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Silicon PV 2025

Degradation and Accelerated Recovery of Surface Passivation in n^+ *poly*-Si/SiO_x Passivating Contacts for TOPCon Solar Cells

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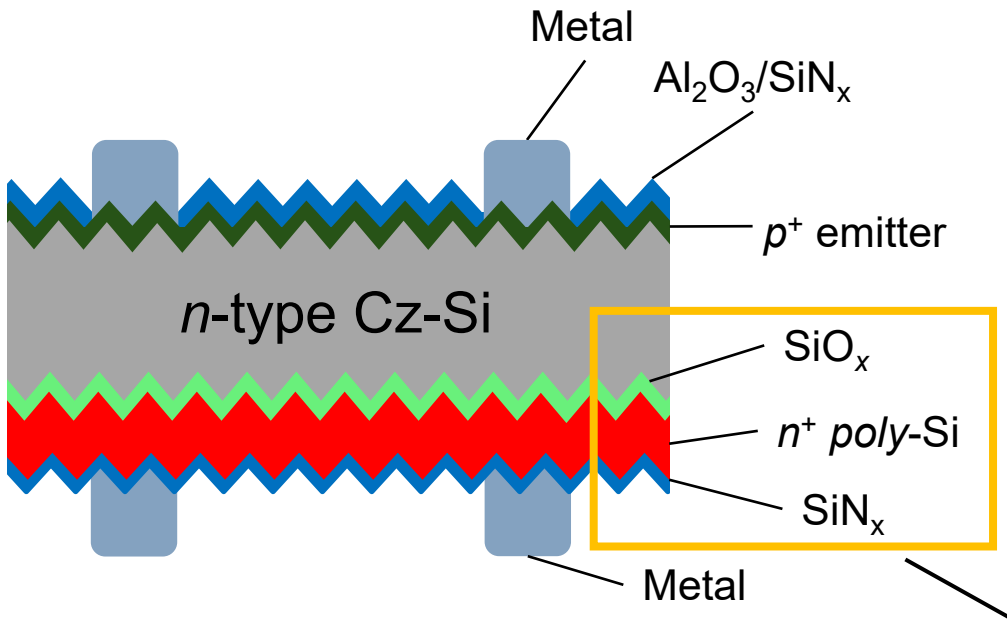
TOPCon solar cell and its Reliability

TOPCon solar cell



- Cell efficiency ~24%
- ~52 % current PV market share
- ~70-80% in next 5 years

Reliability issues in TOPCon		
Type of failure	% P_{mpp} Degradation	Test Temperature
LID/LeTID	0.2%	25/75 °C
Thermal Cycling	0.7%	-40/85 °C
Damp Heat	1.6%	85 °C
PID	1.6 - 2.0%	85 °C
UVID	5%	60 °C
Surface Passivation Degradation (SPD) of *poly*-Si/SiO_x passivating contact	**~ 2 - 3 %**	**> 200 °C**

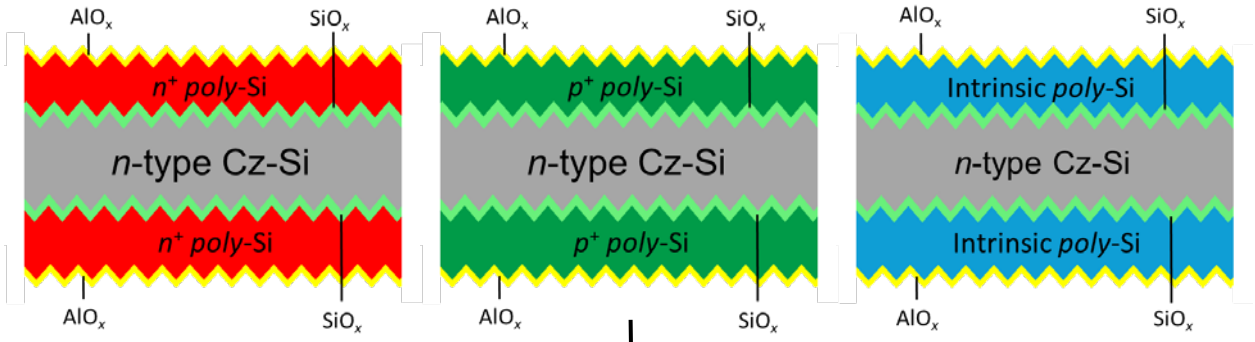
Standard reliability tests cannot detect surface passivation degradation

Feldman, Solar industry update (May 2024).
pv-magazine, Why TOPCon will Keep Domination in Future Five Years? (Sept 2024).

