X-ray Induced Radiation Damage in Segmented p+n Silicon Sensors

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Outline

- Motivation: Radiation hard silicon sensors for the XFEL
- Introduction to X-ray induced radiation damage
- Characterization and determination of damage related parameters
- Influence on electric properties of segmented sensors
- Summary
Motivation:

Development of radiation hard (0 - 1 GGy!) silicon pixel sensors for experiments with hard X-rays (3 keV – 25 keV) at the European XFEL.

Method:

- Extract microscopic parameters related to X-ray irradiation → this talk
- Understand the influence of X-ray irradiation on electrical properties of segmented sensors → this talk
- Implement the extracted parameters in TCAD simulation and verify results with measurements on segmented sensors
- Optimize sensor design using TCAD simulation → J. Schwandt et al., arXiv:1111.4901

Main effects in silicon sensors @ XFEL:

- No bulk damage for $E_{\text{x-rays}} < 300$ keV
- Surface damage: oxide charges and interface traps build up
  → increase leakage current (noise + power dissipation)
  → reduce breakdown voltage
  → increase inter-pixel capacitance and full depletion voltage
  → charge losses below the Si-SiO$_2$ interface
X-ray induced defects in silicon sensors

Formation of defects induced by X-ray ionizing radiation:

- X-rays produce electron-hole pairs in SiO$_2$ [$\sim 18$ eV/pair]
- Fraction of electron-hole pairs recombine:
  $\rightarrow$ field dependent yield of e-h pairs
- Remaining electrons escape from SiO$_2$ [$\mu_e \sim 20$ cm$^2$/(V·s)]
- Holes trapped in vacancies near Si-SiO$_2$ interface
  [$\mu_h < 10^{-5}$ cm$^2$/(V·s)]
  
  e.g., $V_{ox} + h^+ \rightarrow V_{ox}^+$ \(\longleftrightarrow\) oxide charges ($N_{ox}$)
- Protons get released and react with passivated dangling bonds at the interface:
  
  e.g., $V_{ox}H_2 + h^+ \rightarrow V_{ox}H_2^+ \rightarrow V_{ox}H + H^+$
  $H^+ + SiH_{int} \rightarrow Si^+ + H_2$
  
  interface traps ($N_{it}$)

* from J.R. Schwank, 2008
Current-Voltage (I-V) measurement on Gate-Controlled Diode (GCD) for $I_{\text{surface}}$ ($\mu$A/cm$^2$):

- Increase of surface current $I_{\text{surface}} \leftarrow D_{it}^{\text{mid-gap}}$ (eV$^{-1}$cm$^{-2}$)

Accumulation: $I_{\text{bulk,diode}} + I_{\text{diff}}$

Depletion: $I_{\text{bulk,diode}} + I_{\text{diff}} + I_{\text{surface}} + I_{\text{bulk,gate}}$

Inversion: $I_{\text{bulk,diode}} + I_{\text{diff}} + I_{\text{bulk,gate}}$

$\rightarrow I_{\text{surface}} = |I_{\text{depletion}} - I_{\text{inversion}}|$

$\rightarrow$ Surface current density = $I_{\text{surface}}/A_{\text{gate}}$
Thermal Dielectric Relaxation Current (TDRC) measurement on MOS capacitor for $N_{it}^{(i)}$ (cm$^{-2}$):

- Measurement technique: Thermal Dielectric Relaxation Current (TDRC)
  1. Bias the MOS capacitor to accumulation → fill interface traps with electrons
  2. Cool down to 10 K → freeze traps
  3. Reverse bias voltage and heat up to 290 K → trapped charges at the Si-SiO$_2$ interface get released

\[
N_{it}^{(i)} = \int_{E_v}^{E_c} D_{it}^{(i)} (E_{it}) dE_{it}
\]

- Properties of 3 dominant interface traps in silicon band gap after X-ray irradiation:

<table>
<thead>
<tr>
<th></th>
<th>$D_{it}^{1}$</th>
<th>$D_{it}^{2}$</th>
<th>$D_{it}^{3}$</th>
</tr>
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<tbody>
<tr>
<td>$E_c$-$E_{it}$ [eV]</td>
<td>0.39</td>
<td>0.48</td>
<td>0.60</td>
</tr>
<tr>
<td>FWHM [eV]</td>
<td>0.26</td>
<td>0.13</td>
<td>0.071</td>
</tr>
<tr>
<td>$\sigma_{eff}$ [cm$^2$]</td>
<td>$1.2\times10^{-15}$</td>
<td>$5.0\times10^{-17}$</td>
<td>$1.0\times10^{-15}$</td>
</tr>
</tbody>
</table>
Capacitance/Conductance-Voltage (C/G-V) measurement on MOS capacitor + model calculation for $N_{ox}$ (cm$^{-2}$):

- Frequency shift of C/G-V curves $\leftarrow N_{it}^{(i)}$
- Shift in gate voltage $\leftarrow N_{ox} + N_{it}^{(i)}$
- TDRC spectra + model $\rightarrow$ reproduce measured C/G-V curves $\rightarrow N_{ox}$

