Upgrade of ATLAS silicon semiconductor tracker for the SLHC

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1. LHC experiment and ATLAS detector
2. super LHC
3. P-bulk test samples and irradiation
4. IV, CV/CCE, isolation measurement results
5. Summary
LHC experiment and ATLAS detector

- Proton-Proton collider
- CM energy: 14 TeV
- Luminosity: $10^{34}$ cm$^{-2}$s$^{-1}$
- Collision interval: 25 nsec
- 700 fb$^{-1}$ by 2014~2016

Start in 2007
Inner detector and semiconductor tracker

SCT Radiation tolerance
\(~< 2 \times 10^{14} (1 \text{MeV-n-eq/cm}^2)\)  
(10 years of LHC experiment)

SCT property
- N-type sensor
  - be fully depleted for signal readout
- With fluence, full depletion voltage increase.
- Operation Voltage limits the lifetime

\[ \text{Neff} \propto \text{full depletion voltage} \]
Super-LHC

SLHC parameters

- Luminosity: $10^{35}$/cm$^2$/s
- Integrated luminosity: 3000 fb$^{-1}$
- Collision interval: 12.5 ns
- Particle fluence

ATLAS Inner Detector needs re-designed

- Replace TRT with silicon detector
- Need more rad-hard silicon detector

Developing P-type sensor

Advantage of N$^+$-on-P sensor:

- Signal can be accumulated even under partial depletion (operational at reduced HV).

R&D goals:

- Evaluate high resistive p-type wafers → stability against radiation
- Electrical isolation between N$^+$ readout strips.

~$1 \times 10^{15}$ (1MeV n-eq/cm$^2$) @R=30 cm
P-bulk test Samples for rad-hard silicon

40 samples

- wafer types: Floating Zone (FZ), Magnetic Czochralski (MCZ)
- 5 p-stop structures (IPSTP, CPSTP, IPSTPDF, CPSTPDF, AF)
- 2 p-stop/p-spray concentrations
- 2 fluences

<table>
<thead>
<tr>
<th>wafer No</th>
<th>p-stop</th>
<th>p-spray</th>
</tr>
</thead>
<tbody>
<tr>
<td>7,8</td>
<td>1E+12</td>
<td>1E+12</td>
</tr>
<tr>
<td>17,18</td>
<td>2E+13</td>
<td>---</td>
</tr>
</tbody>
</table>

P-stop (Common, Indiv.)

P-spray

Field Plate (poly Si)

AC Field Plate

P-bulk

SiO\textsubscript{2}

N\textsuperscript{+}

P-stop

N\textsuperscript{+}

P-bulk

Field Plate (poly Si)

P-stop + DC Field Plate (Common, Indiv.)

wafer 7/17: irradiated to $0.7 \times 10^{14}$ /cm\textsuperscript{2} (low fluence)

wafer 8/18: irradiated to $0.7 \times 10^{15}$ /cm\textsuperscript{2} (high fluence)
P-bulk test Samples for rad-hard silicon

Floating Zone (FZ) crystal growth
- Resistively ~1.5k Ω·cm
- Very low impurity

Magnetic Czochralski (MCZ) crystal growth
- Resistively ~1k Ω·cm
- Oxide rich
  (expected to decrease full depletion voltage for any irradiation)

Full depletion voltage/Micro discharge/Strip isolation are compared for FZ and MCZ samples.
Irradiation@Tohoku Univ. CYRIC

- 70MeV protons
- Center position determined by position monitor
- Irradiate evenly by scanning the sensors
- Fluence evaluated by Al activation

Beam profile

Scan

Beam line

Position monitor

Sensor (10x10 mm²)
Measurements of sensor characteristics

- **I-V** micro discharge?
- **C-V/ CCE** (Charge Collection Efficiency) evaluate full depletion voltage
- **Isolation** evaluate electrical isolation between readout strips

**Diagram:***
- LCR meter
- I-V measurement
- C-V measurement
- Isolation measurement
- Isolated: \(~1.5 \, \text{uA}\)
- Not isolated: Larger
Full depletion voltage (FZ)

C-V $1/C^2$ : plot \( \frac{1}{C} \propto d \propto \sqrt{V_{\text{bias}}} \)

