PAUL SCHERRER INSTITUT

FONDAZIONE BRUNO KESSLER

M.Carulla :: Photon Science Detector Group :: Paul Scherrer Institut

Development of sensors for soft X-ray hybrid detectors

17-20 March 2024 :: International Forum on Detectors for Photon Science:: Port Jefferson :: USA

* On behalf of Photon Science Detector group and FBK collaboration

Outline

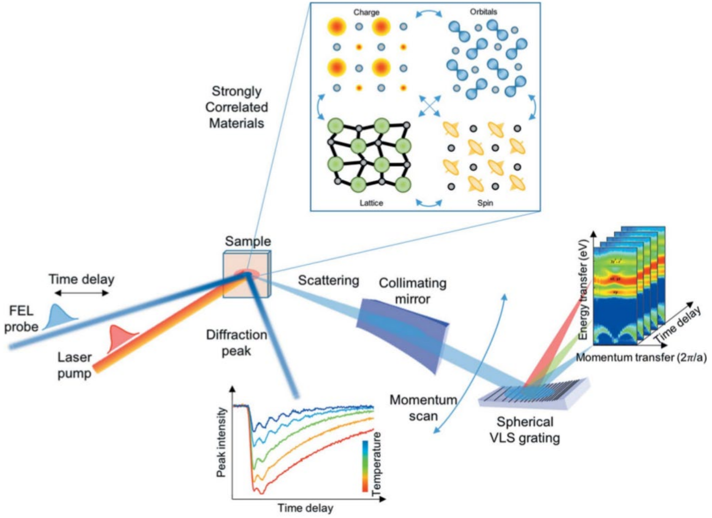
- Soft X-rays
- Detector requirements and limitations
- Challenges for soft X-ray detection
- Development Strategy
- LGAD technologies
- QE improvement
- Depth dependence of gain in iLGADs
- Single-photon counting with iLGADs
- Summary

Soft X-rays (200 eV to 2 keV)

L-edges of 3d transition metals
- Mn, Fe, Cu, …
- Materials: multiferroic materials, correlated materials
- Applications: Superconductors, memories, spintronics

K-edges light elements and 'water window'
- C, N, O, S, …
- Materials: Biological samples in its aqueous environment, organic semiconductors

Applications with 2D detectors
- R-SoXS
- Lensless CDI: Ptychography
- RIXS, TR-RIXS



Time-resolved resonant inelastic X-ray scattering (RIXS)
R. Abela et al 2019 J. Synchrotron Rad. 26, 1073-1084

PAUL SCHERRER INSTITUT PSI

Detector requirement and limitations

Photoelectric (Probability 1) -> RIXS (Probability 10^{-5})

- **Detector requirements:**
  - High QE for soft X-rays
  - Large area
  - Good spatial resolution (~ 5 µm)
  - Low noise (< 5 e- r.m.s)
  - High frame rate (> 100 Hz SwissFEL)

- **Limitations of available systems:**

EMCCD

- ☺ High QE (55% @ 250 eV)
- ☹ Limited area (~ 2 x 2 cm²)
- ☺ High spatial resolution (≤ 5 µm)
- ☺ Low noise (≤ 1 e^{-})
- ☹ Slow readout (~ 1Hz)

Scientific CMOS

- ☺ High QE (62% @ 250 eV)
- ☹ Limited area (~ 2 x 2 cm²)
- 😐 High spatial resolution (≤ 10 µm)
- ☺ Low noise (~ 1-2 e^{-})
- 😐 Frame rate (< 50 Hz)

Hybrid pixel detectors

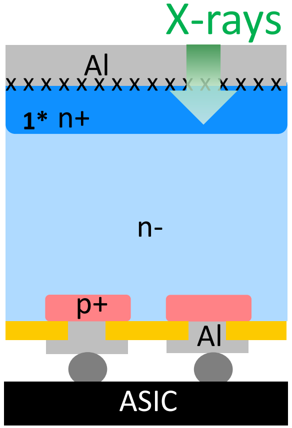
- ☹ Low QE (< 1 % @ 250 eV)
- ☺ Large area (> 4 x 8 cm²) tiled
- 😐 Spatial resolution (< 5 µm*)
- 😐 Noise (~ 35 e^{-})
- ☺ High frame rate(> 2kHz)

*Interpolation with Mönch (Hard X-rays)

