Development of LGADs and Pixel Sensors for Soft X-rays at FBK

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Future Detectors for the European XFEL

FONDAZIONE
BRUNO KESSLER

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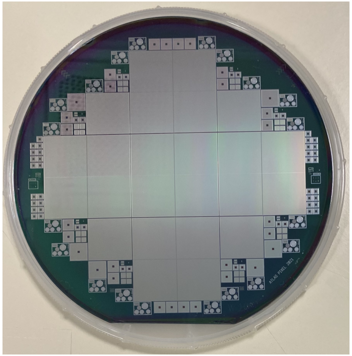
Fondazione Bruno Kessler

6 inch (150 mm)
Custom CMOS-like process

Sensor technologies:

- Planar pixel and strip
- SiPM
- SDD
- 3D sensors
- LGADs

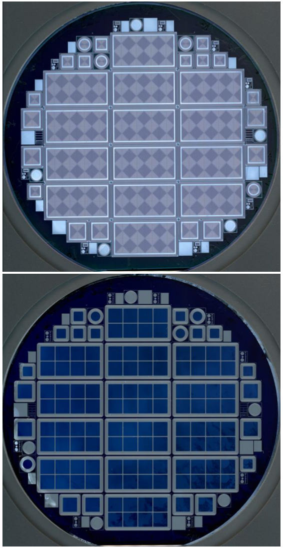


- Presentation about sensors $\Rightarrow$ hybrid detectors
- Pixel pitch of 50 μm produced for ATLAS and CMS
- Pixel pitch of 25 μm for PSI

“Hard” X-rays (3-13 keV)

- Maximize sensor thickness
- Current capability: 1 mm
- Double sided process on 1 mm for SDDs
- $V_{dep} \approx 100$ V
- Gettering on n-type to reduce leackage
- Dark current $\sim$ 1 nA/cm^2

Possible future upgrade to 1.5 mm

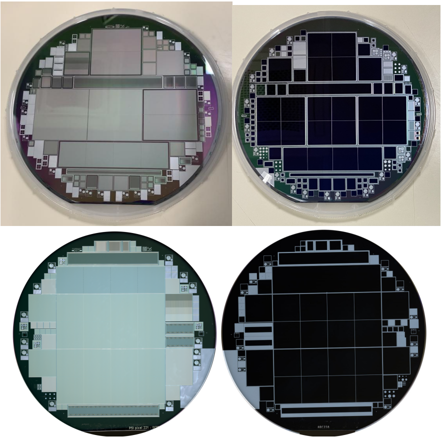


Soft X-rays (0.4-3 keV)

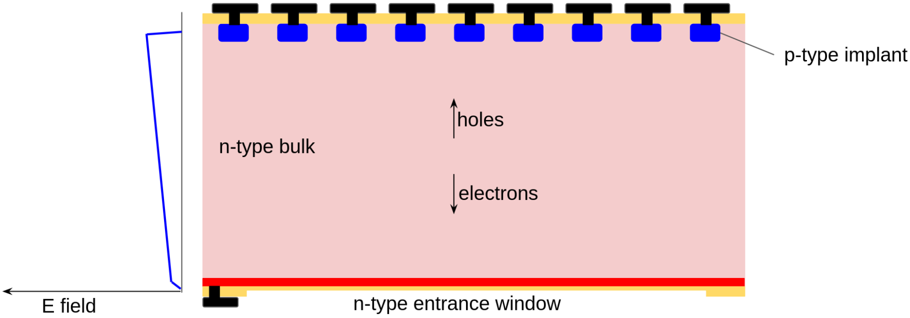
Extend detector capability by only changing the sensor

- Collaboration with PSI
- 200-2000 eV x-rays with hybrid sensors
- 2 developments necessary
  - QE $\rightarrow$ Thin Entrance Window (TEW)
  - SNR $\rightarrow$ charge multiplication
    (threshold for photon counting,
    single photon resolution for charge integrating)
- 2 sensor types
  - planar pixels and strips
  - Low Gain Avalanche Diodes (LGADs)

