Pixelated 3D sensors for tracking in radiation harsh environments

Jordi Duarte-Campderrós on behalf of RD50 Collaboration
High Luminosity LHC upgrade → very large particle fluences

CMS inner Tracker
Radiation at HL-LHC

- High Luminosity LHC upgrade → very large particle fluences

**ATLAS**
3D Pixel sensors

“Novel” technology, but well established
(S. Parker et. Al. NIMA 395 (1997) 328)

- Main characteristic: Inter-electrode distance (L) **decoupled** from active sensor thickness (Δ)

→ Fast response time and inherently radiation tolerant
Advantages

- Low depletion voltage → low power dissipation
- Short charge collection distance
  - Fast response
  - Less trapping probability after irradiation
- Active/slim edges
3D Pixel sensors

null points → delayed signal (diffuse first)


Drawbacks

- Non uniform spatial response
  - Charge losses inside electrodes
  - Low field regions between same type electrodes
- Higher capacitance than planar
  - Higher noise
- Complicated technology
3D Pixel sensors

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S. Terzo et al. JINST 14 (2019) 06, P06005

Recovers efficiency

Tilting sensors
3D Pixel sensors

- **Single Side Processes**
  - Overall good yield

- **Drawbacks**
  - Non uniform spatial response
    - Charge losses inside electrodes
  - Low field regions between same type electrodes
  - Higher capacitance than planar
    - Higher noise
  - Complicated technology

6” Si-Si Direct Wafer Bonding
Single Side (Deep Reactive Ion Etching)
3D Pixels @ LHC/HL-LHC

LHC

– ATLAS: IBL forward region (25% total IBL)

Double sided, n-in-p, 50 x 250 x 230 μm³

– CMS-TOTEM PPS

HL-LHC

– ATLAS Upgrade
   Innermost layer of the ITk

Single sided, n-in-p, 50x50x150/25x100x150 μm³

– CMS Upgrade
   Being considered for Pixel Barrel (Layers 1-2) and Endcap (1st ring)
3D-pixels sensors @ RD50

- Qualification and characterization of small-pitch 3D sensors for the HL-LHC experiments with (pre-)production chip(s) (RD53A) ITkPix/CROC

- Time performance for 3D pixel sensors
  - 3D-trenched electrodes: uniform fields with 3D-geometry

[D03] 3D-trench Silicon Pixels with 20ps timing resolution

- 3D pixel sensors radiation hardness at extreme fluences > $1 \times 10^{17} \text{n}_{\text{eq}}/\text{cm}^2$
  - “Sensor maintain function” at FCC expected irradiation levels

HL-LHC lifetime expected fluence CMS IT innermost layer
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Not covered in this presentation

HL-LHC lifetime expected fluence CMS IT innermost layer

A. Lai et al. NIMA 981 (2020) 164491
M. Manna et al. NIMA 979 (2020) 164458
G. Kramberger et al. NIMA, 934 (2019), p. 26
CNM/FBK 3D productions compatible with RD53A chip

- **FBK**: Si-Si 6”, DWB substrates: p++ low-resistivity CZ and high-resistivity FZ. DRIE for columns. SS process

  - (2\(^{nd}\) 3D-SS) Batch with Mask Aligner lithography (FZ 130 \(\mu\)m thickness)
  - (3\(^{rd}\) 3D-SS) Batch with Stepper lithography (FZ 150 \(\mu\)m thickness)

- **CNM**: SOI/Si-Si 4”, substrates: p++ low-resistivity CZ and high-resistivity FZ, SS process

  - SOI
  - Si-Si
Pixel Geometries

- ATLAS/CMS considered pixel geometries (CMS final decision by Q1/2021)
  - ATLAS choice: 25x100 μm² 1E barrel, 50x50 μm² rings
**Single chip assemblies**

- **RD53A**\(^2\): a demonstrator readout chip for HL-LHC upgrade of ATLAS and CMS
  - 65 nm CMOS technology
  - Not a production chip
    - Chip divided in regions with 3 different analog front ends
      - CMS choice **Linear AFE**
      - ATLAS choice: **Differential AFE**

- Sensor+RD53A mounted over adapters cards for readout

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• Test beams are used to characterize sensor performance under similar conditions than in the real experiment.

\[
\text{Efficiency} = \frac{N(\text{hit})}{N(\text{track})}
\]

Device Under Test

Telescope planes

...
Hit Efficiency

S. Terzo et al. JINST 14 (2019) 06, P06005

https://indico.cern.ch/event/803258/contributions/3582778/attachments/1962445/3262150/204-terzo-hiroshima.pdf

FRESH

\[ \Phi = 0.5 \cdot 10^{16} \text{n_{eq}/cm}^2 \]
Hit Efficiency

S. Terzo et al. JINST 14 (2019) 06, P06005
https://indico.cern.ch/event/803258/contributions/3582778/attachments/1962445/3262150/204-terzo-hiroshima.pdf

$\Phi = 0.5 \cdot 10^{16} n_{eq}/cm^2$

$\Phi = 1 \cdot 10^{16} n_{eq}/cm^2$

$\Phi = 1 \cdot 10^{16} n_{eq}/cm^2$

$99\% @ 60 V$

$99\% @ 60 V$

$99\% @ 60 V$
Hit Efficiency

J. Duarte-Campderros et al. NIMA 944 (2019) 162625
https://indico.cern.ch/event/803258/contributions/3582883/attachments/1962451/3262153/300-Meschini-3D_Pixel_CMS.pdf

- Efficiency > 98% (few $V_{bias}$)
  - Tilted $\rightarrow$ > 99%

$\Phi = 1 \cdot 10^{16} n_{eq}/cm^2$

FRESH

Mask Aligner, 130 $\mu$m thick
Stepper, 150 $\mu$m thick

VERTEX2020, Oct. 5-8, 2020
Pixelated 3D sensors -- jordi.duarte@cern.ch
Resolution

M. Meschini et al. NIMA 978 (2020) 164429
https://indico.cern.ch/event/803258/contributions/3582883/attachments/1962451/3262153/300-Meschini-3D_Pixel_CMS.pdf

Mask Aligner, 130 μm thick

Resolution:
- ~ 5 μm (50 μm pitch)
- ~ 3 μm (25 μm pitch)

- Almost no degradation in resolution after irradiation

Φ = 1 \times 10^{16} n_{eq}/cm^2

V_{bias} = 146 V
Power consumption

\[ \Phi = 1 \cdot 10^{16} \text{n}_{\text{eq}}/\text{cm}^2 \]

- Power dissipation below 10 mW/cm\(^2\) for operational range
  - Fulfill ATLAS specs (CMS are less stringent)
Conclusions

- Small-pitch 3D pixel sensors bump-bonded to pre-production ROC (RD53A) have proven to have an excellent radiation tolerance up to $1 \cdot 10^{16} \text{ neq/cm}^2$
  - High efficiency ($> 97\%$ normal incidence)
  - Maintain spatial resolution
  - Low operational bias voltages (40-140 V)
  - Low power dissipation ($<10 \text{ mW/cm}^2 @ -25 \text{ C}$)
  - Both 25x100 and 50x50 designs show similar performance, in particular 25x100-1E is able to reach requirements (no need for 2E)
  - Comply with ATLAS/CMS baseline performance requirements

- Samples irradiated to $2 \cdot 10^{16} \text{ neq/cm}^2$, to be tested in beam soon

- Preparing final radiation tolerance study with production ROCs (ITkPixV1 & CROC)