Pixel Detectors in HEP Experiments - Status and New Developments

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Outlook

1. Introduction

2. Pixel detector technologies
   • Historical excursion
   • Hybrid and monolithic pixel detectors

3. Pixel detectors in present HEP experiments

4. Future developments
1. Introduction

ALICE Collaboration: Run 137161, 2010-11-09, Global Tracks
Pixels in every day life

Silicon pixel detectors are employed in many consumer products:

- Silicon detectors are widely used in high energy physics experiments – and not only there!
- ...but it was not always like that:

http://www.electronics-eetimes.com
Sept. 18, 2012

https://www.ephotozine.com/
Aug. 2, 2016,
Complete Guide To Image Sensor Pixel Size

http://electronicdesign.com/
May 30, 2013, Infineon news
3D sensor chip for gesture recognition
Tracking using a Bubble Chamber

Example: Big European Bubble Chamber (CERN), till 1984

Tracking and particle interaction technology of the 50s, 60s, .....
Sampling the trajectories of the particles as they fly from the collision point.
40 million frames per second to be recorded, 7 orders of magnitude more than in the
~1975 bubble chambers

S. McMahon/STREAM Kick-off meeting
...in HEP

Z → µµ event with 25 reconstructed vertices.
Silicon Tracking Detectors

- Complex systems operated in a challenging high track density environment
- Innermost regions usually equipped with pixel detectors
Pixel Detectors

At the heart of (almost) all HEP experiments

Example: CMS
Pixel Detectors in HEP Experiments

Are **high granularity** tracking detectors which provide **unambiguous and precise hit information** in the **harsh environment** close to the interaction point.

- Position resolution down to few microns
- Unambiguous hit information in high track density region
- Improved primary and secondary vertex resolution
- “Light” detectors
- Fast readout
- High level of radiation hardness
Position Resolution

Pixel = high spatial resolution
O(10\(\mu\)m) on hybrid and down to
O(1-3\(\mu\)m) on MAPS

Multiple Scattering

Pixel = light detectors
Thin detectors on light carbon fibre
supports O(1-2%/0.2% X/X0 per layer)
• Excellent impact parameter resolution is mandatory for reconstruction of heavy flavor vertex (c and b vertex)

• Secondary vertices reconstruction strongly depends on impact parameter resolution

• Impact parameter resolution is strongly effected by
  • **Intrinsic point** resolution and alignment at higher momentum
  • **Multiple scattering in detector material** (in particular for low pt tracks)
Pixels help us to entangle this:

Tens of thousands of charged particles
ALICE – 5.02 A TeV Pb-Pb (2015)
2. Pixel Detector Technologies
Disclaimer

• This historical review is a personal view, and does not claim to be complete.

I was not there 😊

• Apologies for any omissions I might have made!
Early Trackers

- **CCD (1969 Bell Labs)**
- First use of “pixel”-like silicon detector in a physics experiment (SLD/SLAC and NA11/32, from ~1981)
- Charges are shifted through potential wells to the edge of the detector to the anodes
- Small pixel sizes (O(10 µm), matrix readout slow, low radiation tolerance
...the 70s/80’s

• End of the 70s: intensive R&D in silicon detectors to measure short lived particles \((10^{-12} – 10^{-13} \text{ s})\)

• R&D at CERN, Pisa,... [Heijne et al., NIM 78, 1980, Amendolia et al., NIM 78, 1980]

• 1980 first use of planar technology (standard IC process) to produce silicon strip sensors


• First use of silicon strip detectors by NA11 (CERN) and E706 (FNAL)

(A) NA11 (1981): 6 planes (24 x 36mm2): resistivity 2-3 kΩcm, thickness 280µm, pitch 20µm

(B) E706 (1982): 4 planes (3x3 cm2) + 2 planes (5x5cm2)
ASICs to Readout the Sensors

• **Next step:** use VLSI technology to couple ASIC amplifier directly to the detectors

• Industrial CMOS processing and custom design

• Tight connection between pixels and industrial CMOS developments

From E. Heijne, Silicon detectors 60 years of innovation
https://indico.cern.ch/event/537154/


Jan. 27, 2017  INFIERI - USP, P.Riedler
First Pad Tracker

Hermetic Si pad detector for UA2

Cylindrical detector array collaboration with
Claus Gößling and Alan Clark
U. Dortmund, U. Genève

~5 mm thin CILINDER around beam pipe
ONLY POSSIBLE using "AMPLEX" chip
16-channel circuit design Pierre Jarron

R. Ansari et al. NIMA279(1989) 388

1986 – 1988 in LAA microelectronics project
More Silicon Trackers

• 1990s - LEP, first silicon vertex detectors were installed in DELPHI and ALEPH experiments, then OPAL and L3

• Strip detectors show ambiguity at high multiplicities. Started to become apparent already in DELPHI.

