Radiation-hard detectors for very high luminosity colliders

Andrea Candelori
(INFN Padova)

On behalf of the RD50 Collaboration
(http://rd50.web.cern.ch/rd50/)
Outline

- Motivations: the LHC upgrade
- The RD50 Collaboration
- Radiation effects in silicon detectors
- Leakage current density increase
- Oxygen and effective doping concentrations
- Czochralski and Magnetic Czochralski silicon
- Thin detectors: thinned and epitaxial
- 3-D, Semi 3-D and Stripixel detectors
- p-type substrate
- CCE simulations for pixel detectors
- CCE in SiC and GaN
- Summary
LHC upgrade: from LHC to Super-LHC

(M. Hutinen: “Radiation issues for S-LHC”, S-LHC Electronics Workshop, 26/2/04, CERN
O. Bruning: ”Accelerator upgrades for S-LHC”, S-LHC Electronics Workshop, 26/2/04, CERN)

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>S-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Energy</td>
<td>7 TeV</td>
<td>15 TeV</td>
</tr>
<tr>
<td>Collision rate</td>
<td>40 MHz</td>
<td>80 MHz</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$10^{34}$ cm$^{-2}$×s$^{-1}$</td>
<td>$10^{35}$ cm$^{-2}$×s$^{-1}$</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>500 fb$^{-1}$</td>
<td>2500 fb$^{-1}$</td>
</tr>
</tbody>
</table>

![Graph showing radiation levels and channel hadron fluxes](image)

Andrea Candelori, Radiation-hard detectors for very high luminosity colliders, Vertex 2004 Conference
### Approach for tracker upgrade

<table>
<thead>
<tr>
<th>Radial distances</th>
<th>Expected S-LHC fluence for fast hadrons</th>
<th>Expected S-LHC dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>of the actual CMS tracker</td>
<td>cm</td>
<td>cm$^{-2}$</td>
</tr>
<tr>
<td><strong>Pixel:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 cm</td>
<td>$1.6 \times 10^{16}$</td>
<td>420</td>
</tr>
<tr>
<td>11 cm</td>
<td>$2.3 \times 10^{15}$</td>
<td>94</td>
</tr>
<tr>
<td><strong>Microstrip:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22 cm</td>
<td>$8 \times 10^{14}$</td>
<td>35</td>
</tr>
<tr>
<td>115 cm</td>
<td>$1 \times 10^{14}$</td>
<td>9</td>
</tr>
</tbody>
</table>

The current detector technologies can operate up to $\approx 10^{15}$ cm$^{-2}$!

<table>
<thead>
<tr>
<th>Region</th>
<th>Approach for the tracker upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>R $&lt; 20$ cm</td>
<td>=&gt; R&amp;D required</td>
</tr>
<tr>
<td>20 cm $&lt; R &lt; 60$ cm</td>
<td>=&gt; Improving pixel technology</td>
</tr>
<tr>
<td>R $&gt; 60$ cm</td>
<td>=&gt; Improving microstrip technology</td>
</tr>
</tbody>
</table>

(see talk by R. Horisberger on CMS upgrade for S-LHC, yesterday)
The RD50 Collaboration

**RD50: Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders**

1. Formed in November 2001
2. Approved by CERN in June 2002

**Main objective:**
Development of ultra-radiation hard semiconductor detectors for the luminosity upgrade of LHC to $10^{35}$ cm$^{-2}$s$^{-1}$ (S-LHC).

**Challenges:**
- Radiation hardness up to fluences of $10^{16}$ cm$^{-2}$ required;
- Fast signal collection (10 ns bunch crossing);
- Low mass (reducing multiple scattering close to interaction point);
- Cost effectiveness.