PVEL, PV Module Reliability Scorecard, 2024

Long term stability of n^+, p^+ and i *poly*-Si/SiO_x structures

Symmetric *poly*-Si/SiO_x passivating structures



Firing at 670 °C peak

Accelerated tests
1. Dark
2. Illumination: AM 1.5 G spectrum

PCD measurements

Degradation and recovery of surface passivation

- Winter, M. *et al.*, *IEEE J-PV* **10**,423 (2020)
- Kang *et al.*, *Sol. Energy Mater. Sol. Cells* **215** (2020)
- Chen *et al.*, *Sol. Energy Mater. Sol. Cells* **236**,111491 (2022)

In this talk:

- Effect of dopants in *poly*-Si
- Temperature and illumination dependency
- Cyclic nature
- Proposed kinetic model
- Industrially relevant surface passivation recovery (SPR) process

Degradation and recovery of n^+, p^+ and i *poly*-Si/SiO_x structures

Symmetric n^+, p^+ and intrinsic *poly*-Si/SiO_x contacts

↓

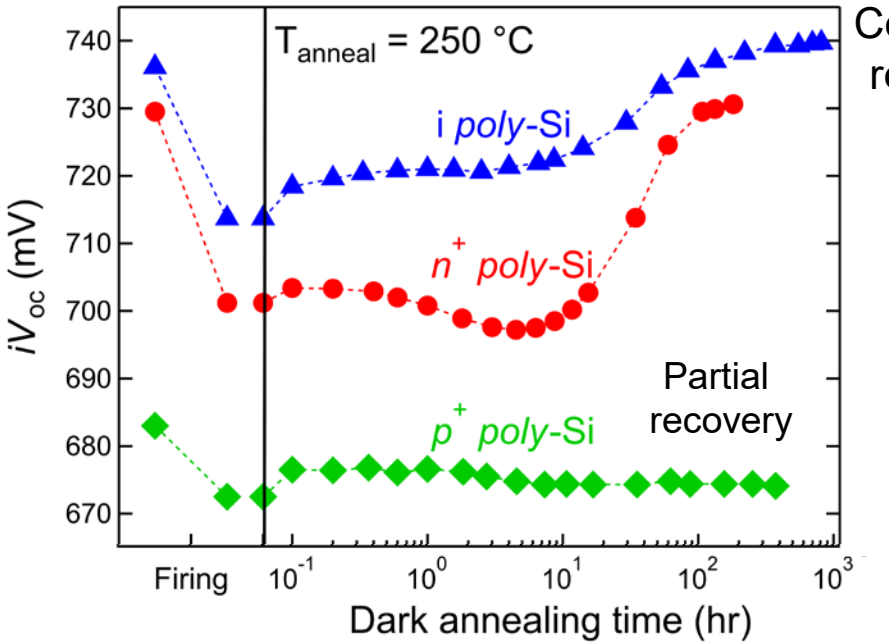
Fired at 670 °C peak

↓

Dark annealing 250 °C

↓

PCD measurements



Complete recovery

1. n^+ *poly*-Si : Degradation- Complete recovery
2. i *poly*-Si : Complete recovery
3. p^+ *poly*-Si : Partial recovery