We need pixels.......
Pixel Detectors

- **1987/88 First pixel prototype sensors** for SLAC/SSC, Shapiro and Galema, no special pixel electronics yet

- **1986 LAA project, CERN, first development of dedicated pixel electronic and parallel efforts in many other research institutions**

From E. Heijne, Silicon detectors 60 years of innovation
https://indico.cern.ch/event/537154/

First design in collaboration with EPFL

Krummenacher et al. NIM A288(1990)176
(presented at Munich Symp Feb 1989)

Chip ready
Summer 1989
published at IEEE Nucl Sc Symp 1989

Chip layout Dec 1988
Krummenachher & Enz EPFL

Campbell et al. NIM A290 (1990) 149
results including spectra taken with radioactive sources
Flip chip bonding:
- Controlled collapse chip connection – C4 by IBM ~1969 (e.g. mainframe computers)
- Studies in automotive for voltage regulators (GM Delco)

From E. Heijne, Silicon detectors 60 years of innovation
https://indico.cern.ch/event/537154/
The great wall of bump bonds by N. Ishikawa, Fujitsu Ltd.
Key ingredients for pixels

Main ingredients required for first (hybird) silicon pixel detectors (after planar process allowed to produce pixel sensors):

- **VLSI** (Very Large Scale Integration) technology to produce complex ASICs (Application Specific Integrated Circuit) – Hybrid, Monolithic

- Interconnect technology based on flip-chip bonding (connections of ~20μm between each sensor pixel cell and the corresponding readout cell in an ASIC) - Hybrid
First use in WA94/97 and NA57

- Study of the strange and multi-strange particle production in Pb-Pb collisions at the CERN SPS

- 1992 the first fully operational hybrid silicon micropattern detector was successfully tested in a fixed target experiment environment
  - WA94 heavy ion experiment at the OMEGA spectrometer of the CERN SPS
  - WA94 pre-decessor of the WA97/NA57 heavy ion experiment

[A hybrid silicon pixel telescope tested in a heavy ion experiment“, Nucl. Instr. and Meth. A 332 (1993) 188-201]
Omega 2 and 3 Ladders

6 readout ASICs connected to 1 silicon pixel sensor
- 7 pixel planes
- 1.1 M pixels
- Pixel size 75 um x 500 um
- 153 tracks reconstructed
- High multiplicity
- No B-field
- No noise hits

\(^{208}\text{Pb ion at 158 A GeV/c on Pb target}\)
Hybrid and Monolithic Pixels

Monolithic Pixels
- Charge generation volume integrated into the ASIC
- Many different variants (see last part of this presentation)

Hybrid Pixels
- Sensor and ASIC are independent units
- Interconnection technology needed to connect each pixel in the sensor to a readout cell in the ASIC
Pixel Technologies in HEP

- Most HEP experiments are using hybrid pixels
- There are few monolithic detectors at the moment in HEP experiments due to limitations in radiation hardness, speed,...
- But, there are exciting new developments which have allowed the first LHC experiment to adopt a monolithic pixel detector for its upgrade.
Mainly produced in a **planar process**: 

- High resistivity wafers (few kΩcm), 4”- 6” diam. O(200-300 μm) thick
- Specialized producers (~10 world wide) no industrial scale production like in CMOS processing
- Sensor prices scale roughly with the number of mask layers (single sided and double sided processing)
3D Sensors

- Both electrode types are processed inside the detector bulk
- Max. drift and depletion distance set by electrode spacing - **reduced collection time and depletion voltage**
- Very good performance at high fluences
- Production time and complexity for larger scale production
- Used in ATLAS IBL

ATLAS IBL Sensor (Threshold: 1600 e⁻ per cm²)
- p-irrad: $5 \times 10^{15}$ n$_{eq}$/cm$^2$ with 24 MeV protons
- n-irrad: $5 \times 10^{15}$ n$_{eq}$/cm$^2$ by nuclear reactor

