Characterization of charge integrating detectors with iLGAD sensors in the soft X-ray energy range

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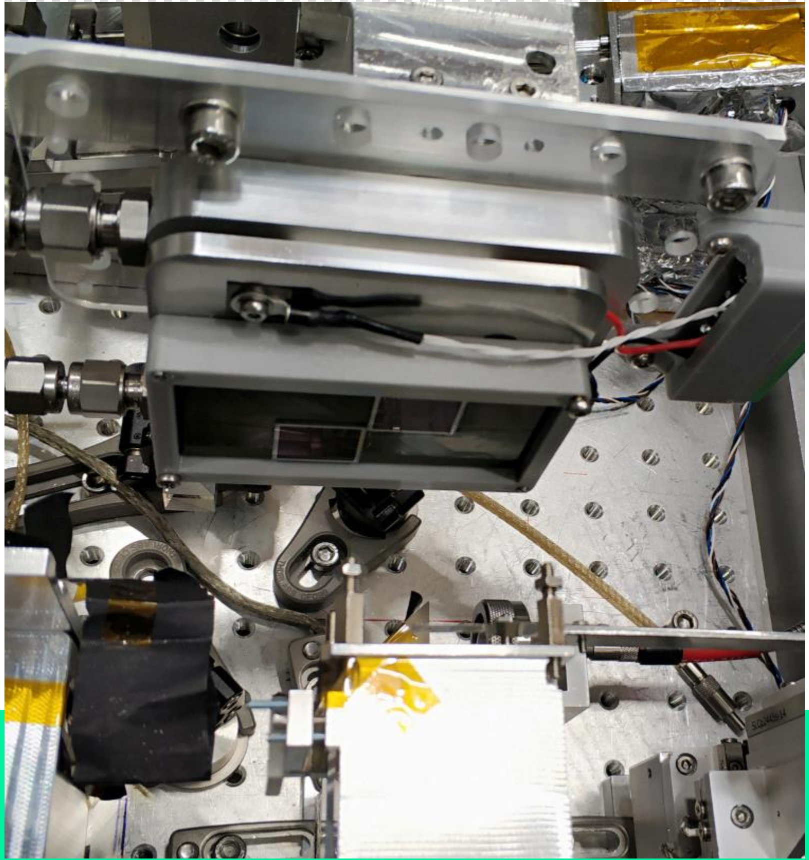
25th iWoRID, Lisboa, July 2, 2024



Outline

Hybrid pixel detectors for photon science

2D detectors for soft X-rays

Challenges for soft X-rays detection

Development Strategy

QE improvement

iLGADs for soft X-ray detection

Depth dependence of gain in iLGADs

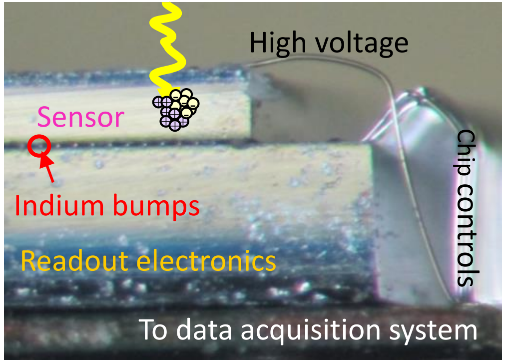
Single photon resolution

Comparison between gain layers

Paul Scherrer Institut

PSI

Hybrid pixel detectors for photon science



- ☺ Sensor and readout are optimised separately
- ☺ Direct conversion
- ☺ Highly parallelised readout -> High frame rate(> 2kHz)
- ☺ Large area (> 4 x 8 cm²) tileable
- ☹ Bump bonding limits pixel pitch
- ☹ Input capacitance increases the electronic noise

Single photon counting for synchrotons

- ☺ Counts
- ☺ Fluorescence rejection

SLS 2.0 →

Charge integrating for XFEL

- ☺ Large dynamic range
- ☺ High flux
- ☹ Calibration

Single photon resolution for soft X-rays

2D detectors for soft X-rays (200 eV to 2 keV)

PSI

L-edges of 3d transition metals

- Mn, Fe, Cu, …

K-edges light elements and 'water window'

- C, N, O, S, …

RIXS & TR-RIXS → V. Hinger's talk, July 4 at 12:20

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)

EMCCD

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

Scientific CMOS

- ☺ High QE (62% @ 250 eV)
- ☹ Limited area (~ 2 x 2 cm^2)
- 😕 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 cm^2) tiled
- 😕 Spatial resolution (< 5 µm*)
- 😕 Noise (~ 35 e^-)
- ☺ High frame rate(> 2kHz)

*Interpolation with Mönch (Hard X-rays)

Challenges for soft X-ray detection

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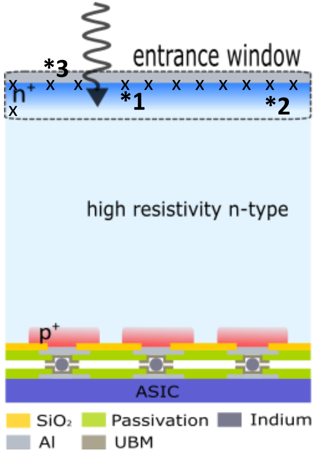
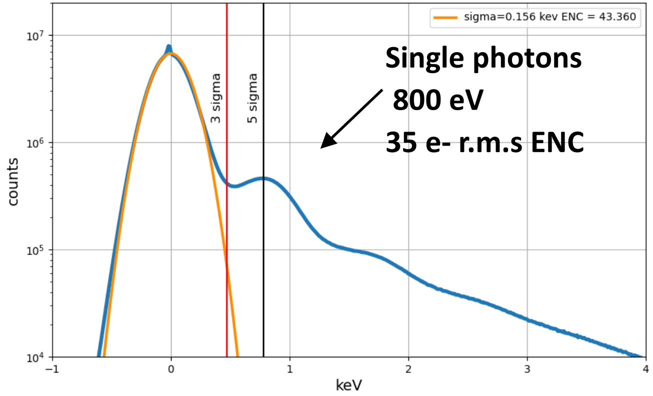
Low quantum efficiency

1. Auger recombination in n+ L_h=200nm
   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
- SNR > 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

