Understanding the boron-oxygen defect: properties, kinetics and deactivation mechanisms
Motivation

- $p$-type silicon dominant for foreseeable future

Fig. 36: World market shares for different wafer types.
Motivation

- $p$-type silicon dominant for foreseeable future
- PERC cells seeing an increasing market share

![Different cell technology](image)

**Fig. 41:** Worldwide market shares for different cell technologies.
Motivation

- $p$-type silicon dominant for foreseeable future
- PERC cells seeing an increasing market share
- Surface passivation quality is improving

Fig. 25: Predicted trend for recombination currents $J_0$bulk, $J_0$front, $J_0$rear for $p$-type and $n$-type cell concepts.
Motivation

• \( p \)-type silicon dominant for foreseeable future
• PERC cells seeing an increasing market share
• Surface passivation quality is improving

→ Strong imperative to:
  (a) Improve bulk quality
  (b) Minimise cell degradation

Fig. 25: Predicted trend for recombination currents J0_bulk, J0_front, J0_rear for \( p \)-type and \( n \)-type cell concepts.
Motivation

• Boron-oxygen defects are the most important source of LID in commercial Cz solar cells

• Cell efficiency loss:
  – PERC: 1-12%\textsubscript{rel}
  – Al-BSF: 1-6%\textsubscript{rel}

  – For a cell manufacturer producing 1,000 MW\textsubscript{p}/year:
    • 60-120 MW\textsubscript{p}/year in lost production
    • USD $12-24 million/year in lost savings

Mitigation of BO defects is of vital importance
The boron-oxygen defect causes Light Induced Degradation. But it can be... Temporarily Deactivated. Permanently Deactivated.

- **Light Soaking (1 sun, 25 °C)**
- **Illuminated Annealing “Regeneration” (~1 sun, >85 °C)**
- **Light Soaking (1 sun, 25 °C)**

**Open Circuit Voltage** vs **Time**
The boron-oxygen defect

- Behaviour described by 3-state model

- Focus of this work:
  1. Recombination properties
  2. Reaction kinetics
  3. Deactivation mechanisms
Recombination properties of the boron-oxygen defect
Recombination properties of BO

\[ \frac{1}{\tau_{\text{eff,DA}}} = \frac{1}{\tau_{\text{surf}}} + \frac{1}{\tau_{\text{bulk,non-BO}}} \]

\[ \frac{1}{\tau_{\text{eff,LS}}} = \frac{1}{\tau_{\text{surf}}} + \frac{1}{\tau_{\text{bulk,non-BO}}} + \frac{1}{\tau_{\text{SRH,BO}}} \]

\[ \frac{1}{\tau_{\text{SRH}}} = \frac{(np - n_i^2)}{\Delta n \cdot \left[ \tau_{p0}(n + n_1) + \tau_{n0}(p + p_1) \right]} \]

\[ p_1 = n_{i,\text{eff}} \times e^{\left( \frac{E_i - E_{\text{trap}}}{k_B T} \right)} \]

\[ \tau_{n0} = \frac{1}{N_{\text{trap}} \sigma_n \nu_{th,e}} \]

\[ \tau_{p0} = \frac{1}{N_{\text{trap}} \sigma_p \nu_{th,h}} \]

\[ k = \frac{\sigma_n}{\sigma_p} \]

Si wafer → DA → Si wafer

Dark anneal

Light-soaking

LS → BO → LS
Recombination properties of BO

Is the value of $E_{\text{trap}, BO}$ correct?

What is the real value of $k_{BO}$?
Statistical uncertainty?
Is $k_{BO}$ temperature-dependent?

