Development of enhanced double-sided 3D radiation sensors for pixel detector upgrades at HL-LHC

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Trento, Italy - February 20, 2012

[Work supported by INFN CSN V, projects "TREDI" (2005-2008) and "TRIDEAS" (2009-2011)]
Outline

High Energy Physics experiments at LHC
  The Large Hadron Collider
  The ATLAS experiment
  The current ATLAS silicon tracker
  The ATLAS Insertable B-Layer (IBL)

Radiation damage in silicon
  Summary
  Countermeasures

3D detectors
  Originally proposed architecture
  The ATLAS 3D sensor collaboration

Enhanced 3D technology at FBK
  Design choices and motivations
  Detailed electrical characterization
  Functional characterization

Possible technological improvements

Additional applications
The Large Hadron Collider (LHC)

- Largest particle collider ever built
- Near Geneva, underneath the Swiss/French border
- Total ring length of about 27 Km
- First started in 2008
- The official physics program started in 2009

Basic machine parameters

- Proton or Lead Ion collisions
- Nominal proton energy of 7 TeV (per beam)
- Bunch spacing of 25 ns
- Design luminosity $10^{34} \text{ cm}^{-2} \text{s}^{-1}$

Physics program

- Discovery of new particles/theories
- Particles collide inside the four experiments
- ATLAS and CMS: general purpose
- ALICE: study lead ions collision
- LHCb: specialized in b-physics
General purpose experiments
A Toroidal LHC ApparatuS (ATLAS)

Basic parameters

- 45 meters long
- 25 meters in diameter
- weights about 7000 tons

Structure (inside-out)

1. Inner detector
2. Calorimeters
3. 2 Tesla solenoid magnets
4. Muon spectrometers

The inner detector

- Several layers of silicon detectors and one layer of straw tube detectors
- Needed to reconstruct the particle interaction point
- Required to be very fast
- Operates in extremely harsh conditions
The current ATLAS silicon tracker

**Barrel cross-section**

- Total radius of roughly 1 m
- **Pixel detector**: 3 layers of *n-in-n pixel sensors*
- **Strip detector**: 4 layers of *p-in-n strip sensors*
- **Transition Radiation Tracker**: straw tubes interleaved with scintillating fibers

**The pixel detector**

- Three barrel layers at radiiuses 50.5, 88.5, 122.5 mm
- 6 end-caps (three on each side)
- Pixel size $50 \times 400 \ \mu m^2$
- Covers an area of $\sim 1.7 \ m^2$
- Approximately 67 million channels
- **Designed to withstand a fluence of** $1 \times 10^{15} \ 1 \text{ MeV \ n_{eq}cm}^{-2}$
The ATLAS Insertable B-Layer (IBL)
Planned installation during the first long shutdown (2013-2014)

**CURRENT PIXEL DETECTOR**

**RENDERING OF THE IBL**

Addition of a fourth pixel layer close to the beam pipe

**Motivations**

- Maintain the event pile-up under control as LHC luminosity increases
- Add redundancy to recover partial failure of modules in the other pixel layers
- Increase tracking and reconstruction accuracy

**Main design parameters**

- Need to reduce the beam pipe radius by 4mm
- Placed at 33.25 mm from the center of the beam pipe
- Will need to withstand a fluence of $5 \times 10^{15} \text{n}_{\text{eq}} \text{cm}^{-2}$

[M. Capeans, (The ATLAS Collaboration), ATLAS-TDR-019]
The ATLAS Insertable B-Layer (IBL)

Sensor requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of staves</td>
<td>14</td>
<td>-</td>
</tr>
<tr>
<td>Pixel size ($\Phi$, $z$)</td>
<td>50, 250</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Dead edge extension</td>
<td>200</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Sensor thickness</td>
<td>$&lt;250$</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>NIEL dose tolerance</td>
<td>$5 \times 10^{15}$</td>
<td>$n_{eq}/cm^2$</td>
</tr>
<tr>
<td>Hit efficiency in active area</td>
<td>$&gt;97%$</td>
<td>-</td>
</tr>
<tr>
<td>Operating bias voltage</td>
<td>$&lt;1000$</td>
<td>V</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-15</td>
<td>$^\circ$C</td>
</tr>
</tbody>
</table>

- Reduced pixel size in the $z$ direction (250 $\mu$m) to increase the spatial resolution
- No tilt possible in the $z$ direction $\rightarrow$ need for reduced dead area at the edges

