Performances of depleted Monolithic Active Pixel Sensor in a high-resistivity CMOS process for X-ray detection

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Position Sensitive Detector 11, Milton Keynes, UK

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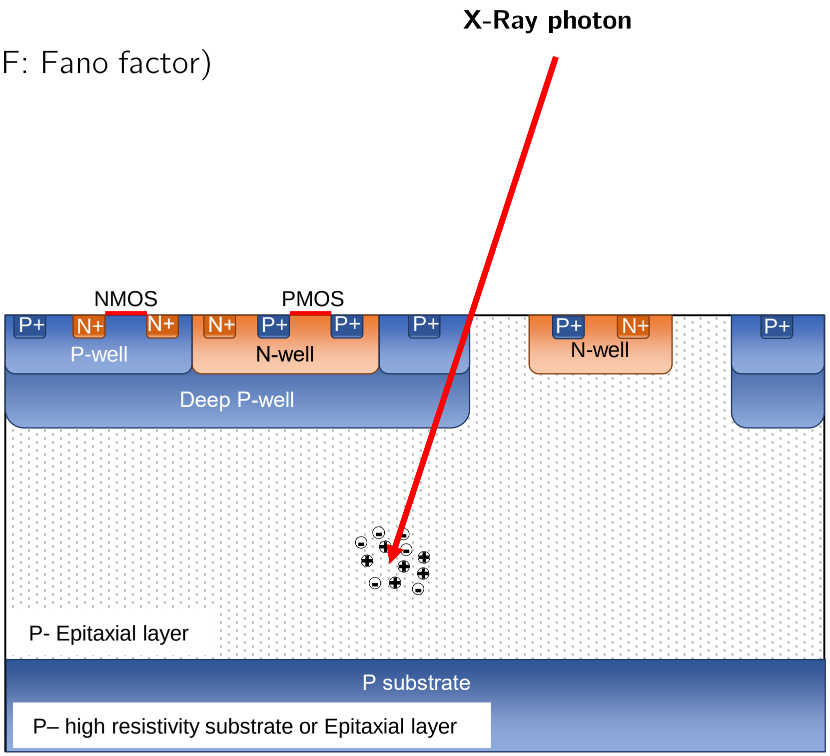
STRASBOURG

Outline

- **Soft X-ray detection with MAPS**
- **PIPPER-2**
  - ❑ Description of the sensor
  - ❑ Detection performances
  - ❑ Radiation hardness (NIEL)
- **Determination of the depletion depth in MAPS**
  - ❑ TCAD simulations
  - ❑ Determination with ^{55}Fe and ^{90}Sr irradiations

Soft X-ray detection with MAPS

- **Soft X-rays range: A few eV to 10 keV**
- **Photoelectric effect dominates below 50 keV in Silicon**
  - Creation of N electron hole pairs : $N \approx \frac{E_\gamma}{3.62\,[eV]}$, $\langle \Delta N^2 \rangle = F \cdot N$ (F: Fano factor)



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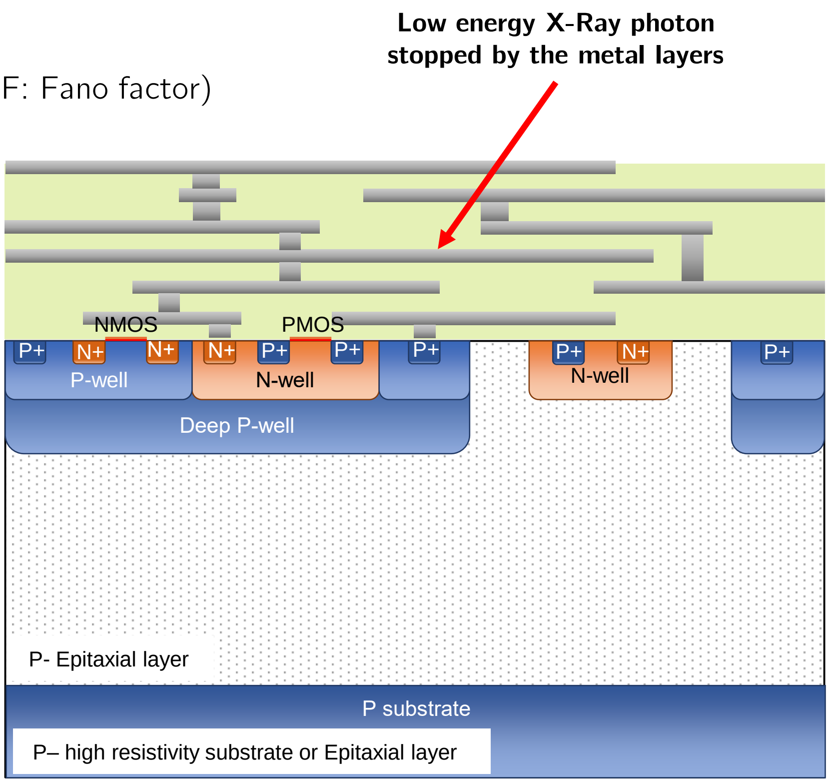
  - ❑ **Backside illumination mandatory with full depletion**



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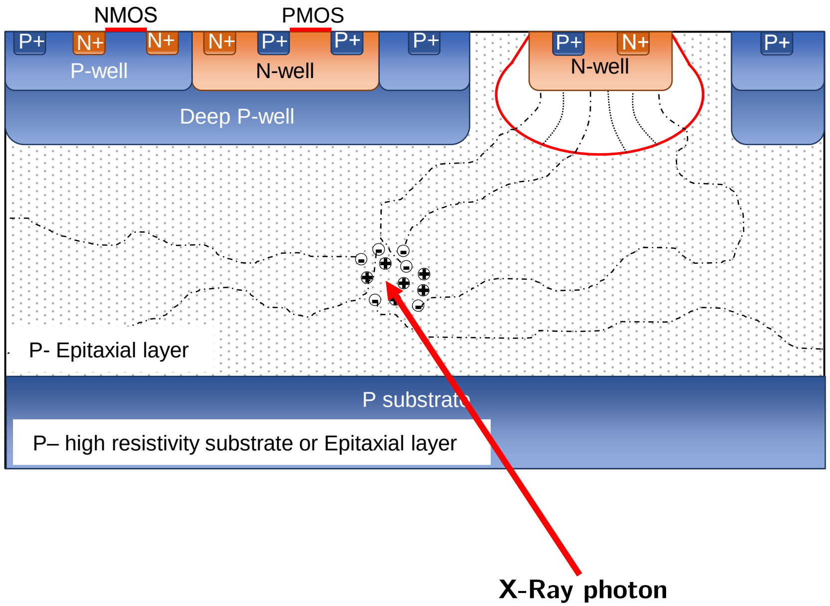

