PAUL SCHERRER INSTITUT

FONDAZIONE BRUNO KESSLER

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

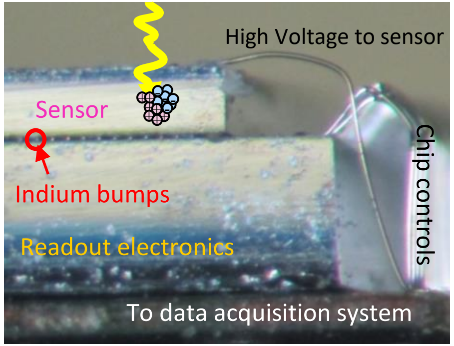
Soft X-ray detection with single photon resolution using LGAD sensors

19-23 June 2023 :: High Precision X-Ray Measurements 2023 :: Frascati :: Italy

* On behalf of Photon Science Detector group and FBK collaboration

Photon science detector group

Photon counting and charge integrating hybrid detectors: (Aldo's talk on Thursday at 12)

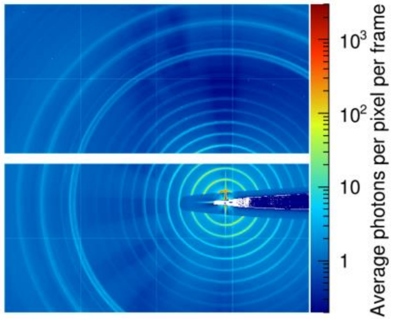


Hybrid detectors:
- Material and process optimized separately

Performance:
- **2-40 kframes/s**
- High dynamic range
- Large area
- High efficiency for $\mathbf{E_{ph} > 1.2\ keV}$

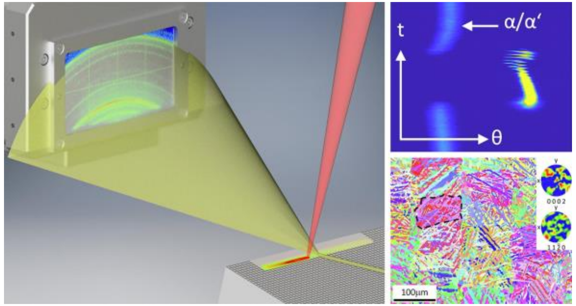
Applications

Powder diffraction



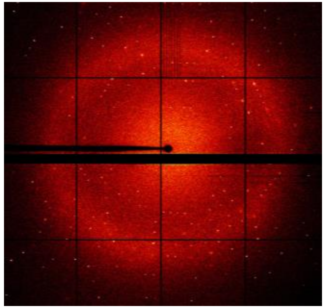
C.J. Milne *Appl. Sci.* **2017**, *7*(7), 720; https://doi.org/10.3390/app7070720

Operando diffraction



Hocine et al.; Materials today, **2020**; https://doi.org/10.1016/j.mattod.2019.10.001

Macromollecular crystallography



Leonarski et al.; Nature methods, **2018**; https://doi.org/10.1038/s41592-018-0143-7

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Single photon resolution of soft X-rays

Soft X-rays (200 eV – 1.2 keV):

- Energy between K-edges of C and O: polymers, organic electronics, aerosols, and biological materials
- L-edges of 3d transition metals: cuprate, Mott insulators and ferromagnetic and antiferromagnetic materials

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Our goal is to optimize the sensors of our hybrid detector to achieve single photon resolution for soft X-rays

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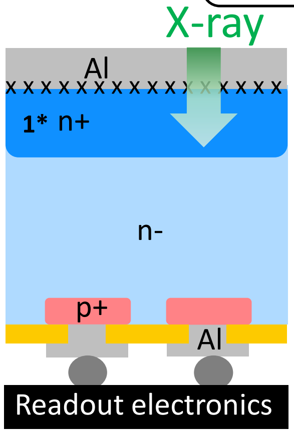
Low quantum efficiency



1. Recombination in the n+ region,
   L_h = 200 nm

Single photon resolution of soft X-rays

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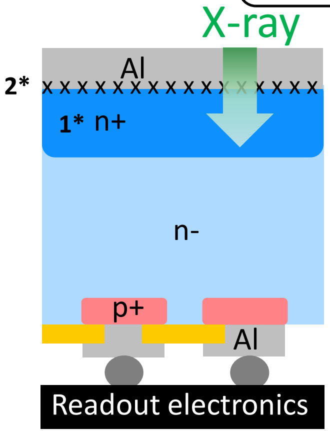

1. Recombination in the n+ region, L_h = 200 nm
2. Recombination velocity at Si/Al interface is 10^7 cm/s due to interface traps

Single photon resolution of soft X-rays

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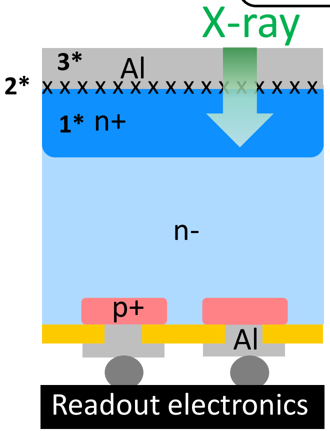

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3. Absorption in the surface layers

Reduce losses in the entrance window

Single photon resolution of soft X-rays

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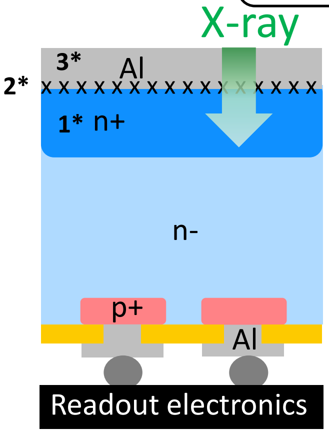

1. Recombination in the n+ region, L_h = 200 nm
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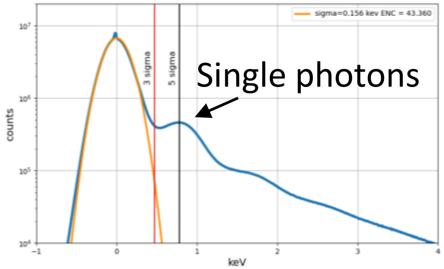
Low signal-to-noise ration



*V. Hinger et al 2022 JINST **17** C09027*

- At least a SNR of 5 is required to achieve single photon resolution
- Just 55 e-h pairs are created for 200 eV photons giving a SNR of 1.3

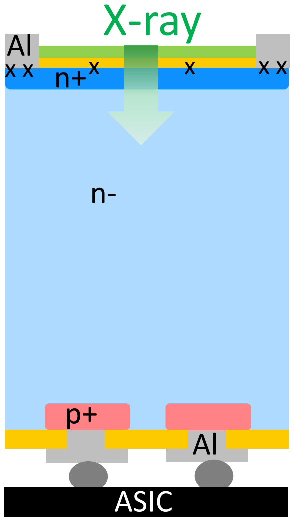
Reduce losses in the entrance window + Increase the signal by internal multiplication

Development of two technologies

In collaboration with Fondazione Bruno Kessler, we developed two optimized technologies for soft X-rays detection

Entrance window technology

- Optimization of the n+
- Passivation of the surface



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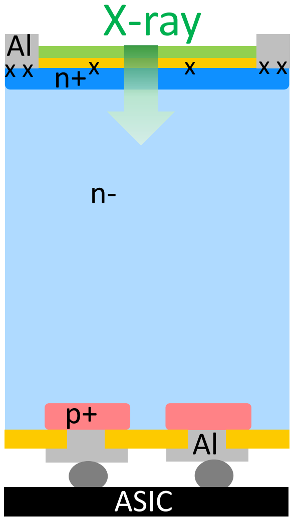
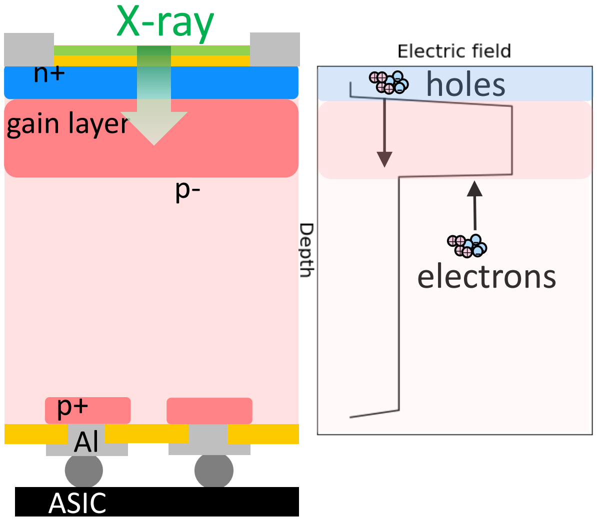
Inverse low gain avalanche diode (iLGAD) technology

