Paradoxes
of steady-state and pulse operational mode characteristics of silicon detectors
irradiated by ultra-high doses of γ-rays

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1\textsuperscript{st} RD50 Workshop on radiation-hard semiconductor devices for very high luminosity colliders
CERN, 2-4 October 2002
Outline

1. Motivation and earlier results
2. Experimental
   - Steady-state characteristics
3. Dependences of $V_{fd}$ and $N_{eff}$ vs. dose in detectors from standard and oxygen-rich Si:
   - experimental C-V dependencies;
   - space charge sign verification using TCT
   - modeling of $N_{eff}$ vs. D dependencies
4. Changes of I-V characteristics with dose accumulation
5. Temperature dependencies of the reverse current
   - Characteristics of pulse operational mode
6. Distortions of current pulse response shapes in detectors from standard and oxygen-rich Si irradiated by ultra-high dose of $\gamma$-rays
7. Room temperature polarization in detectors from oxygenated Si
8. Discussion
   - Conclusions

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
Motivation and earlier results

High doses of γ-rays play a significant role in a linear collider


Standard Si:
gradual $V_{fd}$ reduction till the SCSI

Si oxygen-rich (Si HTLT processed at BNL):
no SCSI up to 575 Mrad

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**Experimental**

**BNL detectors:** n-Si Wacker; $\rho = 1$ kOhm-cm; orientation $\langle 111 \rangle$;  
**Oxygenation:** BNL High Temperature Long Time process  
  + Thermal Donors: Si HTLT(TD)

**CIS detectors:** n-Si Wacker; $\rho = 4$ kOhm-cm; orientation $\langle 111 \rangle$ and $\langle 100 \rangle$;  
**Oxygenation:** CIS Diffusion Oxygen Float Zone (DOFZ) process;  
oxygenation time: 24, 48, 72 h

**MS detectors:** n-Si Wacker; $\rho = 15$ kOhm-cm; orientation $\langle 111 \rangle$;  
**Oxygenation:** MS DOFZ process + TD

**Experimental technique**

1. C-V and I-V measurements;
2. TCT measurements with a red laser ($\lambda = 660$ nm);
3. I-T measurements

**Irradiation:** BNL, $^{60}$Co source

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E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
Detectors irradiated up to ultra-high $D$

<table>
<thead>
<tr>
<th>producer</th>
<th>#</th>
<th>material</th>
<th>orientation</th>
<th>$D$ (Mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL</td>
<td>904-96</td>
<td>standard</td>
<td></td>
<td>339</td>
</tr>
<tr>
<td></td>
<td>904-100</td>
<td>&quot;&quot;</td>
<td>&lt;111&gt;</td>
<td>1647</td>
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<tr>
<td></td>
<td>906-97</td>
<td>oxygenated + TDs</td>
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<td>947</td>
</tr>
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<td></td>
<td>906-101</td>
<td>&quot;&quot;</td>
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<td>947</td>
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<tr>
<td>MS</td>
<td>1940-18-5</td>
<td>standard</td>
<td>&lt;111&gt;</td>
<td>339</td>
</tr>
<tr>
<td></td>
<td>1940-18-6</td>
<td>&quot;&quot;</td>
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<td>835</td>
</tr>
<tr>
<td></td>
<td>2015-11-5</td>
<td>oxygenated + TDs</td>
<td></td>
<td>1758</td>
</tr>
<tr>
<td></td>
<td>2015-11-6</td>
<td>&quot;&quot;</td>
<td></td>
<td>947</td>
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<tr>
<td>CIS</td>
<td>CA0749</td>
<td>standard</td>
<td>&lt;111&gt;</td>
<td>1647</td>
</tr>
<tr>
<td></td>
<td>CB0249</td>
<td>oxygenated</td>
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<td>1758</td>
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<td>CC1549</td>
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<td>&lt;100&gt;</td>
<td>1260</td>
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<td>CF0449</td>
<td>oxygenated</td>
<td>&lt;100&gt;</td>
<td>947</td>
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<tr>
<td></td>
<td>CG1049</td>
<td>&quot;&quot;</td>
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<td></td>
<td>CH2149</td>
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<td></td>
<td>1758</td>
</tr>
</tbody>
</table>

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
Steady-state characteristics of $\gamma$-irradiated detectors

**C-V characteristics**

**Si standard**, Ultra-high dose: $D = 0$-1.65 Grad

CIS $\langle 111 \rangle$  CA0749

**Standard Si:**
- $V_{fd}$ changes non-monotonically (similar to n/p)
- “bump” in C-V characteristics may appear after $V_{fd}$ minimum was reached

$D$ (Mrad):
- 42.7
- 190
- 338
- 519
- 835
- 1050
- 1260
- 1647

$C$ (pF) vs $V$ (Volt)

$f = 10$ kHz

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
SCSI in detectors from standard Si

D = 338 Mrad  BNL 904-100

SCSI is observed in all detectors from standard Si
Di is different

Laser illumination on the p+ side: electron collection

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
**C-V characteristics: Si oxygenated**

**Ultra-high dose:** \( D = 0-1.76 \text{ Grad} \) MS # 2015-11-5

- \( V_{fd} \) increases slowly and monotonically with \( D \)

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E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
Si oxygenated: positive space charge detectors

Ultra-high dose D = 1.76 Grad CIS <111> CB0249

Space charge is positive!