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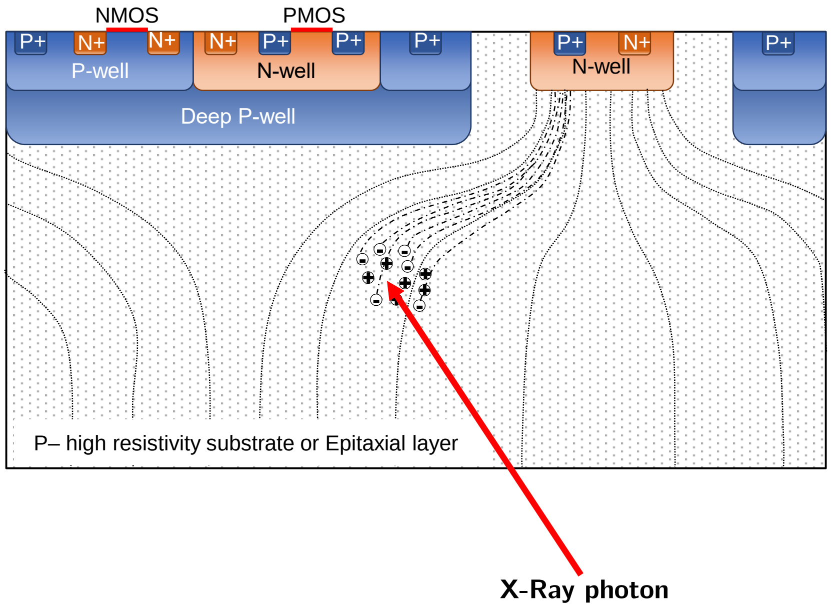
- **Depleted substrate collection**
  - ❑ **Drift of the charges**
  - ❑ **Full collection** (in a single pixel) before recombination
- **Depletion Depth in a dissymmetric junction**
  - ❑ Deep depletion ≡ High resistivity and/or increased bias voltage
- **Depletion from the top**
  - ❑ No backside contact ➔ thin entrance window
  - ➔ Soft X-rays not blocked



Soft X-Rays detection
MAPS vs. Hybrids vs. CCDs

	CCD	Monolithic Active Pixel Sensor	Hybrid Pixel Detector (Si)
Strength	• **Small pixel pitch** within large matrices • Wide Energy range (50 eV – 40 keV) • **Energy resolution close to Fano limit** • **Fully depleted** • Low noise …	• **Small pixel pitch** within large matrices • Single particle counting • Low noise (a few e$^-$ achieved) at room temperature or with moderate cooling • **Low cost** • Min. detectable energy > **100 eV** • Depletion (fully depleted with backbias)	• Single particle counting • **Very high counting rate** • **Fully depleted** (up to 1 mm) • **High radiation hardness** (> Grad) • Advanced in-pixel processing because of …
Weakness	• … at very low temperatures (< **-50 °C**) • No single particle image • Expensive • **Limited readout speed**	• **Moderate counting rate** • Less in-pixel processing than hybrid pixel detectors	• … (very) **large pixel pitch** (except MÖNCH) • Noise impacted by the detector connection (> 50 e$^-$) • Lowest energy detectable (> **1.75 keV**) depending on the threshold applied • **High cost** (bonding, detector)

DOI: 10.1107/S0021889813016592
DOI: 10.1109/TNS.2012.2228410
DOI: 10.1109/NSSMIC.2011.6154370

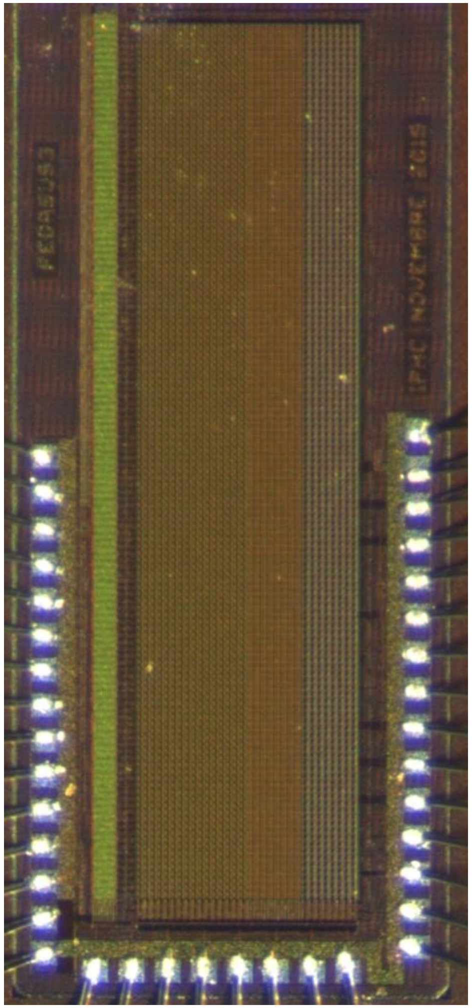
DOI: 10.1016/j.nima.2010.07.066
DOI: 10.1088/1748-0221/11/11/C11020
DOI: 10.1088/1748-0221/12/01/C01039

DOI: 10.1109/TNS.2007.906163
DOI: 10.1016/j.nima.2007.01.153
DOI: 10.1063/1.4938166
DOI: 10.1109/NSSMIC.2009.5402196
DOI: 10.1088/1748-0221/9/05/C05015
DOI: 10.1088/1748-0221/10/01/C01032
DOI: 10.1088/1742-6596/425/6/062001