$k_{BO} = 14$

Recombination properties of BO

\[ N_{\text{trap}} = \frac{1}{\tau_{n0} \cdot \sigma_n \cdot \nu_{th,e}} \]

At low injection (\( \Delta n = 0.1 \times N_A \)):

\[ N_{\text{trap}} \propto \frac{1}{\tau_{\text{SRH,BO}}} \]

\( \propto \left( \frac{1}{\tau_{Ls}} - \frac{1}{\tau_{DA}} \right) = NDD \)

(Normalised Defect Density)
Recombination properties of BO

**$N_{\text{trap}}$**
- Affected by processing conditions

**$E_{\text{trap}}$**
- Low temperatures (< 300 °C)
  - Light soaking, dark annealing, etc
- High temperatures (> 400 °C)
- Offers opportunity for reducing BO during cell fabrication

What is the impact of firing on $NDD$?

Could $k$ also be affected by firing?

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Recombination properties of BO

- SRH properties of the BO defect ($k$, $E_{trap}$)
- Impact of firing on $k$
- Impact of firing on defect density
Recombination properties of BO

• SRH properties of the BO defect ( \( k, E_{trap} \) )

• Impact of firing on \( k \)

• Impact of firing on defect density
SRH Recombination Properties

Methods for determining recombination properties:

- **IDLS**: Injection-Dependent Lifetime Spectroscopy
  - A common characterization method
  - Good sensitivity to $k$ (if $E_{\text{trap}}$ is known)
  - Low sensitivity to $E_{\text{trap}}$ (for mid-gap defects)

- **TDLS**: Temperature-Dependent Lifetime Spectroscopy
  - Good sensitivity to $E_{\text{trap}}$, $k$
  - Analysis at single injection level ($\Delta n$)

- **TIDLS**: Temperature- and Injection-Dependent Lifetime Spectroscopy
  - Best sensitivity to $E_{\text{trap}}$, $k$
  - Analysis over full range of $\Delta n$
SRH Recombination Properties

IDLS analysis

\[
\frac{1}{\tau_{DA}} = \frac{1}{\tau_{\text{surf}}} + \frac{1}{\tau_{\text{bulk, fixed}}} + \frac{1}{\tau_{\text{SRH, non-BO}}}
\]

\[
\frac{1}{\tau_{LS}} = \frac{1}{\tau_{\text{surf}}} + \frac{1}{\tau_{\text{bulk, fixed}}} + \frac{1}{\tau_{\text{SRH, non-BO}}} + \frac{1}{\tau_{\text{SRH, BO}}}
\]

Allow this to vary

Method B (Constrained)

\( k_1 = 12.98 \)

\( \Delta n_{\text{DA}} = \Delta n_{\text{LS}} = 84.7 \, \text{fA/cm}^2 \)

Method D (Free \( J_{\text{0e}} \))

\( J_{\text{0e,DA}} = 84.7 \, \text{fA/cm}^2 \)

\( J_{\text{0e,LS}} = 80.8 \, \text{fA/cm}^2 \)
SRH Recombination Properties

IDLS analysis

\[
\frac{1}{\tau_{DA}} = \frac{1}{\tau_{surf}} + \frac{1}{\tau_{bulk,fixed}} + \frac{1}{\tau_{SRH,non-BO}}
\]

\[
\frac{1}{\tau_{LS}} = \frac{1}{\tau_{surf}} + \frac{1}{\tau_{bulk,fixed}} + \frac{1}{\tau_{SRH,non-BO}} + \frac{1}{\tau_{SRH,BO}}
\]

Not all fitting methods are accurate

Most accurate method (Free \( J_{0e} \))

Good fit

Poor fit

Data from 225 measurements

\( k_{BO} > 9.3 \)

\( k_{BO} = 11.9 \pm 0.45 \)
SRH Recombination Properties

TIDLS analysis

Inverse lifetime at elevated $T$, $\tau_{DA}(T)^{-1}$ (s$^{-1}$)
Excess Carrier Density, $\Delta n$ (cm$^{-3}$)

Increasing $T$

Elevated $T$ (K)
- 298
- 323
- 344
- 364
- 374
- 395
- 420
- 444
- 464

Dark annealed (BO inactive)

Inverse lifetime at elevated $T$, $\tau_{LS}(T)^{-1}$ (s$^{-1}$)
Excess Carrier Density, $\Delta n$ (cm$^{-3}$)

