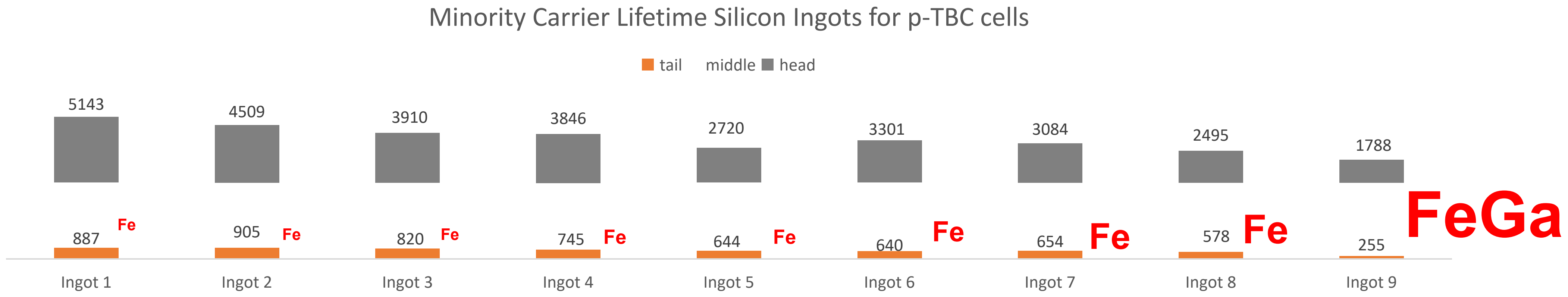
Origin 1: metal adsorption during the last wet chemical process (1~10ppb)

Iron originated from acid should be strictly controled



Origin 2: Fe segregation in silicon ingots, which forms percipitates that dissolves as Fe reservior during high temperature process in cell fabrication

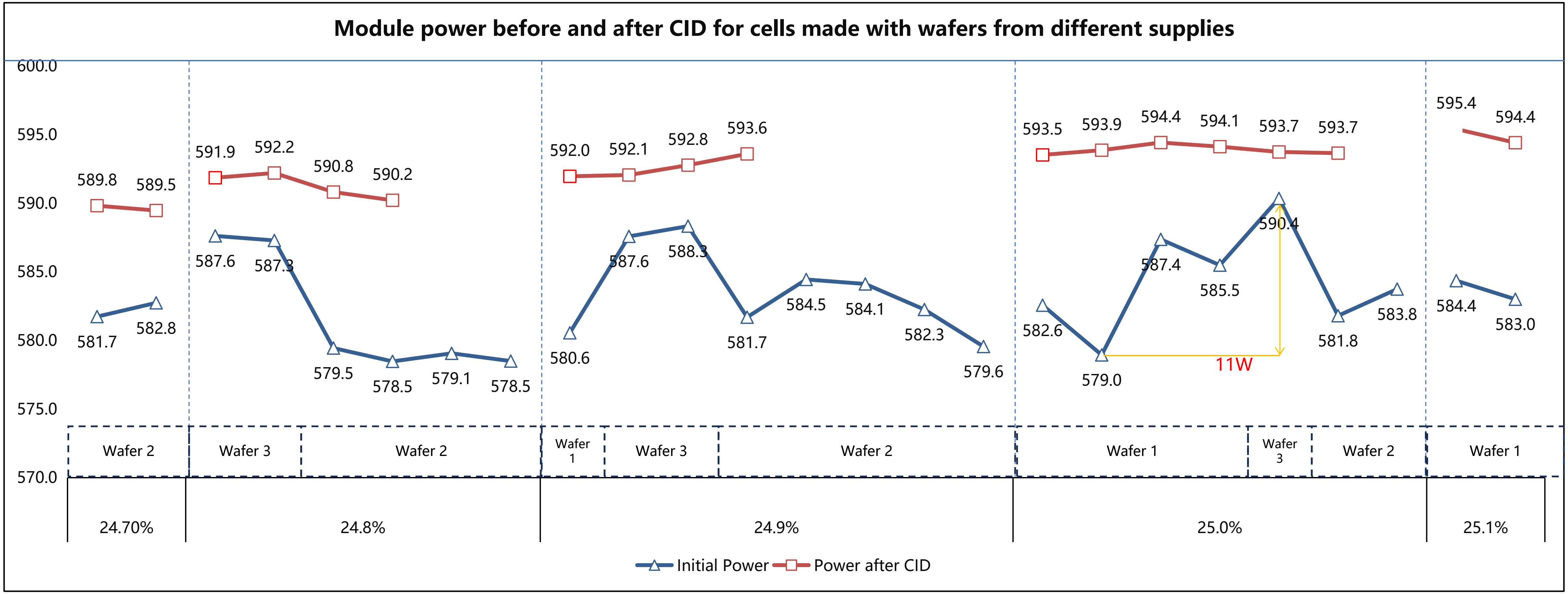
Iron-Gallium pairs are unavoidable since p/Ga doped ingot pulling feedstock comsuption is over 4000 kg per cruicible



