Development of a Pixellised Ultra-Light Double-Sided Ladder for the ALICE Vertex Detector Upgrade

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d> more information on IPHC Web site: http://www.iphc.cnrs.fr/~CMOS-ILC-.html

Contents

• Major outcome of 11 years of CMOS pixel sensor R&D at IPHC:
  ▶ Achieved performances ▶ Applications under way ▶ Plans → 2012/13

• Proposal for the ALICE vertex detector upgrade:
  ▶ Objectives ▶ Deliverables ▶ Context

• Summary
Sensor requirements defined w.r.t. ILD VTX geometries

- 2 alternative geometries:
  - 5 single-sided layers
  - 3 double-sided layers (mini-vectors)
- Pixel array read-out perpendicular to beam lines

Prominent specifications:

- Read-out time target values (continuous read-out version):
  \[
  \begin{align*}
  &\text{SL1/SL2 /SL3 /SL4 /SL5} & \text{DL1 / DL2 / DL3} \\
  &\diamond \text{single-sided: } 25 / 50 / 100 / 100 / 100 \ \mu s & \diamond \text{double-sided: } 25–25 / 100–100 / 100–100 \ \mu s \\
  \end{align*}
  \]
- \[\sigma_{sp} < 3 \ \mu m\] (partly with binary outputs) \(\Rightarrow\) resolution on vertex position \(\sim O(10) \ \mu m\)

- Ladder material budget in sensitive area (\(\lesssim 50 \ \mu m\) thin sensors):
  - \[\text{single-sided: } < 0.2 \ \% \ X_0\]
  - \[\text{double-sided: } \sim 0.2 \ \% \ X_0\]

- \[P_{diss} \lesssim 0.1–2 W/cm^2\]
Main Features and Advantages of CMOS Sensors

- **P-type low-resistivity Si hosting n-type ”charge collectors”**
  - Signal created in epitaxial layer (low doping):
    \[ Q \sim 80 \text{ e-h}/\mu m \leftrightarrow \text{signal} \lesssim 1000 \text{ e}^- \]
  - Charge sensing through n-well/p-epi junction
  - Excess carriers propagate (thermally) to diode with help of reflection on boundaries with p-well and substrate (high doping)

- **Prominent advantages of CMOS sensors:**
  - Granularity: pixels of \( \lesssim 10 \times 10 \mu m^2 \) \( \Rightarrow \) high spatial resolution
  - Low mat. budget: sensitive volume \( \sim 10 - 15 \mu m \) \( \Rightarrow \) total thickness \( \lesssim 50 \mu m \)
  - Signal processing \( \mu \)circuits integrated in the sensors \( \Rightarrow \) compacity, high data throughput, flexibility, etc.
  - Other attractive aspects: cost, multi-project run frequency, \( T_{room} \) operation, etc.

  ▶▶▶ Attractive balance between granularity, mat. budget, rad. tolerance, r.o. speed & power dissipation

- **Limitations:** ✗ Very thin sensitive volume \( \leftrightarrow \) impact on signal magnitude (mV !) \( \Rightarrow \) very low noise FEE
  - Sensitive volume almost undepleted \( \Rightarrow \) impact on radiation tolerance & speed
  - Commercial fab. \( \Rightarrow \) fab. param. (doping profile, etc.) not optimal for charged part. detection
  - etc.
Achieved Performances

with Analog Output Sensors
- 30 different prototypes designed at IPHC (some with IRFU/Saclay)
- ~ 100 chips tested on H.E. beams since 2001 at CERN & DESY, mounted on Si-strip or pixel telescope

⇒ well established performances (analog output):

* Example of well performing technology: AMS 0.35 µm OPTO → ~ 14 & 20 µm epitaxy thickness

* N ~ 10 e⁻ ENC → S/N ≥ 20 – 30 (MPV) at room Temperature

※ Macroscopic sensors: MIMOSA-5 (~ 1.7x1.7 cm²; 1 Mpix); MIMOSA-20 (1x2 cm²; 200 kpix);
MIMOSA-17 (0.76x0.76 cm²; 65 kpix); MIMOSA-18 (0.55x0.55 cm²; 256 kpix)
Detection Efficiency & Spatial Resolution

