Recent results from RD50

- SLHC
- RD50
  - Improving silicon detectors
  - New material
  - New structures
- Conclusions

D. Bortoletto, Purdue University
Representing RD50

http://cern.ch/rd50
SLHC

- Summer 2001: two CERN tasks forces investigate Physics potential (CERN-TH-2002-078) and accelerator requirements (LHC Project report 626) of an LHC upgrade
- March 2002: LHC IR upgrade collaboration meeting: http://cern.ch/lhc-proj-IR-upgrade
- October 2002: ICFA seminar at CERN on “Future Perspectives in High Energy Physics”
- **2004**: Coordinated Accelerator Research in Europe on High Energy High Intensity Hadron Beams (CARE-HHH) network created:
  - WP 1: Advancements in Accelerator Magnet Technologies (AMT)
  - WP 2: Novel Methods for Accelerator Beam Instrumentation (ABI)
  - WP 3: Accelerator Physics and synchrotron Design (APD)

http://care-hhh.web.cern.ch/
LHC upgrade scenarios

- LHC phase 0: maximum performance w/o hardware changes
- LHC phase 1: maximum performance with arcs unchanged
- LHC phase 2: maximum performance with ‘major’ changes

Nominal LHC performance at 7 TeV corresponds to $L=10^{34}$ cm$^{-2}$s$^{-1}$ in IP1 and IP5 (ATLAS and CMS), halo collisions in IP2 (ALICE) and low-luminosity in IP8 (LHC-b)

**PHASE 2**

- Modify injectors to significantly increase beam intensity and brilliance beyond ultimate value (possibly together with beam-beam compensation schemes)
- Equip SPS with s.c. magnets, upgrade transfer lines, and inject at 1 TeV into LHC
- Install new dipoles with 15-T field and a safety margin of 2 T, which are considered a reasonable target for 2015 and could be operated by 2020 beam energy around 12.5 TeV
### Effective luminosity for various upgrade options

<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>nominal</th>
<th>ultimate</th>
<th>shorter bunch</th>
<th>longer bunch</th>
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<td>protons per bunch</td>
<td>$N_b \times 10^{11}$</td>
<td>1.15</td>
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<td>bunch spacing</td>
<td>$\Delta t_{sep}[\text{ns}]$</td>
<td>25</td>
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<td>average current</td>
<td>$I [\text{A}]$</td>
<td>0.58</td>
<td>0.86</td>
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<td>longitudinal profile</td>
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<td>rms bunch length</td>
<td>$\sigma_z [\text{cm}]$</td>
<td>7.55</td>
<td>7.55</td>
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<td>$\beta^*$ at IP1&amp;IP5</td>
<td>$\beta^* [\text{m}]$</td>
<td>0.55</td>
<td>0.50</td>
<td>0.25</td>
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<td>full crossing angle</td>
<td>$\theta_c [\mu\text{rad}]$</td>
<td>285</td>
<td>315</td>
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<td>Piwinski parameter</td>
<td>$\theta_c \sigma_z/(2\sigma^*)$</td>
<td>0.64</td>
<td>0.75</td>
<td>0.75</td>
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<td>peak luminosity</td>
<td>$L [10^{34} \text{cm}^{-2} \text{s}^{-1}]$</td>
<td>1.0</td>
<td>2.3</td>
<td>9.2</td>
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<td>events per crossing</td>
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<td>19</td>
<td>44</td>
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<td>IBS growth time</td>
<td>$\tau_{x,IBS} [\text{h}]$</td>
<td>106</td>
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<td>nuclear scatt. lumi lifetime</td>
<td>$\tau_N/1.54 [\text{h}]$</td>
<td>26.5</td>
<td>17</td>
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<td>lumi lifetime ($\tau_{gas} = 85 \text{h}$)</td>
<td>$\tau_L [\text{h}]$</td>
<td>15.5</td>
<td>11.2</td>
<td>6.5</td>
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<td>effective luminosity</td>
<td>$L_{eff} [10^{34} \text{cm}^{-2} \text{s}^{-1}]$</td>
<td>0.4</td>
<td>0.8</td>
<td>2.4</td>
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<td>($T_{\text{turnaround}} = 10 \text{h}$)</td>
<td>$T_{\text{run}} [\text{h}]$ optimum</td>
<td>14.6</td>
<td>12.3</td>
<td>8.9</td>
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<td>effective luminosity</td>
<td>$L_{eff} [10^{34} \text{cm}^{-2} \text{s}^{-1}]$</td>
<td>0.5</td>
<td>1.0</td>
<td>3.3</td>
<td>2.7</td>
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<td>($T_{\text{turn}} = 5 \text{h}$)</td>
<td>$T_{\text{run}} [\text{h}]$ optimum</td>
<td>10.8</td>
<td>9.1</td>
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</table>

