
WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

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Optimization of planar silicon sensors and LGADs for soft X-ray detection

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*on behalf of the FBK-PSI collaboration

Outline

- Introduction: Hybrid detectors and their current limitation
- Hybrid detectors towards soft X-rays
  - What are the needs:
    - Thin entrance window
    - LGADs adapted for soft X-rays
  - Development strategies:
    - Optimization of thin entrance windows
    - Optimization of LGADs with a thin entrance window
  - First experimental results:
    - Quantum efficiency for the developed thin entrance window
    - Single photon sensitivity of LGADs to soft X-rays
- Summary and outlook

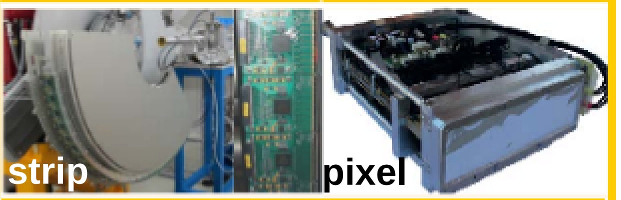
The hybrid X-ray detectors at PSI

- The hybrid strip/pixel detectors developed at PSI
  - Photon-counting detector: Mythen-II/III, Eiger, Matterhorn (for SLS2.0)
  - Charge-integrating detector: Gotthard-I/II, Jungfrau, Moench

} ⟹ demonstrated performance for hard X-rays

Photon-counting detectors

MYTHEN | EIGER



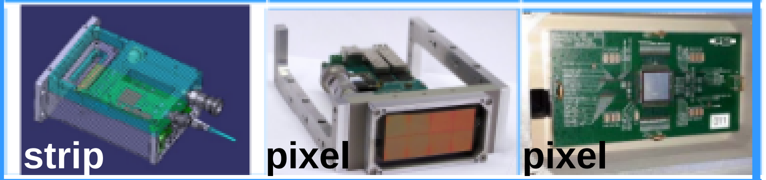
Single photon detection: 3-4 keV

only for hard X-rays

target soft X-ray energy: < 1 keV

Charge-integrating detectors

GOTTHARD II | JUNGFRAU | MÖNCH



Single photon detection (Jungfrau & Moench): 700 eV (SNR = 5, noise=35 e^-)

hard & tender X-rays, soft X-rays < 700 eV without single photon resolution

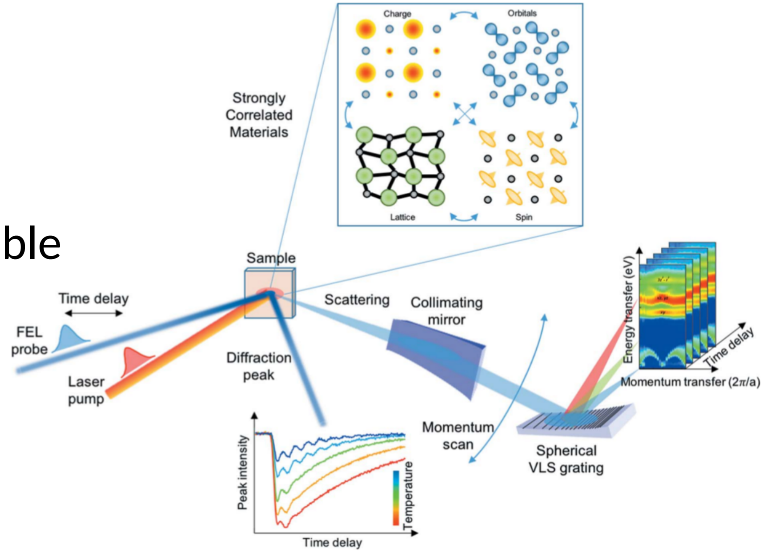
target soft X-ray energy: down to 250 eV

- Hybrid detectors are attractive because of
  - Large dynamic range (e.g. 3.4 x 10^7 e^- from Jungfrau)
  - High frame rate (e.g. a few kHz for pixel detectors)
  - Reasonable noise which can be improved (e.g. 35 e^- r.m.s. for Jungfrau and Moench)
  - Large X-ray detection area due to tilable modular design
  - Radiation hardness

Soft X-ray applications at SwissFEL and SLS

- Soft X-ray applications at SwissFEL and SLS (250 eV – 2 keV)
    - Access K-edges of biologically important elements
        - e.g. water window 250-520 eV
    - L-edges of 3d transition metals, Fe, Cu, etc.
    - Possible applications:
        - RIXS at FELs and synchrotrons
            - Single photon detection necessary and interpolation desirable
        - Contrast enhanced imaging:
            - soft X-ray diffraction
            - ptychography
            - absorption spectroscopy

Time resolved resonant inelastic X-ray scattering (tr-RIXS)



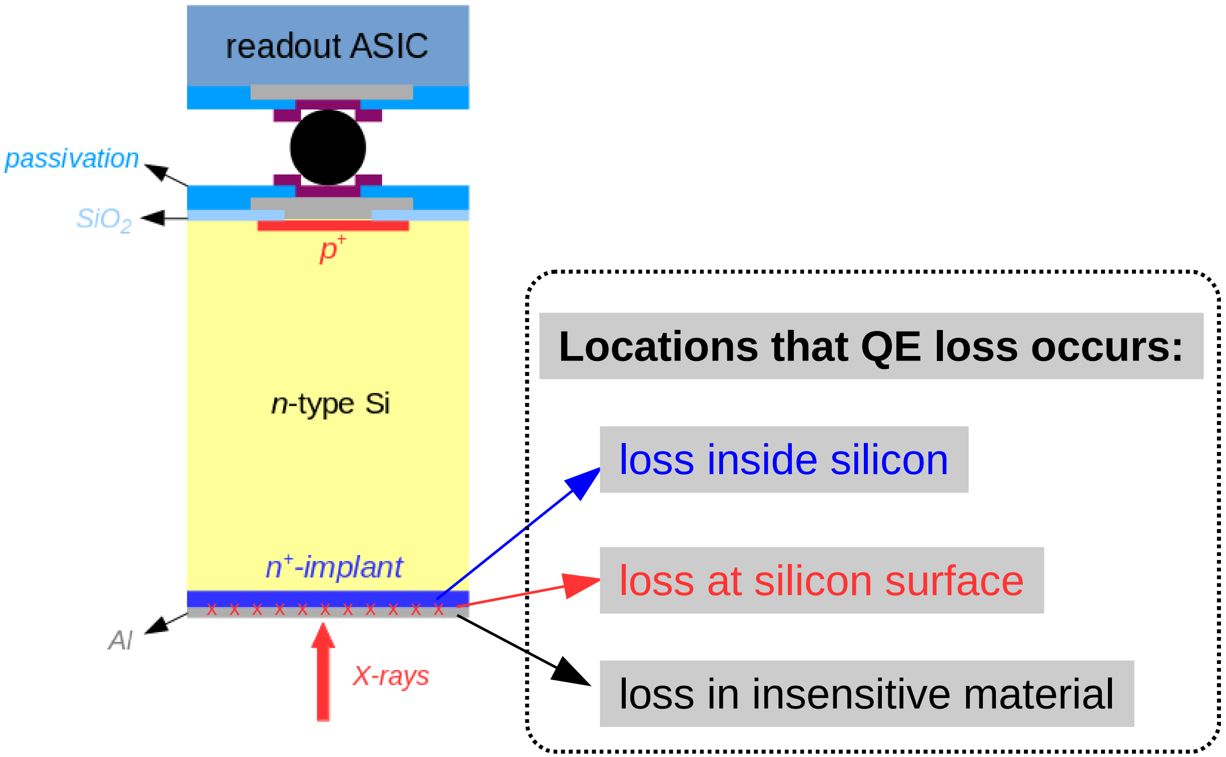
doi: 10.1107/S1600577519003928

- Current limitation of hybrid detectors for soft X-ray detection:
    - quantum efficiency (QE):
      → complete photon losses + incomplete charge collection close to the surface region
    - electronic noise:
      → minimal detectable photon energy with single photon resolution
      → low signal-to-noise ratio (SNR) for soft X-rays, insufficient for interpolation (RIXS) at SwissFEL and SLS