**Presently 280 Members from 55 Institutes**

- **Belgium** (Louvain), **Canada** (Montreal), **Czech Republic** (Prague (2x)), **Finland** (Helsinki (2x), Oulu), **Germany** (Berlin, Dortmund, Erfurt, Halle, Hamburg, Karlsruhe), **Greece** (Athens), **Israel** (Tel Aviv), **Italy** (Bari, Bologna, Florence, Milano, Modena, Padova, Perugia, Pisa, Trento, Trieste, Turin), **Lithuania** (Vilnius), **Norway** (Oslo (2x)), **Poland** (Warsaw), **Romania** (Bucharest (2x)), **Russia** (Moscow (2x), St.Petersburg), **Slovenia** (Ljubljana), **Spain** (Barcelona, Valencia), **Sweden** (Lund) **Switzerland** (CERN, PSI), **Ukraine** (Kiev), **United Kingdom** (Exeter, Glasgow, Lancaster, Liverpool, London, Sheffield, University of Surrey), **USA** (Fermilab, Purdue University, Rutgers University, Syracuse University, BNL, University of New Mexico)

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Radiation effects in silicon detectors

I) Increase of the leakage current:
   
   Increase of the shot noise: $F(\omega) = qI/\pi$
   Decrease of the S/N ratio
   Increase of power dissipation: $P = V \times I$
   Increase of voltage drop on bias resistors: $\Delta V = R \times I$

II) Variation of the depletion voltage ($V_{\text{dep}}$):
   
   $V_{\text{dep}} > V_{\text{breakdown}}$: the detector cannot operate fully depleted
   Decrease of the charge collection efficiency
   Decrease of the S/N ratio

III) Charge trapping:
   
   Decrease of trapping time constant and mean free path
   Decrease of the charge collection efficiency
   Decrease of the S/N ratio
Leakage current density increase

- The leakage current density \( J \) linearly increases with the particle fluence \( \Phi \):
  \[
  J = \alpha \times \Phi
  \]

- The \( \alpha \) parameter scales with the Non Ionizing Energy Loss (NIEL) of the impinging radiation.

- Possible approach for limiting the leakage current density \( J \):
  only by decreasing the operating temperature \( T \).

  \[ J(T_R) = J(T) \left( \frac{T_R}{T} \right)^2 \exp \left( - \frac{E}{2k_B} \left[ \frac{1}{T_R} - \frac{1}{T} \right] \right) \]

  \( (J \text{ scales by a factor } \approx 2 \text{ every } 7.5 \text{ K}). \)
Oxygen and effective doping concentration ($N_{\text{eff}}$)

1. In n-type silicon, radiation induced donor removal and deep acceptor generation causes the Space Charge Sign Inversion (SCSI) effect: the effective doping concentration ($N_{\text{eff}}$), which is initially positive becomes negative. After SCSI the $|N_{\text{eff}}| \propto V_{\text{dep}}$ increase is mitigated for charged hadrons and ions (not for neutrons) in Diffusion Oxygenated Float Zone (DOFZ) silicon, where $[O] > 10^{17}$ cm$^{-3}$ in the substrate.

2. After $\approx 20$ days at RT since irradiation, $|N_{\text{eff}}| \propto V_{\text{dep}}$ reaches a minimum and starts to increase up to saturation (reverse annealing). The reverse annealing amplitude is decreased for charged hadrons and ions (not for neutrons) in DOFZ Si, where $[O] > 10^{17}$ cm$^{-3}$.

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Czochralski (CZ) and Magnetic Czochralski (MCZ) silicon

Advantages:
1. **Intrinsic higher oxygen concentration** in CZ ([O]≈8-10×10^{17} cm^{-3}) and MCZ ([O]≈4-10×10^{17} cm^{-3}) than Float Zone (FZ, [O]<4×10^{16} cm^{-3}) or Diffusion Oxygenated FZ (DOFZ, [O]≈1-4×10^{17} cm^{-3}) Si.
2. No extra process needed for substrate oxygenation.
3. High resistivity (≈1-2 kΩ×cm) p- or n-type CZ and MCZ wafers **commercially available**.
4. CZ and MCZ wafers have **higher diameters** (300 mm) than FZ and DOFZ (150 mm).