F. Ruggiero  
CERN  
LHC upgrade scenarios
Reference LHC Luminosity Upgrade: workpackages and tentative milestones

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<td>Cryogenics: IR, magnets &amp; RF</td>
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<td>Beam-beam compensation test at RHIC</td>
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<td>SPS crystal collimation test</td>
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<td>Install new SPS kickers</td>
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<td>Low-noise crab cavity test at RHIC</td>
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<td>LHC Upgrade Conceptual Design Report</td>
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<td>Nominal LHC luminosity 10^{-34}</td>
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<td>Ultimate LHC luminosity 2.3x10^{-34}</td>
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<td>beam-beam compensation</td>
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<td>Double ultimate LHC luminosity 4.6x10^{-34}</td>
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R&D - scenarios & models
- specifications & prototypes
- construction & testing
- installation & commissioning

Reference LHC Upgrade scenario: peak luminosity 4.6x10^{-34}/(cm^2 s)
Integrated luminosity 3 x nominal ~ 200/(fb/year) assuming 10 h turnaround time
new superconducting IR magnets for beta*=0.25 m
phase 2 collimation and new SPS kickers needed to attain ultimate LHC beam intensity of 0.86 A
beam-beam compensation may be necessary to attain or exceed ultimate performance
new superconducting RF system: for bunch shortening or Crab cavities
hardware for nominal LHC performance (cryogenics, dilution kickers, etc) not considered as LHC upgrade
R&D for further luminosity upgrade (intensity beyond ultimate) is recommended: see Injectors Upgrade

F. Ruggiero
CERN
LHC upgrade scenarios
SLHC and tracking

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Proton Energy</td>
<td>7 TeV</td>
<td>12.5 TeV</td>
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<td>Collision rate</td>
<td>40 MHz</td>
<td>80 MHz</td>
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<tr>
<td>Peak luminosity</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>$10^{35}$ cm$^{-2}$s$^{-1}$</td>
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<tr>
<td>Int. luminosity</td>
<td>500 fb$^{-1}$</td>
<td>2500 fb$^{-1}$</td>
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</table>

~100 pile-up events per bunch crossing for 12.5 ns bunch spacing compared to ~20 at $10^{34}$ cm$^{-2}$ s$^{-1}$ and 25 ns

- If same granularity and integration time as now, the tracker occupancy and radiation dose increases by a factor of 10 $\Rightarrow$ implication for radiation damage and physics

M. Hutinen: "Radiation issues for Super-LHC", SLHC Electronics Workshop, 26/2/04, CERN
SLHC and tracking

- $dn^{\text{cha}}/d\eta$/crossing $\approx 600$ and $\approx 3000$ tracks in tracker $\Rightarrow$ more granularity if we aim at same performance we expect from the LHC trackers

$$H \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^- \ m(\text{higgs})=300 \text{ GeV} \text{ all tracks with } p_T<1 \text{ GeV removed}$$

- Integrated Luminosity (radiation damage) dictates the detector technology
- Instantaneous rate (particle flux) dictates the detector granularity

<table>
<thead>
<tr>
<th>R (cm)</th>
<th>$\Phi$ (p/cm$^2$)</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;50</td>
<td>$10^{14}$</td>
<td>Present p-in-n (or n-in-p)</td>
</tr>
<tr>
<td>20-50</td>
<td>$10^{15}$</td>
<td>Present n-in-n (or n-in-p)</td>
</tr>
<tr>
<td>&lt;20</td>
<td>$10^{16}$</td>
<td>RD needed</td>
</tr>
</tbody>
</table>
SLHC and tracking

- CMS and Atlas are starting look at detector configurations:
  - R&D needed below <20 cm
  - Cost issues everywhere
Objective:
- Development of ultra-radiation hard semiconductor detectors for the luminosity upgrade of LHC to $10^{35} \text{ cm}^{-2}\text{s}^{-1}$