From: *Prototype ATLAS IBL General Meeting*, S. Tsiskaridze (IFAE-Barcelona)
3. Pixel Detectors in HEP Experiments

http://cds.cern.ch/
LHC Pixel Detectors

all based on “Hybrid Pixels”

- amplification by a dedicated R/O chip
- 1-1 cell correspondence
The LHC environment

Given by LHC radiation levels, hit rates and bunch structure

- 25ns
- L1 trigger rate

Example: ATLAS

**Outer Pixel layers**
- Occupancy 1MHz/mm²
- NIEL ~ $10^{15}$ neq/cm²
- TID ~ 50Mrad
- Larger area O(10m²)

**Inner Pixel layers**
- Occupancy 10MHz/mm²
- NIEL ~ $10^{16}$ neq/cm²
- TID ~ 1Grad
- Smaller area O(1m²)
Radiation Damage Effects in Sensors

- Effects observed in ATLAS, CMS and LHCb (lower luminosity in ALICE)

- **Main challenge for the sensors is an increase in leakage current:**
  - Risk of thermal runaway - detector becomes inoperable
  - Operate sensors at low temperatures
  - Increase in shot noise - degraded performance

- Leakage current increases with integrated luminosity in agreement with the predictions

- **Further effects:**
  - Sensor depletion voltage changes with radiation damage
  - Loss of signal due to radiation induced damage
## Radiation Levels at LHC

<table>
<thead>
<tr>
<th></th>
<th>TID [kGy]</th>
<th>Fluence 1MeV n eq. [cm$^{-2}$]</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS Pixel/IBL</td>
<td>500/1000</td>
<td>$1 \times 10^{15}/5 \times 10^{15}$</td>
<td>10 years</td>
</tr>
<tr>
<td>ATLAS Strips</td>
<td>100</td>
<td>$2.0 \times 10^{14}$</td>
<td>10 years</td>
</tr>
<tr>
<td>CMS Pixels</td>
<td>840</td>
<td>$3 \times 10^{15}$</td>
<td>10 years</td>
</tr>
<tr>
<td>CMS Strips</td>
<td>70</td>
<td>$1.6 \times 10^{14}$</td>
<td>10 years</td>
</tr>
<tr>
<td>ALICE Pixel</td>
<td>2.7</td>
<td>$1 \times 10^{13}$</td>
<td>10 years</td>
</tr>
<tr>
<td>LHCb VELO</td>
<td>50</td>
<td>$1.3 \times 10^{14}$**</td>
<td>1 year</td>
</tr>
</tbody>
</table>

ATLAS and CMS values cited for innermost layers for pixels and strips for 500 fb$^{-1}$

* averaged (B-layer to be replaced)

** inner part, inhomogeneous irradiation
Sensor Technology in LHC Experiments

- p-in-n, n-in-p (single sided process)
- n-in-n (double sided process)
- Choice of sensor technology mainly driven by the radiation environment

<table>
<thead>
<tr>
<th></th>
<th>Fluence 1MeV $n_{eq}$ [cm$^{-2}$]</th>
<th>Sensor type</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS Pixel*</td>
<td>$1 \times 10^{15}$</td>
<td>n-in-n</td>
</tr>
<tr>
<td>ATLAS Strips</td>
<td>$2 \times 10^{14}$</td>
<td>p-in-n</td>
</tr>
<tr>
<td>CMS Pixels</td>
<td>$3 \times 10^{15}$</td>
<td>n-in-n</td>
</tr>
<tr>
<td>CMS Strips</td>
<td>$1.6 \times 10^{14}$</td>
<td>p-in-n</td>
</tr>
<tr>
<td>LHCb VELO</td>
<td>$1.3 \times 10^{14}$</td>
<td>n-in-n, n-in-p</td>
</tr>
<tr>
<td>ALICE Pixel</td>
<td>$1 \times 10^{13}$</td>
<td>p-in-n</td>
</tr>
<tr>
<td>ALICE Drift</td>
<td>$1.5 \times 10^{12}$</td>
<td>p-in-n</td>
</tr>
<tr>
<td>ALICE Strips</td>
<td>$1.5 \times 10^{12}$</td>
<td>p-in-n</td>
</tr>
</tbody>
</table>

n-side readout (n-in-n, n-in-p) after inversion:
- Depletion from segmented side (under-depleted operation possible)
- Electron collection
- Favorable combination of weighting field and
- Natural for p-type material

