Technology and characterization results in 3D pixel detectors for future colliders

Francisca Muñoz (IFCA)
fmunoz@ifca.unican.es

M. Lozano
G. Pellegrini
D. Quirion
M. Fernández
R. Jaramillo
F.J. Muñoz
I. Vila

T. Rohe
Outline

- Motivation
- 3D pixel technology and manufacturing
- Electrical characterization
- PSI46 Read Out Chip (ROC) and interconnections
- Radiation resistance studies
- Summary
Motivation

- LHC experiments are expected to undergo a constant increase of radiation levels, a possible HL-LHC scenario will get things tougher.

• New generation of vertex detectors must deal with fluences about $1 \times 10^{16}$ neq/cm²

• Here we are going to assess the radiation resistance of 3D double-sided pixel sensors in terms of:
  - Increase of the depletion voltage (Vfd)
  - Reduction of the CCE
Planar Pixel

3D Pixel

**3D Detectors Advantages**

- Operational. Full depletion of the detector requires lower voltages
- Intrinsic. Shorter collection distances

\[ V_{FD} \alpha L^2 \]
3D- pixels timeline

• 1997. First Proposal of 3D sensors
  S. Parker; “3D - A proposed new architecture for solid-state radiation detectors”

• 1999: first fabrication of 3D sensors
  C. Kenny; “Silicon Detectors with 3-D Electrode Arrays: Fabrication and Initial Test Results”

• 2001: first results with active edge 3D sensors
  C. Kenny; “Results From 3-D Silicon Sensors With Wall Electrodes: Near-Cell-Edge Sensitivity Measurements as a Preview of Active-Edge Sensors”

• 2001: first results irradiated 3D sensors
  S. Parker; “Performance of 3-D Architecture Silicon Sensors After Intense Proton Irradiation“

  ...

• 2010: 3D sensors become a technology for the ATLAS - IBL Upgrade
Technology

- Double-sided configuration (different doping type on each side)
- Safer fabrication process (reduced wafer stress)
- Photo-lithography to define electrode contacts is only necessary on top surface
- HV biasing on the back side by simple wire bonding

REF: G. Pellegrini at the Second Trento Workshop on Advanced Silicon Radiation Detectors, Trento, Italy, 2006
CNM Production and Description

6 wafers:
Wafers 5, 6, 7, 8:
- 285 μm thickness
Wafer 11:
- 230 μm thickness
Wafer 3:
- 285 μm thickness
- Resistor bias grid

* Each wafer includes:
  1 Full Module (8x2)
  20 Single Chips
  8 Strip sensors
  12 Pads
  Test structures
Electrical characterization

- Very Homogeneous Behavior
- Current Values in the expected range

Measured $V_{fd}$ (pad) $\sim 1.5$ V

Using Coaxial approximation,
Extrapolating to sensor geom:

$V_{fd}$ (3D-Detector) $\sim 9$ V
PSI46 ROC
and interconnection process

52 x 80 pixel unit cells.
4160 units
150μm x 150μm

fjmunoz@ifca.unican.es
Scanning electron Microscope
SEM
Bump bonding.
Interconnection process

- Bump bonding yield test
- Using a $^{90}$Sr radioactive source
- An uniform pattern has been observed. Including the holes on the PCB (between sensor and scintillator)
In other cases:

Reason:
There are passivation layers only in one side of the wafer (overlooked during production)

Problem:
The stress during the second re-flow process, bows the Sensor breaking the bumps connections

Provisional Solution:
To put some weight on top of the sensor-chip “sandwich” during 2nd reflow.
Nice Pixel map, and landau fit:

Charge Distribution for Clusters of 1 Pixels Run 2786

<table>
<thead>
<tr>
<th>cQ1_2786</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
</tr>
<tr>
<td>Constant</td>
</tr>
<tr>
<td>MPV</td>
</tr>
<tr>
<td>Sigma</td>
</tr>
</tbody>
</table>

MPV ~ 22 ke$^-$
Irradiation Campaign:

4 pixel samples, 2 strips detectors and 2 pads up to each radiation fluence

- Proton Cyclotron @ KIT (Karlsruhe), 25MeV protons:

\[ 1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2 \]
\[ 5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2 \]

- Tigra Reactor @ JSI (Ljubljana), continuous spectrum neutrons:

\[ 1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2 \]
\[ 5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2 \text{ (ongoing)} \]
\[ 1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2 \]
\textbf{\textsuperscript{90}Sr Characterization}

* Charge Collection in irradiated samples

* Full Depletion Voltage:

- Depletion Area grows in a 3D sensor horizontally

- A new variable:

\[ Er = \frac{\text{Num. of hits}}{\text{Num. of triggers}} \]

- When the Er saturates with bias voltage, we consider that we have depleted the maximum volume in the sensor
MPV vs bias Voltage in irradiated samples

2 samples with protons
2 samples with neutrons

F= $1 \times 10^{15}$ neq/cm$^2$

![Graph showing MPV vs bias Voltage for samples with protons and neutrons.]

