Development of Radiation hard semiconductor devices for very high luminosity colliders

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University and INFN - Pisa

WG-SLHC INFN-Frascati Nov 2005
Tracker upgrade: how to approach

Integrated Luminosity
(radiation damage) dictates the detector technology

Instantaneous rate
(particle flux) constrain the detector geometry

<table>
<thead>
<tr>
<th>Radius (cm)</th>
<th>$\phi$ (cm$^{-2}$)</th>
<th>detector design</th>
<th>Limitation</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>55-100</td>
<td>$\sim 10^{14}$</td>
<td>long strip</td>
<td>Leakage current</td>
<td>present LHC</td>
</tr>
<tr>
<td>25-55</td>
<td>$\sim 10^{15}$</td>
<td>pixel / short strip</td>
<td>Depletion voltage</td>
<td>LHC pixel</td>
</tr>
<tr>
<td>15 -25</td>
<td>$\sim 10^{16}$</td>
<td>pixel</td>
<td>trapping time</td>
<td>R&amp;D necessary</td>
</tr>
<tr>
<td>6-15</td>
<td>$\sim 10^{16}$</td>
<td>small pixel (3 layers)</td>
<td>trapping time</td>
<td>R&amp;D necessary</td>
</tr>
</tbody>
</table>

CMS upgrade plans:

- 8 cm – 15 cm  Pixels 1  100 $\mu$m * 150 $\mu$m  (8, 11, 14 cm)
- 15 cm – 25 cm  Pixels 2  160 $\mu$m * 650 $\mu$m  (18, 22 cm)
- 25 cm – 50 cm  Pixels 3  200 $\mu$m * 5000 $\mu$m  (30, 40, 50 cm)
- 50 cm - Silicon Strips

Two strategies:
CMS: Inside out:  “Fat” pixels, strips
ATLAS Outside in: “Skinny” strips, pixels
RD50: Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

- formed in November 2001
- approved as RD50 by CERN 2002
- 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 (Going from 25ns to 10 ns bunch crossing ?)
  - Low mass (reducing multiple scattering close to interaction point)
  - Cost effectiveness (big surfaces have to be covered with detectors!)

- Presently 260 members from 53 institutes

Belarus (Minsk), Belgium (Louvain), Canada (Montreal), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), Germany (Berlin, Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Padova, Perugia, Pisa, Trento, Turin), Lithuania (Vilnius), 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 (Exeter, Glasgow, Lancaster, Liverpool, Oxford, Sheffield, Surrey), USA (Fermilab, Purdue University, Rochester University, SCIPP Santa Cruz, Syracuse University, BNL, University of New Mexico)
SMART: Structures and Materials for Advanced Radiation-hard Trackers

Funded by INFN (2003 up to 2006)
Companion of the RD50 collaboration at CERN

Spokesperson:
Mara Bruzzi  INFN and University of Florence (…2005), Donato Creanza  INFN and University of Bari (2006)

Members of the collaboration : 7 Institutions, 25 Physicists

Founder institutes: Bari, Firenze, Perugia, Pisa
External institutes: Padova, Trieste
Partner institution: IRST-ITC (Trento, Italy)
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
DLTS Calibration (B. Svensson)

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
- Oxygen Dimer (M. Moll)

New Materials
E: Verbitskaya
(Ioffe St. Petersburg)
Development of new materials with promising radiation hard properties:
- bulk, epitaxial SiC
- GaN
- other materials
GaN (J. Vaitkus)

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

New Structures
R. Bates (Glasgow University)
- 3D detectors
- Thin detectors
- Cost effective solutions
3D (M. Boscardin)
Semi 3D (Z. Li)

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)
Approaches to develop radiation harder tracking detectors

Scientific strategies:

I. Material engineering

II. Device engineering

III. Change of detector operational conditions

CERN-RD39
“Cryogenic Tracking Detectors”

- 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 Si
  - Pre-irradiated Si
  - Influence of processing technology

- New Materials
  - Silicon Carbide (SiC), Gallium Nitride (GaN)
  - Diamond: CERN RD42 Collaboration

- Device Engineering (New Detector Designs)
  - 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
Silicon Materials under Investigation by RD50

<table>
<thead>
<tr>
<th>Material</th>
<th>Symbol</th>
<th>$\rho$ ((\Omega)cm)</th>
<th>$[O_i]$ (cm(^{-3}))</th>
</tr>
</thead>
<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>
</tr>
<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>
</tr>
<tr>
<td>Czochralski Sumitomo, Japan</td>
<td>Cz</td>
<td>~ 1(\times)10(^3)</td>
<td>~ 8–9(\times)10(^{17})</td>
</tr>
<tr>
<td>Magnetic Czochralski Okmetic, Finland (n- or p-type)</td>
<td>MCz</td>
<td>~ 1(\times)10(^3)</td>
<td>~ 4–9(\times)10(^{17})</td>
</tr>
<tr>
<td>Epitaxial layers on Cz-substrates, ITME</td>
<td>EPI</td>
<td>50 – 100</td>
<td>&lt; 1(\times)10(^{17})</td>
</tr>
</tbody>
</table>