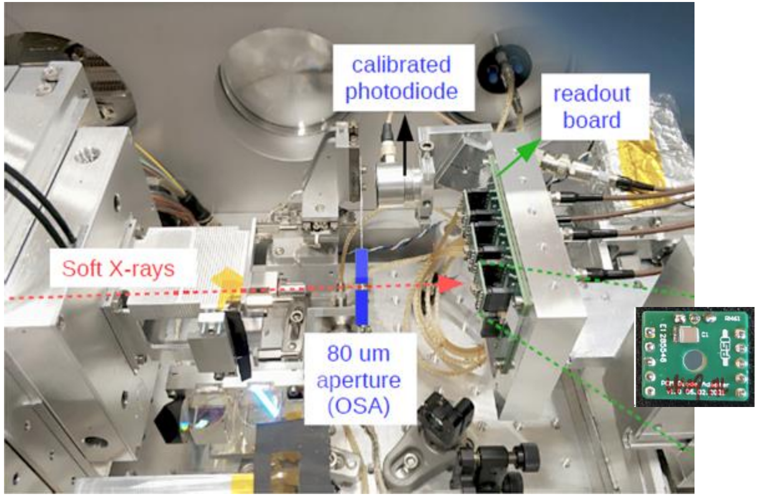
+

Increase the signal by internal multiplication
iLGAD technology

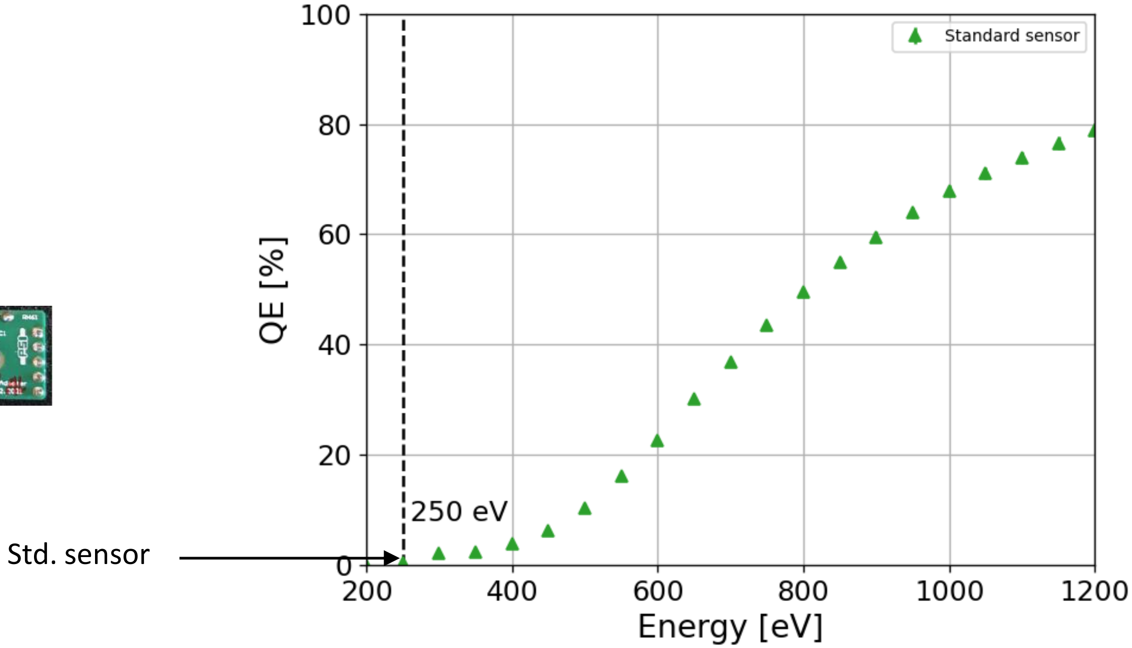
QE improvement

FONDAZIONE BRUNO KESSLER + PSI

Setup at the Surface/Interfaces Microscopy (SLS)



Quantum efficiency

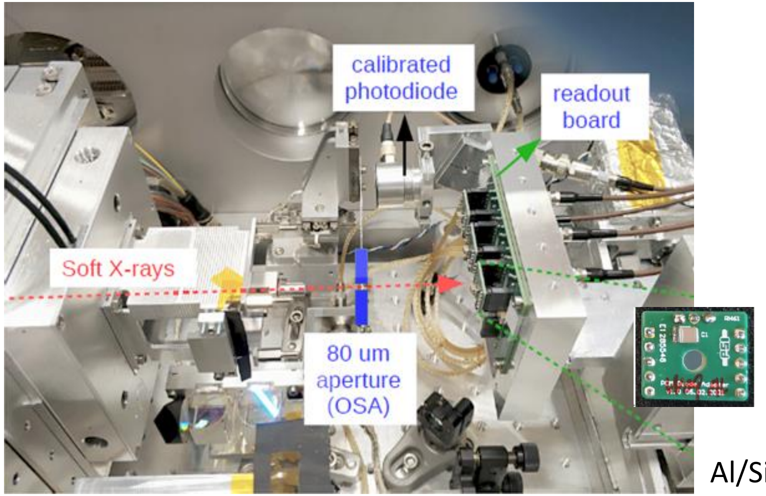


M. Carulla *et al Sensors* **2024**, *24*(3), 942; https://doi.org/10.3390/s24030942

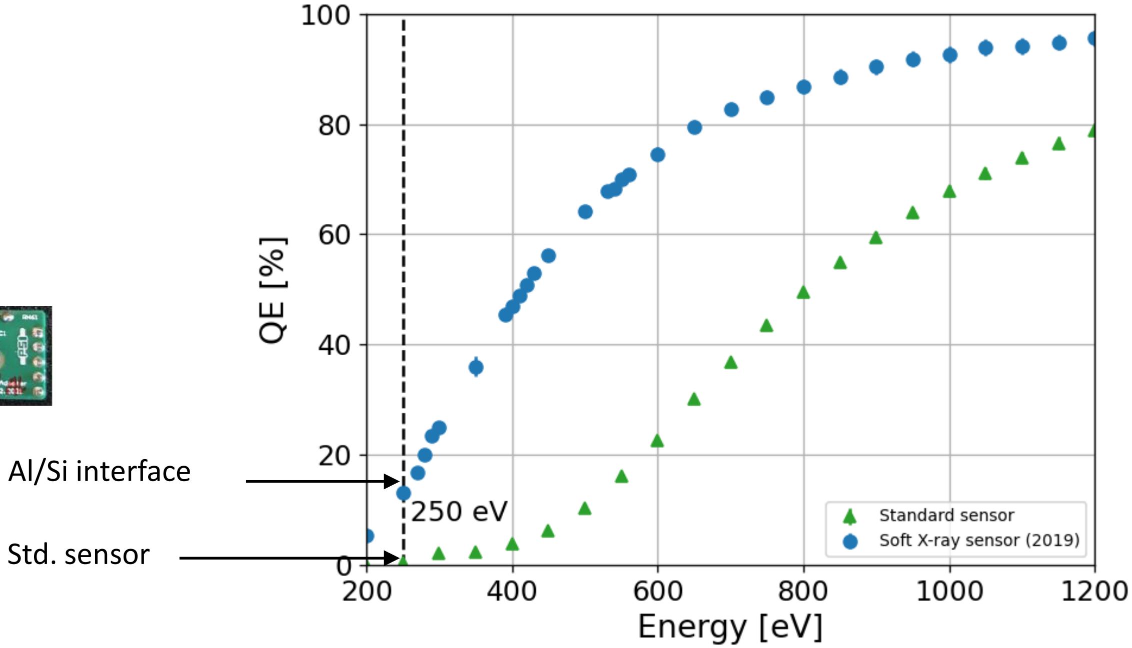
QE improvement

FONDAZIONE BRUNO KESSLER + PSI

Setup at the Surface/Interfaces Microscopy (SLS)



Quantum efficiency



Keys for high QE :