Strips, 3-D, SOI, DEPFET… not mentioned

Depletion studies
Test sensor: PIPPER-2

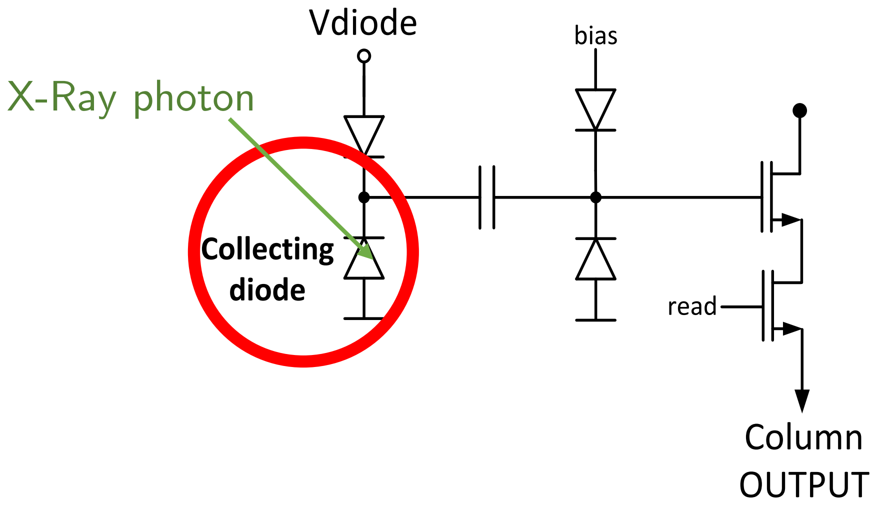
- **P**ixelated sensor for **I**onizing **P**article and **P**hotons **E**nergy **R**esolved detection
- **Analog sensor**
- **Technology : CMOS CIS 180 nm**
- **Designers : Maciej Kachel, Andreï Dorokhov**
- **Substrates:**
  - ❑ HR18: 18 µm high-resistivity epitaxial layer **(> 1 kΩ·cm)**
  - ❑ CZ: 280 µm high-resistivity Czochralski substrate **(> 600 Ω·cm)**
- **128 rows, 32 columns**
- **Pixel pitch : 22 µm**
- **Rolling shutter readout with offline CDS**
  - ❑ Column are readout in parallel
- **4 versions of pixels (8 columns each)**
  - ❑ Depletion studies (AC-coupled 3-T architecture)
    - **Pixel 1: Ø 5µm round collection diode**
    - Pixel 2: Ø 3µm round collection diode
    - Pixel 3: 4 x Ø 4µm round collection diode
  - ❑ Low power amplifier (Pixel 4)

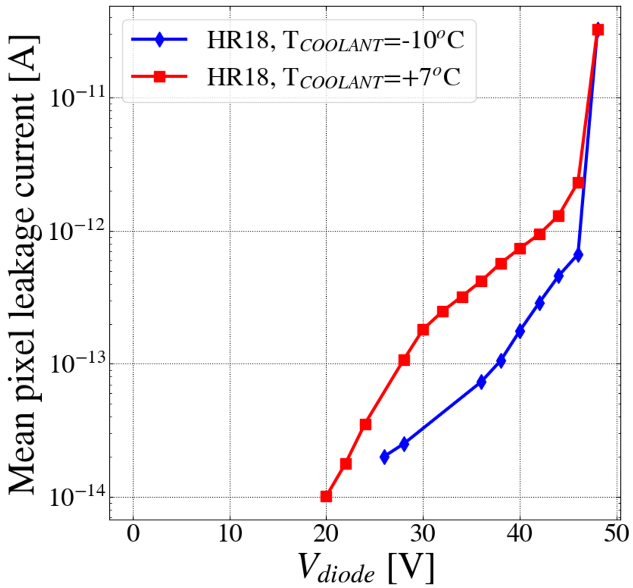


Depletion studies

Test sensor: Pixel architecture

- **Pixel architecture (Pipper-2 pixel 1)**
  - 22 µm pitch
  - Ø 5 µm round collection diode
  - ~21 fF fringe capacitor for AC-coupling
  - Source follower
  - **Depletion voltage applied from the top**
- **Fringe decoupling capacitor preffered over MIM**
  - Lower leakage current
  - Higher breakdown limit
- **Leakage current influenced by cooling**