- **CZ 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)
24 GeV/c proton irradiation

- **Standard FZ silicon**
  - type inversion at $\sim 2 \times 10^{13} \text{ p/cm}^2$
  - strong Neff increase at high fluence

- **Oxygenated FZ (DOFZ)**
  - type inversion at $\sim 2 \times 10^{13} \text{ p/cm}^2$
  - reduced Neff increase at high fluence

- **CZ silicon and MCZ silicon**
  - no type inversion in the overall fluence range
    - donor generation overcompensates acceptor generation in high fluence range

- **Common to all materials:**
  - same reverse current increase
  - same increase of trapping (electrons and holes) within $\sim 20\%$
Effective doping : Stable damage

From study on SFZ-n devices \( N_{\text{eff}} = N_{CO} \cdot \left(1 - \exp(-c \cdot \Phi_{eq})\right) + g_C \cdot \Phi_{eq} \)

~as not inverted

~as inverted

MCz n-type
Inversion ?

MCz n-type
Inversion ?

\( g_c^{Fz} > g_c^{MCz} \)

SMART
For very high fluences (of the order of $10^{14}$ $n_{eq}/cm^2$) a depletion region can be observed on both sides of the device for STFZ $p^+/n$ diodes.

- **Double junction effect** has been observed starting from $\Phi=3\times10^{14}$ $n/cm^2$.
- At the fluence $\Phi=1.3\times10^{15}$ $n/cm^2$ the dominant junction is still on the $p^+$ side.

**TCT measurements**
- No SCSI on MCz up to $\Phi\sim1.3\times10^{15}$ $n_{eq}/cm^2$
- "SCSI" on MCz at $\Phi\sim2\times10^{14}$ $n_{eq}/cm^2$
  1. Minimum on Vdepl vs fluence
  2. Slope at Initial point of annealing curves

**Electric field extracted from fit of TCT data**

**Strip readout side:** no over depletion

Alberto Messineo RD50 CERN Collaboration – SMART WG-SLHCC, November 24th 2005
Annealing after proton irradiation

Effect of reverse annealing significantly reduced in MCz Si after irradiation with 26MeV and 24GeV/c up to $2 \times 10^{15}$ 1MeV cm$^{-2}$ with respect to FZ Si.

M. Scaringella et al., presented at the RD05 Conference, Florence, Oct. 2005

G. Segneri et al., presented at the Liverpool Conference, Sept. 2005

(100 min @ 80°C ≈ 500 days @ RT)
Comparison of SFZ and MCz (n- and p-type) @80°C:

Clear saturation of MCz Si (n or p) beyond 200 minutes at 80 °C

Saturation more effective for n-type

The reduced reverse annealing growth would simplify damage recovery in experimental operational conditions
EPI Devices

- 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 via \(\text{IO}_2\)-defect formation)

No type inversion in the full range up to
~ \(10^{16} \text{ p/cm}^2\) and ~ \(10^{16} \text{ n/cm}^2\) (type inversion only observed during long term annealing)

Proposed explanation: introduction of shallow donors bigger than generation of deep acceptors

G. Lindström et al., 10th European Symposium on Semiconductor Detectors, 12-16 June 2005

Alberto Messineo RD50 CERN Collaboration – SMART WG-SLHCC, November 24th 2005 - 13 -
• Long term annealing?
• Deep acceptors generation or donors annealing
Damage Projection – SLHC
- 50 µm EPI silicon: a solution for pixels ?-

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

- Proposed Solution: thin EPI-SI for small size pixels
  
  Si best candidate: low cost, large availability, proven technology
  
  thickness doesn’t matter! CCE limited at $10^{16}$ cm$^{-2}$ by $\lambda_e \approx 20$ µm, $\lambda_h \approx 10$ µm
  
  small pixel size needed, allows thin devices with acceptable capacitance for S/N
  
  high $N_{\text{efr,0}}$ (low $\rho$) provides large donor reservoir, delays type inversion

G. Lindstroem et al., 7th RD50 Workshop, Nov. 14-16, 2005
Characterization of microscopic defects  
- $\gamma$ and proton irradiated silicon detectors -

- **2003**: Major breakthrough on $\gamma$-irradiated samples
  - For the first time macroscopic changes of the depletion voltage and leakage current can be explained by electrical properties of measured defects!  
  [APL, 82, 2169, March 2003]

- **2005**: Shallow donors generated by irradiation in MCz Si and epitaxial silicon after proton irradiation observed

Levels responsible for depletion voltage changes after proton irradiation:

**Almost independent of oxygen content:**
- Donor removal
- “Cluster damage” $\Rightarrow$ negative charge

**Influenced by initial oxygen content:**
- **I–defect**: 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

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Alberto Messineo RD50 CERN Collaboration – SMART WG-SLHCC, November 24th 2005
**TSC: Comparison between SFZ and MCz n type**

**Shallow Donor Introduction in MCz**

Signal can be saturated for SFZ but not for MCz sample.

