Development of
Radiation Hard Sensors for
Very High Luminosity Colliders
- CERN-RD50 project -

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On behalf of CERN RD50 Collaboration

Complete author list at http://www.cern.ch/rd50
LHC: $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  
10 years operation
fluence of fast hadrons : $\phi(R = 4\text{cm}) \sim 3\cdot10^{15} \text{ cm}^{-2}$

Possible LHC upgrade (“Super-LHC”):  
$\mathcal{L} = 10^{35}\text{cm}^{-2}\text{s}^{-1}$ 
5 years operation

**Anticipated Radiation Environment**  
(CERN-TH/2002-078)

<table>
<thead>
<tr>
<th>Radius (cm)</th>
<th>Fluence of fast hadrons [cm$^{-2}$]</th>
<th>Dose [kGy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$1.6\times10^{16}$</td>
<td>4200</td>
</tr>
<tr>
<td>22</td>
<td>$8.0\times10^{14}$</td>
<td>350</td>
</tr>
<tr>
<td>115</td>
<td>$1.0\times10^{14}$</td>
<td>9.3</td>
</tr>
</tbody>
</table>

Present semiconductor detector technology is not able to operate at such high fluences/doses
RD50 - Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

280 Members from 55 Institutes

Main Objective

Development of ultra-radiation hard semiconductor detectors, able to withstand fast hadron fluences and doses as expected for luminosity upgrade of the LHC to $10^{35}$ cm$^{-2}$s$^{-1}$.

47 European and Asian institutes (34 west, 11 east)
Belgium (Louvain), Czech Republic (Prague (2x)), Finland (Helsinki (2x), Oulu), Germany (Berlin, Dortmund, Erfurt, Halle, Hamburg, Karlsruhe), Greece (Athens), 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)

7 North-American institutes
Canada (Montreal), USA (Fermilab, Purdue University, Rutgers University, Syracuse University, BNL, University of New Mexico)

1 Middle East institute
Israel (Tel Aviv)

Detailed member list: http://cern.ch/rd50

RD50 - Scientific objectives and strategies

Three R&D strategies:

♦ Material engineering
  - Defect engineering of silicon (oxygenation, dimers, …)
  - New detector materials (SiC, …)

♦ Device engineering
  - Improvement of present planar detectors
    (3D detectors, thin detectors, cost effective detectors, …)

♦ Variation of detector operational conditions
  - Low temperature operation
  - Forward bias operation

Further key tasks:

♦ Basic studies
♦ Defect modeling and device simulation
Macroscopic Radiation Damage

1. Change of $V_{\text{dep}}$, $N_{\text{eff}}$ and annealing behavior

$$\Delta N_{\text{eff}} = N_{C0} \left( 1 - e^{-c \cdot \phi} \right) + \left[ g_c + g_a e^{-\frac{t}{\tau_a(T)}} + g_y \left( 1 - e^{-\frac{t}{\tau_y(T)}} \right) \right] \phi$$

![Graph showing changes in $N_{\text{eff}}$ and annealing behavior with $V_{\text{dep}}$ and $\Phi_{\text{eq}}$.]

Before SCSI

$n^+$

Al depleted

Al

After SCSI

$n^+$

p$^+$

inverted

n$^+$

Data from R. Wunstorf '92

After inversion and annealing saturation

$$N_{eff} \sim \beta \cdot \phi$$

2. Increase of leakage current and annealing behaviour

\[ \frac{I_{dep}}{Volume} = \alpha \cdot f \]

\[ \alpha = 3 \cdot 10^{-17} \text{ A/cm} \]
3. Deterioration of the charge collection efficiency

- Trapping of generated e-h at defects
- Under-depletion due to high $N_{\text{eff}}$
- SCSI: keeping high electric field on the read out side will significantly improve charge collection

Signal ($^{106}\text{Ru } \beta$–source) degradation as a function of fluence in a non-homogeneous irradiated detector (n-in-n).
Defect Engineering of Silicon

Impurities incorporation to prevent the formation of divacancy related defects

→ Oxygen can getter vacancies reducing the formation of deeper levels as \( V_2O \)

\[
\begin{align*}
O \quad &\rightarrow \quad VO \quad \text{(not harmful at room temperature)} \\
V \quad &\leftrightarrow \quad VO \quad \rightarrow \quad V_2O \quad \text{(negative space charge)}
\end{align*}
\]

Benefit with gamma and 24GeV/c protons in terms of \( \beta \). No benefit with neutrons.

