DEPLETION OF CMOS PIXEL SENSORS: STUDIES, CHARACTERIZATIONS, AND APPLICATIONS

PhD DEFENCE

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Under the supervision of Jerome Baudot
Amphithéâtre Grünewald, IPHC, 17/07/2018

Institut Pluridisciplinaire Hubert Curien
CMOS Pixel Sensors Applications

(Huawei P20 Pro)
One half of the PXL detector
ALICE ITS
(ALICE Collaboration/CERN)
CMOS Pixel Sensors Applications

Compressed Baryonic Matter Micro Vertex Detector (MVD)
ANDOR Zyla and Neo sCMOS Cameras
Requirements

- **Charged Particle Tracking**: Excellent spatial resolution, Low-noise, Radiation hardness, Low material budget, Easy integration, Low-cost, Fast
- **Particle Identification**: Full charge collection over a known distance, Low-noise, Rad-hard
- **Electron Microscopy**: Good image definition ($\propto$ spatial resolution), Rad-hard, Fast
- **Soft X-Ray Imaging & Spectroscopy**: Low-noise, Excellent energy resolution, Excellent quantum efficiency (QE), Fast readout
Requirements satisfied by CPS

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Applications Requirements for Scientific CPS

Requirements satisfied by depleted CPS

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- Particle Identification: Full charge collection over a known distance, Lower-noise, Rad-hard
- Electron Microscopy: Good image definition ($\propto$ spatial resolution), Rad-hard, Fast
- Soft X-Ray Imaging & Spectroscopy: Lower-noise, Excellent energy resolution, Excellent quantum efficiency (QE), Fast readout
**Applications Studied for This Work**

**Soft X-rays applications**
- Spectroscopy Application: good QE, excellent energy resolution, thin entrance window
- Imaging/counting: Small pixels, high hit rate, thin entrance window

**Positron Imaging in Constrained Environment**
- Full depletion not compulsory
- Low energy positron detection (<3 MeV)
- Minimization of the power dissipation
**Applications Studied for This Work**

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**Questioning**

• How do we deplete?
• What are the performances of the depleted sensors?
• Full depletion?
• Limitations caused by the depletion method?
Depletion with Front-Side Biasing Technique

Performance of a Depleted Sensor with Front-Side Biasing

Evaluation of the Depletion Depth
  Finite Element Simulations
  Estimation from Measurements

Sensor Developments
  Photon Counting
  Intra Cerebral Neuroimaging

Conclusions & Prospects
Inelastic Collisions
Energy loss by successive collisions with atom of absorbing medium.
Ionization or excitation of the medium.

Radiative Loss
Above critical energy \( E_c(Si) = 39 \text{ MeV} \)
Bremsstrahlung: change of direction + loss of energy + emission of a photon.

Charge Deposition
Ionization energy: 3.63 eV
Mean Minimum Ionization Deposition: 74 e\(^-\)/h\(^+\) per µm

Charge deposited by a MIP in silicon
18 µm thick sensitive volume: 1332 e\(^-\)/h\(^+\)
40 µm thick sensitive volume: 2960 e\(^-\)/h\(^+\)
Interaction process

3 contributions depending on the photon energy and medium: **Photoelectric effect** + Compton Scattering + Pair Production

**Attenuation**

\[ \mu = \sigma_{ph} + \sigma_c + \sigma_{pp} \]

Transmitted photons for a photon beam of intensity \( I_0 \) at a distance \( x \)

\[ I(x) = I_0 e^{-x \mu \rho} \]

**Charge Generated by Photoelectric Effect**

\[ N = \frac{h \nu}{e} \text{ e}^-/h^+, \quad < \Delta N^2 > = F \cdot N, \text{ Fano factor: } F=0.11 \]

- \( h \nu = 1 \text{ keV} : 275 \text{ e}^-/h^+, \quad x(I_{0/2}) \approx 2 \mu m \)
- \( h \nu = 5.9 \text{ keV} : 1625 \text{ e}^-/h^+, \quad x(I_{0/2}) \approx 20 \mu m \)
Soft X-Ray Interaction & Charge Collection in CPS

