Future Trends of 3D Si Sensors

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❖ Introduction

❖ Current status of 3D silicon technology

❖ Future challenges and technological trends
MEMS and 3D sensors

Micro-Electro-Mechanical Systems, or MEMS, is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of micro-fabrication, developed in the '70ies was first commercialized in the '80ies.
BOSCH PROCESS: alternating passivation ($C_4F_8$) and etch cycles ($SF_6$):

- Within the plasma an electric field is applied perpendicular to the silicon surface.

- The etch cycle consists of fluorine based etchants which react with silicon surface, removing silicon. The etch rates are ~1-5μm/minute.

- To minimize side wall etching, etch cycle is stopped and replaced with a passivation gas which creates a Teflon-like coating homogenously around the cavity. Energetic fluorine ions, accelerated by the e-field, remove the coating from the cavity bottom but NOT the side walls.
Different shapes depending on applications

Test with ~130nm fast amplifier designed at CERN by G. (Anelli)

Hexagonal or parallel trench shapes: Enhanced speed

This will be used for Micro-dosimetry

Fabrication J. Hasi and C. Kenney, SLAC/Stanford
Existing 3D designs:

Single side, full 3D with active edges requires a support wafer which is removed later.

Double sided full or partially through 3D with slim-fences (~200um)
3D sensors bump-bonded with pixel frontends

Fabricated at CNM Now also being fabricated at FBK and SINTEF applications is synchrotron light sources and Neutron imaging

Medipix2 and Timepix (see LHCb upgrade talk on Monday)

ATLAS FE-I3

CMS (see poster by M. Obertino et al.)
FE-I4 for the ATLAS IBL

total dimension FE-I4: 20.2x19.0mm²
total pixel number: 26880
Total number of holes/chip: >100,000

4 runs were completed in February 2012 by CNM and FBK with double side process with 306 good chips, a total of ~ 100 wafers and an yield exceeding 60% fulfilling the following:

Sensor specifications for IBL:
- Qualify to $5 \times 10^{15} \text{n}_{eq}$
- Max. power dissipation: 200 mW/cm² at -15 C
- Tracking efficiency > 98%
3D sensors signal efficiency compatibility

**Diagrams and Graphs:**
- **Support wafer**
- **Active edge**
- **SINTEF/STANFORD**
- **FBK**
- **CNM**

**Graph:**
- Signal Efficiency [%] vs Fluence [ncm⁻²]
- Comparison between different sensor types:
  - Stanford 210 µm-diode [3]
  - CNM 215 µm column overlap - microstrip readout [2]
  - FE-I4 pixel readout 200 µm or 230 µm column overlap [1]

**Fluence [ncm⁻²]:**
- 0 to ~6000e⁻ for 230µm column overlap

**Graph Details:**
- 71 µm IES

**References:**
- [1] 2011 CNM-FBK IBL Modules. (C. Gemme, A. Micelli, S. Grinstein, lab tests) (test beam coordinated by P. Grenier, J. Wingarted, A. La Rosa), to be published in JINST.
Precise tracking systems challenges at HL-LHC

Precise vertex determination

Important role in pattern recognition/track reconstruction 200 pileup events/bc at $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$

**Key Issues:**

- **Material budget** - less multiple scattering, better primary vertex resolution
  - Thin/small beam-pipe
  - Ultra-light detectors
  - Many channels to reduce occupancy
  - High data rates -

- **High-precision detectors very close to IP**
  - Ultra radiation hard detectors
    - Radiation hardness up to $2 \times 10^{16} \text{1MeV ncm}^{-2}$ at innermost layers at 3000 fb$^{-1}$
    - IBL~$3 \times 10^{15} \text{ncm}^{-2}$ (5X$10^{15} \text{ncm}^{-2}$ with safety) at 300 fb$^{-1}$

- For forward and diffractive physics experiments: dis-homogenous irradiation

Strips ATLAS Radiation Taskforce [ATL-GEN-2005-01]
How can micromachining help coping with the above challenges

- Further improved aspect ratio to reduce electrode size and inefficiency
- Aggressive 3D inter-electrode spacing for improved radiation tolerance
- Control of charge multiplication before and after irradiation to reduce sensor thickness
- New ideas for active edges without support wafer if thicknesses is greater than 150um
- Use of micro-channels for reduced mass embedded cooling on FEC wafer
- Use FEC to apply bias voltage (possible for reduced bias after irradiation)
- Use alternative bias schemes to cope with dis-homogenous irradiation
1- Trends in aspect ratio

- 11:1  1997
- 24:1  2009
- Today  40-60:1
- 110:1!!!