- Large electric field to trigger impact ionization





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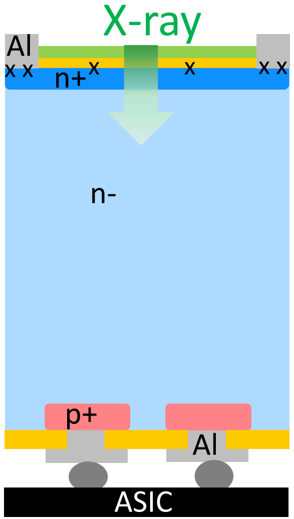
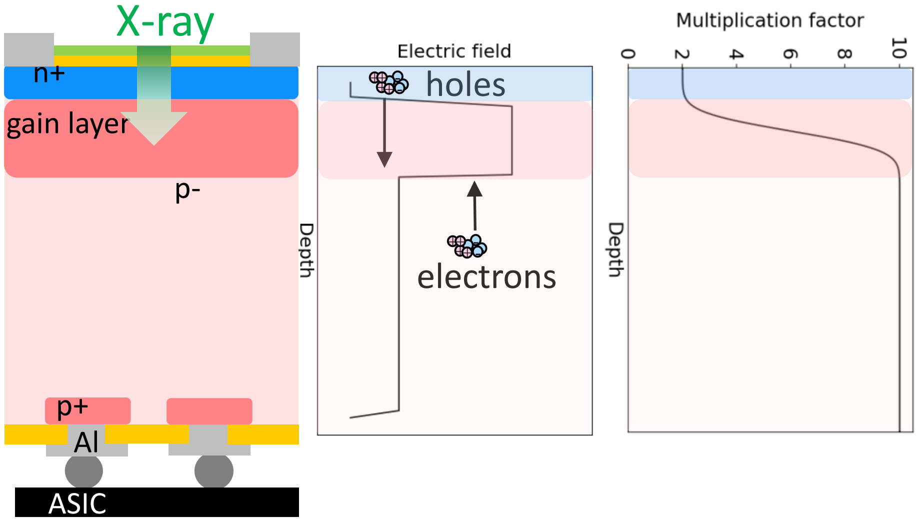


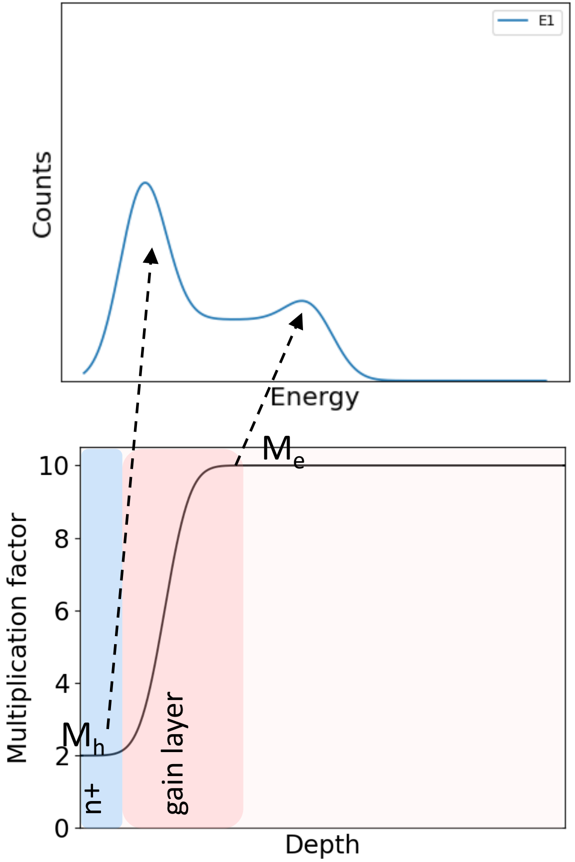
Inverse low gain avalanche diode (iLGAD) technology

- Large electric field to trigger impact ionization
- Multiplication factor depends on absorption depth
- Optimization of the gain layer

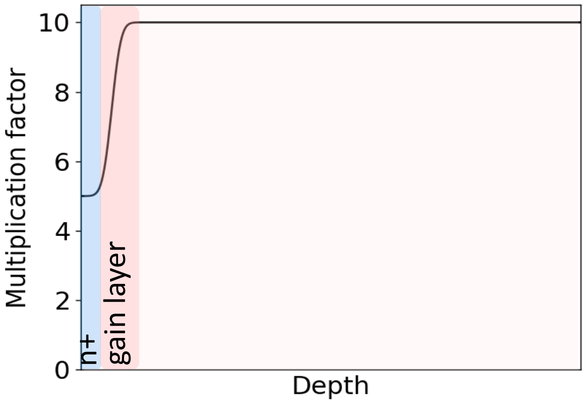


Optimization gain layer

<u>Standard</u>



<u>Ultra-shallow</u>



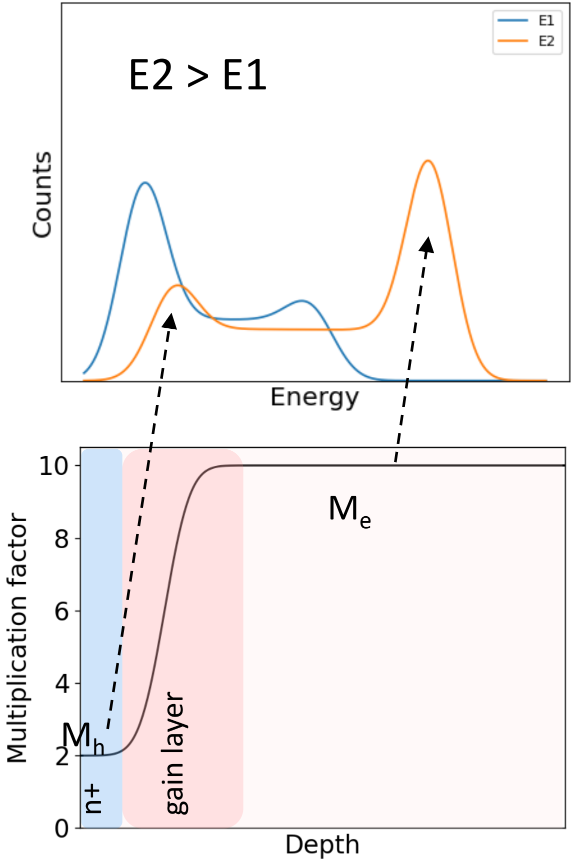
- Spectrum with two peaks

Standard design:

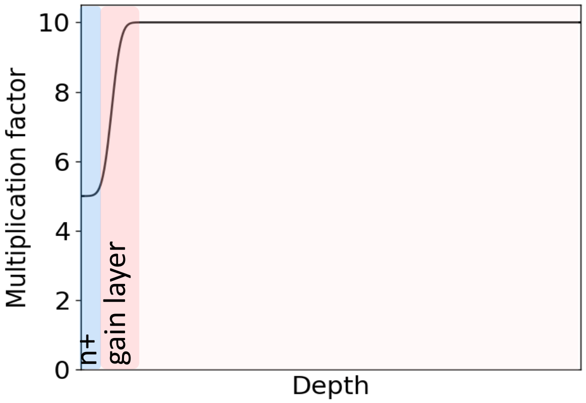
- At low energies high probability for hole started impact ionization

