Superior radiation hardness of 3D pixel sensors up to unprecedented fluences of $3 \times 10^{16}$ n$_{eq}$/cm$^2$

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3D Silicon Pixel Detectors Overview

- 3D Silicon detectors: radiation-hard sensor technology
  - Electrode distance decoupled from thickness
    → fast charge collection, trapping reduced
  - Already applied in ATLAS IBL, AFP, CT-PPS
    - Radiation hardness up to $5 \times 10^{15} \text{n}_\text{eq}/\text{cm}^2$ required and proven
  - Future HEP applications require more radiation hardness and small pixel sizes
    - HL-LHC pixel detectors (2024)
      - Full 4000 fb⁻¹: $2.5 \times 10^{16} \text{n}_\text{eq}/\text{cm}^2$ innermost layer (ATLAS ITk)
      - But FE chip not specified to be so radiation hard
        → Baseline requirement: $1.3 \times 10^{16} \text{n}_\text{eq}/\text{cm}^2$ (replacement of 2 inner layers)
        - 50x50 µm² or 25x100 µm² pixel size to cope with occupancy
    - FCC-hh (far future)
      - $7 \times 10^{17} \text{n}_\text{eq}/\text{cm}^2$ G. Kramberger’s talk
  - Aim: Develop new generation of ultra-radiation-hard 3D pixel detectors
    - In the framework of ATLAS HL-LHC pixel upgrade
    - But exploring limits of technology

S. Parker et al. M. Garcia-Sciveres’ talk
L. Rossi’s talk M. Garcia-Sciveres’ talk
G. Kramberger’s talk
see also H. Oide’s talk for FBK
1. Tested IBL/AFP generation
   - 230 µm thick, double-sided CNM process, 50x250 µm² 2E FEI4 pixels
   - Radiation hardness demonstrated up to ITk fluence (9e15 n_{eq}/cm²)
     
2. Develop prototype small-pitch 3D pixels matched to FEI4
   - Pixel size 50x50 and 25x100 µm²
     - Reduced electrode distance → more radiation hard
     - Only one 50x50 µm² sensor pixel readout by 50x250 µm² chip pixel, rest shorted to ground → 20% active area
     - Double-sided 230 µm CNM run
       - This study
     - Recently produced thinner 100-150 µm single-sided 3D

3. Produce RD53A 3D pixels (on-going)
   - “Real” 50x50 and 25x100 µm²
**Beam Tests and Irradiations**

- **Irradiations**
  - **KIT 23 MeV p:** uniform 5e15 and 1e16 n$_{eq}$/cm$^2$
  - **PS IRRAD 23 GeV p:** non-uniform 12 or 20 mm beam
    → allows probing a large range of fluences on single pixel device
  - Reached up to 3e16 n$_{eq}$/cm$^2$
  - FEI4 chip survived harsh doses beyond specs in many cases! (though not all)

- **Many beam tests at CERN SPS H6, 120 GeV pions**

<table>
<thead>
<tr>
<th>Device</th>
<th>Irradiations</th>
<th>Fluence peak step [1e16 n$_{eq}$/cm$^2$]</th>
<th>Fluence peak total [1e16 n$_{eq}$/cm$^2$]</th>
<th>Annealing</th>
<th>Beam test</th>
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<tbody>
<tr>
<td>7781-W4-C1, 50x50</td>
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<td>PS3 20mm 2017</td>
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<td>1.5</td>
<td>18d@RT</td>
<td>Not working</td>
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<tr>
<td>7781-W3-C1, 50x50</td>
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<tr>
<td>7781-W4-E, 50x50</td>
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<td>1.0</td>
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<td>as irrad.</td>
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<td>7781-W3-E, 50x50</td>
<td>Unirr.</td>
<td></td>
<td></td>
<td>7d@RT</td>
<td>Sep+Oct 2017</td>
</tr>
</tbody>
</table>

Many thanks to F. Ravotti, G. Pezzullo, F. Bögelspacher, A. Dierlamm
Efficiencies before Irradiation

- Test beam with EUDET/AIDA telescope
  - Reference tracks with few µm resolution
    - select Region of Interest (ROI) within active region
      and away from telescope resolution effects
  - 98% plateau efficiency starting at 0 V!
    - Consistent with high charge collection at 0 V in small-pitch 3D strips
    - Thanks to small electrode distance (28-35 µm)

J. Lange et al., 2016 JINST 11 C11024 (plus new data)

M. Manna, 30th RD50 Workshop Krakow 2017
Uniform Irradiation at KIT

- ToT and eff. very uniform over pixel: effect of 3D columns only dominant at low V
- ToT: high charge collection efficiency after irrad.
- Efficiency: already 97% at 40 (100) V for 5e15 (1e16) \(n_{eq}/cm^2\) at 0° tilt
  - Significantly better than for standard IBL/AFP FEI4
  - Further improves at 15° tilt
PS Non-Uniform Irradiation - Methodology

- Fluence normalization obtained with 20x20 mm² Al dosimetry foil
- Profile from
  - Beam profile monitors: 12-20 mm FWHM
  - Also made fluence maps by pixelating Al foil
- Beam position
  - From Al foil profile
  - For first irradiations also in-situ from pixel measurements (eff., noise, threshold before tuning, TDAC after tuning etc.)