- Detection efficiency:
  
  - Ex: MIMOSA-9 data (20, 30 & 40 $\mu$m pitch)
  
  - $\epsilon_{\text{det}} \gtrsim 99.5 - 99.9\%$ repeatedly observed at room temperature (fake rate $\sim 10^{-5}$)
  
  - $T_{\text{oper.}} \gtrsim 40^\circ\text{C}$

- Single point resolution versus pixel pitch:
  
  - clusters reconstructed with eta-function, exploiting charge sharing between pixels (12-bit ADC)
  
  - $\sigma_{\text{sp}} \sim 1 \ \mu\text{m} \ (10 \ \mu\text{m} \ \text{pitch}) \Rightarrow \lesssim 3 \ \mu\text{m} \ (40 \ \mu\text{m} \ \text{pitch})$
  
  - 4-bit ADC simul. $\Rightarrow \sigma_{\text{sp}} \lesssim 2 \ \mu\text{m} \ (20 \ \mu\text{m} \ \text{pitch})$
  
  - measured binary output resolution (MIMOSA-16, -22):
    
    $\sigma_{\text{sp}} \gtrsim 3.5 \ & 4.5 \ \mu\text{m} \ (18.4 \ & 25 \ \mu\text{m} \ \text{pitch})$
Radiation Tolerance: Condensed Summary

- Ionising radiation tolerance (chips irradiated with 10 keV X-Rays):
  - Pixels modified against hole accumulations (thick oxide) and leakage current increase (guard ring)
  - MIMOSA-15 tested with $\sim 5$ GeV $e^-$ at DESY after 10 kGy exposure: Preliminary results
    - $T = -20^\circ$C, $t_{r.o.} \sim 180\ \mu$s
    - $t_{r.o.} \ll 1$ms crucial at $T_{room}$

<table>
<thead>
<tr>
<th>Integ. Dose</th>
<th>Noise</th>
<th>S/N (MPV)</th>
<th>Detection Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$9.0 \pm 1.1$</td>
<td>$27.8 \pm 0.5$</td>
<td>100 %</td>
</tr>
<tr>
<td>1 MRad</td>
<td>$10.7 \pm 0.9$</td>
<td>$19.5 \pm 0.2$</td>
<td>$99.96 \pm 0.04 %$</td>
</tr>
</tbody>
</table>

- Non-ionising radiation tolerance (chips irradiated with O(1 MeV) neutrons):
  - MIMOSA-15 ($20 \mu m$ pitch) tested on DESY $e^-$ beams: Preliminary results
    - $T=-20^\circ$C, $t_{r.o.} \sim 700\ \mu$s
    - $5.8\cdot10^{12} n_{eq}/cm^2$ values with standard & soft cuts

<table>
<thead>
<tr>
<th>Fluence ($10^{12} n_{eq}/cm^2$)</th>
<th>0</th>
<th>0.47</th>
<th>2.1</th>
<th>5.8 (5/2)</th>
<th>5.8 (4/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/N (MPV)</td>
<td>$27.8 \pm 0.5$</td>
<td>$21.8 \pm 0.5$</td>
<td>$14.7 \pm 0.3$</td>
<td>$8.7 \pm 2.$</td>
<td>$7.5 \pm 2.$</td>
</tr>
<tr>
<td>Det. Efficiency (%)</td>
<td>100.</td>
<td>$99.9 \pm 0.1$</td>
<td>$99.3 \pm 0.2$</td>
<td>$77. \pm 2$</td>
<td>$84. \pm 2$</td>
</tr>
</tbody>
</table>

  - MIMOSA-18 ($10 \mu m$ pitch) tested at CERN-SPS (120 GeV $\pi^-$ beam): Preliminary results
    - $T = -20^\circ$C, $t_{r.o.} \sim 3$ ms
    - parasitic 1–2 kGy $\gamma$ gas $\Rightarrow$ N

