RD50 Recent Developments

Mara Bruzzi
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on behalf of the RD50 Collaboration

http://www.cern.ch/rd50
Motivation:

Signal degradation for LHC Silicon Sensors

**Pixel sensors:**
max. cumulated fluence for **LHC**

**Strip sensors:**
max. cumulated fluence for **LHC**

References:
Motivation:

Signal degradation for LHC Silicon Sensors

Pixel sensors:
max. cumulated fluence for LHC and SLHC

Strip sensors:
max. cumulated fluence for LHC and SLHC

SLHC will need more radiation tolerant tracking detector concepts!

Boundary conditions & other challenges:
Granularity, Powering, Cooling, Connectivity, Triggering, Low mass, Low cost!

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

**Main objective:**

Development of ultra-radiation hard semiconductor detectors for the luminosity upgrade of the LHC to $10^{35}$ cm$^{-2}$s$^{-1}$ (“Super-LHC”).

**Challenges:**
- Radiation hardness up to $10^{16}$ cm$^{-2}$ required
  - Fast signal collection (bunch crossing remaining at 25 ns ?)
  - Low mass (reducing multiple scattering close to interaction point)
  - Cost effectiveness (big surfaces have to be covered with detectors!)

**Further objectives:**
- Replacement of LHC detectors
- Generic research on radiation damage in detectors : Link to ILC community
The CERN RD50 Collaboration
- History -

  • Leaving behind a list of open questions regarding radiation damage in silicon
    and a community that is willing to form a new collaboration

• 2000-2001 Difficult time to form collaboration (CERN financial crises)
  • Keep low profile in R&D at CERN (e.g. No CERN member in collaboration management allowed)

• 11/2001: 3 days workshop with discussions on how to set up collaboration
  • Formation of editing team for proposal (3 persons: C.DaVia, C.Joram, M.Moll)
  • Appointment of Spokesperson Search Committee (3 wise men: W.de Boer, E.Heijne, P.Weilhammer)
  • Collection of interested institutes (Every institute to submit a letter of interest stating: motivation,
    present work, man-power, resources, infrastructure, ….)

• 2/2002: Submission of proposal to LHCC (signed by 45 Institutes)

• 2/2002: Formation of the collaboration
  • Formation of Collaboration Board, decision on election procedures, election of CB chair and deputy,
    decision on organizational structure of collaboration, common fund, role of industrial partners,
    publication guidelines, …
  • Election of spokesperson and deputy, nomination of budget holder, CERN contact person, …
  • second CB meeting in 10/2002: establishment of MOU based on discussions in first meeting

• 5/2002: LHCC recommends approval

• 6/2002: Experiment approved as RD50 by Research Board
RD50 Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

250 Members from 48 Institutes

41 European and Asian institutes
Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki), Germany (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), Italy (Bari, Bologna, Florence, Padova, Perugia, Pisa, Torino, Trento), Lithuania (Vilnius), Netherlands (NIKHEF), Norway (Oslo (2x)), Poland (Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona, Valencia), Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Glasgow, Lancaster, Liverpool)

8 North-American institutes
Canada (Montreal), USA (BNL, Fermilab, New Mexico, Purdue, Rochester, Santa Cruz, Syracuse)

1 Middle East institute
Israel (Tel Aviv)

Detailed member list: http://cern.ch/rd50
RD50
Scientific Organization of RD50
Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

Spokespersons
Mara Bruzzi, Michael Moll
INFN Florence, CERN ECP

Defect / Material Characterization
Bengt Svensson
(Oslo University)
Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation
WODEAN project (G. Lindstroem)

Defect Engineering
Eckhart Fretwurst
(Hamburg University)
Development and testing of defect engineered silicon:
- Epitaxial Silicon
- High res. CZ, MCZ
- Other impurities H, N, Ge, …
- Thermal donors
- Pre-irradiation

Pad Detector Characterization
G. Kramberger
(Ljubljana)
• Test structure characterization
  IV, CV, CCE
  NIEL
  Device modeling
  Operational conditions
  Common irradi.
  Standardisation of macroscopic measurements (A. Chilingarov)

New Structures
R. Bates
(Glasgow University)
• 3D detectors
• Thin detectors
• Cost effective solutions