Increasing $T$

Elevated $T$ (K)
- 298
- 326
- 344
- 364
- 373
- 394
- 420
- 445
- 463

Light soaked (BO active)
SRH Recombination Properties

TIDLS analysis

- Determine $E_{\text{trap}}$, $k$

\[
E_C - E_{\text{trap}} = 0.41 \pm 0.10 \\
k_{BO} = 11.5 \pm 1.00
\]
SRH Recombination Properties

TIDLS analysis

- Determine $E_{\text{trap}}, k$

\[ E_c - E_{\text{trap}} = 0.41 \pm 0.10 \]

\[ k_{BO} = 11.5 \pm 1.00 \]

- $T$-dependence of $\tau_{SRH,BO}$

\[ \alpha_{BO} = -2.3 \]

\[ \sigma_{n/p}(T) \propto T^{-2.3} \]
Recombination properties of BO

• SRH properties of the BO defect ($k, E_{trap}$)

• Impact of firing on $k$

• Impact of firing on defect density
Impact of firing – Experiment details

**PECVD SiN<sub>x</sub>:H**

Measure Normalised Defect Density (NDD)
- Dark Anneal: 200 °C, 15 min
- Light Soak: 35 °C, 0.77 suns, 48 hr

**NDD Meas. 1**

![Graph showing temperature (°C) over time (t (s)) for coated and bare samples. The coated sample shows a higher peak temperature compared to the bare sample.](image)
Impact of firing – Experiment details

PECVD SiN$_x$:H

$NDD$ Meas. 1  $NDD$ Meas. 2

Relative change due to firing

<table>
<thead>
<tr>
<th>$N_{\text{fire}}$</th>
<th>Varying $T_{\text{Fired}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 3</td>
<td>1, 2, 3</td>
</tr>
</tbody>
</table>

Not Fired

Varying $T_{\text{Fired}}$

Temperature, $\theta$ ($^\circ$C)

Time, $t$ (s)

$T_{\text{peak}}$ = 827 $^\circ$C
$T_{\text{peak}}$ = 790 $^\circ$C
$T_{\text{peak}}$ = 735 $^\circ$C
$T_{\text{peak}}$ = 686 $^\circ$C
$T_{\text{peak}}$ = 632 $^\circ$C
$T_{\text{peak}}$ = 580 $^\circ$C
$T_{\text{peak}}$ = 518 $^\circ$C
$T_{\text{peak}}$ = 463 $^\circ$C
Impact of firing on $k_{BO}$

Firing has no impact on $k_{BO}$

Evidence of a new CID defect in Cz silicon (firing activated)
Impact of firing on $NDD_{BO}$

- Firing reduces $NDD_{BO}$
- Firing multiple times has no impact (Cooling rate is critical)
Summary – Properties of the BO defect

- SRH properties of BO:
  - Determined $k_{BO} = 11.9 (>9.3)$
  - Confirmed that $E_{trap} = E_C - 0.41$ eV
  - Determined that $\sigma_n/p(T) \propto T^{-2.3}$

- Impact of firing on BO properties:
  - Confirmed that $k_{BO}$ is not affected by firing
  - Demonstrated that firing reduces $NDD_{BO}$
  - Firing can induce other (non-BO) CID defects in Cz silicon
Transition kinetics of the BO system
Transition kinetics of the BO system

Dependence of transition rates on $T$ and illumination ($\Delta n$) are of vital importance!
Transition kinetics of the BO system

- Degradation:
  - $\kappa_{AB}$ appears to be independent of illumination intensity (>0.1 suns)
  - Other studies show $\kappa_{\text{deg}} \propto (p_0)^2$

Which is true?

$\kappa_{AB} \propto (p_0)^2$

$\kappa_{AB} \propto p \cdot p_0$

$\kappa_{AB} \propto (p)^2$
Transition kinetics of the BO system

• Annealing:
  – Known to occur in dark (no carrier dependence assumed)
  – But... one study showed $\kappa_{BA} \propto \frac{1}{p_0}$ for compensated Si

Does $\kappa_{BA}$ have a carrier dependence?