Attention has to be considered for avoiding **thermal donor activation** (V_{dep} increase) during processing steps at 450 °C for n-type CZ and MCZ.

**Test beam results:**
MCZ microstrip detector prototype (AC coupled, with 1024 strips, 6 cm long, w=10 µm, p=50 µm) has been tested by 225 GeV muon beam at CERN with AV1 chips (resolution 10 µm and S/N=10).

Magnetic Czochralski (MCZ) silicon: thermal donor generation

\([O] \approx 4 \times 10^{17} \text{ cm}^{-3}\) in MCZ silicon is suitable to take advantage of thermal donor generation at 450 °C for processing n-type detectors starting from p-type MCZ substrates.

\[
N_{TD} = \left( \frac{a}{b} \right) \left( C_{io} \right)^{\chi} \frac{1}{\left| N_d - N_A \right|^{2}} \left( 1 - e^{-b \times D_i \times C_{io} \times t} \right)
\]

- \(N_{DT}\) is the thermal donor density;
- \(a\) and \(b\) are experimental parameters.
- \(C_{io}\) is the concentration of interstitial oxygen in silicon;
- \(\chi\) is a constant (2 < \(\chi\) < 3);
- \(\left| N_d - N_A \right|\) is the free carrier concentration;
- \(D_i\) is the diffusion constant of interstitial oxygen;
- \(t\) is the time at a given temperature;

(J. Harkonen et al., 4th RD50 Workshop, http://rd50.web.cern.ch/rd50/4th-workshop/)
Magnetic Czochralski (MCZ) silicon: radiation hardness

(Z. Li et al., IEEE TNS 51 (2004) 1901)

$^{60}$Co $\gamma$-ray irradiation
1. SCSI for FZ Si,
   $N_{\text{eff}} < 0$ due to deep acceptor generation.
2. No SCSI for MCZ and DOFZ Si,
   $N_{\text{eff}}$ increases due to thermal donor activation.

Model for space charge build up in $\gamma$-irradiated Si
1. $N_{\text{eff}}$ linearly increases with radiation Dose
   $N_{\text{eff}} = N_{\text{eff,0}} + \beta_\gamma ([O]) \times \text{Dose}$
2. $\beta_\gamma$ linearly depends on the substrate oxygen concentration
   $\beta_\gamma = m [O] + q$
   with $m = 4.99 \times 10^{-9}$ Mrad$^{-1}$
   $q = 1.94 \times 10^9$ Mrad$^{-1}$ cm$^{-3}$

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RD50
Magnetic Czochralski (MCZ) silicon: radiation hardness


Low energy proton irradiation
1. SCSI occurs in **FZ**, **DOFZ** and **MCZ** Si.
2. **MCZ** detectors present a lower $V_{dep}$ variation rate after SCSI than **FZ** and **DOFZ** devices.
3. Oxygen mitigates deep acceptor formation during proton irradiation.

**Proton (p) and neutron (n) irradiations**
The positive effect of high [O] on $|N_{eff}| \propto V_{dep}$ is strongly reduced when detectors are irradiated by neutrons.
Positive effect of substrate oxygen: microscopic

**General microscopic considerations**

1) formation of vacancy (V) related defects such as: VO (neutral at RT) or VO+V=V₂O and V₂ related defects (deep acceptors) are competitive processes: VO is enhanced by "high" [O]:

   a. **γ-rays**: point defects (i.e., interstitial I and vacancies V) in DOFZ, MCZ and CZ, [O]>>[V]: VO enhanced, V₂O and/or V₂ related defects suppressed

   b. **Neutrons**: clusters (i.e., high defect density regions) in DOFZ, MCZ and CZ, [O]<<[V]: V₂O and/or V₂ related defects present;

   c. **Protons**: point defects and clusters: intermediate condition.

2) Thermal donor activation during irradiation is characteristic for high [O].