At least:

- $[\text{VO}]_{\text{MCz}} > 3 \ [\text{VO}]_{\text{SFZ}}$
- $[\text{SD}]_{\text{MCz}} > 5 \ [\text{SD}]_{\text{SFZ}}$

The higher donor introduction rate on MCz can explain the small acceptor introduction rate measured on diodes.

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**24 GeV/c p irradiated, $\Phi=2 \times 10^{14}$ n/cm²**

**26 MeV p irradiated, $\Phi=2.5 \times 10^{14}$ n/cm²**
Development of MCz & FZ Si n- and p-type microstrip/pixel sensors

Two runs 20 wafers each 4” (n- and p-type)
mini-strip 0.6x4.7cm², 50 and 100µm pitch, AC coupled
37 pad diodes and various text structures
P-type: two p-spray doses 3E12 amd 5E12 cm⁻²
(n⁺ strips isolation technique)
Wafers processed by IRST, Trento on 200-500µm
C. Piemonte, 5th RD50 workshop, Helsinki, Oct. 2004

n-type MCZ and FZ Si Wafers processed by SINTEF 300µm
Within USCMS forward pixel project

Thin microstrip detectors on 150-200-300µm thick
processed by Micron Semiconductor L.t.d (UK)
D. Bortoletto, 6th RD50 workshop, Helsinki, June 2005

Micron will produce by the end of the year the microstrips on
300µm and 140µm thick 4” p-type FZ and DOFZ Si.
G. Casse, discussion of FDS, 7th RD50 workshop, Nov. 2005
Fz-MCz(n) $\beta$ particle analysis

Not irradiated sensors
130 MCz(n) 1255 Fz(n) assembled in detector unit

CMS (LHC) F.E.:
APV25, 40 MHz
Optical link….

130-s5 500 V ($V_{fd}\sim405$V) $Q$ 17.8 ± 0.2
noise 1.02

1255-s4 200 V ($V_{fd}\sim43$V) $Q$ 18.8 ± 0.3
noise 0.98

Noise is a bit higher than expected s/n at level of 17-19

Alberto Messineo RD50 CERN Collaboration – SMART WG-SLHCC, November 24th 2005
Depletion Voltages after Irradiation

The depletion voltages of the mini-sensors follow the expected trends from the studies on the corresponding diodes.

**Before Annealing**

**During Annealing**

**Diagram:**
- MCz, n-type, 380°C
- MCz, n-type, 380°C + TDK
- Fz, n-type

**Graphs:**
- Depletion Voltage (V) vs. Fluence (1-MeV n/cm²)
  - Thickness = 300 µm

**Legend:**
- MCz, p-type, 300 µm
- Fz, p-type, 200 µm

**Annotations:**
- Before Annealing
- During Annealing
- SMART
I_{\text{leak}} performance of irradiated micro-strip sensors

IV curves of \textit{n-type} detectors for the full fluence range before annealing (measured at 0°C):

1. Current levels in MCz detectors are comparable with Fz at a given fluence
2. Leakage currents measured at V_{\text{depl}} scale as the received fluences.

The performances of Fz and MCz \textit{p-type} detectors are much improved after irradiation.

Sensors with low p-spray have IV performance comparable with n-type detectors.

Detectors with a high p-spray show improved IV performance for fluence > 4.0 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2.
Interstrip Capacitance

\[ C_{\text{tot}} = C_{\text{back}} + 2(C_{\text{int}}^{1st} + C_{\text{in}}^{2nd} + \ldots) \]

Total capacitance to input amplifier

**MCz n <100>**

Typical of <111> Si

Recovered pre irradiation values

**Fz n <111>**

OK

**MCz Low p spray**

Same problem (slow saturation) found for not irradiated sensors. Slightly improved after irradiation.

**MCz p High p spray**

Recent devices simulation results have shown good agreement with data: step forward understanding strips geometry & Isolation scheme

Alberto Messineo RD50 CERN Collaboration – SMART WG-SLHCC, November 24th 2005
Radiation Damage – III. Decrease of CCE

- **Two basic mechanisms reduce collectable charge:**
  - trapping of electrons and holes (depending on drift and shaping time !)
  - under-depletion (depending on detector design and geometry !)

- **Example:** ATLAS microstrip detectors + fast electronics (25ns)

- **p-in-n : oxygenated versus standard FZ**
  - beta source
  - 20% charge loss after $5 \times 10^{14}$ p/cm$^2$ (23 GeV)

- **n-in-n versus p-in-n**
  - same material, ~ same fluence
  - over-depletion needed

![Graph showing max collected charge (overdepletion) vs. depletion voltage for oxygenated and standard n-in-n detectors.]

![Graph showing CCE (arb. units) vs. bias [volts] for n-in-n and p-in-n detectors. 
Laser (1064nm) measurements.]