Degradation and recovery of n^+, p^+ and i *poly*-Si/SiO_x structures

Symmetric n^+, p^+ and intrinsic *poly*-Si/SiO_x contacts

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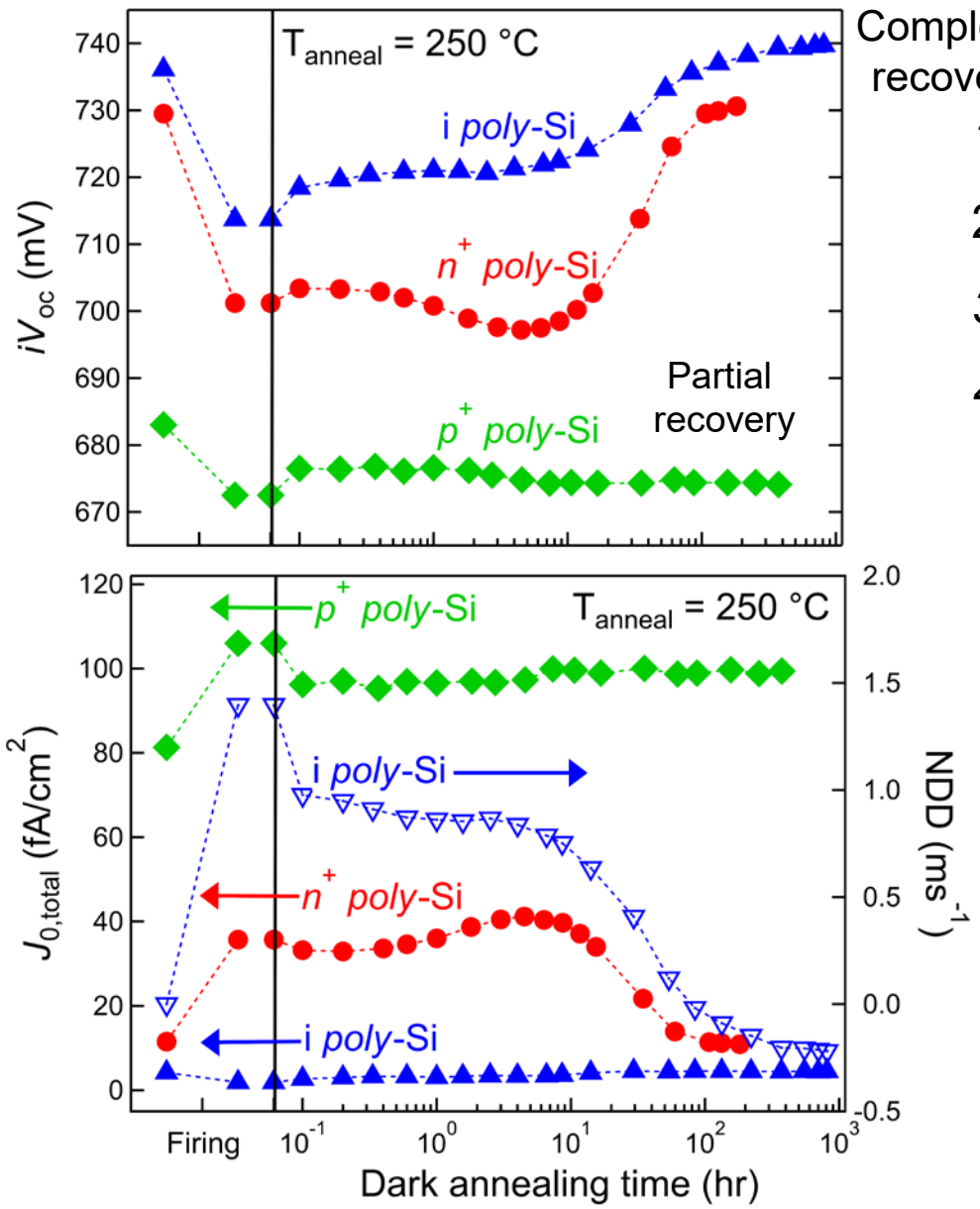
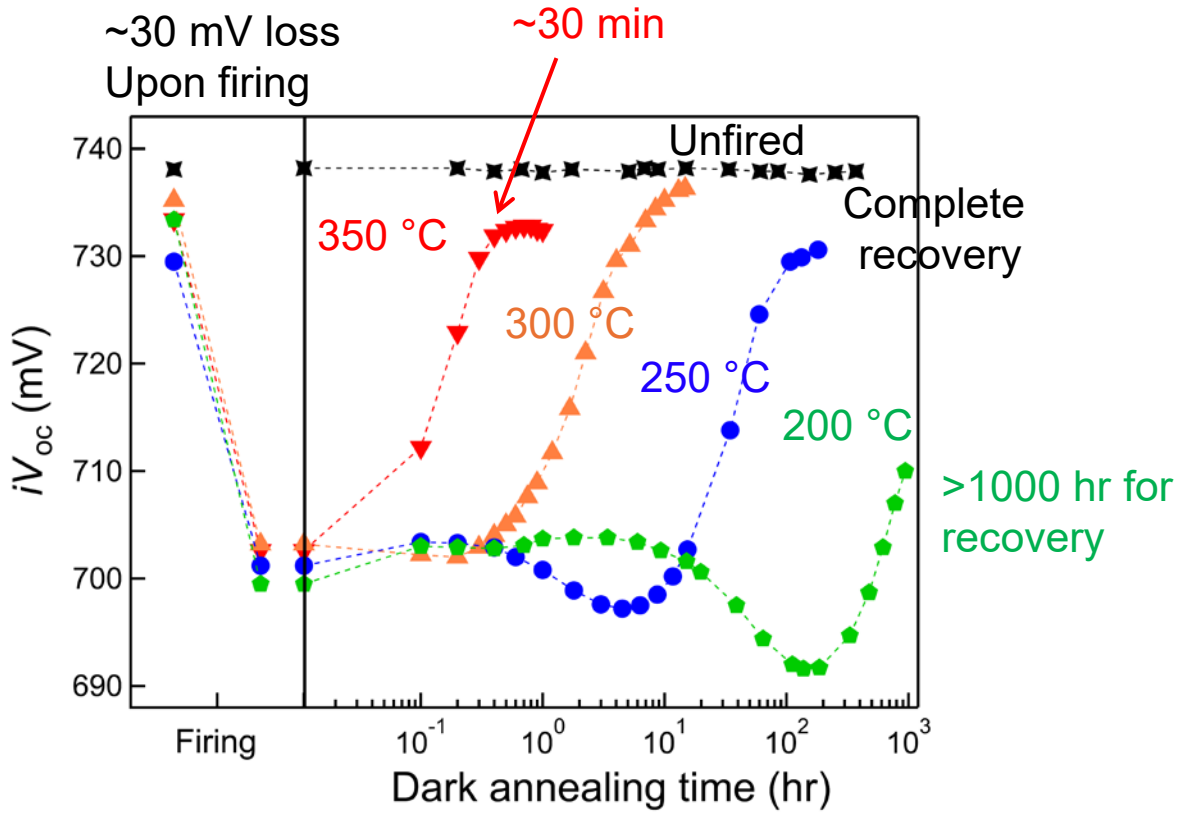


Complete recovery

1. n^+ *poly*-Si : Degradation- Complete recovery
2. i *poly*-Si : Complete recovery
3. p^+ *poly*-Si : Partial recovery
4. J_0 and NDD trends correlate with iV_{oc} indicating changes in surface passivation quality