### 60Co γ-ray irradiation of FZ and DOFZ silicon

<table>
<thead>
<tr>
<th>Effect on J$_{inh}$</th>
<th>FZ silicon</th>
<th>DOFZ silicon</th>
<th>Dose dependence</th>
<th>Microscopic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present</td>
<td>Reduced</td>
<td>Quadratic → Second order defect</td>
<td>VO+V=V₂O?</td>
</tr>
<tr>
<td>Effect on N$_{off}$</td>
<td>Yes (85% in FZ)</td>
<td>Yes (10% in FZ)</td>
<td>Linear</td>
<td>TDD2?</td>
</tr>
<tr>
<td>Energy level</td>
<td>E$_{c}$=0.68 eV</td>
<td>E$_{c}$=0.054 eV</td>
<td>E$_{c}$=0.225 eV</td>
<td>Acceptor (neutral at RT)</td>
</tr>
<tr>
<td>BD center</td>
<td>Shallow Donor</td>
<td>Deep Acceptor</td>
<td>Deep Acceptor</td>
<td></td>
</tr>
</tbody>
</table>

E. V. Monakhov et al. in Phys. Rev. B 68 233203 (2003), investigating the V₂ isothermal annealing at 250 °C by DLTS, proposed that the X center (E$_{c}$=0.47 eV), whose density linear depends on [O], observed after that V₂ has been annealed out, is V₂+O=V₂O.
Czochralski (CZ) silicon: radiation hardness

(E. Fretwurst et al., 3rd RD50 Workshop, http://rd50.web.cern.ch/rd50/3rd-workshop/)

190 MeV pions

24 GeV protons

1) SCSI in **FZ** and **DOFZ** after high energy pion or proton irradiation:
   - the linear $V_{\text{dep}}$ increase for **FZ** and **DOFZ** at high fluences is due to predominant acceptor generation (low $[O]$).
2) No SCSI in **CZ** after high energy pion or proton irradiation:
   - the linear $V_{\text{dep}}$ increase for **CZ** at high fluences is due to predominant donor generation (high $([O])$).
3) The linear $V_{\text{dep}}$ increase rate at high fluences is lower for **CZ** than for **FZ** and **DOFZ**.
Thin detectors

Why thin detectors?
1. Smaller leakage current: $I_{\text{leak}} \propto W$
2. Smaller depletion voltage: $V_{\text{dep}} = qW^2N_{\text{eff}}/2\varepsilon \propto W^2$
3. At S-LHC fluences, charge collection for planar detectors is limited by carrier mean free path, not by the $W \approx 280-300$ $\mu$m detector thickness

Example.
The trapping time constant ($\tau$) rapidly decreases with fluence ($\Phi_{\text{1-MeV n}}$): $1/\tau_{e,h} = \beta_{e,h} \times \Phi_{\text{1-MeV n}}$
with $\beta_e = 5.7 \times 10^{-16}$ cm$^2$/ns, $\beta_h = 7.7 \times 10^{-16}$ cm$^2$/ns.

At $\Phi_{\text{1-MeV n}} = 5 \times 10^{15}$ cm$^{-2}$ the carrier mean free path ($L = v \times \tau$) even at the saturated carrier velocity ($v_{\text{sat,e}} = 1.1 \times 10^7$ cm/s, $v_{\text{sat,h}} = 7.5 \times 10^6$ cm/s) reduces to $L_e = 40$ $\mu$m for electrons and $L_h = 20$ $\mu$m for holes.
Thin detectors: FZ thinned devices (W=50 µm)

1. Tetra Methyl Ammonium Hydroxide (TMAH) etching from back.
2. Phosphorous deposition and diffusion from back.
3. Metal deposition from back.