Full Detector Systems
Gianluigi Casse
(Liverpool University)
• LHC-like tests
• Links to HEP
• Links to R&D of electronics
• Comparison: pad-mini-full detectors
• Comparison of detectors different producers (Eremin)
• Pixel group (D. Bortoletto, T. Rohe)
Two general types of radiation damage to the detector materials:

- **Bulk (Crystal) damage** due to Non Ionizing Energy Loss (NIEL)
  - displacement damage, built up of crystal defects –
    - Change of effective doping concentration (higher depletion voltage, under-depletion)
    - Increase of leakage current (increase of shot noise, thermal runaway)
    - Increase of charge carrier trapping (loss of charge)

- **Surface damage** due to Ionizing Energy Loss (IEL)
  - accumulation of positive in the oxide (SiO$_2$) and the Si/SiO$_2$ interface –
    affects: interstrip capacitance (noise factor), breakdown behavior, …

- Impact on detector performance and Charge Collection Efficiency
  (depending on detector type and geometry and readout electronics!)

**Signal/noise ratio is the quantity to watch**

⇒ Sensors can fail from radiation damage!
RD50 approaches to develop radiation harder tracking detectors

- **Material Engineering -- Defect Engineering of Silicon**
  - 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
    - Oxygen dimer & hydrogen enriched Silicon
    - Influence of processing technology

- **Material Engineering-New Materials** (work concluded)
  - Silicon Carbide (SiC), Gallium Nitride (GaN)

- **Device Engineering (New Detector Designs)**
  - p-type silicon detectors (n-in-p)
  - thin detectors
  - 3D detectors
    - Simulation of highly irradiated detectors
    - Semi 3D detectors and Stripixels
    - Cost effective detectors

- Development of test equipment and measurement recommendations

Available Irradiation Sources in RD50:
- 24 GeV/c protons, PS-CERN
- 10-50 MeV protons, Jyvaskyla +Helsinki
- Fast neutrons, Louvain
- 26 MeV protons, Karlsruhe
- TRIGA reactor neutrons, Ljubljana
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UNDERSTANDING RADIATION DAMAGE

Particle $\rightarrow$ Si$_k$$^S$ $\rightarrow$ Frenkel pair
Vacancy + Interstitial

$E_K > 25$ eV

$E_K > 5$ keV

Point Defects (V-V, V-O .. )

clusters


10 MeV protons 24 GeV/c protons 1 MeV neutrons

Initial distribution of vacancies after $10^{14}$ particles/cm$^2$

More point defects

Mainly clusters
Impact of Defects on Detector properties

Impact on detector properties can be calculated if all defect parameters are known:

- $\sigma_{n,p}$: cross sections
- $\Delta E$: ionization energy
- $N_t$: concentration

**Shockley-Read-Hall statistics (standard theory)**

- $\Delta E$: ionization energy
- $N_t$: concentration
- $t$: concentration

**Inter-center charge transfer model (inside clusters only)**

- Trapping (e and h) $\Rightarrow$ CCE
- Generation $\Rightarrow$ leakage current
- Levels close to midgap most effective
- Enhanced generation $\Rightarrow$ leakage current $\Rightarrow$ space charge

Charged defects $\Rightarrow N_{\text{eff}}, V_{\text{dep}}$

- e.g. donors in upper and acceptors in lower half of band gap
## Silicon Materials under Investigation

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [µm]</th>
<th>Symbol</th>
<th>( \rho ) (Ωcm)</th>
<th>([O_i]) (cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard FZ (n- and p-type)</td>
<td>50, 100, 150, 300</td>
<td>FZ</td>
<td>1–30(\times)10(^3)</td>
<td>&lt; (5\times)10(^{16})</td>
</tr>
<tr>
<td>Diffusion oxygenated FZ (n- and p-type)</td>
<td>300</td>
<td>DOFZ</td>
<td>1–7(\times)10(^3)</td>
<td>(\sim)1–2(\times)10(^{17})</td>
</tr>
<tr>
<td>Magnetic Czochralski Si, Okmetic, Finland</td>
<td>100, 300</td>
<td>MCz</td>
<td>(\sim)1(\times)10(^3)</td>
<td>(\sim)5(\times)10(^{17})</td>
</tr>
<tr>
<td>Czochralski Si, Sumitomo, Japan (n-type)</td>
<td>300</td>
<td>Cz</td>
<td>(\sim)1(\times)10(^3)</td>
<td>(\sim)8-9(\times)10(^{17})</td>
</tr>
<tr>
<td>Epitaxial layers on Cz-substrates, ITME, Poland (n- and p-type)</td>
<td>25, 50, 75, 100, 150</td>
<td>EPI</td>
<td>50 – 100</td>
<td>(&lt;)1(\times)10(^{17})</td>
</tr>
<tr>
<td>Diffusion oxyg. Epitaxial layers on CZ</td>
<td>75</td>
<td>EPI–DO</td>
<td>50 – 100</td>
<td>(\sim)7(\times)10(^{17})</td>
</tr>
</tbody>
</table>