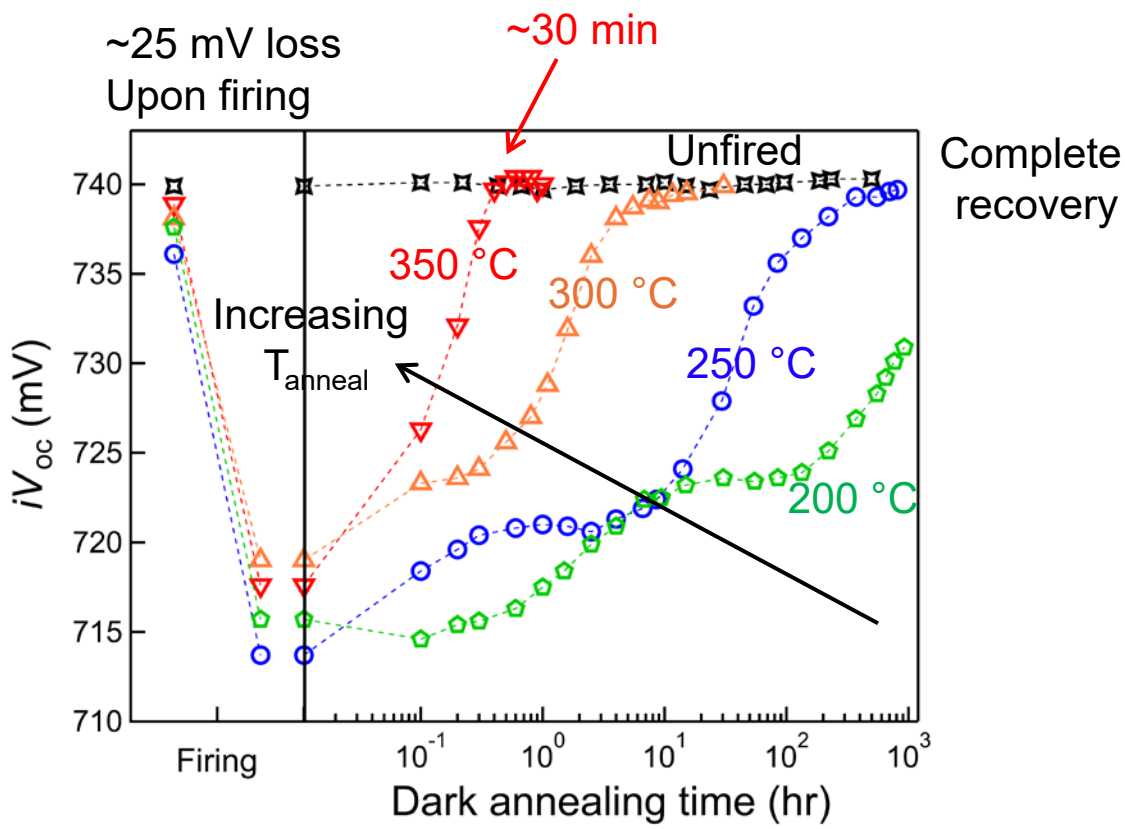
Effect of annealing temperature on stability of n^+ and i *poly*-Si/SiO_x structures

n^+ *poly*-Si contacts



- Degradation followed by recovery

i *poly*-Si contacts



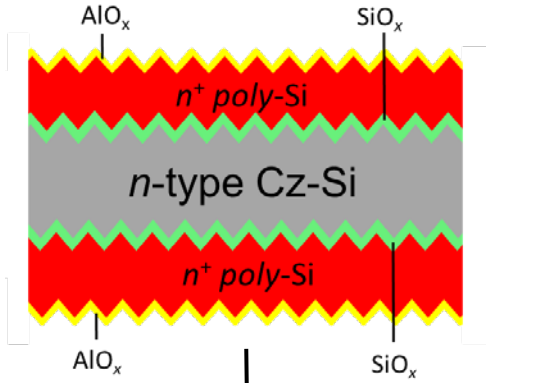
- Direct recovery in iV_{oc}

Chen *et al.*, *Sol. Energy Mater. Sol. Cells* **236**,111491 (2022)

Degradation and recovery processes are thermally activated

Winter, M. *et al.*, IEEE J-PV **10**,423 (2020)
Kang *et al.*, Sol. Energy Mater. Sol. Cells **215** (2020)