[A. Clark, et al., (The ATLAS IBL collaboration), (2012) JINST 7 P11010]

NEED FOR ADVANCED RADIATION HARD DETECTORS
Radiation damage in silicon (summary)

Bulk damage
- Due to Non Ionizing Energy Loss (NIEL)
- Displacement of atoms in the Silicon lattice
- Built-up of crystal defects

Consequences
- Change in effective doping concentration (higher depletion, under-depletion)
- Increase of leakage current (shot noise, thermal runaway)
- Increase of charge trapping (charge losses)

Surface damage
- Due to Ionizing Energy Loss (IEL)
- Radiation generates carriers in SiO$_2$
- Electrons can escape while holes get trapped at the Si/SiO$_2$ interface

Consequences
- Accumulation of charge at the SiO$_2$/Si interface (inter-pixel capacitance and isolation and breakdown behavior)
- Increased charge trapping at the Si/SiO$_2$
- Increased surface recombination velocity

LOWERING OF THE S/N RATIO!

[Michael Moll - MC-PAD Network Training, Ljubljana, 27.9.2010]
Countermeasures

Material engineering
Deliberate incorporation of impurities or defects into the silicon bulk to improve radiation tolerance of the detectors

- Oxygen rich Silicon (FZ, DOFZ, Cz, MCZ)
- Pre-irradiated Silicon

New Materials
- Silicon carbide (SiC)
- Amorphous Silicon
- Diamond

Surface isolation
- Important to assure inter-electrode isolation
- Typically achieved using p-spray, p-stop or a combination of the two

Device engineering
- p-type silicon detectors (n-in-p)
- Thin detectors
- 3D detectors

[Michael Moll - MC-PAD Network Training, Ljubljana, 27.9.2010]
Full 3D detectors
Original idea - PROS and CONS

Features of 3D detectors

- First proposed by S. Parker and collaborators in the mid '90s 
  [NIMA 395 (1997), 328]
- Decouple the active volume from the inter-electrode distance
- Low full depletion voltage (<10 V)
- Short collection distances (~50 μm)
- Low trapping probability after irradiation
- Small dead area along the edges

Disadvantages of 3D detectors

- Columns are partially dead regions
- Non uniform response (low field regions are present)
- Higher capacitance (higher noise)
- Fabrication process complex and more expensive
The ATLAS 3D sensor collaboration

Institutes and processing facilities

- 18 Institutes

- 4 processing facilities:
  - SNF (Stanford, USA)
  - SINTEF (Oslo, Norway)
  - CNM (Barcelona, Spain)
  - FBK (Trento, Italy)

Available 3D technologies

- Full 3D with active-edges (SNF and SINTEF)
- 3D-DDTC with slim-edges (FBK, CNM)
- Full 3D-DDTC with slim-edges (FBK)

Main targets

1. Speed-up the test and industrialization of 3D silicon sensors
2. Production and testing of 3D sensors for the IBL

[C. Da Vià, et al., NIMA694 (2012), 321]
3D technology for the IBL developed at FBK

Main geometrical features

- Double-type column approach
- Fully double-sided
- Columns etched from both wafer sides
- Fully passing through columns
- Empty electrodes (no polysilicon filling)
- Surface isolation by means on p-spray implantations on both wafer sides

SEM cross-section

- Very good etching uniformity
- Columns are all passing through
- Slight shrinking of the column tip (not affecting device behavior)

[G. Giacomini, et al., to appear in IEEE TNS (2013)]
3D technology for the IBL developed at FBK
The common wafer layout and pixel layout

Common wafer layout
- 4 inches wafers
- 8 ATLAS FE-I4 pixel detectors
- 9 FE-I3 pixel detectors
- 3 CMS pixel detectors
- 4 strip detectors (80µm pitch)
- Several planar and 3D test structures

Single pixel layout
- Pixel size: 50×250 µm²
- 2E configuration: 2 n⁺ columns per pixel
- Inter-electrode distance (d): ~67 µm
- With field-plate

[C. Da Vià, et al., NIMA694 (2012), 321]
Motivation for FE-I4 pixel layout

Results from previous technologies

**Previous 3D-DDTC technology at FBK**
- Non-passing through columns
- Pixel size $50 \times 400 \ \mu m^2$ (FE-I3)
- Three pixel layouts (2E, 3E, 4E)