** per year

G. Kramberger, Vertex 2012
## Technology Choices at LHC

<table>
<thead>
<tr>
<th></th>
<th>Sensor [μm]</th>
<th>ASIC</th>
<th>Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>P-in-n</td>
<td>0.25 μm</td>
<td>~27°C</td>
</tr>
<tr>
<td>ATLAS</td>
<td>N-in-n ox</td>
<td>0.25 μm</td>
<td>-10°C</td>
</tr>
<tr>
<td>CMS</td>
<td>N-in-n</td>
<td>0.25 μm</td>
<td>-8°C</td>
</tr>
</tbody>
</table>
Inside 2 T solenoidal magnetic field

Three barrel layers:
- $R = 5\text{ cm (B-Layer)}$
- $R = 9\text{ cm (Layer-1)}$
- $R = 12\text{ cm (Layer-2)}$
1456 barrel modules

Two endcaps:
- three disks each
- 288 forward modules

- 80 million channels
- Three precise measurement points up to $|\eta| < 2.5$:
  - $R\Phi$ resolution: $8\ \mu\text{m (75\ um in z)}$
- Module operation at $-13\ ^\circ\text{C (evaporative C3F8)}$
ATLAS Pixel Module

- **Sensor**
  - 47232 n-on-n pixels with moderated p-spray insulation
  - 250 µm thickness
  - 50 µm (RΦ) × 400 µm (η)
  - 328 rows (x_{local}) × 144 columns (y_{local})
- **16 FE chips (FEI3, 0.25 um CMOS)**
  - bump bonded to sensor
- **Flex Hybrid**
  - passive components
  - Module Controller Chip to perform distribution of commands and event building.
ATLAS Pixel Upgrade during LS1

Refurbished Run-1 Pixel detector: **New Service Quarter Panels (nSQP)** and readout chain

- Kept the pixel detector assembled but rebuilt all on-detector services
- Repaired all accessible failures
- Moved opto-electronics to off-detector location for improved accessibility
- Increased data bandwidth from modules to back-end electronics to be ready for luminosities in Run 2 and beyond ($2\times3 \times 10^{34}$)

H. Pernegger/Seminar, ATI, 4/2016
Insertable B-Layer (IBL)

- Extend the Pixel detector to a 4-Layer pixel system to improve pattern recognition and b-tagging, track reconstruction and additional redundancy for the future
  - Light ! (low multiple scattering using light supports and thin detectors)
  - High resolution ! (smaller pixel size)
  - Bring it close to the collision point -> minimal beam pipe diameter and highly integrated system

- New sensors, FE chips and light detector in center of existing detector

Jan. 27, 2017
INFIERI - USP, P.Riedler
New pixel layer around smaller, new beam pipe (r=24 mm, was 29 mm)

IBL mounted on beampipe!

14 staves arranged at average r=33 mm

Radiation levels: \( \sim 1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2} \)
New FE (FE-I4) in 0.13 µm CMOS technology
  • 19 x 20 mm², 26880 channels

Pixel size reduced: 50 µm x 250 µm

2 sensor types per stave:
  • Double chip planar sensors (200 µm thick, n-in-n ox, reduced edge region by guard rings shifted underneath pixels)
  • Single chip 3D sensors (250 µm thick, vertical electrodes through the bulk)

Each stave:
  • 8 single chip modules (3D) and 12 double chip modules (planar)
  • 12 mio channels

Reduced material budget: ~1.9 % $X_0$
CMS Pixel Detector

Three barrel layers:
• R=4.4 cm
• R=7.3 cm
• R=10.2 cm

Forward disks:
• 2 forward disks on either side
• 66 mio. channels
• 1440 modules
• 15840 readout chips
• Environmental Temperature: -8°C
• 4T magnetic field