Accelerated recovery of n^+ *poly*-Si structures under intense illumination

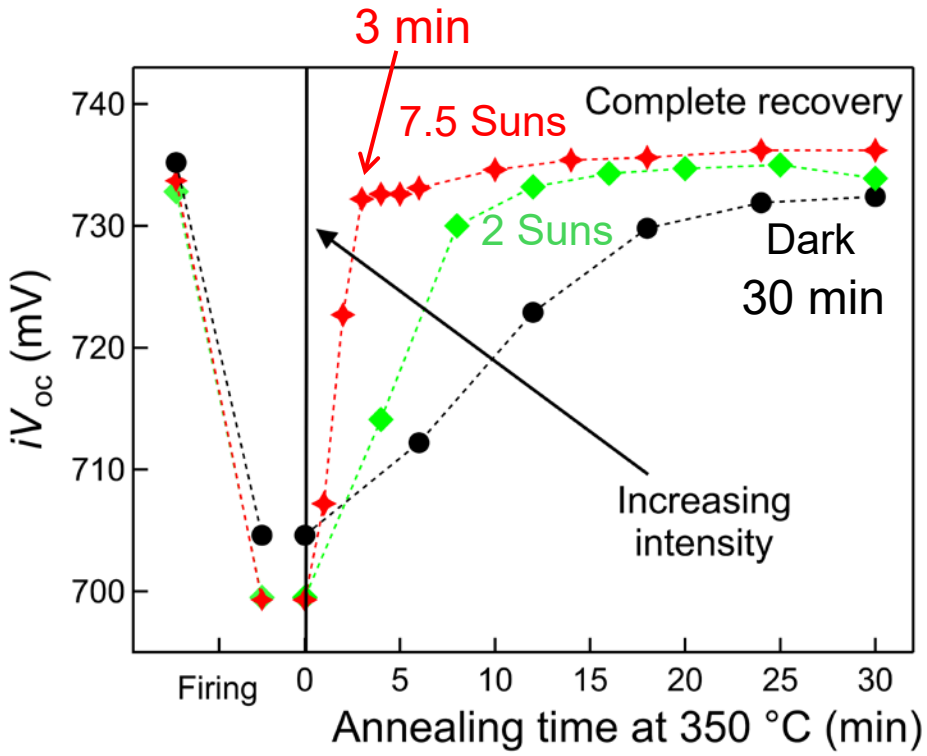


Firing at 670 °C peak

Illumination annealing
0-7.5 Suns and 250-350 °C

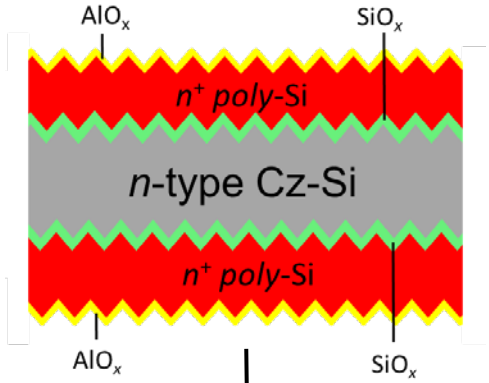
PCD
measurements

350 °C, vary illumination



- Illumination significantly accelerates degradation and recovery processes
- Annealing at elevated temperature and intense illumination for quick recovery

Accelerated recovery of n^+ *poly*-Si structures under intense illumination



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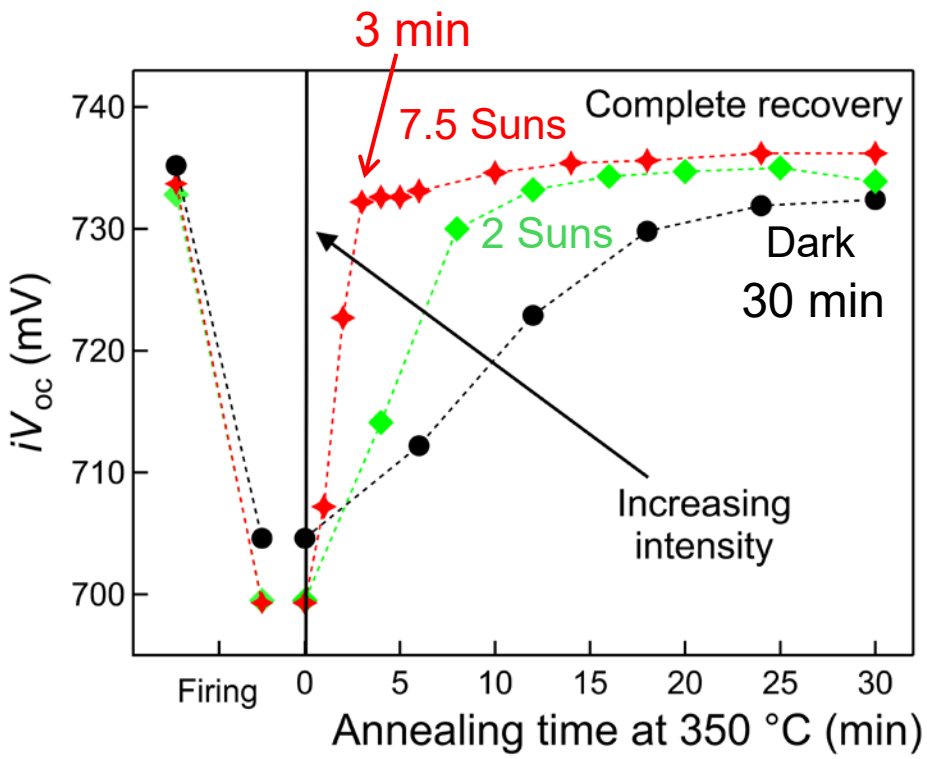
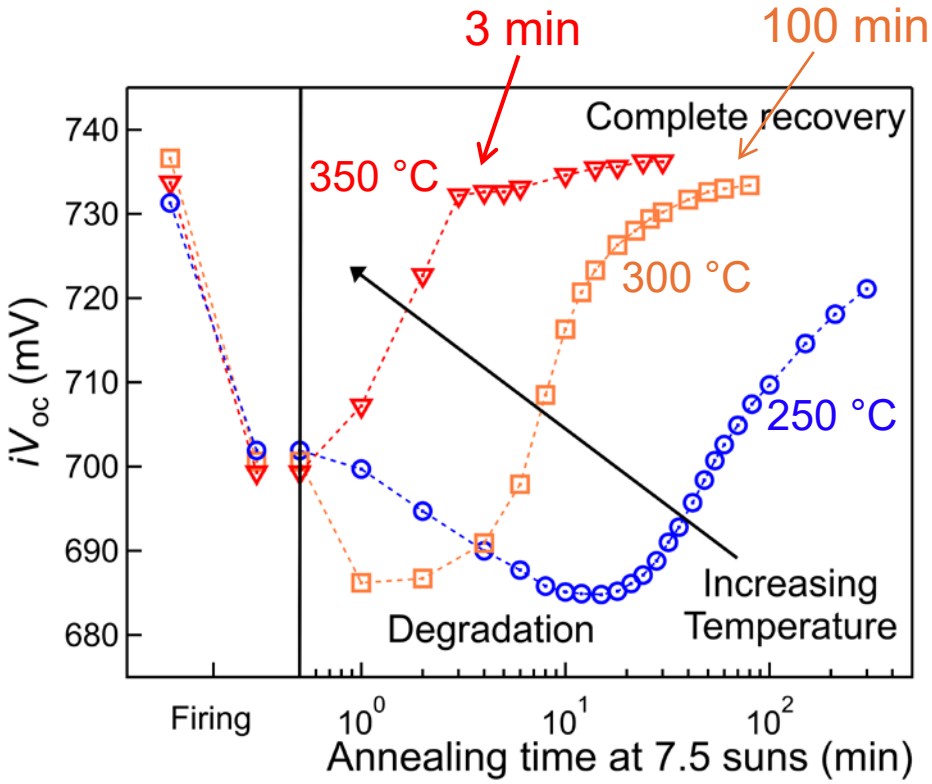