V (Volt):
- 110
- 120
- 130
- 140
- 150
- 170
- 200
- 230
- 250
- 300

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
Full depletion voltage in detectors from standard Si

$V_{fd}$ as-measured:
difference in thickness
~5.5%

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
**Standard Si: Q-V dependencies**

\[ V_{\text{p-off}} = 487 \text{ V} \]

\[ V_{\text{Qsat}} = 595 \text{ V} \]

- \( V_{\text{p-off}} \) – pinch-off occurs
- \( V_{\text{Qsat}} \) – \( E(x) \) is linear, Q-V dependence is close to saturation

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
Results are similar to earlier data in detectors irradiated by p/n

**Space charge concentration** $N_{\text{eff}}$ **in detectors from standard Si**

\[ N_{\text{eff}} = N_{d0} \cdot \exp(-\gamma D) - \beta D \]

- $\gamma$ - donor removal rate
- $\beta$ - acceptor introduction rate

<table>
<thead>
<tr>
<th>#</th>
<th>orientation</th>
<th>$N_{d0}$ (cm$^{-3}$)</th>
<th>$\gamma$ (Mrd$^{-1}$)</th>
<th>$\beta$ (cm$^{-3}$Mrd$^{-1}$)</th>
<th>$D_i$ (Mrd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>904-100</td>
<td>$&lt;111&gt;$</td>
<td>$3.86 \cdot 10^{12}$</td>
<td>$2.47 \cdot 10^{-3}$</td>
<td>$4.8 \cdot 10^9$</td>
<td>325</td>
</tr>
<tr>
<td>1940-18-6</td>
<td>$&lt;111&gt;$</td>
<td>$7.23 \cdot 10^{11}$</td>
<td>$(7.0 \cdot 10^{-5})?$</td>
<td>$8.1 \cdot 10^9$</td>
<td>88</td>
</tr>
<tr>
<td>CA0749</td>
<td>$&lt;111&gt;$</td>
<td>$8.91 \cdot 10^{11}$</td>
<td>$1.88 \cdot 10^{-3}$</td>
<td>$2.7 \cdot 10^9$</td>
<td>190</td>
</tr>
<tr>
<td>CE1549</td>
<td>$&lt;100&gt;$</td>
<td>$9.36 \cdot 10^{11}$</td>
<td>$7.2 \cdot 10^4$</td>
<td>$4.5 \cdot 10^9$</td>
<td>190</td>
</tr>
</tbody>
</table>

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
$V_{\text{fd}}$ and $N_{\text{eff}}$ in detectors from standard and oxygenated Si

In contrast to standard Si in oxygenated detectors $V_{\text{fd}}$ increases slowly and monotonically with dose.

Positive space charge is accumulated with D up to ultra-high dose of 1.75 Grad.

Donor type defect introduction in oxygenated Si is unique for $\gamma$-irradiation.

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
Modeling $N_{\text{eff}}$ vs. $D$ dependencies in detectors from oxygenated Si

Model: $N_{d0} + N_{d1} \cdot D^m$

- donor type defect introduction
- superlinear dependence on $D$

The power in superlinear dependence decreases with oxygenation time?

<table>
<thead>
<tr>
<th>#</th>
<th>oxygen. time (h)</th>
<th>dose range Grad</th>
<th>$N_{d0}$ cm$^{-3}$</th>
<th>$N_{d1}$ cm$^{-3}$/Mrd</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015-11-5 &lt;111&gt;</td>
<td>?</td>
<td>0-1.76</td>
<td>1.625\times10^{12}</td>
<td>1.48\times10^7</td>
<td>1.449</td>
</tr>
<tr>
<td>CB0249 &lt;111&gt;</td>
<td>24</td>
<td>0-1.76</td>
<td>1.13\times10^{12}</td>
<td>5.24\times10^4</td>
<td>2.27</td>
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<tr>
<td>CB0249 &lt;111&gt;</td>
<td>24</td>
<td><strong>0-1.37</strong></td>
<td>1.09\times10^{12}</td>
<td>1.52\times10^7</td>
<td>1.47</td>
</tr>
<tr>
<td>CD2049 &lt;111&gt;</td>
<td>72</td>
<td>0-1.76</td>
<td>1.038\times10^{12}</td>
<td>2.54\times10^8</td>
<td>1.125</td>
</tr>
<tr>
<td>CH2149 &lt;100&gt;</td>
<td>72</td>
<td>0-1.76</td>
<td>7.89\times10^{11}</td>
<td>7.89\times10^7</td>
<td>1.266</td>
</tr>
</tbody>
</table>