<table>
<thead>
<tr>
<th>Fluence ($n_{eq}/cm^2$)</th>
<th>0</th>
<th>$6\cdot10^{12}$</th>
<th>$1\cdot10^{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{clust} (e^-)$</td>
<td>1026</td>
<td>680</td>
<td>560</td>
</tr>
<tr>
<td>S/N (MPV)</td>
<td>$28.5 \pm 0.2$</td>
<td>$20.4 \pm 0.2$</td>
<td>$14.7 \pm 0.2$</td>
</tr>
<tr>
<td>Det. Efficiency (%)</td>
<td>$99.93 \pm 0.03$</td>
<td>$99.85 \pm 0.05$</td>
<td>$99.5 \pm 0.1$</td>
</tr>
</tbody>
</table>

- Conclusion:
  - observed ionising radiation tolerance: O(10 kGy)
  - observed non-ionising rad. tol.: $> 1\cdot10^{13} \ n_{eq}/cm^2 (10\mu m \ pitch)$ & $2\cdot10^{12} \ n_{eq}/cm^2 (20\mu m \ pitch)$

high resolution pixellised ladder,
Applications of Sensors with Analog Output

- Beam telescope of the FP6 project EUDET
  - 2 arms of 3 planes (plus 1 high resolution plane)
  - $\sigma_{\text{extrapol.}} \lesssim 1 \mu m$ EVEN with $e^-$ (3 GeV, DESY)
  - frame read-out frequency $O(10^2)$ Hz
  - running since ’07 CERN-SPS & DESY (numerous users)
  - evolution towards $10^4$ frames/s in 2009, using binary output sensors (see later)

- Several other applications:
  - MIMOSA sensor R&D: Pixel telescope of Strasbourg (TAPI)
  - STAR (RHIC): telescope (3 MIMOSA-14) inside apparatus (2007)
    background measurement, no pick-up!
  - CBM (FAIR): MVD demonstrator (double-sided layers) to be used for high precision tracking in HADES (GSI) $\sim$ 2010
  - Spin-offs: beta imaging, hybrid photo-detector, dosimetre, ...

high resolution pixellised ladder ,
Improving the Read-Out Speed

with Digital Output Sensors
**TC ≡ 1st sensor with integrated zero-suppression**

- **MIMOSA-22** (binary outputs) combined with Ø (SUZE-01)
- Active area: 1152 columns of 576 pixels \((21.2 \times 10.6 \text{ mm}^2)\)
- **Pitch**: \(18.4 \mu m \rightarrow \sim 0.7 \text{ million pixels} \Rightarrow \sigma_{sp} \gtrsim 3.5 \mu m\)
- \(T_{r.o.} \lesssim 110 \mu s \rightarrow \sim 10^4 \text{ frames/s}\)
  \(\Rightarrow \text{suited to} > 10^6 \text{ particles/cm}^2/\text{s}\)
- Ø in 18 groups of 64 col. allowing \(\leq 9\) "pixel strings" / raw
- **Sensor full dimensions**: \(\sim 22 \times 14 \text{ mm}^2\)
- **Data transmission**: 1 output at \(\geq 160 \text{ Mbits/s}\) or 2 outputs at \(\geq 80 \text{ Mbits/s}\)

**Fabricated in 0.35 \(\mu m\) "Opto" technology**:

- Equips the final version of EUDET Beam Telescope (EU-FP6 project)
- Architecture is baseline for STAR, CBM and ILC vertex detectors
- Sensor still being characterised \(\Rightarrow \text{test results are Preliminary}\)
TC Beam Tests: General Remarks

- 6 sensors used:
  - some thinned to 120 $\mu m$
  - assembled in telescope configuration
  - for minimum ionising particle detection performance evaluation