ITC-IRST, Trento
(E. Ronchin et al., NIM A 530 (2004) 134)

<100> silicon wafer

Photograph: front (left) and back (right) view of thinned devices
Area: 10 mm² and I<1 nA/cm² at 20 V

Semiconductor Detector Laboratory, MPI, Munich
(L. Andricek et al., 1st ECFA Workshop, Montpellier, November 2003)

Photograph: front (left) and back (right) view of thinned devices
Area: 10 mm² and I<1 nA/cm² at 20 V

SEM: back view of a thinned device
Areas: 1 mm² - 20 mm² and I<1 nA/cm² at 20 V
1. $\beta = \Delta |N_{ef}| / \Delta \Phi_p = 3.6 \times 10^{-3}$ cm$^{-1}$ comparable with DOFZ.
2. $V_{dep} \approx 64$ V for $W=50$ µm at $\Phi_{\text{max}} = 8.6 \times 10^{15}$ cm$^{-2}$:
   $\rightarrow V_{dep} \approx 2300$ V for $W=300$ µm at $\Phi_{\text{max}} = 8.6 \times 10^{15}$ cm$^{-2}$;
   $\rightarrow W < 300$ µm are required at S-LHC.

1. Stable damage component.
2. Short-term component (positive on $V_{dep}$).
3. Long term component: reverse annealing (negative on $V_{dep}$).
4. SCSI reached before $\Phi_{\text{min}} = 9.5 \times 10^{13}$ p/cm$^2$. 
Thin detectors: epitaxial layer (W=50 µm) on CZ substrate

(Hamburg Group, NIM A 515 (2003) 665)

1. Starting material: low resistivity ($\rho<0.02 \ \Omega\cdot cm$) 300 µm thick Czochralski (CZ) silicon substrate doped by Sb donors.

2. A thin (50 µm) low resistivity ($\rho=50 \ \Omega\cdot cm$), epitaxial silicon layer doped by P donors has been grown by ITME (Warsaw, Poland) on the CZ substrate forming a simple n-n$^+$ structure.

3. p$^+$-n junction formed by B implantation on the epitaxial layer in a standard way using planar technology by CiS (Institute for Micro Sensors gGmbH, Erfurt, Germany) in order to obtain p$^+$-n-n$^+$ silicon detectors.

4. The detector active thickness is that of the epitaxial layer.

Advantages

1. Thin detectors present moderate depletion voltages even if highly doped ($V_{\text{dep},0}=qW^2N_{\text{eff},0}/2\varepsilon$), with the advantage that the Space Charge Sign Inversion (SCSI) effect of the active layer, if present, is moved to higher fluences.

2. The CZ substrate is the backside n$^+$ ohmic contact, which is not depleted due to the high Sb doping level and acts also as a mechanical support for the thin epitaxial detector.

3. Due to the high oxygen concentration in the CZ substrate ($[O]\approx 10^{18} \text{ cm}^{-3}$), O diffuses into the epitaxial layer during the high temperature growth process improving the detector radiation hardness.
Thin detector radiation hardness: epitaxial vs thinned


20-24 GeV proton irradiation

FZ thinned (type inverted to p)
- short term $\rightarrow V_{dep}$ decrease
- long term $\rightarrow V_{dep}$ increase
  (predominant acceptor generation)

Epitaxial (no type inverted)
- short term $\rightarrow V_{dep}$ increase
- long term $\rightarrow V_{dep}$ decrease
  (predominant acceptor generation)
- no $V_{dep}$ reverse annealing at RT!

FZ thinned (type inverted to p)
- "low" [O]
  predominant acceptor generation during irradiation

Epitaxial (no type inverted)
- "high" [O]
  predominant donor generation during irradiation
Epitaxial sensors can be type-inverted by neutrons ("low" [O] for cluster defects → predominant acceptor generation during irradiation) but the high doping of the epitaxial layer moves the SCSI point to high fluences, and $V_{dep}$ is expected to be not higher than 125 V at $\Phi_{eq}=10^{16}$ cm$^{-2}$, so confirming the extreme radiation hardness of this technology.
3-D detectors

-Called 3-D because, in contrast to silicon planar technology, have three dimensional (3-D) electrodes penetrating the silicon substrate.
-Important researches are now under investigation by a collaboration (not in RD50) within Brunel Univ., Hawaii Univ., Stanford Univ., and CERN (see talk by A. Kok, tomorrow).