Challenges for soft X-ray detection

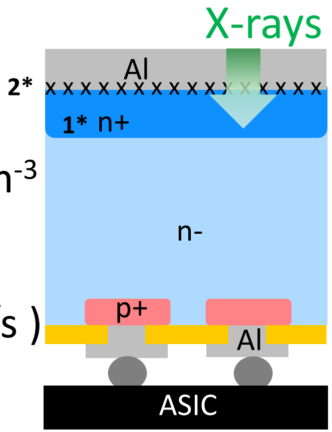
Low quantum efficiency

1. Auger recombination in n+
   L_h = 200 nm Conc ~ 10^{20} cm^{-3}



Challenges for soft X-ray detection

Low quantum efficiency



1. Auger recombination in n+
   L_h = 200 nm Conc ~ 10^{20} cm^{-3}

2. SRH recombination at Si/Al interface (S_0 ~ 10^7 - ∞ cm/s)

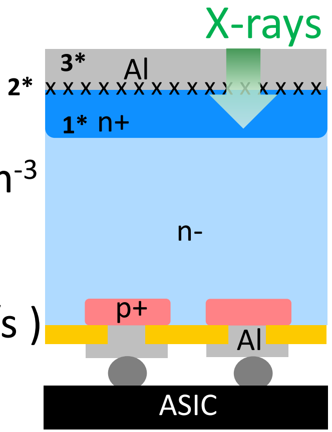
Challenges for soft X-ray detection

Low quantum efficiency

1. Auger recombination in n+
   L_h = 200 nm Conc ~ 10^{20} cm^{-3}

2. SRH recombination at Si/Al interface (S_0 ~ 10^7 - ∞ cm/s)

3. Absorption in the surface layers



Reduce losses in the entrance window

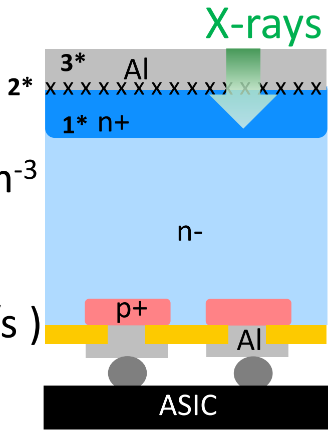
[Entrance window technology]

PAUL SCHERRER INSTITUT

Challenges for soft X-ray detection

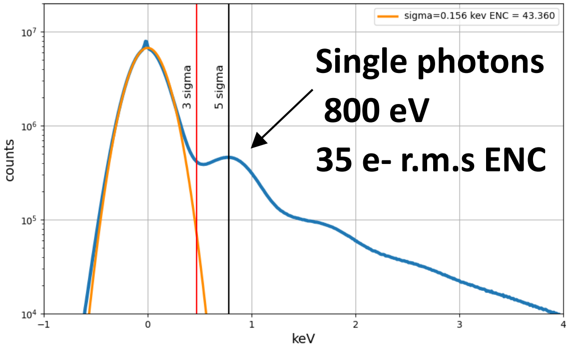
Low quantum efficiency

1. Auger recombination in n+
   L_h = 200 nm Conc ~ 10^{20} cm^{-3}
2. SRH recombination at Si/Al interface (S_0 ~ 10^7 - ∞ cm/s)
3. Absorption in the surface layers



Low signal-to-noise ratio

- SNR ≈ 1.6 for 200 eV
- At least an SNR of 5 is required to achieve single photon resolution



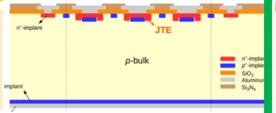
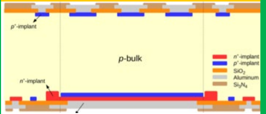
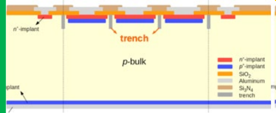
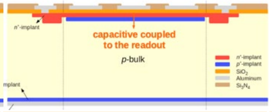
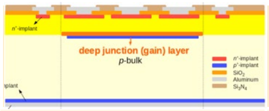
*V. Hinger et al 2022 JINST **17** C09027*
https://doi.org/10.1088/1748-0221/17/09/C09027

Reduce losses in the entrance window
Entrance window technology

+

Increase the signal by internal multiplication
LGAD technology

LGAD technologies

	LGAD	inverse-LGAD (iLGAD)	trench-isolated LGAD (TI-LGAD)	AC-coupled LGAD (AC-LGAD)	deep junction LGAD (DJ-LGAD)	ideal LGAD
cross section						?
process*	standard	double-sided	stepper	standard	epi-growth	standard
complexity	low	low	medium	high	high	low
collected charge	e^-	h^+	e^-	e^- (bipolar)	e^-	e^- or h-
readout	DC	DC	DC	AC	DC	DC
non-gain region (fill factor)	> 40 um low	0 um 100%	6-7 um high	0 um 100%	0 um 100%	0 um 100%
gain depends on absorption depth	no	yes	no	no	no	no
detection area	large	medium-large	small	medium-large	medium-large	large
multiplication of surface current	no	yes	no	yes	yes	no
risk/yield	low/good	medium/medium	medium/medium	medium/medium	high/low	low/good

