Can silicon operate beyond $10^{15}$ n/cm$^2$?

**DEFECT ENGINEERING – Oxygen Dimer Si**

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**OUTLINE**

1- **BACKGROUND**
2- **KEY ISSUE – signal efficiency in irradiated detectors**
3- **SOLUTIONS**
   a  **OPERATING CONDITIONS** ( T, Forward/Reverse Bias ? )
   b  **DEFECT ENGINEERING** ( Dimer oxygenated Si)
   c  **DEVICE ENGINEERING** ( e.g. 3D Sherwood Parker)
4- **CONCLUSIONS**
**Signal** = \( q \times P_{qc}(x) \times \text{CORR} \times (V_c - V_x) \)

\[
\begin{align*}
P_{qc} & \approx e^{-\frac{t_D}{t_{\text{eff}}}} \\
\frac{1}{t_{\text{eff}}} & = \frac{1}{\tau_T} - \frac{1}{2} \frac{t_D}{\tau_T} \\
\frac{1}{t_{\text{eff}}} & = k \phi
\end{align*}
\]

**Drift Time** = \( d/\mu E \)

\[
\tau_T = \left( N_T \sigma V_{th} \right)^{-1}
\]

\( t_{\text{eff}} \) and \( \mu \) vary with temperature

\( P_{qi} = 1 - P_{qc} \)

\( P_{qi} \) prop. \( 1/t_{\text{eff}} \)

**RAMO’s theorem + trapping**
Vacancy-Oxygen

Signal density = $10^{16}$ cm$^{-3}$, Trap density = $10^{15}$ cm$^{-3}$

\[ \tau_c = \left( n_s \sigma v_{th} \right)^{-1} \]

\[ \tau_T = \left( N_T \sigma v_{th} \right)^{-1} \]

\[ \tau_e \text{ prop. exp}(\Delta E/kT) \]

\[ 1/\tau = 1/\tau_e + 1/\tau_c \]

Same theory as used in CCD's

For depletion case (Reverse Bias)

- $T < 200K$  Trapping Controlled
- $T > 200K$  Emission Controlled

For Forward Bias

Always Trapping Controlled
For electron trapping – $t_D = 10$ ns

Conclusion

NIEL Violation

Charged hadrons worse

Aside:

$P_{qi} = (\tau/\tau_T) \times (1 - \exp(-t_D/\tau))$

Same in CCDs

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO</td>
<td>0.6</td>
<td>0.96</td>
</tr>
<tr>
<td>V2 + Cluster</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Introduction rates (cm$^{-1}$)

Temperature (K)
Electron Trapping - calculation scaled to Kramberger data at 250K

\[ k = \left( \frac{t_{\text{eff}}}{\text{Fluence}} \right) \left( 10^{-16} \text{ ns}^{-1} \text{ cm}^2 \right) \]

Temperature (K)

**Note:**

Kramberger et al. See NIEL Violation
n/p trapping NOT the same for same equiv.
1 MeV n fluence.

**Conclusion:**
VO causes this difference

**NOTE:** Below 200K this parameter is the same for Forward and Reverse bias
**EFFECTIVE DRIFT LENGTH**

\[ L_{\text{eff}} = \tau_{\text{eff}} \times V_{\text{drift}} \]

Data for neutron and protons for effective trapping time 220K-300K from Kramberger et al.
SIGNAL FORMATION - RAMO'S THEOREM

IMPORTANCE OF THE WEIGHTING POTENTIAL

PADS AND SEGMENTED DETECTORS ARE VERY DIFFERENT

**Graphs showing the relationship between signal formation and weighting potential in different types of detectors.**
CONCLUSION – collect electrons !!!!!
If one can remove VO then we should do better
SOLUTIONS (b) DEFECT ENGINEERING - O DIMER

HIGH TEMPERATURE $^{60}\text{Co} \gamma$ IRRADIATION
AT T > 350 °C VO BECOMES MOBILE AND CAUSES OXYGEN TO CLUSTER

QUASI CHEMICAL REACTIONS:

\[
\begin{align*}
V + O_i & \rightarrow VO_i \\
VO_i + O_i & \rightarrow VO_{2i} \\
I + VO_{2i} & \rightarrow O_{2i}
\end{align*}
\]

\[
\begin{align*}
& \text{VO} \quad \longrightarrow \quad VO_2 \quad \text{NEUTRAL} \\
& \text{V}_2\text{O} \quad \longrightarrow \quad \text{V}_2\text{O}_2 \quad \text{NEUTRAL}
\end{align*}
\]

EXPECT CHANGE IN MACROSCOPIC EFFECTS
SHOULD IMPROVE CCE FOR ELECTRONS

ALSO – $O_{2i}$ diffuses very rapidly. Possibility of low-tem diffusion For DOFZ !!!!