**Best performances from 3E devices (71 \ \mu m)**
- Noise $\sim 205 \ \text{e}^-$
- Good CCE up to $1 \times 10^{15} \ \text{n}_{eq}/\text{cm}^2$
- Tracking efficiency $>98\%$ at $1 \times 10^{15} \ \text{n}_{eq}/\text{cm}^2$

$\Phi_{eq}=1 \times 10^{15} \ \text{n}_{eq}/\text{cm}^2$

[A. Micelli, NIMA650 (2011), 150]

[A. La Rosa, NIMA681 (2012), 25]
**Edge termination (SLIM-EDGE)**

**Motivation and design**

**Slim-edges in the $z$ direction**
- **Requirement:** $\leq 200$ $\mu$m in the beam ($z$) direction
- **Motivation:** not possible to tilt modules in the $z$ direction due to space constrains
- Fence of ohmic columns to prevent the depletion region to reach the scribe line
- Designed with the aid of numerical simulations

**Computer aided design**
- Simulation of a structure including the last junction column and the ohmic fence
- Simulation domain highlighted with the dashed rectangle
- Scribe line model with a low lifetime region ($< 1$ ns)
- Monitor the current of the last junction column
- No avalanche models
Edge termination (SLIM-EDGE)

Motivation and design

Simulation results

- Different bulk doping concentrations tested
- No signs of current increase up to 500 V (well above expected operation voltage)
- The depletion region extends outside the active area by about 75 µm at 300 V
- Safe device operation with a 200 µm slim-edge
- **Note:** conservative design!
On wafer selection
Motivation and procedure

BUMP-BONDING

1. Chip
2. Chip
3. Chip
4. Sensor

On-wafer sensor selection
- The bump-bonding is complex and very expensive
- Assemble only good sensor tiles
- Wafer with more than 3 good sensors are sent for bump-bonding

Temporary metal layer
- Deposited on top of the frontside passivation
- Strip-like metalization
- 80 strips connecting 336 pixels each
- Automatic current measurements
- The sum of all strip currents gives the total sensor current

[G. Giacomini, et al., to appear in IEEE TNS (2013)]
On wafer selection
Example test results

GOOD WAFER (ATLAS12)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation temperature</td>
<td>$T_{op}$</td>
<td>20-24 °C</td>
</tr>
<tr>
<td>Depletion voltage</td>
<td>$V_{depl}$</td>
<td>&lt;15 V</td>
</tr>
<tr>
<td>Operation voltage</td>
<td>$V_{op}$</td>
<td>$\geq V_{depl} + 10$ V</td>
</tr>
<tr>
<td>Leakage current at $V_{op}$</td>
<td>$I(V_{op})$</td>
<td>&lt;2 µA</td>
</tr>
<tr>
<td>Breakdown voltage</td>
<td>$V_{bd}$</td>
<td>&gt;25 V</td>
</tr>
<tr>
<td>Current &quot;slope&quot;</td>
<td>$I(V_{op})/I(V_{op} - 5V)$</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>

Wafer/sensor selection

- Good sensors always have currents much lower than the set limit
- Breakdown voltages are typically higher than 30 V for good detectors
- Confirmation of the selection method comparing current pre/after bump-bonding
- **Yield of IBL production at FBK: 56.82%**

NOTE: further investigation needed on some aspects

- The breakdown is lower than for standard planar detectors (can be critical after irradiation)
- In some cases the behavior is not very uniform
- Necessary to perform a thorough electrical characterization
Detailed electrical characterization
3D diodes

3D diode
- Two terminal device having an area of roughly 10 mm²
- Electrodes of the same type are shorted together
- All the geometries of larger detectors are reproduced
- Eases the characterization

Performed tests
- I-V and C-V measurements as a function of the temperature
- Numerical simulations to confirm the findings and gain a deeper understanding of the device behavior

[M. Povoli, et al., NIMA699, (2013), 22]
IV measurements with variable temperature

IV Curves

Setup

- Devices coming from wafer W20 of the ATLAS09 batch
- Devices were diced and wire bonded on small PCBs
- Wire bonding contribution is negligible
- Temperature variation between $-20^\circ C$ and $35^\circ C$ inside a climatic chamber
- Measurements performed with HP4145

Preliminary results

- Each type of device has its own characteristic behavior
- Breakdown voltages between 40 and 50V
- Different current slope for different devices
- More details in the next slide...
Data analysis
Intrinsic electric behavior