Quantum efficiency limit

- Soft X-rays (~ a few hundred eV) absorbed in the first micron of silicon sensor
  - For conventional process, e.g. p^+-n sensor: n^+-implant depth ≈ 1-2 micron + aluminum
    - Significant efficiency loss for X-rays below 1.2 keV → not usable for soft X-rays! (< 50% below 800 eV)

Conventional assembly and efficiency loss



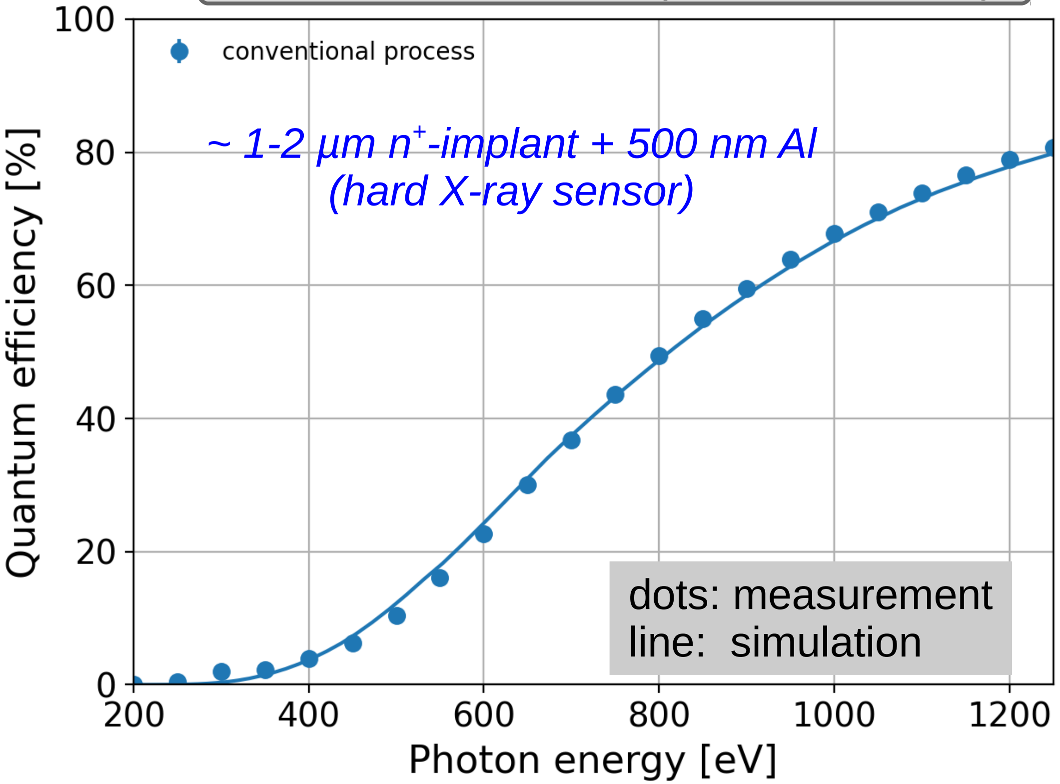
Locations that QE loss occurs:

loss inside silicon

loss at silicon surface

loss in insensitive material

Measured / simulated quantum efficiency



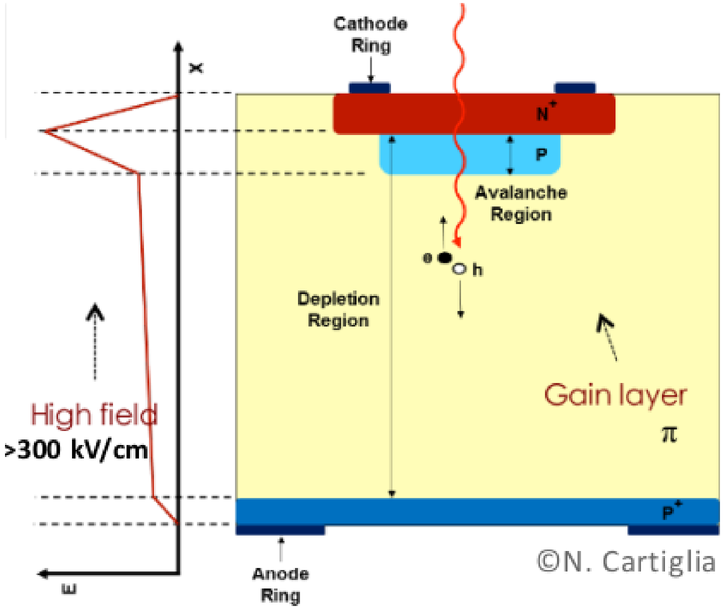
dots: measurement
line: simulation

- For soft X-ray detection, it is necessary to develop a thin entrance window process to improve the quantum efficiency (QE) and the charge collection efficiency (CCE)

Electronic noise limit

- Single photon detection limit due to electronic noise:
  - For photon-counting (PC) detectors: 3 – 4 keV
  - For charge-integrating (CI) detectors (Jungfrau & Moench): ENC = 35 e^- → E = 5xENCx3.6 eV = 700 eV
- Overcome the limit of electronic noise:
  - Low Gain Avalanche Diode (LGAD) sensor
    - → increases signal amplitude → better separation between signal and noise
    - → does not need to change readout ASIC but only the sensor

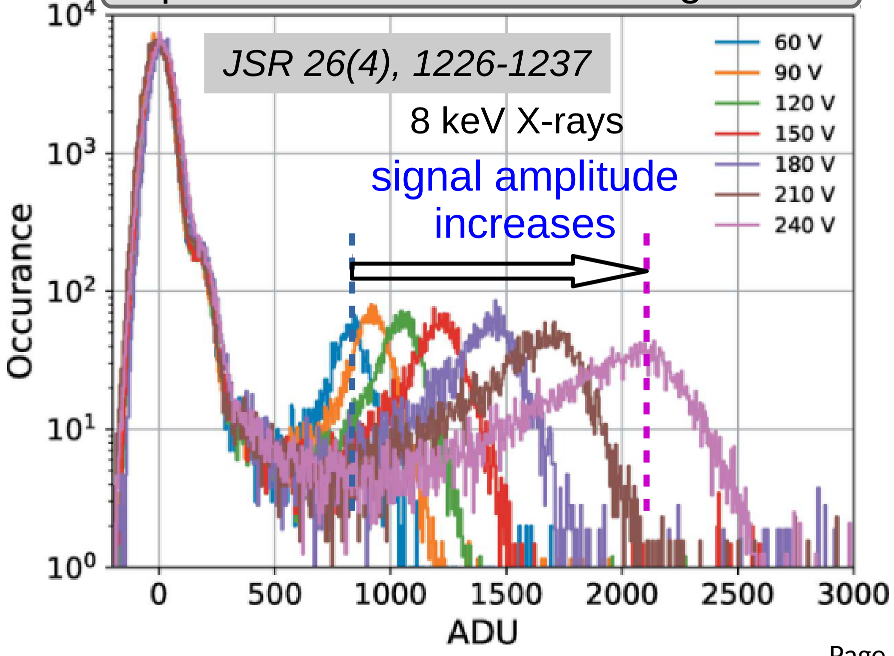
Work principle of LGAD



LGAD principle:

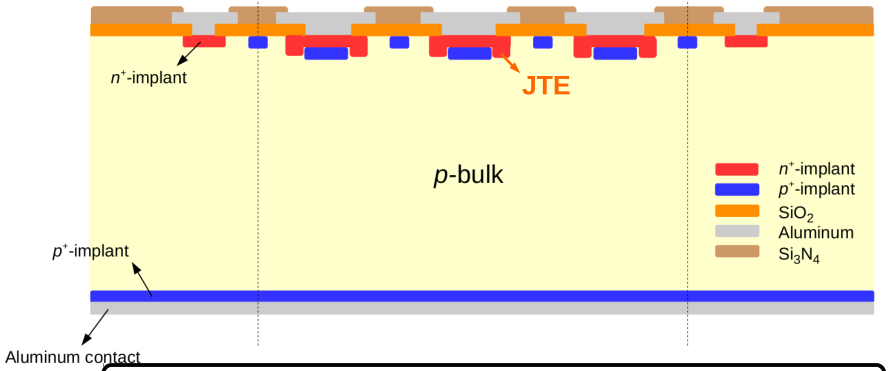
- e/h pair generation
- e/h drift to electrodes
- impact-ionization process at moderate electric field before triggering avalanche
  - → charge multiplication
  - → output = input charge x *M*

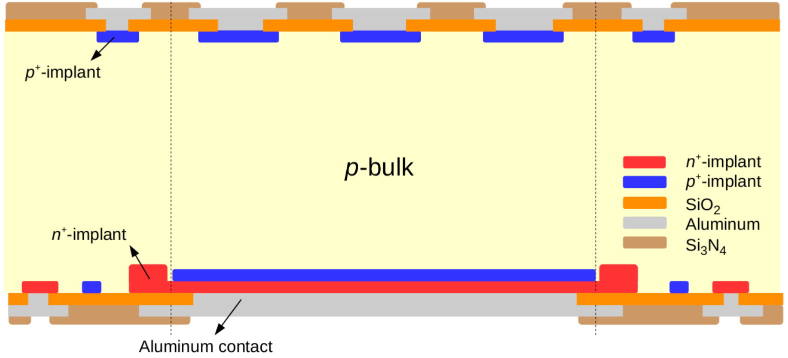
Spectrum from Gotthard using LGAD



Most common LGAD technologies

- First investigation for X-ray applications started in 2017
- The types of LGAD sensors: **LGAD** with Junction-Termination-Extension (JTE) *vs.* **inverse LGAD** (iLGAD)

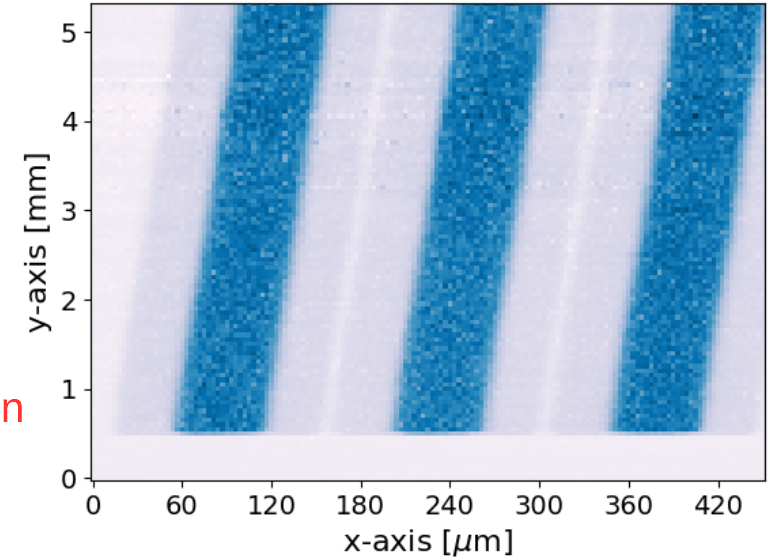

LGAD with gain layer on readout side

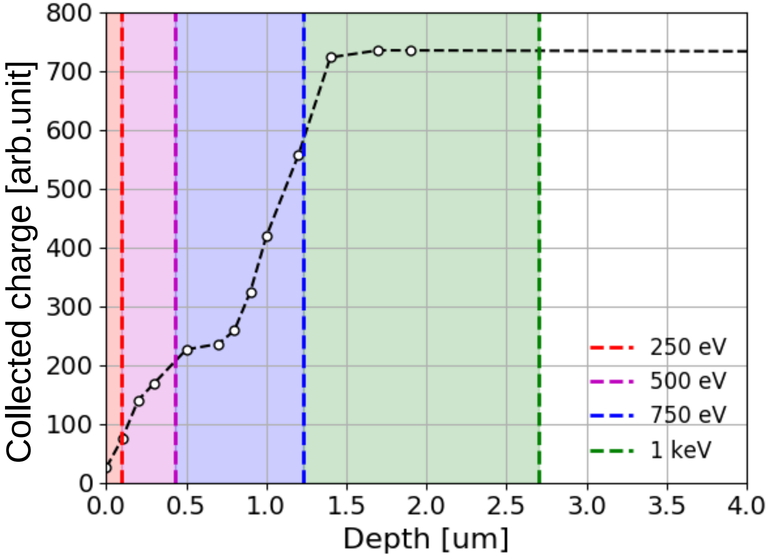

iLGAD with gain layer on sensor backside

← our pick

Pros. & cons.:

+ gain independent on depth for soft X-ray absorption
+ standard process
- electron readout
- limited fill factor
- interpolation through charge sharing for high spatial resolution is not allowed


Pencil beam scan for LGAD (measurement)


Gain variation for iLGAD (simulation)

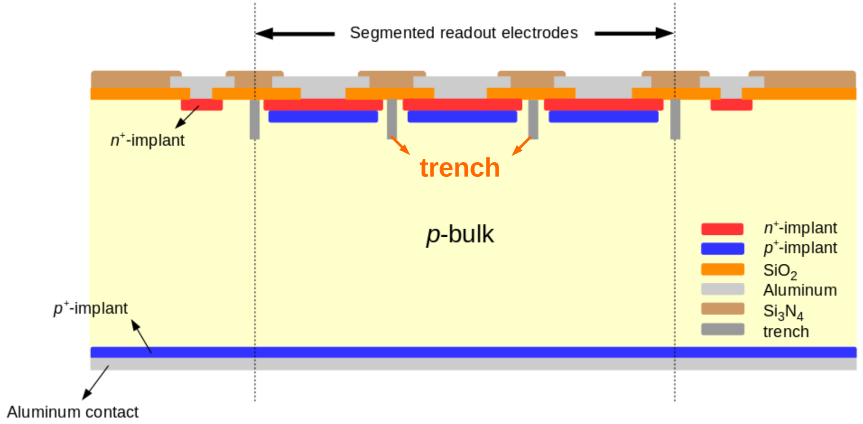
Pros. & cons.:

+ 100% fill factor
+ hole readout
+ interpolation through charge sharing for high spatial resolution is possible
- need to be compatible with optimized TEW
- double sided process
- gain depending on depth of X-rays absorption

Other LGAD technologies

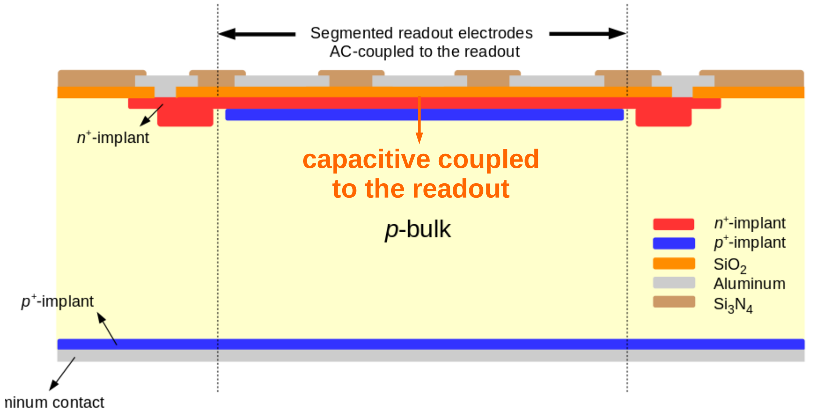
- Recent developments with good progress:
  - trench-isolated LGAD (TI-LGAD) → replace JTE with trenches to reduce the non-gain region
  - AC-coupled LGAD (AC-LGAD) → capacitive couple to the readout electronics
  - deep junction LGAD (DJ-LGAD) → deep junction with the gain layer buried in the sensor bulk