Etching rate depends on exposed area

Etching rate depends on aspect ratio
2 - Radiation Tolerance of 3D sensors

\[ \lambda = \tau \times v \]

Drift Length Time  
Trapping Velocity (saturated)

\[ S = \frac{\lambda}{L} \left[ 1 - \exp \left( -\frac{L}{\lambda} \right) \right] \]

L = Inter-Electrode Spacing

2E = 103um  
3E = 71um (IBL DESIGN)  
4E = 56um  
5E = 47um

At 9x10^{15} ncm^{-2} And biases below 200V

<table>
<thead>
<tr>
<th>L = IES [um]</th>
<th>105</th>
<th>71</th>
<th>56</th>
<th>47</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Efficiency [%]</td>
<td>45</td>
<td>51</td>
<td>66</td>
<td>68</td>
</tr>
<tr>
<td>Charge 50um [e−]</td>
<td>1800</td>
<td>2040</td>
<td>2640</td>
<td>2720</td>
</tr>
<tr>
<td>Charge 100um [e−]</td>
<td>3200</td>
<td>4080</td>
<td>5280</td>
<td>5440</td>
</tr>
</tbody>
</table>

**Expected pixel dimension with 65nm technology**

- 125-150um
- Inter-Electrode Spacing = 35um

**Simulation Marco Povoli, Trento/Manchester**

**PRE-IRRADIATED RESPONSE**

- Expected charge in 50um silicon is equal to 4000 electrons
- Collected charge is reported at different integration times (1, 5, and 10 ns)
- At 5 and 10ns integration time full collection is reached well before 5V of bias
- If the proper bias voltage is applied (e.g. 30V) devices can collect full charge in less than 1ns

**<200ps Rise time at 30V**
50x50x50um³

Simulations after irradiation at $2 \times 10^{16}$ ncm$^{-2}$

Depletion evolution
Leakage current
Signal versus bias.

$V = 31.25 \times 10^{-9}$ cm$^3$

$dI = 35$ nA

$\alpha = \frac{dI}{(V \Phi_{eq})} = 5.6 \times 10^{-17}$

Simulation Marco Povoli, Trento/Manchester
Charge Multiplication by design in 3D sensors

- Charge Multiplication has been observed in 3D sensors after irradiation
- Can we control it by design to compensate the signal loss in thinner sensors before (and after) irradiation?

Yes if IES is small enough (hence E-field is high)
Smaller 3D cells are possible with fine pitch bump bonding or vertical integration

Possible geometries for enhanced e-field before irradiation

GF. Dalla Betta, C. Da Via, C-H. Lai, M. Povoli (simulations), S. Watts
Charge Multiplication Simulations

- n-side readout for electron multiplication
- MIPs hitting at different positions
- CM possible before irradiation at ~100V
- Gains up to 7-8, good spatial uniformity
Full 3D with active edges FE-I3 ATLAS

Current design requires the use of a support wafer which should be removed afterwards

Active Edge = 543-537 = 6±9.8 μm

Electrodes response is not zero if filled with poly-silicon


J. Hasi PhD Thesis
To simplify the process, the IBL design uses 200 μm guard fences with a total edge region of ~240um.

3D-CNMM34, irradiated with protons at 5E15neq/cm2: 1D hit efficiency in the long pixel direction for edge pixels. All edge pixels have added together.

Operating conditions:
- FE-I4 threshold = 1300e, bias voltage = -140V, magnetic field = 1.6T, tilt angle = 0 degrees.

Efficiency at 50% is ~200um: field penetrates within fences.
Improved edge designs with double side processing

Narrow trenches in place of columns

\[ V_{\text{bias}} = 50 \text{V} \]
Alternative active edge design in double-side 3D

A p⁺ doped wall exploiting diffusion from small trenches ...

Doping Concentration [cm⁻³]
Low mass 3D system with embedded cooling

- Processing vias on thin silicon requires a support wafer
- In 3D Capacitance decrease with thickness
- EPI silicon can be grown up to 150um
- The EPI-Cz interface can stop etching
- The support wafer can be removed after bump bonding (or after UBM using reversible wafer bonding)

Micro-channels fabricated at FBK in collaboration with the Pisa group
Existing activity and forthcoming 3DATLAS Prototype (ALICE+LHCb)

See presentation from J. Buytaert
Micro-channel cooling for LHCb VELO upgrade

3D sensors 230 microns

FE-I4 ROC 100 microns

Micro-channels

Pyrex 500 microns

Giulia Romagnoli
Jerome Noel
Paolo Petagna
Alessandro Mapelli
(Jan McGill)
(Alan Honma)

For this test we will use The LHCb VELO snake design

Driving CERN +EPFL group
Dis-homogenous irradiation

Affects precise tracking and vertex reconstruction close by the beam

Examples:
- LHCb,
- TOTEM,
- Atlas Forward Physics (AFP)

A possible solution is multiple bias operation using section divider active edges.

Prototypes are presently being fabricated at Stanford

S. Parker et al. NIMA 685(2012), 98
Last but not least: 3D structures on diamond substrate

...the benefits of 3D with no noise

Process flow

Single crystal diamond

3D electrodes graphitization with an IR high power laser

After metallization

Mapping using at the DIAMOND synchrotron micro-beam

Spot size: 3µm /* Beam Energy: 15keV /* HV = -40V /* Absorber 24

Samples from DDL
Processing made in Saclay and Manchester

Alexander Oh (Manchester)
Benoit Caylar (CEA Saclay)
Michael Pomorski (CEA Saclay)
Thorsten Wengler (CERN)
Stephen Watts (Manchester)
Iain Haughton (Manchester)
Harris Kagan (Ohio State)
Cinzia Da Via (Manchester)
ATLAS 3D Silicon Sensors
R&D Collaboration

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18 institutions and 5 processing facilities

*spokesperson