Breakdown voltages
- Breakdown between 40 and 50V
- Linear increase with temperature
- The increase is between $\sim 50$ and $\sim 80\, mV/\degree C$
- In agreement with the expectation

$[\text{Crowell, C. R. and S. M. Sze, Appl. Phys. Lett. 9, 6 (1966) 242-244.}]$

Purpose
Distinction between thermal and avalanche generation

Equation

$$I(T) = I(T_R) \left( \frac{T}{T_R} \right)^2 \exp \left[ \frac{E}{2k_B} \left( \frac{1}{T_R} - \frac{1}{T} \right) \right]$$

Results
- $T_R=293.15\, \degree K$
- Very good agreement at low biases
- The agreement is lost as breakdown approaches
Investigation through numerical simulations

Simulated structure

- A quarter of elementary cell (thanks to symmetry)
- Bulk doping: $7 \times 10^{11} \text{ cm}^{-3}$ (p-type, measured)
- One columnar electrode per type
- Measured p-spray profiles
- Measured n$^+$ and p$^+$ surface implantations
- Device layout fully reproduced

Incremental addition of the layout details

- Used to estimate the contribution of each component of the device capacitance
- Allows discriminate between inter-electrode and surface capacitance

Simulation of the full structure

- Estimation of the expected breakdown voltage and current levels
- Analysis of the distribution of electrical quantities (e.g. Electric field and Electrostatic potential)
C-V measurements vs. C-V simulations
FE-I4 diode with field-plate

Results

- Electrodes contribution: \( \sim 51.4 \text{pF} \) (constant)
- **p-spray** causes an increase of \( \sim 30 \text{pF} \) (basically constant)
- \( P^+ \) implantation and metal on the back side do not cause much increase
- \( N^+ \) implantation and metal on the front side cause an increase of \( \sim 63 \text{pF} \) at a bias voltage of 20V
- At higher biases the contribution of front side saturates to a value similar to the one obtained only with electrodes and p-spray (\( \sim 103 \text{pF} \))
- Measured capacitance does not fully saturate at 40V (instrument limitations)
Distribution of electrical quantities
FE-I4 diode - Electric field

- Large field peaks on both the upper and lower surfaces
- Peaks are placed at the n\(^+\) to p-spray junction
- Particularly critical due to the high dose p-spray implantation
- Both structures have similar field-peaks on the backside
- The field-plate redistributes and lowers the field on the frontside
Front-side surface irradiation

X-Rays - 2 Mrad (60 minutes irradiation)

P-spray compensation to increase the breakdown voltage
How large is the increase?

- Irradiation performed at "Laboratori Nazionali di Legnaro" (LNL, Padova, Italy, thanks to Serena Mattiazzo)
- Use of MOS capacitors to monitor the increase in oxide charge
- Two irradiations: without and with bias (20 V)
- Considerably larger charge when irradiation is performed under bias

- Two different FE-I4 diodes with field-plate
- Current increase do to surface generation
- Limited breakdown increase
- Pre-irradiation trend maintained after
- Confirm that the breakdown occurs on the backside
Functional characterization of FE-I4 pixel detectors
Readout chip and measurement setups

ATLAS FE-I4 readout chip

- Designed to withstand a TID of 250 Mrad
- Leakage compensation
- Double stage charge amplifier with constant current discharge
- Discriminator after charge amplifier
- Operates in Time Over Threshold (ToT) mode
- The ToT is representative of the collected charge

The USBPix system
[http://icwiki.physik.uni-bonn.de/twiki/bin/view/Systems/UsbPix]

The EUDET Telescope
Functional characterization of FE-I4 pixel detectors
Radioactive source scans ($^{90}$Sr, Lab)

**PRE-irradiation**
- Comparison between FBK and CNM detectors
- Calibration: 10 ToT at 20 keV
- Most Probable Value of the "all-cluster" charge distribution
- FBK → charge saturation before 10 V
- CNM → charge saturation at roughly 25 V
- Numerical simulations (dashed line) confirm the measurement results

**POST-irradiation**
- Lowering of charge collection due to trapping
- FBK detector irradiated at $5 \times 10^{15}$ n$_{eq}$/cm$^2$ (red) shows a hint of charge saturation at roughly 150 V
- Confirmed by numerical simulations (red dashed line)
- Measurement not available for $2 \times 10^{15}$ n$_{eq}$/cm$^2$ but simulations can be trusted (violet dashed line)
- Satisfactory performances