Method variation on L. Lindstroem work
DEFECTS IN “DIMERED” MATERIAL

309D Oxygenated and “dimered”
366D Standard and “dimered”

<table>
<thead>
<tr>
<th>Electron (E) or Hole (H) trap</th>
<th>Energy Level (eV)</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(170)</td>
<td>$E_c - 0.32$</td>
<td>Probably VOH [11]</td>
</tr>
<tr>
<td>H(200)</td>
<td>$E_v + 0.36$</td>
<td>$C_i O_i$ (0/+)-Charge state [1]</td>
</tr>
<tr>
<td>H(144)</td>
<td>$E_v + 0.2$</td>
<td>Unknown</td>
</tr>
<tr>
<td>H(80?)</td>
<td>Approx. $E_v + 0.1$</td>
<td>Not fully resolved. Unknown.</td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS
IV and \( N_{\text{eff}} \) AFTER 24 GeV/c p–irradiation

- Oxygenation shows normal improvement
- Leakage current looks the same in all samples. 
  \( \alpha \sim 3 \times 10^{-17} \, \text{A cm}^{-1} \)
Small improvement – do not expect anything spectacular at this fluence – also a PAD detector
CONTROL OF THE SPACE CHARGE WITH TEMPERATURE

energy level occupancy ~ $e^{-\Delta E/kT}$

241Am

MCA 2us shaping

Temperature 85K to 300K

X-RAY source

detector

Li N

Phosphorus doping level

energy level occupancy ~ $e^{-\Delta E/kT}$

X-RAY source

1x10^{14} n/cm^2 > type inverted : -ve SC

+ve SC

T [K]

To be published

C Da Via
ELECTRIC FIELD DISTRIBUTION
VERSUS TEMPERATURE AFTER 1E14 n/cm$^2$
OXYGEN DIMERED SILICON AFTER 24GeV/c PROTON IRRADIATION

Anneal at 80 °C – Equiv. to about 13 yr RT

Radiation induced traps DLTS spectra

SC after reverse annealing Measurements at 220K
Depletion voltages in various samples before and after annealing

<table>
<thead>
<tr>
<th>Material</th>
<th>$V_{Dep}$ 300K Volts</th>
<th>$V_{Dep}$ 223K Volts Note 2</th>
<th>$\Delta V$ RA 300K Volts Note 3</th>
<th>$\Delta V$ RA 223K Volts Note 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>288</td>
<td>200</td>
<td>975</td>
<td>65</td>
</tr>
<tr>
<td>Oxygenated</td>
<td>189</td>
<td>100</td>
<td>740</td>
<td>40</td>
</tr>
<tr>
<td>Standard Dimered</td>
<td>288</td>
<td>90</td>
<td>-</td>
<td>0 to 10</td>
</tr>
<tr>
<td>Oxygenated Dimered</td>
<td>180</td>
<td>100</td>
<td>-</td>
<td>40</td>
</tr>
</tbody>
</table>

Note 1: Inferred from CV measurement at room temperature
Note 2: Inferred from x-ray count-rate measurement as function of voltage at 223K.
Note 3: Calculated using Hamburg parameterisation of standard and oxygenated silicon.
Note 4: Inferred from x-ray count-rate measurement as function of voltage.
TEMPERATURE DEPENDENCE OF DEPLETION VOLTAGE

- Occupancy prop. $\exp(\Delta E/kT)$
- SRH $\Delta E = E_g - 2E_T$
- Inter-Centre Charge Transfer (ICT) $\Delta E = E_g - 2E_T + E_D$

For $V_2$ $\Delta E = -0.28 \text{ eV}$ SRH, $\Delta E = -0.08 \text{ eV}$ ICT

Temp. Dependence of RA part of depletion voltage = -0.2 eV

Temp. Dependence of Non -RA part of depletion voltage Approx -0.06 eV (depends on material)
CORRELATION BETWEEN RA - CLUSTER INTRO. RATE & TEMP DEPENDENCE OF DEPLETION VOLTAGE (PRIOR TO RA)

- Slow $V_{\text{dep}}$ change with T
- Fast $V_{\text{dep}}$ change with T
- Temp. Dependence of space charge
- Activation Energy (eV) - See Caption

**Introduction Rate for E(225) DLTS Peak (cm$^{-1}$)**

**Max. Depletion Voltage Change (Volts)**

**Bad**

**Reverse Annealing**

**Good**

Prior to RA
Cobalt-60 Irradiation Measure Minority Carrier Lifetime
Expect VO to be important in standard Si

1 Krad = 2.25E12 γ cm\(^{-2}\)

Steps: 0, 15, 30, 45 Krad

1/τ = 1/τ\(_0\) + φ/K\(_τ\)

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ(_0)</td>
<td>287μs</td>
<td>258μs</td>
</tr>
<tr>
<td>K(_τ)</td>
<td>(1.0+/-0.1) *1E11</td>
<td>(2.0+/-0.2) *1E11</td>
</tr>
</tbody>
</table>

Units γ scm\(^{-2}\)

Factor 2 better for standard dimered silicon
VERY PRELIMINARY CONCLUSIONS
FOR DIMER OXYGENATED SILICON

Evidence

• That charge trapping has been improved
• That reverse annealing is suppressed in low [O] dimered Si
• Reverse annealing seems to be correlated with E(225) “cluster” peak
• That space charge temperature dependence is different in low [O] dimered Si
• Temperature dependence of depletion voltage BEFORE RA correlated to the size of voltage change after RA !!!
• Better damage parameter for minority carrier lifetime in low [O] dimered Si after gamma irradiation.

LOT OF THINGS TO DO YET

NB: First look at how reverse annealing amplitude varies with temperature. This may help to identify the defect causing RA
Lots of possibilities $O_i$ to $O_{2i}$ to $O_{3i}$ during processing.
Low [O] and high [O] material