Optimization gain layer

Standard



Ultra-shallow

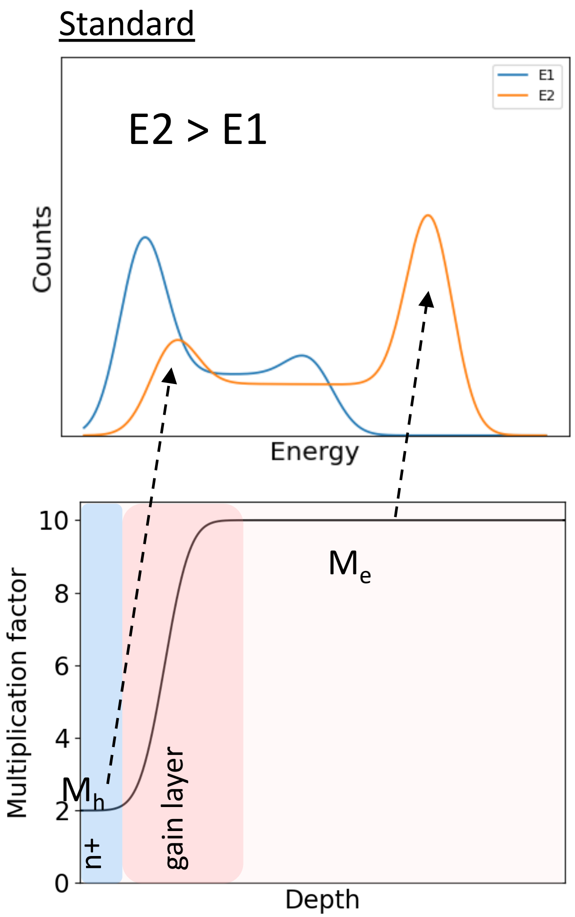


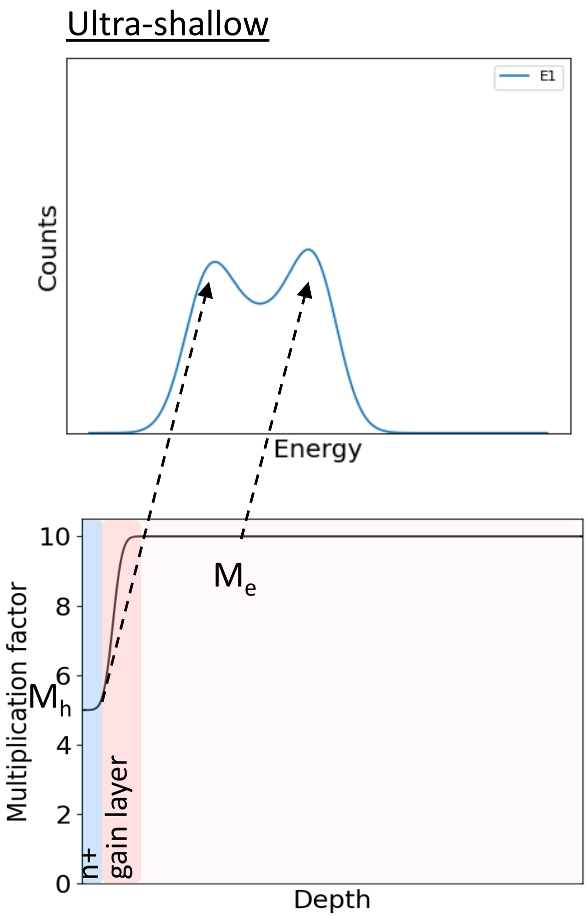
- Spectrum with two peaks

Standard design:

- At low energies high probability for hole started impact ionization
- At high energies, high probability for electron started impact ionization

Optimization gain layer





- Spectrum with two peaks

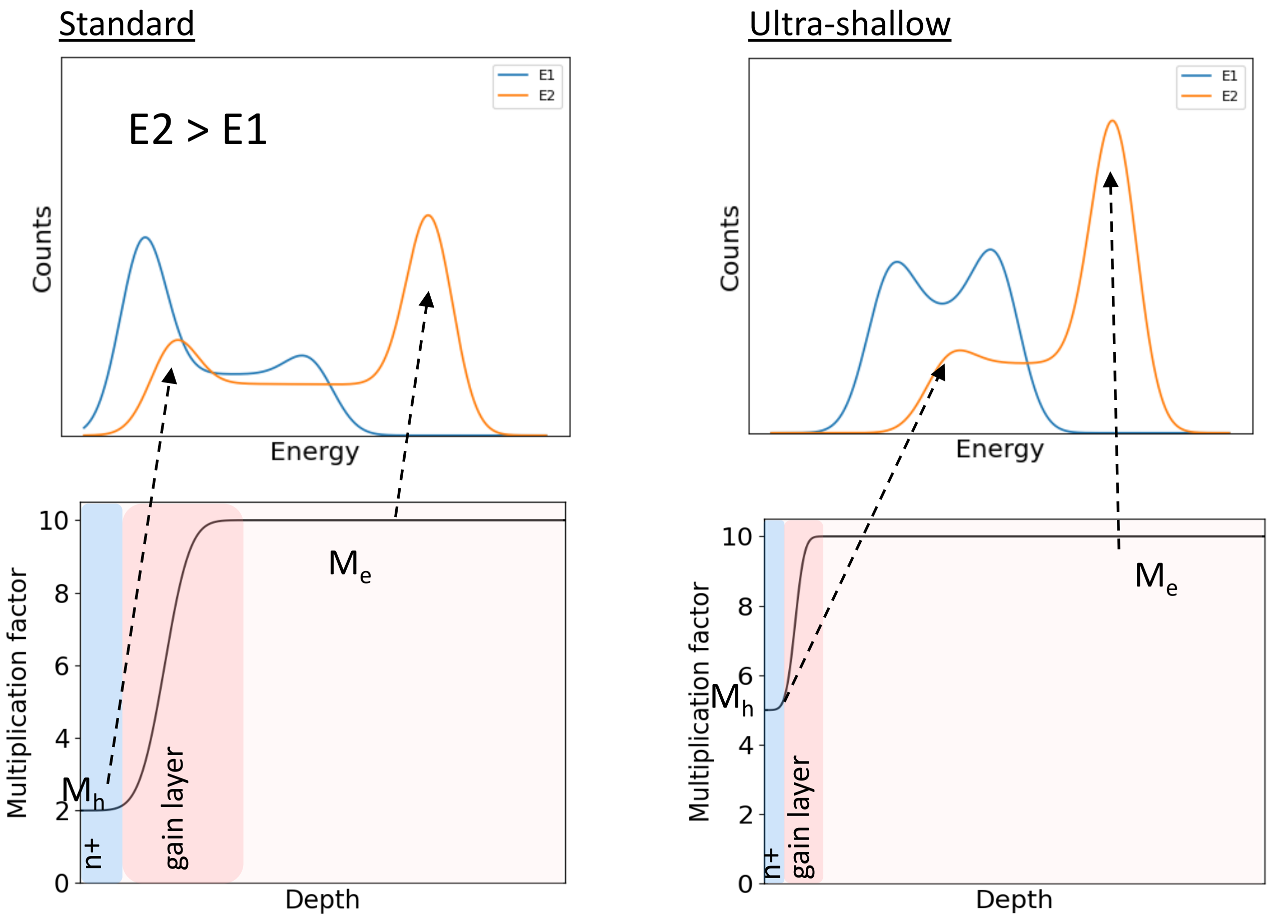
Standard design:

- At low energies high probability for hole started impact ionization.
- At high energies, high probability for electron started impact ionization.

Ultra-shallow design:

- At low energies the probability for electron started impact ionization is larger

Optimization gain layer



- Spectrum with two peaks

Standard design:

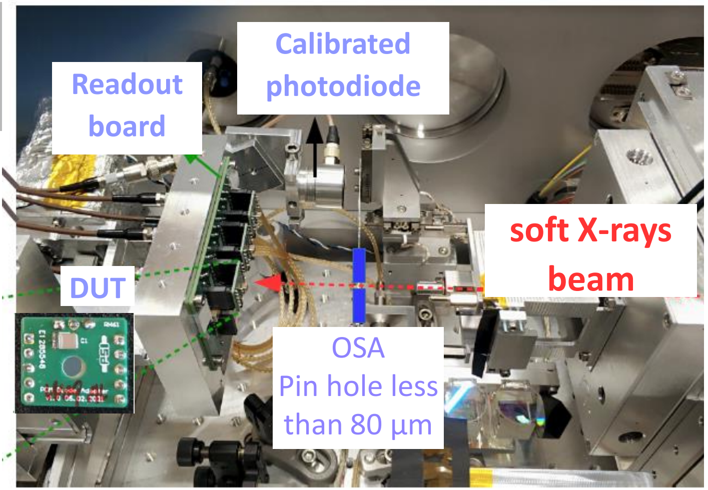
- At low energies high probability for hole started impact ionization.
- At high energies, high probability for electron started impact ionization.