Non-irrad

\[
\begin{align*}
&0.7 \times 10^{14} \\
\text{Bias voltage (V)} & 150 \\
\end{align*}
\]

\[
\begin{align*}
&0.7 \times 10^{15} \\
\text{Bias voltage (V)} & 260 \\
\end{align*}
\]

\[
\begin{align*}
&0.7 \times 10^{14} \\
\text{Bias voltage (V)} & 500 \\
\end{align*}
\]

CCE : ampl$^2$ plot \( \text{ampl} \propto d \propto \sqrt{V_{\text{bias}}} \)

Non-irrad

\[
\begin{align*}
&0.7 \times 10^{14} \\
\text{Bias voltage (V)} & 170 \\
\end{align*}
\]

\[
\begin{align*}
&0.7 \times 10^{15} \\
\text{Bias voltage (V)} & 190 \\
\end{align*}
\]

\[
\begin{align*}
&0.7 \times 10^{15} \\
\text{Bias voltage (V)} & 420 \\
\end{align*}
\]
Full depletion voltage (MCZ)

Non-irrad 0.7E+14

- $y = 0.016x + 3.1083$
- $y = 11.6$

Non-irrad 0.7E+15

- $y = 0.0112x + 6.9524$
- $y = 12.6$

Non-irrad

- $y = -9.46E-05x + 4.57E-03$

Non-irrad 0.7E+14

- $y = -1.82E-04x + 1.16E-03$
- $y = 0.09$

Non-irrad 0.7E+15

- $y = -1.34E-04x + 6.88E-03$
- $y = 0.1$

Bias voltage (V):

MCZ-11 T=20degC
IPSTP
CPSSTP
IPSTPDF
CPSTPDF
AF

MCZ-7 T=20degC
IPSTP
CPSSTP
IPSTPDF
CPSTPDF
AF

MCZ-18 T=20degC
IPSTP
CPSSTP
IPSTPDF
CPSTPDF
AF

MCZ-W19 non-irrad

MCZ-W7&17 0.7E+14

MCZ-W8&18 0.7E+15

Bias Voltage (V):
Full depletion voltage dependence on fluence

- **FZ**
  - ~150 V before irradiation
  - Increases to ~500 V after $0.7 \times 10^{15}$

- **MCZ**
  - ~1 kV before irradiation
  - Decreases to ~500 V after $0.7 \times 10^{13}$ Vfd after $0.7 \times 10^{15}$

We have conducted more systematic irradiation:
Data to be ready in a month.
I-V Curve before/after irradiation

After irradiation, micro discharge disappears. Current is about 10 uA at T= -20°C (1 cm² sensor).
Strip Isolation of FZ
dependence on p-stop concentration (before irradiation)

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<thead>
<tr>
<th>wafer No</th>
<th>p-stop</th>
<th>p-spray</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2E+12</td>
<td>2E+12</td>
</tr>
<tr>
<td>6</td>
<td>5E+12</td>
<td>---</td>
</tr>
<tr>
<td>11</td>
<td>2E+13</td>
<td>---</td>
</tr>
</tbody>
</table>

P-stop with DC Field Plates is better than without.

Need ~2E+13 p-stop (W11) to isolate (concentrations for W1/6 are not enough)
Strip Isolation of FZ after irradiation (P-stop concentration: 2E+13)

At low fluence, isolation is still good.

At high fluence, IPSTP/CSTP becomes worse. DC field plate remains OK.
AF samples are not isolated at $V_{gate}=0$ and HV below $\sim 650\,\text{V}$ (non-irrad). HV below $\sim 300\,\text{V}$ (irradiated).

Isolation is achieved at $V_{gate} \sim -50\,\text{V}$ (non-irrad) and $\sim -10\,\text{V}$ (irradiated).

Irradiation relaxes the isolation conditions.
Strip Isolation of MCZ

MCZ samples are all OK. Also for AC Field Plate with Vgate=0

Low fluence

High fluence
Summary

• We have been developing radiation tolerant silicon sensors for the SLHC.

• MCZ wafer is better at present data.