Challenges:
- Radiation hardness of semiconductor detectors up to hadron fluences of $10^{16} \text{ cm}^{-2}$
  - Fast signal collection ($25\text{ns} \rightarrow 12.5 \text{ ns bunch crossing}$)
  - Low mass (reduce multiple scattering near interaction point)
  - Cost (big surfaces)

RD50 was formed in November 2001 and approved in June 2002. Presently there are 254 Members from 19 countries:
Belgium (Louvain), Belarussia (Minsk), Canada (Montreal), Czech Republic (Prague (2x)), Finland (Helsinki, Lappeenranta), Germany (Berlin, Dortmund, Erfurt, Friburg, Hamburg, Karlsruhe), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Milano, Padova, Perugia, Pisa, Trento, Trieste, Turin), Lithuania (Vilnius), Poland (Warsaw (2x)), Norway (Oslo (2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona, Valencia), Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Exeter, Glasgow, Lancaster, Liverpool, Sheffield, Guilford), USA (Albuquerque, BNL, Fermilab, Purdue, Rochester, Rutgers, Santa Cruz, Syracuse)
Radiation Damage in Si

- **Bulk damage**
  - Effective doping concentration change
    - $V_{\text{depletion}}$ changes $\Rightarrow$ space charge sign inversion (SCSI). Model with double junction are available and achieve better agreement with data (talk by VC)
  - S/N and charge collection efficiency (CCE) decrease
  - Leakage current increase
    - Shot noise increase, S/N decrease
    - Power dissipation
  - Charge carrier trapping increase
    - Decrease of carriers free path and CCE

- **Surface damage**
  - Accumulation of positive charges in oxide ($\text{SiO}_2$) and Si/SiO$_2$ interface
  - Affects: $C_{\text{interstrip}}$, $V_{\text{breakdown}}$,...

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Daniela Bortoletto Vertex 2005 Nikko Japan
Radiation hard devices

● Silicon Defect Engineering
  ● Understanding radiation damage
    – Macroscopic effects and Microscopic defects
    – Simulation of defect properties & kinetics
    – Irradiation with different particles & energies
  ● Oxygen rich Silicon
    – DOFZ, Cz, MCZ, EPI
  ● Oxy. dimer & hydrogen enriched Si
  ● Pre-irradiated Si
  ● Influence of processing technology

● New Materials
  ● Silicon Carbide (SiC), Gallium Nitride (GaN)
  ● Diamond: CERN RD42 Collaboration (HK’s talk)
  ● Amorphous silicon

● Device Engineering
  ● p-type silicon detectors (n-in-p)
  ● thin detectors
  ● 3D and Semi 3D detectors
  ● Stripixels
  ● Cost effective detectors
  ● Simulation of highly irradiated detectors
  ● Monolithic devices

● Change operational conditions
  ● CERN-RD39 “Cryogenic Tracking Detectors”
Oxygen in Silicon

- Rd48 results showed that DOFz is more rad hard
- This stimulated interest in Cz silicon (also cheaper than FZ)

<table>
<thead>
<tr>
<th>SILICON MATERIAL</th>
<th>Symbol</th>
<th>$\rho$ ((\Omega)cm)</th>
<th>$[O_i]$ cm(^{-3})</th>
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<tbody>
<tr>
<td>Standard n or p-type FZ</td>
<td>FZ</td>
<td>(1-7 \times 10^3)</td>
<td>(&lt;5 \times 10^{16})</td>
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<tr>
<td>Diffusion Oxygenated FZ n or p-type</td>
<td>DOFZ</td>
<td>(1-7 \times 10^3)</td>
<td>(1-2 \times 10^{17})</td>
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<tr>
<td>Magnetic Czochralski Okmetic, Finland</td>
<td>MCz</td>
<td>(~1 \times 10^3)</td>
<td>(8-9 \times 10^{17})</td>
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<tr>
<td>Epitaxial on Cz, ITME</td>
<td>EPI</td>
<td>50-100</td>
<td>(1 \times 10^{17})</td>
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FZ, DOFZ, Cz and MCz Silicon

- **Standard FZ silicon**
  - type inversion at $\sim 2 \times 10^{13}$ p/cm²
  - $N_{\text{eff}}$ increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at $\sim 2 \times 10^{13}$ p/cm²
  - reduced $N_{\text{eff}}$ increase at high fluence

- **CZ silicon and MCZ silicon**
  - **no type inversion** in the fluence range (verified for CZ silicon by TCT)
    \[ \Rightarrow \text{donor generation overcompensates acceptor generation in high fluence range} \]
- Common to all materials (after hadron irradiation):
  - reverse current increase
  - increase of trapping (electrons and holes) within $\sim 20\%$
DOFZ n-in-p

- N-side read-out is advantageous and is used for ATLAS and CMS pixels, LHCb-VELO microstrips.
- P-type DOFZ silicon for n-side read-out detectors (n-in-p).
- Benefit: Single sided processing (almost 50% cheaper than n-in-n, junction side always on read-out side).