Project summary: J. Zhang et al. 2022 JINST 17 C11011



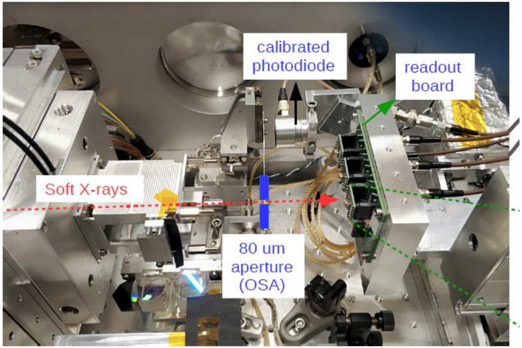
Pixel Sensors with TEW

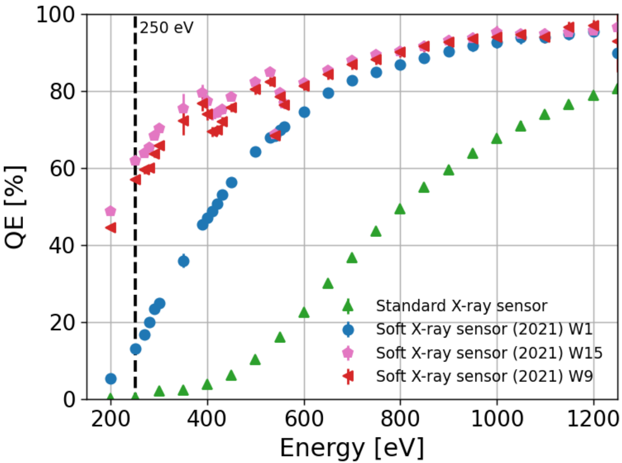


- Double sided process
- TEW ⇒ minimize:
  - Recombination at Si-SiO_2 interface
  - Recombination in undepleted Si
  - Passivation thickness

TEW Pixel QE

[M. Carulla HPXM 2023]





- Photocurrent measurement
- SIM beamline of SLS

QE > 60% @250 eV

TEW Pixel Outlook

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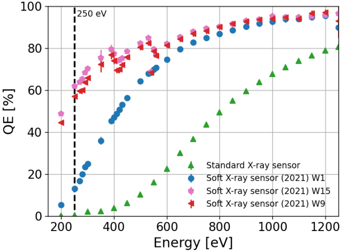
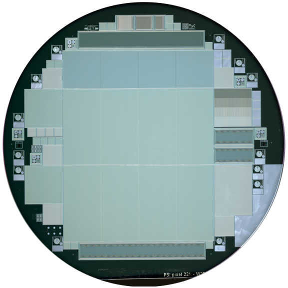
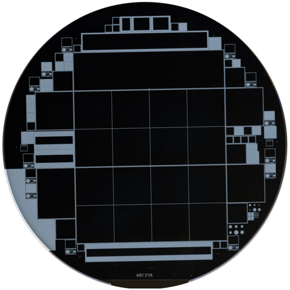
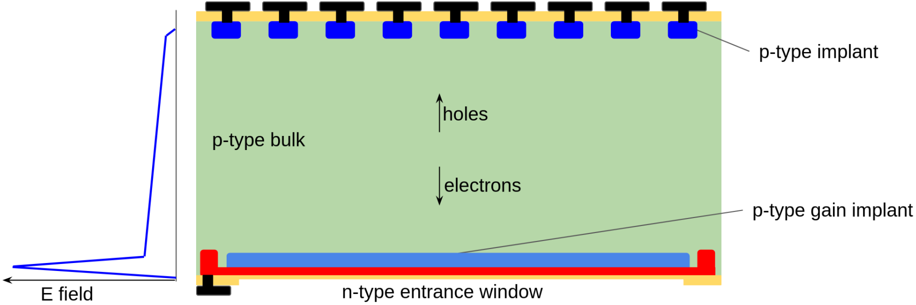
- Production batch with best TEW being completed
- New R&D batch being produced:
  - Reduce dielectric thickness
  - Test different dopig profiles
  - Aiming at QE $\gtrsim$ 80% @ 250 eV