Metallization layers (process)
Absorption of softer X-rays
BSI with full depletion mandatory

Undepleted Substrate
Charge diffusion
Collection with small depleted volume next to the diode
Slow charge collection

Why not HV-CMOS
Large electrode: large pixel pitch and high noise. Incompatible for soft X-rays
Metallization layers (process)
Absorption of softer X-rays
BSI with full depletion mandatory

Undepleted Substrate
Charge diffusion
Collection with small depleted volume next to the diode
Slow charge collection

Fully Depleted Substrate
Charge drift
(Single pixel) full charge collection

Depletion Expansion
Low Doped substrate $\equiv$ High Resistivity
High bias voltage

Why not HV-CMOS
Large electrode: large pixel pitch and high noise. Incompatible for soft X-rays
Backside contact for HV=thick entrance window: absorption of soft X-rays
DEPLETION WITH FRONT-SIDE BIASING TECHNIQUE
**The PIPPER-2 Sensor**

- Pixelated sensor for Ionizing Particle and Photons Energy Resolved detector
- Designed by Maciej Kachel and Andreï Dorokhov (IPHC, 2015) in TowerJazz 180 nm CIS
- Fabricated on two different substrates:
  - 18 µm high resistivity epitaxial layer (> 1 kΩ cm) [HR18]
  - 280 µm Czochralski high resistivity substrate (> 600 Ω cm) [CZ]
- A few CZ sensors thinned to 50 µm (≈ 40 µm sensitive)
- Thinned sensors backside processed using PULSION® process (by Ion Beam Services): thin entrance window (20–50 nm)
- Pixel pitch: 22 µm
- 128 rows, 32 columns. 8 columns of the selected submatrix connected to its own output pad.
- Rolling shutter readout
- 4 pixel architectures: 3 for depletion studies, 1 amplifier design
Pixel Architecture for Depletion Studies

Frontside Application of the Depletion Voltage

- Bias from the process side of the sensor
- Through the collecting diode
- No backplane contact required: small entrance window
- AC-coupling: 1.8 V electronics side decoupled from the high voltage bias
- No process modification required

Pixel Architecture

Study on submatrix 1

- Round diode (Ø5 µm)
- 21 fF coupling capacitor (fringe)
- Source follower amplifier ($g=0.78$)
**Pixel Architecture for Depletion Studies**

**Frontside Application of the Depletion Voltage**

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**Pixel Architecture**

**Study on submatrix 1**

- Round diode ($\varnothing 5 \, \mu m$)
- 21 fF coupling capacitor (fringe)
- Source follower amplifier ($g=0.78$)
Performance of a Depleted Sensor with Front-Side Biasing
### Experimental Setup

#### Main Characteristics

- PIPPER-2 (HR18 and CZ thinned to 50 µm) wirebonded to its PCB (*proxy*)
- Opening in PCB under the sensor: **Backside Illumination**
- Each analog output amplified on board ($A_{proxy} = 3.91 \pm 0.04$)
- Proxy connected to its *auxiliary* board: chip steering and data distribution to ADC
- 14-bit, 50 MS/s digitizer in NI PXIe-1071 crate. Allows 40 µs/frame
- Chilled to guarantee operating conditions. Coolant at 5 °C ≈ chip at 11 °C

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#### Front Side

![Front Side Image]

#### Back Side

![Back Side Image]
### Photon Energies Available

#### $^{55}$Fe soft X-ray source
- Emits two characteristic rays: Mn-K$_\alpha$ at 5.89 keV (90 %), and Mn-K$_\beta$ at 6.49 keV (10 %)
- 3D printed source holder for FSI and BSI: same distance between source and sensor