CCE (7.5 *10^{15} p/cm^2) > 6,500 e^- (@900V)

G. Casse talk at ATLAS upgrade meeting, Genova, July 2005

Charge collection in planar silicon detectors might be sufficient for all but inner-most Pixel layer!

CCE Studies after annealing on p-type sensors show no adverse effects.
INFN SMART

- RD50 common wafer procurement with Okmetic
- Wafer Layout designed by the SMART Collaboration
- Masks and process by ITC-IRST: LTO, no LTO, different sintering temperatures (avoid thermal donors formation @400-600 °C)
- 10 different strip geometries
- Low dose p-spray (3E12 cm⁻²)
- High dose p-spray (5.0E12 cm⁻²)

Run I p-on-n
22 Wafers Fz, MCz, Epi

Run II n-on-p
24 Wafers Fz and MCz

Test1: Diode+Mos
Test2: GCD, Van der Paw

Square MG-diodes
Microstrip detectors

Round MG-diodes

http://www.infn.it/esperimenti/esperimentien.php?gruppo=5&sigla_naz=SMART

Daniela Bortoletto Vertex 2005 Nikko Japan
Pre-irradiation studies

- **n-type detectors:**
  - Good performances of the detectors in terms of $V_{\text{breakdown}}$, and $C_{\text{interstrip}}$
  - CCE studies with LHC electronics: S/N ~17.5 @ 500 V (FZ S/N ~19.2 @ 200 V)

- **p-type detectors:**
  - Non-uniform wafer resistivity, explained by different O concentration leading to a spread in the thermal donor activation
  - Low breakdown for high $\rho$ p-spray
  - $C_{\text{interstrip}}$ of p-type sensors decreases with $V_{\text{bias}}$, reaching saturation at $V>>V_{\text{depletion}}$ (~100V)

**SMART**

**V. Radicci RD05 October 5-7, 2005 - Florence, Italy; Messineo @ 9th ICATAPP Como, October 2005**
Irradiation studies

- Irradiation with 24 GeV/c protons at CERN SPS: 3 fluences: $6.0 \times 10^{13}$, $3.0 \times 10^{14}$, $3.4 \times 10^{15}$ 1-MeV n/cm²
- Irradiation with 26 MeV protons at the Cyclotron of the Forschungszentrum Karlsruhe: 11 fluences: $1.4 \times 10^{13}$ - $2.0 \times 10^{15}$ 1-MeV n/cm²

No type inversion (?) Confirmed by microscopic studies (see AB’s talk)

MCz: improved reverse annealing is expected to simplify the operational conditions
Other studies

- Sensors with low p-spray have $V_{\text{breakdown}}$ comparable with n-type detectors in all the fluence range.
- Detectors with a high p-spray dose have breakdown problems for $\Phi < 4.0 \times 10^{14} \, \text{1-MeV n/cm}^2$. Excellent performance at highest $\Phi$.
- Saturation problem of the $C_{\text{interstrip}}$ improves after irradiation.
- The saturation is faster for low p-spray and large pitches.

- Same radiation damage constant for p-on-n and n-on-p diodes of Fz and MCz silicon

\[ \Delta I = \alpha(t, T_a) \cdot \Phi^N \cdot V \]

Daniela Bortoletto Vertex 2005 Nikko Japan
Purdue-USCMS MCz

- RD50 common wafer procurement (produced by Okmetic - Vantaa, Fi)
- 5 MCz wafers were processed by SINTEF (along with 15 standard wafers for preproduction of the FPiX CMS project).

