Performance of 3D-trench silicon sensors designed for high time resolution

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Developments on future tracking/vertex detectors go in the direction of a full 4D approach ...

Severe requirements for future detector:

- Space and time measuring capabilities at the single pixel level
  - space resolutions below 10 µm
  - time resolutions below 50 ps
- Sustain fluences greater than some $10^{16}$ n$_{eq}$ cm$^{-2}$
- Very low material budget

Several R&D studies of silicon sensors are ongoing

3D silicon pixel sensors: a very promising technology to be fully explored

3D successfully used in current tracking systems and good candidates for HL-LHC tracker upgrades

→ Radiation hardness proved up to $10^{16}$ n$_{eq}$ cm$^{-2}$
The TimeSPOT project

Main target:
Develop and realize a demonstrator consisting of a complete reduced size tracking system, integrating ~ 10^3 read-out pixel channels, satisfying the following requirements:

- Pixel pitch: \( \leq 55 \mu m \)
- Radiation hardness: \( 10^{16} - 10^{17} n_{eq}/cm^2 \) (sensors) – greater than 1 Grad (electronics)
- Time resolution: \( \leq 50 \) ps per pixel
- Real time track reconstruction algorithms and fast read-out (data throughput > 1 TB/s)

Activities are organized in 6 work packages:
1. 3D silicon sensors: development and characterization
2. 3D diamond sensors: development and characterization
3. Design and test of pixel front-end with timing measurement
4. Design and implementation of real-time tracking algorithms
5. Design and implementation of high-speed readout boards
6. System integration and tests

3 years work program + 1 year possible extension (2018-2021)
3D sensors for timing measurements

**PROs**

- Possibility to decouple sensor thickness and drift distance
  - large signal amplitude & short collection time
- Lateral electric field and charge collection
  - Signal concentrated in time
  - Time uncertainties from non-uniform ionization (Landau fluctuations) minimized

**CONs**

- Non-uniform electric field
- Electrodes are partially dead regions
- High capacitance
- Complicated fabrication technology (cost, yield)

Low-field regions in between electrodes of same type
**TimeSPOT: 3D pixel with trench electrodes**

Different geometries based on hexagonal and square pixel with columnar and trench shaped electrodes designed and simulated (electric field, weighting field and carrier drift velocity, induced instant current).

**Configuration with parallel trenches chosen**

- Electric field map
- Column geometry
- Trench geometry

- Continuous $p^+$ trench
- Dashed $n^+$ trench
- Continuous $p^+$ trench

Bias electrode ($p^+$)
Readout electrode ($n^+$)
**TimeSPOT 3D pixel simulation**

Electric field map at different $V_{\text{bias}}$

- Total charge deposit for MIP $\approx 2$ fC
- Full depletion @ few volts, velocity saturation @ $> 30$ V
- Pixel capacitance (from simulation) $\sim 110$ fF

Study carried out using Synopsys Sentaurus TCAD
First 3D-trench batch

3D Test structures

- Single/double pixels
- Pixel strips

Continuous p+ trench
Dashed n+ trench

Structures with different n+ trench width/gap size produced

Schematic design

Two examples:

Timepix compatible device
- 256x256 pixels
- 55 µm pitch
First 3D-trench batch: fabrication technology

Photolithography with stepper

- Minimum feature size 350 nm
- Alignment accuracy 80 nm
- Max exposure area ~2x2 cm²
- Full size reticle for two blocks: Timepix sensor and test structures

Delivered on June 2019
First 3D-trench batch: electrical measurements

18x18 pixel test structures

Measurements on wafer (FBK)

~10 pA/pixel on working devices

Measurements after dicing (Torino and Trento laboratory)

Measured capacitance ~110 fF/pixel (in agreement with simulation)

Full depletion @ ~ 12 V
First 3D-trench batch: response to laser pulses

1030 nm, 200 fs, 40 MHz pulsed laser

5 \mu m diameter laser spot on sensor (20x optics)

10-pixel strip + amplifier board with discrete components (KU board), not optimized for our sensors