#### Rigaku Geigerflex X-ray generator
3 X-ray tubes available with monochromator:
- Cr: 5.4 keV (+ 10.8 keV)
- Cu: 8.05 keV (+ 16.1 keV)
- Mo: 17.48 keV

*Always set at 20 kV, and 20 mA*
**Data Acquisition**

**Leakage Current**
- Applied depletion voltages: 0–45 V
- Bunches of 30,000 consecutive frames (data file size minimization, data bottleneck prevention)

**Running Conditions**
- 30,000 frames of noise (without source)
- 6,000,000 frames illuminated per side

**Data Treatment**
- Offline correlated double sampling (CDS): difference of 2 consecutive frames to reconstruct one

High-voltage bias provided by a Keithley 237 high voltage source + picoammeter
Hit Reconstruction

Readout fast enough to distinguish hits w.r.t. illumination

$^{55}\text{Fe}$ hits, HR18 biased at 30 V
**Collected Charge Within Clusters**

- **Seed Pixel**: pixel with the largest signal in cluster
- **Neighbouring Pixels**: pixels surrounding seed pixel
- **Cluster**: Seed + Neighbours

Spectra reconstruction: histogram of collected charge (in ADCu)

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**Seed pixel charge spectrum**

![Seed Charge Spectrum](image)

**Neighbour pixels charge spectrum**

![Neighbour Charge Spectrum](image)

$^{55}$Fe - HR18 - 30 V

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Crystal Ball Function

- Lossy processes modelisation: charge sharing
- Power-law at low energy side of the Gaussian distribution

Main Parameters Obtained

- $\mu$: peak position
- $\sigma$: standard deviation

Performance Obtained With the Parameters

Calibration factor (needed for ENC), linearity, detection gain, capacitance, energy resolution
**Common Performance**

- Equivalent Noise Charge: ENC=24 electrons
- Linear up to 16 keV
- Conversion gain: 17 µV/electron
- Input Capacitance=9 fF (limited by the interwell capacitance)

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**HR18**

- Energy resolution: 280 eV at 5.9 keV
- In average, 90% of cluster charge collected on seed pixel

**CZ 50 µm**

- Energy resolution: 288 eV at 5.9 keV
- In average, 87% of cluster charge collected on seed pixel (FSI). BSI: 85%
### Energy Resolution

#### Full Width at Half Maximum (FWHM) of the calibration peak

Obtained by using the Crystal Ball fits results ($\sigma_T$)

\[
\text{FWHM} = 2.355 \cdot \sigma_T = 2.355 \sqrt{\sigma_{\text{ENC}}^2 + \sigma_D^2(E) + \sigma_X^2(E^2)}
\]

#### Equivalent Noise Charge

\[
\sigma_{\text{ENC}}[\text{eV}] = \epsilon \sigma_{\text{ENC}}[\text{e}^-]
\]

#### Fano Noise

\[
\sigma_D(\sqrt{E}) = \sqrt{\epsilon FE}
\]

#### Additional Component

\[
\sigma_X(E) = E \sigma_g
\]

$\sigma_g$ : Gain spread proportion at an energy $E$

#### Fano limit at 5.9 keV ($^{55}\text{Fe source : Mn-K}\alpha$)

With $\sigma_{\text{ENC}} = 0$, $\sigma_X = 0$, $F=0.11$, and $\epsilon=3.63$ eV

\[
\text{FWHM}(5.9 \text{ keV})_{\text{min}} = 2.355 \sqrt{\epsilon FE} \approx 114.3 \text{ eV}
\]
Components of the Energy Resolution

Example: HR18 biased at 8 V

$^{55}$Fe Mn-K$\alpha$ fit

$FWHM(5.9 \text{ keV}) = 280 \text{ eV} : \sigma_{TOT} = 32.84 \text{ electrons}$
Components of the Energy Resolution

Example: HR18 biased at 8 V

$^{55}\text{Fe Mn-K}\alpha$ fit

$FWHM(5.9 \text{ keV}) = 280 \text{ eV} : \sigma_{TOT} = 32.84 \text{ electrons}$