Ultra-shallow design:

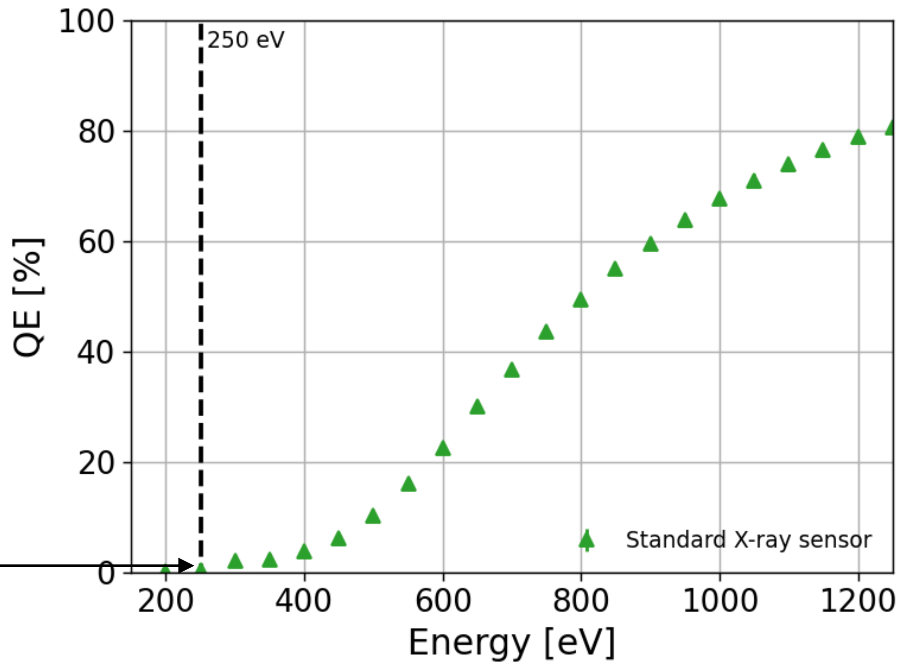
- At low energies the probability for hole started impact ionization is larger
- Design with high electric field in small region
- Difference between M_h and M_e is smaller.

Efficiency of the entrance window technology

Setup at the Surface/Interfaces:Microscopy @ SLS



Quantum efficiency



Std. sensor

Efficiency of the entrance window technology

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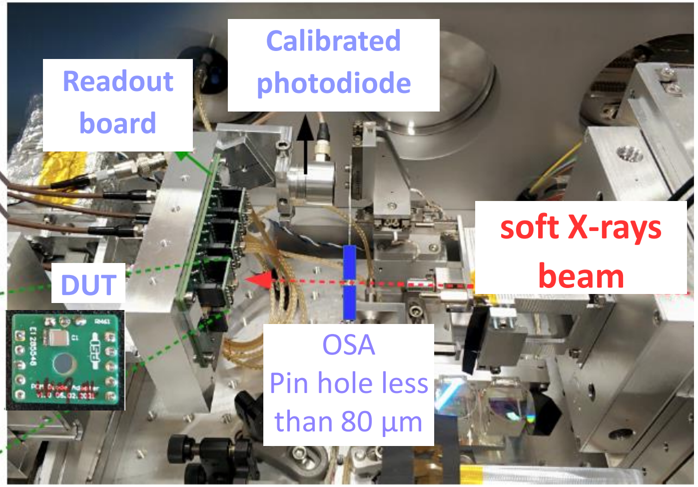
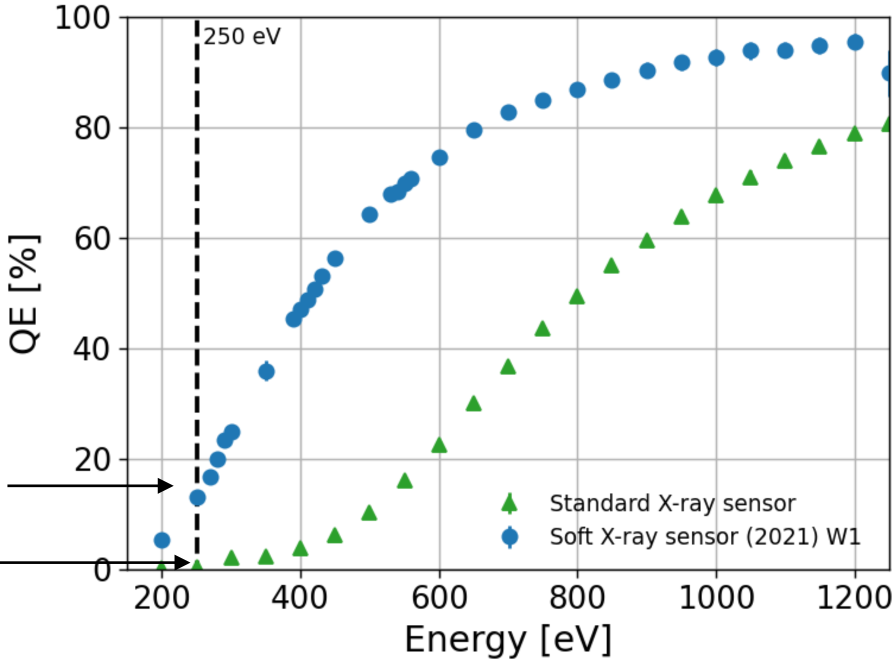


Quantum efficiency



Al/Si interface

Std. sensor

Keys for high QE :

- Optimization of the n+

Efficiency of the entrance window technology

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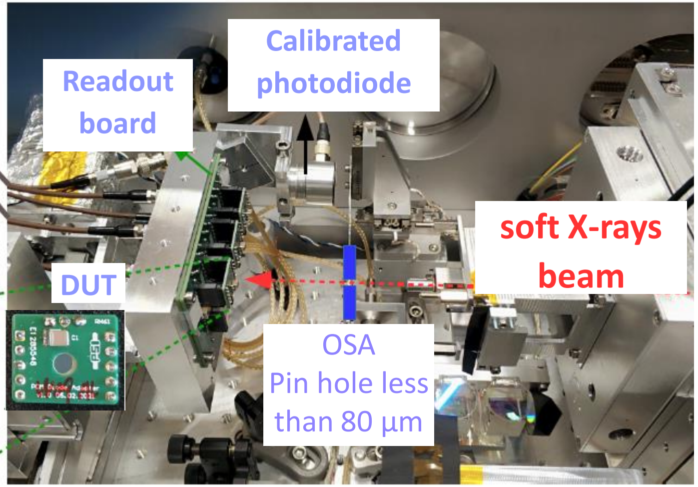

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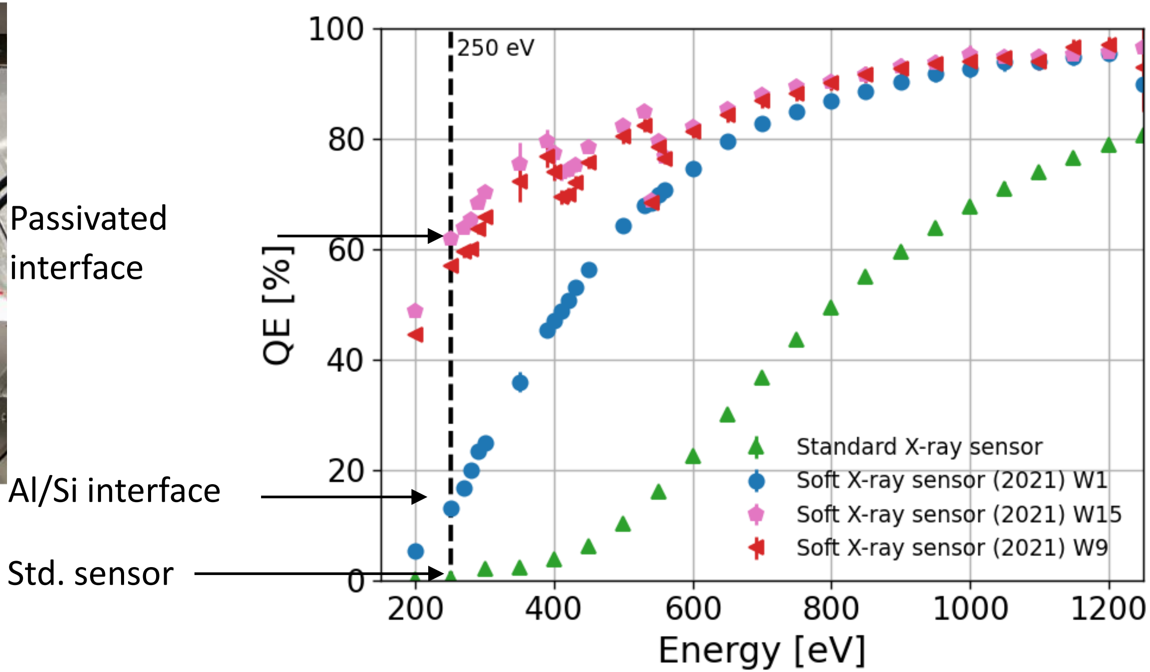
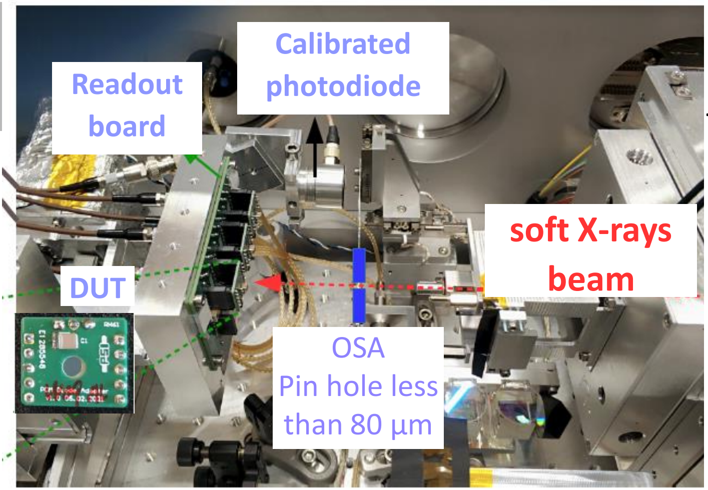