[M.Moll [Data: P.Allport et all, NIMA 501 (2003) 146]

[M.Moll: Data: P.Allport et al, NIMA 513 (2003) 84]
n-in-p microstrip detectors

- no type inversion, high electric field stays on structured side
- collection of electrons

- Miniature n-in-p microstrip detectors (280 µm)
- Detectors read-out with LHC speed (40 MHz) chip (SCT128A)
- Material: standard p-type and oxygenated (DOFZ) p-type
- Irradiation:
  - At the highest fluence: Q~6500e at \( V_{bias} = 900V \)
  - CCE ~ 60% after \( 3 \times 10^{15} \) p cm\(^{-2} \) at 900V (standard p-type)
  - CCE ~ 30% after \( 7.5 \times 10^{15} \) p cm\(^{-2} \)
    - 900V (oxygenated p-type)

Data: G. Casse et al., NIMA535(2004) 362

[Diagram showing fluence vs. CCE with data points for different radii of curvature (sLHC) and proton irradiation (24 GeV/c)]
Simulation of $n^+\text{-}p$ microstrip on DOFZ substrate

Good agreement with measurement performed with $^{106}\text{Ru}$ source and readout with LHC-like electronics up to $5.3\times10^{15}\text{n}_{eq}/\text{cm}^2$

Charge collection in Planar Silicon Detectors might be sufficient for all but inner-most Pixel layer?

Epitaxial devices good candidates

For 3-D after $1\times10^{16}\text{n/cm}^2$, predicted collected charge is $11,000\text{e}^-$
Charge Collection Efficiency in epitaxial Si

- **CCE measured with** $^{244}$Cm α-particles
  - (5.8 MeV, R≈30 µm)
  - **Integration time window 20 ns**

  - CCE degradation linear with fluence if the devices are fully depleted
    \[ \text{CCE} = 1 - \beta \alpha \Phi \]
    \[ \beta \alpha = 2.7 \times 10^{-17} \text{ cm}^2 \]
    \[ \text{CCE}(10^{16} \text{ cm}^{-2}) = 70 \% \]

  - G. Lindstroem et al., 7th RD50 Workshop, Nov. 14, 2005

- **CCE measured with** $^{90}$Sr electrons (mip’s), shaping time 25 ns

  - CCE no degradation at low temperatures!
  - CCE measured after n- and p-irradiation
    \[ \text{CCE}(\Phi_p=10^{16} \text{ cm}^{-2}) = 2400 \text{ e (mp-value)} \]

  - trapping parameters = these for FZ diodes for small Φ,
  - For large Φ less trapping than expected!

  - See: G. Kramberger et al, NIM A, in press
Device Engineering: 3D detectors

- **Electrodes:**
  - narrow columns along detector thickness-“3D”
  - diameter: **10mm** distance: **50 - 100mm**

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

- **Hole processing :**
  - Dry etching, Laser drilling, Photo Electro Chemical
  - Present aspect ratio (RD50) 30:1

(Introduced by S.I. Parker et al., NIMA 395 (1997) 328)

3D detector developments within RD50:

1) **Glasgow University – pn junction & Schottky contacts**
   Irradiation tests up to $5 \times 10^{14}$ p/cm² and $5 \times 10^{14}$ π/cm²:
   $V_{fd} = 19$V (inverted); CCE drop by 25% ($\alpha$-particles)

2) **IRST-Trento and CNM Barcelona (since 2003)**
   CNM: Hole etching (DRIE); IRST: all further processing
diffused contacts or doped polysilicon deposition
3D Detectors: New Architecture

Plan for 2005

- **Simplified 3D architecture**
  - n⁺ columns in p-type substrate, p⁺ backplane
  - operation similar to standard 3D detector

- **Simplified process**
  - hole etching and doping only done once
  - no wafer bonding technology needed

- **Fabrication planned for end 2005**
  - INFN/Trento funded project: collaboration between IRST, Trento and CNM Barcelona

- **Simulation**
  - CCE within < 10 ns
  - worst case shown (hit in middle of cell)

![Diagram of 3D detector architecture](image)

Simulation:
- CCE within < 10 ns
- worst case shown (hit in middle of cell)

[C. Piemonte et al., NIM A541 (2005) 441]
STC-3D detectors - by IRST-Trento


Sketch of the detector:

- ionizing particle
- cross-section between two electrodes
- grid-like bulk contact
- n⁺-columns
- p-type substrate
- electrons are swept away by the transversal field
- holes drift in the central region and diffuse towards p⁺ contact

Functioning:

Adv. over standard 3D: etching and column doping performed only once
Further simplification: holes not etched all through the wafer

- No need of support wafer.
- Bulk contact is provided by a backside uniform p+ implant
- Single side process.
Fabrication process in 2005

MAIN STEPS:
1. Hole etching with Deep RIE machine
   (step performed at CNM, Barcelona, Spain)
2. n+ diffusion (column doping)
3. passivation of holes with oxide
4. contact opening
5. metallization

CHOICES FOR THIS PRODUCTION:
- No hole filling (with polysilicon)
- Holes are not etched all through the wafer
- Bulk contact provided by a uniform p+ implant

Hole depth: 120µm
“Large” strip-like detectors

Small version of strip detectors

Planar and 3D test structures

“Low density layout” to increase mechanical robustness of the wafer
Strip detectors – layout

- Inner guard ring (bias line)
- Metal
- p-stop
- Hole
- Contact opening
- n⁺
At fluences up to $10^{15}$cm$^{-2}$ (Outer layers of a SLHC detector) the change of the depletion voltage and the large area to be covered by detectors is the major problem.

