Degradation Mechanisms in TOPCon/POLO Solar Cells

David Young
NREL

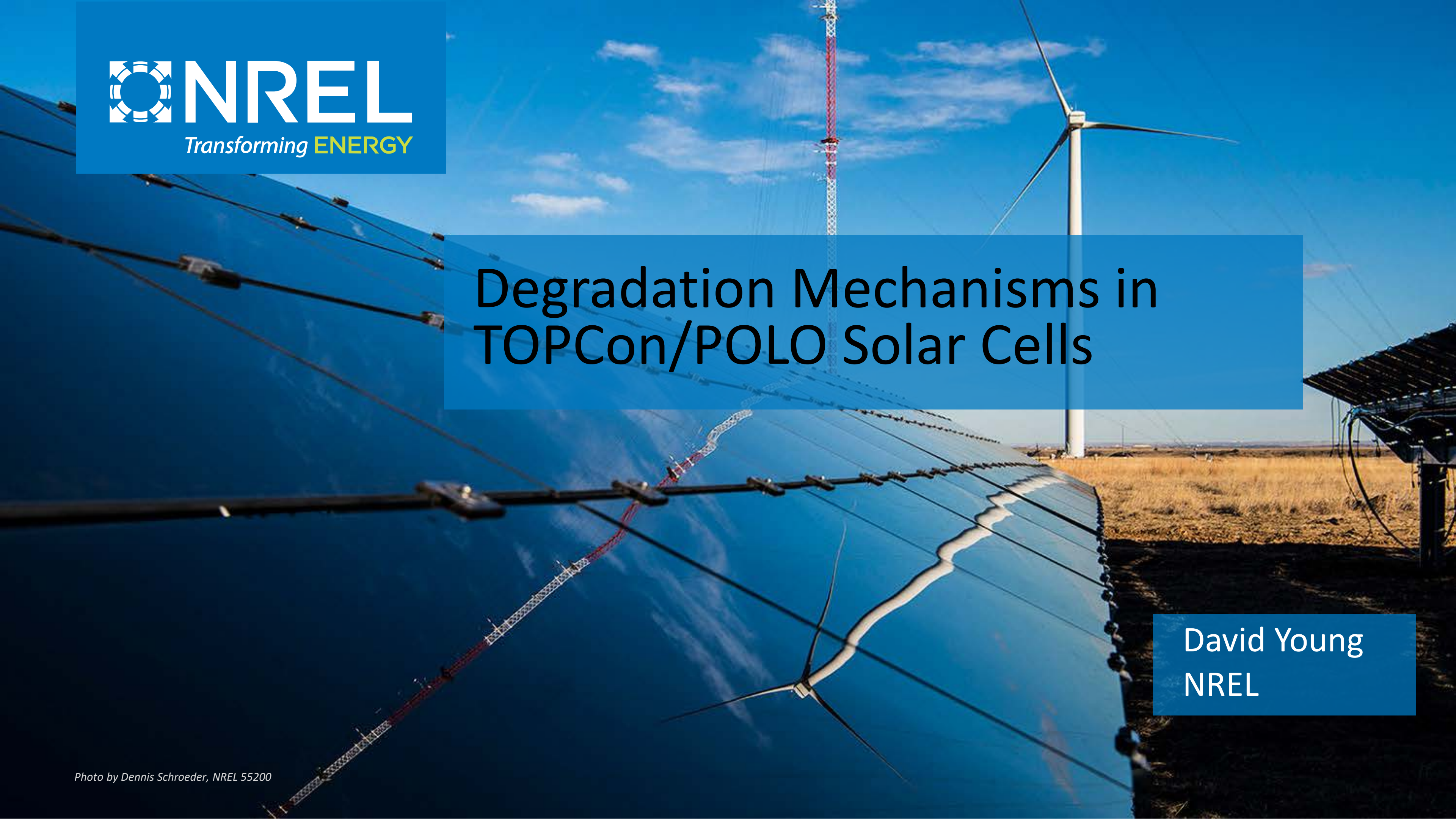


Photo by Dennis Schroeder, NREL 55200

What is a TOPcon cell?

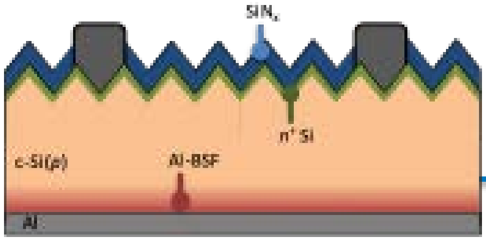
Old Technology → Current Standard → Next Generation (likely US buildout)

Old Technology
- P-diffused emitter
- Al-"Back surface field"

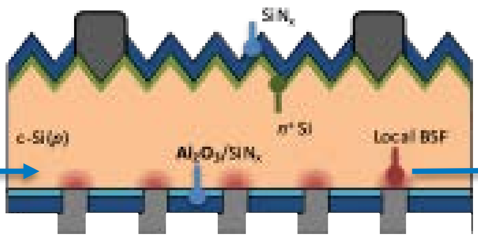
Current Standard
- $SiNx/Al_2O_3$ passivation
- Laser openings
- Point Al-BSF contacts

Next Generation (likely US buildout)
- B-diffused junction
- SiO_2/Poly-Si back contact

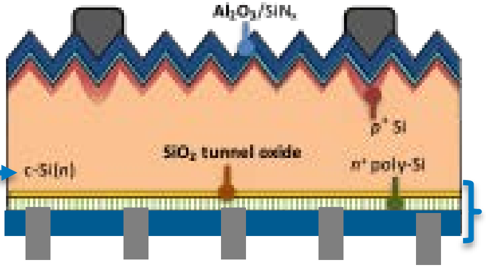
Al-BSF



PERC



TOPCon

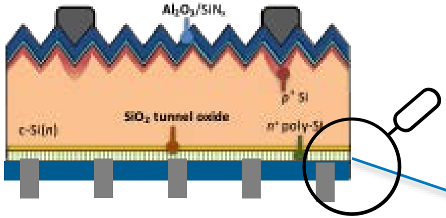


	Al-BSF	PERC	TOPCon
Efficiency:	16-20%	~22-24.5%	~24-26% (28.7% Theo. max η)
Wafer:	P-type wafer	P-type wafer	N-type wafer
Bulk degradation:	LID	LID, LeTID	LeTID

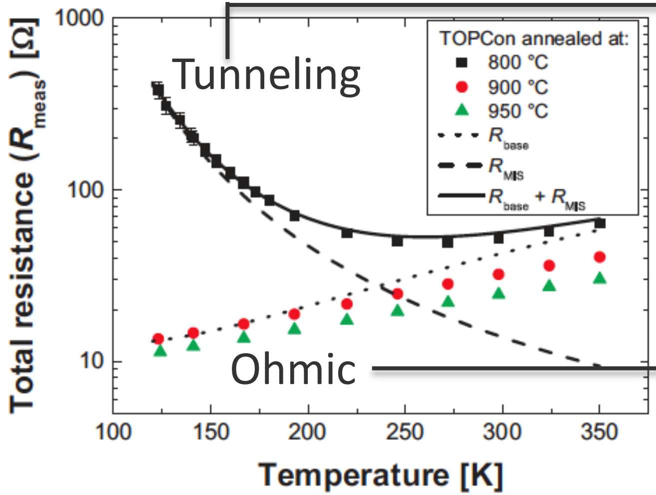
TaiyangNews "TOPCon Solar Technology" 2021

SiO_2/Poly-Si Contacts

TOPCon cell



Different transport mechanisms



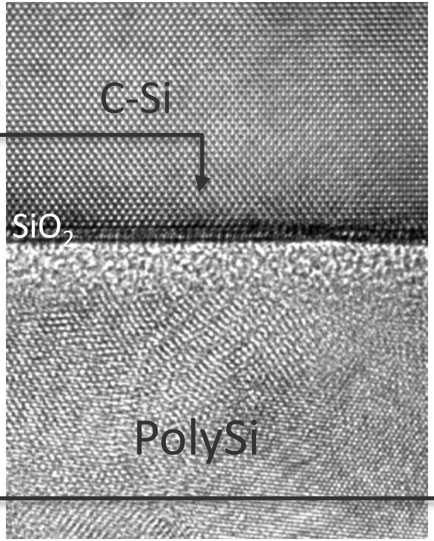
Feldmann et al., Sol. Mat. 178 p 15-19 (2018)

"TOPCon contact"