**Model for MOS capacitor**

- Capacitance and conductance of isolation layer
- Inversion capacitance
- Depletion capacitance depends on thickness of depletion layer
- Recombination/generation resistance
- Capacitance and conductance of un-depleted region

**C/G-V measurement on irradiated MOS capacitor**

- Dots: measurements
- Lines: calculation

- 5 MGy, 120 min @ 80°C
- 1 kHz, 3 kHz, 10 kHz, 30 kHz, 100 kHz
Investigations:
- Orientation: \(<111>\) vs. \(<100>\)
- Vendor: CiS and Hamamatsu
- Insulator: \(\text{SiO}_2\) vs. \(\text{SiO}_2 + \text{Si}_3\text{N}_4\)

Conclusions:
- \(N_{\text{ox}}\) and \(I_{\text{surface}}\) saturate with dose: typically \(N_{\text{ox}} \sim (1.5 - 4.0) \times 10^{12} \text{ cm}^{-2}\), \(I_{\text{surface}} \sim (3 - 7) \mu\text{A/cm}^2\)
- Differences observed for orientations, \(\text{SiO}_2\) vs. \(\text{SiO}_2 + \text{Si}_3\text{N}_4\), vendors
- Saturation mechanism of \(N_{\text{ox}}\): equilibrium between hole trapping and electron recombination
Investigations:
- CiS <100> MOS capacitor and Gate-Controlled Diode (~ 350 nm SiO₂ + 50 nm Si₃N₄)
- Electric field in the oxide $E_{\text{ox}}$: ~ (0 - 0.7) MV/cm [oxide breakdown: ~ 10 MV/cm]

Conclusions:
- $N_{\text{ox}}$ and $I_{\text{surface}}$ increase for $E_{\text{ox}} > 0$
- No strong $E_{\text{ox}}$ dependence for $E_{\text{ox}} < 0$
- $p^+n$ sensor: $E_{\text{ox}} < 0 \rightarrow$ not a problem!
Results: $N_{it}$ vs. $E_{ox}$

TDRC spectra and $N_{it}$:

- Dependence on $E_{ox}$ similar to $I_{surface}$
- TDRC spectra:
  - 100 kGy → change of amplitude
  - 100 MGy → change of shape and amplitude

Field dependence of interface trap density

- $330 \text{ nm SiO}_2 + 50 \text{ nm Si}_3\text{N}_4 - 100 \text{ kGy}$
- $360 \text{ nm SiO}_2 + 50 \text{ nm Si}_3\text{N}_4 - 100 \text{ MGy}$

\[ \text{TDRC spectra of } 100 \text{ kGy dose} \]

-25 V after annealing for 10min@80 °C
-10 V
-0 V
-10 V
-25 V

\[ \beta = 0.183 \text{ K/s} \]

\[ \text{TDRC spectra of } 100 \text{ MGy dose} \]

-25 V after annealing for 10min@80 °C
-10 V
-0 V
-10 V
-25 V

\[ \beta = 0.183 \text{ K/s} \]
C-V curves of p⁺n strip sensor

- $V_{\text{dep}}$ increases $\sim 10$ V after irradiation due to the presence of surface charges (not due to change of doping concentration).
- Strong frequency dependence of total capacitance observed for $V_{\text{bias}} < 300$ V.

![Diagram of p⁺n strip sensor structure]

- Before irradiation
- 1 & 10 MGy

$V_{\text{merge}}$ for $f = 100$ kHz (after 60 min @ 80°C)

Total Capacitance (in series)

Total Capacitance after 10 MGy (in series)
I-V curves of p+n strip sensor

- Leakage current: \( I_{\text{leakage}} = I_{\text{bulk}} + I_{\text{surface}} \)

- Increase of \( I_{\text{leakage}} \) after irradiation \( \leftarrow \) interface trap density \( N_{it} \)
- “Linear” increase of \( I_{\text{leakage}} \) with bias voltage \( \leftarrow \) depleted area \( A_{\text{dep}} \) at Si-SiO\(_2\) interface
- Decrease of \( I_{\text{leakage}} \) with irradiation dose \( \leftarrow \) result of competition between \( N_{it} \) and \( A_{\text{dep}} \)

- For irradiation under bias, \( I_{\text{leakage}} \) larger by \( \sim 100 \) nA

J. Becker, DESY

VERTEX 2012, 16th-21st Sept. 2012, Jeju, Korea
• 660 nm red laser injection (absorption length in silicon ~ 3 μm) into DC coupled sensor (T. Poehlsen)

Signals of $p^+n$ strip sensor

Readout (a)  red laser injection  Readout (b)

Readout (b)

Readout (c)

transients for strip L at $x=12 \mu$m

transients on the rear side at $x=12 \mu$m
Charge losses in p⁺n strip sensor

- Charge losses only close to Si-SiO₂ interface

- Sensor with SiO₂ passivated
  
  **un-irradiated:**
  
  - dry air: ramping up → electron losses (~40% @ 200 V)
    
    ramping down → hole losses
  
  - humid air: no losses

  **irradiated with X-rays:**

  - dry air: ramping up → electron losses (~90% @ 200 V)

    ramping down → electron losses (~20% @ 200 V)