Keys for high QE :

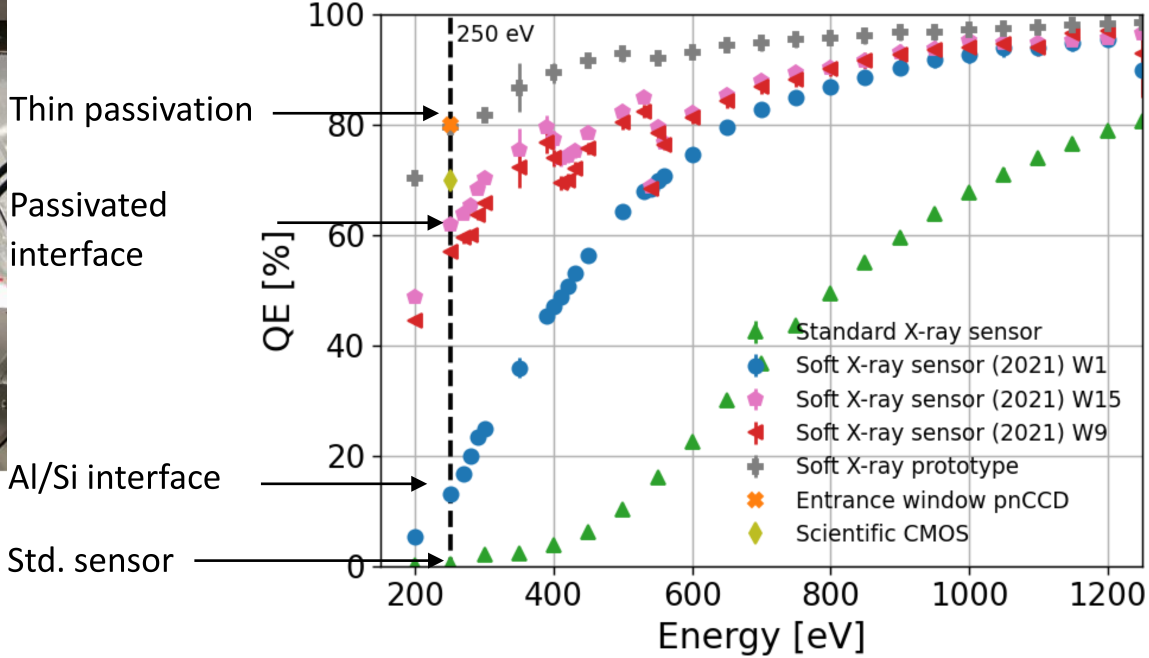
- Optimization of the n+
- Surface passivation

Efficiency of the entrance window technology

Setup at the Surface/Interfaces Microscopy @ SLS



Quantum efficiency



Keys for high QE :

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

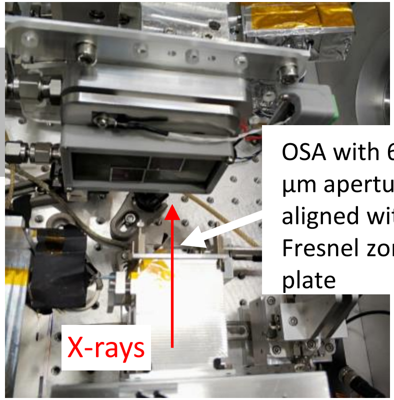
QE above 70 % of backside illuminated scientific CMOS* and equal to 80 % of entrance window pnCCD**

*K. Desjardins, et al. 2020, J. Synchrotron Rad. 27, 1577–1589.

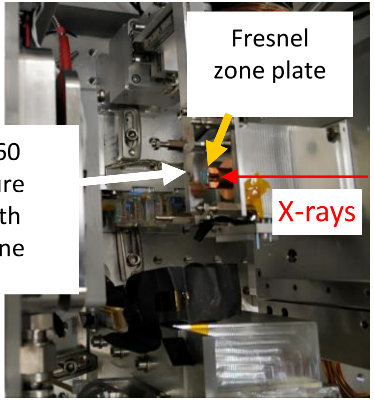
** S. Send, et al. 2013, NIMA. 711, 132-142.