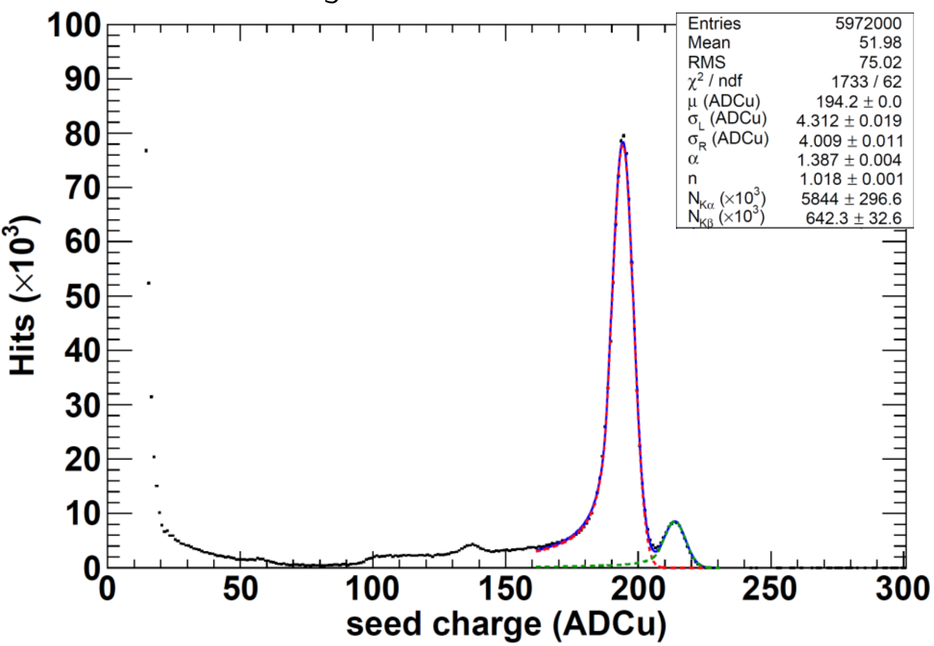
X-Ray detection performances

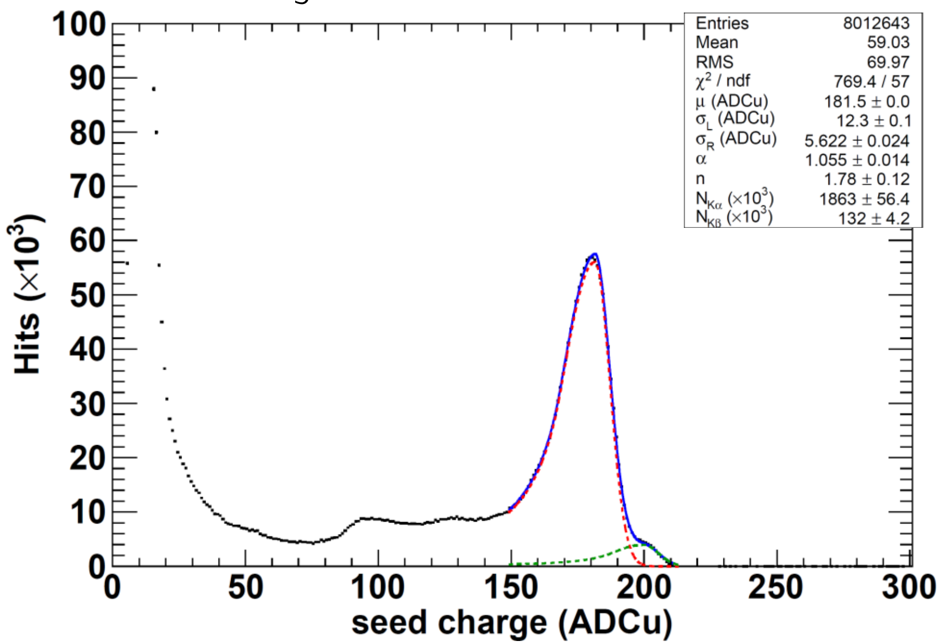
HR-18 & Czochralski at 30 V

After clustering ➔ Seed pixel charge distribution

- **18 µm thick epitaxial layer (HR18)**
  - ENC = 24 e⁻
  - FWHM (5.9 keV) = 298 eV
  - 30.38 eV/ADCu
  - Si escape peak visible (138 ADCu)
  - 75 % of the charges collected on the seed pixel on average

- **280 µm thick Czochralski (CZ)**
  - ENC = 26 e⁻
  - FWHM (5.9 keV) = 686 eV
  - 32.51 eV/ADCu
  - Mn-Kα and Mn-Kβ merging
  - 68 % of the charges collected on the seed pixel on average

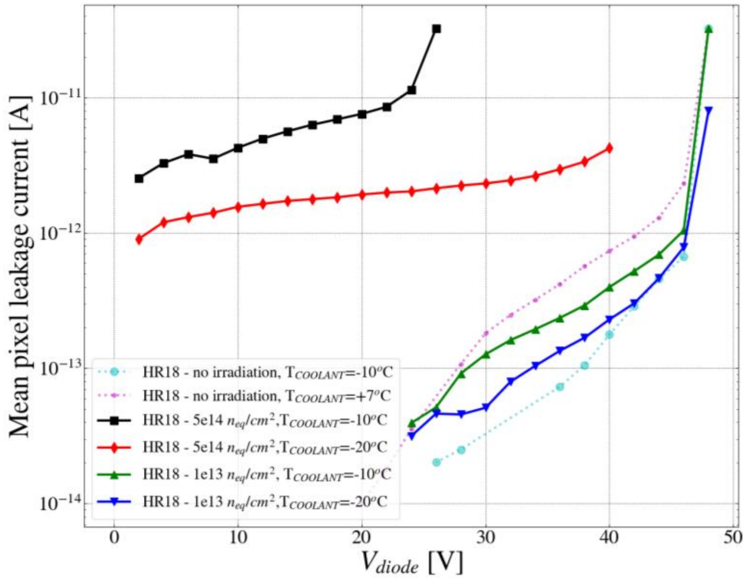




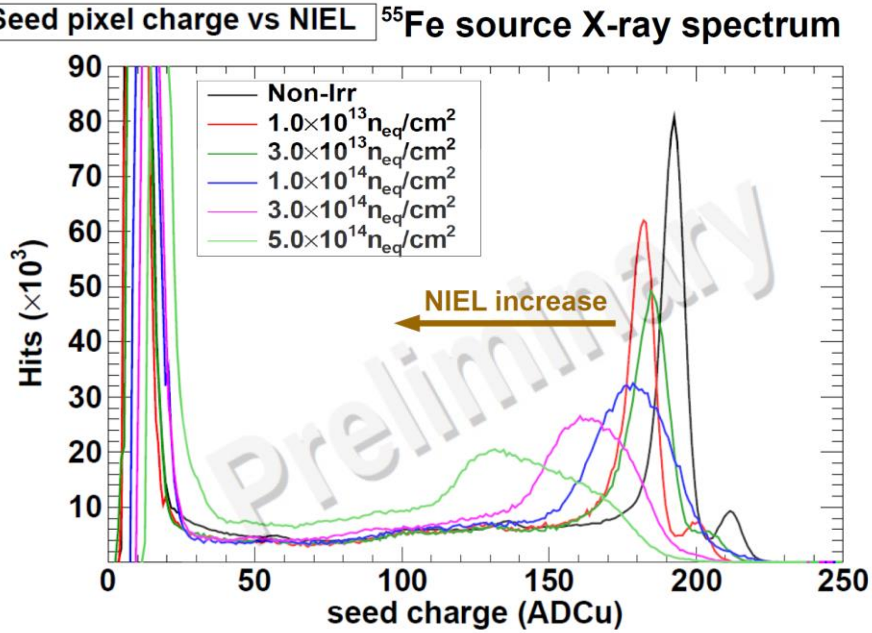
Pipper-2 measurements (presc. 2, $T°_{cool}$=7 °C, V_{diode}=30V) ^{55}Fe irradiation – 400000 frames

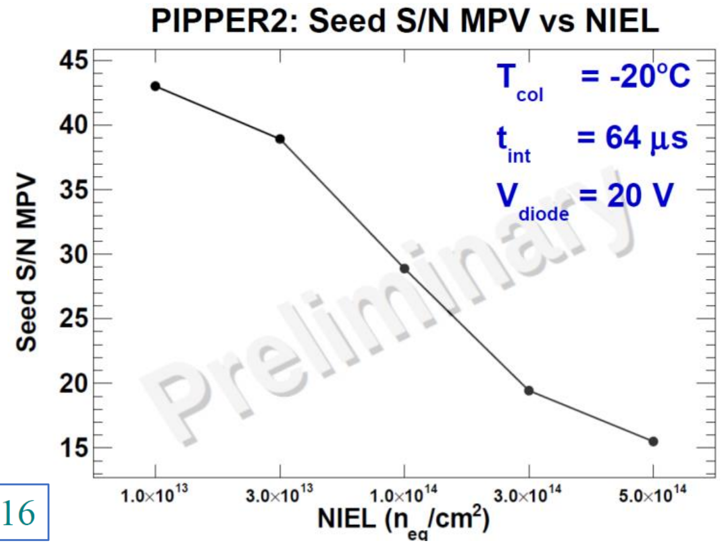
Radiation hardness
NIEL

- **HR18 sensors cooled to -20 °C**
- **Non ionizing irradiation**
- **Leakage current increased with fluence (improved with cooling)**
- **Deterioration of collection efficiency**
  - Calibration peaks merged above $1\text{x}10^{14}\ n_{eq}/cm^2$
- **SNR acceptable for <u>tracking</u> to fluences up to $5\text{x}10^{14}\ n_{eq}/cm^2$**
- **Depletion allows fast charge collection before trapping**