  - humid air: electron losses (~45% @ 200 V → 0% @ 500 V)

- Similar results for detector with different technology and passivation (SiON)
Summary:

**Characterization of damage related parameters**
- 3 dominant interface traps $D_{it}^n$ after irradiation $\rightarrow$ parameters extracted
- C/G-V measurements can be described by $D_{it}^n$ and $N_{ox}$
  
  surface current density + fixed oxide charge density as function of dose & field
  
  saturation with dose and field pointing to the gate
  
  results different according to orientations, insulators and vendors

**Influence of X-ray induced damage on $p^+n$ segmented sensors**
- Changes of electrical properties explained by $N_{ox}$ and $N_{it}$

**Observation of charge losses close to Si-SiO$_2$ interface**
- big effect (but only for charges within $\sim$μm of interface!)
- depends on dose, environmental condition and operation voltage

**Relevance for sensor:**

**Optimization of sensor with better performance needs damage parameters**

**Short range charged particles or photons entering $p^+$ side meets charge losses**
Thanks for your attention!

Work done within the AGIPD Collaboration.
**Results of annealing: $N_{ox}$ vs. time**

**Annealing of $N_{ox}$:**

- Exponential decay: $N_{ox}(t) = A \cdot \exp\left(-\frac{t}{\tau}\right) + y_0 \rightarrow$ description inadequate

![Annealing behavior of oxide charge density](image)

- “Tunnel anneal” model [T. R. Oldham et al., 1986]:

$$N_{ox}(t) = N_{ox}^0 \cdot \left(1 + \frac{t}{t_0}\right)^{-\frac{\lambda}{2\beta}} \quad \text{with} \quad t_0(T) = t^*_0 \cdot \exp\left(\frac{\Delta E}{k_BT}\right)$$

<table>
<thead>
<tr>
<th>$N_{ox}^0$ [cm$^{-2}$]</th>
<th>$\lambda/2\beta$</th>
<th>$t^*_0$ [s]</th>
<th>$\Delta E$ [eV]</th>
<th>$T$ [$^\circ$C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.6 \times 10^{12}$</td>
<td>0.070</td>
<td>5.4 $\times 10^{12}$</td>
<td>0.91</td>
<td>80</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>60</td>
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<td>20</td>
</tr>
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</table>

$\Delta E = E_t(SiO_2) - E_F(Si) \rightarrow E_t(SiO_2) \sim 6.0$ eV, compatible with existing data

$\Delta E$: energy difference between trap level and silicon Fermi level

$\lambda$: characteristic length ($\sim$ nm); $N_{ox}^0$: $N_{ox}$ at $t = 0$

$N_{ht}(x) = \lambda \cdot N_{ox}^0 \cdot \exp(-\lambda \cdot x)$

$\tau_0^*$: tunneling time constant

$\beta$: parameter related to barrier height; $t_0^*$: effective tunneling time constant
Results of annealing: $I_{\text{surface}}$ vs. time

Annealing of $I_{\text{surface}}$:

- Exponential decay: $I_{\text{surface}}(t) = A \cdot \exp\left(-\frac{t}{\tau}\right) + y_0$ → description inadequate
- Power law:

$$I_{\text{surface}}(t) = I_{\text{surface}}^0 \cdot (1 + t/t_1)^{-\eta} \quad \text{with} \quad t_1(T) = t_1^* \cdot \exp\left(\frac{E_a}{k_B T}\right) \quad \text{and} \quad \eta = \frac{k_1}{2k_2}$$

Two-reaction model (M. L. Reed 1987):

→ Dangling bonds: $\frac{d}{dt} [\text{Si} \cdot] = -k_1 [\text{Si} \cdot][H]$
→ Hydrogen: $\frac{d}{dt} [\text{H}] = -2k_2 [\text{H}][\text{H}]$

$k_1$ & $k_2$: reaction rate

<table>
<thead>
<tr>
<th>$I_{\text{surface}}^0$ [$\mu\text{A/cm}^2$]</th>
<th>$\eta$</th>
<th>$t_1^*$ [s]</th>
<th>$E_a$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1</td>
<td>0.21</td>
<td>1.4 x 10^{-8}</td>
<td>0.70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$T$ [$^\circ$C]</th>
<th>80</th>
<th>60</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$ [s]</td>
<td>140</td>
<td>549</td>
<td>15298</td>
</tr>
</tbody>
</table>

Data described by power law predicted by “two-reaction model”

Data show that same function with different parameters for the different traps $N_{it}^{(i)}$ describes data
Results based on calculation for 5 MGy dose (results scalable to other doses):

- Slow annealing for $N_{ox}$: e.g., at 20 °C, $\Delta N_{ox}/N_{ox}$ by less than 50% in 3 years (but...)
- Reduction of $I_{surface}$ in days: e.g., at 20 °C, $\Delta I_{surface}/I_{surface}$ by 50% just in 5 days!