[G.-F. Dalla Betta, et al., VERTEX2012, submitted to POS]
Functional characterization of FE-I4 pixel detectors
Test-beam results (tracking efficiency)

Beam tests during 2011-2012
- CERN - SPS: 120 GeV pions
- DESY: 4 GeV positrons
- EUDET Telescope
- Both un-irradiated and irradiated samples
- IBL operating conditions
- Planar sensor always used as reference

(b) PRE-irrad. efficiency map
- Good tracking efficiency (98.8%)
- Electrodes appear as less efficient regions
- Possible to obtain higher efficiency by tilting the device with respect to the beam

(c,d) POST-irrad. efficiency map
- FBK90 \( (2 \times 10^{15} \text{ n}_\text{eq}/\text{cm}^2) \) shows great efficiency (99.2%) at 60 V of bias when tilted by 15°
- FBK87 \( (5 \times 10^{15} \text{ n}_\text{eq}/\text{cm}^2) \) exhibits not sufficient efficiency (95.6%) at the chosen bias (140 V)
- **NOTE:** when the proper bias is used (e.g. 160 V) the efficiency is back within IBL requirements (98.2%)

[P. Grenier, et al., "IBL TestBeam Results", presented at the IBL Sensor Review, CERN, 4-5 July 2011]
Proton irradiated 3D diodes

80µm pitch

FE-I4

- Irradiation performed at Los Alamos with 800 MeV protons (thanks to Martin Hoeferkamp)
- Only half of the requested fluence was delivered
- Increase in breakdown between few volts and ∼100 V

Important!

- Devices were selected prior to irradiation
- The FE-I4 diode irradiated at $2 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ shows a breakdown voltage of roughly 125 V
- A proper sensor selection will assure optimal operating voltages after irradiation!
SLIM-EDGE characterization
Electrical tests

Performed test

- Several cuts performed by means of a diamond saw
- Each cut is closer to the active area
- I-V measurement after each cut

[M. Povoli, et al., JINST 7 (2012) C01015]

Results

- Intrinsic device behavior is equal to roughly 60 V
- No increase in reverse current up to the fourth cut
- Possible to reduce the total edge extension to roughly 100 µm

NOTE: critical only before irradiation
SLIM-EDGE characterization

Functional tests (FE-I4 diode)

Laser scan $V_b=15$ V

Edge efficiency (Test beam data, $2 \times 10^{15}$ $n_{eq}/cm^2$)

[Laser scan (Lab)]
- Laser: $\lambda=1060$ nm
- Readout: CSA + 20 ns shaper
- Very good agreement with simulations

Edge efficiency after irradiation (test beam)
- Full efficiency inside the active-area
- Roughly 25 $\mu$m of the slim-edge are active

Numerical simulation

[p+ n+ p+]
Possible technological improvements
Investigation through numerical simulations

- The high field region on the backside can be critical!
- It is of paramount importance to use large operating voltages!
- Lifting the $n^+$ column tip will eliminate the critical region on the backside
- At the same time the fabrication will be easier and faster

[M. Povoli, et al., IEEE NSS12 Conf. Record, pp. 1334-1338]

- Important to also improve the field distribution on the frontside
- The field-plate is important
- Some of the designed structures include a floating $n^+$ ring which is intended to interrupt the electrostatic potential of the p-spray
- The design is performed by means of numerical simulations
Simulation results

Effect of the floating ring

- The potential of the inner p-spray is lower
- The field at the main junction is lower and the field-plate works properly
- Large peak on the outer ring junction → causes breakdown
- The ring placement is critical due to space constrains

Simulated I-Vs

- All devices show larger breakdown than in the previous technology
- The floating ring limits the performances but could act as additional shielding from surface currents
- Raising the $n^+$ column should deliver breakdown voltages larger than 100 V
New SLIM-EDGE implementation

Pixel detectors slim-edge

- Reduced by 50 $\mu$m following the indications obtain from previous tests
- Conservative design to avoid problems

New slim-edge implementation for some 3D diodes

- Double row of short trenches (mimicking the active-edge)
- Dead area of roughly 50 $\mu$m
- Maintains the mechanical integrity and does not require support wafer
- Simulation results at 50 V of bias show how this solutions does not allow the depletion region to reach the scribe line