Issue with reaction rate studies

- Process $T \neq$ Measurement $T$

**Required parameters**

$$p(T) = p_0(T) + \Delta p(T)$$

$$G(T) = \frac{\Delta n(T)}{\tau_{eff}(T, \Delta n)}$$

**Measured parameters**

$$p(300K) = p_0(300K) + \Delta p(300K)$$

$$G(300K) = \frac{\Delta n(300K)}{\tau_{eff}(300K, \Delta n)}$$

Need a method to determine $\Delta n(T)$ from $\tau_{eff}(300K)$ and $G(300K)$
Reaction kinetics of the BO system

• Model to obtain $\tau_{\text{eff}}(T)$ from $\tau_{\text{eff}}(300 \, K)$

• Temporary deactivation (annealing) kinetics

• Degradation kinetics
Temperature dependence of lifetime

\[ G(T) = \frac{\Delta n(T)}{\tau_{eff}(T, \Delta n)} \]

Generation rate correction factor, \( f_{corr}(T) \)

Measurement temperature, \( T \) (K)
Temperature dependence of lifetime

\[ G(T) = \frac{\Delta n(T)}{\tau_{eff}(T, \Delta n)} \]

\[ \frac{1}{\tau_{DA}(T, \Delta n)} = \frac{1}{\tau_{surf}(T, \Delta n)} + \frac{1}{\tau_{bulk, fixed}(T)} + \frac{1}{\tau_{SRH, non-BO}(T)} + \frac{1}{\tau_{SRH, BO}(T, \Delta n)} \]

\[ J_{0e}(T) \]

\[ \tau_{bulk}(T) \]

Step 1: Fit \( \tau_{DA}(T, \Delta n) \) and \( \tau_{LS}(T, \Delta n) \) at each temperature
Temperature dependence of lifetime

\[ G(T) = \frac{\Delta n(T)}{\tau_{\text{eff}}(T, \Delta n)} \]

\[
\frac{1}{\tau_{DA}(T, \Delta n)} = \frac{1}{\tau_{\text{surf}}(T, \Delta n)} + \frac{1}{\tau_{\text{bulk, fixed}}(T)} + \frac{1}{\tau_{\text{SRH, non-BO}}(T)}
\]

\[
\frac{1}{\tau_{LS}(T, \Delta n)} = \frac{1}{\tau_{\text{surf}}(T, \Delta n)} + \frac{1}{\tau_{\text{bulk, fixed}}(T)} + \frac{1}{\tau_{\text{SRH, non-BO}}(T)} + \frac{1}{\tau_{\text{SRH, BO}}(T, \Delta n)}
\]

Step 2: Apply this relation for each fitted parameter:

\[ \text{Param}(T) = \text{Param}(300K) \times \left( \frac{T}{300} \right)^{\alpha_{\text{param}}} \]
Temperature dependence of lifetime

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Relevant lifetime component</th>
<th>Exponent of temperature dependence</th>
<th>Value for $a_{\text{param}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{\text{bulk, fixed}}^*$</td>
<td>$\tau_{\text{bulk, fixed}}(T)$</td>
<td>$\alpha_b$</td>
<td>$2.880 \pm 0.032$</td>
</tr>
<tr>
<td>$S_{\text{eff}}$</td>
<td>$\tau_{\text{surf}}(T)$</td>
<td>$\alpha_{\text{Seff}}$</td>
<td>$-1.395 \pm 0.030$</td>
</tr>
<tr>
<td>$J_0$</td>
<td>$\tau_{\text{surf}}(T)$</td>
<td>$\alpha_{j0}$</td>
<td>$41.449 \pm 0.044$</td>
</tr>
<tr>
<td>$\tau_{n0,BO}$</td>
<td>$\tau_{\text{SRH, BO}}(T)$</td>
<td>$\alpha_{n0,BO}$</td>
<td>$1.870 \pm 0.003$</td>
</tr>
<tr>
<td>$\tau_{n0,\text{non-BO}}^*$</td>
<td>$\tau_{\text{SRH, non-BO}}(T)$</td>
<td>$\alpha_{n0,\text{non-BO}}$</td>
<td>$-1.420 \pm 0.006$</td>
</tr>
</tbody>
</table>

