Novel Stripixel Detectors on High Resistivity p-type Magnetic Czochralski Silicon for Experiments at Super LHC

Zheng Li, D. Lissauer, D. Lynn, P. O’Connor, and V. Radeka

Brookhaven National Laboratory, Upton, NY 11973, USA

This research was supported by the U.S. Department of Energy: contract No: DE-AC02-98Ch10886

Presented at the IEEE Nuclear Science Symposium, October 16-22, 2004, Rome, Italy
OUTLINE

• Introduction
• Detector Design Considerations
  Detector Layout
  Detector Material
  Detector Simulations
• Detector Design
• Detector Fabrication Plan
• Summary
Introduction


2d position sensitivity
One-sided process
Stereo angle between u (or X) and Y strips
X and Y pixels interleaved for charge sharing
Detector Design Considerations

US ATLAS Upgrade

- For LHC Upgrade (Super LHC), due to high luminosity, tracking detectors should have short strips, more radiation hardness and low cost

- Stripixel detectors with short strips is a good fit

- In the inter-medium region of SLHC, expected radiation fluence of charged particles for strip detectors is about $2.0 \times 10^{15}$ $n_{eq}$ (1 MeV neutron equivalent)/cm$^2$.

- MCZ p-type Si is intrinsic radiation hard and processing is simple

Pixel pitches: 620 $\mu$m (X) and 50 $\mu$m (Y)
Strip pitches: 50 $\mu$m (u) and 50 $\mu$m (Y)
Stereo angle between u and Y strips: 4.6 °
MCZ p-type, detector thickness 200 $\mu$m
Novel n on p and n on n 2d-sensitive Si Stripixel detectors on MCZ wafers
For US-ATLAS Upgrade

MCZ p-type (3 kΩ-cm)
(or n-type after SCSI)

Pixel Y-pitch 620 µm
Pixel X-pitch 50 µm

X-strip pitch 50 µm

200 µm 8.33 µm 5 µm

p-spray implant

U (or Y)-strips
2nd Al

X-strips 1st Al

X-strip pitch 50 µm

u (or Y)-strip

Pixel Y-pitch 620 µm

4.6°

X-strips

1st Al

0.25

MCZ p-type (3 kΩ-cm)
(or n-type after SCSI)

#1

#2

#3

#4

Pixels

8.33 µm 5 µm

200 µm

U (or Y)-strips
2nd Al

MCZ p-type (3 kΩ-cm)
(or n-type after SCSI)

Pixel Y-pitch 620 µm

50 µm

X-strip pitch 50 µm

u (or Y)-strip

4.6°

X-strips

1st Al

0.25
Detector processing parameters

- **n⁺ implant:** $4 \times 10^{14}/\text{cm}^2$
- **p⁺ implant:** $2 \times 10^{12}/\text{cm}^2$
Detector Materials

- Magnetic Czochralski (MCZ) Si used for its intrinsic radiation hardness to charged particles (about a factor of 5 better than control float zone Si, and a factor of 2 better than oxygenated float zone Si [Z. Li et al., TNS Vol. 51, No.4, Aug. 2004, pp1901-1908])

- p-type Si used for the following advantages:
  - No SCSI
  - One-sided process (much simpler than n on n)
  - More radiation hardness in terms of higher CCE than n-type Si [G. Casse et al., Performances of miniature microstrip detectors made on oxygen enriched p-type substrates after very high proton irradiation, presented at Vienna Conference, 2004, submitted to NIMA]
Electric simulation on the Novel n on p and n on n 2d-sensitive Si Stripixel detectors on MCZ wafers For US-ATLAS Upgrade After $2 \times 10^{15}$ $n_{eq}$/cm$^2$ radiation

Detector Simulations

Hole concentration

Potential profile

Electric field

Fully depleted at 400 volts
Whole wafer layout --- 2 2.56cm x 6cm chips

Pixel: 50µm×620µm
Array: 512 ×48
Stereo angle: 4.6°

2.56 cm (512 × 50µm)

3cm (48 × 620µm)

X-strips

u (Y)-strips

Chip #1

Chip #2

3.33 µm
No dead space

100 mm dia.

