AC-coupled n-in-p pixel detectors on MCz silicon with atomic layer deposition (ALD) grown thin film process

A. Gädda\textsuperscript{1,3)}, J. Ott\textsuperscript{1,5)}, S. Bharthuar\textsuperscript{1)}, M. Kalliokoski \textsuperscript{1,5)}, A. Karadzhinova-Ferrer\textsuperscript{2)}, E. Brücken\textsuperscript{1)}, S. Kirschenmann\textsuperscript{1)}, V. Litichevsky\textsuperscript{1)}, M. Golovleva\textsuperscript{1)}, L. Martikainen\textsuperscript{1)}, T. Naaranoja\textsuperscript{1)}, V. Chmill\textsuperscript{2)}, M. Bezak\textsuperscript{2)}, P. Luukka\textsuperscript{1,4)} and J. Härkönen\textsuperscript{2)}

\textsuperscript{1)} Helsinki Institute of Physics (HIP), Helsinki, Finland
\textsuperscript{2)} Ruđer Bošković Institute (RBI), Zagreb, Croatia
\textsuperscript{3)} Advacam Oy, Espoo, Finland
\textsuperscript{4)} Lappeenranta University of Technology
\textsuperscript{5)} Aalto University
Outline

1. HIP CMS upgrade and research projects
   • HIP location and background
   • Project members

2. Detector R&D
   • For prototype processing
   • Detector process flow

3. Characterization and selected results

Summary
HIP location and background

- The institute is responsible for the Finnish research collaboration with CERN.
- The HIP CMS Upgrade Project is in charge of the Finnish participation in the CMS Tracker and its future upgrade, as well as participation in the (silicon) endcap region of the CMS MIP Timing Detector.

Finland: CERN member since 1991
CMS experiment upgrade and detector R&D

Compact Muon Solenoid (CMS) experiment at CERN LHC

- Finland had a significant role in the Phase I pixel upgrade: delivery of 250 full pixel modules +
- Currently the modules in the innermost layer of the CMS pixel detector need to be replaced
  - UBM, Plating and Flip chip bonding: Advacam
  - BB Quality assurance: HIP
HIP CMS upgrade and RBI PaRaDeSEC project teams

12th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD12) at Hiroshima, Japan

*PhD student
CMS experiment upgrade and detector R&D

• Next generation pixel sensor (general requirements)
  • Radiation hardness
  • Relatively low costs
  • Feasibility in large scale / industrial production
  • Robustness

Measurement and characterization ➞ HIP knowledge and skills
FOR PROTOTYPE PROCESSING
### Micronova and Nanofabrication Center cleanroom facilities in Espoo

#### Main Cleanroom spec.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Area</td>
<td>2 600 m²</td>
</tr>
<tr>
<td>(M1, M2 with Aalto Univ.)</td>
<td></td>
</tr>
<tr>
<td>Process tool</td>
<td>IC, non IC</td>
</tr>
<tr>
<td>Wafer size</td>
<td>4 - 8 inch</td>
</tr>
<tr>
<td>Cleanroom Classification</td>
<td>ISO 4…ISO 6 (10…1000)</td>
</tr>
<tr>
<td>Clean bays</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>21 °C ± 0,5 °C</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>45 % ± 5%</td>
</tr>
</tbody>
</table>
Magnetic Czochralski silicon (MCz-Si)

• High resistivity MCz-Si
  • High level of oxygen (typically $10^{16} - 10^{17}$ cm$^{-3}$)
  • Adjustable oxygen content by magnetic fields
  • Available over 150 mm wafer sizes
  • Depletion layer affected by
    a) oxygen concentration
    b) thermal history (process)

• Cost effectiveness compared to FZ
Atomic Layer Deposition (ALD)

- ALD is pinhole free deposition
- ALD results in conformal conformal coating
- ALD provides interesting material thin films
  - Metal oxides e.g. Al2O3, TiO2, SnO2, ZnO, HfO2 etc.
- ALD can tailor amount and type of oxide charge

Conformal coverage in ALD

[1] S. Franssila

Beneq TFS-500 batch-type ALD reactor
DETECTOR PROCESS FLOW
Process Flow

Si sensor wafer
P-type 150mm
( >4 kOhmcm)

(RCA clean)

Dry oxidation

Alignement
marks
lithography*

RIE SiO2 and Si
etch

ALD Al2O3
deposition

Implantation
Lithography*

Ion implantation
Both sides

BHF SiOx etch

RCA clean

Dry oxidation

Drive-in

BHF SiOx etch

ALD or PVD
TiN deposition

Bias resitors
lithography*

(RCA clean)