Seed pixel charge vs NIEL



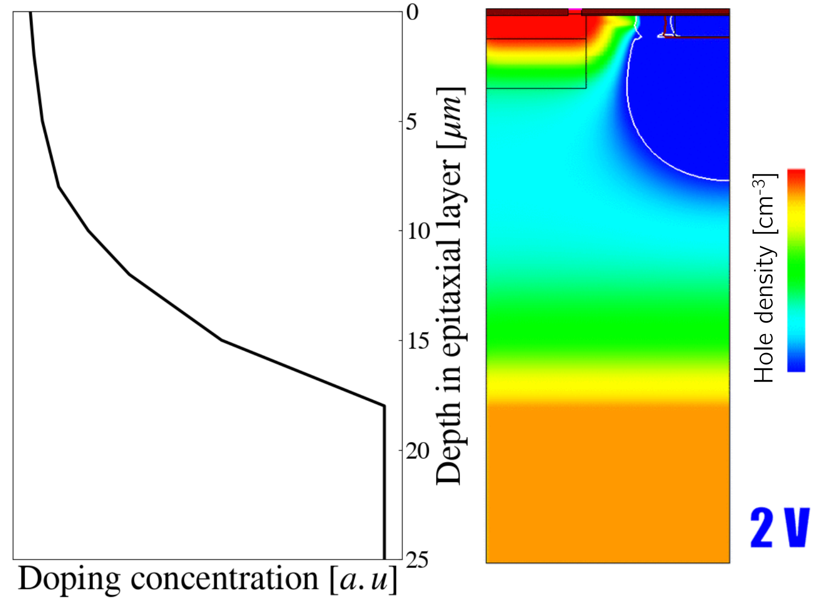


Alejandro Pérez Pérez, IEEE NSS/MIC, N53, Nov. 3rd 2016

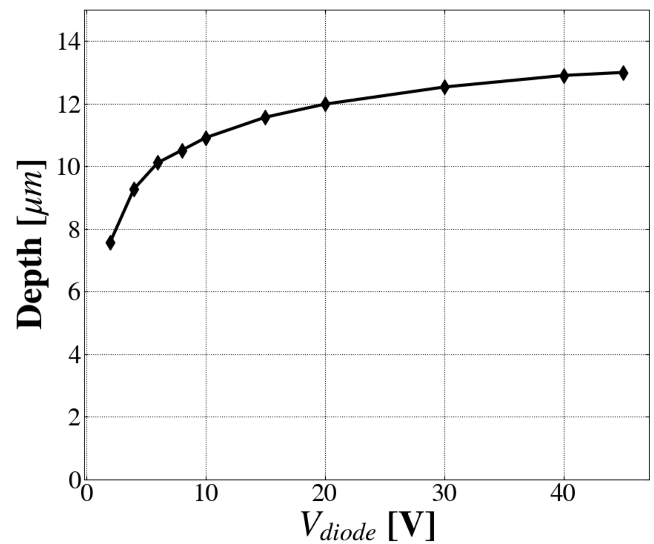
TCAD simulations of the depleted volume

HR18

- **Epitaxial layer**
  - Supposed to be 18 µm thick, > 1 kΩ·cm (> $1.3 \cdot 10^{13}$ cm^{-3})
  - Maximum measured > **10 kΩ·cm**
  - Epitaxial layer meets substrate at ≈ 18 µm
  - 1 kΩ·cm reached at ≈ 10.5 µm



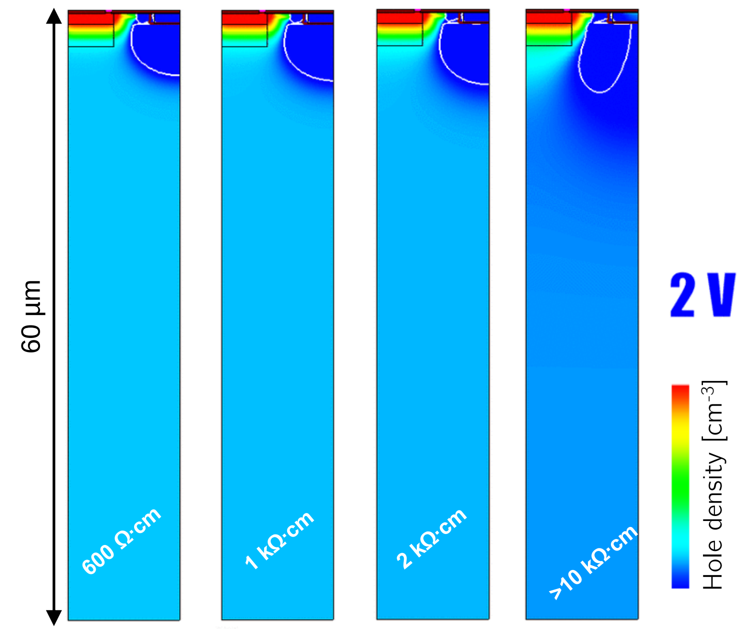
- **Simulation**
  - Doping profile of the epitaxial layer implemented
  - Spherical depleted volume before merging, then plane
  - Saturation of depleted depth at ≈ 13 µm
    - **The doping profile of the epitaxial layer is limiting the extension of the depletion**
  - At V_{DIODE} ≈ 15 V → Merging of the depleted volume between two adjacent pixels