- CRN-SPS (T4-H6)
  - $\gtrsim$ 120 GeV $\pi^-$ beam
  - 10 days of run in Sept. 2009
  - $3 \times 10^6$ triggers collected, out of which $\sim$ 80 % events reconstructed
TC Beam Tests: Summary

- TC sensors quite extensively characterised by now (quantitative results still preliminary):
  - TC operating with $\gtrsim 99.5\%$ detection efficiency over the whole sensitive area, with a fake rate $\lesssim \mathcal{O}(10^{-4})$
  - Optimal discri. threshold $\sim 5-6 \times$ Noise value
  - $\sigma_{sp}^{TC} \lesssim 4.5 \pm 0.2 \mu m$ (preliminary)
    - $\hookrightarrow$ room for improvement towards $\sigma_{sp}^{TC} \lesssim 4 \mu m$

- Conclusion:
  - TC operationnal for the final EUDET BT $\checkmark$
  - TC architecture validated for devt of application specific sensors:
    - $\Rightarrow$ STAR-PIXEL, CBM-MVD, ILD-VTX, ...

MIMOSA 26 (chip 1) unthinned, vref2=98, 80 MHz

- High resolution pixellised ladder,
On-Going Application to STAR-HFT

- 1st generation sensor for the HFT-PIXEL of STAR (PHASE-1):
  - full scale extension of MIMOSA-22 (no Ø)
  - 640x640 pixels (30 \( \mu m \) pitch) \( \Rightarrow \) active surface: 19.2 x 19.2 mm\(^2\)
  - integration time : 640 \( \mu s \)
  - designed and fabricated in 2008 \( \Rightarrow \) currently under production test at LBNL
  - 3 + 9 ladders to equip with 10 sensors thinned to 50 \( \mu m \) (1/4 of P\( \text{IXEL} \))
  - 1st physics data expected in 2011

- Final HFT-PIXEL sensor :
  - MIMOSA-26 with active area \( \times 1.8 \)
    & improved rad. tolerance
    \( \leftrightarrow \) 1088 col. of \( 10^3 \) pixels (20 x 18.5 mm\(^2\))
  - Pitch : 18.4 \( \mu m \) \( \Rightarrow \) \( \sim \) 1.1 million pixels
  - Integration time \( \lesssim 200 \mu s \)
  - Design in 2009 \( \Rightarrow \) fab. Q1 (2010)
  \( \Rightarrow \) 1st physics data expected in 2012/13
- **Move from** $0.35 \ \mu m$ **to feature size** $\leq 0.18 \mu m$
  \[ \Rightarrow \] improved clock frequency, more metal layers, more compact peripheral circuitry, etc.

- **ILD VTX inner layers** ($t_{int} \sim 25 - 50 \mu s$):
  - double-sided r.o. $\Rightarrow$ twice shorter (= faster) columns
  - pitch $\lesssim 15 \mu m$
  - binary r.o. $\Rightarrow$ $\sigma_{sp} \lesssim 3 \mu m$

- **Implement elongated pixels on one side of double-ladder:**
  - pixel pitch of $\sim 14 \times 50-80 \mu m$
  - reduced nb of pixels per column
    $\Rightarrow$ shorter read-out (goal: factor 4–6)
  - depleted epitaxial layer
    $\Rightarrow$ wider sensing diode spacing (next slide)
    $\rightarrow \lesssim 10 \mu s$ may be reachable
- High Resistivity Sensitive Volume

- Advantages of depleted epitaxial layer:
  - faster charge collection ($< 10$ ns) $\Rightarrow$ faster frame read-out frequency possible
  - shorter minority charge carrier path length $\Rightarrow$ improved tolerance to non-ionising radiation

- Exploration of 0.6 $\mu$m techno: $\sim 15$ $\mu$m thick epitaxy; $V_{dd} \leq 5$ V; $\rho \sim O(10^3) \Omega \cdot cm$
  - MIMOSA-25: fabricated in 2008 & tested at CERN-SPS before/after $O(1$ MeV) neutron irradiation