Tunnel Oxide Passivated Contact

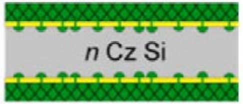
800 ˚C – 850 ˚C

Uniform tunneling oxide ~1.5 nm



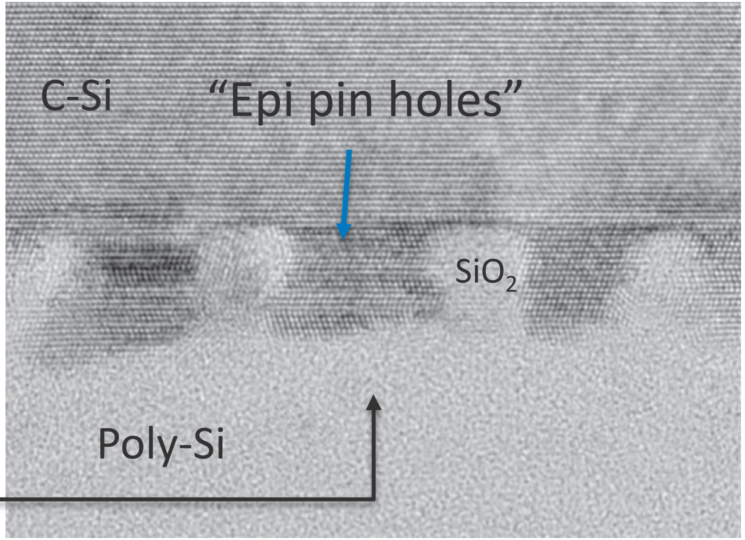
"POLO contact"

POLycrystalline silicon on Oxide



900 ˚C – 1050 ˚C

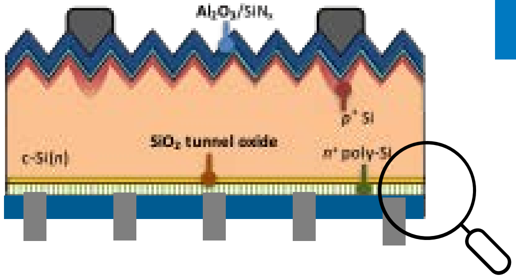
2.4 nm oxide -> Pin holes



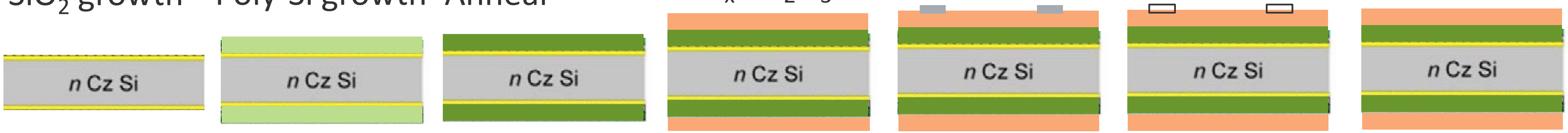
"PolySilicon Emitters for silicon concentrator solar cells"
Jon-Yiew Gan, Stanford University 1990 *thesis. Dr. Swanson advisor*

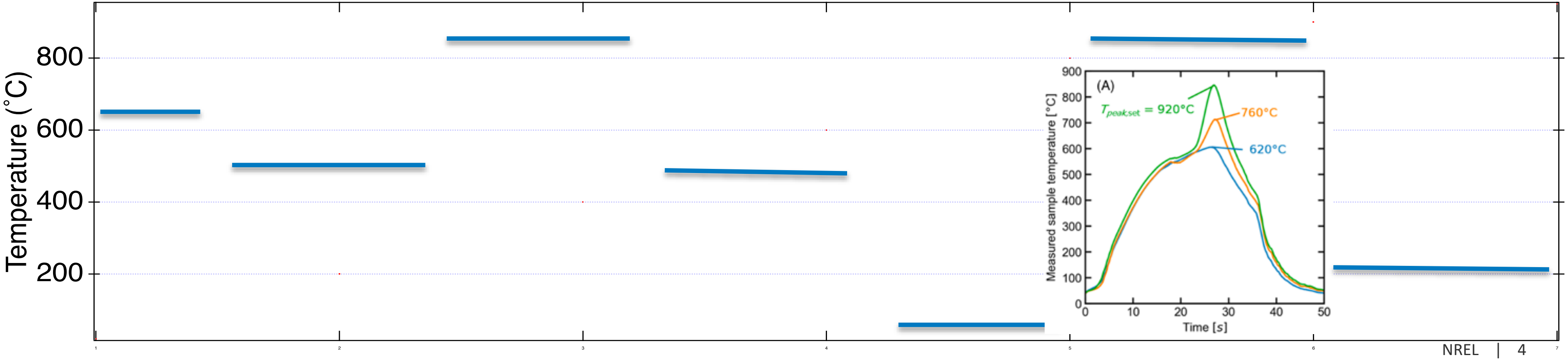
Hollemann et al., Sci Rep **10**, 658 (2020)

Symmetric Poly-Si/SiO_2 contact samples



SiO_2 growth | Poly-Si growth | Crystallization Anneal | Dielectric Growth SiN_x (Al_2O_3) | Screen print contacts (not done) | Contact firing (without metal) | Accelerated Degradation Anneals (100 – 300 ˚C many hours)





$\tau_{effective}$ and J_o

Measured by Photoconductance Decay tool (Sinton lifetime tester)

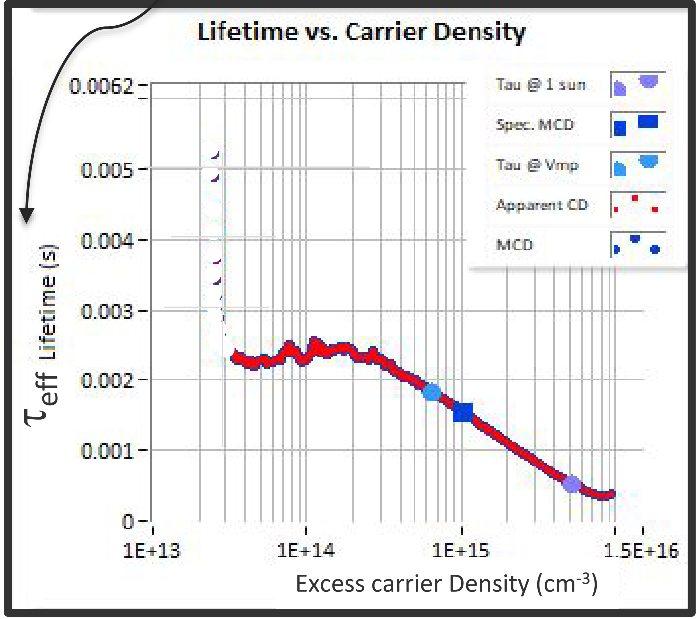
(B-O LID, LeTID)

Surface recombination parameter (fA/cm^2)

(< 10 fA/cm^2)

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{A\text{-}M}} + \frac{1}{\tau_{rad}} + \frac{2J_0(N_{dop} + \Delta n)}{qWn_i^2}$$

(1-10 ms)



Cuevas et al., Solar Energy 76 (2004) 255–262

$\tau_{effective}$ and J_o

Measured by
Photoconductance Decay tool
(Sinton lifetime tester)

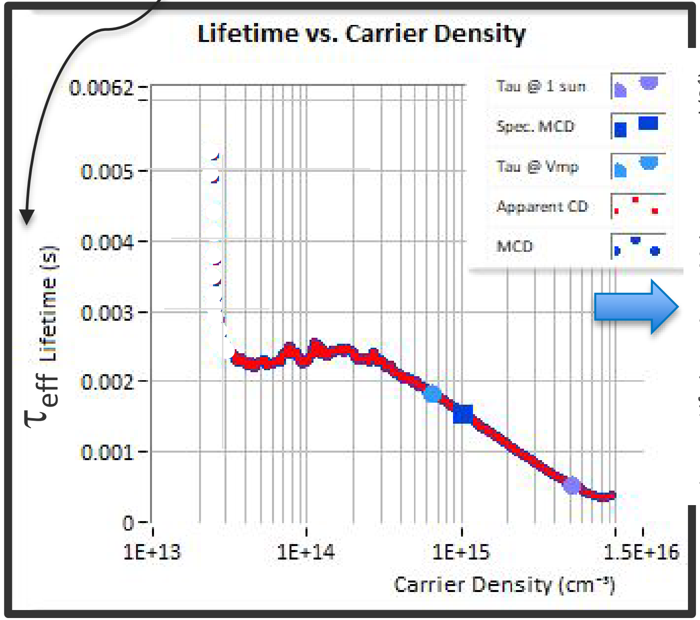
(B-O LID, LeTID)