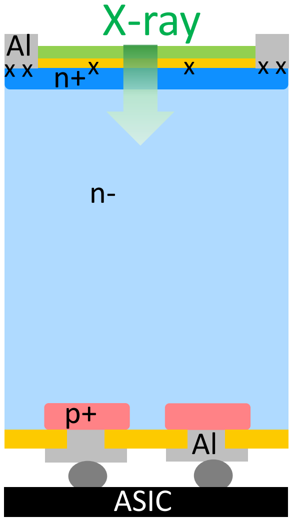
development @ PSI & FBK

*New developments not listed: Resistive AC-LGAD and MARTHA

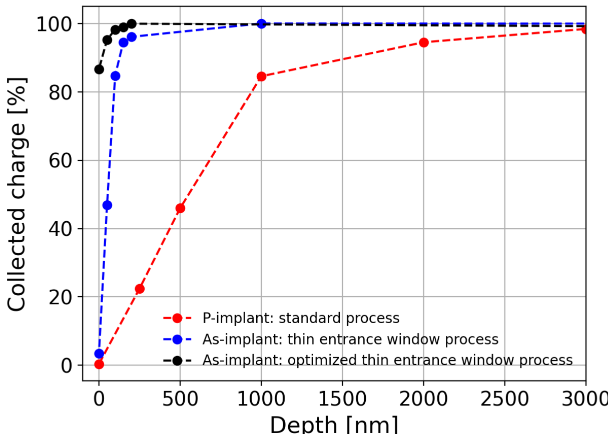
Development strategy

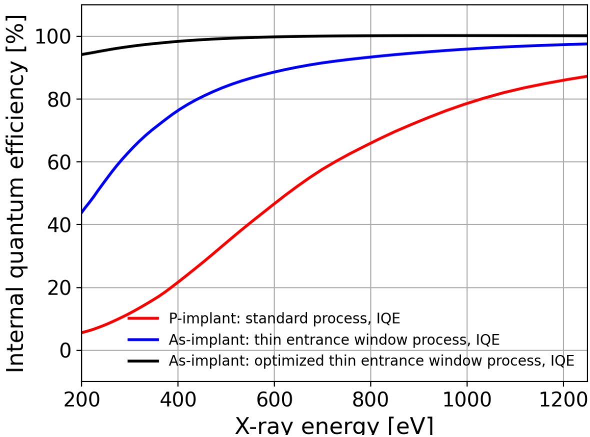
Thin entrance window technology

- Optimization of the n+
- Passivation of the surface



TCAD simulation of the process and device





<u>Internal QE larger than 90 %</u>

J. Zhang *et al* 2022 *JINST* **17** C11011

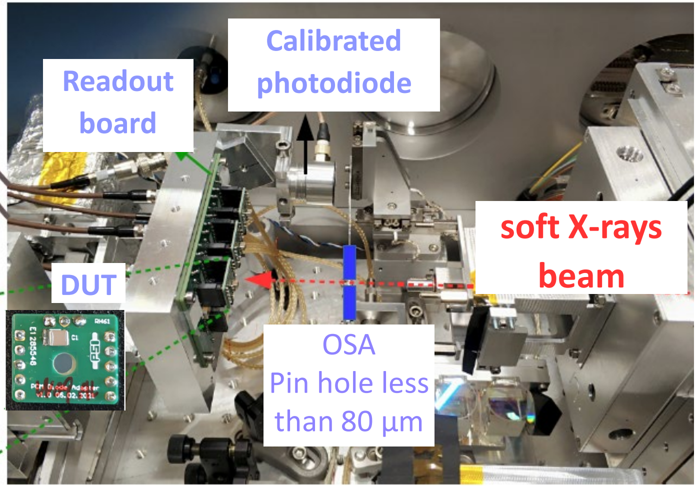
https://doi.org/10.1088/1748-0221/17/11/C11011