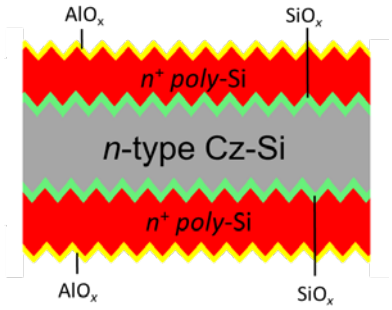
7.5 Suns, vary temperature



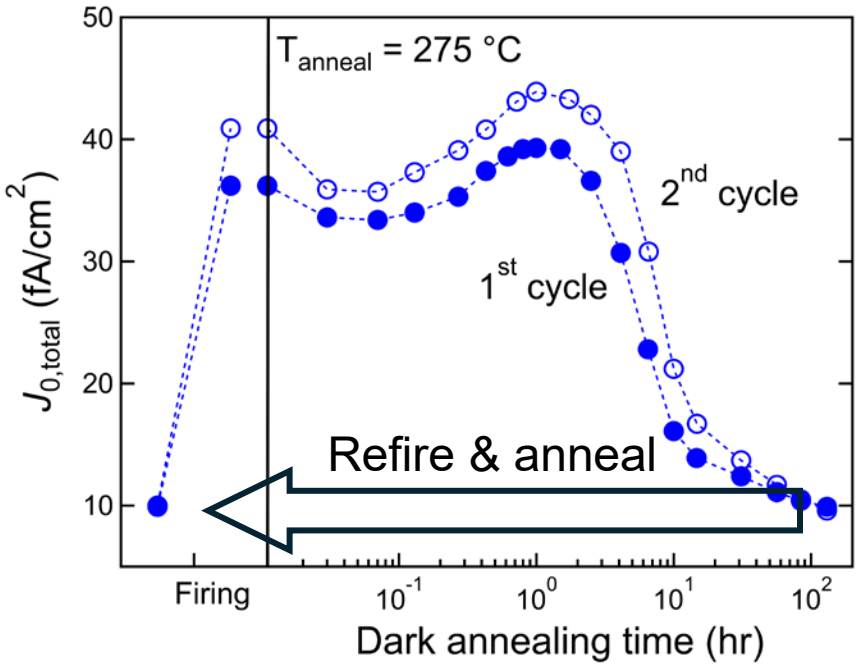
- Illumination significantly accelerates degradation and recovery processes
- Annealing at elevated temperature and intense illumination for quick recovery