* may be specific to wafers used in this study
Reaction kinetics of the BO system

• Model to obtain $\tau_{\text{eff}}(T)$ from $\tau_{\text{eff}}(300 \, K)$

• Temporary deactivation (annealing) kinetics

• Degradation kinetics
Annealing kinetics

Defect dissociation:
- $T = 478 \text{ K} (205 \, ^\circ\text{C})$
- $T = 448 \text{ K} (175 \, ^\circ\text{C})$
- $T = 438 \text{ K} (165 \, ^\circ\text{C})$
- $T = 433 \text{ K} (160 \, ^\circ\text{C})$
- $T = 428 \text{ K} (155 \, ^\circ\text{C})$

Inverse lifetime, $\tau(t,T=300 \text{ K})$ (ms$^{-1}$)

Anneal time, $t$ (s)

Defect dissociation ($B \rightarrow A$)

Rate extracted

$K_{BA} \propto \frac{1}{p(T)}$
Annealing kinetics

\[ \kappa_{BA} = \nu_{BA}' \cdot e^{\frac{-E_{a,BA}}{k_BT}} \]

\[ \kappa_{BA} \] - not normalised

\[ \kappa_{BA} \] - normalised to \((p/N_v)^{-1}\)

**Graphs:**
- **Left Graph:**
  - Dark anneal temperature (°C)
  - \(E_{a,BA} = 1.26 \pm 0.14 \text{ eV}\)
  - \(\nu_{BA}' = 10^{12.6 \pm 1.6} \text{ s}^{-1}\)

- **Right Graph:**
  - Dark anneal temperature (°C)
  - \(E_{a,BA} = 1.32 \pm 0.04 \text{ eV}\)
  - \(\nu_{0,BA} = 10^{9.54 \pm 0.48} \approx 3.16^{+0.40}_{-1.04} \times 10^9 \text{ s}^{-1}\)

**Equations:**
- \(\kappa_{BA} = \nu_{BA}' \cdot e^{\frac{-E_{a,BA}}{k_BT}}\)
- \(\kappa_{BA} = \nu_{0,BA} \cdot \left[ \frac{N_c(T)}{p(T)} \right] \cdot e^{\frac{-E_{a,BA}}{k_BT}}\)

**Data:**
- This work
- Rein et al. (2001)
- Schmidt et al. (2004)
- Schmidt et al. (2002)
- Lim et al. (2011)

**Fit line to data in this work**
Reaction kinetics of the BO system

- Model to obtain $\tau_{\text{eff}}(T)$ from $\tau_{\text{eff}}(300 \, K)$

- Temporary deactivation (annealing) kinetics

- Degradation kinetics
Degradation kinetics

\[ \kappa_{AB} \propto [p(T)]^2 \]

\[ p \text{-type Cz } (N_A = 8.41 \times 10^{15} \text{ cm}^{-3}) \]

\[ T = 75 \text{ °C (348 K)} \]

Fractional Defect Density, \( FDD(t) \)

Process time, \( t \) (s)

\( R_{\text{gen}} = \text{const} \)

Defect Generation Rate, \( R_{\text{gen}} \) (1/min)

Illumination Intensity \( I \) (mW/cm\(^2\))

\( R_{\text{gen}} \propto \text{Intensity} \)

\( p/N_c \) (\( \times 10^{-3} \))

Degradation kinetics

\[ \kappa_{AB} = \nu_{AB}' \cdot e^{-\frac{E_{a,AB}}{k_B T}} \]

\[ \kappa_{AB} = \nu_{0,AB} \cdot \left[ \frac{p(T)}{N_C(T)} \right]^2 \cdot e^{-\frac{E_{a,AB}}{k_B T}} \]


\[ \kappa_{AB} \text{ - not normalised} \]