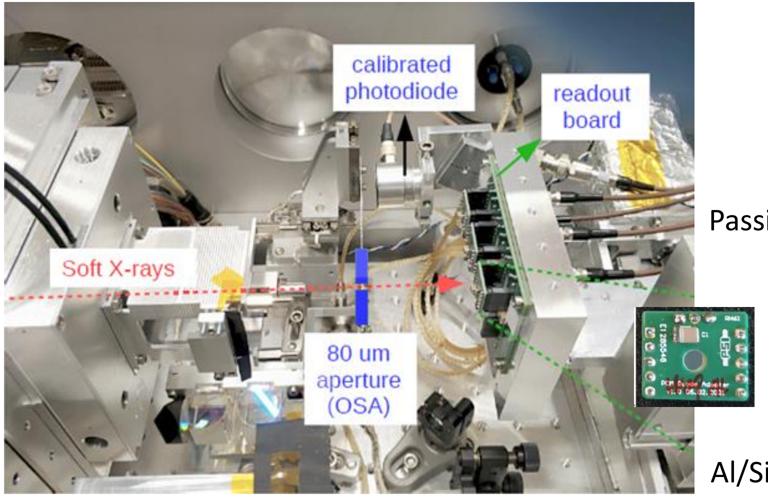
- Optimization of the n+

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

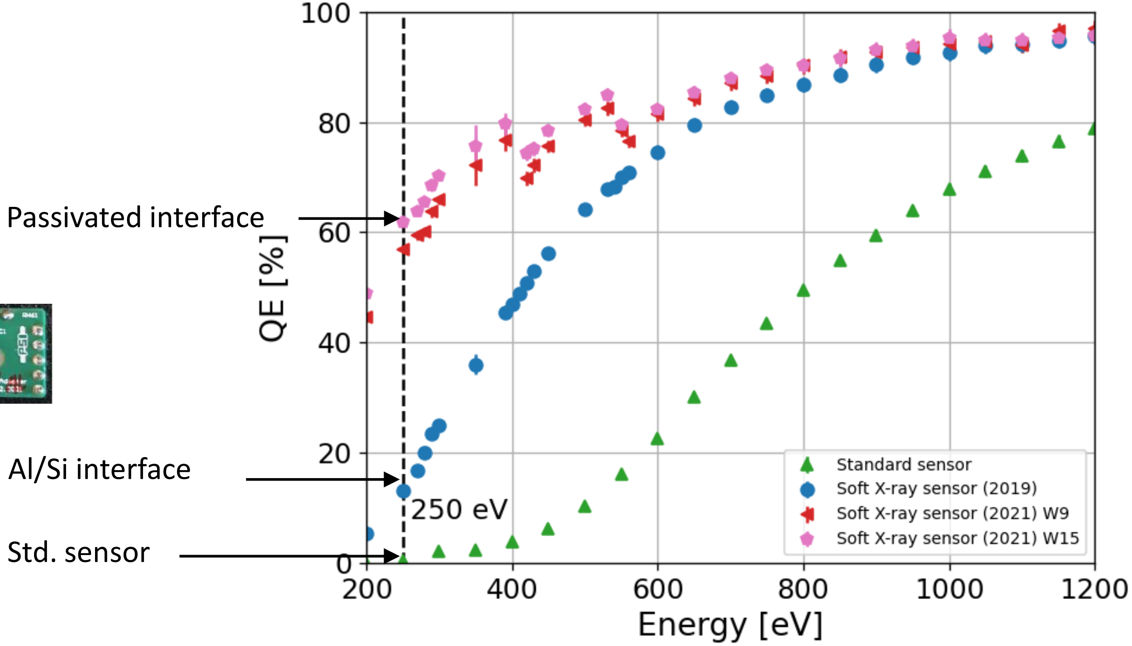
QE improvement

FONDAZIONE BRUNO KESSLER + PSI

Setup at the Surface/Interfaces Microscopy (SLS)



Quantum efficiency



Keys for high QE :

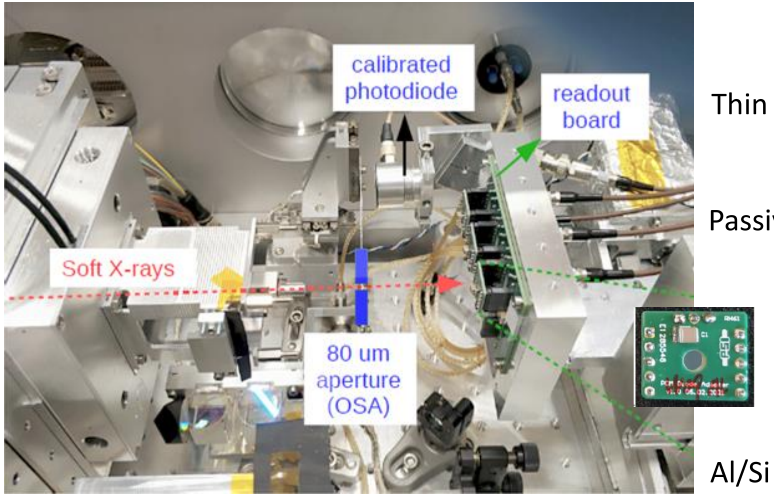
- Optimization of the n+
- Surface passivation

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

QE improvement

FONDAZIONE BRUNO KESSLER + PSI

Setup at the Surface/Interfaces Microscopy (SLS)



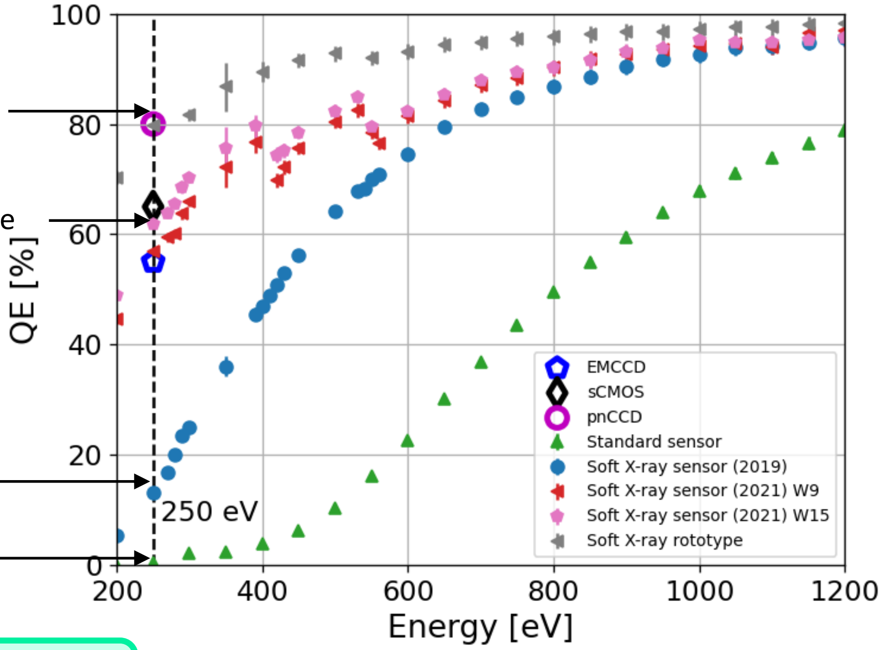
Quantum efficiency

Thin passivation

Passivated interface

Al/Si interface

Std. sensor



Keys for high QE :

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

QE = 80% (250 eV)

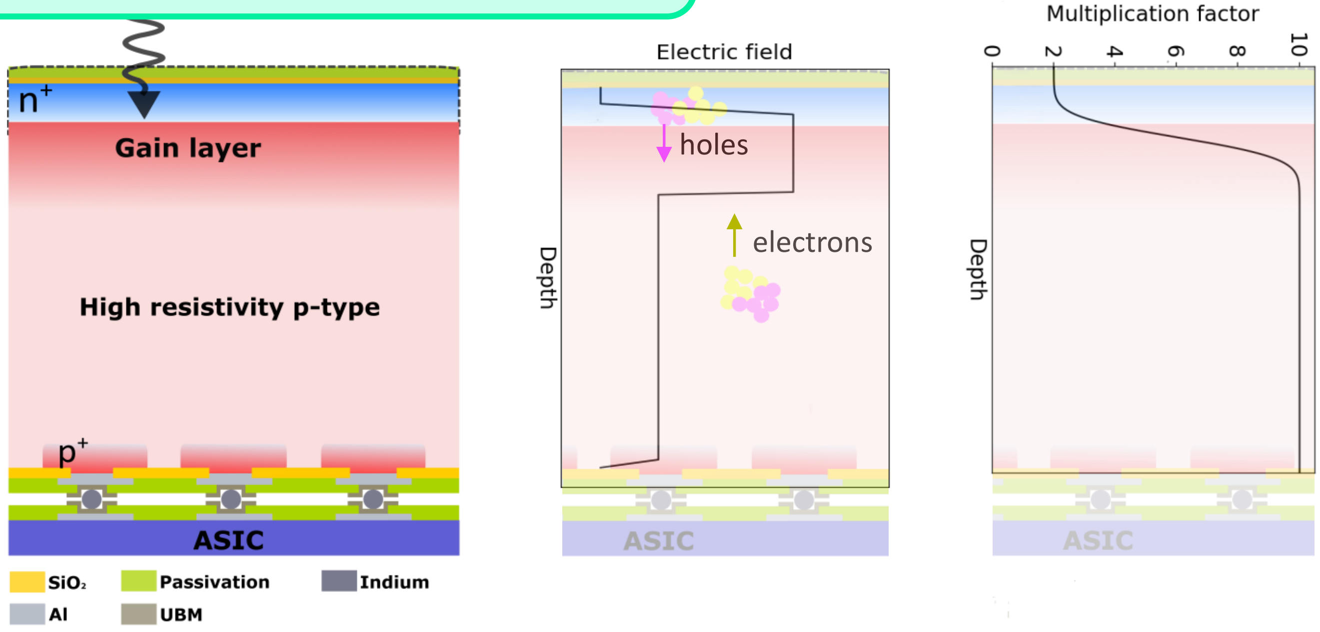
M. Carulla *et al Sensors* **2024**, *24*(3), 942; https://doi.org/10.3390/s24030942

iLGADs for soft X-ray detection

FONDAZIONE BRUNO KESSLER + PSI

Inverse low-gain avalanche diode (iLGAD) technology

- Large electric field triggers impact ionization
- Gain depends on absorption depth