- **DOFZ silicon** - Enriched with oxygen on wafer level, **inhomogeneous** distribution of oxygen
- **CZ/MCZ silicon** - high O\(_i\) (oxygen) and O\(_{2i}\) (oxygen dimer) concentration (**homogeneous**)
  - formation of shallow Thermal Donors possible
- **Epi silicon** - high O\(_i\), O\(_{2i}\) content due to out-diffusion from the CZ substrate (inhomogeneous)
  - thin layers: high doping possible (low starting resistivity)
- **Epi-Do silicon** - as EPI, however additional O\(_i\) diffused reaching **homogeneous** O\(_i\) content
RD50

Earlier Works: $\gamma$ Co$^{60}$ irradiation

2003: To investigate only point defects; Main focus on differences between standard and oxygen enriched material and impact of the observed defect generation on pad detector properties.

Beneficial oxygen effect consists in:
- (c) suppressing deep acceptors responsible for the type inversion effect in oxygen lean material. So-called I and $\Gamma$ close to midgap acceptor like levels and are generated in higher concentrations in STFZ silicon than in DOFZ;
- shallow donors (BD) creation as well;

![Graph showing TSC signal and $\Delta n$](image)

![Graph showing $\Delta n$ vs. Co$^{60}$ gamma irradiation dose](image)

[I. Pintilie, APL, 82, 2169, March 2003]
RD50 Proton irradiation: FZ, DOFZ, Cz and MCz Silicon

- Strong differences in $V_{\text{dep}}$
  - Standard FZ silicon
  - Oxygenated FZ (DOFZ)
  - CZ silicon and MCZ silicon

- Strong differences in internal electric field shape
  (type inversion, double junction, …)

- Different impact on pad and strip detector operation!

Common to all materials (after hadron irradiation):
  - reverse current increase
  - increase of trapping (electrons and holes) within $\sim 20\%$
2004: Levels responsible for depletion voltage after 23 GeV proton irradiation:

Almost independent of oxygen content:

- Donor removal
- “Cluster damage” $\Rightarrow$ negative charge

Influenced by initial oxygen content:

- deep acceptor level at $E_C-0.54eV$
  (good candidate for the $V_2O$ defect)$\Rightarrow$ negative charge

Influenced by initial oxygen dimer content (?):

- BD-defect: bistable shallow thermal donor
  (formed via oxygen dimers $O_{2i}$)$\Rightarrow$ positive charge

TSC after irradiation with 23 GeV protons with an equivalent fluence of $1.84x10^{14}\text{ cm}^{-2}$ recorded on Cz and Epi material after an annealing treatment at 600C for 120 min.
2005: Shallow donor generated by proton irradiation in MCz and Epitaxial silicon

MCz n-type 26 MeV p irradiated, $\Phi=4 \times 10^{14}$ cm$^{-2}$

$[SD]_{MCz}/[SD]_{FZ} > 5$

M. Scaringella et al.
NIM A 570 (2007) 322–329


[G. Lindstroem, RD50 Workshop, Nov. 2005]

MCz n-type and p-type 24 GeV p irradiated, $\Phi=4 \times 10^{14}$ cm$^{-2}$

[M. Bruzzi, Trento Workshop, Feb. 2005]
**The WODEAN Project**

- **WODEAN project** (initiated in 2006, 10 RD50 institutes, guided by G. Lindstroem, Hamburg)
  - **Aim:** Identify defects responsible for Trapping, Leakage Current, Change of $N_{eff}$
  - **Method:** Defect Analysis on identical samples performed with the various tools available inside the RD50 network:
    - C-DLTS (Capacitance Deep Level Transient Spectroscopy)
    - I-DLTS (Current Deep Level Transient Spectroscopy)
    - TSC (Thermally Stimulated Currents)
    - PITS (Photo Induced Transient Spectroscopy)
    - FTIR (Fourier Transform Infrared Spectroscopy)
    - RL (Recombination Lifetime Measurements)
    - PC (Photo Conductivity Measurements)
    - EPR (Electron Paramagnetic Resonance)
    - TCT (Transient Charge Technique)
    - CV/IV