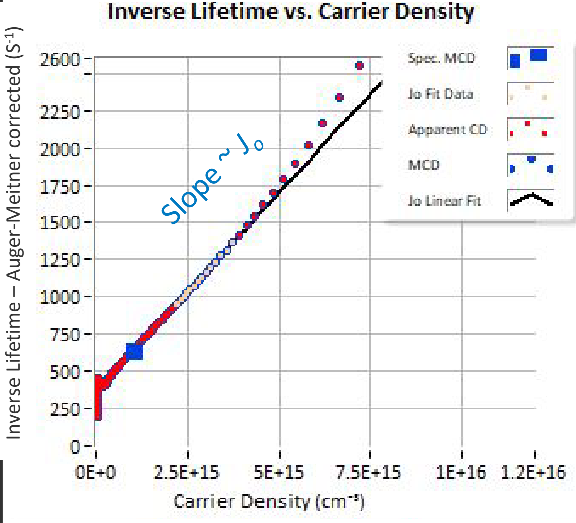
Surface recombination parameter (fA/cm^2)

($< 10\ fA/cm^2$)

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{A\text{-}M}} + \frac{1}{\tau_{rad}} + \frac{2J_0(N_{dop}+\Delta n)}{qWn_i^2}$$

(1-10 ms)





Cuevas et al., Solar Energy 76 (2004) 255–262

$\tau_{effective}$ and J_o

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Photoconductance Decay tool
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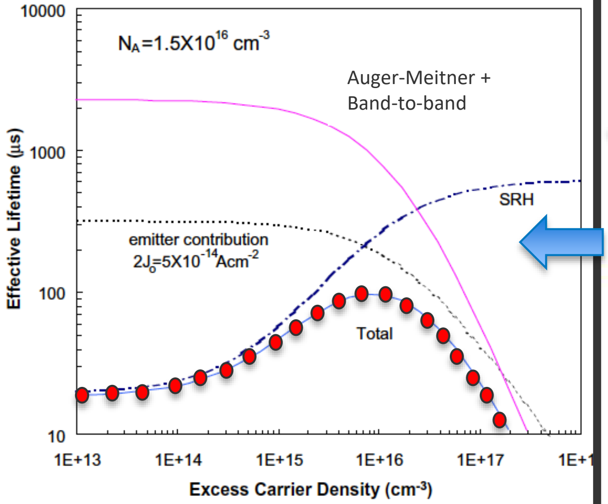
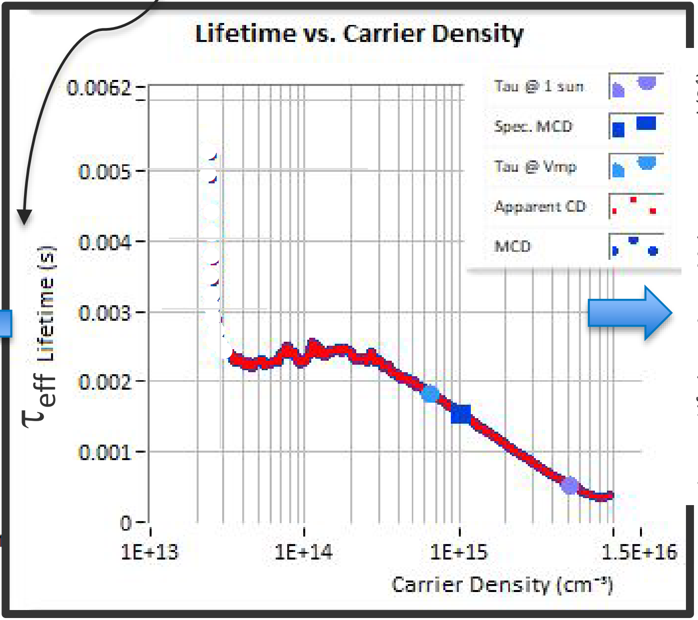
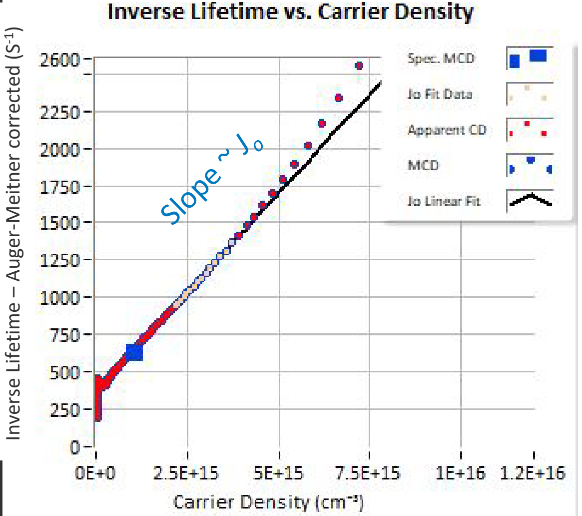


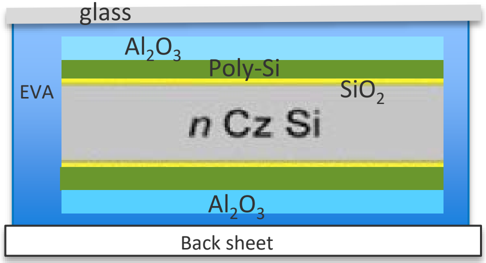




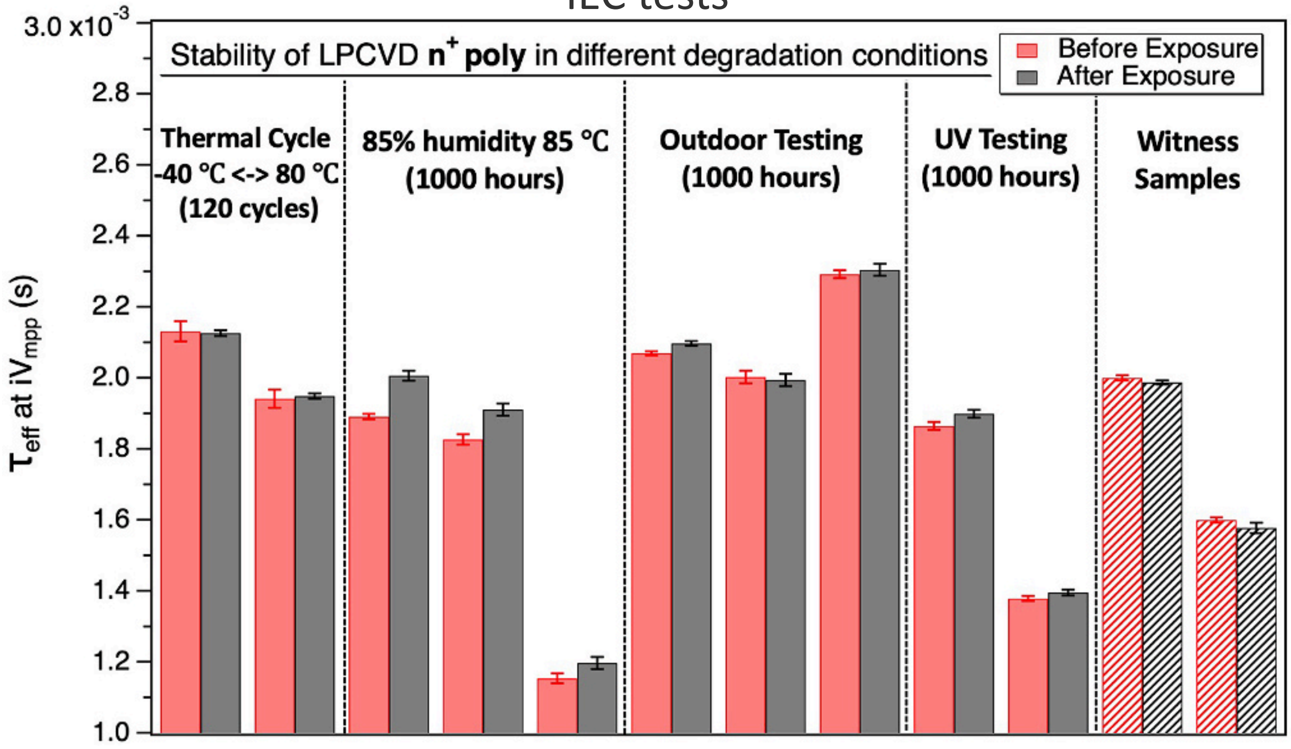
Cuevas et al., Solar Energy 76 (2004) 255–262