NIM A, 2013
http://dx.doi.org/10.1016/j.nima2013.04.001
CMS Pixel Module

Kapton signal cable
21 traces, 0.3mm pitch

Alu-power cable
6 x 250µ ribbon

High Density Print
3 Layers, 48µ thick

N-in-n Silicon Sensor
t=285µ
100µ x 150µ pixels

16 x Readout Chips
(CMOS) 175µ thick
4160 pixels/chip

SiN base strips
250µ thick, screw holes
CMS Pixel Detector
ALICE Pixel Detector

Two barrel layers:
- R = 3.9 cm
- R = 7.6 cm
- No forward disks

- 9.8 mio channels
- Area 0.21 m²

- 120 modules
- 1200 pixel chips
- Environmental temperature ~ 27°C
- 0.5 T magnetic field
ALICE Pixel Detector
ALICE Pixel Module

2 p-in-n sensors
- 200 μm thick
- 70 mm x 14 mm
- Pixel size: 50 μm x 425 μm

5 ASICs connected to one sensor
- 8192 pixels/chip
- Chips thinned to 150 μm

Multi-chip module
- 3 ASICs
- max. height: 5 mm

Multilayer Al flex cable
- 1200 pixel chips
- 9.83 x 10⁶ pixels
- 1.14% X₀ per layer
Pixels outside LHC

• Pixel detectors are also installed in non-LHC experiments!

• Hybrid pixel detectors were used for example in NA60 and are now used in NA62.

• Monolithic pixel detectors are installed in STAR and Belle and will be discussed in the next section
NA62 – Gigatracker GTK

• Measure $O(100) K^+ \rightarrow \pi^+ \nu \nu$ events with $\sim 10\%$ background at the CERN SPS

• $\pi/K/p$ ($\sim 6\% K^+$)
  • Precise momentum and direction measurement of kaon and pion
  • Precise (!) timing measurement to associate the outgoing pion to the correct incoming parent kaon

3 GTK pixel stations
Hybrid pixels: 1 sensor+10 FE chips
18000 pixels/station
NA62 – GTK (taking data)

- Pixel size: 300 µm x 300 µm
- Precise timing information: $\sigma(t) \sim 150$ ps rms on single track
- Material budget per station: 0.5% $X_0$ to preserve beam divergence for precise downstream measurement and to limit beam hadronic interactions
- High and non-uniform rate (~1.5 MHz/mm² in hot center, ~0.8-1.0 GHz total)
- High fluence levels: $\sim 2 \times 10^{14}$ n$_{eq}$ cm$^{-2}$ in 100 days (~1 year)
- Operation in beam vacuum
- Microchannel cooling
NA60 (\(\mu\)-Spektrometer and Si Teleskope)

Track matching in coordinate **and** momentum space

- Improved dimuon **mass resolution** (from 70MeV to 20MeV for the \(\omega\))
- Distinguish prompt from decay muons (transverse plane resolution 40-50 \(\mu\)m)
  
  ➔ sufficient to **separate prompt dimuons from open charm decay** (\(D^+\): \(ct=312\) \(\mu\)m; \(D^0\): \(ct=123\) \(\mu\)m)
4. Future Developments
Upgrades

- All LHC experiments are building/planning **upgrades to their existing pixel systems**. Also the LHCb VELO will be replaced with a pixel system.
- They will have to operate in an even more challenging environment.

<table>
<thead>
<tr>
<th></th>
<th>BX time [ns]</th>
<th>Particle Rate [kHz/mm²]</th>
<th>Fluence [n_{eq}/cm² per lifetime]</th>
<th>Ion. Dose [Mrad per lifetime]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC (10^{34} cm²s⁻¹)</td>
<td>25</td>
<td>1000</td>
<td>2 x 10^{15}</td>
<td>79</td>
</tr>
<tr>
<td>HL-LHC (10^{35} cm²s⁻¹)</td>
<td>25</td>
<td>10000</td>
<td>2 x 10^{16}</td>
<td>&gt;500</td>
</tr>
<tr>
<td>LHC HI (6 x 10^{27} cm²s⁻¹)</td>
<td>20 000</td>
<td>10</td>
<td>10^{13}</td>
<td>0.7</td>
</tr>
<tr>
<td>RHIC (8 x 10^{27} cm²s⁻¹)</td>
<td>110</td>
<td>3.8</td>
<td>few 10^{12}</td>
<td>0.2</td>
</tr>
<tr>
<td>SuperKEKB (10^{35} cm²s⁻¹)</td>
<td>2</td>
<td>400</td>
<td>~3 x 10^{12}</td>
<td>10</td>
</tr>
<tr>
<td>ILC (10^{34} cm²s⁻¹)</td>
<td>350</td>
<td>250</td>
<td>10^{12}</td>
<td>0.4</td>
</tr>
</tbody>
</table>