Final fluence maps for analysed data

<table>
<thead>
<tr>
<th>PS1</th>
<th>PS3</th>
<th>PS3</th>
<th>PS4</th>
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<tr>
<td>W4-C1</td>
<td>W4-C1</td>
<td>W3-C1</td>
<td>W3-C1</td>
</tr>
<tr>
<td>1.4e16</td>
<td>2.5e16</td>
<td>2.3e16</td>
<td>2.8e16</td>
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</tbody>
</table>
PS Non-Uniform Irradiation - Uncertainties

- Introduce variations by +/- 1 mm in beam $\sigma$, beam centre offset, Al foil offset (both $x$, $y$)
- Vary in all combinations
- Determine maximum deviation from default value (envelope) for all variation combinations → take as systematic uncertainty (conservative)
- 15-20% uncertainty at highest fluence, 45% (70%) at lowest fluence for 20 (12) mm beam

![Graphs showing mean fluence uncertainty for different PS conditions and variations](image-url)
Efficiency vs. Fluence

- W4-C1 PS1
  - Large range of fluence on single device
  - Efficiency decreases with fluence at low voltage
  - Efficiency improves with voltage
  - NB: Fluence uncertainties large at low fluence range (~50%)
Efficiency vs. V Compilation

- Compile only at (or close to) highest fluence with lowest uncertainty (~15-20%)
- Also KIT uniform irradiation added
  - PS+KIT agree well at $1e16 \text{ n}_{eq}/\text{cm}^2$
- 98% plateau efficiency reached even after $2.7e16 \text{ n}_{eq}/\text{cm}^2$
Operation Voltage vs. Fluence

- $V_{97\%}$: estimate of operation voltage
- Highly improved operation voltage for 50x50 $\mu$m$^2$ 3D compared to IBL/AFP generation
- At ITk baseline fluence of 1.3e16 $n_{eq}$/cm$^2$ only 100 V needed
  - Thin planar needs $\sim$500 V
- Even at 2.7e16 $n_{eq}$/cm$^2$: $V_{97\%} < 150$ V

N. Savic et al., JINST 11 (2016) C12008

Different 3D Geometries, $d=230$ $\mu$m, 0° tilt
IV and Power Dissipation

- Important parameters for thermal run away
- From one pixel device only extractable for uniform irrad. (KIT)
  - At fixed $V$, $50 \times 50 \ \mu m^2$ has higher $I_{\text{leak}}$, but same at $V_{97\%}$
  - Power dissipation improves due to lower $V_{97\%}$
- For non-uniform PS irradiation PS, $V_{97\%}$ from test beam efficiency combined with n-irradiated 3D strip IV
- Considerably lower $P$ than for IBL 3D gen. and planar devices ($25 \ \text{mW/cm}^2$ at $1e16 \ \text{neq/cm}^2$)  
  N. Savic et al., JINST 11 (2016) C12008
Thin 3D run with small-pitch FEI4 prototypes just finished
- 100 and 150 µm single-sided on SOI wafers
- Probing and dicing on-going

3D runs with RD53A sensors on-going
- Single-sided 72, 100+150 µm on SOI and double-sided 200 µm
- 50x50 µm² 1E, 25x100 µm² 1E and 2E
- Production on-going → expected for end of year
- UBM + flip-chip to be done in-house by CNM + IFAE
  → sensors expected on time for arrival of RD53A
Conclusions and Outlook

- Studied 230 µm CNM 3D production with small pixel size up to unprecedented fluences of $3 \times 10^{16}$ n$_{eq}$/cm$^2$ beyond full ITk fluences
  - First time pixel devices irradiated to such high fluences (and survived)
  - Highly reduced operational voltage and power dissipation wrt. IBL/AFP generation and planar after irradiation
    - 98% efficiency at 0 V before irradiation
    - 97% efficiency at 100 V and 13 mW/cm$^2$ for $1.4 \times 10^{16}$ n$_{eq}$/cm$^2$
      $\rightarrow$ safe operation at ITk baseline fluence (1 replacement)
    - 97% efficiency reached at <150 V after $2.7 \times 10^{16}$ n$_{eq}$/cm$^2$
    - No indication that limit has been reached...