(Bothe and Schmidt, 2004)

\[ \kappa_{AB} \text{ - normalised to } \left( \frac{p}{N_c} \right)^2 \]

(This work)
Implications of degradation kinetics

- Fast initial degradation ("FRC")
  - May be partially related to $p^2$ dependence

\[ \kappa_{AB} \text{ is not constant (due to } p^2 \text{ dependence)} \]
Implications of degradation kinetics

- Regeneration rates
  - Regen (B → C) occurs only after degradation (A → B)
  - $\kappa_{BC}$ will be limited by $\kappa_{AB}$

$\kappa_{BC}$ must be determined starting from State B (LS), not State A (DA)

A: ~100%
B: 100%
C: ~100%

Starting State: B (fast recovery)
Starting State: A (slow recovery)

A. Herguth et al., Progress in Photovoltaics: Research and applications 16, pp.135-140, 2008
Summary – Reaction Kinetics

• Developed parameterization to obtain $\tau_{\text{eff}}(T)$ from $\tau_{\text{eff}}(300\,K)$

• Carrier dependence confirmed for annealing ($A \rightarrow B$), degradation ($B \rightarrow A$)

• Carrier dependence explains other observed kinetics phenomena
Mechanisms for permanent deactivation of BO defects
Permanent deactivation

Why does permanent deactivation occur?

Thermal formation

Defect precursors

BO defect

Thermal deactivation

Deactivation mechanisms

• Why does regeneration occur?

• Why does thermal deactivation occur?

• Are they related?
Experimental Details

Measure Normalised Defect Density (NDD)
- Dark Anneal: 200 °C, 15 min
- Light Soak: 35 °C, 0.77 suns, 48 hr

NDD Meas. 1

PECVD SiN_x:H
Thermal SiO_2
Bare
Regeneration

PECVD Si$_{x}$:H (hydrogen)

Thermal SiO$_2$ (no hydrogen)

Bare (no hydrogen)

**NDD Meas. 1**

Relative change due to firing

- Fired
- Not Fired

**NDD Meas. 2**

Relative change due to regeneration

**NDD Meas. 3**

Regeneration

Illuminated Anneal: 172 °C, 0.66 suns, 2 hr
Regeneration

Regeneration (in a reasonable time-frame) requires hydrogen

Multiple pathways for regeneration
Fast: Hydrogen passivation of BO
Slow: Unknown mechanism

Rel. change in NDD due to regen.
Some improvement in hydrogen-lean wafers
Regeneration observed in hydrogen-lean samples (very long time scales)

Deactivation mechanisms

- Why does regeneration occur?

- Why does thermal deactivation occur?

- Are they related?
Thermal deactivation

PECVD SiN<sub>x</sub>:H (hydrogen)

Thermal SiO<sub>2</sub> (no hydrogen)

Bare (no hydrogen)

Relative change due to firing

Varying

\( T_{\text{Fired}} \)

\( N_{\text{fire}} = 1, 2, 3 \)

Not Fired

Temperature, \( \theta \) (°C)

Time, \( t \) (s)

\( T_{\text{peak}} = 827 \) °C
\( T_{\text{peak}} = 790 \) °C
\( T_{\text{peak}} = 735 \) °C
\( T_{\text{peak}} = 686 \) °C
\( T_{\text{peak}} = 632 \) °C
\( T_{\text{peak}} = 580 \) °C
\( T_{\text{peak}} = 518 \) °C
\( T_{\text{peak}} = 463 \) °C

\( NDD \) Meas. 1

\( NDD \) Meas. 2

\( NDD \) Meas. 3
Thermal deactivation

Normalised Defect Density, NDD_{after} (ms^{-1})

T_{peak} (°C)

Before Firing

After Firing

New, non-BO CID defect

Wafers with SiNx:H dielectric

BO → X?
Thermal deactivation

Reaction: \( BO \rightarrow X \)