Digital CFD on scope [50% Threshold]

\[ \sigma_t = \frac{\sigma_{\text{meas}}}{\sqrt{2}} \]

\( \sigma_t \sim 20 \text{ ps} @ \text{MIP equivalent laser signal} \)
First 3D-trench batch: test beam

Several 3D structures test with beam at PSI

(A) Pixel-strip (10 pixels connected on the same read-out pad)
(B) Single and double pixel
(C) Hexagonal (column) pixel device, based on FBK 3D Single Sided Technology

Devices connected to electronics by wire bonding (Al, 25 µm diameter, ~ 5 mm length)
Test beam setup

πM₁ beam line
- π⁺ beam (negligible e⁺ contamination)
- Momentum: 270 MeV/c
- Radius on the spot: $\sigma \sim 1.5$ cm
Test beam setup: system inside the “black box”

DUT front end:
- broadband amplifier board with discrete components

INFN-Ge Front End

KU Front End

Time Taggers:
- Quarz Cherenkov radiator + MCP
- Area: 5x5 cm^2
- $\sigma_t \sim 15$ ps

Beam
Test beam setup: trigger & DAQ

**DAQ:** Oscilloscope Rohde&Shwarz RTP084 - Sampling frequency: 20 Gsample/s - Bandwidth: 4 GHz (or 8 GHz)

**Trigger:** Coincidence of MCP2 and Si sensor

**Silicon sensor**

**Beam RF signal** (50 MHz)

**MCP 1 & 2** (time taggers)

**MCP1**

**MCP2**
First 3D-trench batch: test beam results

DUT: Double pixel

INFN-Ge Front End Board
(1 amplification stage, G~30
2 GHz bandwidth)
+ external broadband amplifier
(G=10, 2 GHz bandwidth)

Measurements performed at different $V_{BIAS}$

<table>
<thead>
<tr>
<th>$V_{BIAS}$ (V)</th>
<th>Nevent</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20</td>
<td>20k</td>
</tr>
<tr>
<td>-50</td>
<td>20k</td>
</tr>
<tr>
<td>-80</td>
<td>3k</td>
</tr>
<tr>
<td>-110</td>
<td>20k</td>
</tr>
<tr>
<td>-140</td>
<td>20k</td>
</tr>
</tbody>
</table>

$V_{BIAS} = -140$ V

MIP MPV $\sim 25$ mV

FIT: Gaussian (noise) + Landau (signal) + error step function (trigger)

The Max/FWHM ratio is compatible with a Landau distribution of a 150 µm thick silicon
First 3D-trench batch: time resolution (I)

ToA: numerical leading edge discriminator with a fixed threshold $Th=5mV$ (no TOT correction)

Numerical filters to reduce high frequency noise applied

ToA: Numerical CFD with a 35% threshold

$\chi^2 / \text{ndf} = 252.4 / 145$

Yield/200 = $78.91 \pm 0.63$

$\mu \ [\text{ns}] = -0.5527 \pm 0.0007$

$\sigma_{\text{core}} \ [\text{ns}] = 0.04414 \pm 0.00052$

$\lambda \ [\text{ns}] = 0.1031 \pm 0.0039$

$\text{frac}_{\text{core}} = 0.7517 \pm 0.0123$

$\sigma_t = (44.1 \pm 0.5) \text{ ps}$

$V_{\text{BIAS}} = -140 \text{ V}$

$\chi^2 / \text{ndf} = 367.8 / 124$

Yield/200 = $77.07 \pm 0.62$

$\mu \ [\text{ns}] = -0.5004 \pm 0.0005$

$\sigma_{\text{core}} \ [\text{ns}] = 0.02874 \pm 0.00035$

$\lambda \ [\text{ns}] = 0.0923 \pm 0.0025$

$\text{frac}_{\text{core}} = 0.6793 \pm 0.0102$

$\sigma_t = (28.7 \pm 0.4) \text{ ps}$

$V_{\text{BIAS}} = -140 \text{ V}$

FIT: $f \cdot \text{Gaus}(\mu, \sigma) + (1-f) \exp(\lambda) \otimes \text{Gaus}(\mu, \sigma)$
First 3D-trench batch: time resolution (II)

\[ \sigma_t = (26.9 \pm 0.4) \text{ ps} \]