Non-Fired Encapsulated PolySi/SiO_2 Contacts

- Symmetric n-type TOPCon contact structures
- Glass/back sheet mini module

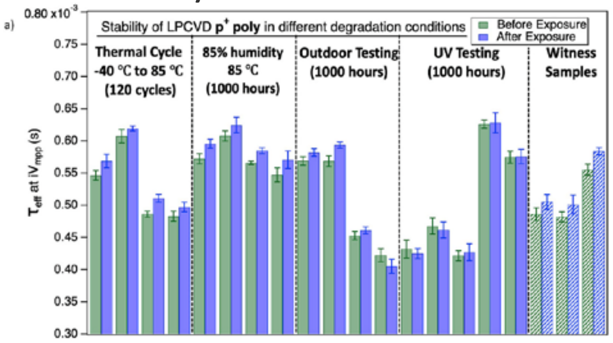


IEC tests



- No degradation under IEC test conditions
- No adhesion issues observed

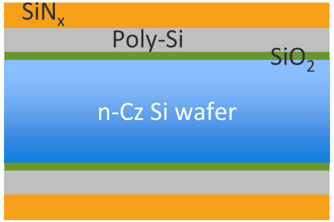
Same story for p-type Poly-Si:B contacts



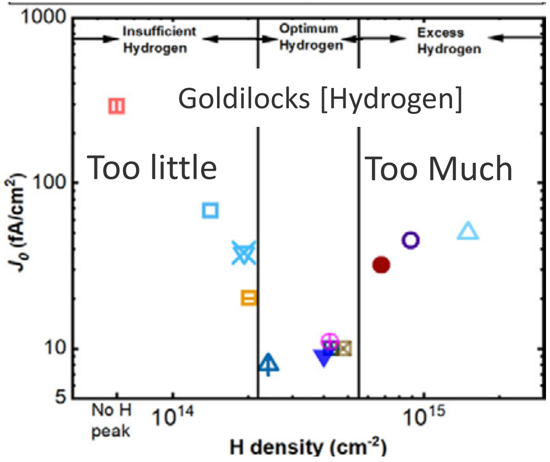
San Theingi et al. Solar Energy Materials & Solar Cells 236 (2022) 111469

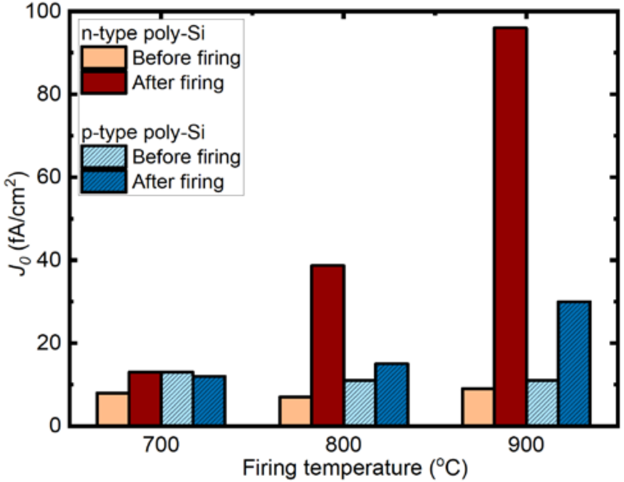
Fired Symmetric PolySi/SiO_2 Contacts

T_{fire} = 800 ˚C

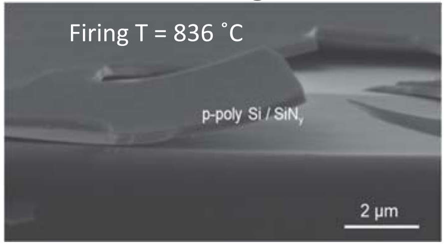


- Firing lowers surface passivation (increases J_o)
- Optimum [H] -> Optimum J_o
- H effuses to tunneling SiO_2 layer
- Thermal stress creates defects in Poly-Si layer
- Blisters if T_{fire} is too high

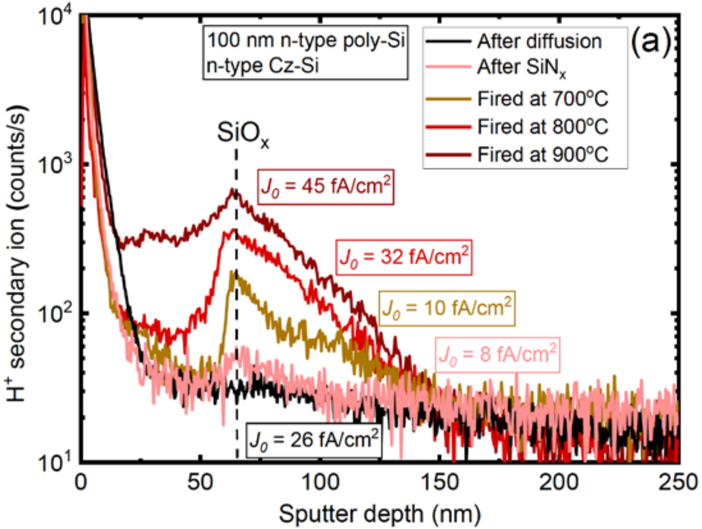




"blistering"



Soeriyadi et al. SiliconPV 2021
AIP Conf. Proc. 2487, 050006-1



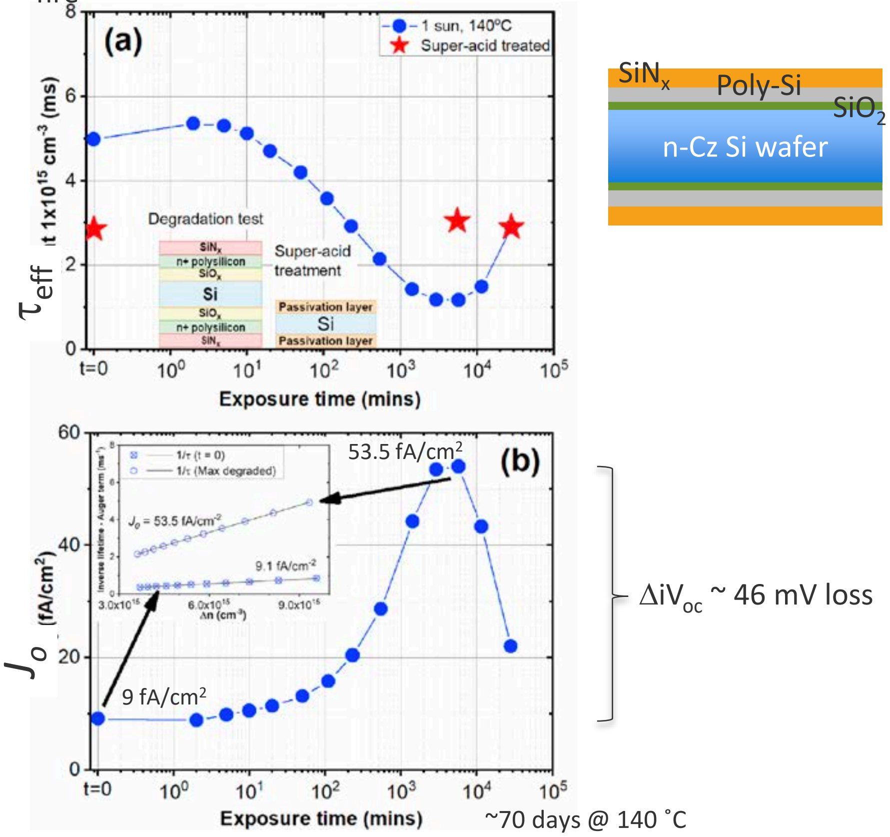
Kang et al., 2021 48th IEEE PVSC

Kang et al., ACS Appl. Mater. Interfaces 2021, 13, 46, 55164−55171

Hollemann et al., PiP 2022, 30:49-64

Poly-Si/SiO_2 Degradation/Regeneration Cycle Observed "Is it LeTID?"