[G.-F. Dalla Betta, et al., NSS11 Conf. Record, pp. 1334-1340]
Fabricated devices
Preliminary electrical characterization

Available devices

- 4 FE-I4 pixel detectors (2 versions)
- 26 CMS pixel detectors (8 versions)
- 2 MEDIPIX-II detectors
- 3D diodes in several different flavors

Preliminary results

- Batch completed in mid October 2012
- A few IV measurements on 3D diodes here reported
- Leakage current higher than expected but acceptable
- Sizable increase of breakdown voltage

[M. Povoli, et al., IEEE NSS12 Conf. Record, pp. 1334-1338]
The ATLAS Forward Physics (AFP)

Motivation and requirements

- Measure protons scattered from the collision
- Located at roughly 200 m both upstreams and downstreams
- Requires reduced edge extension
- FE-I4 modules are investigated

[The ATLAS Collaboration, CERN-LHCC-2011-012]

Performed tests

- The edge of interest is the one not "IBL-like"
- Same cut and measure tests were performed
- Proper operation up to the 6th cut (75 \(\mu\)m edge)

Aspect to investigate...

- Very un-uniform irradiation
- Tests are being performed on CNM devices

[S. Grinstein, RESMDD12, submitted to NIMA]
Planar detectors with active-edges
Standard vs. Active Edge detectors

**Standard detectors**

- In standard detectors a dead border region must be present
- In a good design cracks and damages on the edges should be at least at a few hundreds of micrometers away from the depleted region
- Total dead region \( a + d \geq 500 \mu m \)

**How to limit dead region?**

- Cut lines not sawed but etched with Deep Reactive Ion Etching (DRIE) and doped
  

**Problems**

- Process is more complicated
- Need for support wafer
- Finding the correct "d" to limit early break-down phenomena

[M. Povoli, NIMA658 (2011), 103]
Planar detectors with active-edges

Device and wafer layout

Single-sided p-in-n devices (support wafer)

General device layout (test diode)

1. Distance between $n^+$ and $p^+$ doping (GAP)
2. Field-plate
3. Bias pad (connected to the doped trench)
4. Floating $p^+$ ring

Trench etching

- Designed to be 4 µm
- Not well defined at first
- Optimized etching in the second part of the batch (roughly 10 µm width)
- Partial polysilicon filling needed to restore the surface planarity

Wafer layout

- Strip detectors with inter-strip pitches of 50, 80, and 100 µm (AC or DC coupled)
- Pixel detectors compatible with the readout chips of the ALICE experiment
- Several test diodes in many different flavors
- Standard planar test structures
Planar detectors with active-edges
Electrical and functional characterization

[G.-F. Dalla Betta, et al., NSS11 Conf. Record, pp. 1334-1340]

Electrical characterization (I-V)

- Good reverse current values and uniformity
- Clear trend with GAP size
- Once again the field-plate proves its effectiveness

Functional tests

- Bi-dimensional X-Ray scan performed at Diamond Light Source, Didcot, UK.
- 15 keV X-rays, spot size \( \sim 3 \ \mu m \) FWHM
- Very good signal efficiency up to less than 20 \( \mu m \) away from the edge

[M. Povoli, et al., NIMA (2012)
http://dx.doi.org/10.1016/j.nima.2012.09.035]
Thin 3D detectors with built-in charge multiplication
Evidence and exploitation of this effect

Motivation
- Increasing interest in reducing the total material budget
- Reduction of the sensor thickness
- Lower thickness → less detection volume
- Reduction in available charge for particle detection

Idea and investigation through numerical simulations
- A shrinking of all geometries by a factor of ~3 will allow to also reduce inter-electrode spacing and column diameter
- Bulk thickness: ~70 µm
- Column diameter: ~4 µm
- Higher field at lower voltages

Charge multiplication (CM)
- Evidence of CM was found in irradiated planar and 3D detectors
- CM was observed in older generations of both FBK and CNM 3D detectors
  [A. Zoboli, et al., NSS08 Conf. Record, 2721]
  [M. Köhler, et al., NIMA659 (2011), 272]
- Triggered by high electric field at the tip of the junction columns
- Confirmed by numerical simulations
  [G. Giacomini, et al., VERTEX2011, POS]
- Can charge multiplication be exploited?!?
Thin 3D detectors with built-in charge multiplication
Simulation results