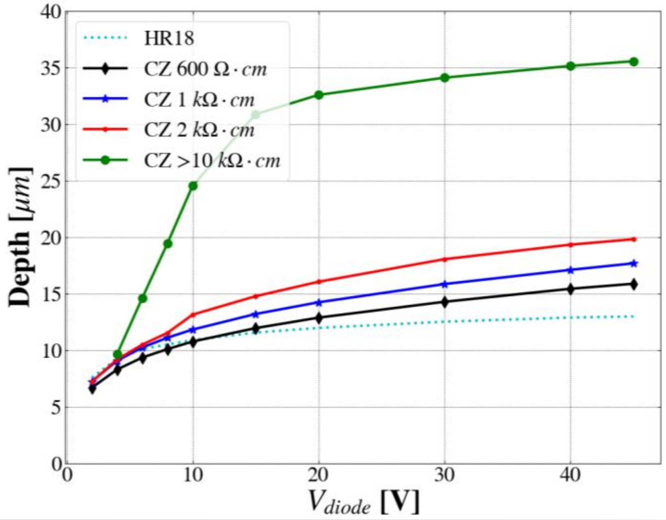


TCAD simulations of the depleted volume

Czochralski

- **Czochralski substrate**
  - ❑ 60 µm thick simulated
  - ❑ No backside contact
  - ❑ 4 constant doping profile implemented
    - 600 Ω·cm (Prototype value)
    - 1 kΩ·cm
    - 2 kΩ·cm
    - > 10 kΩ·cm (max. of HR-18)
- **Simulation**
  - ❑ 600 Ω·cm
    - Depletion reaches ≈ 16 µm
    - Improved with higher resistivities
      - 20 µm with 2 kΩ·cm
    - Late merging (40 V)
  - ❑ Very high resistivity
    - Depth up to 35 µm
    - May be bigger since the substrate is close to be intrinsic

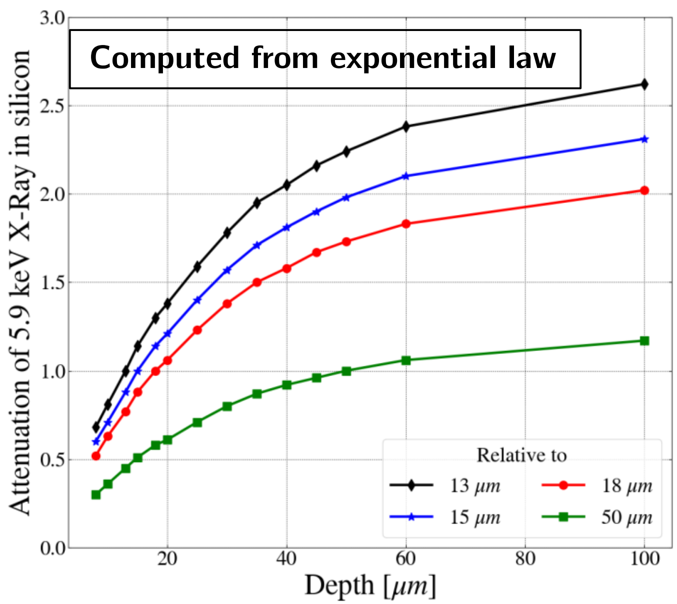




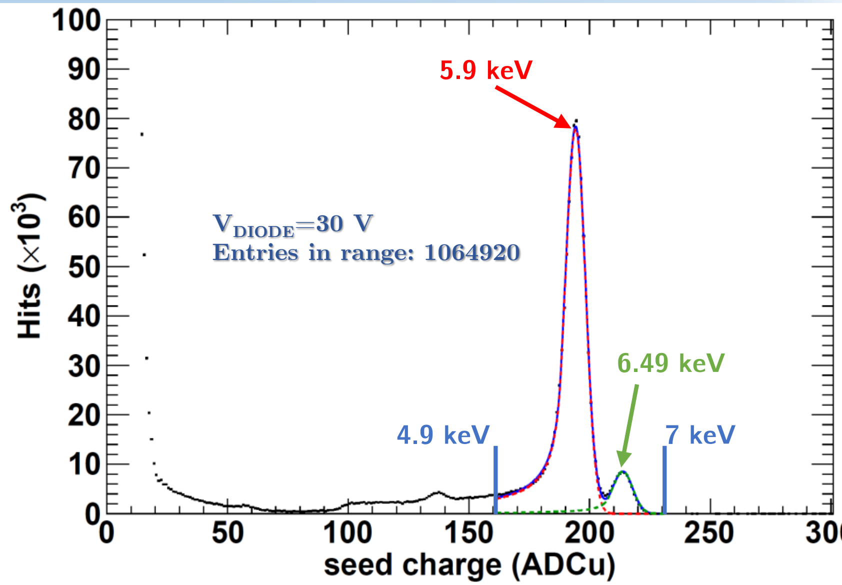
Determination of the collection depth

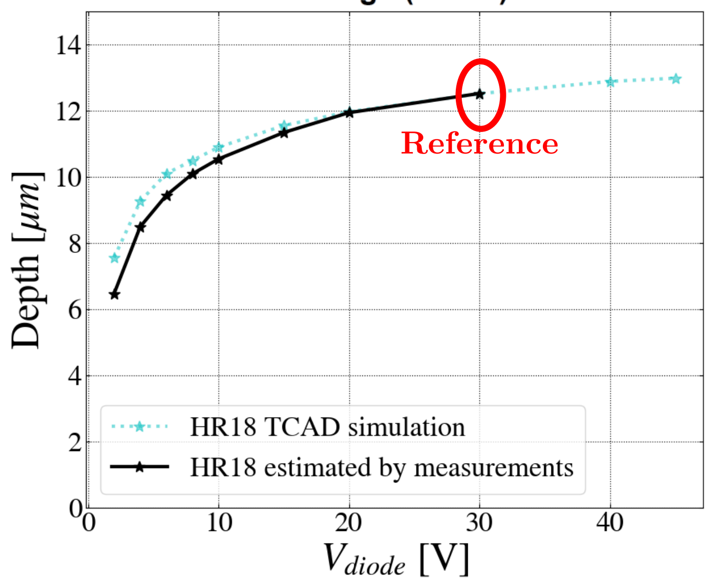
Using the ^{55}Fe calibration peaks

- **18 µm thick epitaxial layer**
- **CrystalBall fit of the calibration peaks**
  - Peak position ➔ Calibration
  - Sigma extraction ➔Energy resolution
  - Entries counted between 4.9 keV and 7 keV