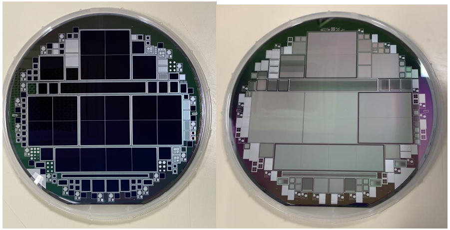
Double Sided (Inverted) LGADs



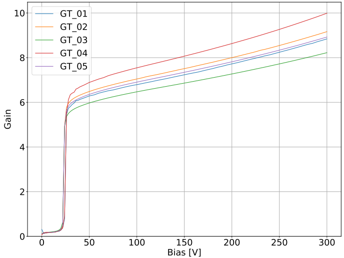
- Double sided process
- Continuous gain area in the active region ⇒ 100% fill factor
- TEW for x-rays
- Gain and TEW on same side

[G.F. Dalla Betta et al. NIMA 796 (2015) 154]

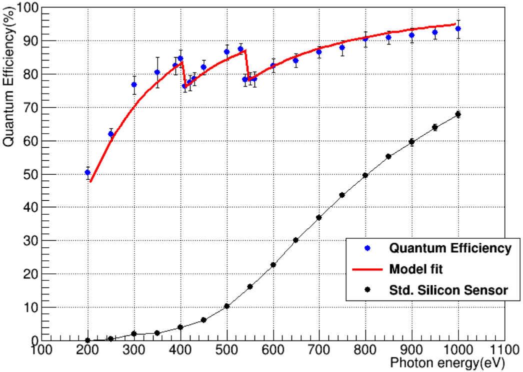
LGAD Gain and QE



Gain with LED (STD gain structure)



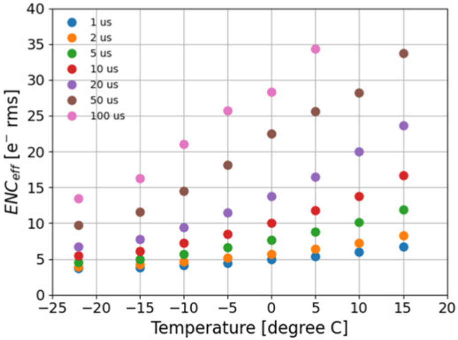
[A. Liguori TREDI2023]
Sensors w/o gain

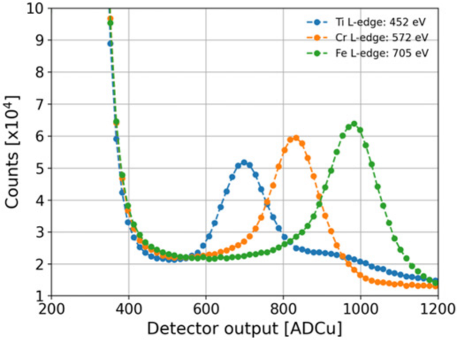


Maintained pixel performance:
QE > 60% @ 250 eV

LGAD Single Photon Resolution and ENC

[J. Zhang et al. 2022 JINST 17 C11011]





$$ENC_{eff}[e^-] = \frac{\sigma[ADU]}{gain[ADU/keV]} \cdot \frac{1000}{3.6eV}$$

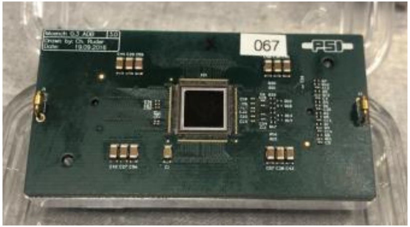
- Noise reduction through charge multiplication
- Lower T $\Rightarrow$ lower current, higher gain