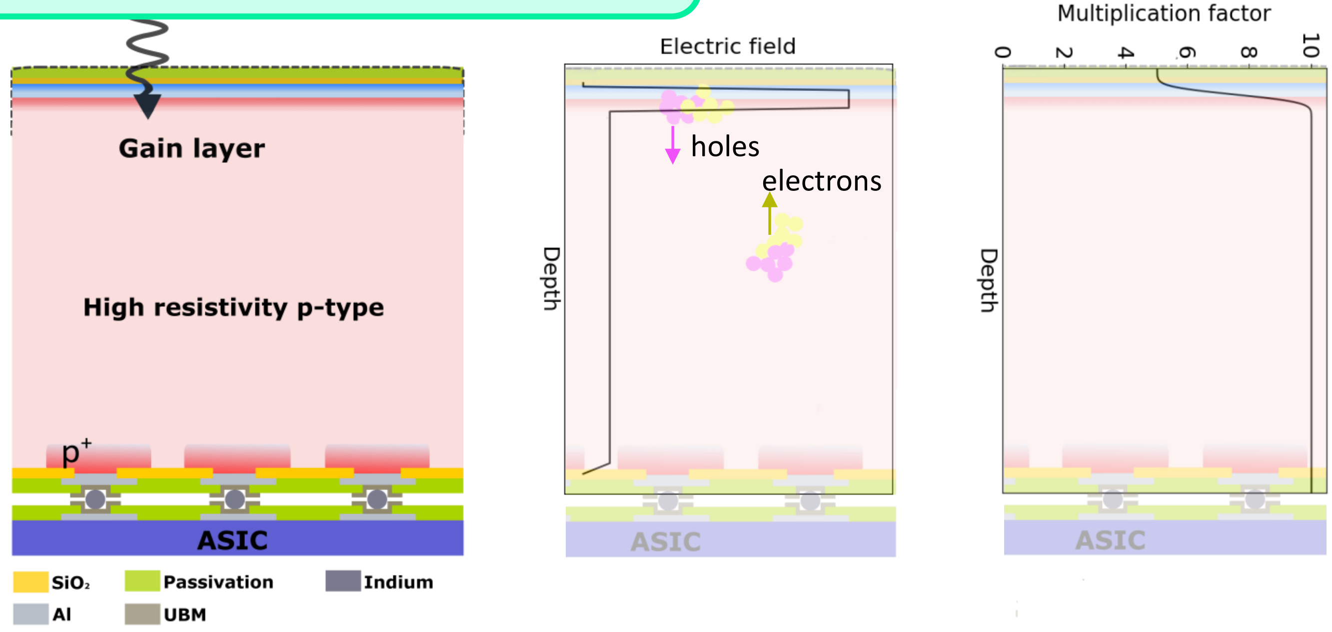


iLGADs for soft X-ray detection

FONDAZIONE BRUNO KESSLER + PSI

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

FONDAZIONE BRUNO KESSLER + PSI

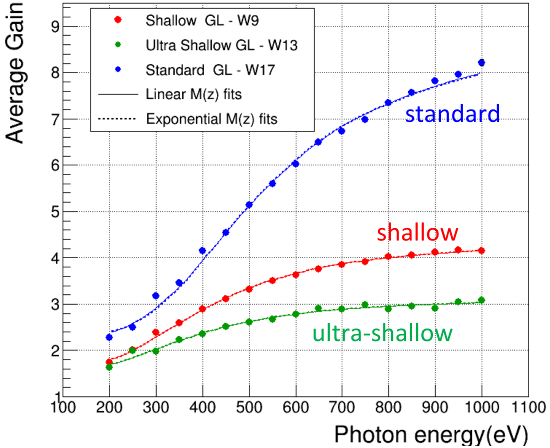
QE value equal to the TEW batch

- ~ 60 % for 250 eV photons

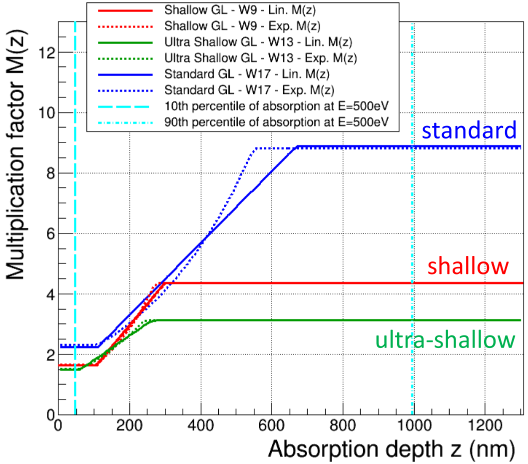
Averaged gain measured for different gain-layer designs

- 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 an overestimation of the impact ionization coefficients

A. Liguori *et al* 2023 *JINST* **18** P12006
https://doi.org/10.1088/1748-0221/18/12/P12006

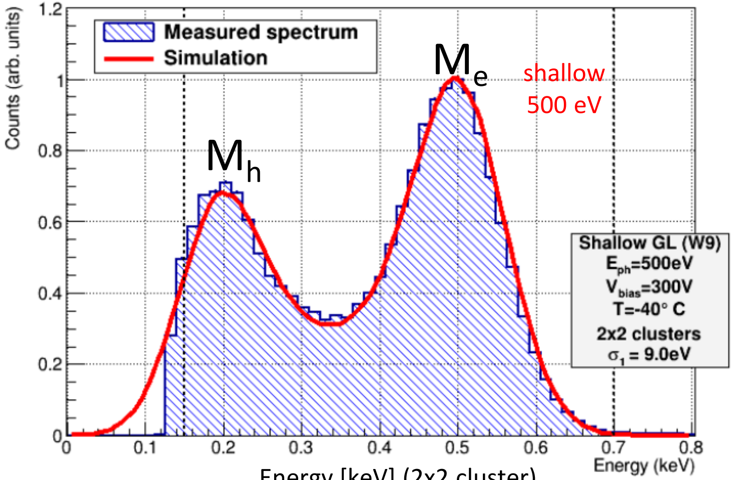
Depth dependence of gain in iLGADs

FONDAZIONE BRUNO KESSLER + PSI

Monte-Carlo simulation of charge drift, diffusion and multiplication

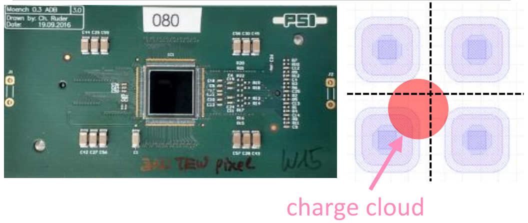
- Mönch (25 µm pitch) with Shallow gain-layer design
- Photon energy 500 eV
- Cluster 2x2

Simulation vs. measurement



Energy [keV] (2x2 cluster)