- Single-sided thin (72-150 µm) 3D productions under way at CNM
  - Also with RD53A-chip geometry in addition to FEI4 prototypes
    $\rightarrow$ expected to have even better performance with new optimised readout chip

Unprecedented radiation hardness of 3D pixel detectors demonstrated
3D Detector Principle

- **Advantages**
  - Electrode distance decoupled from sensitive detector thickness
    - \( \rightarrow \) lower \( V_{\text{depletion}} \)
    - \( \rightarrow \) less power dissipation, cooling
    - \( \rightarrow \) smaller drift distance
    - \( \rightarrow \) faster charge collection
    - \( \rightarrow \) less trapping
  - Active or slim edges are natural feature of 3D technology

- **Challenges**
  - Complex production process
    - \( \rightarrow \) long production time
    - \( \rightarrow \) lower yields
    - \( \rightarrow \) higher costs
  - Higher capacitance
    - \( \rightarrow \) higher noise
  - Non-uniform response from 3D columns and low-field regions
    - \( \rightarrow \) small efficiency loss at 0°
Different 3D Technologies

- Double sided (available at CNM)
  - IBL/AFP-proven technology
  - No handling wafers needed → thickness limited to ≥200 µm and wafers to 4”
  - 3D columns ~8 µm diameter

- Single sided (available at FBK, SINTEF, CNM)
  - On handling wafer (SOI or Si-Si bonding) → 6” possible (FBK, SINTEF)
  - Active thickness range 50-150 µm being explored
  - Narrow 3D columns ~5 µm possible

Si-Si bonding

M. Boscardin, FBK

Double-sided

G. Pellegrini, CNM
First Small-Pixel CNM Run for HL-LHC

- Run 7781 finished in Dec 2015 (RD50 project)
- 5x 4” wafers, p-type, 230 µm double-sided, non-fully-passing-through columns (a la IBL)
- Increased aspect ratio 26:1 (column diameter 8 µm)
- **First time small pixel size 25x100+ 50x50 µm²** (folded into FEI4 and FEI3 geometries)
- Also strips and diodes down to 25x25 µm² 3D unit cell

D. Vázquez Furelos et al., 2017 JINST 12 C01026
J. Lange et al., 2016 JINST 11 C11024
Sample Characterisations

Pixel IV

- Pixel devices bump-bonded and assembled at IFAE
- IVs
  - $V_{BD} \sim 15-40$ V
  - Improved in new productions after CNM process optimization
- C $< 100$ fF/pixel (within RD53 limit)
- Noise 100-160 e similar to standard 3D FEI4s
- Sr90 source scans on pixels
  - Similar charge as in standard FEI4s
- Sr90 and laser scans on strips
  - 17 ke charge as expected for both 50x50 µm² and 30x100 µm² (unirr.)
  - Almost full charge even at 0-2 V → low $V_{dep}$ due to low $L_{el}$
  - Uniform even after 1e16 $n_{eq}/cm^2$
  - Measurements up to 2e16 $n_{eq}/cm^2$ in progress

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<tbody>
<tr>
<td>25x100</td>
<td>2E 42</td>
<td>84</td>
<td>160</td>
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<tr>
<td>50x50</td>
<td>1E 37</td>
<td>37</td>
<td>105-140</td>
</tr>
</tbody>
</table>

(*) from pad diodes

D. Vázquez Furelos et al., 2017 JINST 12 C01026

Strips charge collection (unirr.)

- Strips laser scan 25x100 µm², 1e16, 150 V

Efficiency before Irradiation

- Select ROI within active region
  → avoid inactive area + telescope smearing

- Efficiency in ROI
  - 97% already from 1 V at 0°: very early depleted due to small electrode distance
  - Improvable by tilting: avoids hitting only low-efficiency regions

In-Pixel Efficiency (0° tilt)

- 50x50 1E (C)
- 25x100 2E (D)

J. Lange et al., 2016 JINST 11 C11024

Graph showing the hit efficiency vs. voltage for different samples.

15° tilt

Figure showing the active area and ROI within the detectors.
State of the Art: IBL/ AFP Generation

- 230 µm thick sensors by CNM and FBK (double-sided)
- FEI4s: 50x250 µm² 2E, 67 µm inter-el. distance
- Radiation hardness up to 5e15 n_{eq}/cm² established (IBL)
- Explored limits further with irradiations up to HL-LHC fluences
  - At 9.4e15 n_{eq}/cm²: 97.8% efficiency at 170 V!
  - Power dissipation 15 mW/cm² at 1e16 n_{eq}/cm² and -25°C

→ Good performance at HL-LHC fluences even for existing 3D generation

J. Lange et al., 2016 JINST 11 C11024