- n-type substrate with <100> direction
- Thickness: ~ 300 µm
- Two diodes and 9 sensors per wafer
- Resistivity:
  - 3~4KΩcm (standard)
  - 1~1.5KΩcm (MCZ)
- n –pixels on n-type MCz with p-stop isolation
Pre-irradiation Studies

**MCz**

- Average breakdown voltage is ~740V for MCZ and ~520V for FZ.
- Yield measured requiring \( V_{\text{breakdown}} > 300 \text{ V} \) and \( I_{\text{leakage}}@300\text{V} < 1\text{nA/mm}^2 \) lower than expected.
- Sintef identified photolithographic defects causing large \( I \) at low \( V \): n+ implant spots in the p+ implanted area.
- Further studies of MCz properties (including CCE) before and after irradiation will follow now that final ROC available.

**Depletion voltage: ~250V (MCZ)**

- **High p+ current devices**

- **Fz**

- **High p+ current devices**
Epi Material Parameters

- Epitaxial silicon grown by ITME
  - Layer thickness: 25, 50, 75 µm; resistivity: ~ 50 Ωcm
  - Oxygen: \([O] \approx 9 \times 10^{16} \text{cm}^{-3}\); Oxygen dimers (detected)

  ![Oxygen depth profiles](image1)
  ![Resistivity profiles](image2)

- Oxygen depth profiles
  - SIMS measurements after diode processing
  - O diffusion from substrate to epi-layer

- Resistivity profiles
  - Excellent homogeneity in epi-layers

SR-measurements: E. Nossarzwska, ITME

SIMS-measurements: A. Barcz/ITME, Simulations: L. Long /CiS
EPI Irradiation

- **No type inversion** in the full range up to $\sim 10^{16}$ p/cm$^2$ and $\sim 10^{16}$ n/cm$^2$ (type inversion only observed during long term annealing)
- **Proposed explanation:** introduction of shallow donors bigger than generation of deep acceptors

- **Epitaxial silicon:** Decrease of $V_{\text{depletion}}$ with annealing time $\Rightarrow$ No need for low temperature during maintenance of SLHC detectors!

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Daniela Bortoletto Vertex 2005 Nikko Japan
Signal in irradiated EPI

- Epitaxial silicon: CCE measured with beta particles ($^{90}$Sr)
  - 25ns shaping time
  - proton and neutron irradiations of 50 µm and 75 µm epi layers

CCE (50 µm): $\Phi = 6 \times 10^{15}$ cm$^{-2}$ (24GeV/c protons): 2400 electrons

CCE (75 µm): $\Phi = 2 \times 10^{15}$ n/cm$^{-2}$, 4500 electrons

CCE (50 µm): $\Phi_{eq} = 8 \times 10^{15}$ n/cm$^{-2}$, 2300 electrons

[G.Kramberger et al., RESMDD - October 2004]
EPI SLHC Scenarios

50 µm and $\Phi_p = 1.1 \times 10^{16}$ cm$^{-2}$

- Radiation @ 4 cm: $\Phi_{eq} (\text{year}) = 3.5 \times 10^{15}$ cm$^{-2}$
- SLHC-scenario:
  - 1 year = 100 days beam (-7°C)
  - 30 days maintenance (20°C)
  - 235 days no beam (-7°C or 20°C)

**Detector with cooling when not operated**

Annealing measurements at 20°C can be fitted with Hamburg model

G.Lindström et al., 10th European Symposium on Semiconductor Detectors, 12-16 June 2005 (Damage projection: M.Moll)