Spectrum of iLGAD sensors

Setup at the Surface/Interfaces:Microscopy (SIM) beamline from SLS

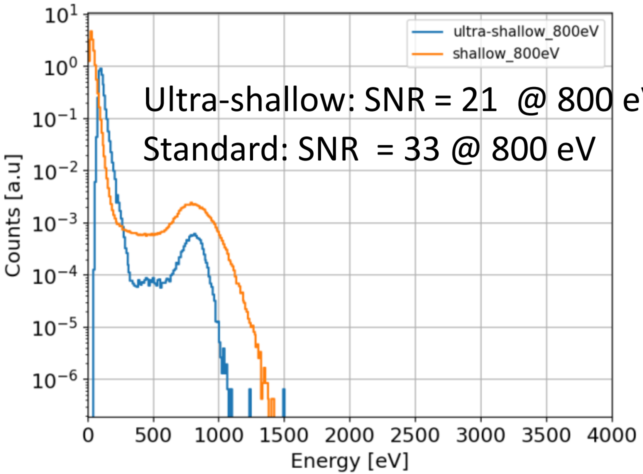


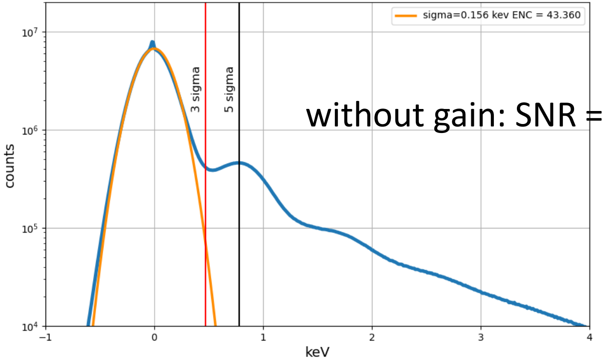
Front side picture



Right side picture

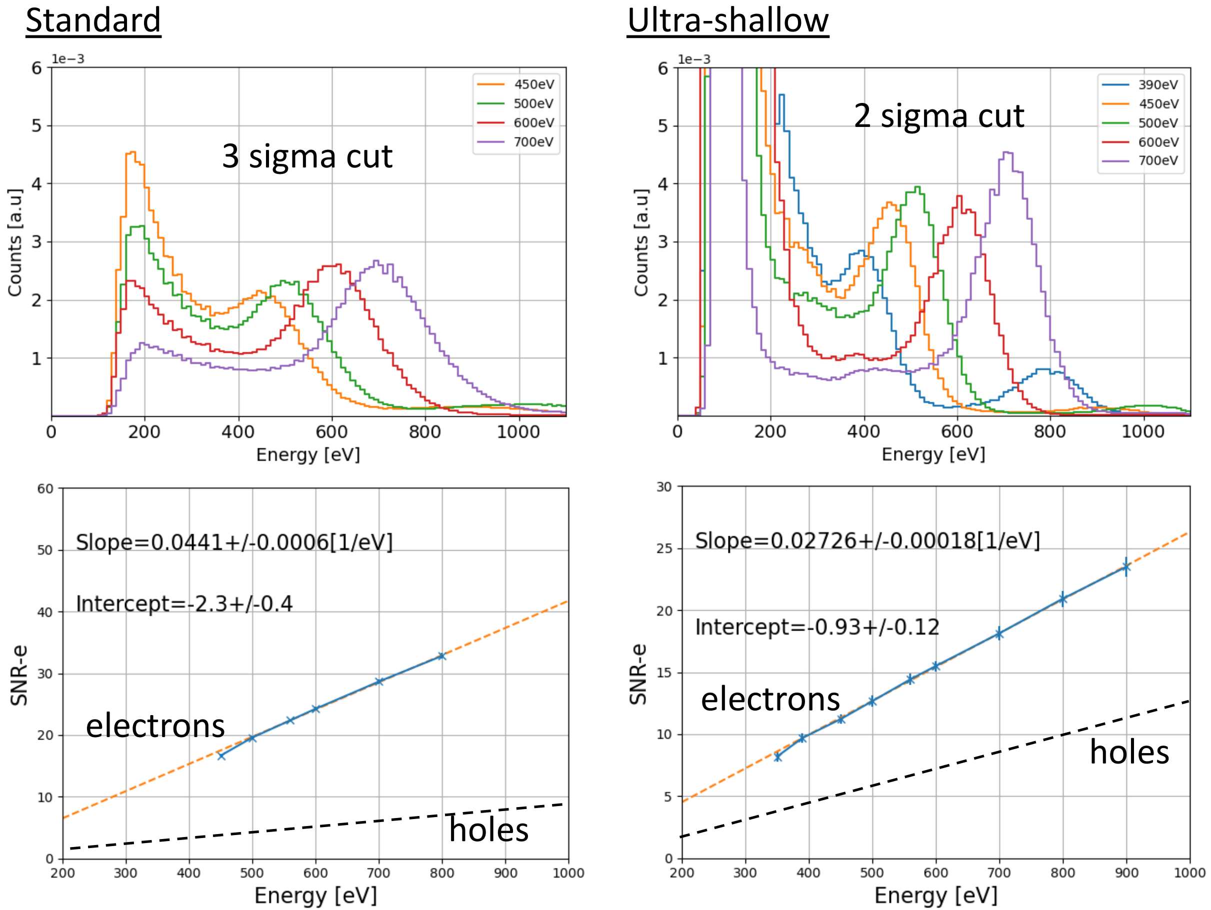
- Two designs tested with JUNGFRAU : Standard & ultra-shallow





In comparison to the design without gain, the SNR has increased by a factor of 4 for ultra-shallow and 6 for the standard.

Spectrum of iLGAD sensors



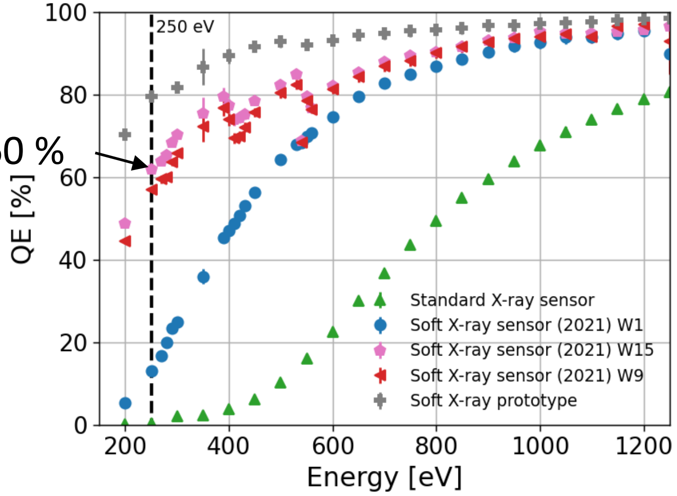
- Ultra-shallow design show low SNR due to the low gain in comparison to standard design
- Probability of electron started impact ionization for ultra-shallow design is larger than in standard
- The gain needs to be increased for detection of hole started impact ionization at 400 eV

Summary

Can we obtain single photon resolution of soft X-rays with our fast detector system?

Optimization of the entrance window to reduce the losses in the surface and n+

QE > 60 %



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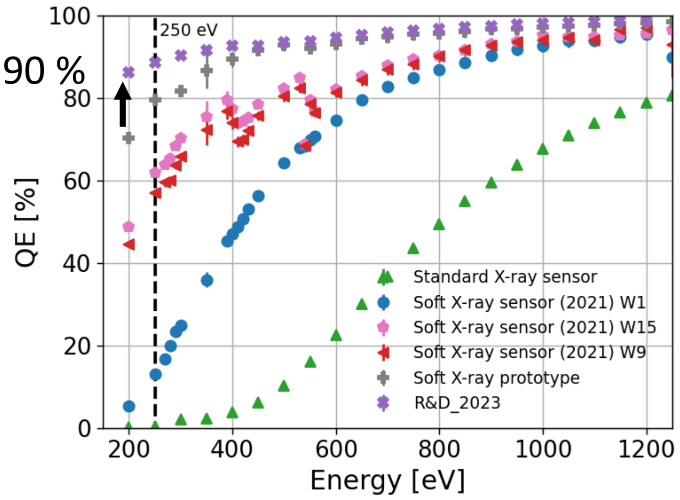
QE > 90 %



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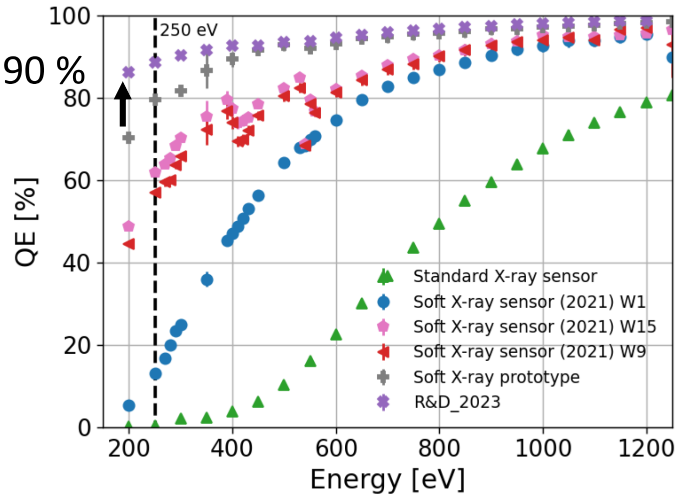
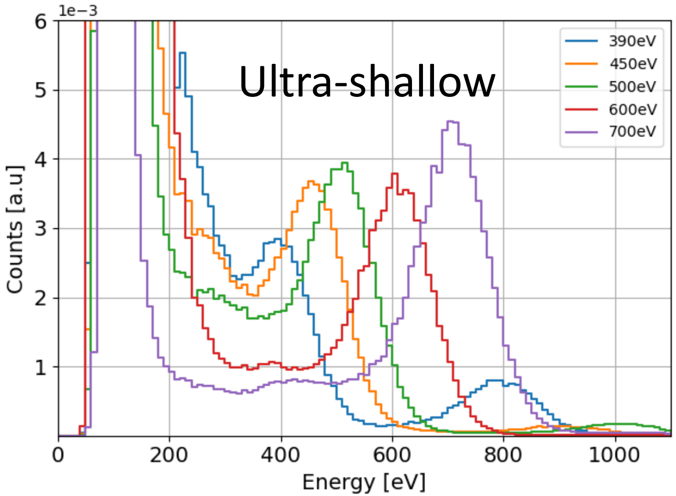


Optimization of the iLGAD design to increase the gain and the probability of photon absorption after the multiplication layer.



Combining the entrance window technology together with the iLGAD technology, our detector systems can detect 400 eV photons at high frame rates.

Acknowledgement

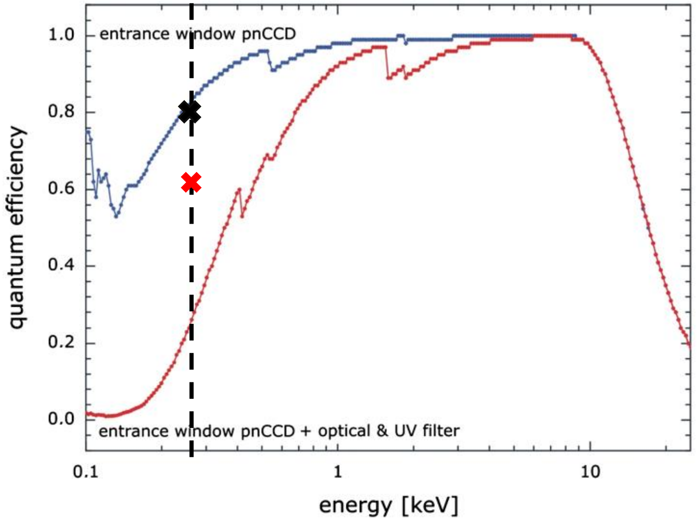
My thanks go to:

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

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, P. Kozlowski, F. Baruffaldi, K. Paton and X. Xie