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
**I-V characteristics**

Si standard, BNL 904-100

Si oxygenated, MS 2015-11-5

- Current values are different at the same D
- Standard Si, beyond SCSI: at $V<V_{fd}$ edge current on the $n^+$-side, different from stabilization of the reverse current in detectors as-irradiated by high F of neutrons/protons

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
**Reverse current density on dose dependencies**

Comparison of standard and oxygenated Si

**Standard Si:**
- reverse current density at $V_{fd}$ shows superlinear increase with dose

**Oxygenated Si:**
- For $D < 1$ Grad: linear increase
- Damage coefficient of $10^{-15}$ A/cm²·rad
- For $D > 1$ Grad: sublinear increase

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
**Reverse current vs. temperature dependences**

![Graph showing reverse current vs. temperature](image)

**Micron Semicond.**
- Si stand., 1940-18-6; 835 Mrd
- Si oxyg., 2015-11-6; 947 Mrd

**CIS <111>**
- Si stand., CA0749; 16470 Mrd
- Si oxyg., CC1549; 957 Mrd
- Si oxyg., CB0249; 1759 Mrd

**D**: 0.84-1.76 Grad  
**T**: 295 to 200 K  
**Bulk generation current** is analyzed: $I_{at} V > V_{fd}$

**Model:**  
Shockley-Read-Hall statistics

**I-T analysis**: [E. Verbitskaya et al., 5th ROSE Workshop, March 2000, CERN LEB 2000-005, p.300]

**Si standard**: various slope at different $T$  
Effective generation level: $E_j = 0.64-0.68$ eV  
two gen. levels: midgap level $\sim 0.57$ eV (lower $T$); and $E_j \approx 0.8$ eV

**Si oxygenated**: single slope, $E_j = 0.77-0.79$ eV

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
**Detector characteristics in pulse operational mode**

<table>
<thead>
<tr>
<th>Si standard</th>
<th>BNL 904-100</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>electron collection</strong></td>
<td></td>
</tr>
<tr>
<td>$D = 519$ Mrad</td>
<td></td>
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<tr>
<td>laser illumination of the $p^+$ side</td>
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</tr>
<tr>
<td>V (Volt):</td>
<td></td>
</tr>
<tr>
<td>110</td>
<td></td>
</tr>
<tr>
<td>115</td>
<td></td>
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<td>120</td>
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<td>170</td>
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<tr>
<td>180</td>
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<tr>
<td>200</td>
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<td>220</td>
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<tr>
<td>20</td>
<td></td>
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<tr>
<td>300</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Si oxygenated</th>
<th>CB0249</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>hole collection</strong></td>
<td></td>
</tr>
<tr>
<td>$D = 1.76$ Grad</td>
<td></td>
</tr>
</tbody>
</table>

**DJ effect** – non-uniform double peak $E(x)$ in heavily irradiated detectors originated from free carrier trapping from detector reverse current


- no initial fast rise of response
- abnormal increase of the slope
- time dependent $N_{\text{eff}} (+N_{\text{eff}} \uparrow)$
- $E$ at the $n^+$ contact drops to zero

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
Room temperature polarization in detectors from oxygenated Si

D = 1.76 Grad; V = 300 V (V ≈ 2 V_{fd})

hole collection: degradation of pulse response

• Initially: collection in fully depleted detector, E > 0
• Holes are trapped during drift and increase positive N_{eff}
• difference between E_{min} and E_{max} increases in time
• pulse response degradation occurs due to polarization

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
Dependence of CCE degradation on reverse bias voltage

**h hole collection**

- CCE<sub>h</sub> degradation is sharp
  - E (at the n<sup>+</sup> contact) drops to 0,
  - neutral base region evolves at n<sup>+</sup>
  - holes can’t be collected
  - the higher is V, the larger is t<sub>top</sub>

**e electron collection**

- CCE<sub>e</sub> degradation is gradual
  - CCE ~ w/d,
  - initially: w = d,
  - at t>t<sub>top</sub> gradual reduction of w

at V fixed
t<sub>top</sub> is the same
for e and h

E. Verbitskaya et al, 1<sup>st</sup> RD50 Workshop, CERN, 2-4 October 2002
**Polarization controlled by trapping of thermally generated holes**