50 µm EPI silicon: a solution for pixels ?-

50 µm EPI SLHC scenario

Detector without cooling when not operated
<table>
<thead>
<tr>
<th>Material</th>
<th>Cost euros/wafer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siltronix (France) &lt;br&gt;p-type (low quantities) &lt;br&gt;(large quantities should similar to MCZ)</td>
<td>70</td>
</tr>
<tr>
<td>Okmetic MCz 4” DSP (only large orders &gt;200 wafers)</td>
<td>44</td>
</tr>
<tr>
<td>Okmetic MCz 6” DSP (only large orders &gt;2000 wafers)</td>
<td>50</td>
</tr>
<tr>
<td>EPI 4” ITME 150µm  &lt;br&gt;Small order of 9 wafers</td>
<td>100</td>
</tr>
<tr>
<td>EPI 4” ITME 75µm</td>
<td>70</td>
</tr>
</tbody>
</table>
## Novel Materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>GaN</th>
<th>4H SiC</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$ [eV]</td>
<td>5.5</td>
<td>3.39</td>
<td>3.26</td>
<td>1.12</td>
</tr>
<tr>
<td>$E_{breakdown}$ [V/cm]</td>
<td>$10^7$</td>
<td>$4 \cdot 10^6$</td>
<td>$2.2 \cdot 10^6$</td>
<td>$3 \cdot 10^5$</td>
</tr>
<tr>
<td>$\mu_e$ [cm$^2$/Vs]</td>
<td>1800</td>
<td>1000</td>
<td>800</td>
<td>1450</td>
</tr>
<tr>
<td>$\mu_h$ [cm$^2$/Vs]</td>
<td>1200</td>
<td>30</td>
<td>115</td>
<td>450</td>
</tr>
<tr>
<td>$v_{sat}$ [cm/s]</td>
<td>$2.2 \cdot 10^7$</td>
<td>-</td>
<td>$2 \cdot 10^7$</td>
<td>$0.8 \cdot 10^7$</td>
</tr>
<tr>
<td>$Z$</td>
<td>6</td>
<td>31/7</td>
<td>14/6</td>
<td>14</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>5.7</td>
<td>9.6</td>
<td>9.7</td>
<td>11.9</td>
</tr>
<tr>
<td>e-h energy [eV]</td>
<td>13</td>
<td>8.9</td>
<td>7.6-8.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Density [g/cm$^3$]</td>
<td>3.515</td>
<td>6.15</td>
<td>3.22</td>
<td>2.33</td>
</tr>
<tr>
<td>Displacem. [eV]</td>
<td>43</td>
<td>19.2±2</td>
<td>25</td>
<td>13-20</td>
</tr>
</tbody>
</table>

- **Wide bandgap (3.3eV)**
  - $\Rightarrow$ < leakage current than silicon
- **Signal:**
  - Diamond 36 e/$\mu$m
  - SiC 51 e/$\mu$m
  - Si 89 e/$\mu$m
  - $\Rightarrow$ charge than diamond
  - $\Rightarrow$ displacement threshold than silicon
  - $\Rightarrow$ radiation harder than silicon (?)

Recent review: P.J. Sellin and J. Vaitkus on behalf of RD50 “New materials for radiation hard semiconductor detectors”, submitted to NIMA

**SiC: CCE after irradiation**

- Material: epitaxial layers by CREE Res. Inc. and IKZ (Institut für Kristallzüchtung, Berlin)
- Devices: Schottky diodes, Alenia Marconi Systems (Rome)
- Depletion depth: 20-40 µm
- Effective doping: $5.3 \times 10^{14}$ cm$^{-2}$
- Irradiated with protons at CERN PS to $1.6 \times 10^{16}$/cm$^2$ and neutrons at Ljubjana to $7 \times 10^{15}$/cm$^2$
- CCE before irradiation: 1100 e$^-$ @400 V with α particles, 1400 e$^-$ at 200 V with MIPS (100% CCE)

![Graph showing efficiency vs. bias voltage for different proton fluences](image)

- CCE after irradiation with α particles
  - neutron irradiated samples
    - 20% CCE (α) after $7 \times 10^{15}$ n/cm$^2$!
    - 35% CCE (β) (CCD ~6µm ; ~ 300 e$^-$) after $1.4 \times 10^{16}$ p/cm$^2$ much less than in silicon

S.Sciortino et al., presented on the RESMDD 04 conference, in press with NIMA
Device Engineering: 3D detectors

- Combine **VLSI** and **MEMS** (Micro Electro Mechanical Systems).

- **Electrodes:**
  - Narrow columns processed inside the bulk instead then implanted on surface: 3D
  - diameter: 10\(\mu\)m, distance: 50-100\(\mu\)m

- Lateral depletion:
  - lower depletion voltage
  - thicker detectors possible
  - short collection distance \(\Rightarrow\) fast signal
  - More rad hard

- Processing: Wafer bonding, Deep reactive ion etching, Low pressure chemical vapor deposition, Metal deposition

**Production of 3D sensor matched to ATLAS Pixel readout chip under way (S.Parker, Pixel 2005)**

- Drawback: Long, Complex and Not-standard fabrication process
- Mass production expensive
3D DETECTOR FABRICATION