Short strips used to:
Meet the multiplicity requirement
Low the capacitance
Quarter wafer

Side bonding pads ---- zero dead space between two chips
Bonding pad on the side

X-strips (512) (50 µm pitch)

u-strips (512) (50 µm pitch)

u-bonding pads
128 ch x 4, 48 µm pitch

X-bonding pads
128 ch x 4, 48 µm pitch

2.56 cm

3 cm

6411 µm

1356 µm
Detector Chip (half wafer)

US ATLAS Stripixel Detector: 2 halves of 48×512 array of 620 \( \mu \)m×50 \( \mu \)m pixels
Interleaving pitch: 8.33 \( \mu \)m, 5 \( \mu \)m line width
512 u and 512 X strips/half with 50 \( \mu \)m pitch and 4.6 stereo angle
Detector size: 6.37 cm×2.98 cm
Sensitive area: 5.97 cm×2.58cm
Quarter wafer (half of detector chip)
Bonding pads

128 channels, 48 µm pitch
Strip routing to the sides
Contact vias for strips between 1\textsuperscript{st} and 2\textsuperscript{nd} Al layers

X strip contacts

u strip contacts
Contact vias for strips between 1\textsuperscript{st} and 2\textsuperscript{nd} Al layers
Connections between the Y pixels for the formation of u-strips
Bonding pads

Bonding pads, 70x300 \( \mu \text{m}^2 \)
128 ch, 48 \( \mu \text{m} \) pitch
Detector Fabrication plan

- Mask set for the first prototype batch has been ordered
- A pre-check batch on n-type MCZ wafers has started in November, 2004 (completion by 1/05)
- The first prototype batch on p-type MCZ wafers will start in 1/05
- Testing of the first prototype detectors before and after proton radiation:
  - IV, CV
  - TCT
  - CCE’s
Summary

• Novel Si stripixel detectors has been proposed for US-ATLAS Upgrade
  – 2d position sensitivity
  – One-sided process
  – Short strips to low the capacitance and met multiplicity requirement

• P-type MCZ Si wafers will be used
  – Intrinsically radiation hard due to nature high [O]
  – No SCSI
  – One-sided processing
  – Possible higher CCE than n-type Si
  – Partial depletion mode possible

• Simulations show normal electric properties
• Processing of prototype detectors is now underway
High Energy Physics experiments

- The Large Hadron Collider (LHC) at CERN (Geneva, Switzerland)

- EPA: Electron Proton Accelerator
- PS: Proton Synchrotron
- SPS: Super Proton Synchrotron
- LEP: Large Electron Positron
High Energy Physics experiments at LHC

- **ATLAS:**
  *A Toroidal Lhc Apparatus*

- **CMS:**
  Compact Muon Solenoid

- **ALICE:**
  *A Large Ion Collider Experiment*

- **LHC-B:**
  Beauty experiment
p+/n-/n+ Cz-Si Detectors Processed on p-type Boron Doped Substrates with Thermal Donor Induced Space Charge Sign Inversion

J. Härkönen¹), E. Tuovinen¹), P. Luukka¹), Z. Li²)

¹) Helsinki Institute of Physics, CERN/PH, Switzerland
²) Brookhaven National Laboratory, Upton, NY11973-5000, USA

In Framework of CERN RD50 Collaboration

This research was supported in part by the U.S. Department of Energy: contract No: DE-AC02-98CH10886
OUTLINE

• Cz-Si detector processing issues

• Thermal Donors (TD) in oxygen rich silicon

• TCT results

• Proton irradiation

• Conclusions
Processing of Cz-Si Detectors

• Basically no difference from standard Fz-Si detector process, except...

• High O content leads to Thermal Donor (TD) formation at temperatures 400°C – 600°C.

• TD formation can be enhanced if H is present.

• Typical process steps at 400°C – 600°C
  - Aluminum sintering (e.g. 30min @ 450°C)
  - Passivation insulators over metals PECVD (Plasma Enhanced CVD)
    Si3N4 @3000°C, which contains H2
Thermal Donor generation

\[
N_{TD} = \left( \frac{a}{b} \right) C_{io} \chi \frac{1}{\left| N_d - N_A \right|^2} \left\{ 1 - e^{-bD_i C_{io} t} \right\}
\]

\[
D_i = 0.13 e^{-\frac{E_A}{kT}} \quad \chi = 2.45 \quad E_A = 2.53 \text{eV}
\]


Cz-Si,
\( O_i \approx 8 \times 10^{17} \text{ cm}^{-3} \)

MCz-Si,
\( O_i \approx 4 \times 10^{17} \text{ cm}^{-3} \)

Oxygenated Fz-Si,
\( O_i \approx 1 \times 10^{17} \text{ cm}^{-3} \)
Thermal Donor generation (experimental results)

High resistivity region

- p-type
- n-type
- p+/n/n+
- p+/p/n+
- TD generation
We have not observed enhanced TD generation when the passivation was made by PECVD (Plasma Enhanced CVD) Si$_3$N$_4$ @300$^0$C, which contains H$_2$ 10-30%.