(DICING)

Diode

Al sputtering

Contact mettallization
lithography*

TiN etch

UBM
sputtering

Metal lift-off

UBM
sputtering

UBM
sputtering

Al etch

Al etch

Metal lift-off

Diode test

(Diode test)

PCB Assembly

Flip Chip Bonding

UBM
sputtering

Wire bonding

Detector
test

Read out chip

(Sintering)

* lithography = coat/expose/develop

12th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD12) at Hiroshima, Japan
Detector design and outcome

Pixel array: 52 columns × 80 rows = 4160 pixels
Detector bias design

PSI46dig pixel detector

Bias connection via Al metal line

Bias connection via Implantation window

Solder bumps

- The read out chip (ROC) is PSI46dig used in CMS experiment.
- Solder bump (~29um dia.)

<table>
<thead>
<tr>
<th>No</th>
<th>Region</th>
<th>Mean um</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>23978.82</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>23982.71</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>23994.96</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>23952.42</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>23983.70</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>23988.54</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>23943.22</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>23936.80</td>
</tr>
<tr>
<td>Avg.</td>
<td></td>
<td>23955.75</td>
</tr>
</tbody>
</table>

Very high uniformity

+/- 1.5 um
Hybridization

- Flip Chip bonder
  - Align X,Y and θ (microscope optics)
  - Leveling (autocollimator)
  - Thermocompression bonding (°C, Kg, Sec.)
    - Alignment accuracy: 0.5μm
    - Post_biond accuracy: 3μm

Green color cross = Chip
Red color cross = substrate
Aligned
CHARACTERIZATION AND SELECTED RESULTS
TCT measurements at HIP

Voltage scan with IR (670nm)

spatial scan performed at 100V

\[ V_{FD} = 40V \]

12th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD12) at Hiroshima, Japan
TCT xy-area scans for pixel detectors

- Each TCT xy-scan is about 60,000 data points.
- The amplitude of the signal is converted into color scale.

TCT area scans for 50 $\mu$m pixels

Laser Settings:
- 1064 nm
- 50 Hz
- 1000 x 1000$\mu$m$^2$
Source test
HIP AC-coupled pixel detector

- PSI46digi design
- Flip chip bonded detector
- 60keV Gamma from Am-241
- 8000-15000s irradiation time
- 3cm distance

34/4160 < 1%

Am241 spectrum
Summary

- We fabricated 150mm p-MCz Si wafers with our sensor design.
- Detectors are processed at Micronova / Nanofabrication center in Finland.
- Atomic Layer Deposition (ALD) technology has many properties for radiation detector fabrication processes.
- AC-coupling of small pixels connected with each other by metal-nitride thin film bias resistors.
- Flip-Chip bonding of sensor and CMS PSI 46dig CMOS ROC was performed.
- Pixel detectors were tested both HIP and RBI.
- Currently, protective passivation by ALD-HfOx is being researched (ref: see slide 11 right picture).
Thank you for your attention.

2. J. Ott et al., Presented at 33rd RD50 Workshop, CERN, Geneva, Switzerland, November 28th 2018, Processing of pixel detectors on p-type MCz silicon using atomic layer deposition (ALD) grown aluminium oxide

3. Jaakko Härkönen, Presented at Croatian Particle Physics Days, Dec 09 2019

4. Esa Tuovinen, PROCESSING OF RADIATION HARD PARTICLE DETECTORS ON CZOCHRALSKI SILICON (Doctoral dissertation), 2008

http://paradesec.irb.hr/
http://research.hip.fi/hwp/cmsupg/
http://research.hip.fi/detlab/index.htm
http://www.micronova.fi/
intentionally blank page
Each square is TCT xy-scan of about 60,000 data points. The amplitude of the signal is converted into color scale.
Backup slides: ALD process for metal oxide deposition

(A) \( \text{Al-OH}^* + \text{Al(CH}_3\text{)}_3 \rightarrow \text{Al-O-Al-(CH}_3\text{)}_2^* + \text{CH}_4 \)

(B) \( \text{Al-CH}_3^* + \text{H}_2\text{O} \rightarrow \text{Al-OH}^* + \text{CH}_4 \)

\[
2\text{Al(CH}_3\text{)}_3 + 3\text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 + 6\text{CH}_4
\]

Ref. https://www.glassonweb.com/article/atomic-layer-deposition-glass-industry