[RD48-NIMA 465(2001) 60]
Different kind of Si materials investigated by RD50

<table>
<thead>
<tr>
<th>Material</th>
<th>Symbol</th>
<th>$\rho , \Omega , \text{cm}$</th>
<th>$[O_i] , \text{cm}^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard n- or p-type FZ</td>
<td>STNFZ</td>
<td>$1-7 \cdot 10^3$</td>
<td>$&lt; 5 \cdot 10^{16}$</td>
</tr>
<tr>
<td>Diffusion Oxygenated FZ p or n-type</td>
<td>DOFZ</td>
<td>$1-7 \cdot 10^3$</td>
<td>$\sim 1-2 \cdot 10^{17}$</td>
</tr>
<tr>
<td>Epi-layer 50 µm on CZ n-type ITME</td>
<td>EPI</td>
<td>50-100</td>
<td>substrate: $1 \cdot 10^{18}$</td>
</tr>
<tr>
<td>Czoehralski Sumitomo, Japan</td>
<td>CZ</td>
<td>$1.2 \cdot 10^3$</td>
<td>$\sim 8-9 \cdot 10^{17}$</td>
</tr>
<tr>
<td>Magnetic Czoehralski Okmetic Finland</td>
<td>MCZ</td>
<td>$1.2 \cdot 10^3$</td>
<td>$\sim 5-9 \cdot 10^{17}$</td>
</tr>
</tbody>
</table>

- Microscopic study of radiation induced defects
- Changes in the macroscopic parameters of single pad detectors
- Performance of segmented devices
Microscopic study of radiation induced defects

Interpretations for the $V_2O$ energy level structure

- “I defect”  
  Acceptor + Donor  
  $E_c - 0.545 \text{ eV} + E_v + 0.23 \text{ eV}$  
  induced by irradiation  
  [I.Pintilie et al., APL 82 (13), 2169 (2003)]

- “X-defect”  
  Double-acceptor  
  $E_c - 0.467 \text{ eV} + E_c - 0.233 \text{ eV}$  
  irradiation + annealing of $V_2$  
  [E.Monakhov et al., PRB 65(2002)233207]

I defect responsible for type inversion in Standard FZ Si after $^{60}$Co $\gamma$–irradiation and for increase of leakage current with dose. It appears in oxygen lean Si.
Presence of a bistable donor which overcompensate radiation induced deep acceptors

It has been proven that the beneficial effect of oxygen consists not only in suppression of deep acceptors but creation of donors as well!!

Study of the role of shallow donors in oxygen enriched material in progress in the low T range 4.2- 80K

Macroscopic Effects: recent results on Czochralski Si

190 MeV $\pi$ irradiation Villigen
Cz from Sumitomo Sitix, Japan

24 GeV/c $p$ irradiation CERN
Cz from Sumitomo Sitix, Japan

Data From G. Lindstrom et al.

- No type inversion (SCSI)
- Reverse current and charge trapping comparable to FZ silicon
10-30 MeV proton Jyväskylä, Finland
Magnetic Cz-Si Okmetic, Finland

Improvement in $V_{\text{dep}}$, $N_{\text{eff}}$
Observed SCSI
Reduction of reverse current ??