TILGAD



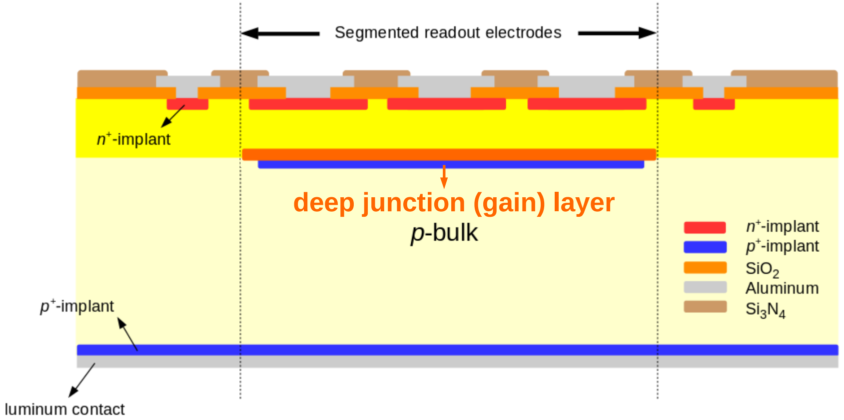
+ significant improvement of fill factor (non-gain region ~ 6-7 um)
+ gain independent on depth where soft X-ray photons are absorbed
+ electron collection
- small area with stepper

AC-LGAD



+ 100% fill factor
+ gain independent on depth where soft X-ray photons are absorbed
+ electron collection
- require good process control on n^+ profile (RC for discharge)
- require compatible readout

DJ-LGAD



+ 100% fill factor
+ gain independent on depth where soft X-ray photons are absorbed
+ electron collection
- complex process and high risk

TI-LGAD → *G. Poternoster et al.*, *doi: 10.1016/j.nima.2020.164840*
AC-LGAD → *N. Cartiglia et al.*, *doi: 10.1016/j.nima.2020.164383*
DJ-LGAD → *SCIPP group*, *arXiv: 2101.00511*

Development strategies

- The two enabling development for hybrid detectors towards soft X-rays:
  - Thin entrance window (TEW) process
  - LGADs optimized for soft X-rays

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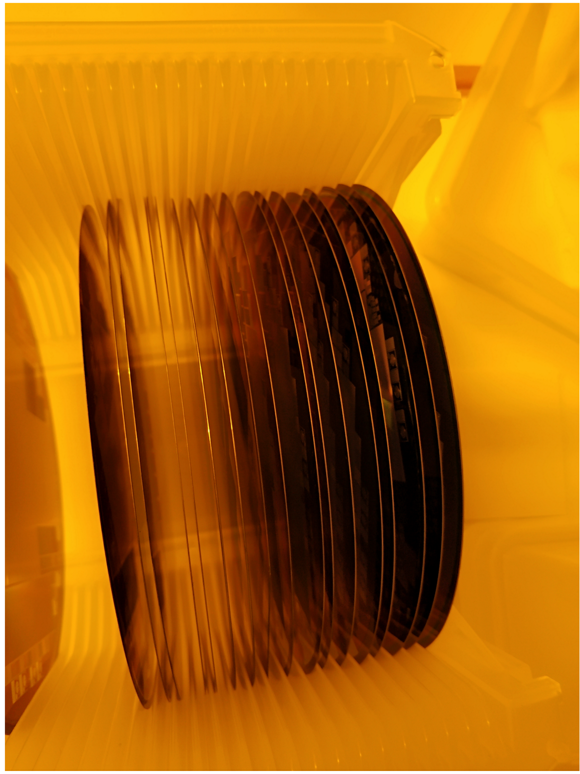
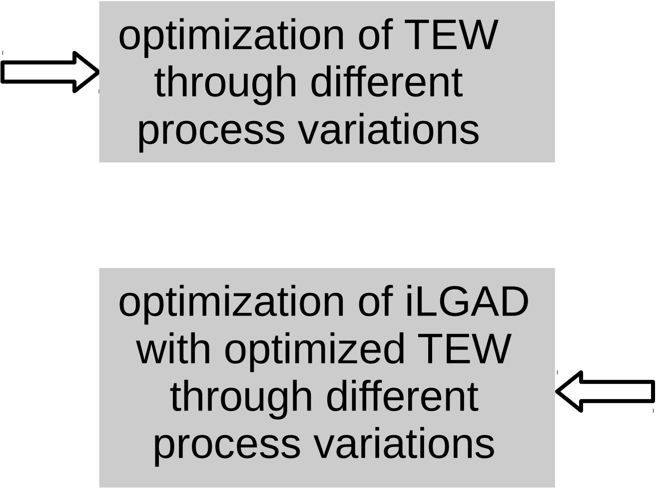
6-inch planar wafers with TEW (2021)

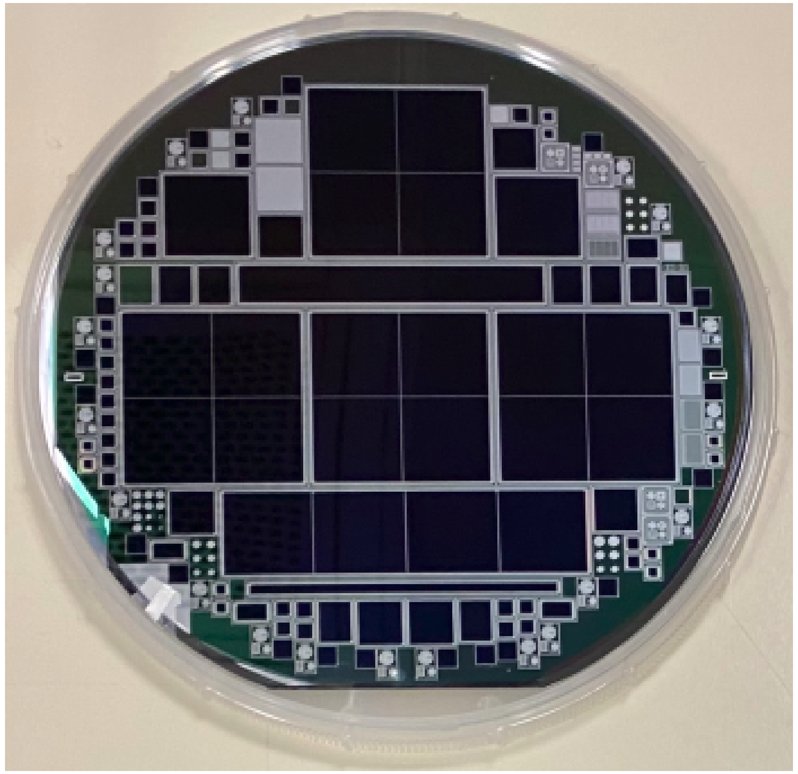


6-inch iLGAD wafer from 1st R&D batch (2022)