T_{fire} = 700 ˚C + 140 ˚C, 1-sun anneal



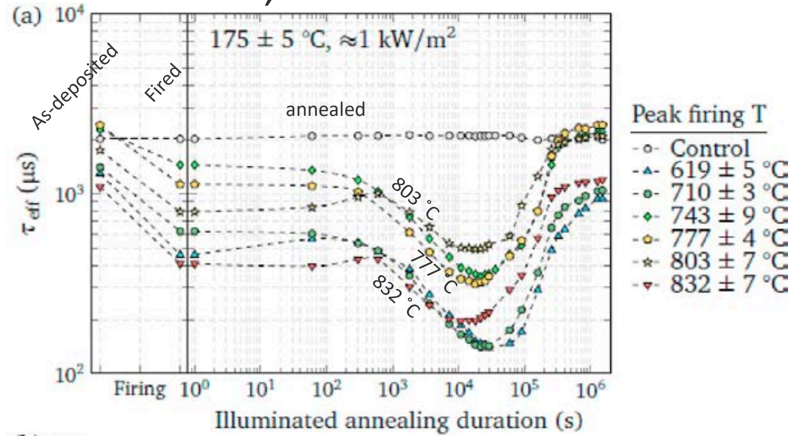
- Degradation followed by regeneration cycle
- τ_{eff} decreases due to J_o increase
  - *J_o is constant with LeTID*
- τ_{bulk} remains constant (super-acid passivation)
  - *Bulk changes with LeTID*

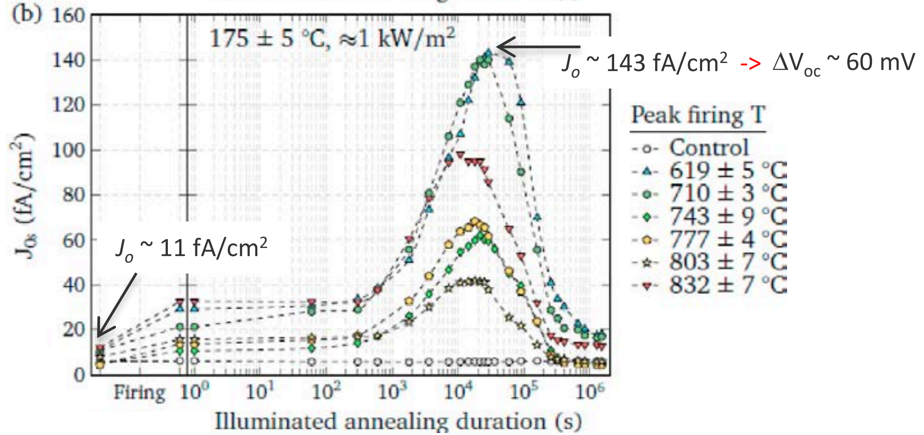
- Poly-Si did not change structurally (XRD)
- LPCVD and PECVD poly-Si show similar cycle (independent of poly-Si grain size)
- Different SiN_x layers (density) show slightly different cycles.
  - *LeTID cycles vary considerably with SiN_x parameters*

Kang et al., Sol. Ener. Mats & Solar Cells, 215 (2020) 110691

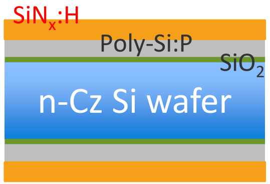
Poly-Si/SiO_2 Degradation/Regeneration Cycle as a Function of T_{fire}

1-sun, 175 ˚C





T_{fire} = 619 - 832 ˚C



- Non-fired, control sample:
  - τ_{eff} and J_o are stable
- Fired samples:
  - τ_{eff} and J_o show degrade/regen cycle improving beyond the as-deposited state
  - No correlation of cycle with firing temperature on
    - time to max degrade/regen
    - magnitude of degrade
    - LeTID shows faster time to degrade and larger magnitude of degradation with increasing T_{fire}
  - Hollemann et al. found firing belt speed influences J_o (temperature gradient)

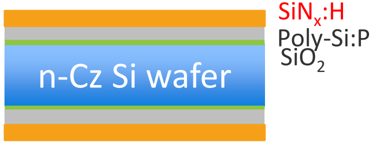
Chen et al., Solar Energy Materials & Solar Cells 236 (2022) 111491

Hollemann et al., PiPV Res App (2021)

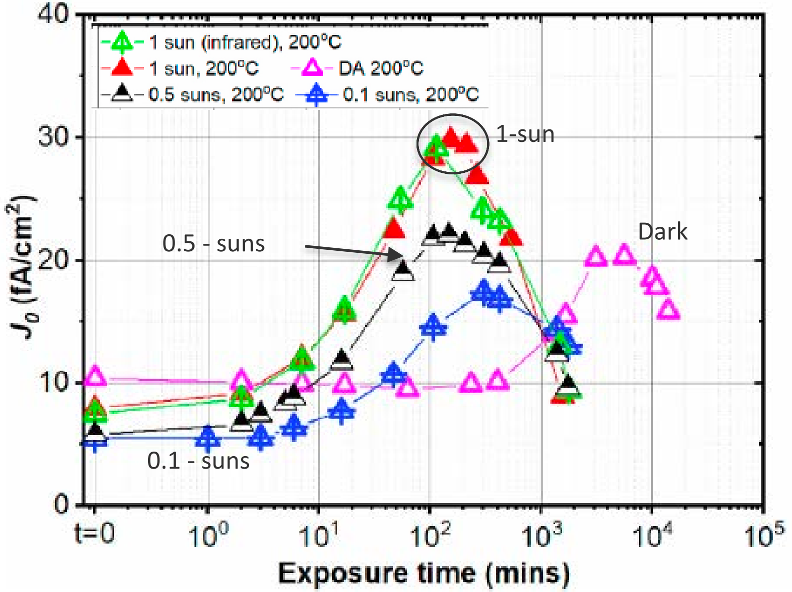
Annealing Illumination and Temperature

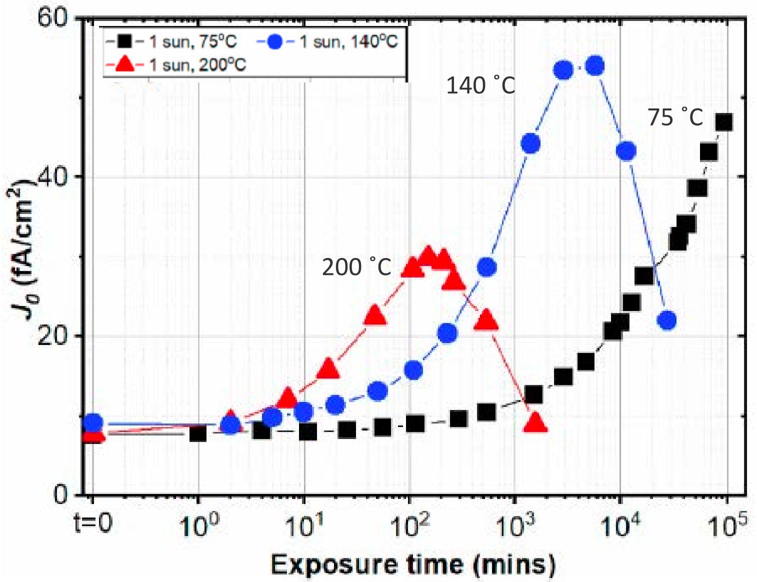
- Degrade/Regen cycle time decreases with increasing illumination.
- Dark anneal shows similar cycle.

T_{fire} = 600 - 770 ˚C



- Degrade/Regen cycle *time* and *magnitude* decrease with increasing annealing temperature.
- Cycle is a thermal process