QE improvement

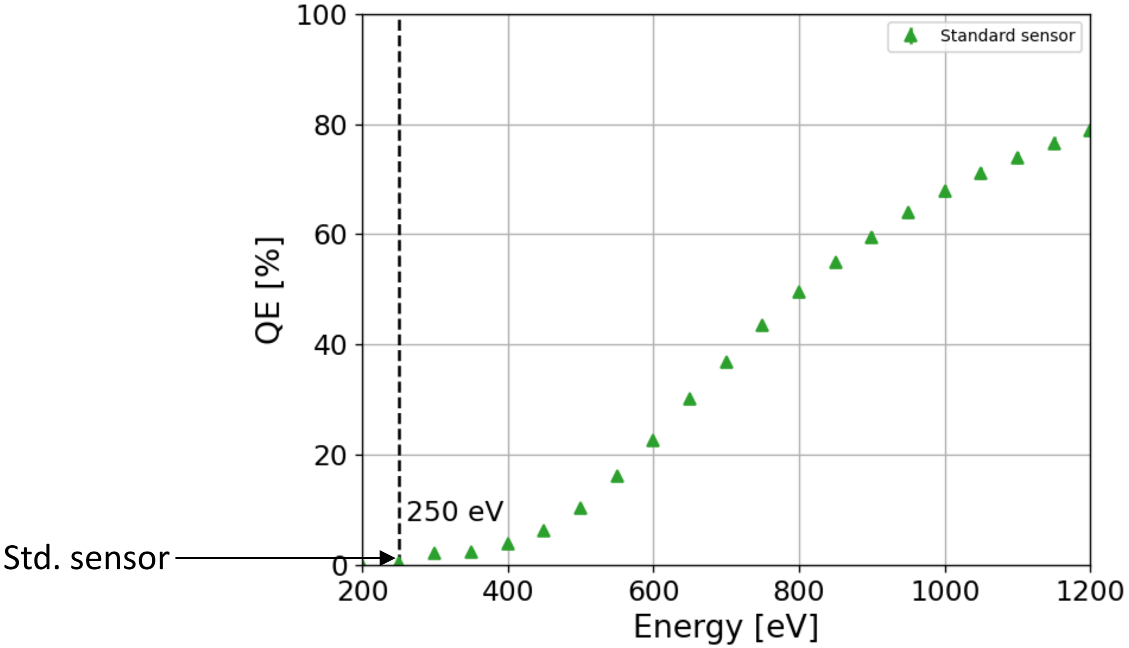
M. Carulla *et al* 2023 *JINST* **18** C01073

M. Carulla *et al* *Sensors* **2024**, *24*(3), 942; https://doi.org/10.3390/s24030942

Setup at the Surface/Interfaces Microscopy (SLS)



Quantum efficiency

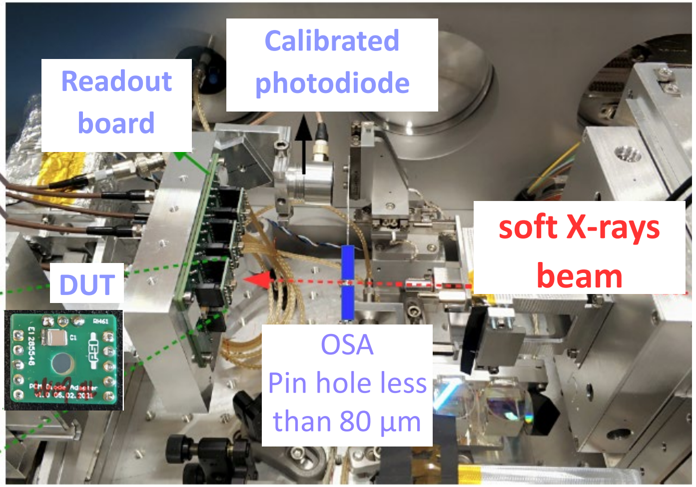


QE improvement

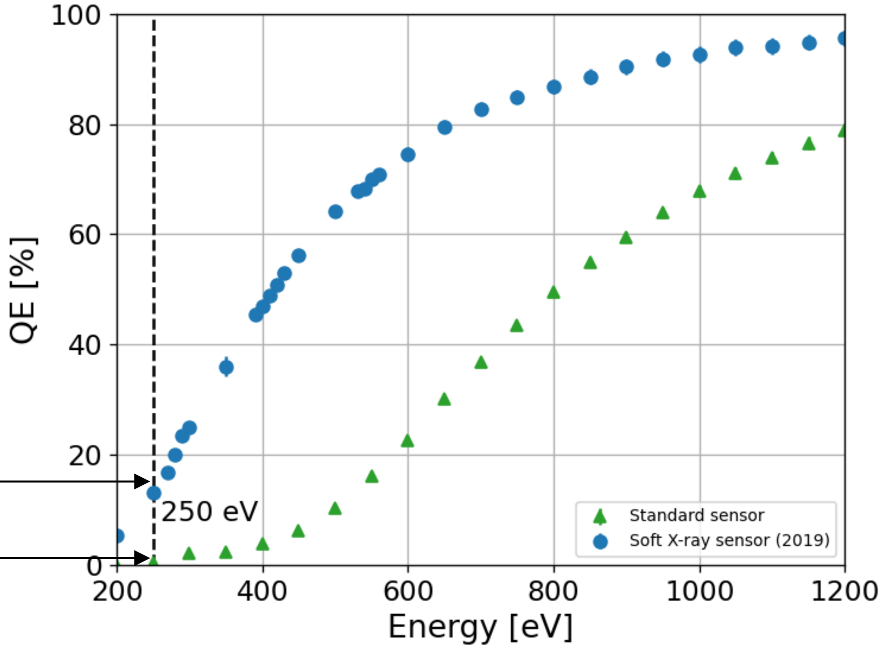
M. Carulla *et al* 2023 *JINST* **18** C01073