ENC

$\sigma_{ENC} = 22.5 \text{ e}^-$

(Figure showing data for energy resolution at different energies, with ENC (22.5 e-) shown as a horizontal line)
Components of the Energy Resolution

Example: HR18 biased at 8 V

$^{55}\text{Fe Mn-K}\alpha$ fit

$FWHM(5.9\text{ keV}) = 280\text{ eV}: \sigma_{TOT} = 32.84\text{ electrons}$

ENC

$\sigma_{ENC} = 22.5\text{ e}^{-}$

Fano Noise

$\sigma_D(\sqrt{E}) = 13.4\text{ e}^{-}$

(HR18 biased at 8 V)
Components of the Energy Resolution

**Example: HR18 biased at 8 V**

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$FWHM(5.9 \text{ keV}) = 280 \text{ eV} : \sigma_{TOT} = 32.84 \text{ electrons}$

**ENC**

$\sigma_{ENC} = 22.5 \text{ e}^-$

**Fano Noise**

$\sigma_D(\sqrt{E}) = 13.4 \text{ e}^-$

**Gain Dispersion**

$\sigma_X(E) = \sqrt{32.84^2 - 13.4^2 - 22.5^2}$

$\frac{\sigma_g}{g} = 1.2 \%, \sigma_g \approx 200 \text{ nV/electron}$

(HR18 biased at 8 V)

Improvement with low noise, low dispersion amplifier
APPLICATION OF THE ENERGY RESOLUTION: X-RAY FLUORESCENCE

- Fluorescence pills samples provided by the SOLEIL synchrotron
- Samples: Ti, V, Cr, Mn

![Image of samples: Ti, V, Cr, Mn]
Application of the Energy resolution: X-Ray Fluorescence

- Fluorescence pills samples provided by the SOLEIL synchrotron
- Samples: Ti, V, Cr, Mn

HR18 biased at 40 V. Cu illumination
Data acquired by M. Kachel
Background removed after analysis
• 5 HR18 sensors irradiated with neutrons
• NIEL fluence: 
  \(10^{13} - 5 \times 10^{14} \ \text{n}_{\text{eq}} \text{cm}^{-2}\)
• Cooling at \(-20 \, ^\circ\text{C}\)
• Leakage current increased: noise increased
• Almost no signal loss from a \(^{90}\text{Sr}\) \(\beta\)-rays source observed. Improvement with faster readout
• SNR remains acceptable for fluences up to \(5 \times 10^{14} \ \text{n}_{\text{eq}} \text{cm}^2\)

Bias voltage: 20 V
(Reproduced from A. Perez-Perez - IEEE NSS 2016)
EVALUATION OF THE DEPLETION DEPTH
Evaluation of the Depletion Depth

Finite Element Simulations
### Realistic Geometry

- 2 versions: CZ and HR18
- Cylindrical N-well: collecting diode (doping profile from TJ doc.). Ø 5 µm, height from TJ doc. P++ implant: forward bias
- HR18: Epitaxial doping profile from Spreading resistance profiling (SRP). Total thickness: 50 µm
- CZ: Constantly doped p-type substrate (60 µm thick). \( \rho = 0.6, 1, 2, \ (>10 \text{ k}\Omega \text{ cm}) 
- P-wells: isolated CMOS process. Doping and depth from datasheet
- Opening between N-well and P-well
- Non-conductive SiO\(_2\) layer on top with opening for contacts
CZ $\rho = 600 \, \Omega \text{ cm}$

CZ $\rho = 2 \, \text{k}\Omega \text{ cm}$

HR18
**Theoretical Evaluation of the Depleted Depth**

![Graph showing the relationship between bias voltage and depth](image)

- **Planar (\(\rho=600 \, \Omega \, \text{cm}\))**
- **Planar (\(\rho=2 \, k\Omega \, \text{cm}\))**
Theoretical Evaluation of the Depleted Depth