900 MeV electron
Elettra (Trieste, Italy)
CZ-Si Sumitomo Japan, EPI-ITME

Decrease of CCE observed only beyond $10^{15}$ ecm$^{-2}$ for CZ and EPI
New Materials: Silicon Carbide and GaN

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>Si</th>
<th>4H- SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$ [eV]</td>
<td>5.5</td>
<td>1.12</td>
<td>3.3</td>
<td>3.39</td>
</tr>
<tr>
<td>$\mu_e$ [cm$^2$/Vs]</td>
<td>1800</td>
<td>1450</td>
<td>800</td>
<td>1000</td>
</tr>
<tr>
<td>$\mu_h$ [cm$^2$/Vs]</td>
<td>1200</td>
<td>450</td>
<td>115</td>
<td>30</td>
</tr>
<tr>
<td>e-h pair creation [eV]</td>
<td>13</td>
<td>3.6</td>
<td>7.6-8.4</td>
<td>8.9</td>
</tr>
<tr>
<td>Displacement [eV]</td>
<td>43</td>
<td>13-20</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>Signal [e/$\mu$m]</td>
<td>36</td>
<td>89</td>
<td>51-55</td>
<td>~50</td>
</tr>
<tr>
<td>Density [g/cm$^3$]</td>
<td>3.515</td>
<td>2.329</td>
<td>3.22</td>
<td>6.15</td>
</tr>
</tbody>
</table>

- Wide bandgap
  ⇒ lower leakage current than silicon

- Higher displacement threshold than silicon
  ⇒ radiation harder than silicon (?)

- Signal:
  ⇒ more charge than diamond

Common SiC RD50 test structures under way, coordinated by Hamburg, Glasgow, Tel Aviv. Several research activities already in action.
**Epitaxial SiC Schottky Barriers**

- n epilayer $N_{eff} \sim 5 \times 10^{13} \text{cm}^{-3}$ 40$\mu$m by IKZ Berlin on CREE substrate
- Schottky and Ohmic contacts produced by Alenia System
- Charge collection efficiency tested with $\alpha$ $^{241}$Am and $\beta$ $^{90}$Sr
- Irradiation tests with 24GeV proton in progress

\[ Q \sim 2200e \text{ corresponding to CCE 100\% at } V_{dep} = 60V \]

<table>
<thead>
<tr>
<th>Circular Schottky contact</th>
<th>Ohmic contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ni_2Si , \phi = 1.5 \text{ mm}$</td>
<td>$Ti/Pt/Au$</td>
</tr>
<tr>
<td>n, 4H – SiC, 40 $\mu$m epitaxial</td>
<td>C-face</td>
</tr>
<tr>
<td>n$^+$, 4H – SiC, 360 $\mu$m substrate</td>
<td></td>
</tr>
</tbody>
</table>

Data from F. Nava, S. Sciortino, M. Bruzzi et al.
Proton-irradiation induced defects in epitaxial 4H-SiC Schottky Barriers

Research activity by the group of Bologna in collaboration with Torino

- n epilayer 7µm
- N_{eff} \sim 7 \times 10^{15} \text{cm}^{-3}
- Schottky Barriers Ti or Ni
- Ohmic contacts Ti/Ni/Ag
- Deep levels by C-DLTS
- 6.5MeV p up to 6.4 \times 10^{13} \text{cm}^{-2}

Six traps detected

- E = 0.18 - 1.22 \text{eV}
- s = 10^{-13} - 10^{-18} \text{cm}^{-2}
- N_t = 10^{11} - 5 \times 10^{14} \text{cm}^{-3}

The creation of energy levels with N_t of the same order of magnitude of the doping density does not affect the charge transport in the detector. This probably due to the shallow energies of the traps.
2. SiC Triode Detector structures

Produced and tested at Ioffe Physico-Technical Institute, St. Petersburg, Russia

♦ Development of radiation-hard triode (transistor) detector structures based on SiC layers. Triode detector to get amplification of a charge generated in the detector bulk and realize the gain of the detector signal compared to that in the diode structure.