M. Carulla *et al* *Sensors* **2024**, *24*(3), 942; https://doi.org/10.3390/s24030942

Setup at the Surface/Interfaces Microscopy (SLS)



Quantum efficiency



Al/Si interface

Std. sensor

Keys for high QE :

- Optimization of the n+

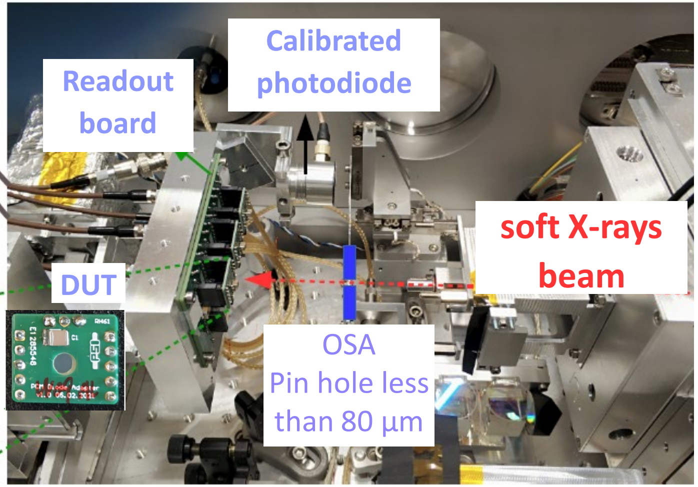
PAUL SCHERRER INSTITUT

QE improvement

M. Carulla *et al* 2023 *JINST* **18** C01073

M. Carulla *et al* *Sensors* **2024**, *24*(3), 942; https://doi.org/10.3390/s24030942

Setup at the SIM (SLS)

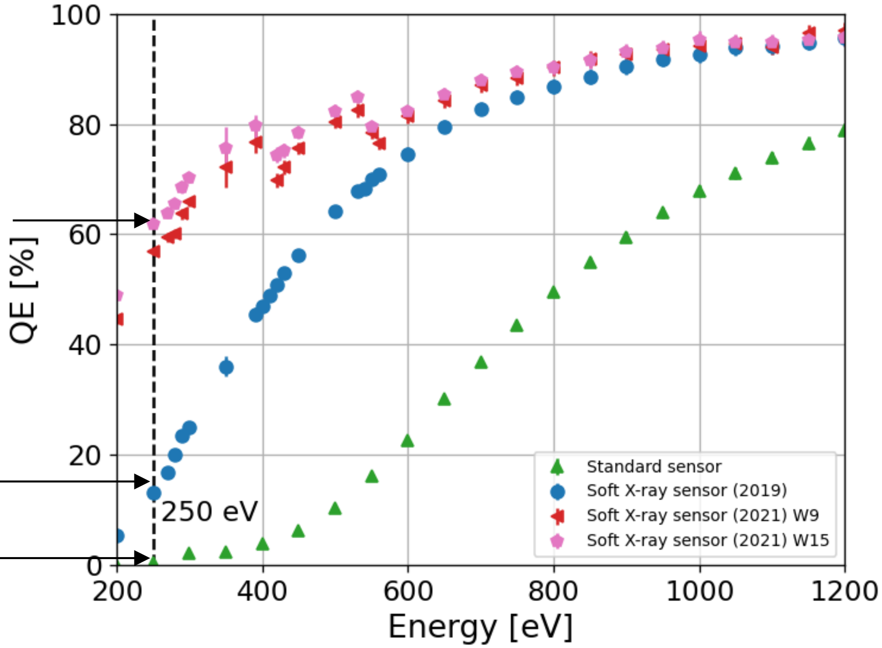


Quantum efficiency

Passivated interface

Al/Si interface

Std. sensor



Keys for high QE :