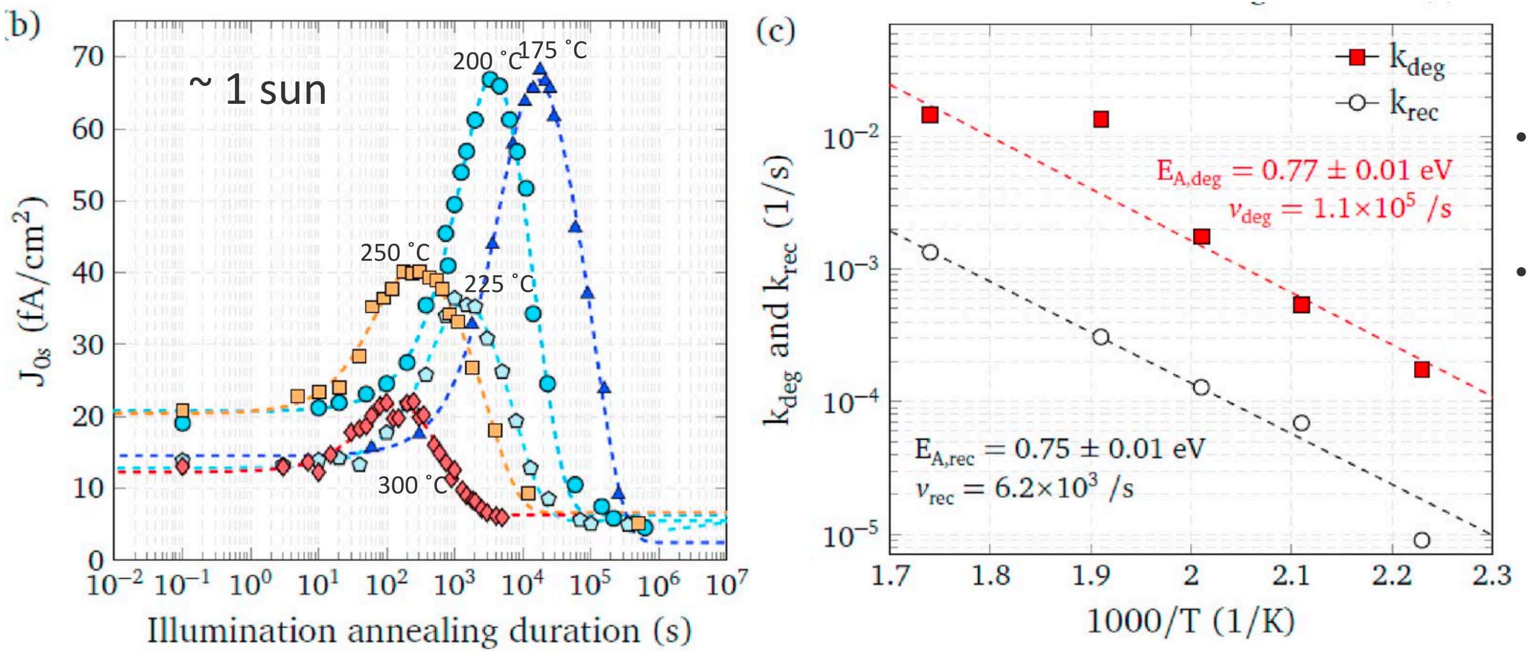


Kang et al., Solar Energy Materials & Solar Cells 215 (2020) 110691

Poly-Si/SiO_2 Degradation/Regeneration Cycle have Similar $E_{activation}$

T_{fire} = 777 ˚C

$$k = \nu e^{\frac{-E_{act}}{RT}}$$



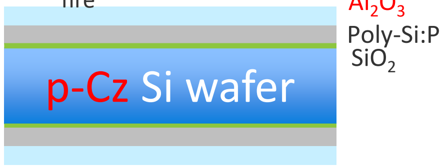
- Similar E_{act} for degrade and regen modes
- ν differ by ~ 100 which may help distinguish nature of processes.

Chen et al., Solar Energy Materials & Solar Cells 236 (2022) 111491

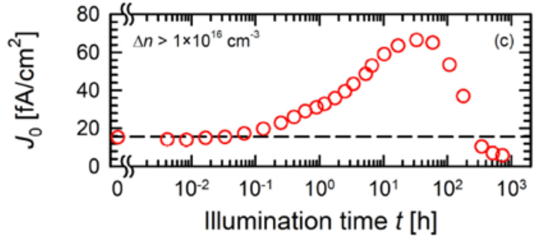
"TOPCon Solar Cell Degradation via Pinhole Nucleation", Molecular Dynamics Simulations, Gergely T. Zimanyi, UC Davis, PVSC 2023

Poly-Si/SiO_2 Degradation/Regeneration Cycle with Fired Al_2O_3

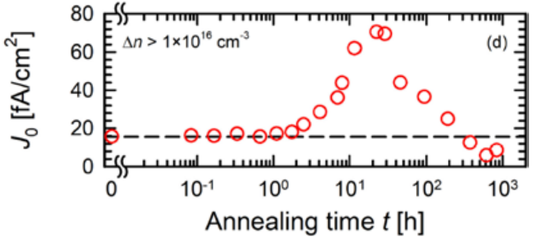
T_{fire} = 800 ˚C



Light anneal: 1-Sun, 185 ˚C

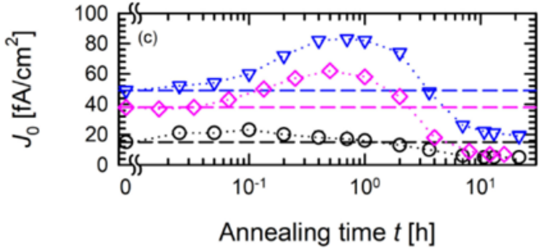


Dark anneal: 200 ˚C

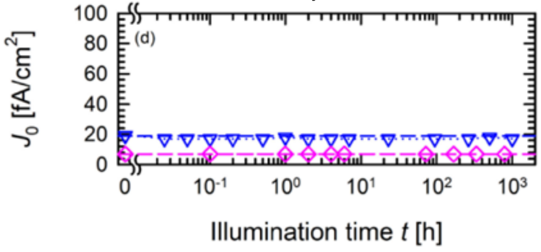


- Fired Al_2O_3 is similar to fired SiN_x
- After degrade/regen cycle J_o improves beyond the as-deposited state
- Dark anneal gives same result at light anneal

Dark anneal: 300 ˚C

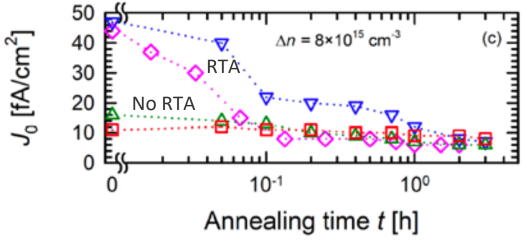


1-Sun, 80 ˚C

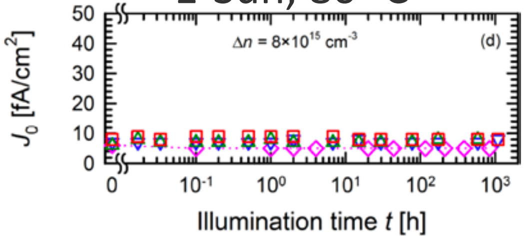


- Dark anneal at 300 ˚C gives similar results but 100 x faster compared with 200 ˚C anneal
- 1-sun, 80 ˚C anneal shows poly-Si/SiO_2 contact is stable to 1000 hrs

Dark anneal: 400 ˚C



1-Sun, 80 ˚C

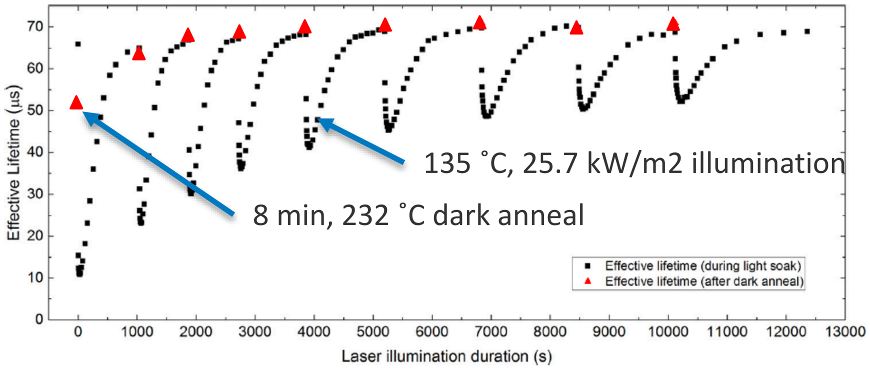


- Dark anneal at 400 ˚C improves J_o 10 x faster than 300 ˚C anneal
- No degradation seen, only regen in J_o
- J_o < 10 fA/cm² after 6 mins for "typical" TOPcon processing steps.
- J_o remains stable to 1000 hrs with 1-Sun, 80 ˚C anneal

Winter et al., IEEE JPV, VOL. 10, NO. 2, 2020

Poly-Si/SiO_2 long-term stability

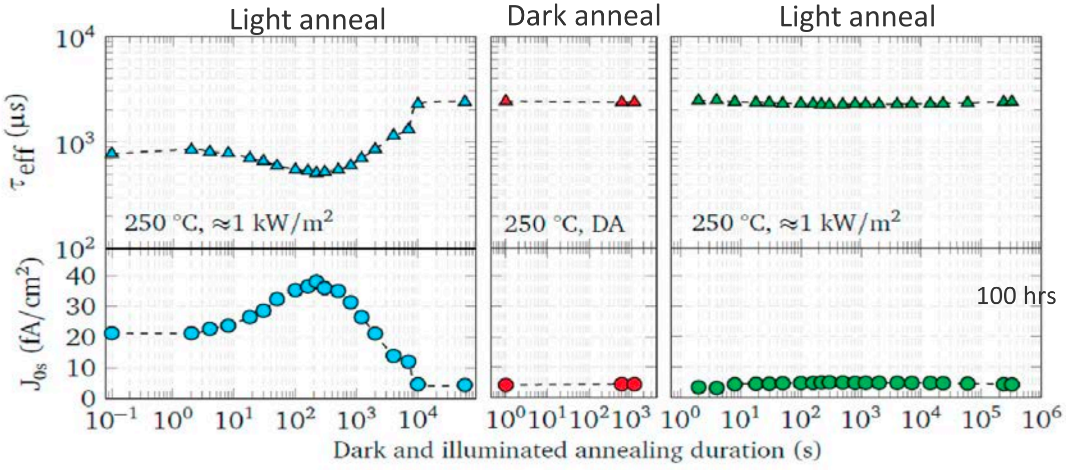
LeTID



- LeTID can be "reset" after a dark anneal.