- ~ 240 samples irradiated with protons and neutrons
- first results presented on 2007 RD50 Workshops, further analyses in 2008 and publication of most important results in Applied Physics Letters

**11 Institutes/Institutions Involved**

- CERN
- Bucharest NIMP
- Florence University
- Hamburg University
- Ljubljana JSI
- London King’s College
- Minsk University
- Minsk NAS
- Oslo University
- Warsaw ITME
- Vilnius University
C-DLTS studies – fluence $3 \cdot 10^{11}$ cm$^{-2}$

C-DLTS requires $N_i << N_d$ → low fluence only

**Electron traps:**
- VO at $T=80$ K
- $V_2(=/-)$ at $T=120$ K → strongly suppressed due to potential barrier surrounding cluster
- V related defects in cluster at $T=170-220$ K, $V_2(=/-)$, E4/E5, E205a

**Band structure in a disordered region**

**Hole trap:**
- $C_{iO_i}$ at $T=180$ K

**Increasing temperature: Cluster dissolution**
- "Cluster-peak" at 200 K decreases
- potential barrier drops
- $V_2(=/-)$ and VO increase
Hole traps $H_{116}$ K, $H_{140}$ K, and $H_{152}$K, cluster related defects (not present after $\gamma$-irradiation) observed in neutron irradiated $n$-type Si diodes during 80 °C annealing.

Hole traps $H_{116}$ K, $H_{140}$ K, and $H_{152}$K concentration in agreement with Neff changes during 80 °C annealing, they are believed to be causing the long term annealing effects.

**Summary – defects with strong impact on the device properties at operating temperature**

**Point defects**

- $E_{i}^{BD} = E_{c} - 0.225$ eV
- $\sigma_{n}^{BD} = 2.3 \cdot 10^{-14}$ cm$^2$
- $E_{i}^{I} = E_{c} - 0.545$ eV
  - $\sigma_{n}^{I} = 2.3 \cdot 10^{-14}$ cm$^2$
  - $\sigma_{p}^{I} = 2.3 \cdot 10^{-14}$ cm$^2$

**Cluster related centers**

- $E_{i}^{116K} = E_{v} + 0.33$ eV
- $\sigma_{p}^{116K} = 4 \cdot 10^{-14}$ cm$^2$
- $E_{i}^{140K} = E_{v} + 0.36$ eV
- $\sigma_{p}^{140K} = 2.5 \cdot 10^{-15}$ cm$^2$
- $E_{i}^{152K} = E_{v} + 0.42$ eV
- $\sigma_{p}^{152K} = 2.3 \cdot 10^{-14}$ cm$^2$
- $E_{i}^{30K} = E_{c} - 0.1$ eV
- $\sigma_{n}^{30K} = 2.3 \cdot 10^{-14}$ cm$^2$

0 charged at RT

$\text{VO}^{0}$

$\text{V}_{2}^{0}$

$\text{C}_{i}\text{O}_{i}^{0}$

$\text{B}^{0}$

$\text{H}_{152K}^{0}$

$\text{H}_{140K}^{0}$

$\text{H}_{116K}^{0}$

$\text{E}_{30K}^{0}$

$\pm$ charged at RT

$\text{P}^{0/+}$

$\text{BD}^{0/++}$

$\text{I}_{p}^{0/-}$

Point defects

extended defects

I. Pintilie, NSS, 21 October 2008, Dresden
Summary – defects with strong impact on the device properties at operating temperature

**Point defects**

- $E_{i}^{BD} = E_{c} - 0.225 \text{ eV}$
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  - $\sigma_{n}^{I} = 2.3 \cdot 10^{-14} \text{ cm}^2$
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- $E_{i}^{116K} = E_{v} + 0.33 \text{ eV}$
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- $E_{i}^{152K} = E_{v} + 0.42 \text{ eV}$
- $\sigma_{p}^{152K} = 2.3 \cdot 10^{-14} \text{ cm}^2$
- $E_{i}^{30K} = E_{c} - 0.1 \text{ eV}$
- $\sigma_{n}^{30K} = 2.3 \cdot 10^{-14} \text{ cm}^2$