- \( N_{\text{fire}} = 1 \)
  - \( E_{a,f} = 0.77 \pm 0.1 \text{ eV} \)
  - \( (\kappa'_{f} \cdot t_{\text{step}}) = 10^{4.15 \pm 0.6} \)

- \( N_{\text{fire}} = 2 \)

- \( N_{\text{fire}} = 3 \)

Linear fit (all \( N_{\text{fire}} \))

- \( N_{\text{fire}} = 1 \) only

- \( E_{a,f} = 0.79 \pm 0.08 \text{ eV} \)
  - \( (\kappa'_{f} \cdot t_{\text{step}}) = 10^{4.19 \pm 0.5} \)

Thermal deactivation

Thermal deactivation likely due to defect dissociation into precursors

Fits OK, but needs adjustment

Deactivation mechanisms

• Why does regeneration occur?

• Why does thermal deactivation occur?

• Are they related?
Thermal deactivation

Normalised Defect Density (ms$^{-1}$)

<table>
<thead>
<tr>
<th></th>
<th>Fired</th>
<th>Non-fired</th>
<th>Fired</th>
<th>Non-fired</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiN$_x$:H</td>
<td></td>
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<tr>
<td>SiO$_2$</td>
<td></td>
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</tbody>
</table>

Peak firing temperature, $T_{\text{peak}}$ ($^\circ$C)

Impact of dielectric

Similar thermal reduction in oxide & nitride passivated samples
(i.e. Thermal deactivation is not hydrogen-related)
# Regeneration

<table>
<thead>
<tr>
<th></th>
<th>Fired</th>
<th>Non-fired</th>
<th>Fired</th>
<th>Non-fired</th>
<th>Fired</th>
<th>Non-fired</th>
</tr>
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<tbody>
<tr>
<td>No dielectric</td>
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<tr>
<td>SiN$_x$:H</td>
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</table>

**Similar thermal reduction in oxide & nitride passivated samples**
(i.e. Thermal deactivation is not hydrogen-related)

**Regeneration only occurs in nitride passivated samples**
(i.e. Regen is hydrogen-related)

Hydrogen-related reduction in FDD due to regeneration
Revision to 3 state model?

Can they be combined?
4 state model

- **State D**: Defect precursors
- **State A**: BO defect
- **State B**: High temperature Thermal effects
- **State C**: Hydrogenation + other minor effects

**Thermal formation** and **Thermal deactivation** connections between states.
Summary – Permanent deactivation

- Effective regeneration requires sufficient quantities of hydrogen. Regeneration could involve other mechanisms (slower).

- Thermal deactivation occurs independent of regeneration. Likely not hydrogen-related.

- Thermal deactivation is likely to be defect dissociation

- 4-state model proposed to account for thermal deactivation
Implications of this work
Implications

1. Improved understanding of the BO defect
   - Recombination properties
   - Mechanism of permanent deactivation
   - 4-state model

Impact:
- Easier identification of the BO defect
- Multiple, tailored solutions to mitigate BO defect
Implications

2. Accurate reaction kinetics modelling for BO

- 4-state model
- Conversion from $\tau_{\text{eff}}(300K)$ to $\tau_{\text{eff}}(T)$
- Carrier dependence of reactions

Impact:
- Better estimate of regeneration time-scales for industrial wafers / solar cells
Acknowledgements

• Funding sources
  – Australian Renewable Energy Agency (ARENA)
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  – UK Institution of Engineering and Technology (IET) / A.F. Harvey Engineering Prize.
  – Commercial partners (ARENA 1-A060)
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• Hydrogenation group

• Laboratory:
  – MAiA processing team
  – LDOT team
  – Others

• Admin staff:
  – TETB
  – SPREE

• Friends and family
Thank you for your attention

nnampalli@gmail.com
Motivation

- $p$-type silicon dominant for foreseeable future
- PERC cells seeing an increasing market share
- Surface passivation quality is improving
- “Reliable kWh” is increasingly important

Fig. 48: Expected trend for product warranties and degradation of c-Si PV modules