QE pnCCD and scientific CMOS



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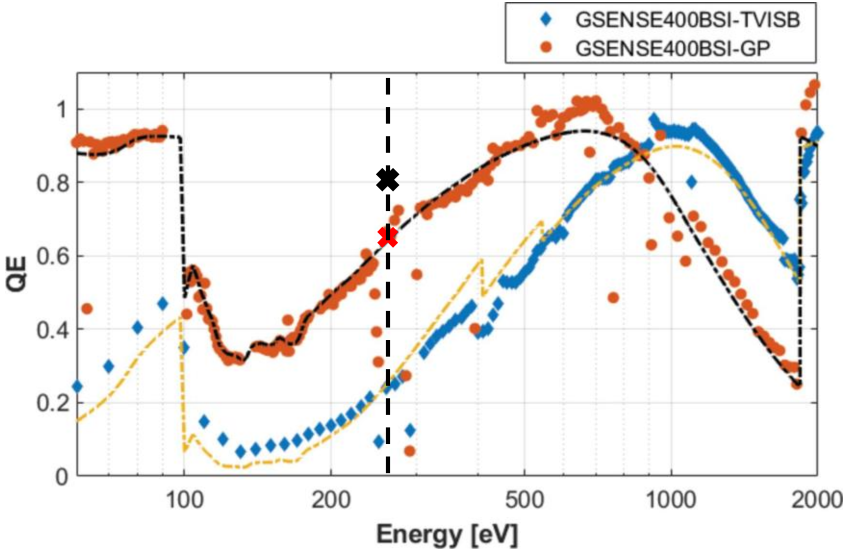
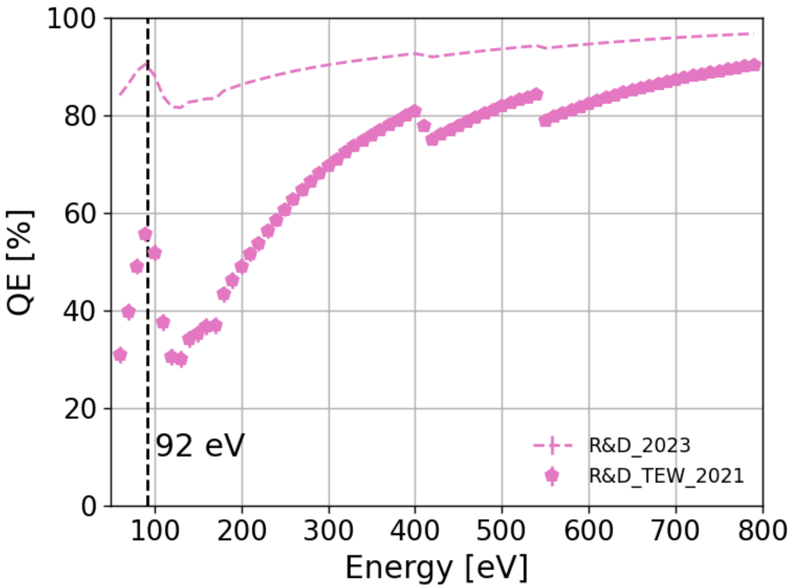


K. Desjardins, et al. 2020, J. Synchrotron Rad. 27, 1577–1589.

- ✖ QE > 0.62 current TEW and iLGAD sensors
- ✖ QE > 0.8 current prototype

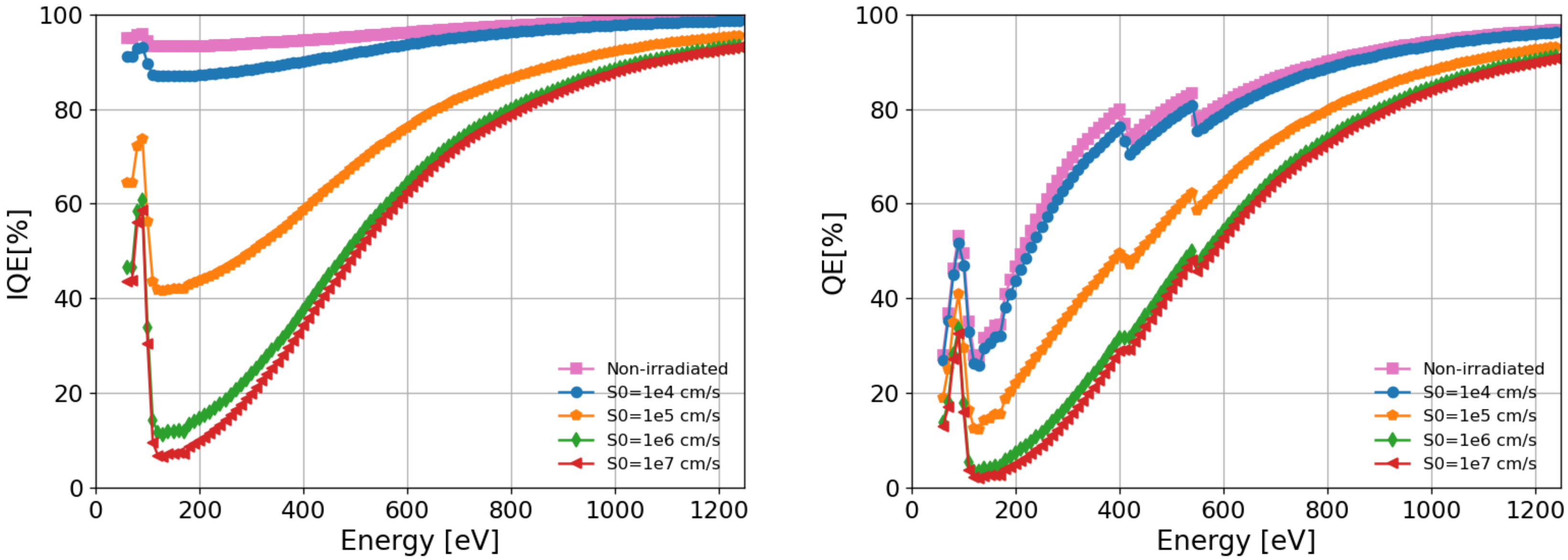
R&D 2023



100
80
60
40
20
0
QE [%]
100
200
300
400
500
600
700
800
Energy [eV]
92 eV
R&D_2023
R&D_TEW_2021

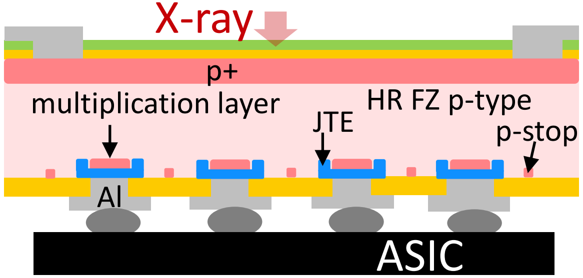
IQE and QE after irradiation

S0 saturates to 1e4 cm/s

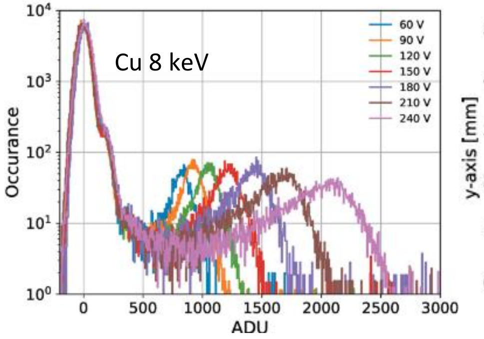


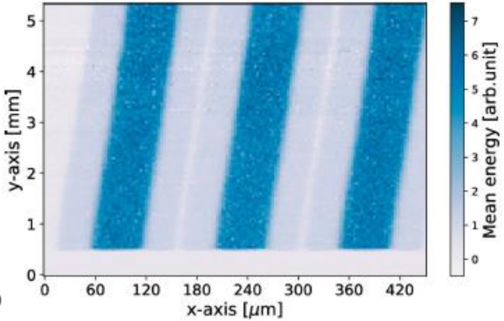
LGAD vs iLGAD

LGAD technology:



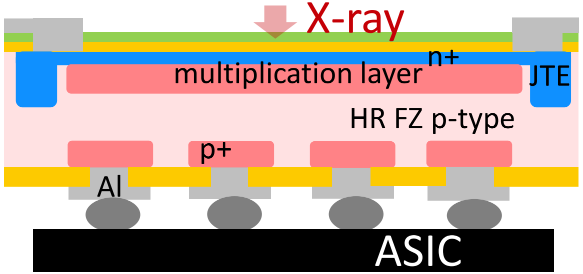
- ✓ SNR larger than 5
- ✓ Gain independent on the photon absorption depth
- X Low fill factor