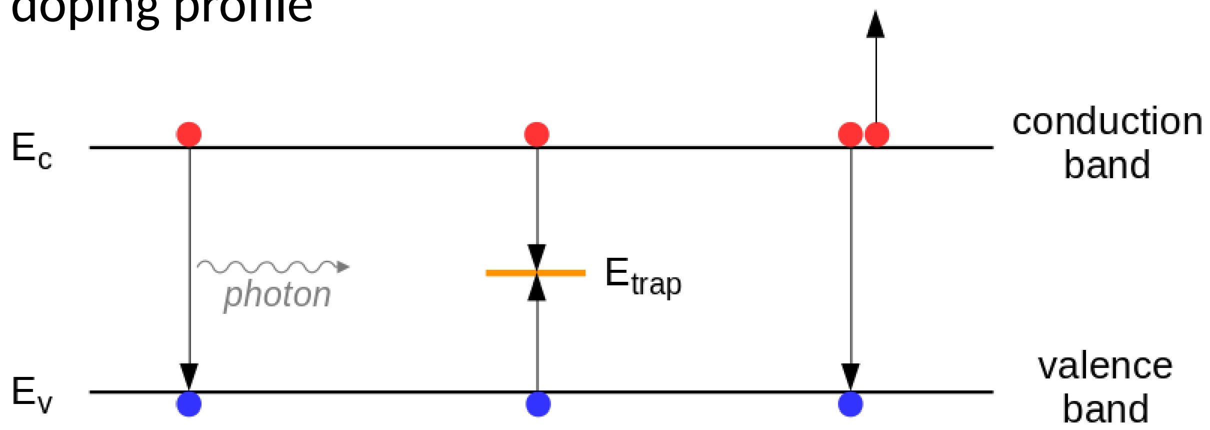
optimization of TEW through different process variations

optimization of iLGAD with optimized TEW through different process variations



Reasons for QE loss

- QE loss in insensitive layer → thickness of insensitive layer
- QE loss in silicon → doping profile



Mechanism of recombination ⇒

band-to-band radiative recombination	**SRH trap-assisted recombination**	**Auger recombination**
⊗ - negligible for silicon	✓ - traps in Si - traps at surface	✓ - dominant at high doping

⇒ **doping dependent**

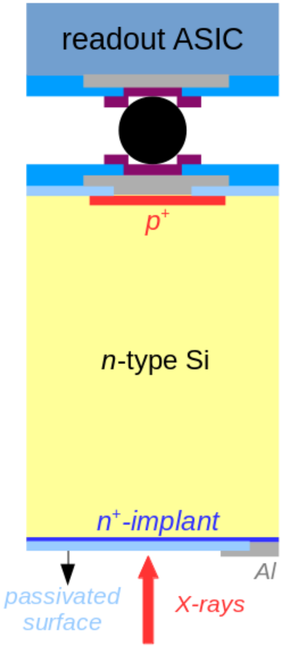
  - Lifetime of minority carriers reduced due to recombination process → diffusion length of minority (h^+)
  - Diffusion length <u>**~ 200 nm**</u> for doping concentration of *O*(10^{20} cm^{-3})

→ <u>Indication: An implant depth of a couple of hundred *nm* seems to be enough</u>

- QE loss at silicon surface due to surface recombination → surface passivation
  - $\tau_{surf} << O(ns)$ for Si/Al interface: $S_0 = O(10^7 - \infty)\ cm/s$

QE & CCE optimization

- Optimization philosophy: make minority carriers live longer and let them diffuse (<< 1 ns)
- Optimization target: a doping profile (~ 200 nm, < 10^{20} cm^{-3}) + passivated surface (low S_0)
- Simulations of QE and CCE
  - **Standard process**: Phosphorus implant, implant depth of > 1 um, high S_0 ~ 10^7 cm/s
  - **Thin entrance window process**: Arsenic implant, implant depth of ~ 200 nm, high S_0 ~ 10^7 cm/s
  - **Optimized thin entrance window process**: Arsenic implant, implant depth of ~ 200 nm, low S_0 ~ 10 cm/s



CCE *vs.* depth where X-ray absorbed

CCE [%]

simulation

G. Borghi & J. Zhang

QE *vs.* energy

no Al

simulation

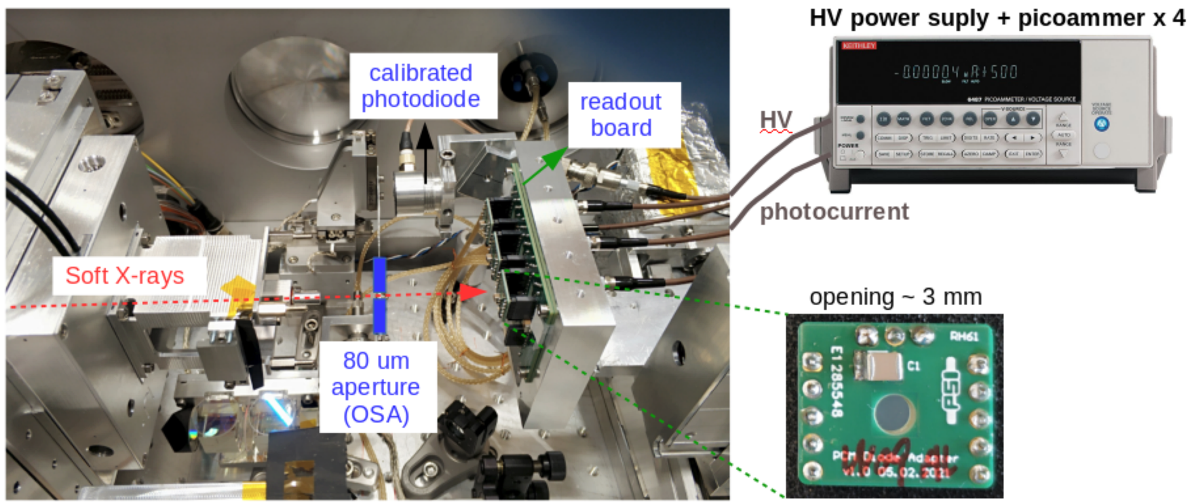
High QE & CCE can be achieved with a shallow implant (couple of hundred nm) + passivated surface.

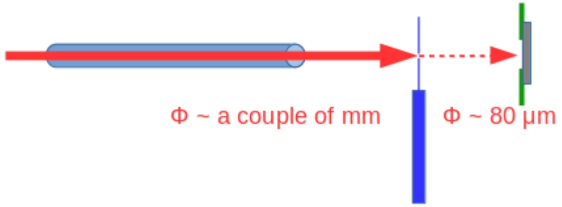
QE investigation

- Set-up at SIM (and Phoenix) for QE measurement
  - Photocurrent measured by planar photodiodes: Standard, TEW, optimized TEW w/o reduced surface layer
  - Comparing photocurrent to a calibrated photodiode: $QE(E) = \frac{I_{ph}(E)}{I_{ph,cal}(E)} \cdot QE_{cal}(E)$
- QE results: At 250 eV, QE > 60% for optimized TEW, QE > 80% for a prototype with further reduced surface layer

Measurement set-up at SIM beamline, SLS

QE *vs.* X-ray photon energy





Energy range for measurement:
200 eV → 1250 eV

measurement

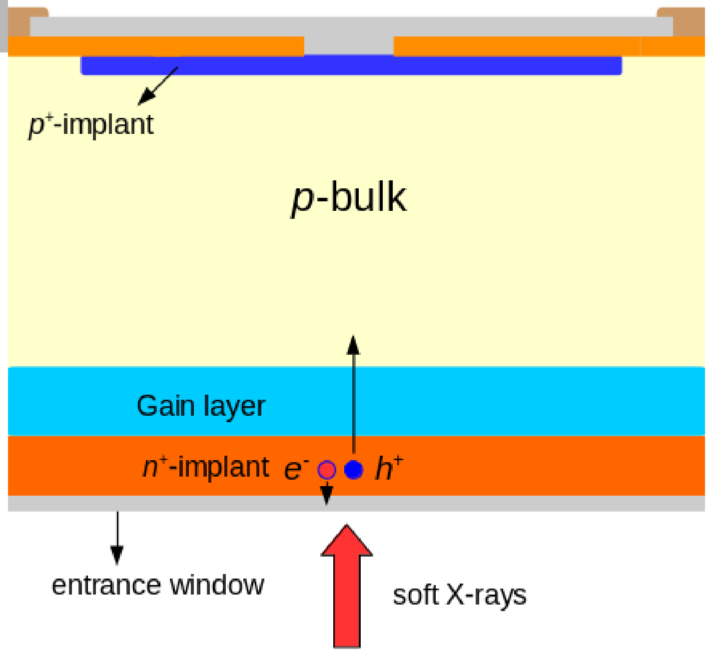
Maria Carulla &
M. Centis Vignali

→ For more details on process variations, please visit the poster of Maria Carulla (PSI)