Advantages:
-depletion thickness depends on p⁺ and n⁺ electrode distance, not on the substrate thickness;
-lower collection length than planar technology;
-lower charge collection time than planar technology.
3-D detectors: going on activity in RD50

(M. Boscardin et al., 4th RD50 Workshop, http://rd50.web.cern.ch/rd50/4th-workshop)

- Detector masks: Glasgow University
- Deep reaction ion etching: CNM, Barcelona
- Detector processing: ITC-IRST, Trento

<table>
<thead>
<tr>
<th></th>
<th>Surface</th>
<th>Top</th>
<th>Botton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly</td>
<td>1.05μm</td>
<td>0.8μm</td>
<td>0.7μm</td>
</tr>
<tr>
<td>TEOS</td>
<td>0.96μm</td>
<td>0.7μm</td>
<td>0.6 μm</td>
</tr>
</tbody>
</table>
Semi-3D detectors

(see talk by G. Kramberger, tomorrow)

Single-side detectors with alternative p- and n- strips on the front side.

Advantages:
2. After SCSI, the depletion occurs from both sides reducing the depletion voltage by factor 2.5.

Under investigation:
Complex electric field distribution before and after SCSI.

Stripixel detectors


Pixel electrodes arranged in a projective X-Y readout.

Characteristics:
1. Projective readout of double-sided strip detectors minimizing the read-out channels;
2. Two-dimensional position resolution of pixel electrode geometry;
3. Single-side detector process with double metal technology;
4. Key parameter: standard deviation of the collected charge distribution: $\chi \approx 10 \, \mu m$.

- Individual pixels alternatively connected to X- and Y-read-out.
- Charge must be collected at least by two pixels.
- Key condition: $\chi \geq$ pitch
- Resolution can be better than pitch.

- Each pixel is divided in two parts (X- and Y-cell).
- Charge must be collected at least by one X- and by one Y-cell.
- Key condition: $\chi \geq$ interleaved distance between X- and Y-cells
- If pitch $> \chi$ the resolution is fixed by the pitch.

Alternative to macro-pixel detectors in the S-LHC upgrade between 15 cm and 60 cm?
n^+-p detectors on DOFZ substrate


1. CCE(V) is improved if the read-out is at the high electric field contact: n^+-p detectors (no SCSI) better than p^+-n sensors after SCSI.
2. DOFZ p-type substrates are expected to be more radiation hard than FZ p-type Si.

Miniature n^+-p microstrip detectors on DOFZ substrate

Area: 1x 1 cm^2
Thickness: 280 µm
Number of strips: 100
Read-out: SCT128 chip at 40 MHz
Source for CCE: \(^{106}\)Ru

Charge, collected at 900 V bias after 7.5x10^{15} 24-GeV p/cm^2 (5x10^{15} 1-MeV equivalent neutrons/cm^2) for DOFZ p-type detector, is 6500 electrons (corresponding to the charge deposited in a 90 µm thick un-irradiated silicon sensor).
Hypothesis:
1. Pixel dimensions: 70×70 \( \mu \text{m}^2 \) to cope with increased track density at SLHC.
2. \( T=-10 \) °C.
3. Read-out at the high electric field side:
   - n-side for FZ and DOFZ (type inverted);
   - p-side for Cz and Epitaxial (no type inverted).
4. \( V_{\text{bias}} \): 600 V for FZ, DOFZ and CZ;
   150 V for Epitaxial.

(see talks by T. Lari and G. Kramberger, tomorrow)

\( 10^{15} \ n_{\text{eq}}/\text{cm}^2 \) fluence:
- DOFZ better than FZ when the latter is no longer fully depleted at 600 V.
- DOFZ (n-side read-out) slightly better than CZ (p-side read-out).
- Epitaxial signal very low (because of thin sensor).