See talk by Esa Tuovinen at 3rd RD50 Workshop
http://rd50.web.cern.ch/RD50/3rd-workshop/
MCZ-P33, p-type, p⁺/p/n⁺ detector, 307 µm, 430 °C, 35 min (TDG) laser (red) front
MCZ-P33, p-type, p⁺/p/n⁺ detector, 307 μm, 430 °C, 35 min (TDG) laser (red) back

200 V
170 V
150 V
100 V
50 V
MCZ-P37, p-type inverted to n, p⁺/n/n⁺ detector, 307 µm
430 ºC, 75 min (TDG), laser (red) back

n-type (SCSI)
MCZ-P37, p-type inverted to n, p+/n/n+ detector, 307 μm 430 °C, 75 min (TDG), laser (red) front
24 GeV/c irradiation

![Graph showing the relationship between proton fluence and full depletion voltage.](image-url)
24 GeV/c irradiation

Vfd_irrad/Vfd_preirrad
TD formation and $O_i$ exponential dependence?

It is commonly accepted that the TD generation $\propto O^4$.


There is agreement between Wiranajakula’s equation only if TD generation $\propto O^{2.45}$

Conclusions

• High O content p⁺/n⁻/n⁺ detectors can be processed with p-type boron doped Cz-Si wafers by inverting p → n with TD’s

• It is low temperature, low cost process >> feasible solution for large scale experiments

• Resistivity range is very wide in p → n TD-process $500\Omega \text{cm} < \sigma < \sim 10\ k\Omega \text{cm}$

• TD generation provides a easy, low temperature technology to make high resistivity (>10 kΩcm ) p-type and n-type MCZ Si and Si detectors
Silicon Crystal Growth

CZ Crystal Growth

Schematic drawing of CZ puller

Ref.[2]
Silicon Crystal Growth

CZ Crystal Growth

Modern computer controlled CZ puller

Ref.[2]
Silicon Crystal Growth

CZ Crystal Growth

- Incorporation of impurities:
  Doping the impurity of choice (P, B, As, Sb)

- Factors influence the ingot properties:
  - Temperature fluctuation:
    - dimensional nonuniformities
    - resistivity variations
  - Pull-rate:
    - dislocation density
  - Rotation:
    - doping concentration
Silicon Crystal Growth

FZ Crystal Growth

- A molten zone is passed through a poly-Si rod of approximately the same dimensions as the final ingot.
- A needle-eye coil provides RF power to the rod to establish the molten zone.
- A neck is formed to obtain dislocation-free crystal region.
- A taper is then induced to allow crystal formation at the desired diameter.
- The Si does not come into contact with any substance other than ambient gas in the growth chamber.
Silicon Crystal Growth

FZ Crystal Growth

Schematic of the FZ process

Ref.[2]
Summary

- **FZ crystal growth:**
  
  - higher inherent purity
  - low oxygen ($\sim 10^{15}-10^{16}$ cm$^{-3}$)
  - high resistivity (1 to 10k$\Omega$-cm possible),
  - good for HEP detectors
  - severe microscopic resistivity variations
  - costly

- **CZ crystal growth**
  
  - larger diameter
  - less expensive
  - good resistivity uniformity
  - low resistivity range
  - higher impurity concentration
  - high oxygen concentration ($\sim 10^{17}$ cm$^{-3}$)
## Silicon Crystal Growth

### Summary

**Comparison of selected properties of CZ & FZ crystals:**

<table>
<thead>
<tr>
<th>Properties</th>
<th>CZ crystal</th>
<th>FZ crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity (P doping) n-type (Ω·cm)</td>
<td>1-50</td>
<td>1-20k</td>
</tr>
<tr>
<td>Resistivity (B doping) p-type (Ω·cm)</td>
<td>0.5-50</td>
<td>up to 20k</td>
</tr>
<tr>
<td>Resistivity gradient (four-point probe) (%)</td>
<td>5-10</td>
<td>20</td>
</tr>
<tr>
<td>Minority carrier lifetime (μs)</td>
<td>30-300</td>
<td>50-500</td>
</tr>
<tr>
<td>Oxygen (cm⁻³)</td>
<td>$10^{16}$-$10^{17}$</td>
<td>$10^{15}$-$10^{16}$</td>
</tr>
<tr>
<td>Carbon (cm⁻³)</td>
<td>$10^{16}$</td>
<td>$10^{15}$-$10^{16}$</td>
</tr>
<tr>
<td>Heavy-metal impurities (cm⁻³)</td>
<td>$&lt;10^{19}$</td>
<td>$&lt;10^{21}$</td>
</tr>
</tbody>
</table>
MCZ Si wafers

A magnetic field can be applied in the crystal growth system in order to damp the oscillations in the melt. The applied field creates an electric current distribution and an induced magnetic field in the electrically conducting melt. This produces a Lorentz force that influences the flow and reduces the amplitude of the melt fluctuations.