N. Wermes, CERN Seminar, 29/11/2013
Lifetime: LHC, HL-LHC: 7 years; ILC: 10 years; others: 5 years
Increased luminosity requires
Higher hit-rate capability
Higher segmentation
Higher radiation hardness
Lighter detectors
Low noise & power

Radiation hardness improvement compared to now
Key Sensor Issues for the Upgrades

- **Radiation damage** will increase to several $10^{16}$ n_{eq} cm^{-2} for the inner regions in ATLAS and CMS
  - Example of common activities to develop radiation harder sensors within the RD50 collaboration
  - Operational requirements more demanding (low temperature and all related system aspects)

- **Increased performance:**
  - Higher granularity
  - Lower material budget

- **Control and minimize cost**
  - Large areas
  - Stable and timely production

<table>
<thead>
<tr>
<th>Upgrades</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE ITS</td>
<td>10.3 m²</td>
</tr>
<tr>
<td>ATLAS Pixel</td>
<td>8.2 m²</td>
</tr>
<tr>
<td>ATLAS Strips</td>
<td>193 m²</td>
</tr>
<tr>
<td>CMS Pixel</td>
<td>4.6 m²</td>
</tr>
<tr>
<td>CMS Strips</td>
<td>218 m²</td>
</tr>
<tr>
<td>LHCb VELO</td>
<td>0.15 m²</td>
</tr>
<tr>
<td>LHCb UT</td>
<td>5 m²</td>
</tr>
</tbody>
</table>
Readout ASICs

• The present ASICs will not meet the challenges of the upgrade (200 piled up events!)

• The new generation of Pixel FE chip is currently being designed in the framework of the R53 collaboration (joint ATLAS and CMS) in a smaller technology node (0.65 nm)

See next talk by L. Ratti
Monolithic Pixels

- Monolithic pixel detectors are presently not used in the LHC experiments.
- Since their proposal ~1990 lots of progress was made and now one LHC experiment will build an entire tracker out of monolithic pixel detectors.
Why Monolithic Pixels?

• Commercial process (8” or 12” wafers)
• Multiple vendors
• Potentially cheaper interconnection processes available
  • Capacitive coupling gluing, oxide/Cu-Cu bonding,…
  • See talk by R. Patti
• Smaller pitch due to separation between CMOS sensor/analog tier and digital tier
• Thin sensor (50-100 um) have less material and reduce cluster size at large eta.
Thinning

- Thinning of CMOS wafers is a standard process. Silicon thicknesses of 50 µm can be achieved by back-grinding in standard grinding tools \( \rightarrow 0.053\% \times_0 \)
- **Example:** STAF HFT, ALICE ITS upgrade use 50 µm thin pixel sensors

---

**Main challenge:**

Pick very large dies (O(few cm\(^2\))) from the grinding tape

- Manual procedures
- Automatic procedures (preferred for large numbers)
Impact parameter resolution at low momentum dominated by multiple scattering → reduce material for first layers (and get closer to IP)

S. Alekhin et al.  

Jan. 27, 2017
The **actual silicon thickness** is only part of the contribution and can be in the order of 50 µm (e.g. STAR HFT, ALICE ITS upgrade).

The **power consumption** will impact the overall material budget through cables and cooling.

- Analog power: depends on collected charge over capacitance \( \frac{Q}{C} \) in the pixel \( \rightarrow \) optimize sensing node

\[
P \sim \left( \frac{S}{N \cdot Q/C} \right)^m \text{ with } 2 \leq m \leq 4
\]

- Digital power: depends on architecture and cluster size

- Data transmission: depends on cluster size and possible data reduction

![Collection diode- 
\( \sim 2-3 \ \mu m \ \phi, \ C \sim O(few \ fF) \)
\( 22 \ \mu m \times 22 \ \mu m \) pixel](image)

T Kugathasan, NSS 2013
Monolithic Pixels in Experiments

Owing to the industrial development of CMOS imaging sensors and the intensive R&D work (IPHC, RAL, CERN)

... several HI experiments have selected CMOS pixel sensors for their inner trackers