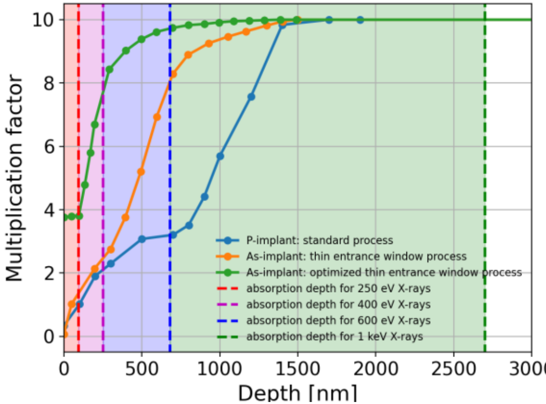


M. Andra, J. Synchrotron Rad. (2019). 26, 1226–1237
https://doi.org/10.1107/S1600577519005393

iLGAD technology:



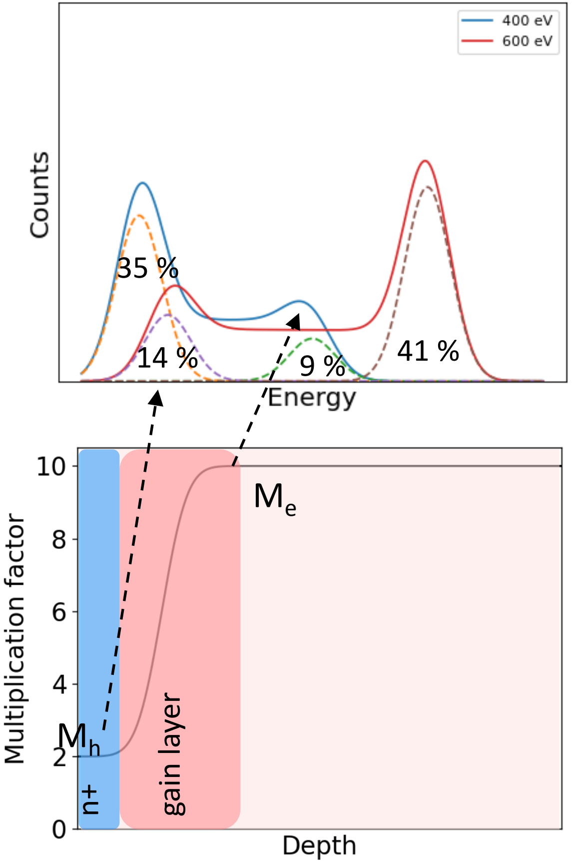
- ✓ SNR larger than 5
- ✓ 100 % fill factor
- X Gain depends on photon absorption depth



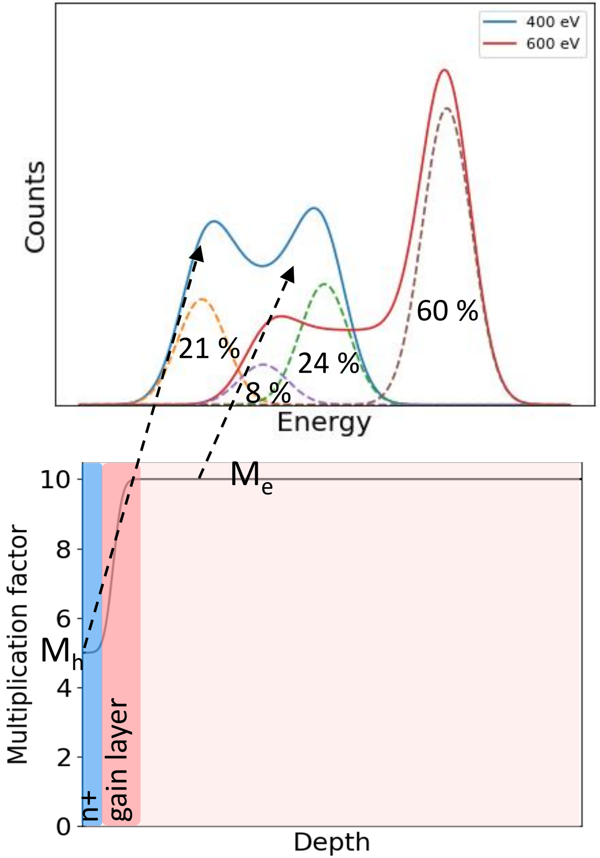
J. Zhang, https://doi.org/10.48550/arXiv.2210.12993

Optimization gain layer

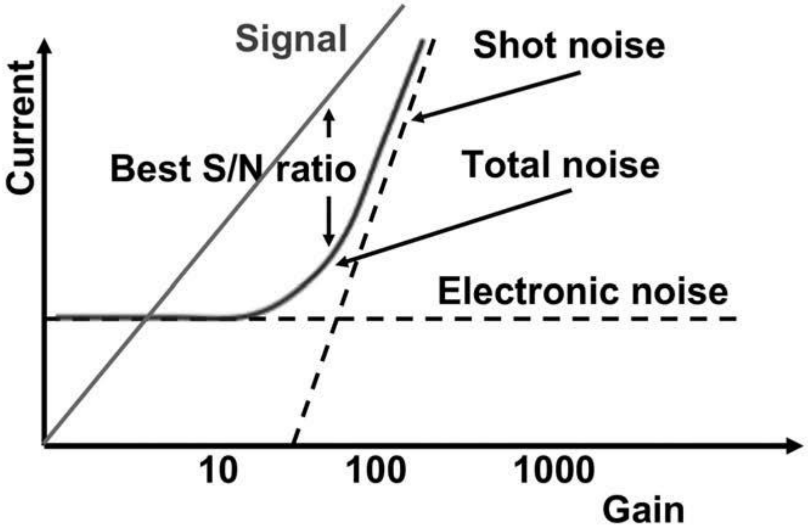
<u>Standard</u>



<u>ultra-shallow</u>

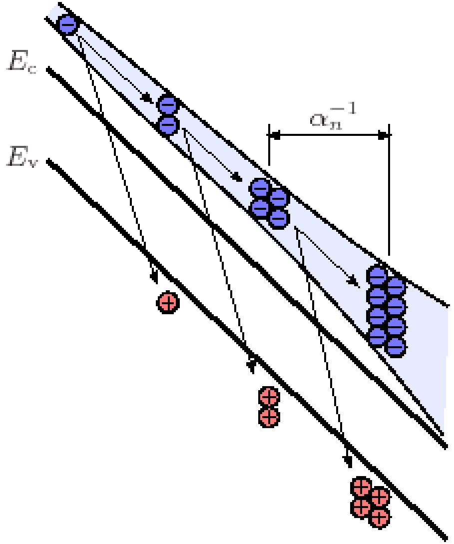


SNR vs Gain



M.Ferrero et al. “An introduction to Ultra-Fast Silicon Detectors”

Impact ionization

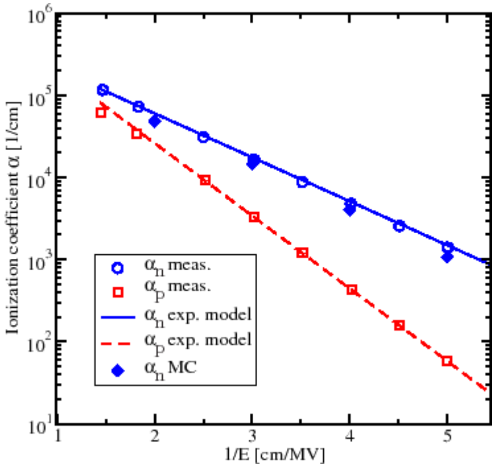


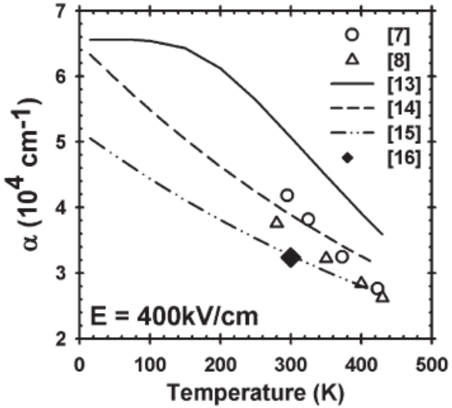
Pure electron started impact ionization

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

Relationship with electric field and temperature:

$$\alpha_\nu = \alpha_\nu^\infty \cdot exp\left(-\left(\frac{C_\nu + D_\nu T}{E}\right)^{\beta_\nu}\right)$$





D. Massey, “Temperature dependence of impact ionization in submicrometer silicon devices”