- W6_11B_10_15_n_LJ
- W6_21B_10_15_n_LJ
- W6_21A_10_15_p_KIT
- W6_12A_10_15_p_KIT

fjmunoz@
Er vs bias Voltage in irradiated samples

2 samples with protons
2 samples with neutrons

$F = 1 \times 10^{15}$ neq/cm$^2$

$V_{fd} = 120$ V
MPV and Er vs bias Voltage in irradiated samples

Vfd=180 V

F= $5 \times 10^{15}$ neq/cm² (p-KIT)

F= $5 \times 10^{15}$ neq/cm² (p-KIT)

fjmunoz@ifca.unican.es
Francisca Muñoz
MPV vs Fluence

- $V_{fd} = 20V$
- $V_{fd} = 120V$
- $V_{fd} = 180V$

Fluence $10^{15}$ neq/cm²
FUTURE WORK:

- Studies on the ROC performance after $1 \times 10^{16}$ neq/cm$^2$
- Test Beam @ DESY in March (Tracking Eff.)
- Capacitance meas. In the two different patterns

CONCLUSIONS:

- Sensors show a good performance up to $5 \times 10^{15}$ neq/cm$^2$
- Mechanical stress reduces the bump-bonding yield. A problem to fix in a future production
- Still plenty of work ahead testing samples
Acknowledgements:

- PSI and ETH – CMS pixel team
- Specially
  - Hans Christian kaetsli
  - Andrey Starodumov
  - Dmitry Hits
  - Silvane Streuli
- KIT & KJ irradiation facilities
- AIDA project

THANK YOU FOR YOUR ATTENTION!

fjmunoz@ifca.unican.es
Francisca Muñoz
Backup
Depletion Area in 3D-Pixels

- Coaxial Symmetry
- \( r_1 \) is the electrode radius
- \( r_2 \) is the distance between columns (38\( \mu \)m|pad, 90\( \mu \)m|sensor)
- The depletion voltage is the minimum voltage at which the bulk of the sensor is fully depleted

\[
V_{fd} = \frac{1}{2} \frac{Nq}{\varepsilon} \left[ r_1^2 \ln \left( \frac{r_2}{r_1} \right) - \frac{1}{2} \left( r_2^2 - r_1^2 \right) \right]
\]

\( V_{fd} \) (coax) = 0.9 \cdot \( V_{fd} \) (planar)
Vfd Calculation

- Measured Value has to be extrapolated to the device structure dimensions (electrodes distances were not the same in pad and detector)
- Coaxial formula instead planar one:

$$V_{fd} = \frac{1}{2} \frac{Nq}{\varepsilon} \left[ r_1^2 \ln \left( \frac{r_2}{r_1} \right) - \frac{1}{2} \left( r_2^2 - r_1^2 \right) \right]$$

- \( r_{2,\text{detector}} = 2.4 \times r_{2,\text{pad}} \)
- \( V_{fd,\text{detector}} = 6 \times V_{fd,\text{pad}} \)

\[ V_{fd,\text{detector}} = 6.6 \times V_{fd,\text{pad}} \] Coax.

\[ V_{fd,\text{detector}} = 6^* V_{fd,\text{pad}} \] Planar Formula
Electrical Characterization. IV Curves

* Homogeneous behavior and acceptable current values
Wafer layout

* In the back side, two columns pattern.
  - Dense → reduced drift distance
    Expected higher radiation resistance
  - Sparse → larger drift distance
    Expected lower noise (lower capacitance)

Sparse pattern of holes P:
Rectangular matrix of 150x100um²

Dense pattern of holes P:
Rectangular matrix of 75x100um²

* Full module has been designed with sparse pattern and single guard ring
* Wafer with a polysilicon resistor implemented for biasing without ROC
Biasing studies. Wafer 3

Only guard connected → “punch through” polarization
Only bias connected → pixel by pixel polarization

Biasing studies. Detector 12B

![Graph showing biasing studies.](image)
Silicon detectors in HEP

- In CMS pixels (n+ on n), the pn junction is on the bottom, so the depletion region forms from the bottom up
- No signal until full depletion
- Diffusion across the junction is suppressed. Current across the junction is very small “leakage current”!
Readout Chip

- Paths of column token through double-column (green)
- Paths of the readout Token through the double- column peripheries

- When the column token stops at a pixel with hits. All hit information (pulse height, address...) is transferred to the column periphery where it is stored in data buffer

- Pixels without hits are skipped by the token
- Other double columns without hits for this Trigger are not affected and continue data acquisition
Address levels and trimming

Trimming

cisca Muñoz IFCA
Readout format

TBM header within an event counter

16 CHIPS

TBM trailer

1 CHIP

Pulse height

header col row

M 40.0ns Ch 4 2.36 V

Chip 1,2,3,4--> no data
Chip 5--> 1 data
Chip 6--> no data

...
ROC QUALIFICATION

- Calibrate Signal inputs
  - $V_{cal}$
  - $V_{ana}$
  - $V_{thrc}$
  - $Cal_{Del}$