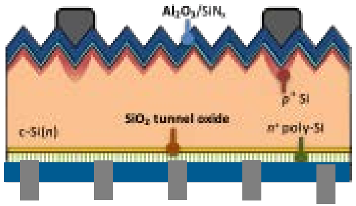
Fung et al., Solar Energy Materials and Solar Cells 184 (2018) 48–56

Poly-Si/SiO_2 contact

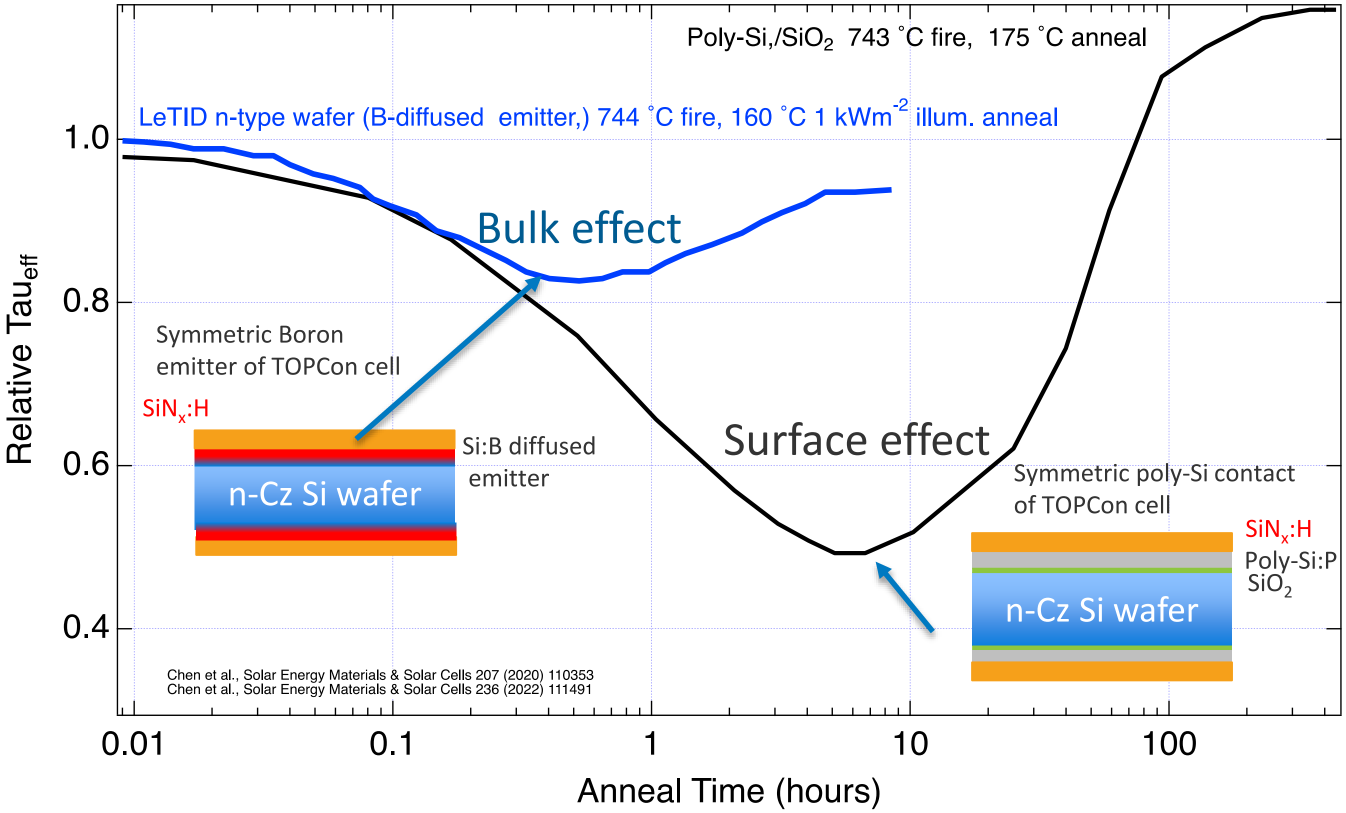


- Poly-Si/SiO_2 passivation remains stable after initial degrade/regen cycle

Chen et al., Solar Energy Materials & Solar Cells 236 (2022) 111491

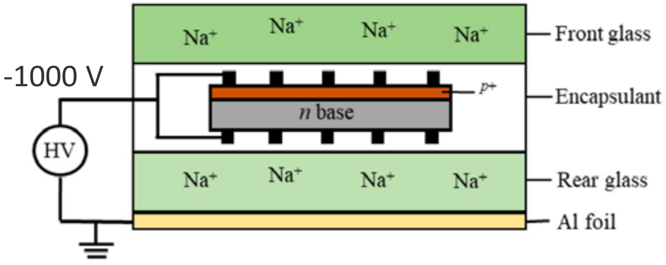


Compare LeTID with Poly-Si/SiO$_2$ degradation

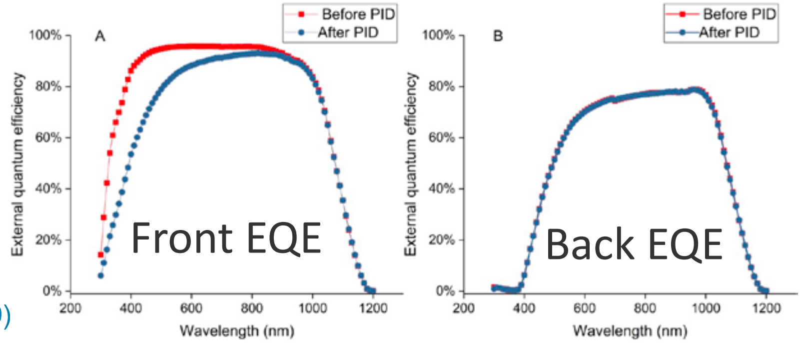


- LeTID in n-type materials is small and fast compared with TOPCon contact surface degradation
- TOPCon contact degrade/regen cycle < 100 hrs at 175 ˚C
- TOPCon improves beyond as-fired state.

TOPCon Module Studies: PID

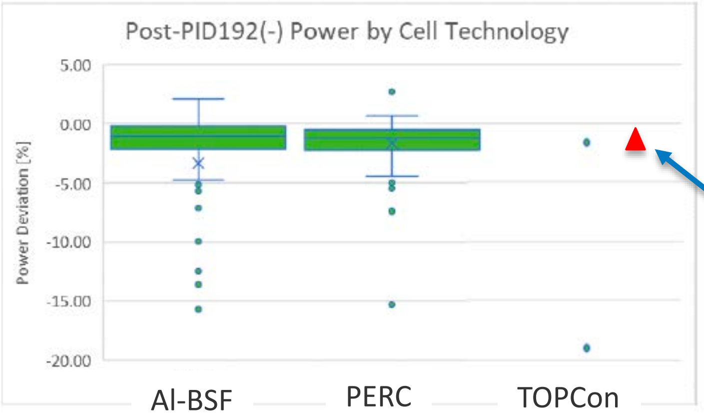


Lou et al., Solar Energy Materials and Solar Cells 195 (2019)



- Polarization PID seen in B-emitter
- Poly-Si contact showed no degradation.