Depth dependence of gain in iLGADs

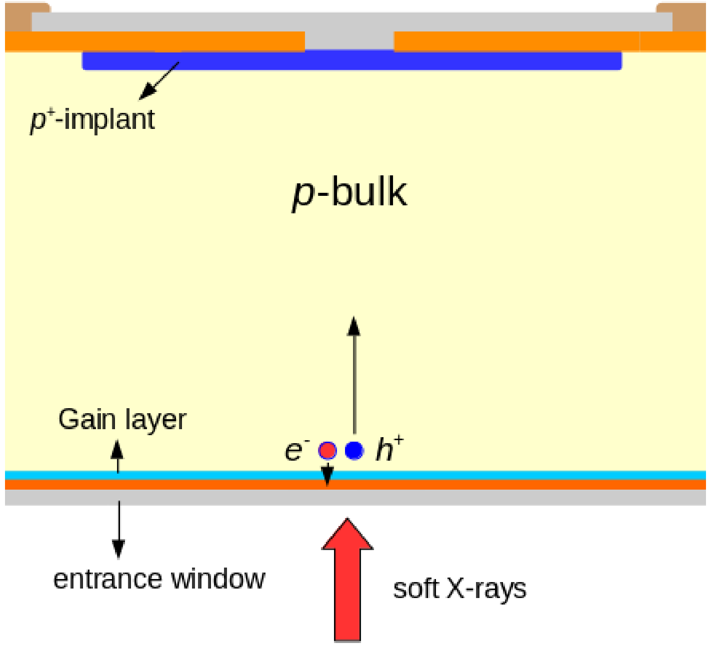
- Depth of the gain layer and its transition region:

Deep gain layer into silicon



lower gain with holes traveling through the gain layer

Shallow gain layer close to surface



higher gain with electrons traveling through the gain layer

Gain variations for different gain layers

Gain (multiplication factor)

M. Centis Vignali
G. Borghi
J. Zhang

simulation

500 eV

1 keV

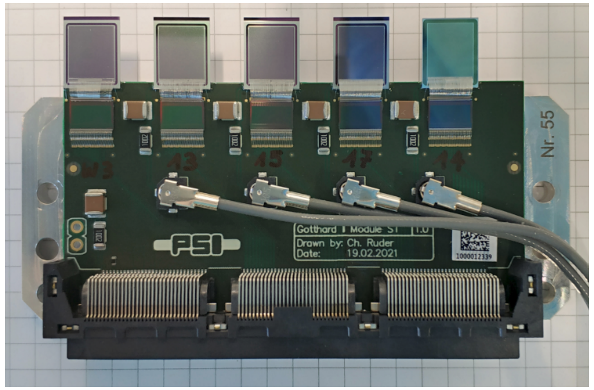
→ optimize gain layer towards the surface

First tests of iLGAD strip sensors at RT

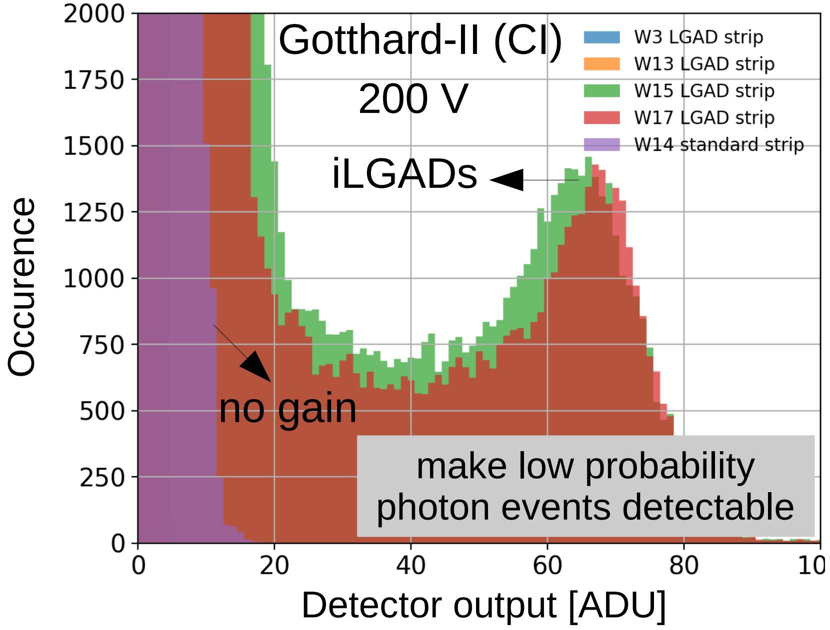
- Tests of the iLGAD strip sensors with CI readout chip Gotthard-II*:
  - Room temperature (RT), nominal gain *M* = 8-9 @ 200 V, 500 ns exposure time
  - 5 variations (4 with gain + 1 without gain)
  - nominal noise of 300 e^- with standard sensor (SNR=5 @ 5.4 keV)

* also measured using PC readout chip MY3 not shown here

iLGAD strip assembly

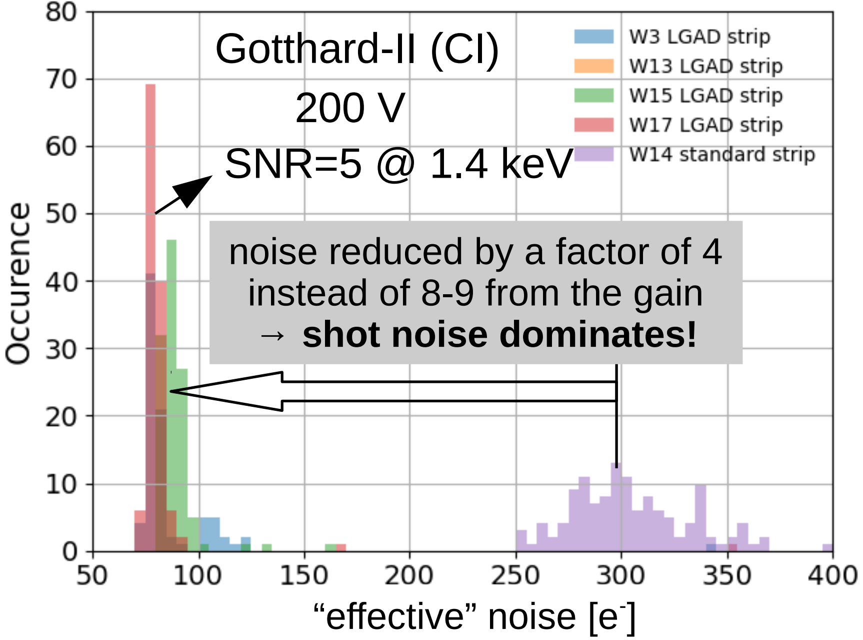


Spectra from Ti k_a-line (4.5 keV)



make low probability photon events detectable

Noise distribution for iLGADs



noise reduced by a factor of 4 instead of 8-9 from the gain → **shot noise dominates!**