Power instability of p-TBC module

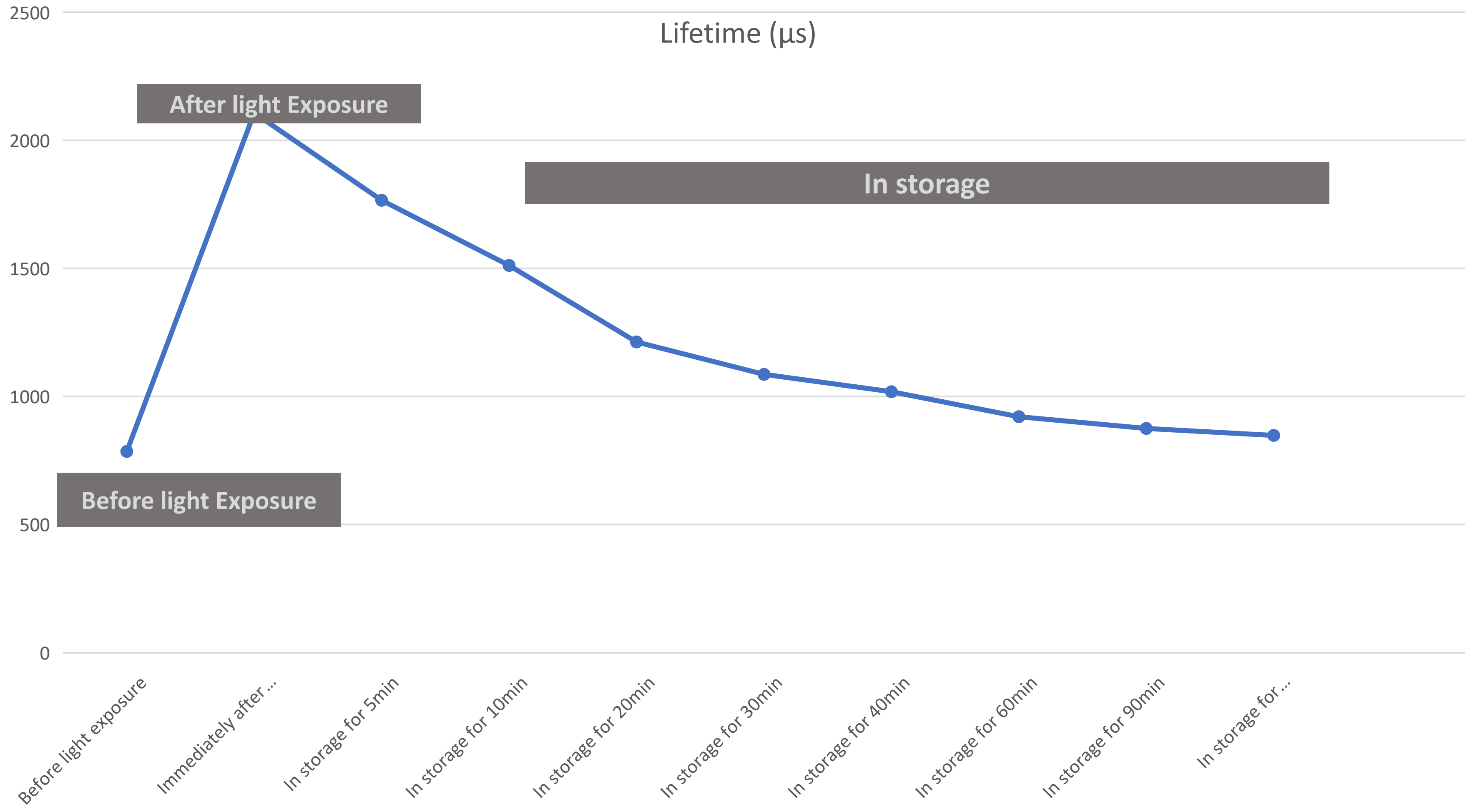
Photo-injection can cause temporary efficiency increase for p-TBC cells，so should current injection