\( 10^{16} \ n_{\text{eq}}/\text{cm}^2 \) fluence:
- All detectors are similar (trapping dominant).
## CCE in SiC and GaN

(A. Blue et al., 4th RD50 Workshop, http://rd50.web.cern.ch/rd50/4th-workshop/)

<table>
<thead>
<tr>
<th>Material</th>
<th>Unirradiated CCE</th>
<th>Irradiated CCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>100 % (MIPS) [2]</td>
<td>50 % (2x $10^{14}$ 24GeV protons/cm$^2$) [2]</td>
</tr>
<tr>
<td>SiC (100 μm bulk V doped)**</td>
<td>60 % (5.486 Am$^{241}$ alpha) [3]</td>
<td>50 % (10$^{13}$ 300 MeV/c pions/cm$^2$) [3]</td>
</tr>
<tr>
<td>SiC (epi layer 30 μm)</td>
<td>90 % (5.486 Am$^{241}$ alpha) [4]</td>
<td>60 % (10$^{14}$ 24 GeV/c protons/cm$^2$) [5]</td>
</tr>
<tr>
<td>Diamond</td>
<td>24 % (Mips) [6]</td>
<td>18 % (10$^{13}$ 300 MeV/c pions/cm$^2$) [6]</td>
</tr>
</tbody>
</table>
| GaN            | 95 % (5.486 Am$^{241}$ alpha) | 77 % (10$^{14}$ 1 MeV neutrons/cm$^2$)
10% (10$^{15}$ 1MeV neutrons/cm$^2$)
5% (10$^{16}$ 1MeV neutrons/cm$^2$) |

Si assumed to have 100 % CCE for all radiation types before irradiation
** 10$^{18}$ cm$^{-3}$ Vanadium (V) doped  SiC maximum CCE 60 % [7]

Summary

General considerations:
1. Leakage current can be limited only by decreasing temperature ($\times 2$ every 7.5 K);
2a. Charge collection at the S-LHC fluences ($\geq 4-6 \times 10^{15}$ cm$^{-2}$) is limited by carrier mean free path and for planar technologies is less dependent on the detector thickness W.
2b. Benefits from W decrease: 1) $I_{\text{leak}} \propto W$; B) $V_{\text{dep}} \propto N_{\text{eff}} \times W^2$; C) $N_{\text{eff,0}} \propto V_{\text{dep,0}} / W^2$
3. High [O] required for limiting $V_{\text{dep}}$ after irradiation thanks to donor generation (BD center) and mitigation of the acceptor generation (VO and $V_2O$ or $V_2$ related defects are competitive processes): interesting results for MCZ (no SCSI with $\gamma$-rays), CZ (no SCSI with high energy charge hadrons), and Epitaxial on CZ (no reverse annealing for high energy charge hadrons);

Different technologies are under investigation in RD50:
1. Experimental data on different technologies are fundamental inputs for devices simulations in order to determine the W, [O] and $N_{\text{eff,0}}$ values for the LHC upgrade. W can be decreased accordingly to the maximum $\Phi$ and CCE required.
2. CZ and MCZ take advantage from higher [O] than FZ and DOFZ.
2. Thinned devices (50 $\mu$m) take advantage from $V_{\text{dep}} \propto W^2$, but small area sensors.
3. Epitaxial (50 $\mu$m) on CZ takes advantage from $V_{\text{dep}} \propto W^2$, high [O] and high $N_{\text{eff,0}}$ (SCSI postponed), large area sensors. Possible to increase the thickness to 100 $\mu$m to increase CCE.

Different detector layouts are under investigation in RD50:
1. 3-D ($V_{\text{dep}}$ depends on the p-n electrode distance not on W). Semi 3-D ($V_{\text{dep}}$ lower by a factor 2.5, but complex electric field), Stripixel (Single-side detector process with double metal technology for two-dimensional read-out, alternative to macro-pixels).
More material on the RD50 WEB site:
http://rd50.web.cern.ch/rd50/