♦ p-type epilayer SiC grown by sublimation epitaxy on n⁺ SiC wafers:
  - 6H-SiC (processed at Ioffe Institute) 10µm
  - 4H-SiC (processed in Linkoping University, Sweden) 30µm

Emitter: n⁺ SiC wafer Base: p⁺ epi-layer Collector: Schottky barrier

♦ Irradiation at Ioffe Institute with 8 MeV protons up to $10^{13}$-$10^{14}$cm⁻², corresponding to $10^{16}$cm⁻² 1GeV protons

♦ Charge collection efficiency investigated with $\alpha$-particles $E_\alpha = 3.5 - 5.45$MeV
Results on Triode epitaxial SiC Detector after irradiation with 8 MeV p up to $10^{14}$cm$^{-2}$

<table>
<thead>
<tr>
<th>Material</th>
<th>6H-SiC</th>
<th>4H-SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence [cm$^{-2}$] and particle</td>
<td>$2 \cdot 10^{13}$ 8MeV protons</td>
<td>$10^{14}$ 8MeV protons</td>
</tr>
<tr>
<td>Eq Fluence [cm$^{-2}$] 1 GeV proton</td>
<td>$1.3 \cdot 10^{15}$</td>
<td>$1.1 \cdot 10^{16}$</td>
</tr>
<tr>
<td>thickness of the epilayer [μm]</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>$N_{\text{eff}}(0)$ [cm$^{-3}$]</td>
<td>$7.5 \cdot 10^{14}$</td>
<td>$(3-5) \cdot 10^{15}$</td>
</tr>
<tr>
<td>$N_{\text{eff}}(\Phi)$ [cm$^{-3}$]</td>
<td>$1.8-2.6 \cdot 10^{13}$</td>
<td></td>
</tr>
<tr>
<td>$V_{\text{dep}}(0)$ [V]</td>
<td>125</td>
<td>8500</td>
</tr>
<tr>
<td>$V_{\text{dep}}(\Phi)$ [V]</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Gain at $V_{\text{dep}}$</td>
<td>18</td>
<td>Not achieved</td>
</tr>
<tr>
<td>$\alpha$-particle energy</td>
<td>3.5 MeV</td>
<td>5.5 MeV</td>
</tr>
<tr>
<td>CCE % after irradiation</td>
<td>~ 100 %</td>
<td>~ 80 %</td>
</tr>
</tbody>
</table>

Data From E. Verbitskaya et al.

$\phi = 10^{14}$ cm$^{-2}$ 8MeV p

$E_\alpha = 5.45$ MeV

3. SiC p\textsuperscript{+}n junction detectors

Research activity of the Perugia group in collaboration with Florence, IMM-CNR Bologna and INSA-CEGELY, Lyon France

\[ W = 40 \ \mu m \quad \text{N}_{\text{eff}} = 1.1 \cdot 10^{15} \text{cm}^{-3} \]

\[ V_{\text{dep}} \sim 1600 \text{V} \quad \text{Tested at Florence with } \beta \text{ from } ^{90}\text{Sr} \]

At 900V from C-V, depletion depth \( \sim 30 \mu m \), charge collected 1720e \( \rightarrow \) CCE 100%

Data from F. Moscatelli et al.
Semi-Insulating SiC detectors

Research activity of Glasgow, Surrey, Vilnius. Bulk SiC has incomplete charge collection (no e transport) and suffers for polarisation effects (traps e.g. Vanadium and micropipes)

Simulated CCE of bulk and epi devices up to fluences of $10^{16}$ cm$^{-2}$ in talk N33-3 by Tina Quinn et al.

Data from M. Rahman et al.

Semi-Insulating GaN detectors

Research activity of Vilnius, Glasgow, Surrey

- SI-GaN epitaxial layer on n-type GaN substrate (University of Tokushima Japan)
- Au Schottky contacts 1.5 mm diameter
- Charge Collection tested with $\alpha$-particles $^{241}$Am by Glasgow, Surrey groups
- Irradiated by X rays 600MRad
- Irradiated by neutrons in Ljubljana up to $5 \times 10^{14}$cm$^{-2}$

<table>
<thead>
<tr>
<th>SI-GaN</th>
<th>Energy</th>
<th>Fluence</th>
<th>CCE %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Irradiated</td>
<td></td>
<td></td>
<td>92</td>
</tr>
<tr>
<td>Irradiated by X-rays</td>
<td>10keV</td>
<td>600MRad</td>
<td>100</td>
</tr>
<tr>
<td>Irradiated by neutrons</td>
<td>100keV</td>
<td>$5 \times 10^{14}$cm$^{-2}$</td>
<td>77</td>
</tr>
</tbody>
</table>

Future work: study thicker SI-GaN epilayers

See P. Sellin and J. Vaitkus talks at 2$^{nd}$ RD50 workshop

www.cern.ch/rd50
Device Engineering: 3D and Semi3D detectors

- Semi 3-d devices, proposed by Z. Li, BNL, made in collaboration with US groups
- 3-d devices, proposed by S. Parker.