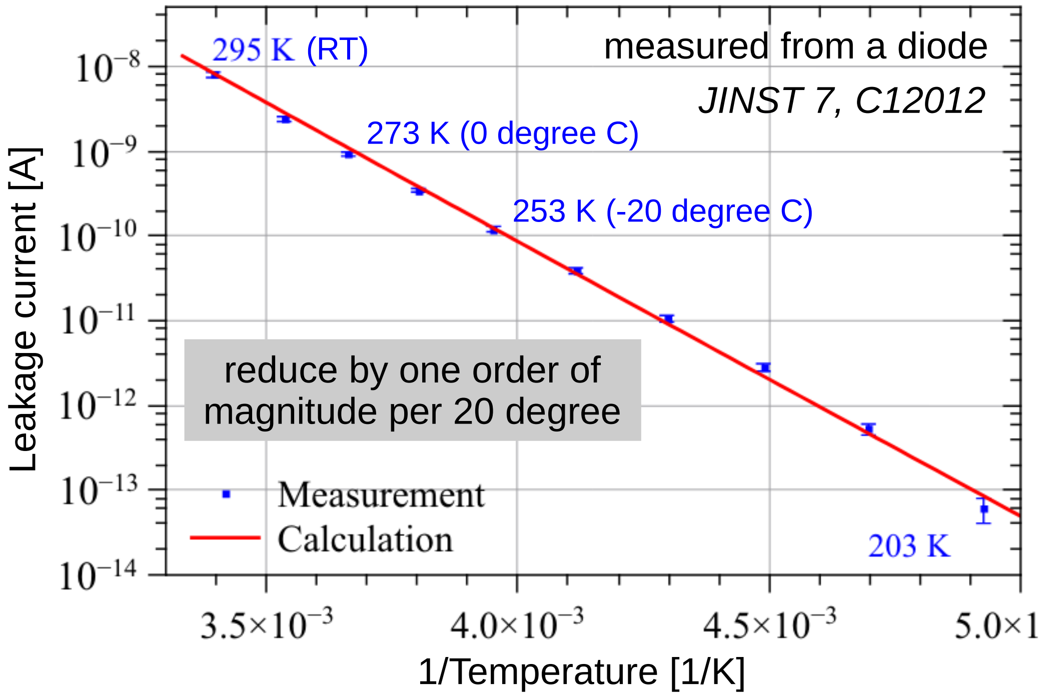
- **Indication: Cooling is necessary!**
  - Reduce the shot noise for soft X-rays below 1 keV
  - Reduce the leakage current to prevent the saturation of the pre-amplifier of PC and CI detectors, otherwise fast settings must be used (fast shaping time & short exposure time)

Temperature dependence of noise

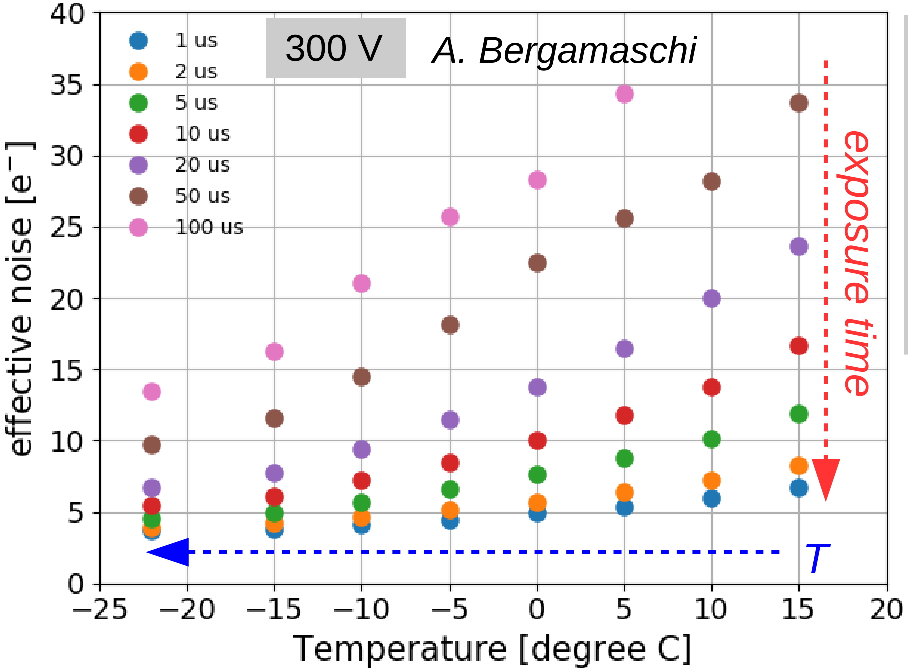
- Effect of the shot noise:
  - Shot noise: $i_{shot}^2 \sim \frac{2(I_{leakage}+I_{ph})M^2F}{q_0}$, *M* – multiplication factor, *F* – excess noise factor
  - Leakage current is sensitive to the temperature (T), reducing T and exposure helps with the noise
- iLGAD pixel sensors of 25 um pitch with Moench readout chip:
  - nominal noise of 35 e^- with standard sensor at RT (SNR=5 @ 700 eV)
  - Various temperatures, RT down to -22 °C to reduce the “effective” noise

“effective” noise = $\frac{\textit{noise } [e^- \textit{ r.m.s.}]}{M}$

Temperature dependence of leakage current



“Effective” noise *vs.* T & exposure time



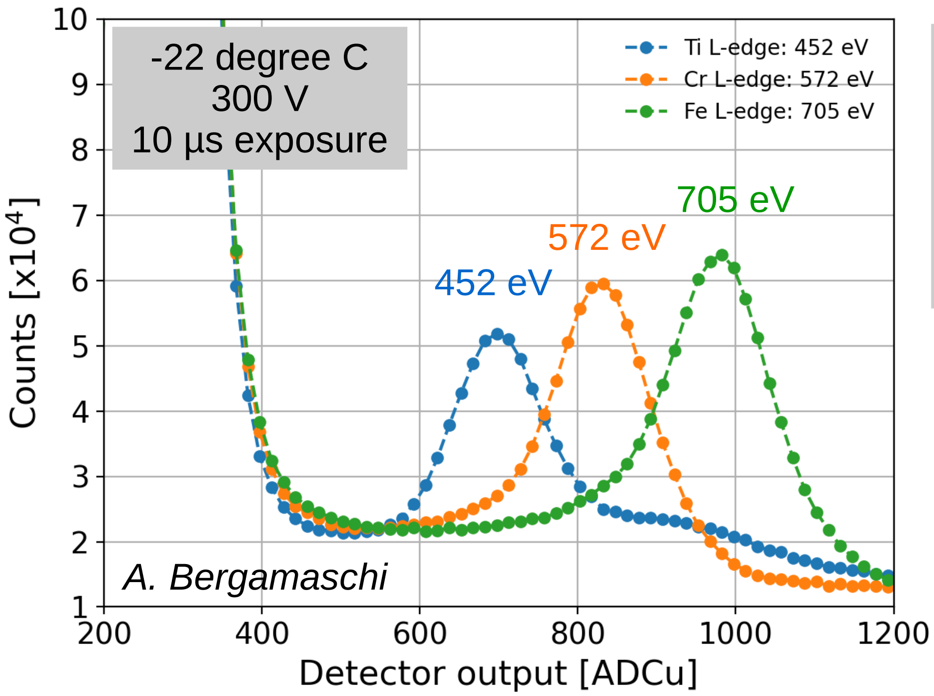
down to 3.7 e^- at <u>-22 ºC</u> with <u>1 µs</u> exposure: SNR > 5 for soft X-rays above 67 eV (134 eV with 2x2 clustering).