Si-sensor time resolution after deconvolving the MCP time resolution

Combination of 3 main effects:
- Spurious signals (algorithm and in-time EMI noise)
- Partial charge deposit (neighbour un-read pixels)
- Weak field spots
Future production

New 3D-trench batch:
- design completed
- production at FBK almost ready to start
- foreseen delivery: second half of 2020

- New (and old) devices will be extensively tested in laboratory (with laser and β-source)
- Test beam @ PSI in December 2020
- Irradiation campaign will be carried out in 2020

R. Mendicino, ‘3D trenched-electrode sensors for charged particle tracking and timing’ NIMA 927 (2019)
Conclusion

- First measurement of timing performance of 3D Silicon pixel sensors based on parallel trench electrodes: time resolution below 30 ps
  - Measurement still limited by the front-end electronics
  - New trench electrode design represents a significant step forward towards the optimization of the timing performance of 3D silicon sensors
- Design of the second batch of 3D sensor complete; delivery foreseen in 2020
- Improved dedicated electronics (both discrete components and 28-nm CMOS ASIC) under development
Backup slides
Laser setup @INFN Cagliari

- 1030 nm, 200 fs, 40 MHz pulsed laser
- Pulse-picker to select pulses from 40 MHz to 1 MHz
- Monomode fiber to microscope
- 5x and 20x optics
- Optical filters for light intensity attenuation
- Microscope with IR camera
# First 3D-trench batch: test beam “online” results

<table>
<thead>
<tr>
<th>Test structure</th>
<th>Front-end type</th>
<th>( \sigma_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel strip</td>
<td>KU* modified prod. 1 – unshielded</td>
<td>40 – 50 ps</td>
</tr>
<tr>
<td>Single pixel</td>
<td>KU modified prod. 1 – unshielded</td>
<td>35 ps</td>
</tr>
<tr>
<td>Hexagonal column (FBK DS process)</td>
<td>KU modified prod. 1 – unshielded</td>
<td>(~ 60 \text{ ps (preliminary)})</td>
</tr>
<tr>
<td>Double pixel</td>
<td>GE** board SiGe BJT + BB amp – shielded</td>
<td>&lt; 30 ps</td>
</tr>
<tr>
<td>Single pixel</td>
<td>GE board SiGe BJT + GALI – shielded</td>
<td>Bad (Oscillations)</td>
</tr>
<tr>
<td>ATLAS Phase2 50x50 with poly connection</td>
<td>KU modified prod. 1 – unshielded</td>
<td>High values (&gt;100 ps) (preliminary)</td>
</tr>
<tr>
<td>Diamond 110</td>
<td>KU modified prod. 2</td>
<td>(~ 320 \text{ ps . Worse S/N ratio})</td>
</tr>
<tr>
<td>Diamond 55</td>
<td>KU modified prod. 2</td>
<td>(~ 230 \text{ ps . Worse S/N ratio})</td>
</tr>
</tbody>
</table>

A. Lai – HSTD12 (Hiroshima) – Dec2019
TimeSPOT readout chip

Front-End ASIC prototype on 28nm CMOS technology with full pixel readout chain.

55-pitch pixel integrating CSA+Disc+TDC

«High» power (7.2 µA)
«Low» power (4.1 µA)

\[ \sigma_j \sim 30 \text{ ps (simulation)} \]

- Input stage → Charge Sensitive Amplifier (CSA) with sensor leakage current compensation
- Discriminator → Leading Edge with discrete-time offset compensation
- 1 TDC per channel based on all-digital architecture

First prototype produced with the mini@sic approach (1.5x1.5 µm² chip): 3 TDC, 8 CSA+Leading Edge Discriminator, 1 DAC

Measured jitter ~60 ps
A second modified version will be submitted in mid 2020