Bias Voltage [V] vs. Depth [µm]

- Planar ($\rho=600$ Ω cm)
- Planar ($\rho=2$ kΩ cm)
- Merging point like diode ($\rho=600$ Ω cm)
- Merging point like diode ($\rho=2$ kΩ cm)
THEORETICAL EVALUATION OF THE DEPLETED DEPTH
Theoretical Evaluation of the Depleted Depth

![Graph showing the relationship between Bias Voltage (V) and Depth (µm) with different TCAD realistic scenarios, including ρ=600 Ω cm, ρ=2 kΩ cm, and HR18.]
**Electric Field**

**HR18**

![Graph of Electric Field for HR18]

- For 2 V, the electric field is moderate.
- For 8 V, the electric field is significantly higher and more pronounced near the surface.
- For 30 V, the electric field is even higher and shows a steep decrease near the surface.

**CZ**

![Graph of Electric Field for CZ]

- For 2 V, the electric field is low and consistent throughout the depth.
- For 8 V, the electric field increases gradually and shows a notable peak.
- For 30 V, the electric field is high and shows a sharp increase near the surface.
Electric Field

HR18

Intensity of the Electric Field

Electron collection over 40 µm in 10 ns: $E=370 \text{ V cm}^{-1}$

CZ

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Intensity of the Electric Field

Electron collection over 40 µm in 10 ns: $E = 370 \text{ V cm}^{-1}$
Evaluation of the Depletion Depth

Estimation from Measurements
### Depth Determination From Relative Attenuation & Reference Depth

#### Relative Attenuation Between Two Thicknesses

$$ R = \frac{1 - e^{-x_1 \mu \rho}}{1 - e^{-x_0 \mu \rho}} $$

$\mu$: energy dependent, 
$\rho$(Si)=2.33 g cm$^{-3}$, $x_0$ fixed

#### Ratio of Counts in Spectra

$$ \frac{N_1}{N_0} = R $$

#### Depth from Ratio of Counts and Reference Depth

$$ x_1 = - \frac{\log \left( Re^{-x_0 \mu \rho} - R + 1 \right)}{\mu \rho} $$

**Reference**: TCAD simulations - HR18 at 40 V : $x_0$=13 µm

![Graph showing relative attenuation in silicon to 13 µm against depth for different photon energies.](https://via.placeholder.com/150)

- Photon energy: 5.41 keV
- 5.89 keV
- 8.05 keV
- 17.48 keV

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Evaluation of the Depth Using Selected Hits

Only hits with total charge (seed + 8 neighbours) above a given threshold selected

$^{55}\text{Fe} - Q_{\text{TOT}}>250\text{ ADCu}$

$^{95}\text{Mo} - Q_{\text{TOT}}>800\text{ ADCu}$
**Evaluation of the Depletion Depth Using a Finite Range of Energies**

- Amount of entries in the calibration peak
- Peak position from Crystal Ball fits
- Integral in range of energies (converted in ADCu from the calibration factor)
  - Cr: 4–13 keV
  - $^{55}$Fe: 4.9–7 keV
  - Cu: 7–18 keV
  - Mo: 14–20 keV
- Similar to the selection of single pixel hits
Depletion Depth Estimations from Entries in Calibration Peak

![Graph showing depletion depth estimations](image-url)
### Conclusions

<table>
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<tr>
<th>HR18</th>
<th>CZ</th>
</tr>
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<td>• Fully depleted at 13 μm</td>
<td>• Depleted up to 20 μm</td>
</tr>
<tr>
<td>• Collection by drift with depletion voltage &gt;6 V</td>
<td>• Collection up to $\approx 35 \mu m$</td>
</tr>
<tr>
<td></td>
<td>• Resistivity of the substrate $\approx 2 k\Omega cm$</td>
</tr>
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Higher resistivities required for full depletion

Shape of the depleted volume not evaluated. Beam test could allow the reconstruction of the shape.
SENSOR DEVELOPMENTS
SENSOR DEVELOPMENTS