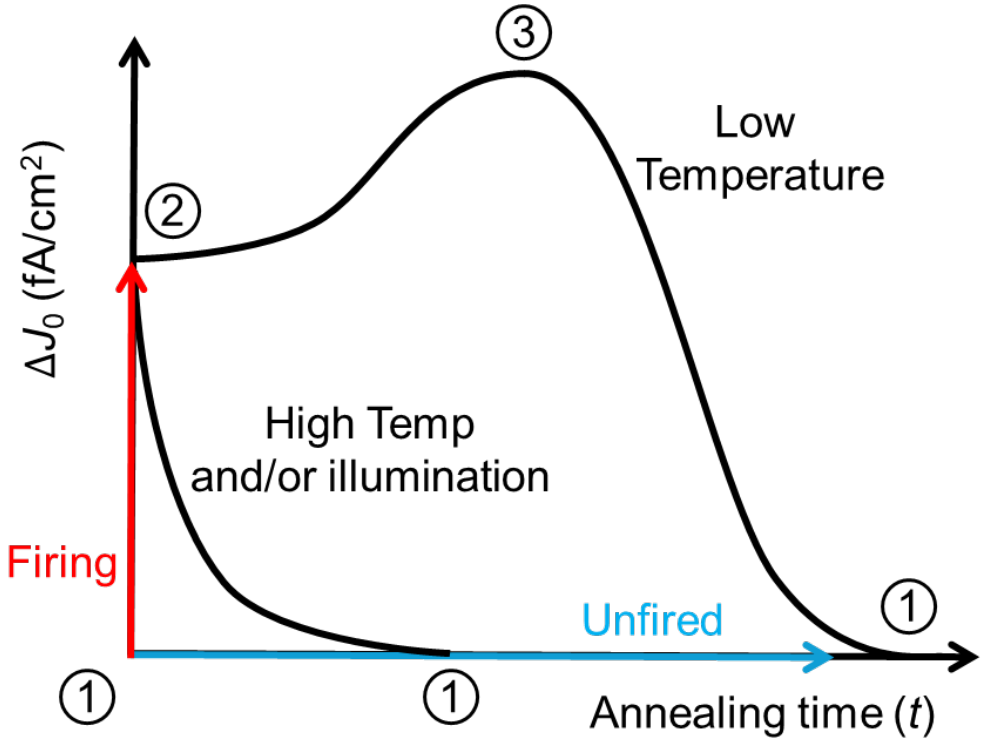
Cyclability of degradation and recovery processes

Symmetric n^+ *poly*-Si structures



Repeated firing and annealing





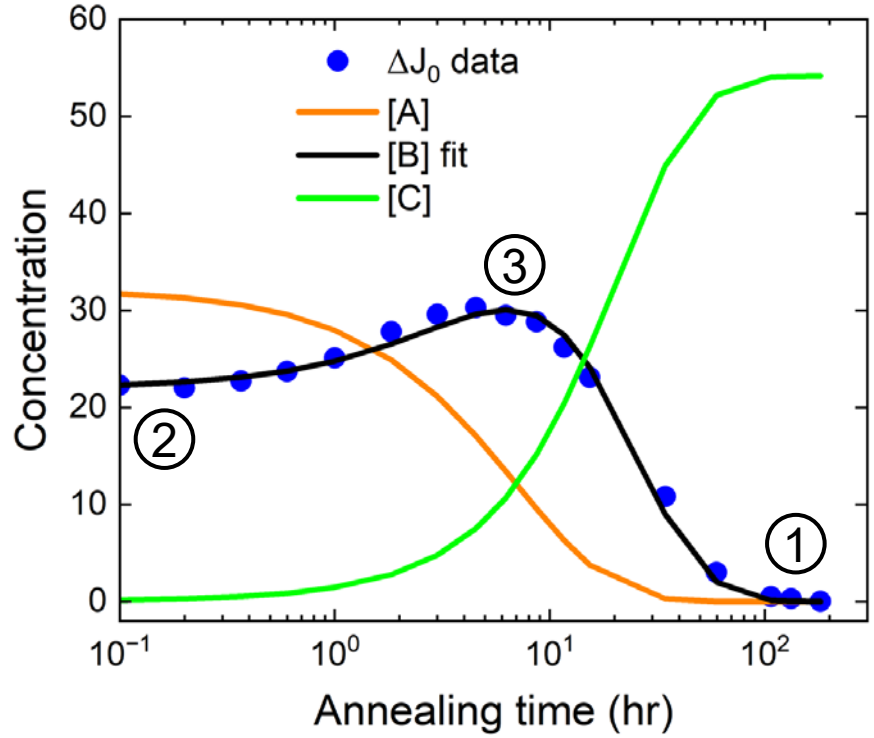
- Identical J_0 evolution for 2 consecutive cycles
- Cyclic nature of degradation and recovery
- Cyclability is not unique to specific
  - Annealing temperature or
  - Light intensity
- Also observed for symmetric i *poly*-Si structures

Define states:

1. Unfired or completely recovered
2. Fired
3. Completely degraded

Kinetic model for degradation and recovery processes

Main observations	
1. Cyclic nature	Recovered = Unfired
2. i) Unfired: stable J_0 ii) Firing: increases J_0 iii) Annealing: further increases J_0	Surface defect and its precursor created after firing
3. Degradation and recovery	Thermally activated
4. Illumination	lowers energy barriers



$$A \xrightarrow{k_{deg}} B \xrightarrow{k_{rec}} C$$

Defect precursor — Defect — Stable state

$$\Delta J_0 \propto [B]$$

	n^+ *poly*-Si		Intrinsic *poly*-Si	
Effective activation energy (eV)	Dark	Illuminated 7.5 Suns	Dark	Illuminated 7.5 Suns
Degradation	1.24	0.76	-	0.75
Recovery	1.51	1.15	1.55	1.11