1) ETCHING THE ELECTRODES

- IR picture of 2 bonded wafers
- WAFER BONDING (mechanical stability)
  \[ \text{Si-OH} + \text{HO-Si} \rightarrow \text{Si-O-Si} + \text{H}_2\text{O} \]
- DEEP REACTIVE ION ETCHING (electrodes definition)
  - Bosh process
  \[ \text{SiF}_4 \text{(gas)} + \text{C}_4\text{F}_8 \text{(teflon)} \]
- C shaped test structure
  \(~1 \mu m \text{ difference between top and bottom}\)

2) FILLING THE ELECTRODES

- METAL DEPOSITION
  - Shorting electrodes of the same type with Al for strip electronics readout
  - or deposit metal for bump-bonding
- LOW PRESSURE CHEMICAL VAPOR DEPOSITION
  - (Electrodes filling with conformal doped polysilicon)
  \[ 2\text{P}_2\text{O}_5 + 5 \text{Si} \rightarrow 4\text{P} + 5 \text{SiO}_2 \]
  \[ 2\text{B}_2\text{O}_3 + 3\text{Si} \rightarrow 4\text{B} + 3 \text{SiO}_2 \]

Aspect ratio: \( D:d = 11:1 \)
Device Engineering: 3D detectors

• IRST-Trento and CNM Barcelona

3D Single Type Column (3D-STC) aiming at process simplification
– n+ columns in p-type substrate
– Bulk contact provided by a uniform p+ contact on backside
– Holes not etched through the wafer
– No hole filling (holes are doped but not filled with polysilicon)
– CNM: Hole etching (DRIE); IRST: other processing (contacts or polysilicon deposition, etc.)

Hole depth: 120μm

Pozza and Boscardin RD05 Florence
3D-SCT Detectors

- P-type substrate:
  - FZ (500 µm) $\rho = 5.0 \text{K}\Omega \text{cm}$
  - Cz (300 µm) $\rho = 1.8 \text{K}\Omega \text{cm}$
- Sintering: FZ 420 °C, Cz 380 °C
- Simulation
  - CCE within < 10 ns
  - worst case shown (hit in middle of cell)

[C. Piemonte et al., NIM A541 (2005) 441]
3D-SCT Detectors

- Strip detect layout:
  - No columns: 12,000-15,000
  - Inter-column pitch 80-100 μm
  - Holes d = 6-10 μm
  - P-stop and p-spray isolation
  - Two p-stop layouts
  - AC and DC coupling

- Average current per column < 1 pA
- Early breakdown for p-spray pre-irradiation

First results are very promising
DRIE does not affect device performance

Pozza and Boscardin RD05 Florence
Other new structures: Stripixel

- Several concepts for new (planar and mixed planar & 3D) detector structures aiming for improved radiation tolerance or less costly detectors (see e.g. Li - 6th RD50 workshop, or Bortoletto-5th RD50 Workshop)
- Example: Stripixel concept or semi 3D:

- Y-cell (1st metal)
- X-cell (1st metal)
- 2nd Metal X-strip
- 2nd Metal Y-strip
- Bonding Pad for Y-strip
- Go to Bonding Pad for X-strip
- FWHM for charge diffusion

Z. Li, D. Lissauer, D. Lynn, P. O’Connor, V. Radeka
Summary

- At fluences up to $10^{15}$ cm$^{-2}$ (Outer layers of a SLHC detector) the change of depletion voltage and the large area is the major problem:
  - CZ silicon detectors could be a cost-effective radiation hard solution (no type inversion, use p-in-n technology)
  - p-type silicon microstrip detectors show very encouraging results: CCE $\approx 6500$ e; $\Phi_{eq} = 4 \times 10^{15}$ cm$^{-2}$, 300 $\mu$m, collection of electrons no reverse annealing observed in CCE measurement!

- At the fluence of $10^{16}$ cm$^{-2}$ (Innermost layer of a SLHC detector) the active thickness of any silicon material is significantly reduced due to trapping. The promising new options are:
  - Thin/EPI detectors: drawback: radiation hard electronics for low signals needed e.g. 2300e at $\Phi_{eq}$ $8 \times 10^{15}$ cm$^{-2}$, 50 $\mu$m EPI, 
    ..... thicker layers will be tested in 2005/2006
  - 3D detectors: drawback: technology has to be optimized
    ..... steady progress within RD50
  - New Materials like SiC and GaN (not shown) have been characterized. 
    CCE tests show these materials to be still not radiation harder than silicon