**Reverse annealing**

- Positive charge
  - (higher introduction after proton irradiation than after neutron irradiation)
- Leakage current
  - + neg. charge
  - (current after $\gamma$ irradiation)
- Reverse annealing
  - (neg. charge)
RD50 Test Sensor Production Runs (2005-2008)

- Recent production of Silicon Strip, Pixel and Pad detectors (non exclusive list):
  - **CIS Erfurt, Germany**
    - 2005/2006/2007 (RD50): Several runs with various epi 4” wafers only pad detectors
  - **CNM Barcelona, Spain**
    - 2006 (RD50): 22 wafers (4”), (20 pad, 26 strip, 12 pixel), (p- and n-type), (MCZ, EPI, FZ)
    - 2006 (RD50/RADMON): several wafers (4”), (100 pad), (p- and n-type), (MCZ, EPI, FZ)
  - **HIP, Helsinki, Finland**
    - 2006 (RD50/RADMON): several wafers (4”), only pad devices, (n-type), (MCZ, EPI, FZ)
    - 2006 (RD50): pad devices, p-type MCz-Si wafers, 5 p-spray doses, Thermal Donor compensation
    - 2006 (RD50): full size strip detectors with 768 channels, n-type MCz-Si wafers
  - **IRST, Trento, Italy**
    - 2004 (RD50/SMART): 20 wafers 4” (n-type), (MCZ, FZ, EPI), mini-strip, pad 200-500µm
    - 2004 (RD50/SMART): 23 wafers 4” (p-type), (MCZ, FZ), two p-spray doses 3E12 and 5E12 cm⁻²
    - 2005 (RD50/SMART): 4” p-type EPI
    - 2008 (RD50/SMART): new 4” run
  - **Micron Semiconductor L.t.d (UK)**
    - 2006 (RD50): 4”, microstrip detectors on 140 and 300µm thick p-type FZ and DOFZ Si.
    - 2006/2007 (RD50): 93 wafers, 6 inch wafers, (p- and n-type), (MCZ and FZ), (strip, pixel, pad)
  - **Sintef, Oslo, Norway**
    - 2005 (RD50/US CMS Pixel) n-type MCZ and FZ Si Wafers
  - **Hamamatsu, Japan [ATLAS ID project – not RD50]**
    - In 2005 Hamamatsu started to work on p-type silicon in collaboration with ATLAS upgrade groups
      (surely influenced by RD50 results on this material)

Hundreds of samples (pad/strip/pixel) recently produced on various materials (n- and p-type).

Mara Bruzzi on behalf of the RD50 CERN Collaboration, RD50 Recent Developments, MPGD2009, June 13, 2009
RD50

Test equipment: ALIBAVA

- **ALIBAVA – A LIverpool BArcelona VAlenicia collaboration**
- **System supported by RD50**: Will enable more RD50 groups to investigate strip sensors with ‘LHC-like’ electronics

**System:**
- Software part (PC) and hardware part connected by USB.

**Hardware part**: a dual board based system connected by flat cable.
- **Mother board intended:**
  - To process the analogue data that comes from the readout chips.
  - To process the trigger input signal in case of radioactive source setup or to generate a trigger signal if a laser setup is used.
  - To control the hardware part.
  - To communicate with a PC via USB.
- **Daughter board**:
  - It is a small board.
  - It contains two Beetle readout chips.
  - It has fan-ins and detector support to interface the sensors.

**Software part**:
- It controls the whole system (configuration, calibration and acquisition).
- It generates an output file for further data processing.

[R.Maro-Hernández, 13th RD50 Workshop, Nov.2008]
n-in-p microstrip detectors

- n-in-p microstrip p-type FZ detectors (Micron, 280 or 300µm thick, 80µm pitch, 18µm implant)
- Detectors read-out with 40MHz (SCT 128A)

CCE: ~7300e (~30%) after ~1×10^{16} cm^{-2} 800V

- no reverse annealing in CCE measurements for neutron and proton irradiated detectors

n-in-p sensors are strongly considered for ATLAS upgrade (previously p-in-n used)
• CCE increases over expectation for very high fluence
• CCE > 100% for high bias voltage
• There is charge multiplication! (Avalanche effect?)