* Operation at RT with long exposure requires low leakage current → to be optimized in next batch.

iLGAD pixel sensors at low temperature

- Spectra measurements using 25 um pitch Moench readout chip*
  - Biased at 300 V and cooled to −22 °C to reduce the “effective” noise and improve the SNR
  - Spectra measured from L-edges of Ti, Cr and Fe: 452 eV, 572 eV and 705 eV
- Gain dispersion over area: temperature + multiplication factor
  - ~ 3% at -22 °C over an area of 1 cm x 1 cm [~ 7.3% over 2 cm x 2 cm from Jungfrau]

Spectra output from Moench using 2x2 cluster



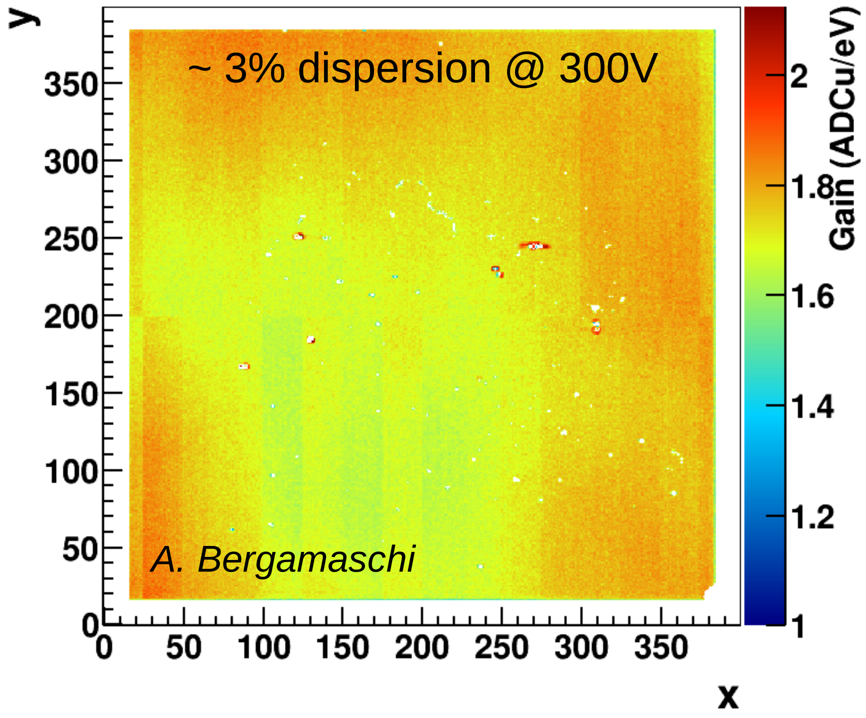
-22 degree C
300 V
10 µs exposure

A. Bergamaschi

single photon detection demonstrated at 452 eV with SNR = 23 (SNR = 11.5 using 2x2 cluster)

* Lowest detectable photon energy to be measured at the SIM beamline using mono-energetic soft X-ray photons down to 200 eV

Gain uniformity from Moench



~ 3% dispersion @ 300V

A. Bergamaschi

→ Similar results obtained with 75 µm Jungfrau, please visit the poster of Viktoria Hinger (PSI)

Summary

- The development of LGADs with TEW enables soft X-ray detection using hybrid X-ray detectors:
  - PC detectors below 1 keV for diffraction and ptychography
  - CI detectors with interpolation for RIXS at SwissFEL and SLS
- Two technologies need to be developed for hybrid X-ray detectors:
  - Thin entrance window: higher QE & CCE are essential for soft X-ray detection
  - iLGAD: implementation of the optimized TEW and further optimization for soft X-rays
- Investigations show promising results:
  - QE > 80% @ 250 eV can be achieved
  - Cooling is mandatory to reduce the shot noise and leakage current for LGADs
  - For Moench CI readout:
    - “effective” noise of 3.7 e^- at -22 ^{o}C with 1 µs exposure SNR=5 @ 67 eV, @ 134 eV with clustering
      → caution: QE and gain variation of iLGAD at lower photon energy
- Good for FEL applications (low noise with short exposure time)
- Next steps:
  - Production batch of TEW sensors (2022)
  - Identify the lowest photon energy that can be detected for PC and CI for different gain variations from the R&D batch (> 10 process splits) → beam tests planned at the SIM beamline, SLS
  - New R&D batch of iLGAD@FBK (early 2023):
    - Exploration of the gain layer limit towards the surface for soft X-rays
    - Optimize the leakage current from process for operations at RT & long exposure

Ackowledgment

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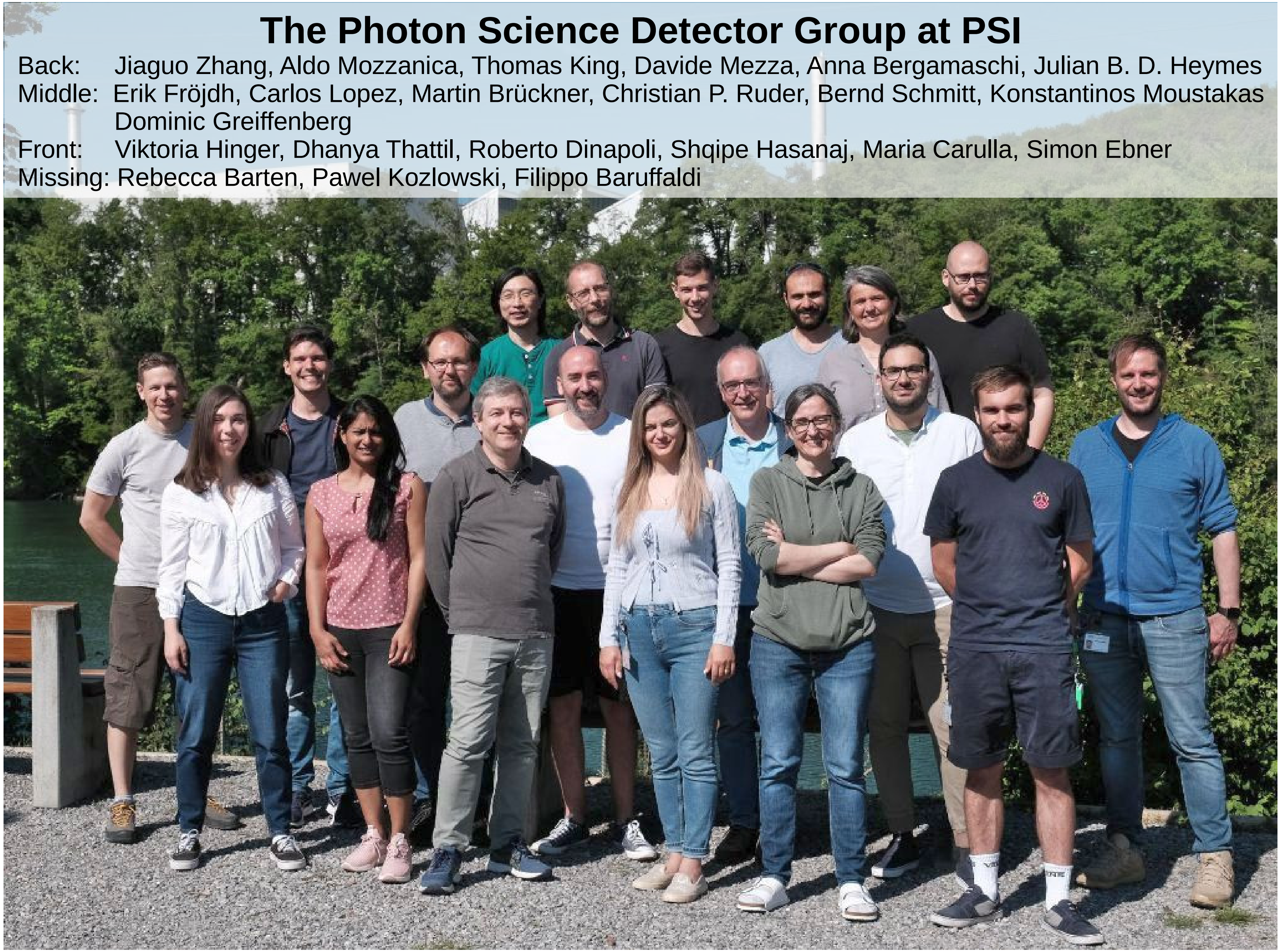

The Photon Science Detector Group at PSI

Back: Jiaguo Zhang, Aldo Mozzanica, Thomas King, Davide Mezza, Anna Bergamaschi, Julian B. D. Heymes
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Dominic Greiffenberg
Front: Viktoria Hinger, Dhanya Thattil, Roberto Dinapoli, Shqipe Hasanaj, Maria Carulla, Simon Ebner
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