Holes processing: dry etching, Laser drilling, Photo electrochemical. Present aspect ratio (within RD50) 13:1, target > 30:1

Some result (α spectroscopy) before and after $10^{14}$ 300 MeV/c $\pi$ cm$^{-2}$

Very promising silicon devices for speed and radiation hardness.

Data from P. Roy, 2nd RD50 workshop

Device engineering: Thin SiC detectors by micromachining

The active thickness of the device after heavy irradiation is limited by the effective drift lengths $e:\sim 150\mu m$, $h:\sim 50\mu m$ after $1\text{MeV}$ neutron irradiation at $10^{15}\text{cm}^{-2}$ (Kramberger et al.).

Thin Si detectors $50-100\mu m$: low $V_{\text{dep}}$, limited leakage current

Two technical Approaches:

- **Thinning by micromachining**: research activity of the IRST-Trento group in collaboration with the other italian groups.

Cross section of a thinned silicon detector by IRST-Trento

<table>
<thead>
<tr>
<th>Thickness [$\mu m$]</th>
<th>Leakage Current [nA/cm$^3$]</th>
<th>$V_{\text{dep}}$ [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>80</td>
<td>12</td>
</tr>
<tr>
<td>99</td>
<td>30</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>57</td>
<td>55</td>
<td>$&lt;1$</td>
</tr>
</tbody>
</table>

Ready to be irradiated.

- **Epitaxial Si detectors**: wafers by ITME, processed by CiS, now irradiated up to $9.24\times 10^{15}$ $24\text{GeV}$ p/cm$^2$ at CERN, measurements (Hamburg group) in progress.
Talks of RD50 group members at IEEE 2003 NSS and RTSD

N4-5 Super radiation hard technologies: 3D and widegap detectors M. Rahman et al.
N20-6 Measurement of the Trapping Time constants in proto-irradiated, Si …. O. Krasel et al.
N20-4 Radiation damage in bipolar transistors caused by thermal neutrons, I. Mandic et al.
N26-17 Lithium Ion Irradiation effects on diodes manufactured on epitaxial Si, A. Candelori et al.
N26-20 Radiation damage tests of all-p type termination structures …. C. Piemonte et al.
N26-21 An enhanced device simulation of heavily irradiated silicon … F. Moscatelli et al.
N26-22 TSc analysis of gamma irradiated standard and oxygenated diodes … D. Menichelli et al.
N33-2 Radiation Hardness of high resistivity CZ Si detectors after gamma…. Z. Li et al.
N33-3 Comparison of Bulk and Epitaxial 4H-SiC detectors T. Quinn et al.
N36-117 Single Neutron pixel detectors based on medipix-1 Device, I. Iakubek et al.
R15-2 On the physical processes induced by particle irradiation … by A. Cavallini et.
R18-4 Performance of Silicon Carbide Radiation Detectors, F. Nava et al.
Summary

RD50: Development of Ultra Radiation Hard semiconductor detectors for Super LHC. Promising results have been obtained:

♦ Radiation hardening by defect engineering: reduction of $N_{\text{eff}}$ at high fluences of fast hadrons and gamma doses using oxygen enriched Si (DOFZ, Cz, MCz, epitaxial)

♦ SiC and GaN → good charge collection properties but thicker layers required to be competitive with Si

♦ 3-D detectors: promise of radiation hardness ($\sim 10^{14}$ p/cm$^2$), improvement of aspect ratio, electrodes in progress

♦ device engineering by thinning, edge-less detectors, semi-3d: projects running

♦ Irradiations at very high doses ($10^{16}$ cm$^{-2}$) of single pad and segmented devices in progress