- CZ silicon detectors could be a cost-effective radiation hard solution
  (no type inversion, use p-in-n technology)
- Oxygenated p-type silicon microstrip detectors show very encouraging results:
  $\text{CCE} \approx 6500$ e; $F_{\text{eq}} = 4 \times 10^{15}$ cm$^{-2}$, 300µm
- No reverse annealing visible in the CCE measurement in 300µm-thick p-type FZ Si detectors irradiated with 24GeV p up to $7 \times 10^{15}$cm$^{-2}$ if applied voltage 500-800V.
- n- and p-type MCz Si show reduced reverse annealing than FZ Si.
- n-MCz Si not type inverted up to a 23GeV proton fluence of $2 \times 10^{15}$cm$^{-2}$.

- New Materials like SiC and GaN (not shown) have been characterized.
  Tests made on SiC up to $10^{16}$cm$^{-2}$ showed that detectors suffer no increase of leakage current but CCE degrade significantly. Maximum thickness tested: 50µm.
At the fluence of $10^{16}\text{cm}^{-2}$ (Innermost layer of a SLHC detector) the active thickness of any silicon material is significantly reduced due to trapping.

The two most promising options so far are:

**Thin/EPI detectors**: drawback: radiation hard electronics for low signals needed
no reverse annealing – room T maintenance beneficial
thickness tested: up to 75$\mu$m.
CCE measured with $^{90}\text{Sr}$ e, shaping time 25 ns, 75$\mu$m
$\Phi_p=10^{16} \text{ cm}^{-2} = 2400 \text{ e (mp-value)}$
processing/qualification of 150$\mu$m n-epi and p-epi under way

**3D detectors**: process performed at IRST-Trento of 3D-sct in 2005
• feasibility of 3D-stc detectors
• **Low leakage currents** ($< 1\text{pA/column}$)
• Breakdown @ 50V **for p-spray** and $>100\text{V for p-stop structures}$
• Good process yield (typical detector current $< 1\text{pA/column}$)
Threshold (Thr) need to suppress false hits \( \text{Thr} = n^* \sigma + \text{threshold dispersion} \delta \text{Thr} \)

SCT: \( \sigma \approx 600 + C^* 40 \approx 1500 \text{e}^- \), \( n = 4 \) \( \longrightarrow \) \( \text{Thr} \approx 6000 \text{e}^- \)

Pixels: \( \sigma = 260 \text{e}^- \), \( \delta \text{Thr} = 40 \text{e}^- \), \( n = 5 \) \( \longrightarrow \) \( \text{Thr} \approx 1300 \text{e}^- \)

**Signal/Threshold**

x Pre-rad

◊ Post 2500 fb\(^{-1}\)
### Workplan for 2006 (1/2)

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<th>Defect and Material Characterization</th>
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<td>• Characterization of irradiated silicon:</td>
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<tr>
<td>▪ Understand role of defects in annealing of p- and n-type MCz vs FZ Si</td>
</tr>
<tr>
<td>▪ Continue study of influence of oxygen dimers on radiation damage</td>
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<tr>
<td>▪ Extend studies to neutron irradiated MCz &amp; FZ Si</td>
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<th>Defect Engineering</th>
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<tr>
<td>• Processing of High resistivity n- and p-type MCZ-silicon</td>
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<tr>
<td>• Processing of epitaxial silicon layers of increased thickness</td>
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<tr>
<td>• Hydrogenation of silicon detectors</td>
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<tr>
<td>• Optimization of oxygen-dimer enriched silicon</td>
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<td>• Characterization (IV, CV, <strong>CCE with α- and β-particles</strong>) of test structures produced with the common RD50 masks</td>
</tr>
<tr>
<td>• Common irradiation program with fluences up to $10^{16}$cm$^{-2}$</td>
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</table>

<table>
<thead>
<tr>
<th>New Materials</th>
</tr>
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<tbody>
<tr>
<td>• Significant radiation damage observed in SiC ⇒ limited efforts to study possible improvements in material/geometry</td>
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</table>
### Workplan for 2006 (2/2)

#### New Structures
- Production of 3D detectors made with $n^+$ and $p^+$ columns
- Measurement of charge collection before and after irradiation of the processed 3D detectors
- Production of thinned detectors (50-200mm) with low resistivity $n$-type FZ and MCZ Si. Comparison with epitaxial layers to fast hadron fluences of $10^{16}$cm$^{-2}$

#### Full Detector Systems
- Production, irradiation and test of common segmented structures continues ($n$- and $p$-type FZ, DOFZ, MCz and EPI) on 4” and 6”
- Measurement of S/N on segmented sensors irradiated in 2005
- Investigation of the electric field profile in irradiated segmented sensors
- Continue activities linked to LHC experiments
Submission of 4” fabrication run in Common RD50 Project

Goals:
- a. P-type isolation study
- b. Geometry dependence
- c. Charge collection studies
- d. Noise studies
- e. System studies: cooling, high bias voltage operation,
- f. Different materials (MCz, FZ, DOFZ)
- g. Thickness

