Degradation Mechanisms in TOPCon/POLO Solar Cells
What is a TOPcon cell?

**Old Technology**
- P-diffused emitter
- Al-”Back surface field”

**Current Standard**
- SiNx/Al₂O₃ passivation
- Laser openings
- Point Al-BSF contacts

**Next Generation** (likely US buildout)
- B-diffused junction
- SiO₂/Poly-Si back contact

- **AI-BSF**
  - Efficiency: 16-20%
  - Wafer: P-type wafer
  - Bulk degradation: LID

- **PERC**
  - Efficiency: ~22-24.5%
  - Wafer: P-type wafer
  - Bulk degradation: LID, LeTID

- **TOPCon**
  - Efficiency: ~24-26%
  - Wafer: N-type wafer
  - Bulk degradation: LeTID

**SiO₂**

TaiyangNews “TOPCon Solar Technology” 2021
SiO$_2$/Poly-Si Contacts

“TOPCon contact”
Tunnel Oxide Passivated Contact

- Uniform tunneling oxide ~1.5 nm
- 800 °C – 850 °C

“POLO contact”
POLycrystalline silicon on Oxide

- 2.4 nm oxide -> Pin holes
- 900 °C – 1050 °C


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

Symmetric Poly-Si/SiO$_2$ contact samples

SiO$_2$ growth  Poly-Si growth  Crystallization  Anneal

Dielectric Growth  SiN$_x$ (Al$_2$O$_3$)  Screen print contacts  (not done)  Contact firing  (without metal)

Accelerated Degradation Anneals  (100 – 300 °C  many hours)

Temperature (°C)

Measured sample temperature (°C)

Contact firing temperature: 920°C  760°C  620°C
\( \tau_{\text{effective}} \) and \( J_0 \) measured by Photoconductance Decay tool (Sinton lifetime tester) (B-O LID, LeTID) Surface recombination parameter (fA/cm^2) 

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

Excess carrier Density (cm\(^{-3}\))


< 10 fA/cm\(^2\)

(1-10 ms)
\( \tau_{\text{effective}} \) and \( J_0 \)

(B-O LID, LeTID)

Surface recombination parameter \( (\text{fA/cm}^2) \)

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

(< 10 fA/cm²)

(1-10 ms)

Measured by Photoconductance Decay tool (Sinton lifetime tester)


Inverse Lifetime vs. Carrier Density

Inverse Lifetime – Auger-Meitner corrected (S⁻¹)

Measured by Photoconductance Decay tool (Sinton lifetime tester)

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

Measured by Photoconductance Decay tool (Sinton lifetime tester)

Non-Fired Encapsulated PolySi/SiO\textsubscript{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
Fired Symmetric PolySi/SiO₂ Contacts

$T_{\text{fire}} = 800 \, ^{\circ}\text{C}$

- Firing lowers surface passivation (increases $J_0$)
- Optimum [H] $\rightarrow$ Optimum $J_0$
- H effuses to tunneling SiO₂ layer
- Thermal stress creates defects in Poly-Si layer
- Blisters if $T_{\text{fire}}$ 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
$T_{\text{fire}} = 700 \, ^\circ C + 140 \, ^\circ C$, 1-sun anneal

- Degradation followed by regeneration cycle
- $\tau_{\text{eff}}$ decreases due to $J_o$ increase
  - $J_o$ is constant with LeTID
- $\tau_{\text{bulk}}$ 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
Poly-Si/SiO₂ Degradation/Regeneration Cycle as a Function of $T_{\text{fire}}$

- Non-fired, control sample:
  - $\tau_{\text{eff}}$ and $J_0$ are stable
- Fired samples:
  - $\tau_{\text{eff}}$ and $J_0$ 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 $T_{\text{fire}}$
- Hollemann et al. found firing belt speed influences $J_0$ (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.

$T_{\text{fire}} = 600 - 770 \, ^\circ\text{C}$

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

Poly-Si/SiO$_2$ Degradation/Regeneration Cycle have Similar $E_{\text{activation}}$

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

$T_{\text{fire}} = 777 \, ^\circ C$

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

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/SiO₂ Degradation/Regeneration Cycle with Fired \( \text{Al}_2\text{O}_3 \)

- Fired \( \text{Al}_2\text{O}_3 \) is similar to fired SiNx.
- After degrade/regen cycle \( J_o \) improves beyond the as-deposited state.
- Dark anneal gives same result at light anneal.

- 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/SiO₂ contact is stable to 1000 hrs.

- 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.
Poly-Si/SiO₂ long-term stability

- LeTID can be “reset” after a dark anneal.
  

- Poly-Si/SiO₂ 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/repair cycle < 100 hrs at 175 °C
- TOPCon improves beyond as-fired state.

LeTID n-type wafer (B-diffused emitter) 744 °C fire, 160 °C 1 kWm$^{-2}$ illum. anneal

Poly-Si/SiO$_2$ 743 °C fire, 175 °C anneal

Bulk effect

Surface effect

Bulk effect

Surface effect

Relative $\tau_{\text{eff}}$

Anneal Time (hours)
TOPCon Module Studies: PID

-1000 V


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

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’s initial PID tests on TOPCon modules

PVEL TOPcon Report, Jinko Tests

**Thermal Cycling**

- Post-TC600 Power by Cell Technology
  - Jinko results: 2.08%

**Damp heat**

- Post-DH2000 Power by Cell Technology
  - Jinko results: 1.75%

**LID + LeTID**

- Post-LID+LETID Power by Cell Technology
  - Jinko results: 0.56%

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“The Role of PV Technologies in Enhancing PV Module Reliability” Mohammed Saady Dweik, Jinko Solar

PV Mag. Webinar Aug. 30, 2022

NREL, ASU and a top-tier module manufacturer are studying TOPCon mini-modules.
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 ($J_0$), 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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