- Optimization of the n+
- Surface passivation

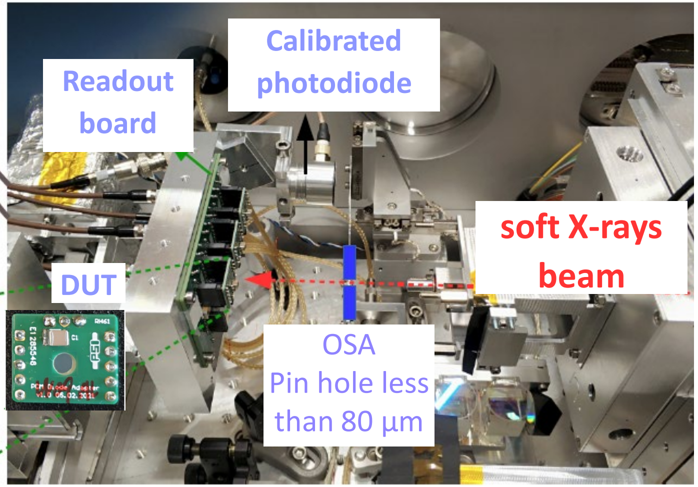
Internal QE close to 90 % -> X-ray absorbed in the passivation

M. Carulla *et al* 2023 *JINST* **18** C01073

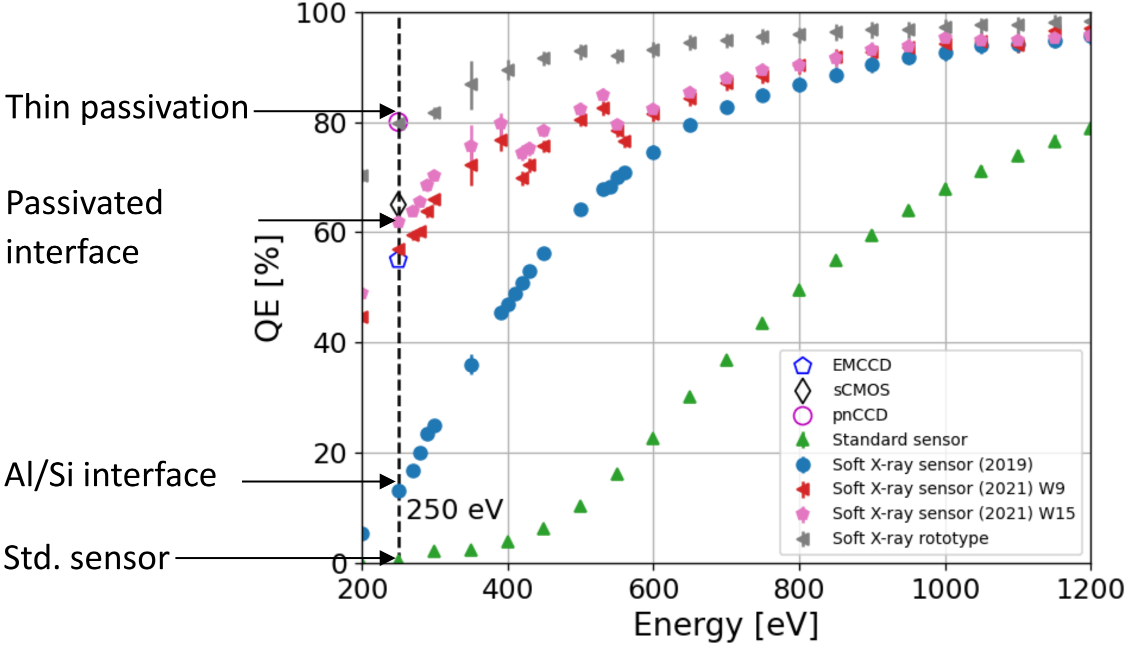
M. Carulla *et al* *Sensors* **2024**, *24*(3), 942; https://doi.org/10.3390/s24030942

QE improvement

Setup at the Surface/Interfaces Microscopy (SLS)



Quantum efficiency



Keys for high QE :

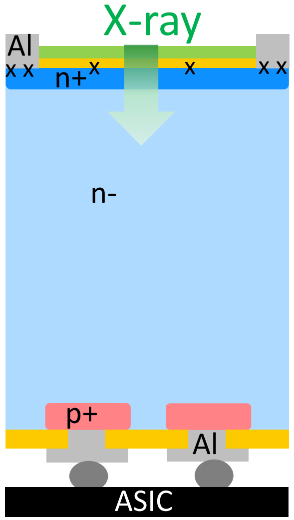
- Optimization of the n+
- Surface passivation
- Reduction of the passivation layer

QE = 80% (250 eV)