Allocated Budget: 55Keuro
2 runs foreseen (n- p-type)

Company: IRST, CNM
<table>
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<th>Device</th>
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<th>Pitch</th>
<th># of strips</th>
<th>Length</th>
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<th>Bias</th>
<th>Coupling</th>
<th>Isolation</th>
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<th>p-implant</th>
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<tr>
<td>PSI etc</td>
<td>Pixel 2</td>
<td>2</td>
<td>1.02 x 0.99</td>
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<td>Liverpool/MPI</td>
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<td>128</td>
<td>1</td>
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<td>All?</td>
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<td>All?</td>
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</table>

**Devices:** microstrip 3 cm to match 1% occupancy (r>20 cm)  
**Pixel (Atlas-CMS like)** (r<20 cm)  
on Epitaxial or MCz : read-out electronics available
Submission of 6” fabrication run in Common RD50 Project

Goals:
-a. P-type isolation study
-b. Geometry dependence
-c. Charge collection studies
-d. Noise studies
-e. System studies: cooling, high bias voltage operation,
-f. Different materials (MCz, FZ, DOFZ)
-g. Thickness

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Allocated Budget: 57Keuro
1 run foreseen

Company: Micron, Sintef
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<th>Bias</th>
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<td>AC</td>
<td>Mod p</td>
<td>0.3</td>
<td>50</td>
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</tr>
</tbody>
</table>

Devices: microstrip 3 cm to match 1% occupancy (r>20 cm)
microstrip 6 cm to match 1% occupancy (r>60 cm)
BNL 2D (stripixel) design to equip large r
Pixel (Atlas-CMS like) (r<20 cm)
Common schedule plan

Design & device production
1. masks and wafers available by January 2006
2. 4" devices ready by April 2006
3. 6” Micron could finish production by June 2006,

Device irradiation
Irradiations at CERN Spring/Summer 2006 Target Fluence: Few * 10^15
Irradiation in other facilities: after device qualification (not needed schedule)

Radiation hardness evaluation
Late summer 2006
## Si Wafers Suppliers in Europe

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Address</th>
<th>Contact Information</th>
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<tr>
<td>ITME</td>
<td>Institute of Electronic Materials Technology, Warszawa, Poland, <a href="mailto:nossar@itme.edu.pl">nossar@itme.edu.pl</a></td>
<td>4” - High resistivity Cz Si, n- and p-type, epitaxial Si</td>
</tr>
<tr>
<td>Okmetic</td>
<td>OKMETIC Oyj Pitie 2 PO Box 44 FIN-01510 Vantaa, Finland</td>
<td>4”-6”, High resistivity Cz, MCz Si, n- and p-type, epitaxial Si</td>
</tr>
<tr>
<td>Siltronix</td>
<td><a href="http://www.siltronic.com">http://www.siltronic.com</a> ( Wacker-Chemie Italia S.r.l. )</td>
<td>6” epitaxial layers on CZ, 100mm thick p- and n-type, 6” p-type FZ, thickness 300mm</td>
</tr>
<tr>
<td>Siltronix</td>
<td>Linderupvej 4, DK - 3600 Frederikssund, Denmark, <a href="mailto:topsil@topsil.com">topsil@topsil.com</a></td>
<td>4”-6”, High resistivity Fz Si, n- and p-type</td>
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<td>Institute of Electronic Materials Technology, Warszawa, Poland, <a href="mailto:nossar@itme.edu.pl">nossar@itme.edu.pl</a></td>
<td>4” - High resistivity Cz Si, n- and p-type, epitaxial Si</td>
</tr>
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**Mara Bruzzi, Firenze**

Photograph of a Czochralski furnace with a grown 200 mm crystal (Wacker Siltronic)
## Availability of high ρ wafers

<table>
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<tr>
<th></th>
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<th>Toshiba</th>
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<td>No FZ</td>
<td>1~4 kΩ cm* 4&quot; &lt; 111&gt;, 300 μm 6&quot; &lt; 100&gt;, 400 μm both sides polish</td>
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<tr>
<td><strong>p-FZ</strong></td>
<td>300 μm, 4&quot; &gt; 1 kΩ cm, &lt; 100/111, 6&quot; &gt; 2 kΩ cm &lt; 100 both sides polish</td>
<td>No FZ</td>
<td>1~4 kΩ cm* 4&quot; &lt; 111&gt;, 300 μm 6&quot; N/A (no demand) both sides polish</td>
<td>no</td>
</tr>
<tr>
<td><strong>n-Cz/MCz</strong></td>
<td>4&quot;, &lt; 30 Ω cm, 6&quot;, &lt; 60 Ω cm</td>
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<td>6&quot; &gt; 0.5 μm or &gt; 1 kΩ cm, 625 μm, &lt; 100 one side polish</td>
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<td>4&quot;, &lt; 200 Ω cm, 6&quot;, &lt; 200 Ω cm</td>
<td>unknown ρ, for &gt; 0.5 kΩ cm spec</td>
<td>8&quot; &gt; 0.5 kΩ cm (one furnace for 4-6&quot;)</td>
<td>no</td>
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</table>