Recovery mechanism could be same for n^+ and i *poly*-Si contacts

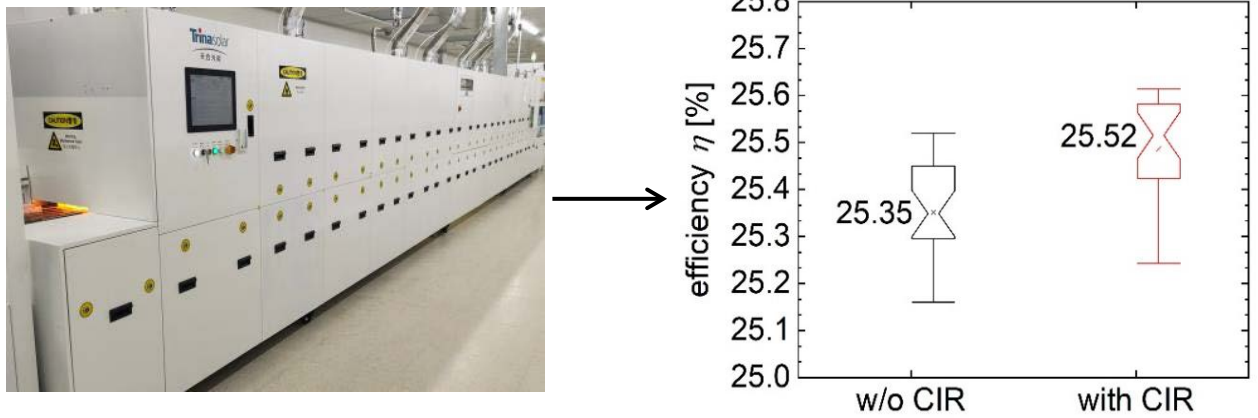
Industrially relevant surface passivation recovery (SPR) process

For a fielded TOPCon module installed in		
City (Average temperature)	Years to degrade	Years to recover
Kansas city (~ 60 °C)	>10	>60

Standard reliability tests cannot detect surface passivation degradation

Trina solar

Carrier induced regeneration (CIR) tool using light and heat



Daming Chen, Silicon workshop, July 2024, Breckenridge.

Jinko/UNSW

Illumination of cells using LED source at temperatures over the range of 400-600 °C.

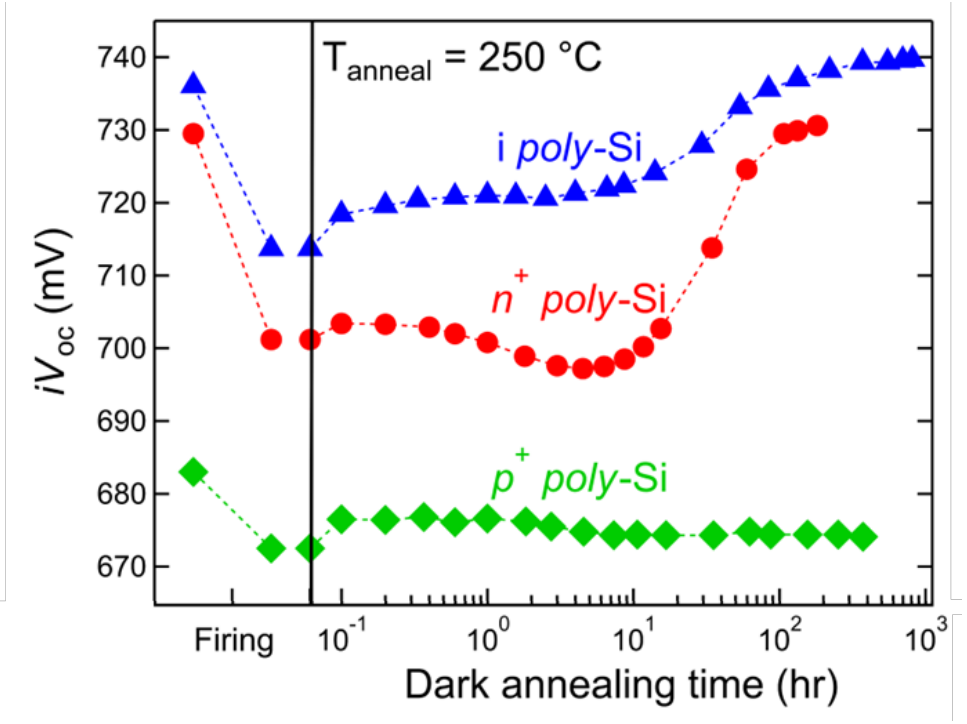
	V_{OC} (mV)	Efficiency (%)
Before	696.3	23.51
After	703.2	24.15
Difference	6.9	0.64

Chen et al., Prog. Photo Volt. 2021;29:1213.

Ask the manufacturer whether they have implemented the surface passivation recovery process. If they haven't, cells will degrade.

Summary

- Long term reliability of n^+, p^+ and i *poly*-Si/SiO_x passivating contacts
- Surface passivation degradation:
  - Role of Dopants
  - Significant loss after firing
  - Degradation and recovery upon annealing
  - Cyclic processes
  - Accelerated by adding illumination
  - Kinetic model
- Industrial Surface Passivation Recovery (SPR) process:
  - Annealing at elevated temperatures and intense illumination



- Ask the manufacturer whether the cells are treated with Surface Passivation Recovery (SPR).

Thank you for your attention! Questions?

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