Development strategy

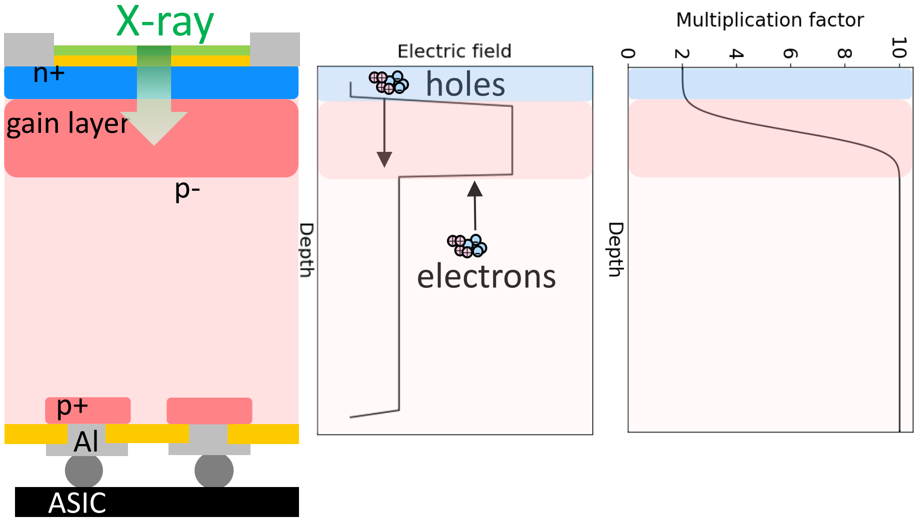
Thin entrance window technology

- Optimization of the n+
- Passivation of the surface



Inverse low-gain avalanche diode (iLGAD) technology

- Large electric field triggers impact ionization
- Gain depends on absorption depth
- Move gain layer to the surface



Depth dependence of gain in iLGADs

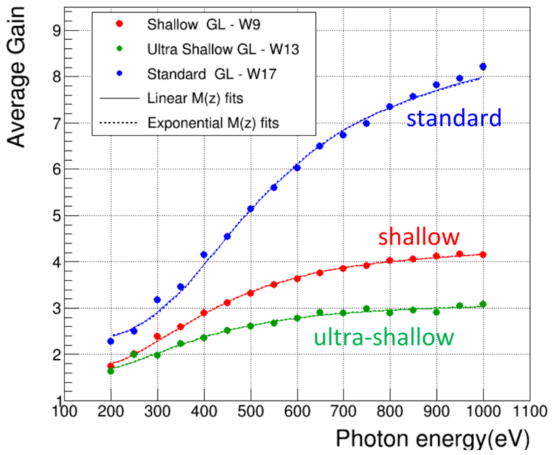
QE value equal to the TEW batch

- ~ 60 % for 250 eV photons

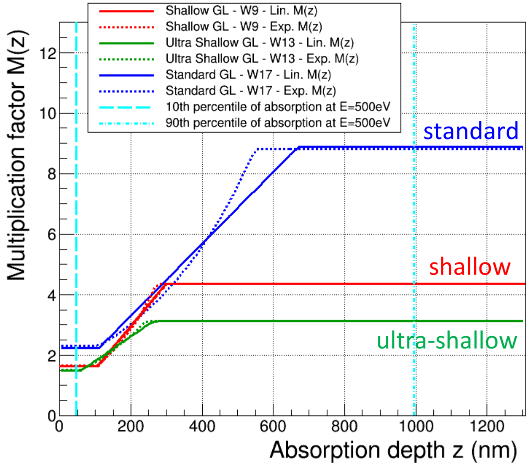
Averaged gain measured for different gain-layer designs

- standard, shallow and ultra-shallow gain-layer designs

Averaged gain *vs.* photon energy



Gain *vs.* absorption depth



Shallow

- Gain-layer ~ 300 nm
- Smaller ratio between Me/Mh
- Low Me gain due to not proper simulation model