In-wafer ρ FZ/Δρ/ρ < 0.3 seems not much experience FZ/Δρ/ρ < 0.5 other ranges possible > 2, > 4 kΩ cm higher price for purer poly-Si

**K. Hara (Univ. of Tsukuba)**
### Detector Materials for Pixels for R ≈ 5 cm

**Results from RD39, RD42,…**

<table>
<thead>
<tr>
<th>Material</th>
<th>Collected Signal [e⁻]</th>
<th>Issues</th>
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<td>10¹⁶cm⁻²</td>
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<tr>
<td>Si</td>
<td>~ RT</td>
<td>24,000</td>
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<td>Si -75µm</td>
<td>Epi</td>
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<td>Cryo</td>
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<td>Single X-tal</td>
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3D sensor

Atlas pattern

50 µm

400 µm

n⁺ n⁺
p⁺ p⁺ p⁺

left active edge
(bump pads not shown)
• No Guard Rings
• No Dead Area at Edge
• Allows Seamless Tiling
• Edge is an Electrode
• Efficient Wafer Use
Pixel readout circuit with 3D detector under test at LBL
Results with ATLAS Chips

- Limited this year, to the use of sensors that had been fabricated in a 5-week run (2 – 3 months is normal).
- Fabrication run was completed before the development of yield-enhancement steps.
- Useful information was obtained, showing the capacitance was low enough for the front-end readout chip to work, and that source sensitivity was found.
- However, there were pixels with a high enough leakage current to limit the bias voltage in many cases.
- Fabricated, tested small devices of different types; could make many of each type – small + many: high yield not a problem.
- Now need larger sensors with good yield, so will put in yield enhancement steps.
In the first Totem fabrication run, only 1 of 28 sensors had 99% or more good strips.

Detectors should be ready for LHC operation!

Results from the fabrication run with the 5 added yield-enhancement steps.

This run produced 13 / 20 = 65% of sensors with > 99.4 % good strips.

Process is challenging task

1. There are 37 basic steps, each of which contains many sub-steps with a number of parameters for each one.
2. Eight of these are lithography / mask steps – often more difficult than others.
3. ..............

It would be best to have commercial fabricators. Some discussions have been held with companies making sensors.
TRAPPING

\[ \tau_t = \frac{1}{\sigma v_{th} N_t} \]

The thermal velocity \( v_{th} \approx 10^7 \text{cm/s} \)

\( 10^{16} \text{cm}^{-2} \) irradiation produces \( N_t \approx 3-5 \times 10^{16} \text{ cm}^{-3} \) with \( \sigma \approx 10^{-14} \text{cm}^2 \)

Particle generated charge carrier drifts 20-30\( \mu \text{m} \) before it gets trapped regardless whether the detector is fully depleted or not!

In S-LHC conditions, 80-90\% of the volume of \( d=300\mu \text{m} \) detector is dead space!
DETRAPPING

\[ \tau_d = \frac{1}{\sigma v_{th} N_C e^{-E_t/kT}} \]

If a trap is filled (electrically non-active) the detrapping time-constant is crucial.

The detrapping time-constant depends exponentially on T

For A-center (O-V at \( E_c -0.18 \) eV with \( \sigma \approx 10^{-15} \text{ cm}^2 \))

<table>
<thead>
<tr>
<th>T(K)</th>
<th>300</th>
<th>150</th>
<th>100</th>
<th>77</th>
<th>60</th>
<th>55</th>
<th>50</th>
<th>45</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_d )</td>
<td>10ps</td>
<td>10ns</td>
<td>10( \mu )s</td>
<td>6ms</td>
<td>12.3s</td>
<td>5min</td>
<td>3.6 h</td>
<td>15 days</td>
<td>13 years</td>
</tr>
</tbody>
</table>
The key advantage:
The shape of $E(x)$ is **not affected** by fluence
CERN RD39 Collaboration: Cryogenic Tracking Detectors

CCE to $^{90}$Sr source at various temperatures for CID

Close to 0 at RT!
SMART : Wafer layout, 4”

- RD50 common wafers procurement
- Wafer Layout designed by SMART collaboration
- Masks and process by ITC-IRST (Trento)

Edge structures
Square MG-diodes
Microstrip detectors
Inter strip Capacitance test
Pad detector
Test2
Test1

RUN I p-on-n
22 wafers Fz, MCz, Cz, Epi
March 04

RUN II n-on-p
24 wafers Fz, MCz
September 04

Microstrip detectors
50 um pitch
100 um pitch

Round MG-diodes

Alberto Messineo RD50 CERN Collaboration – SMART WG-SLHCC, November 24th 2005
Sensors design features

a) Pitches 50, 100 µm to match active thickness (EPI) and for a low occupancy level

b) Strips length ~45 mm to exploit tracking detector performances (noise)

c) Implants geometry to investigate leakage current level, breakdown performances and strip capacitance effects