<table>
<thead>
<tr>
<th>Wafer type</th>
<th>Full depletion voltage</th>
<th>Micro discharge</th>
<th>Strip isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FZ</td>
<td>~150 V (non-irrad)</td>
<td>At 800 V (non-irrad)</td>
<td>•Need 2E+13 P-stop concentration</td>
</tr>
<tr>
<td></td>
<td>~500 V (0.7E+15)</td>
<td></td>
<td>•AC Field Voltage = -50 V</td>
</tr>
<tr>
<td>MCZ</td>
<td>~1k V (non-irrad)</td>
<td>At 400 V (non-irrad)</td>
<td>All samples are good</td>
</tr>
<tr>
<td></td>
<td>~500 V (0.7E+14) to be re-evaluated (0.7E+15)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• We have new data, covering fluence of 5E15 with 6 fluence points
Back up
Leakage Current @ Vfd

Leakage current are,

For FZ,
\[ I_{\text{leak}18} = 3.5 \times 10^{-4} \pm 5 \% \ A \]
\[ I_{\text{leak}8} = 5.1 \times 10^{-4} \pm 8 \% \ A \]
\[ I_{\text{leak}17} = 0.69 \times 10^{-4} \pm 15 \% \ A \]
\[ I_{\text{leak}7} = 4.8 \times 10^{-4} \pm 12 \% \ A \]

For MCZ
\[ I_{\text{leak}18} = 4.7 \times 10^{-4} \pm 5 \% \ A \]
\[ I_{\text{leak}8} = 4.0 \times 10^{-4} \pm 4 \% \ A \]
\[ I_{\text{leak}17} = 1.8 \times 10^{-4} \pm 20 \% \ A \]
\[ I_{\text{leak}7} = 1.2 \times 10^{-4} \pm 6 \% \ A \]
Damage constant

\[ \frac{\Delta I}{\text{Volume}} = \alpha \Phi \]

Damage constant \( \alpha \) are,

For FZ,
\[ \alpha_{18} = 1.7 \times 10^{-17} \pm 5\% \ (A/cm) \]
\[ \alpha_{8} = 2.5 \times 10^{-17} \pm 8\% \ (A/cm) \]
\[ \alpha_{17} = 3.3 \times 10^{-17} \pm 15\% \ (A/cm) \]
\[ \alpha_{7} = 23 \times 10^{-17} \pm 10\% \ (A/cm) \]

For MCZ,
\[ \alpha_{18} = 2.2 \times 10^{-17} \pm 5\% \ (A/cm) \]
\[ \alpha_{8} = 1.9 \times 10^{-17} \pm 5\% \ (A/cm) \]
\[ \alpha_{17} = 5.8 \times 10^{-17} \pm 20\% \ (A/cm) \]
\[ \alpha_{7} = 8.7 \times 10^{-16} \pm 5\% \ (A/cm) \]
Fluence evaluation from Al activation

\[ P + \text{Al} \rightarrow ^7\text{Be} + \chi \]

\[ \Phi \approx \frac{N_{\text{mes}} \exp(\lambda \Delta t)}{N_t \sigma \lambda E_{\text{eff}} \Gamma} \]

- \( N_{\text{mes}} \): # of \( \gamma \) per second
- \( \lambda \): \(^7\text{Be} \rightarrow \gamma \) (477KeV) decay rate
- \( \Delta t \): time from beam off to measurement
- \( N_t \): # of Al atom
- \( \Gamma \): \(^7\text{Be} \rightarrow \gamma \) (477KeV) Branching ratio
- \( \sigma \): cross section
- \( E_{\text{eff}} \): SSD efficiency

Al (6x6cm²) on sensor
Silicon detector and laser

The laser in this measurement is solid-state laser which cavity is YAG (yttrium, aluminum, garnet) crystal doped Nd (neodymium). 1064nm laser is emitted by excitation and transition of Nd$^{3+}$ ion.

- Although almost laser pass through the silicon, can create electron-hole pair in a probability. Evenly for the silicon depth.
  - Can control number of creation by adjusting light quantity.

<table>
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<tr>
<th>Nd:YAG laser</th>
<th>1064nm=1.16eV</th>
</tr>
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<tr>
<td>Silicon energy gap</td>
<td>=1.12eV</td>
</tr>
</tbody>
</table>

- Charged particle
  - ~20000 pairs
  - ~3fC
P-stop shape

Individual

Common

P-stop

N⁺ strips
The advantage of P-bulk sensor

P-on-N sensor (present SCT)

- Need to be fully depleted to read out signal.

N-on-P sensor
- No Type inversion

- Signal can be read out even under partial depletion