Mönch front-end + iLGAD



- Two peaks M_e and M_h
- M_e X-ray is absorbed after the gain layer (G ↑)
- M_h X-ray is absorbed before the gain layer (G ↓)

Antonio Liguori *et al* 2023 *JINST* **18** P12006
https://doi.org/10.1088/1748-0221/18/12/P12006

Single photon resolution

FONDAZIONE BRUNO KESSLER + PSI

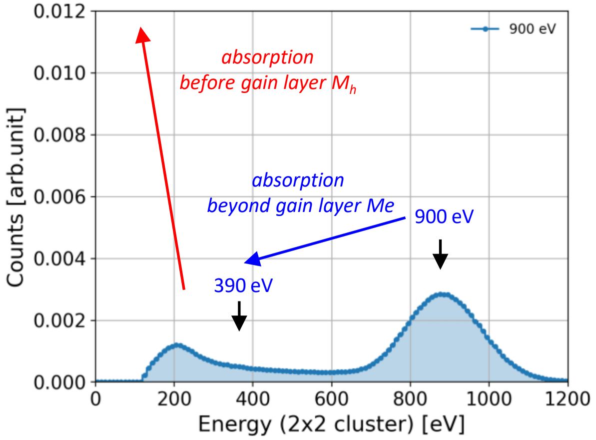
T= -40 °C

iLGAD measurement @ SIM (SLS):

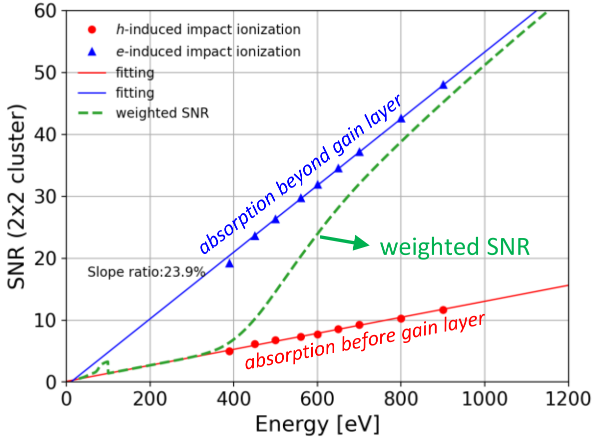
- Photon energies: 390 eV to 900 eV
- Standard gain-layer design
- Temperature ↓ ⟶ Leakage current ↓Gain ↑
- Photon energy ↓ ⟶ M_e counts ↓ M_h counts ↑

V. Hinger et al, Front. Phys., 28 February 2024
Sec. Radiation Detectors and Imaging
Volume 12 - 2024 | https://doi.org/10.3389/fphy.2024.1352134

Spectral response (standard)



Signal-to-noise ratio



- Single photon resolution (E > 390 eV)
- Two peaks (Me and Mh)
- Weighted SNR -> SNRh (E < 500 eV)
- Requires 2x gain @ 250 eV

Comparison between gain layers

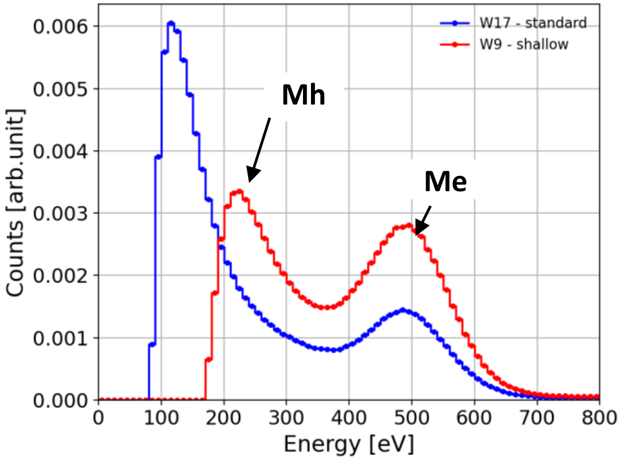
FONDAZIONE BRUNO KESSLER + PSI

T= -40 °C

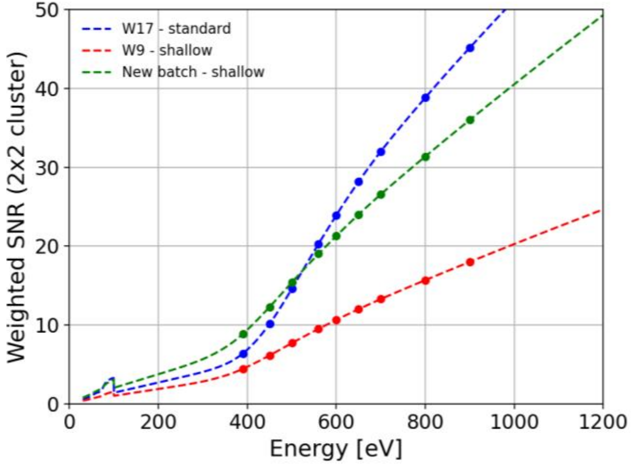
iLGAD measurement @ SIM (SLS):

- Standard and shallow gain-layer designs (500 eV)
- Shallow design shows large # of count for M_e
- Weighted SNR (shallow), gain needs to be increased by a factor of 2 (like standard)

Spectral response (standard and shallow)



Signal-to-noise ratio (SNR)



- *Higher # counts in Me (shallow)*
- *Similar effective SNR (E < 350eV)*
- *Next R&D Shallow design with x2 gain*

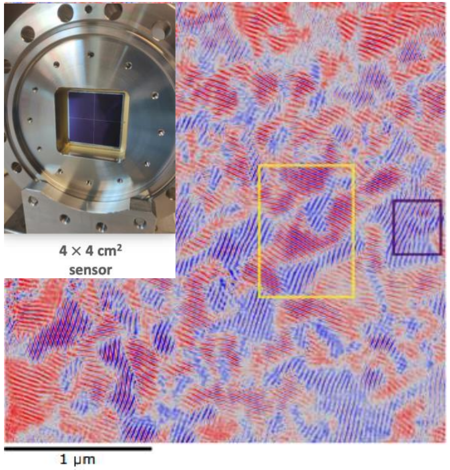
Summary and Outlook

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 optimisation of the passivation is expected in October
- Systematic study of the QE after irradiation

iLGAD development for soft X-rays:

- The spectral response shows two peaks
- Single photon resolution down to 390 eV for standard and shallow design of the gain layer
- Shallow design shows a higher probability of photon absorbed after the gain layer
- First user experience of Eiger+iLGAD to study $BiFeO_3$ thin film. Spin cycloids ->64 nm period.
- Study of the gain suppression effect. Jiaguo's poster in Session 2 (ID: 141) July 3, 14:00 - 15:10
- Study of the iLGAD response at high intensities.
- Next iLGAD batch, SPC and CI + iLGAD detectors with single photon resolution (E>250 eV)



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

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- Colleagues from FBK
- K.Vogelsang and C.Wild from LXN
- A. Kleibert, J. Raabe, S. Finizio and T. Butcher from the SLS.
- A. Liguori from University Bari
- Two of the authors (V. Hinger and K. A. Paton) have received funding from MSCA PSI-FELLOW-III-3i (EU grant agreement No. 884104)

Postdoc positions open:

LGAD **ASIC**

Photon Science Detector Group

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

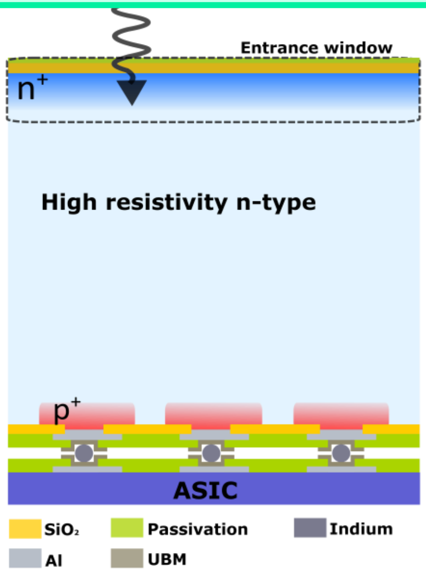
Backup

Development strategy

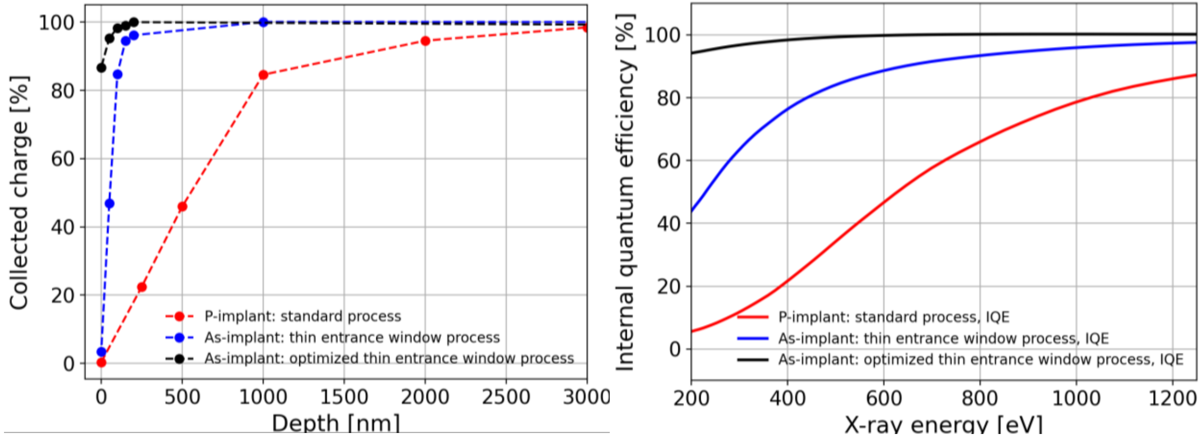
FONDAZIONE BRUNO KESSLER + PSI

Thin entrance window technology

- Optimization of the n+
- Passivation of the surface



TCAD simulation of the process and device

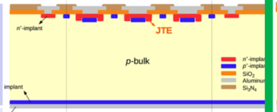
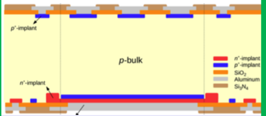
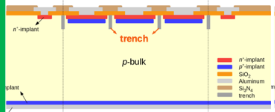
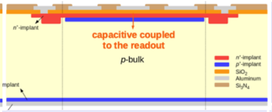


Internal QE larger than 90 %

J. Zhang *et al* 2022 *JINST* **17** C11011
https://doi.org/10.1088/1748-0221/17/11/C11011

LGAD technologies

PSI

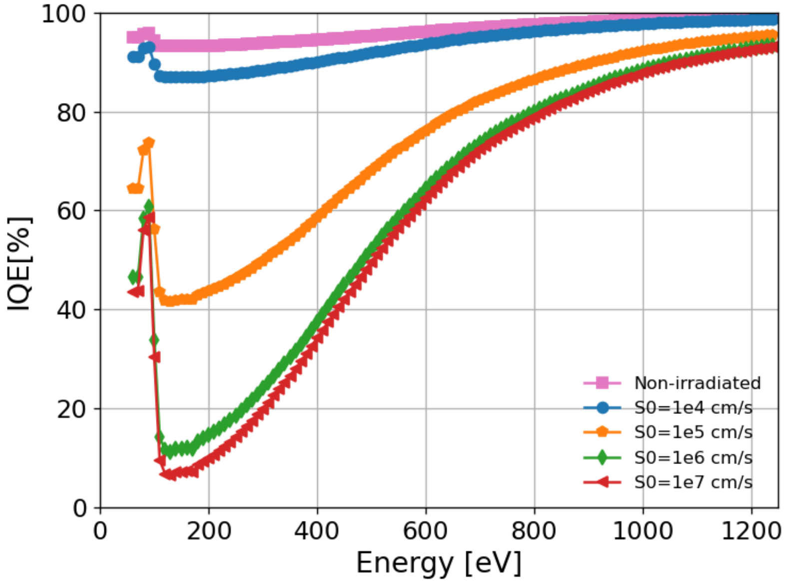
	LGAD	inverse-LGAD (iLGAD)	trench-isolated LGAD (TI-LGAD)	AC-coupled LGAD (AC-LGAD)	deep junction LGAD (DJ-LGAD)	ideal LGAD
cross section						?
process*	standard	double-sided	stepper	standard	epi-growth	standard
complexity	low	low	medium	high	high	low
collected charge	e^-	h^+	e^-	e^- (bipolar)	e^-	e^- 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

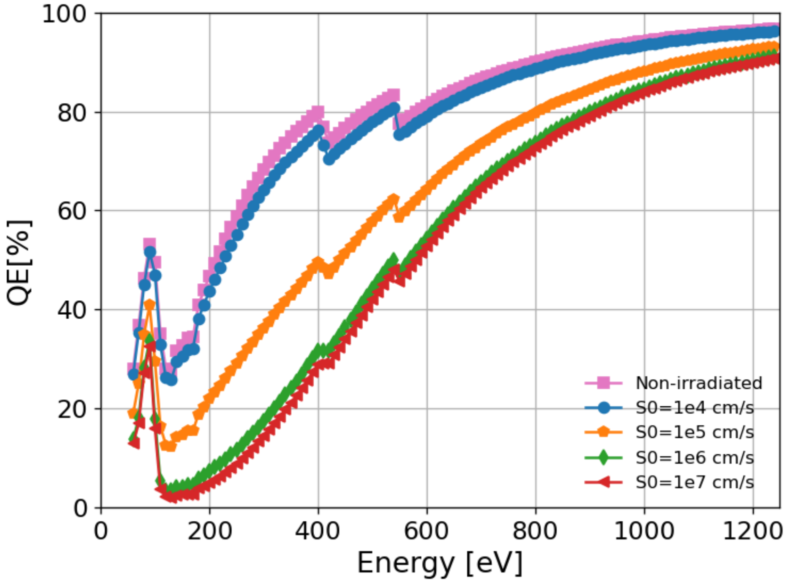
development @ PSI & FBK

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

IQE and QE after irradiation

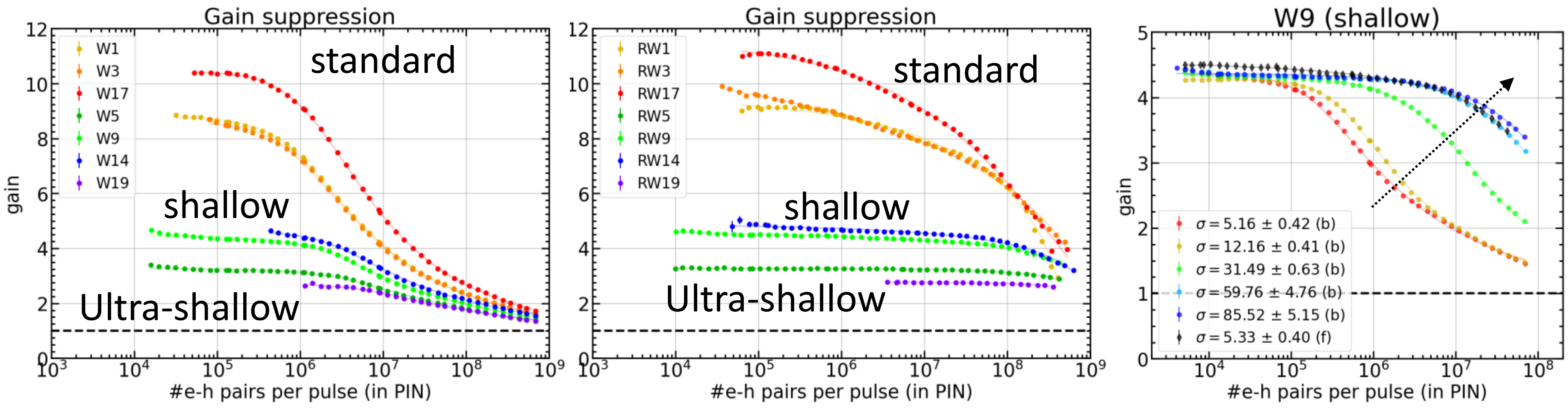
S0 saturates to 1e4 cm/s





Gain suppresion

- Red laser (660 nm), repetition rate (5 MHz), Beam σ ~ 4 µm
- Observed gain suppression for front(gain layer) and back (pixel) side illumination
- Gain suppression depends on :
  - Beam intensity and size (# e-h pairs per pulse and density)
  - Charge-carrier density at the gain layer
  - Gain layer design and multiplication factor