STAR HFT
0.16 m² – 356 M pixels

CBM MVD
0.08 m² – 146 M pixel

ALICE ITS Upgrade (and MFT)
10 m² – 12 G pixel

sPHENIX
0.2 m² – 251 M pixel
Imaging Sensors

Anatomy of the Active Pixel Sensor Photodiode

Courtesy: N. Guerrini, Rutherford Appleton Laboratory
Vth School on detectors and electronics for high energy physics, astrophysics, and space and medical physics applications, Legnaro, April 2013
MIMOSA, ULTIMATE (STAR)

- Only few transistors per cell (size ~ 20 µm x 20 µm)
- Rolling shutter architecture (readout time $O(100 \, \mu s)$)
- 0.35 µm CMOS technology with only one type of transistor
- Charge collection mostly by diffusion
- Limited radiation tolerance for “traditional sensors” $< 10^{13} \, n_{eq} \, cm^{-2}$
Monolithic Active Pixel Sensors – MAPS

- **2 barrel layers**
- **ULTIMATE chip** developed by IPHC Strasbourg (2 cm x 2 cm)
- 0.35 µm CMOS process
- **Pixel size 20.7 µm x 20.7 µm** (hit res. 6 µm)
- Rolling shutter readout with discriminators at the end of column
- Integration time 185.6 µs, in-pixel CDS
- Power dissipation ~170 mW/cm² @ 3.3V
- Chips thinned to 50 µm

**Radiation environment:**
20 to 90 krad / year
2*10^{11} to 10^{12} 1MeV n_{eq}/cm²

**Material budget:**
0.37 % X₀ per layer
356 M pixels ~0.16 m²
Detector installed end 2013, started data taking in Au-Au run 2014
Spare detectors available for replacement!
Operation experience shows resolution performance as expected
Limited radiation tolerance ($\sim 10^{13} n_{eq}$)

A. Dorokhov et al. (IPHC Stassbourg)

Taken from W. Snoeys, Hiroshima 2013
Charge Collection

• **Thicker charge generation layers will yield more signal.** For example thicker epi-layers, partially or fully depleted substrates.

![Diode schematic](image)

• For levels beyond $10^{13} \text{n}_{\text{eq}} \text{cm}^{-2}$ → charge collected by drift

• Several strategies how this can be achieved based on the depletion depth $d$ depending on the

  • Reverse bias $V$
  
  $$d \sim \sqrt{(\rho \cdot V)}$$

  • Resistivity $\rho$
Different Monolithic Pixel Designs

Ideally one would like to achieve:

- Low capacitance $\rightarrow$ low power
- Good S/N
- $\sim$ns time resolution
- High rate capability ($>10$ MHz/mm$^2$)
- Full depletion $\rightarrow$ radiation tolerance
- Single sided processing $\rightarrow$ low cost mass production

High resistivity substrate with back side processing and simple amplification stage in pixel, e.g:
- DEPFET (see next slides)
- Junction on the back (W. Snoeys, S. Parker, J. Plummer, C. Kenney)

High resistivity epi layer with full CMOS circuitry in pixel:
- ALICE ITS upgrade (see next slides)

All circuit inside deep n-well collection electrode, e.g:
- LePIX
- HV CMOS (see next slides)

No unique solution for all yet, but some aspects addressed. Examples:
Belle II Pixel Detector at SuperKEKB: DEPFET

Pixel detector based on **DEPFET** sensors

- 2 barrel layers ($r=1.4$ cm and 2.2 cm)
- Pixel size 50 µm x 75 µm
- Row-wise read-out (rolling shutter), 20 µs/frame
- Special thinning of the matrix area to reduce material budget (75 µm thick)

**Radiation environment:**
- ~ 1.9 Mrad / year
- ~ $1.2 \times 10^{13}$ 1MeV $n_{eq}/cm^2$ per year

**Material budget:**
- 0.21 % $X_0$ per layer
DEPFET

- Depleted p-channel FET on high resistivity substrate (Kemmer & Lutz, 1987)

- First stage amplification in pixel
- Fully depleted bulk
- Charge is stored underneath an internal gate causing a modulation in the transistor current
- Charge needs to be cleared after readout
- Requires off-chip read-out circuitry

- Used in the BELLE II pixel detector upgrade
Belle II Pixel Detector at SuperKEKB