Gain before irradiation
- All investigated structures show CM
- The onset of CM changes with geometry
- Lower operating voltages for structures having trench ohmic electrodes
- A good gain uniformity was found within the entire investigated cell

Gain after HEAVY irradiation
- Results reported only for the rectangular cell
- Bulk radiation damage modeled with a 3 level trap model
- Reduction of the collected charge due to trapping (expected)
- No change in CM onset voltage
- Completely recover charge trapping
Thin 3D detectors with built-in charge multiplication
Surface isolation and electrode efficiency

Final sensor geometry

- Rectangular cell shape
- P-spray and ~4 µm field-plate
- Raise the n⁺ column to avoid critical regions on the backside
- Modification of the tip shape in order to avoid early breakdown phenomena
- Extracted 1D electric field profiles show that the surface and tip field are under control
- Possible to operate in CM mode

Electrode response

- Crucial to have polysilicon filling and sufficiently large lifetimes in it
- Lifetimes calibrated to match the electrode efficiency found for Stanford detectors

Full 3D MIP simulation (proposed shaping time of 10 ns)

- Three hit points investigated (bulk and both electrode types)
- CM properties similar to the simplified structure
- p⁺ electrode is fully efficient and show good CM
- n⁺ electrode is less efficient and shows lower CM
- Multiplication of the charge generated under the tip
HYbrid DEtectors for neutrons (HYDE)

Neutron detection
- Bare silicon is not able to detect neutrons
- Need for a converting material
- The most used converter is LiF
- Most of the commercial devices are able to only detect thermal neutrons

Neutron detectors produced with 3D technology
- Purposely designed cavities
- Cavities are filled with the converter
- Increased interaction probability between reaction products and silicon

The HYDE project (INFN)
- Innovative polysiloxane converter
- Detects both thermal and fast neutrons
- Reaction products: recoil protons and light in the blue to red range

Realized detectors
- The cavities are connected through columnar pillars
- Both with and without polysilicon filling
- Good leakage currents and breakdown voltages
- The converter is deposited at Laboratori Nazionali di Legnaro

![Graph showing the relationship between current and reverse bias for different devices with varying parameters.](image)
HYbrid DEtectors for neutrons (HYDE)

SEM pictures
- Fabricated cavity with connecting pillars (LEFT)
- The same after filling with converter (RIGHT)

\(\alpha\)-particle measurements
- Measurements from both sides of the sensors
- Main peak correspond to \(^{241}\)Am alphas (except for the energy loss in air)
- Lower peak from the trench side: geometrical motivations

Neutron beam measurements
- Calibration with radioactive sources \((\alpha, \gamma)\)
- Bare sensor as comparison and two sensors with converter
- Indication of increased statistics in the range from 0.5 to 1.25 MeV (VERY PRELIMINARY)

\[
\begin{align*}
\text{Normalized counts} & \\
\text{Energy [MeV]} & \\
\text{METAL CONTACT SIDE} & \\
\text{TRENCH SIDE} & \\
V_{\text{bias}} = 40 \text{ V} & \\
0 & 0.1 \\
0.0001 & 0.001 \\
0.01 & 0.1 \\
0.1 & 1 \\
1 & 10 \\
10 & 100 \\
100 & 1000 \\
1000 & 10000 \\
10000 & 100000 \\
100000 & 1000000 \\
\end{align*}
\]

\[
\begin{align*}
\text{Gamma source calibration, NO-conv.} & \\
\text{n28-350-150, WITH-conv. (}V_{\text{bias}}=50\text{V)} & \\
\text{n8-300-50, WITH-conv. (}V_{\text{bias}}=35\text{V)} & \\
\text{n21-400-100, NO-conv. (}V_{\text{bias}}=50\text{V)} & \\
\end{align*}
\]
CONCLUSIONS

- An enhanced 3D-DDTC sensor concept with fully passing through columns was designed at University of Trento and fabricated at FBK.
- All the performed studies allowed to gain a better understanding of the behavior of 3D detectors both from the electrical and the functional point of views.
- 3D Pixel detectors compatible with the FE-I4 readout chip proved to operate efficiently in IBL operating conditions.
- These devices were chosen, together with CNM 3D detectors and planar 3D detectors, to populate the ATLAS Insertable B-Layer which will be installed during the first long shutdown of the LHC (2013-2014).
- The large amount of activities performed in the framework of the ATLAS 3D sensor collaboration triggered new ideas that are currently being investigated and will be soon tested.
Thank you!