- Pixel readout circuits
  - Pixel
  - Trim bit
  - Bump-Bonding
  - Pixel Address

- Functionality of the module
  - Noise
  - Trimming
  - Gain and Pedestal
  - IV
  - Thermal Cycle
VthrComp vs CalDel

VthrComp → Injecting a signal with fixed amplitude (Vcal), finding the value at the comparator at which this signal is above threshold

CalDel → Delay of the internal calibrate signal with respect to the trigger

Working area

- **VthrComp**
- **CalDel**

---

**VthrCompCalDel_c15r15_C0**

- Entries: 32400
- Mean x: 68
- Mean y: 95.91
- RMS x: 28.35
- RMS y: 21.92

---

Threshold

Comparator Threshold

0 20 40 60 80 100 120 140 160 180

VthrComp [DAC units]

0 1 2 3 3.5 4

CalDel [DAC units]

0 0.5 1 1.5 2 2.5 3 3.5

Low Threshold

High Threshold
Pixel test
VthrComp, Vtrim and the Trim Bits

- These are the DAC's used to adjust the thresholds of the comparators of the PUC
- VthrComp adjusts the threshold for every pixel on the ROC
- Vtrim sets range of thresholds the trim bits can be used to program the PUC to have
- Higher VthrComp and Vtrim translates into lower thresholds
- Trim Bits of 0 gives the lowest possible threshold for a given VthrComp and Vtrim
- Increasing Vtrim gives more range of threshold, yes it increases the step size of a trim bit
- The goal of setting Vtrim and the trim bits is to make up for the small differences in transistors due to limitations of IBM process used to manufacture the ROC
- These differences vary from pixel to pixel, and it is important to have the same threshold across the entire ROC
Bump bonding. Interconnection process
## Devices

<table>
<thead>
<tr>
<th>Name</th>
<th>Qty</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS_MC</td>
<td>1</td>
<td>Large module, matrix 8x2 detectors, <em>sparse</em> pattern of P columns and <em>single</em> guard ring</td>
</tr>
<tr>
<td>CMS_SC_11</td>
<td>5</td>
<td>Single chip detector with <em>sparse</em> pattern of P columns and <em>single</em> guard ring</td>
</tr>
<tr>
<td>CMS_SC_12</td>
<td>5</td>
<td>Single chip detector with <em>sparse</em> pattern of P columns and <em>double</em> guard ring</td>
</tr>
<tr>
<td>CMS_SC_21</td>
<td>5</td>
<td>Single chip detector with <em>dense</em> pattern of P columns and <em>single</em> guard ring</td>
</tr>
<tr>
<td>CMS_SC_22</td>
<td>5</td>
<td>Single chip detector with <em>dense</em> pattern of P columns and <em>double</em> guard ring</td>
</tr>
<tr>
<td>3D-Strip detector</td>
<td>8</td>
<td>3D-strip detectors with 128 strips of 80 µm pitch, 15µm strip width and <em>single</em> guard ring</td>
</tr>
<tr>
<td>3D-Pad detector</td>
<td>12</td>
<td>3D-pad detector with <em>single</em> guard ring</td>
</tr>
<tr>
<td>Test structures</td>
<td>-</td>
<td>Layer deposition test, polysilicon resistance test, hole alignment test</td>
</tr>
</tbody>
</table>
TEST BEAM in 2012:
@ PS Facilities. 1-15 Aug
@ SPS Facilities. 18-30 Nov

PS Test-beam
* No tracking results, very low data rate in the telescope, most of the beam time debugging the telescope
* Irradiated 3D-samples not on time
* One Unirradiated 3D sample in 2 different angles

SPS Test-beam
* Not much beam time, and in parasitic mode
* Bump connections reduced after irradiation (mechanical stress)
TEST BEAM @ PS

An unirradiated sensor has been measured at two different angles

SENSOR 12B: \[ MPV^{(0)} = MPV^{(\alpha)} \cdot \cos(\alpha) \]
\[ 296.9 = 317.8 \cdot \cos(\alpha) \]
\[ \Rightarrow \alpha = 21^\circ \]

Occupancy Maps for the two Different angles

Landau distributions
TEST BEAM @ SPS

Bump connections reduction after irradiation due to the mechanical stress

Occupancy map before irradiation in PSI laboratory

Occupancy map after irradiation in SPS Test Beam

fjmunoz@ifca.unican.es  Francisca Muñoz IFCA (CSIC-UC)
Irradiated up to $1 \times 10^{15}$ neq/cm$^2$

W6_21B @ 150V  
T=-20ºC

NEUTRONS
Irradiated up to $5 \times 10^{15}$ neq/cm²

Protons

$V = 180$ V @ -20°C