- Effect of $3 \cdot 10^{13} n_{eq}/cm^2$ at room temperature:
  - SNR(MPV): $\sim 60 \Downarrow \sim 30 \Downarrow \epsilon_{det}: 99.9\ldots\% \Downarrow 99.5\%$ at $T_{room}$ with 20$\mu$m pitch & 80$\mu$s r.o. time
  - thin depleted epitaxy approach validated for $\gtrsim 10^{14} n_{eq}/cm^2 \Downarrow 0.35$ $\mu$m version available soon

- Exploration of a new VDSM techno. with depleted substrate: project LePIX (see talk of W.Snoeys)
  - aim for very short integration time

\[\sigma_{sp} \sim 2.5 \pm 0.2 \mu m\]
System Integration : PLUME Project

- PLUME project
  - Pixelised Ladder using Ultra-light Material Embedding

- Objectives :
  - achieve a double-sided ladder prototype for an ILC vertex detector by 2012
  - evaluate benefits of 2-sided concept (mini-vectors) : $\sigma_{sp}$, alignment, shallow angle pointing, elongated vs square pixels

- Collaboration:
  - Bristol - DESY - Oxford - Strasbourg
  - Synergy with Vertex Detector of CBM/FAIR

- Perspective:
  - to be studied with infrastructure foreseen in FP-7 project AIDa (proposal in preparation)
  - interest for (s)LHC experiments ?
**HP-2 project** ➤ **WP-26 (ULISI) ≡ SEnsor Row Wrapped In Extra-Thin film (SERWIET)**

**Objectives:**
- achieve a sensor assembly mounted on flex and wrapped in polymerised film with < 0.1 % $X_0$ in total
- evaluate possibility of mounting supportless ladder on cylindrical surface (serving as mechanical support)
- proof of principle expected in 2012

**Working programme:**
- prototype Nr. 1 (2010) made of 1 sensor:
  - MIMOSA-18 (analog output, $\lesssim 4$ ms)
- prototype Nr. 2 (2011) made of 3 sensors:
  - TC (digital output, $\lesssim 110$ $\mu$s)

**Context of development:**
- Collaboration with IKF-Frankfurt and GSI/Darmstadt (CBM coll.)
- Synergy with Vertex Detector R&D for CBM, ILC, etc.
**Proposition pour l'upgrade du détecteur de vèrtex de l'ALICE**

- **Améliorer la capacité de la reconstruction de points de vèrtex déplacés pour le tagging de charme :**
  - Équiper l'espace libre laissé par le remplacement de la tube par vide de 1 ou 2 échelles pixelées doubles côtés de haute précision (et envisager d'équiper le pipe de faisceau ???)

- **Performances ambitieuses :**
  - **Petits capteurs de pixels (50 µm) offrant une résolution de point unique < 5 µm**
  - **Échelle avec budget de matière complet ∼ 0.2-0.3 % X₀**
  - **2 impacts contigus par particule détectée ⇒ plusieurs bénéfices pour les performances de détection :**
    - Résolution (paramètre d'impact)
    - Reconstruction de trajectoire
    - Alignement (important !)

- **Contexte : R&D en cours à l'IPH-Strasbourg**
  - Développement de capteurs pixelés fins et à haute résolution, CMOS pour STAR & CBM (depuis 2000 & 2003)
    - Design de l'architecture du capteur ∼ mature (capteur opérationnel sur le télescope EUDET/FP-6)
  - Développement d'échelles légères pour CBM, ILC, etc. (depuis 2008) ⇒ WP-26 (HP-2)
    - Plusieurs approches examinées ⇒ prototypage finalisé ∼ 2012/13
  - Premiers données collectées avec STAR-PIXEL (open charme) en 2012/13
    - Échelles un-côté : $\sigma_{sp} \lesssim 4 \mu m$, budget de matière ∼ 0.3 % X₀

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high resolution pixellised ladder ,
CMOS pixel sensors:

- Ambitionned performances (room T):
  - $\sigma < 5 \, \mu m$ ✓
  - thickness $\lesssim 50 \, \mu m$ ✓
  - $t_{ro} \sim 10-20 \, \mu s$ ✓
  - 1 MRad & $10^{14} \, n_{eq}/cm^2$

  $\Rightarrow$ on-going R&D on $t_{ro} (< 50 \, \mu s)$ & rad. tolerance ($> 300 \, kRad$ & $> 10^{13} \, n_{eq}/cm^2$)

- 3 sensor generations under development:
  - 2D with undepleted sensitive volume $\Rightarrow$ $t_{ro} \sim 10-20 \, \mu s$ & 1 MRad (2011/12)
  - 2D with depleted sensitive volume (elongated pixels) $\Rightarrow$ 1 MRad & $10^{14} \, n_{eq}/cm^2$ (2013)
  - 3D with depleted sensitive volume $\Rightarrow$ $t_{ro} \lesssim 5 \, \mu s$ (2015)

Ladder developed along 2 parallel approaches:

- Classical: sensors $\oplus$ flex cable $\oplus$ SiC foam $\oplus$ flex cable $\oplus$ sensors
  $\Rightarrow$ $\lesssim 0.3 \, \% \, X_0$ for the whole 2-sided ladder

- Innovating: sensors (35 $\mu m$) wrapped in polymerised film ($< 10 \, \mu m$)
  $\Rightarrow$ $\lesssim 0.1 \, \% \, X_0$ for 1 unsupported layer (sensors $\oplus$ flex cable $\oplus$ film)
  $\leftrightarrow$ adaptable to various mechanical supports $\Rightarrow$ beam pipe?
Using 3DIT to Improve CMOS Sensor Performances

- **3D Integration Techno.** allow integrating high density signal processing $\mu$circuits inside small pixels by stacking ($\sim 10 \ \mu m$) thin tiers interconnected at pixel level

- **3DIT are expected to be particularly beneficial for CMOS sensors:**
  - combine different fab. processes $\Rightarrow$ chose best one for each tier/functionnality
  - alleviate constraints on peripheral circuitry and on transistor type inside pixel, etc.

- **Split signal collection and processing functionnalities:**
  - *Tier-1: charge sensing*  
  - *Tier-2: analog-mixed $\mu$circuits*  
  - *Tier-3: digital $\mu$circuits*

- **First chips fabricated in 2009 within 3DIC Consortium (2-Tier 130 nm technology):**
  - 1 chip with sensitive area subdivided in "small" matrices running INDIVIDUALLY in fast rolling shutter mode $\Rightarrow$ few $\mu$s r.o. time may be reached (?)
  - 1 chip aiming to combine 2-Tier read-out chip with sensing chip featuring DEPLETED epitaxial layer.
Proposal: investigate possibility of translating ultra-light pixellised ladders developed for CBM & ILC to the specifications of the ALICE vertex detector upgrade, relying on 2 basic components:

- thin, depleted, CMOS pixel sensors (baseline 2D, potentially 3D)
- ultra-light double-sided ladder complemented with potential pixelised beam pipe

CMOS pixel sensors developed for EUDET, STAR, CBM, ILC:

- offer necessary single point resolution and material budget for very high precision vertexing
- have reached required maturity to be used in large (heavy ion) experiments (e.g. STAR-HFT)
  - may be relevant for ALICE vertex detector upgrade > 2015: barrel & forward (CBM-MVD)

Ultra-light ladders developed for CBM & ILC:

- double-sided ladder with $\lesssim 0.3\% X_0$, expected to provide excellent pointing accuracy:
  - impact parameter resolution even at shallow angle, track link with faster detectors, ...
- supportless ladder expected to offer $< 0.1\% X_0$ → explore possibility to equip beam pipe?

Synergetic context to exploit:

- CMOS sensor development with IRFU/Saclay
- ladder development within HP-2 (Frankfurt, GSI), PLUME collaboration (ILC teams)
- perspective: AIDA FP-7 proposal (study of high precision vertex detector alignment issues)