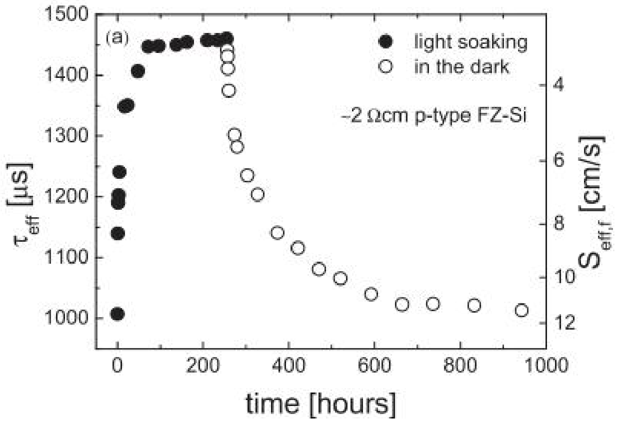
- Current injection can increase module power by 4~11W
- Before current injection, it is hard to predict module power by cell efficiency, due to discrepancies as large as 11W. After current injection, a trend can be established to some extent



Instability of AlO_x passivated p-type wafer surface

- P-type + AlO_x passivated wafer: Carrier lifetime before and after light exposure, as well as in storage (@ $10^{15} cm^{-3}$)





Note: Light exposure here means the flashing used in PL test (BT image IR2)

③Baochen Liao, Rolf Stangl, Thomas Mueller, et al, Journal of Applied Physics 113, 024509 (2013);