A. Liguori *et al* 2023 *JINST* **18** P12006

https://doi.org/10.1088/1748-0221/18/12/P12006

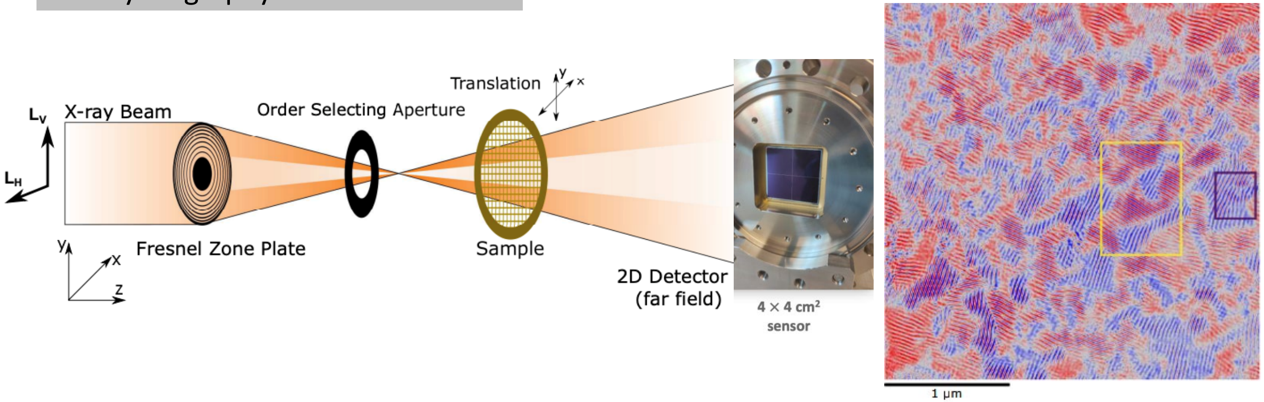
Single-photon counting with iLGADs

T= -30 C

Single-photon counting with Eiger and iLGADS @ SIM-SLS

- Eiger for soft X-rays (down to 500 eV)
- First user experiment using Eiger+ iLGAD for ptychography (User 😊)
- Dichroic contrast at Fe L_3 edge (712.5 eV) of $BiFeO_3$ thin film
- Improved resolution down to 6 nm (vs. 15 nm with Mönch + standard sensor)

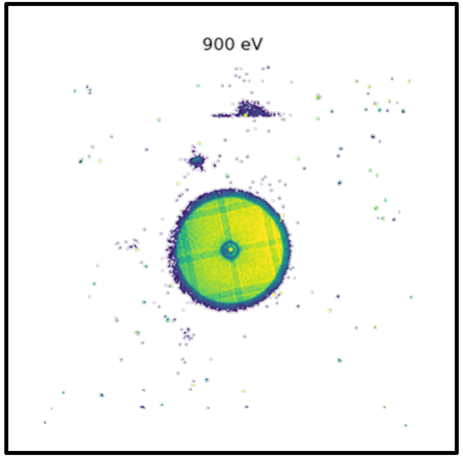
Ptychography EIGER + iLGAD



First user experiment using an iLGAD sensor where spin cycloids with 64 nm period were observed

T. A. Butcher, et al. Ptychographic Nanoscale Imaging of the Magnetoelectric Coupling in Freestanding BiFeO3. Adv. Mater. 2024, 2311157. https://doi.org/10.1002/adma.202311157

Diffraction pattern of FZP (900 – 200 eV)



* credit to Filippo Baruffaldi

Summary

TEW development:

- Important: reduction of concentration and depth of n+, passivation of the surface and thinning of the passivation
- QE was improved from 1% up to 62% (80% prototype) for 250 eV photons
- A new batch with further optimization of the passivation is expected in May

iLGAD development:

- Multiplication factor depends on the photon absorption depth
- The spectral response shows two peaks
- Single photon resolution down to 390 eV for standard and shallow design of the gain layer
- Optimizing the gain layer, the probability of photon absorbed after the gain layer is increased (shallow)
- Single-photon counting down to 500 eV
- Ptychography at 712.5 eV

Future work

New TEW batch:

- QE measurement next October
- Systematic study of the QE after irradiation

Current iLGAD batch:

- Study of the gain suppression effect.
- Study of the iLGAD response at high intensity.
- Systematic study of the noise and gain as a function of temperature, voltage, etc…

New iLGAD batch:

- Focus on the shallow design with a higher gain, higher yield and lower leakage current. Expected next year.

Acknowledgement

My thanks go to:

- M.Centis Vignali, F. Ficorella, G. Borghi, G. Paternoster, M.Boscardin, S. Ronchin, A. Bisht and O. Hammad Ali from FBK
- K.Vogelsang and C.Wild from LXN
- A. Kleibert, J. Raabe, S. Finizio and T. Butcher from the SLS.
- E. Razzoli from the SwissFEL.
- A. Liguori from University Bari

Photon Science Detector Group

Back: J. Zhang, A. Mozzanica, T. King, D. Mezza, A. Bergamaschi, J. Heymes; *Middle:* E. Fröjdh, C. Lopez, M. Brückner, C. Ruder, B. Schmitt, K. Moustakas, D. Greiffenberg; *Front:* V. Hinger, D. Thattil, R. Dinapoli, S. Hasanaj, M. Carulla, S. Ebner; Missing: R. Barten, B. Braham, K. Ferjaoui, P. Kozlowski, F. Baruffaldi, K. Paton, P. Sieberer and X. Xie