<table>
<thead>
<tr>
<th>µ-strip #</th>
<th>pitch (µm)</th>
<th>p+ width (µm)</th>
<th>Poly width (µm)</th>
<th>Metal width (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>50</td>
<td>15</td>
<td>10</td>
<td>23</td>
</tr>
<tr>
<td>S2</td>
<td>50</td>
<td>20</td>
<td>15</td>
<td>28</td>
</tr>
<tr>
<td>S3</td>
<td>50</td>
<td>25</td>
<td>20</td>
<td>33</td>
</tr>
<tr>
<td>S4</td>
<td>50</td>
<td>15</td>
<td>10</td>
<td>19</td>
</tr>
<tr>
<td>S5</td>
<td>50</td>
<td>15</td>
<td>10</td>
<td>19</td>
</tr>
<tr>
<td>S6</td>
<td>100</td>
<td>15</td>
<td>15</td>
<td>23</td>
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<tr>
<td>S7</td>
<td>100</td>
<td>25</td>
<td>20</td>
<td>33</td>
</tr>
<tr>
<td>S8</td>
<td>100</td>
<td>35</td>
<td>30</td>
<td>43</td>
</tr>
<tr>
<td>S9</td>
<td>100</td>
<td>25</td>
<td>20</td>
<td>37</td>
</tr>
<tr>
<td>S10</td>
<td>100</td>
<td>25</td>
<td>20</td>
<td>41</td>
</tr>
</tbody>
</table>
Pre-Irradiation Characterization: Diodes

**SMART2 - $p^+/n - MCz 300\mu m$**

Diode IV: High $V_{bd}$ and good current density

Map of the diodes $V_{depl}$ in a p-type MCz wafer

Probably due to fluctuations of the oxygen concentration in MCz material

(see talk c. Piemonte 5th RD50 workshop Firenze, 14-16 oct 2004 available on: http://rd50.web.cern.ch/rd50/5th-workshop/) high $\rho$ can be tuned by high temperature (400 °C) annealing

**SMART2 - $n^+/p - MCz 300\mu m$**

Diode CV: Uniform $\rho$ at wafer level

MOS CV: uniform process of the wafers

Type inverted region?
Pre-Irradiation Characterization: Minisensors

**SMART2 - p⁺/n - MCz 300μm**

Good performance of the *n*-type detectors in terms of breakdown voltages and current uniformity.

**MCz n-type**

**SMART2 - n⁺/p - MCz 300μm**

Wafer uniform resistivity, effect of strip geometry on $V_{\text{depl}}$ and $C_{\text{tot}}$.

- **MCz p-type Low p-Spray**
- **MCz p-type High p-Spray**

SiO₂

~1e20cm⁻³ p-spray

SiO₂

>1e17cm⁻³

更好的 after irradiation

Alberto Messineo RD50 CERN Collaboration – SMART WG-SLHCC, November 24th 2005
"acceptor" introduction rate

~linear increase at high fluence

Stable damage behaviour improved by Thermal Donor Killing (TDK)

If material is type inverted: Improved $g_c$ value with bulk oxygenation for both p-on-n and n-on-p

Preliminary results

<table>
<thead>
<tr>
<th></th>
<th>nFZ</th>
<th>6.70E-03 cm$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nMCz</td>
<td>5.50E-03 cm$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>pFZ</td>
<td>8.20E-03 cm$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>pMCz</td>
<td>4.90E-03 cm$^{-1}$</td>
</tr>
</tbody>
</table>
Measurements after irradiation and before annealing

- The minimum of $V_{\text{dep}}$ for protons (90-100 V) is higher than for neutrons (40-50 V)
- $V_{\text{dep}} > V_{\text{dep,0}}$ at the maximum fluence ($10^{16}$ p/cm$^2$)
- Radiation effects induced by neutrons and protons are different
A simplified model to study $V_{fd}(N_1,N_2)$
As function of effective doping on junction: $N_1$ (p+ side) $N_2$ (n+ side)

$V_d \sim (N_1+N_2)-3N_1N_2/(N_1+N_2))$

Irradiation effect:
$N'_1 = N_{10} - b_1 \Phi$
$N'_2 = b_2 (\Phi - \Phi_0)$

$\Phi_0$: fluence at which DJ appears

$S = b_2/b_1$

Qualitative agreement between CV/ annealing curves systematic investigation under study
Strip detectors – IV measurements

Number of columns per detector: 12000 - 15000

Current distribution @ 40V of 70 different devices

Leakage current < 1pA/column in most of the detectors

Good process yield
Schematic of a spiral interleaving scheme for ISD (PHENIX Upgrade at RHIC)

The gaps between pixels are enlarged for clear illustrations

Prototype for PHENIX Upgrade at RHIC produced, 2d resolution of 25 μm obtained (80 μm pitches) (Tojo et al., IEEE TNS Vol.51, No.5, pp 2337-2340)
Annealing of p-type sensors

- p-type strip detector (280mm) irradiated with 23 GeV p
  \((7.5 \times 10^{15} \text{ p/cm}^2)\)
- expected from previous CV measurement of \(V_{\text{dep}}\):
  - before reverse annealing:
    \[V_{\text{dep}} \sim 2800 \text{V}\]
  - after reverse annealing
    \[V_{\text{dep}} > 12000 \text{V}\]
- no reverse annealing visible in the CCE measurement!