- **Counts in range 4.9 – 7 keV to determine the depth**
  - Point at 30 V as reference
  - Ratio of counts from 30 V
  - Collection depth determined from relative attenuation to ≈ 13 µm
  - **Similar behavior than TCAD simulations**





Determination of the collection depth

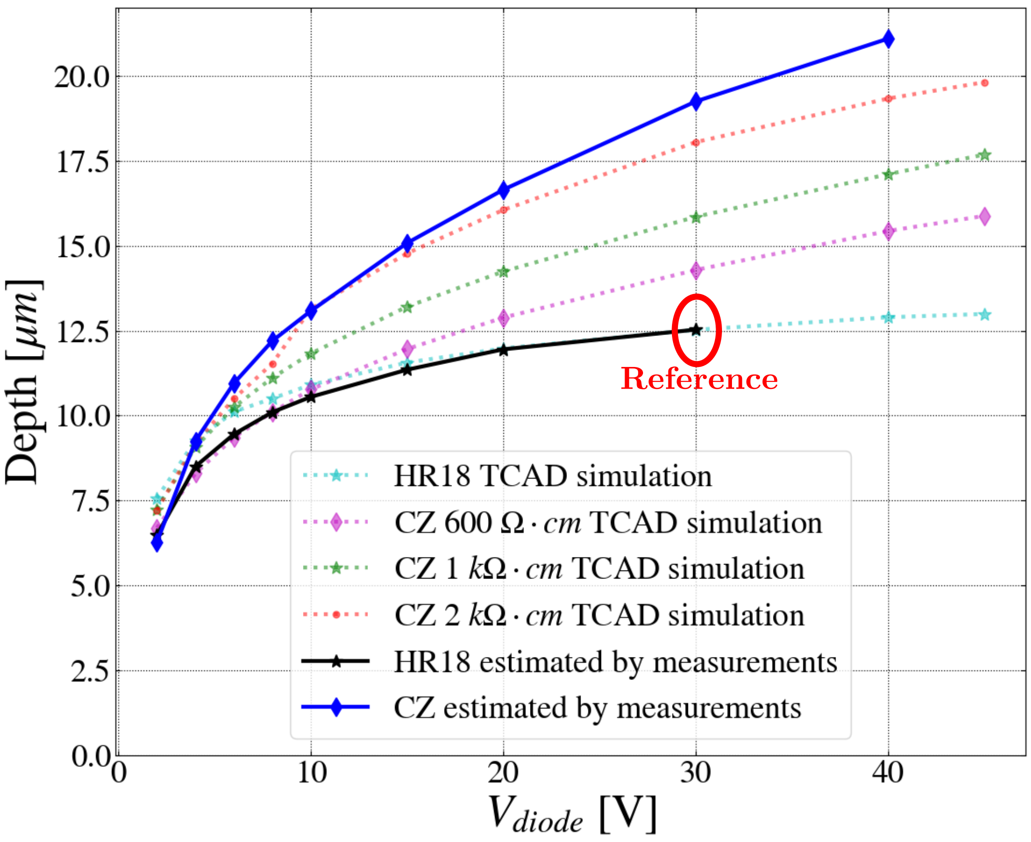
Using the ^{55}Fe calibration peaks – HR-18 vs. CZ

- **Counts in range 4.9 – 7 keV to determine the depth**
  - Ratio of counts from HR18 30 V
  - Collection depth determined from relative attenuation to ≈ 13 µm

➔ **Collection depth with good resolution ≈ 21 µm**

  - Compared to TCAD simulations
    - ➔ Resistivity of ≈ 2 kΩ·cm

➔ **Range 4.9 keV - 7 keV ➔ Similar to select clusters with >90 % of charges in seed pixel**

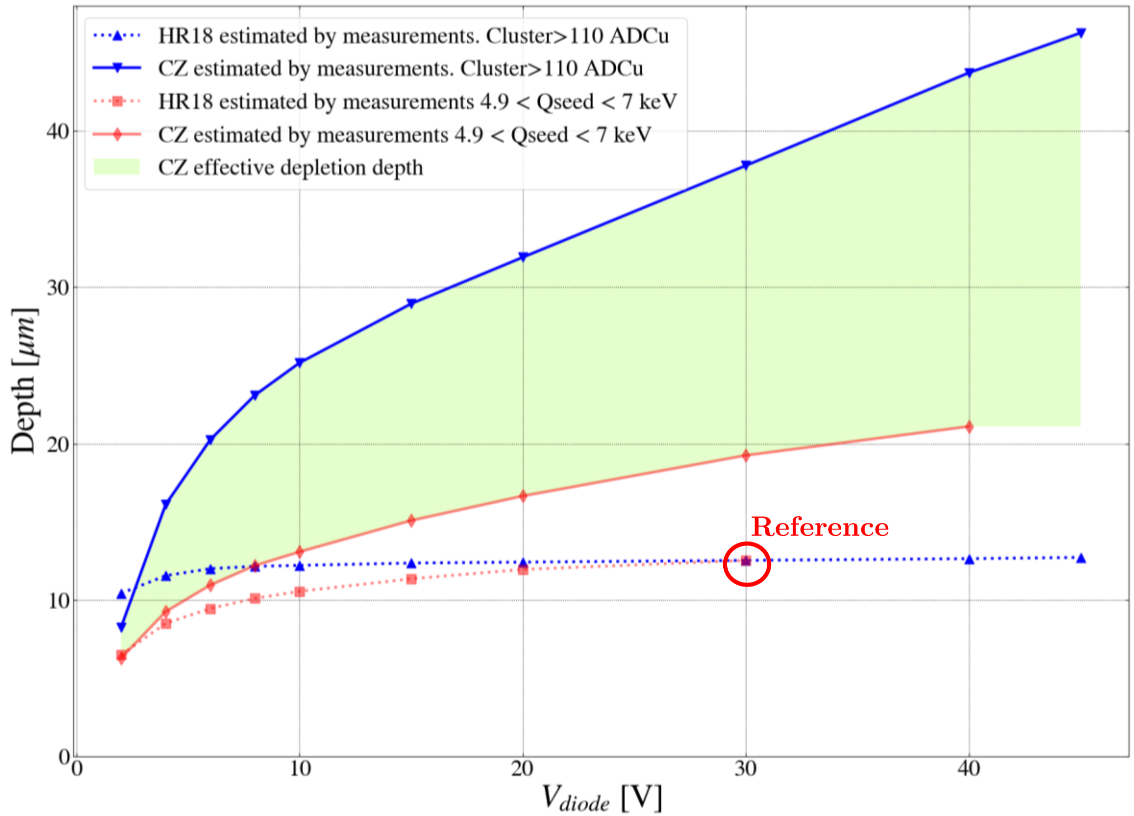


Determination of the collection depth

Using the ^{55}Fe spectrum

- **Total counts in spectrum (cluster charge > 110 ADCu for noise suppression)**
  - Point at 30 V from HR18 as reference
  - Depth determined from relative attenuation from HR-18 at 30 V
  - **HR18:** Quick saturation around 13 µm ➔ **Depletion depth**
  - **CZ:** Collection depth up to 46 µm (81 % attenuation for Mn-Kα) ➔ **Max. collection depth** (limit of sensitivity of ^{55}Fe)