Or other effect, like field dependent de-trapping?
Even after heavy irradiation it is possible to recover the entire ionised charge.

G. Casse, 14th RD50, Freiburg 5-7 June 2009.
### Silicon materials for Tracking Sensors

#### Signal comparison for various Silicon sensors

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<th>Silicon Sensors</th>
<th>Description</th>
<th>References</th>
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<td>p-in-n (EPI), 150 μm [7,8]</td>
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<td>p-in-n (EPI), 75μm [6]</td>
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<tr>
<td>n-in-p (FZ), 300μm, 500V, 23GeV p [1]</td>
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<tr>
<td>SiC, n-type, 55 μm, 900V, neutrons [3]</td>
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</tbody>
</table>

#### Other materials

- SiC, n-type, 55 μm, 900V, neutrons [3]

**References:**

1. p/in-FZ, 300μm, (-30°C, 25ms), strip [Casini 2008]
2. p-FZ,300μm, (-40°C, 25ms), strip [Mandic, 2008]
3. n-SiC, 55μm, (2μs), pad [Moscatelli, 2006]
4. pCVD Diamond, scaled to 500μm, 23 GeV p, strip [Adam et al., 2006, RD42]
5. Flucen normalized with damage factor for Silicon (0.62)
6. 3D, double sided, 250μm columns, 300μm substrate [Penticelli 2007]
7. n-EPI,5μm, (-30°C, 25ms), pad [Kramberger 2006]
8. n-EPI,150μm, (-30°C, 25ms), strip [Mesineo 2007]
RD50 Silicon materials for Tracking Sensors

**Signal comparison for various Silicon sensors**

![Graph showing signal comparison for various Silicon sensors](image)

- **Silicon Sensors**
  - p-in-n (EPI), 150 µm [7,8]
  - p-in-n (EPI), 75 µm [6]
  - n-in-p (FZ), 300 µm, 500 V, 23 GeV p [1]
  - n-in-p (FZ), 300 µm, 500 V, neutrons [1]
  - n-in-p (FZ), 300 µm, 500 V, 26 MeV p [1]
  - n-in-p (FZ), 300 µm, 800 V, 23 GeV p [1]
  - n-in-p (FZ), 300 µm, 800 V, neutrons [1]
  - p-in-n (FZ), 300 µm, 500 V, 23 GeV p [1]
  - p-in-n (FZ), 300 µm, 500 V, neutrons [1]

- **Other materials**
  - SiC, n-type, 55 µm, 900 V, neutrons [3]

**References:**
1. p-in-FZ, 300 µm, (-30°C, 25 ms), strip [Case 2008]
2. p-FZ, 300 µm, (-40°C, 25 ms), strip [Mandic 2008]
3. n-SiC, 55 µm, 2 µs, pad [Moscatelli 2006]
4. p-CVD Diamond, scaled to 500 µm, 23 GeV p, strip [Adam et al. 2006, RD42]
Note: Fluence normalized with damage factor for Silicon (0.62)
5. 3D, double sided, 250 µm columns, 300 µm substrate [Penna 2007]
6. n-EPI, 7 µm, (-30°C, 25 ms), pad [Kramberger 2006]
7. n-EPI, 150 µm, (-30°C, 25 ms), pad [Kramberger 2004]
8. n-EPI, 150 µm, (-30°C, 25 ms), strip [Mesina 2007]

**Note:** Measured partly under different conditions!

**Lines to guide the eye (no modeling)!**

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LHC

SLHC

Highest fluence for strip detectors in LHC: The used p-in-n technology is sufficient

n-in-p technology should be sufficient for Super-LHC at radii presently (LHC) occupied by strip sensors

Mara Bruzzi on behalf of the RD50 CERN Collaboration, RD50 Recent Developments, MPGD2009, June 13, 2009
• LHC Experiments radiation field is a mix of different particles (in particular: charged hadrons \(\leftrightarrow\) neutrons)

• MCZ silicon has shown an interesting behavior:
  • build up of net negative space charge after neutron irradiation
  • build up of net positive space charge after proton irradiation

• Question: What happens when (MCZ) detectors are exposed to a ‘mixed’ radiation field?
RD50 Mixed irradiations: 23 GeV protons+neutrons