Influence of AlO_x passivation instability on PBC cells

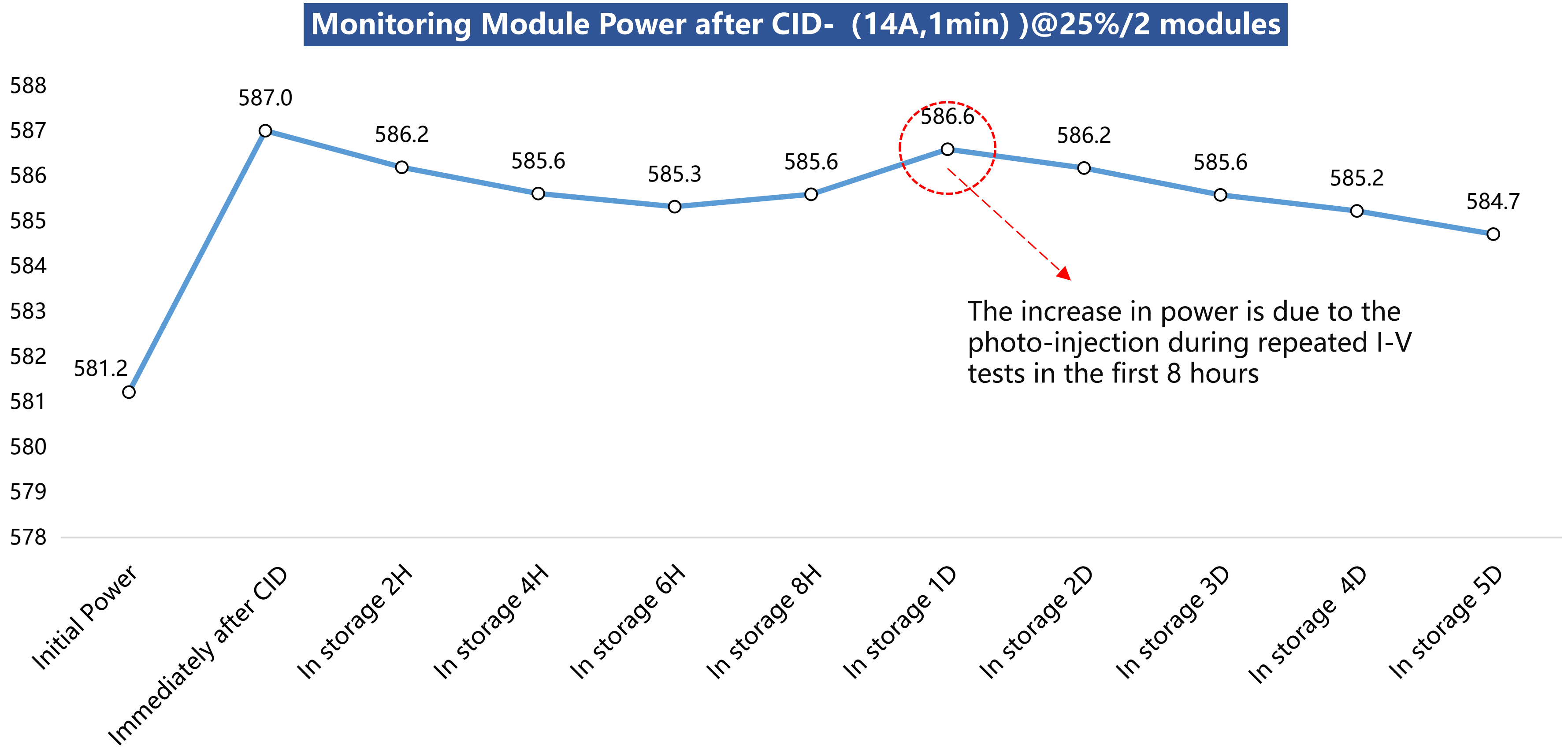
Quokka3 Simulation

- The evolution from BSF cell to PERC cell is primarily the result of the implementation of AlO_x passivation on p-type Si wafers. Due to its high density of fixed negative charges ($Q_f > 10^{12}/cm^3$), AlO_x can effectively repell electrons, the minority carrier in p-type silicon wafers, thereby reducing surface recombination velocity
- According to literature, exposure to light, especially UV light, may lead to an increase in Q_f for AlO_x, which results in enhanced passivation quality. This effect is demonstrated in the following table:

Influence of Fixed Charge density of AlO_x on PBC cells

Fixed Charge/cm-3	Voc/V	Jsc/mA/cm2	FF/%	Eff/%	pFF/%
-1E+12	0.7248	41.35	82.14	**24.62**	85.40
-2E+12	0.7289	41.41	82.65	**24.94**	85.63
-3E+12	0.7301	41.42	82.83	**25.05**	85.71
-4E+12	0.7306	41.42	82.93	**25.10**	85.75
-5E+12	0.7310	41.42	82.99	**25.13**	85.77

Monitoring PBC module power after CID



- Current injection results in 5.8W power gain for modules, but it gradually decreases in storage

Summary

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- It is possible to mass produce p-TBC cells with 25% efficiency, as well as p-TBC modules with 585W power
- p-TBC cells have relatively high tolerance for leakage current. No abnormality is observed when leakage current is under 3A. Generally, **p-TBC has 10 times better tolerance for leakage current than that of PERC. Although further investigation is required if leakage current becomes higher.**
- p-TBC cells under **repeated flashing**, as well as p-TBC modules after **CID**, will exhibit **temporary efficiency gain**
  - A possible cause could be that the FeGa in Ga-doped wafers would decompose under light exposure or under current injection. And such decomposition would enhance cell efficiency temporarily, which reverts when external stimulant (photo- or current injection) is removed
  - Another possible cause is the temporary improvement of AlOx passivation under external stimulant
- There are **irregularities in cell efficiencies**, which is **caused by the differences in wafers from various manufacturers**. Current injection can alleviate such irregularity but
- **CID induced Module power** is not stable
- The stability of photo-induced power gain in modules needs long-term monitoring when they are fielded.

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Thanks!