➔ **Effective depletion depth between collection depth with good resolution (21 µm) and max. collection depth (46 µm)**

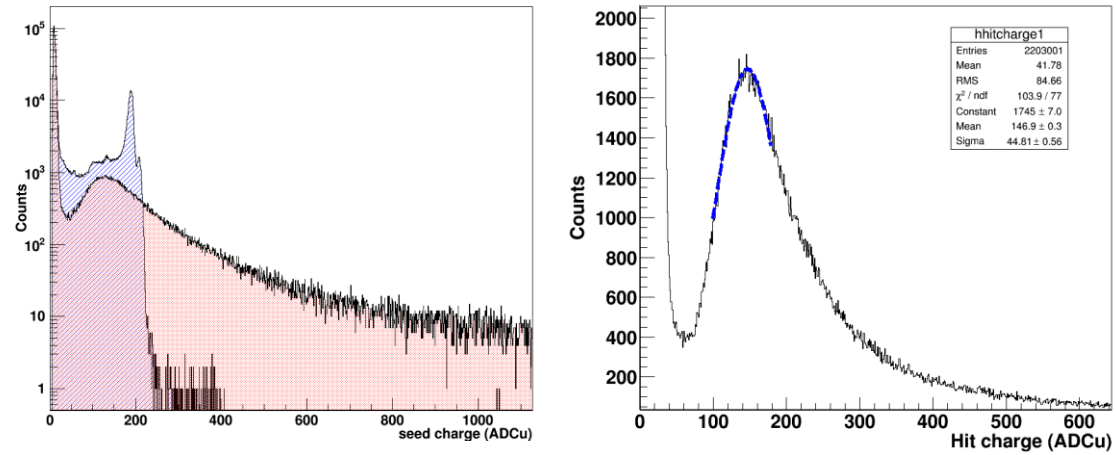


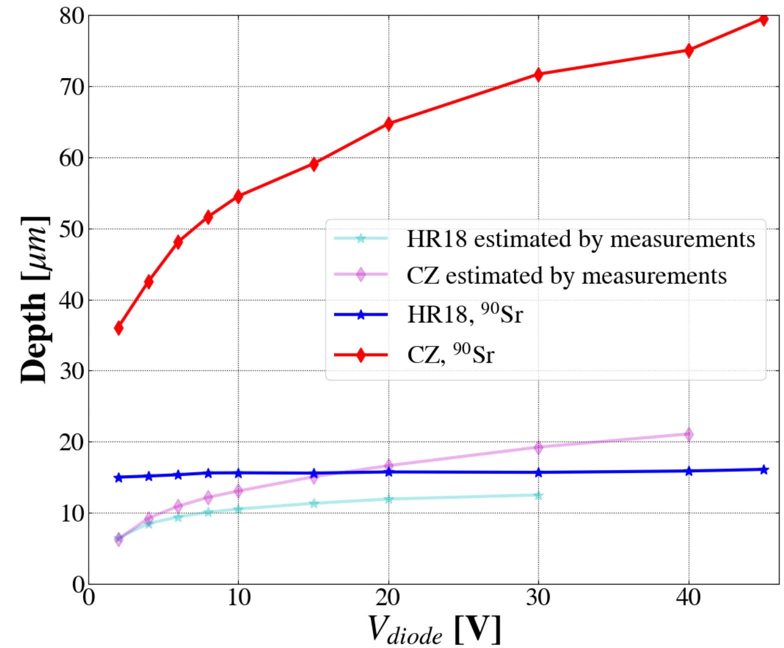
Determination of the collection depth

Using MIPs - ^{90}Sr

- **Measurements with ^{90}Sr**
  - ❑ Pure β emitter
  - ❑ β ➔ Minimum ionizing particle
    - Generation of $\approx \frac{80\ e^-/h^+}{\mu m}$
    - In HR-18 ➔ Generation of 1440 e⁻
  - ❑ Collection depth from total cluster charge
- **HR-18**
  - ❑ Maximum slightly higher than with X-Rays
    - Saturation at ≈ 15 µm
    - ➔ Total collection depth
- **CZ**
  - ❑ Maximum at ≈ 80 µm
  - ❑ <u>**Large overestimation**</u>
    - Source far from the sensor → solid angle
    - ➔ Longer tracks within the depleted volume → More e⁻
    - Electrons generated in non depleted region collected by diffusion (High Res ≡ long lifetime)
      - 280 µm thick substrate → 22400 e⁻
  - ➔ Estimation of the maximum collection depth

Pipper-2, V_{diode}=20 V





Conclusions and perspectives

- **CMOS MAPS with depletion voltage applied from the top**

- **18 µm thick high resistivity epitaxial layer**
  - ENC=24 e^-, Energy resolution at 5.9 keV=298 eV
  - Suitable for tracking with NIEL irradiation up to 5 x 10^{14} n_{eq}/cm^2
  - **Fully depleted at 13 µm**
  - Charges generated at max. 15 µm
  - ➔ Limited by the doping profile

Valid for charged particles tracking in highly radiative environment

- **High resistivity Czochralski substrate**
  - ENC=26 e^-, Energy resolution at 5.9 keV=686 eV
  - Collection with good energy resolution up to 22 µm
  - Collection up to 46 µm (diffusion)
  - **Depletion depth in between ➔Uncertainties on the effective depletion depth**

Required for soft X-rays with thinning to 50 µm

- **Thinned CZ sensors to 50 µm (40 µm sensitive) to be measured**
  - Various backside processing combinations
  - To measure the sensors with front side and back side illumination to determine the effective depletion depth in HR CMOS MAPS