Micron diodes irradiated with protons first and then with 2e14 n cm\(^{-2}\) (control samples p-only, open marker)

- **FZ-p,n**: increase of \(V_{fd}\) proportional to \(\Phi_{eq}\)
- **MCz-n**: decrease of \(V_{fd}\), due to different signs of \(g_{c,n}\) and \(g_{c,p}\)
- **MCz-p** at larger fluences the increase of \(V_{fd}\) is not proportional to the added fluence – as if material becomes more “n-like” with fluence – same as observed in annealing plots

\[
N_C = g_{c,p} \Phi_{eq,p} + g_{c,n} \Phi_{eq,n}
\]

\(g_c\) can be + or -

80min@60°C
Both FZ and MCz show “predicted” behaviour with mixed irradiation
- FZ doses add
  - $|N_{\text{eff}}|$ increases
- MCz doses compensate
  - $|N_{\text{eff}}|$ decreases

Needs further study with both nMCz and pMCz substrates and differing mixed doses

[T.Affolder 13th RD50 Workshop, Nov.2008]
RD50

Development of 3D detectors

- “3D” electrodes:
  - narrow columns along detector thickness,
  - diameter: 10µm, distance: 50 - 100µm

- Lateral depletion:
  - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
  - radiation hard

From STC to DTC

- DDTC: “double-sided double type columns”
- Columnar electrodes of both doping types are etched into the detector from both wafer sides
- Columns are not etched through the entire detector
  - Charge collection expected to be similar to “full 3D” detectors, but the fabrication process is much simpler
1. CNM Barcelona (2 wafers fabricated in Nov. 2007)
   - Double side processing with holes not all the way through
   - n-type bulk
   - bump bond 1 wafer to Medipix2 chips
   - Further production (n and p-type)

2. FBK (IRST-Trento)
   - very similar design to CNM
   - 2 batches produced (n-type and p-type)

First tests on irradiated devices performed (CNM devices, strip sensors, $^{90}\text{Sr}$, Beetle chip, $5 \times 10^{15} n_{eq}/\text{cm}^2$ with reactor neutrons): 12800 electrons
2008 test beam with 3D sensors

- Two microstrip 3D DDTC detectors tested in testbeam (CMS/RD50)
  - One produced by CNM (Barcelona), studied by Glasgow
  - One produced by FBK-IRST (Trento), studied by Freiburg

- Readout: APV25, as used in CMS tracker
  - Analogue readout (40 MHz), 50 ns shaping time
  - Trigger accepted during the entire 25 ns clock window (no TDC), but sampling of the signal always at the same time
    → Average detected signal expected to be ≈ 10% lower
3DDTC sensors (test beam)

- Maximum charge ≈ 20±1 ke⁻ (3.2±0.2 fC)
  - expected for 300 μm silicon: 22000 e⁻ (3.5 fC)
- Charge collection time according to simulations ≈ 45 ns (for n-type, depends also on column depth)
  - No significant ballistic deficit (shaping time 50ns)

[M.Koehler 14th RD50 Workshop, June 2009]
3DDTC sensors (rad. damage)

- Laser scan with small spot ~5μm
- Lower signal in-between the columns as expected from electric field
- CCE after irradiation with 25MeV protons to $9 \times 10^{14}$ neq/cm$^2$ close to 100%

U. Parzefall et al., "Silicon microstrip detectors in 3D technology for the sLHC", doi:10.1016/j.nima.2009.03.122
RD50 achievements & links to LHC Experiments

Some important contributions of RD50 towards the SLHC detectors:

• p-type silicon (brought forward by RD50 community) is now considered to be the base line option for the ATLAS Tracker upgrade

• RD50 results on reverse annealing of p-type silicon (no cooling during maintenance periods needed) are already taken into account by Experiments

• n- and p-type MCZ (introduced by RD50 community) are under investigation in ATLAS, CMS and LHCb

• RD50 results on very highly irradiated silicon strip sensors have shown that planar pixel sensors are a promising option also for the upgrade of the Experiments

Close links to and knowledge exchange with Experiments

• Many RD50 groups are directly involved in ATLAS, CMS and LHCb upgrade activities (natural close contact).

• Many common activities: Irradiation campaigns, test beams, wafer procurement, sensor production, …

• LHC speed front-end electronics (ATLAS, CMS and LHCb) used by RD50 members