Magnetic Czochralski silicon as detector material

J. Härkönen, E. Tuovinen, P. Luukka, H.K. Nordlund and E. Tuominen

Helsinki Institute of Physics
Gustaf Hallstrominkatu 2
00014 University of Helsinki
Finland

Jaakko.haerkonen@cern.ch

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Outline

- Motivation to use Czochralski silicon (Cz-Si).
- Why not before?
- Crystal growth.
- Processing issues.
- Thermal Donors (TD) in Cz-Si
- P-type magnetic Cz-Si
- Radiation Hardness
- Summary

Esa Tuovinen loading MCz-Si wafers into oxidation furnace at the Microelectronics Center of Helsinki University of Technology, Finland.
Why Cz-Si?

- Cz-Si available in larger diameters
- Lower wafer cost
- Better compatibility with advanced CMOS processes
- Oxygen brings significant improvement in thermal slip resistance
- Oxygen gives significant radiation hardness advantage.

Why not before?

* No demand for high resistivity Cz-Si -> No availability
* Price for custom specified ingot 15,000 € - 20,000 €
* Now RF-IC industry shows interest on high resistivity Cz-Si
  (=lower substrate losses of RF-signal)
Crystal growth

Growth parameters

- Gas flow
- Pressure
- Purge tubes (gas flow pattern)
- Crucible rotation
- Crystal rotation
- Temperature distribution
- Magnetic field

Requirements for detector applications

- High resistivity
- Oxygen concentration $5-10 \times 10^{17}$ cm$^{-3}$
- Homogeneity
- High minority carrier lifetime

![Graph showing resistivity and distance from seed]

- Oxygen donor compensation
- Boron/Aluminum contamination
Oxygen concentration in MCz-Si

- O concentration from FTIR measurements
- Thick reference wafer

- Center $4.95 \times 10^{17}$ cm$^{-3}$
- Right $4.89 \times 10^{17}$ cm$^{-3}$
- Left $4.93 \times 10^{17}$ cm$^{-3}$
- Right $4.93 \times 10^{17}$ cm$^{-3}$
The devices were processed at Helsinki University of Technology Microelectronics Center

- with simple 5-8 level mask process:
  - 4 lithographies
  - 2-3 ion implantations
  - 2 thermal dry oxidations
  - 3 sputter metal depositions

AC-pad, bonded to read out
DC-pad, for testing
Bias resistors
Bias line
Guard Ring for isolation
multi GR
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
    (LTO, TEOS etc ~600°C
  + H₂ from Si₃H₄ process gas)
Thermal Donors in Cz-Si

• TDs are oxygen complexes that form shallow states in Si band gap below the conduction band.

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

• TD formation can be enhanced if H is present.

• Effective resistivity can be adjusted in p-type MCz-Si $500 \ \Omega \text{cm} < \sigma < \sim 10 \ \text{k}\Omega\text{cm}$

• With this method it is possible to engineer the $V_{fd}$ of p-type MCz-Si n+/p-/p+ detectors

Thermal Donor generation (experimental results)

- One data point is average of 10 diodes over the wafer diameter
- Error bars represent standard deviation

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Fitting of the Model II

\[ \chi = 1.893 \]
\[ c = 6.824 \times 10^{-20} \]
\[ b = 6.60789 \times 10^{-6} \]

\[ N_{TD}(t, T) = a \times O_i^{1.893} \left( 1 - e^{-bD_iO_i t} \right) + N_{TD}(0) \]
Homogeneity

Full Depletion Voltage with respect of distance from wafer center

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Homogeneity

Leakage current with respect of distance from wafer center

PO68 is $n^+/p^-/p^+$ device with 
p-stop implant ($1\times10^{15}\text{cm}^{-2}$) and 
p-spray $1\times10^{15}\text{cm}^{-2}$
Radiation hardness of MCz-Si


Proton radiation: Less prone for $V_{fd}$ increase than std Fz-Si or Diffusion oxygenated Fz-Si
Neutron radiation: No significant difference

Gamma radiation: Increase of positive space charge. Beneficial for Linear Collider applications?
Summary

• MCz-Si is commercially available in large quantities with resistivity 1000Ω cm (n-type) and 2 kΩ cm (p-type).

• MCz-Si shows better radiation hardeness againsta protons than Fz-Si materials. No improvment against neutron and no difference in leakage current.

• Thermal Donors can be introduced into MCz-Si detectors at 430°C during the aluminum sintering, i.e. b low cost process, no additional process complexity.

• Leakage current and $V_{fd}$ in p-type MCz-Si $n+/p-/p+$ and $p^+/n^-/n^+$ detectors is homogenous over the wafer diameter.