PHOTON COUNTING
Limitations of Fast Hits Repetition of AC-Coupled Architectures

PIPPER Architecture

- Reset transistor can not be implemented as in 3-T pixel
- Bias applied through a forward bias diode
- Absence of reset limits the detection of fast repetitive hits: full well
- Not suitable for Mcps/pixel counting application
**Limitations of Fast Hits Repetition of AC-Coupled Architectures**

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Sim. ENC: 26 e⁻, Sim. energy res.: 250 eV at 5.9 keV
PIPPer Architecture

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Sim. ENC: 26 e⁻, Sim. energy res.: 250 eV at 5.9 keV

Time constant ≈ 18 ms
• Reset switch introduced as in a 3-T architecture
• Standard PMOS with bulk connected to a HV node (isolation with deep P-wells in TJ)
• Switching between HV V and HV-1.8 V: V_{GBmax}=1.8 V
• Reset token can not be propagated with rolling-shutter
• Global reset of the matrix: dead time
• AC-coupled source follower
**Effect of PMOS as Reset Switch**

**$V_b=HV$**

Simulated Noise : 50 e$^-$
Simulated Energy Resolution at 5.9 keV : 430 eV

**$V_b=IN$**

Simulated Noise : 28 e$^-$
Simulated Energy Resolution at 5.9 keV : 270 eV
Low Noise, Low Dispersion Amplifier Architecture

- AC-coupled CSA
- Single cascode stage. Particular care on input transistor
- Power pulsing: minimization of consumption
- Feedback capacitance < 1 fF
- Reset of the feedback
- Source follower for impedance adaptation on column
Simulations of Low Noise, Low Dispersion Amplifier

Simulated Noise: $11 \pm 10^{-11} \approx 0.5 \times \text{ENC(PIPPER-2)}$

Simulated Energy Resolution at 5.9 keV: 160 eV
• Free of charge 5 mm\(^2\) granted through EUROPRACTICE’s first user stimulation programme (one of 10 selected proposition in Europe)
• Designed in AMS-180 nm
• Two levels of wells
• No direct access to substrate as in TJ
• Allows the validation of the concept
• A Pipper-2 like pixel architecture implemented as reference
• Supposed to arrive in May-June 2018...
• Most recent fab out date: 25 August 2018
SENSOR DEVELOPMENTS

INTRA CEREBRAL NEUROIMAGING
Neuroimaging on Awake and Freely Moving Rodents

- Anesthesia effects beyond a simple loss of consciousness
- Effects on physiological processes
- Affection of neural and vascular responses
- Need to perform neuroimaging on awake subjects
- But, PET imaging of awake and restrained animal: non-awaken brain functions
- Behavioral studies with molecular neuroimaging required for drug development
**PIXSIC : INVASIVE APPROACH**

**Principle**

- Typical PET imaging radiotracers ($^{18}$F, $^{15}$O, $^{11}$C)

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**PIXSIC: INVASIVE APPROACH**

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- Direct localization of positrons clusters in the brain next to the sensor (<100 cps/matrix)
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PIXSIC

- Pixelated needle-shaped silicon probe (A) (15 mm long, 500 \(\mu\)m wide and 500 \(\mu\)m thick)
- 10 passive pixels (200 \(\times\) 500 \(\mu\)m\(^2\)). Subject to EM pickup
- Thinned to 200 \(\mu\)m sensitive : became brittle and still sensitive to 511 keV \(\gamma\)-rays
- Readout using the PICPUS ASIC (B)
PIXSIC : INVASIVE APPROACH

**Principle**

- Typical PET imaging radiotracers ($^{18}\text{F}$, $^{15}\text{O}$, $^{11}\text{C}$)
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- Immunity to the 511 keV annihilation $\gamma$-rays