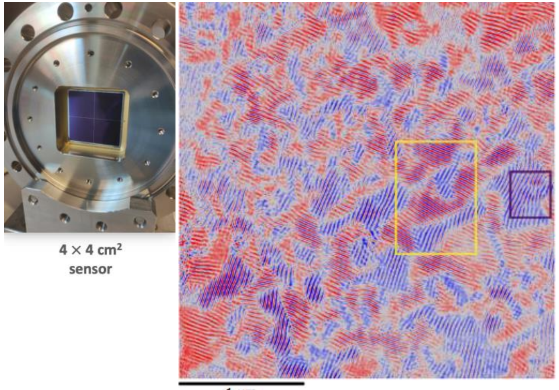
Photon science with iLGADs

PSI

EIGER (single-photon counting) + iLGADS @ SIM-SLS

- EIGER+ iLGAD for ptychography (User friendly 😊)
- 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



T= -30 C

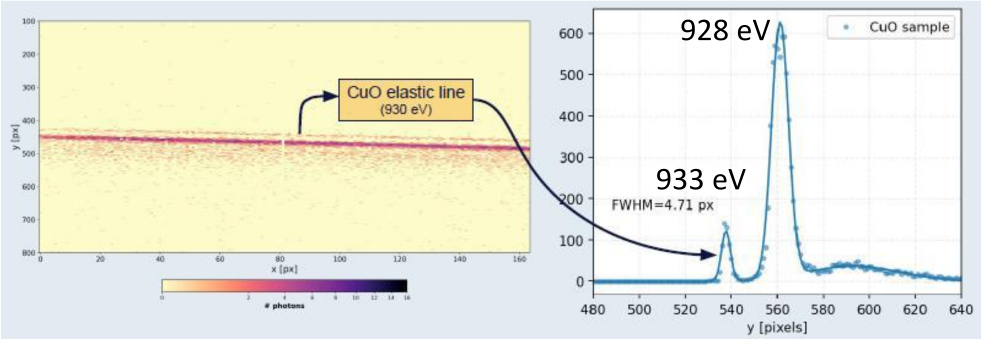
First user experiment using an iLGAD sensor where spin cycloids with 64 nm period were observed

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

JUNGFRAU(charge integrating) + strixel iLGADS @ EuXFEL

- JUNGFRAU+ iLGAD for RIXS

T= -30 C



Energy

Development strategy

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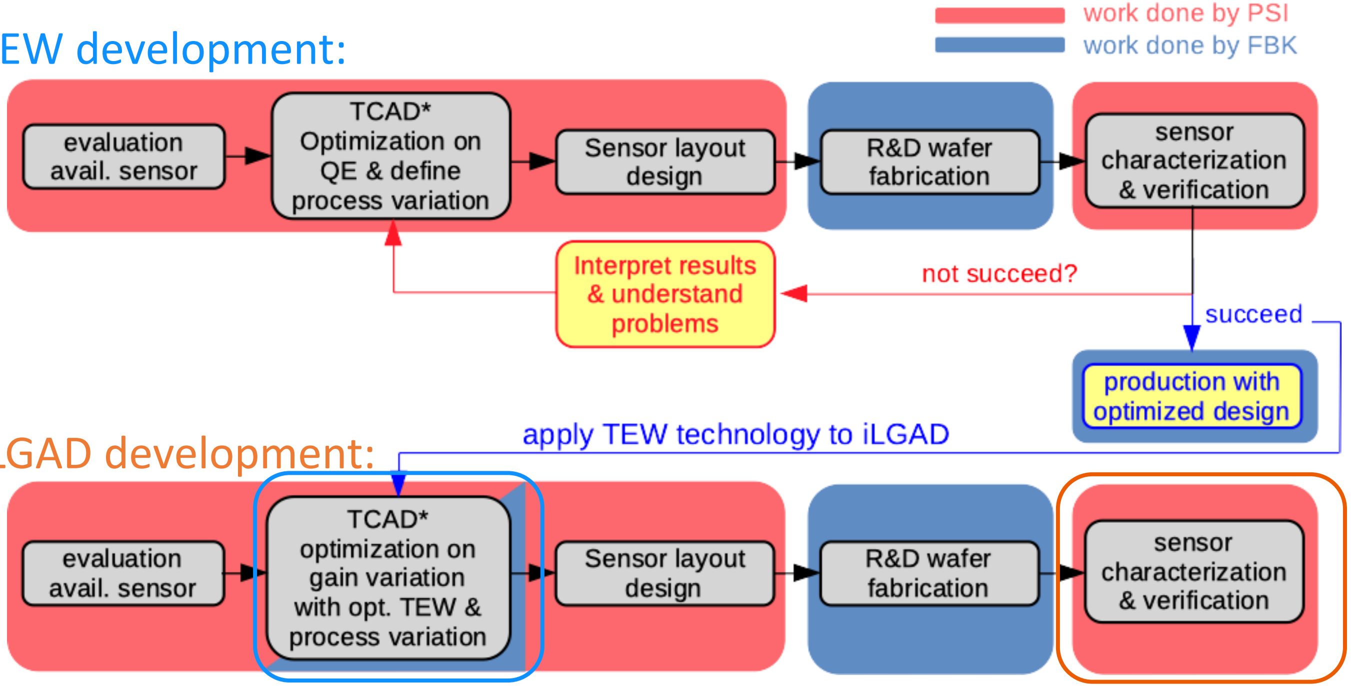
Two developments for hybrid detectors towards soft X-rays:

- Thin entrance window (TEW) process
- iLGADs optimised for soft X-rays

PAUL SCHERRER INSTITUT PSI + FBK FONDAZIONE BRUNO KESSLER

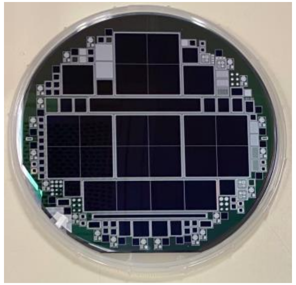
TEW development:

iLGAD development:



6-inch TEW wafers 2021

6-inch iLGAD wafers 2022



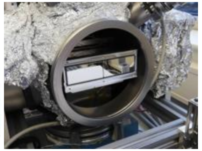
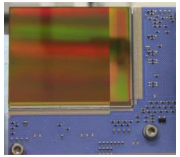
* TCAD: Technology Computer-Aided Design, 1 development cycle → 1 year

commercial | Facility / institute driven development

Parameter	Andor iXon Ultra 888 (EMCCD)	Andor Neo 5.5 sCMOS	Princeton Instruments PIXIS 1024BR (CCD)	Hamamatsu ORCA-Fusion (CMOS)	pnCCD (PNSENSOR)	DSSC (EuXFEL)	PERCIVAL (DESY)	Hybrid X-ray detector (PSI, Jungfrau)
Quantum Efficiency (QE) @250 eV	55% (400 nm UV)	70% (400 nm UV)	< 42% (400 nm UV)	65% (400 nm UV)	80%	52%	90%	80%
Read Noise (e-)	< 1	1.4	4-10	1.4	10.5 (hg)	40-60 (miniSDD) 10 (DEPFET)	16	3 - 5 (LGAD)
Frame Rate (FPS)	26	30 (full frame) 100 (burst)	< 2	< 100	< 100	4.5 MHz (burst)	< 120	2 - 10 k
Dynamic Range (e^-)	80 k	30 k	100 k	15 k	1.6 M	1.1 M	3.5 M	3.44 M (gain=10)
Pixel Size (µm)	13 x 13	6.5 x 6.5	13 x 13	6.5 x 6.5	75 x 75	204 x 236	27 x 27	75 x 75 15 x 375
Pixels	1024 x 1024	2560 x 2160	1024 x 1024	2304 x 2048	512 x 1024	128 x 256	1484 x 1408	512 x 1024
Sensor Area (mm^2)	13.3 x 13.3	16.6 x 14.0	13.3 x 13.3	14.9 x 13.3	38.4 x 76.8 (2 side buttable)	30 x 62 (tiable)	40 x 38	38.4 x 76.8 (tilable)






Interpolation with iLGADs

PSI

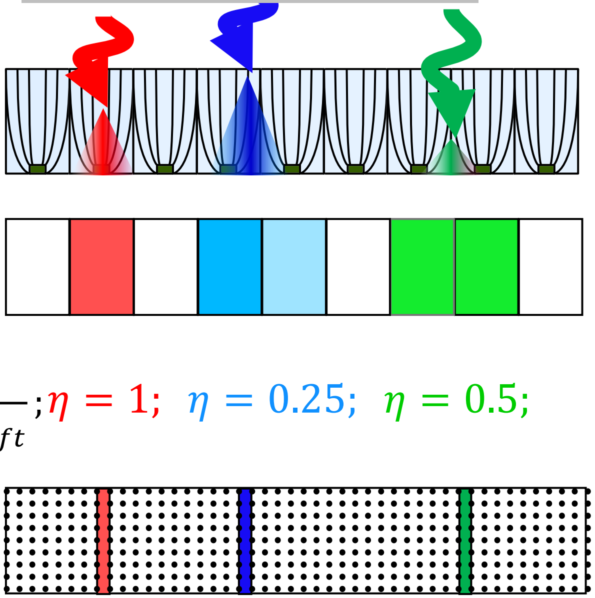
T= -40 C

Soft X-ray interpolation @ POLLUX (SLS)

○25 um pitch Mönch + iLGAD sensor (shallow)

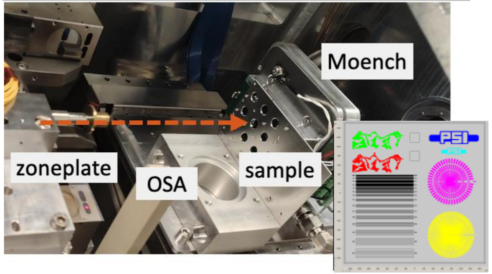
○Demonstr… n @ 500eV

Charge sharing and interpolation

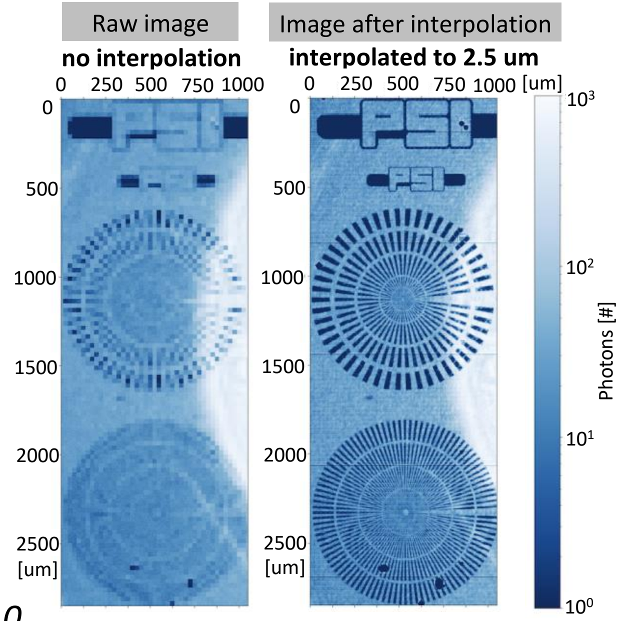


$$\eta = \frac{Q_{right}}{Q_{right} + Q_{left}}; \eta = 1; \ \eta = 0.25; \ \eta = 0.5;$$

Transmission image unfocused beam

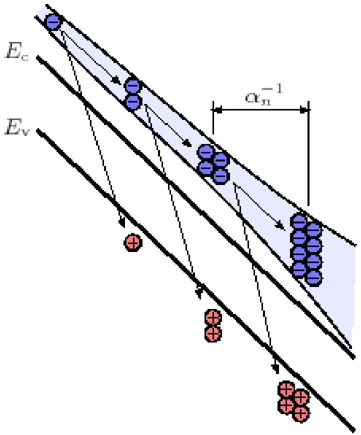


Sample prepared by X-ray Optics group



* *Important for RIXS experiments at SwissFEL and SLS-2.0*

Impact ionization



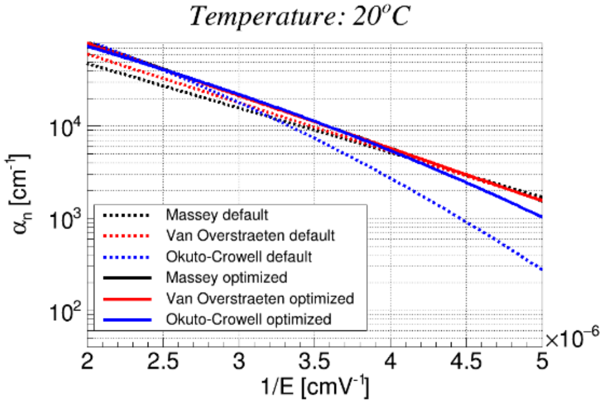
Pure electron started impact ionization

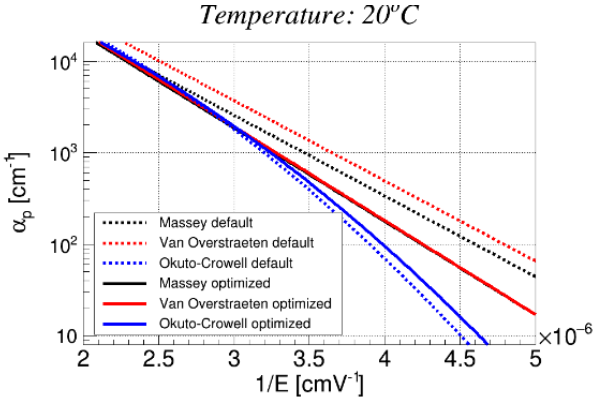
O. Triebl, "Reliability Issues in High-Voltage Semiconductor Devices"

Massey: $$\alpha_{n,p}(E,T) = A_{n,p}\, exp\left(-\frac{C_{n,p} + D_{n,p}T}{E}\right)$$

Van Overstraeten: $$\alpha_{n,p}(E,T) = \gamma\, A_{n,p}\, exp\left(-\gamma\frac{B_{n,p}}{E}\right) \qquad \gamma = \frac{\tanh\frac{\hbar\omega_{op}}{2kT_0}}{\tanh\frac{\hbar\omega_{op}}{2kT}}$$

Okuto-Crowell: $$\alpha_{n,p}(E,T) = A_{n,p}\left(1 + (T-300)C_{n,p}\right)E \times exp\left[-\left(\frac{B_{n,p}\left(1+(T-300)D_{n,p}\right)}{E}\right)^2\right]$$





Currás Rivera and Moll (*IEEE Trans. Electron Devices 2023* ***70*** *2919–2926*)

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