• Ladder contains 2 half-modules with DEPFET sensor and auxiliary ASICS:
  • Three auxiliary ASICS bump bonded to the DEPFET sensor frame:
    • SWITCHER: row selection and clear
    • DCD-B: amplification and digitisation
    • DHP: pedestal subtraction and zero suppression, timing and trigger control
Based on high resistivity epi layer MAPS

3 Inner Barrel layers (IB)
4 Outer Barrel layers (OB)

Radial coverage: 21-400 mm

\( \sim 10 \, \text{m}^2 \)

\( \lvert \eta \rvert < 1.22 \) over 90% of the luminous region

0.3% \( X_0 \)/layer (IB)
0.8 % \( X_0 \)/layer (OB)

Radiation level (L0): 700 krad/10^{13} n_{eq} \, \text{cm}^{-2}

Installation during LS2
Improve impact parameter resolution by a factor of ~3 in (r-\phi) and ~5 in (z)

- Get closer to IP: 39 mm $\rightarrow$ 21 mm (layer 0)
- Reduce beampipe radius: 29 mm $\rightarrow$ 18.2 mm
- Reduce material budget: 1.14 % $X_0$ $\rightarrow$ 0.3 % $X_0$ (inner layers)
- Reduce pixel size: (50 µm x 425 µm) $\rightarrow$ O(30 µm x 30 µm)

**High standalone tracking efficiency and $p_T$ resolution**

- Increase granularity and radial extension $\rightarrow$ 7 pixel layers

**Fast readout**

- Readout of Pb-Pb interactions at 50 kHz (presently 1kHz) and 400 kHz in p-p interactions

**Fast insertion/removal for yearly maintenance**

- Possibility to replace non functioning detector modules during yearly shutdown
**ALICE ITS upgrade tracking performance**

**Impact parameter resolution**

- Improved impact parameter resolution

**Track reconstruction efficiency**

- High standalone tracking efficiency

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Jan. 27, 2017
MAPS produced in CMOS 0.18 µm process by TowerJazz

- Deep p-well allows to have PMOS and NMOS inside the pixel cell
- High resistivity epi layer
- Chip size: 15 mm x 30 mm, thinned to 50 µm
- Pixel pitch ~ 30 µm
- Spatial resolution < 5 µm
- TID: 2.7 Mrad (IB, layer 0)
- NIEL: $1.7 \times 10^{13}$ 1 MeV $n_{eq}$ cm$^{-2}$ (IB, layer 0)

ALICE ITS, SEM picture of prototype chip

3.2 GeV/c electron test beam, pixel size 20 µm x 20 µm
J. Van Hoorne, PoS (TIPP2014) 125
ALPIDE Chip

- Pixel size: 29 x 27 μm² with low power front-end (40 nW)
- Asynchronous sparsified digital readout
- Power density ~300 nW/pixel
- Minimized inactive area on the edge due to pads-over-matrix design (~ 1.1 mm x 30 mm)
- Full size prototypes produced on different epitaxial wafers
- Partial depletion of the sensitive region due to back bias → charge collection by drift
- Extensive tests before and after irradiation

Jan. 27, 2017

INFIERI - USP, P.Riedler
ALPIDE Chip

ALPIDE2 testbeam measurement, 25 µm epitaxial layer, -6V back bias, before and after irradiation

- Efficiency > 99.5% and fake hit rate << 10^5 over wide threshold range
- Excellent performance also after irradiation to 10^{13} (1MeV n_{eq})/cm^2

Efficiency > 99% & Fake hit rate < 10^{-5}
ALPIDE Chip

ALPIDE2 testbeam measurement, 30 µm epitaxial layer, -6V back bias, before and after irradiation

- Space point resolution <5 µm over wide threshold range
- Excellent performance also after irradiation to $1.7 \times 10^{13}$ (1MeV $n_{eq}$/cm$^2$)

Jan. 27, 2017

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ALICE ITS Upgrade

Completion of R &D

2014

2015

2016

2017

2018

Integration, commissioning at surface

High lumi Pb-Pb with upgraded ALICE

Production, construction, tests

Installation in ALICE

LS2

After LS2
Summary

• **Pixels are used in almost all HEP experiments** to provide precise tracking information close to the interaction point.

• Advances closely linked to industrial developments.

• **Hybrid pixel detectors** are still going strong and will be used in the LHC upgrades. **Monolithic pixels** have made significant advancements and are becoming and interesting technology for lower radiation areas.
Thank you!