PVEL's initial PID tests on TOPCon modules



PVEL report "Demonstration durability in n-type modules", Tristan Erion-Lorico, PV Mag. Webinar Aug. 30, 2022

Only two TOPCon modules tested

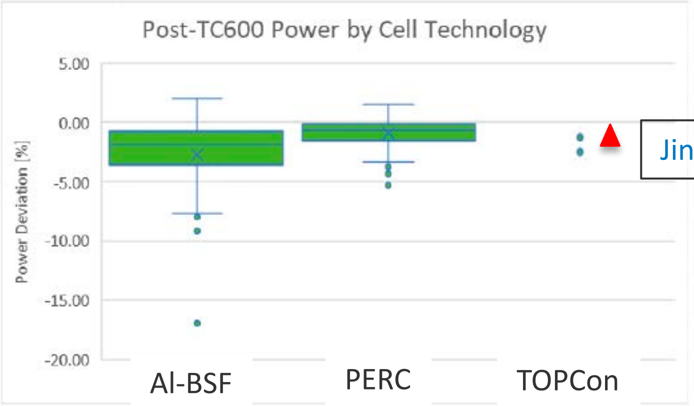
- one passed PID test <2% degradation
- one failed ~18% degradation

Jinko results: 1.03%

"The Role of PV Technologies in Enhancing PV Module Reliability"
Mohammed Saady Dweik, Jinko Solar
PV Mag. Webinar Aug. 30, 2022

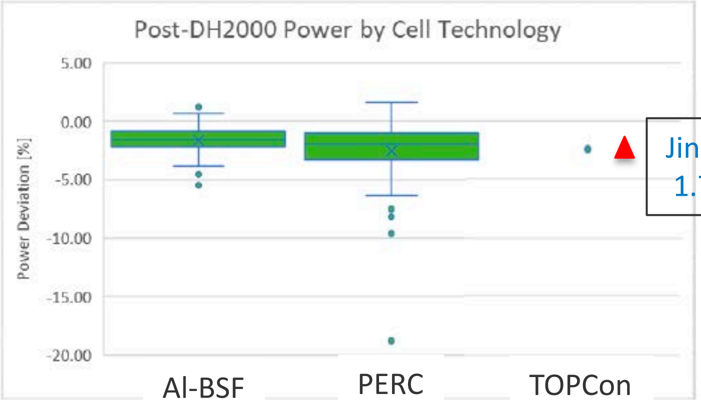
PVEL TOPcon Report, Jinko Tests

Thermal Cycling



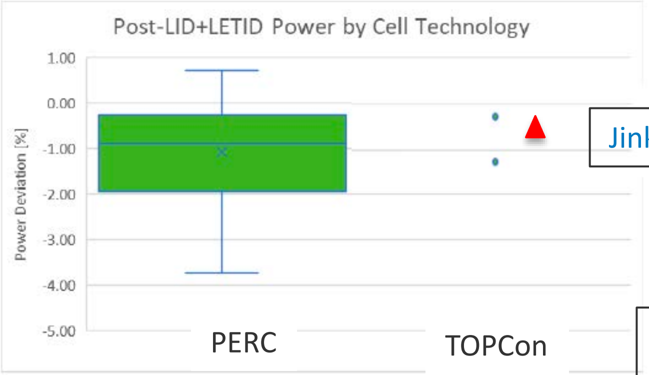
Jinko results: 2.08%

Damp heat



Jinko results: 1.75%

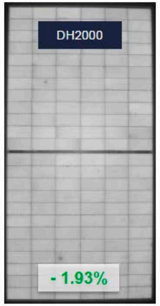
LID + LeTID



Jinko results: 0.56%

PVEL report "Demonstration durability in n-type modules", Tristan Erion-Lorico, PV Mag. Webinar Aug. 30, 2022

"The Role of PV Technologies in Enhancing PV Module Reliability" Mohammed Saady Dweik, Jinko Solar PV Mag. Webinar Aug. 30, 2022



- N-type TOPCon
- Strong damp heat results

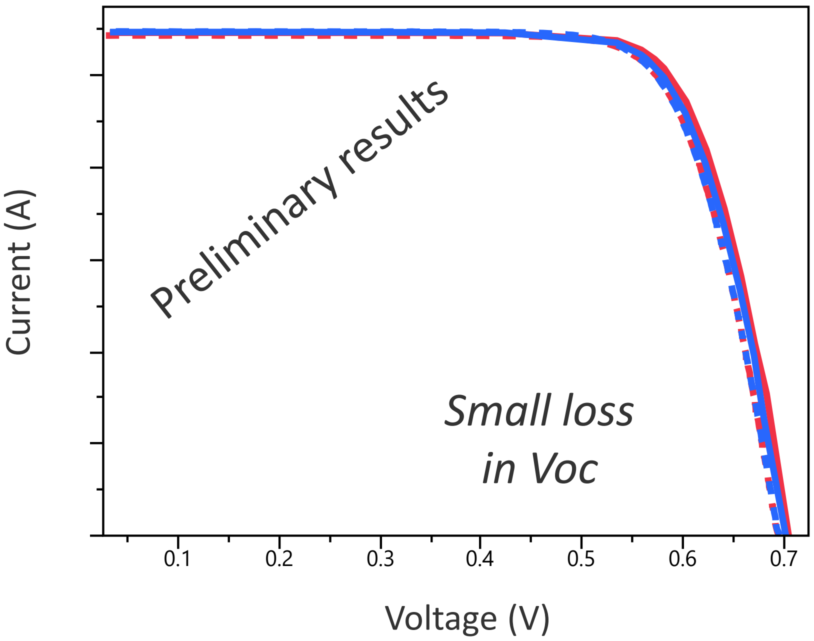
- N-type TOPCon
- Worst damp heat results in PVEL history

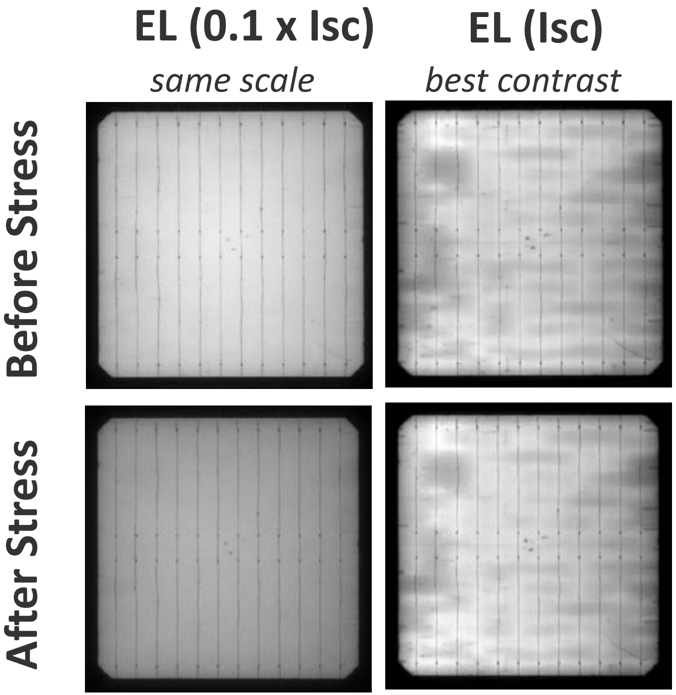
Prototype TOPCon modules Accelerated Screen Testing

Stay tuned

NREL, ASU and a top-tier module manufacturer are studying TOPCon mini-modules

Dry heat + light





Early TOPCon Modules Tests

- Jolywood: LID test +0.5% power gain, LeTID test +1% power gain.

- Jolywood and Jinko TOPCon modules are guaranteed < 1% degradation in the first-year, < 0.4% annual degradation

- PVEL Top Performer Score Card:

ET Solar Inc. has one TOPCon module that was scored a top performer in
LID + LeTID and Thermal Cycling

Conclusions: Degradation Mechanisms in TOPCon/POLO Solar Cells

- Poly-Si/SiO_2 contacts show a post firing degradation/regeneration cycle
- Cycle changes surface passivation (J_o), but not the bulk lifetime
- Cycle time depends on anneal temperature in light or dark. (higher T, faster cycle)
- 400 ˚C anneal eliminates the cycle -> only generation occurs
- Cycle time and magnitude is not correlated with T_{fire}
- Contact passivation is stable after cycling
- Fundamental nature of defect(s) responsible is not known
- TOPCon cells/modules, if constructed well, seem to show minimal degradation issues (PVEL, Jolywood, Jinko, ET Solar)
- NREL/ASU are studying TOPCon cells and UC Davis has a molecular dynamics model for TOPCon – *stay tuned*

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Thank You

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