Electron collection

- Detector is permanently biased;
- Laser is switched on and off - no difference in $t_{\text{op}}$, no influence from laser generated e/h

**Holes are trapped from detector reverse current**

**Polarization:** observed earlier in Si detectors irradiated by neutrons and operated at cryogenic T


**Paradox for $\gamma$-irradiated detectors:**

- Polarization is observed at RT;
- Hole trapping in SCR with $+N_{\text{eff}}$

Possible reason for RT polarization:

- New defects in oxygenated Si induced by $\gamma$-rays:
  
  $E_j = 0.8$ eV, larger $\tau_{\text{detr}}$

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
**Discussion**

1. *Paradoxes of γ-irradiated Si detectors*

<table>
<thead>
<tr>
<th></th>
<th>Si standard</th>
<th>Si oxygenated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{eff}}$</td>
<td>$N_{\text{eff}} = N_{\text{d0}} \cdot \exp(-\gamma D) - \beta D$</td>
<td><strong>Paradox</strong>: positive</td>
</tr>
<tr>
<td></td>
<td><strong>negative</strong> after SCSI</td>
<td>superlinear: $N_{\text{d0}} + N_{\text{d1}} \cdot D^m$</td>
</tr>
<tr>
<td></td>
<td>linear: $\beta \sim 10^9$ cm$^{-3}$Mrd$^{-1}$</td>
<td>$m = 1.1-1.5$</td>
</tr>
<tr>
<td>$I (V_{jd})$: Paradox</td>
<td>superlinear</td>
<td>$D &gt; 0.6$ Grd:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\beta^+ \sim 10^8$ cm$^{-3}$Mrd$^{-1}$</td>
</tr>
<tr>
<td>Pulse operation mode</td>
<td>$D &gt; 0.5$ Grd: distortions due to <strong>DJ effect</strong></td>
<td><strong>Paradox</strong>:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- RT polarization at $D \geq 1$ Grd;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- hole trapping in SCR with $+N_{\text{eff}}$</td>
</tr>
</tbody>
</table>

- Defects responsible for radiation damage and different introduction rate?
- Oxy-Si: **DD or SD?** $\Delta N_{\text{eff}} = (0.8-1.1) \cdot 10^{12}$ cm$^{-3}$; $N_{\text{SD}} = 3 \cdot 10^{11}$ cm$^{-3}$ (low T data)

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
Discussion 2. **Radiation hardness improvement in oxygenated Si detectors**

- $V_{fd0}$ – full depletion voltage before irradiation;
- $V_{fdF}$ – full depletion at the range border (D = 0.95 or 1.65 Grad);
- $j_F$ – reverse current density at $V_{fdF}$;
- $R = \frac{V_{fdF}}{V_{fd0}} - V_{fd}$ *increase ratio* within the dose range;
- $G_F = \frac{R_{st}}{R_{oxy}}$ - gain in the $V_{fd}$ reduction in oxygenated detectors with respect to detectors from standard Si irradiated to the same border dose.

<table>
<thead>
<tr>
<th>#</th>
<th>range, Grad</th>
<th>$G_F$</th>
<th>$j_{F , st}/j_{F , oxy}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MS</strong></td>
<td>0-0.84</td>
<td><strong>22.5</strong></td>
<td>4.4</td>
</tr>
<tr>
<td><strong>CIS &lt;111&gt;</strong></td>
<td>0-0.95</td>
<td>2.0*</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>0-1.75</td>
<td>2.7</td>
<td>4.6</td>
</tr>
<tr>
<td><strong>CIS &lt;100&gt;</strong></td>
<td>0-0.95</td>
<td>3*</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>0-1.75</td>
<td>4</td>
<td>3.3</td>
</tr>
</tbody>
</table>

* $V_{fd0}$ is smaller for CIS <100>*

The difference in $G_F$ and current ratio between the dose ranges arises from different dependencies of $V_{fd}$ and $j$ on D.

E. Verbitskaya et al, 1st RD50 Workshop, CERN, 2-4 October 2002
Conclusions

1. The **radiation hardness improvement** of detectors from oxygenated Si irradiated by $\gamma$-rays actually extends now up to ultra-high dose range of 1.75 Grad.

2. The **gain** in the $V_{fd}$ reduction in oxygen rich detectors with respect to detectors from standard Si is ~2 in the range of 1 Grad and increases to ~3 in the ultra-high dose range 1-1.75 Grad.

3. **Paradox of oxygenated Si:**
   - inhibited degradation of steady-state characteristics even at ultra-high dose;
   - collapse at $D \sim 1$ Grad due to RT polarization in pulse operational mode!