**PIXSIC**

- Pixelated needle-shaped silicon probe (A) (15 mm long, 500 µm wide and 500 µm thick)
- 10 passive pixels ($200 \times 500 \, \mu\text{m}^2$). **Subject to EM pickup**
- Thinned to 200 µm sensitive : became brittle and still sensitive to 511 keV $\gamma$-rays
- Readout using the PICPUS ASIC (B)

Requirements for an Intracerebral CPS

- Using the typical radiotracers used in PET imaging ($^{18}$F, $^{15}$O, $^{11}$C): positrons between 0 and 1.7 MeV
- Direct localization of positrons clusters in the brain next to the sensor (<100 cps/matrix) requires a low detection threshold, thus low noise
- Immunity to the 511 keV annihilation gamma-rays required: thin sensitive volume
- In-chip (in-pixel) amplification and analog to digital conversion.
- Minimization of connections: simplification of the interface (small PCB)
- Invasivity minimization: following the PIXSIC dimensions (15 mm long, 500 µm wide and 500 µm thick)
- Active Pixels $\equiv$ Power Dissipation. Minimization to achieve local heating $< 1 \, ^{\circ}C: \, P<1 \, mW$
IMIC Sensor Design

**IMIC**

- Designed in 2015 in TowerJazz 180 nm CIS by M. Kachel and J Heymes
- Fabricated on HR18 substrate
- 610 µm wide, 12 mm long, 280 µm thick
- 16 × 128 pixels (30 × 50 µm²)
- SPI protocol to program the on-chip DACs
- Measured dissipated power : 160 µW

**Pixel Design**

- Based on the DC-coupled front-end of the ALPIDE sensor (CERN) : undepleted
- Low power : 55 nW/pixel (sim)
- ENC<10 e⁻ : threshold set at ≈ 100 e⁻
- 1 bit memory added to allow rolling-shutter readout
## Characterization Results and Future Steps

<table>
<thead>
<tr>
<th>55Fe hits</th>
<th>90Sr hits</th>
<th>18F hits</th>
<th>γ hit</th>
<th>55Fe 1000 frames</th>
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<td><img src="image1.png" alt="" /></td>
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Characterization Results and Future Steps
CHARACTERIZATION RESULTS AND FUTURE STEPS

- Fully functional needle shaped CPS for in-brain neuroimaging
- Measured dissipated power: 160 µW
- Readout strategy compatible with the awaited low count rate
- Immunity to 511 keV annihilation photons
- Diced and thinned sensors (200–250 µm) glued back-to-back: double sided probes
- Biocompatible polymer (Parylene) deposition
- In-vivo implantation to validate the sensor

Back-to-back sensors

Double sided probe

(L. Ammour, IMNC)

(F. Gensolen, CPPM)
Conclusions & Prospects
Conclusions & Prospects [1/2]

- New depletion method for CPS established
  - Exploits front-side biasing
  - Compatible with small pixel pitch
  - Backside illumination with thin entrance window
- Characterization of a prototype (PIPPER-2)
  - HR18 substrate fully depleted.
  - Thick bulk substrate depletion limited by deep P-wells and resistivity used.
- Prospects
  - Low energy sensitivity with tests in vacuum
  - Beam test to study MIP response (HEP, $\sigma_{SR}$) and to confirm depletion depth (and shape of the volume)
  - Higher resistivities and TJ modified process to increase depletion
Conclusions & Prospects [2/2]

- **HEP:**
  - Sustains $5 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$
  - Faster readout is required (leakage current increase with NIEL)
  - TID should be tested

- **Soft X-Rays:**
  - Collection up to 30 µm: good QE up to 5 keV
  - Deeper depletion needed to increase QE over a wider Energy range (higher $\rho$, modified process)
  - Good energy resolution of 280 eV at 5.9 keV
  - Low noise, low dispersion amplifier to improve energy resolution
  - Architectures in development to count at Mcps/pixel rates

- **Neuroimaging:**
  - Needle shaped sensor with low power dissipated validated in lab
  - Depletion will allow simpler structures
THANK YOU!