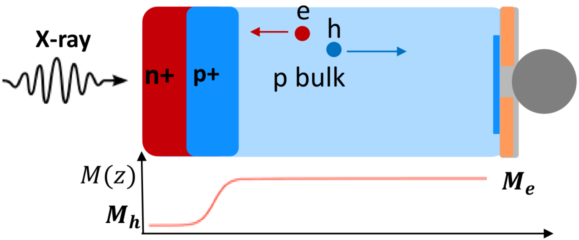
Single photon resolution at 452 eV

LGAD Charge Spectra

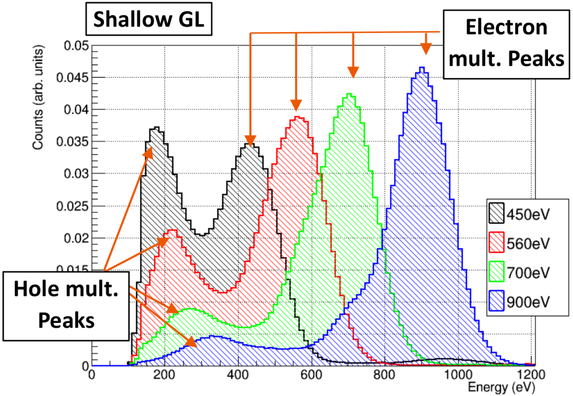
[A. Liguori TREDI2023]

Mönch charge integrating ASIC





Charge spectra

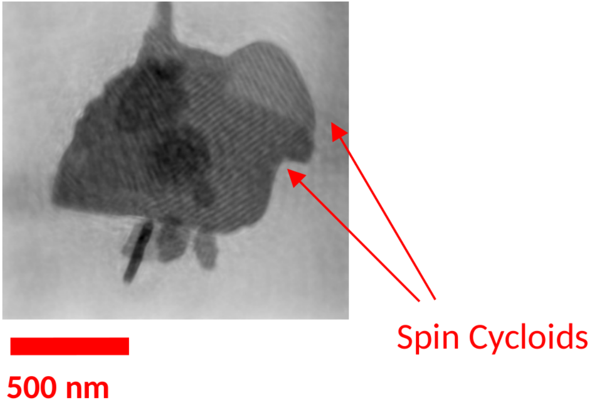


Holes mult. peak visible down to 450 eV

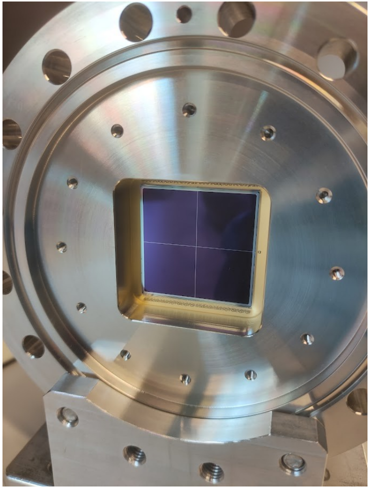
LGAD First Applications

[A. Mozzanica HPXM 2023]

- Ptychographic imaging of $BiFeO_3$ at Fe L3 edge (712 eV)
- Tim Butcher at SIM beamline
- Current resolution $\sim$ 8 nm



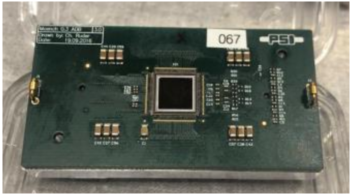
Eiger 512x512 LGAD sensor on vacuum flange

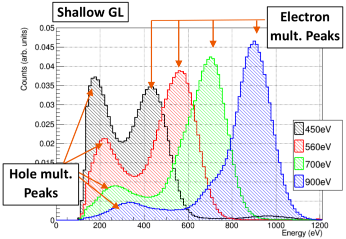


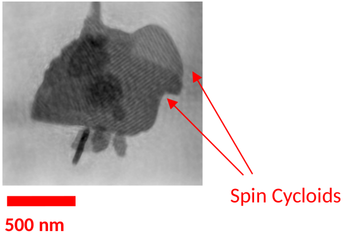
LGAD Outlook

Future R&D batch:

- Improve thin gain structures
- More superficial and narrow gain structures
  - More x-rays get full e^- mult.
  - h^+ gain closer to e^- gain
- Improve TEW



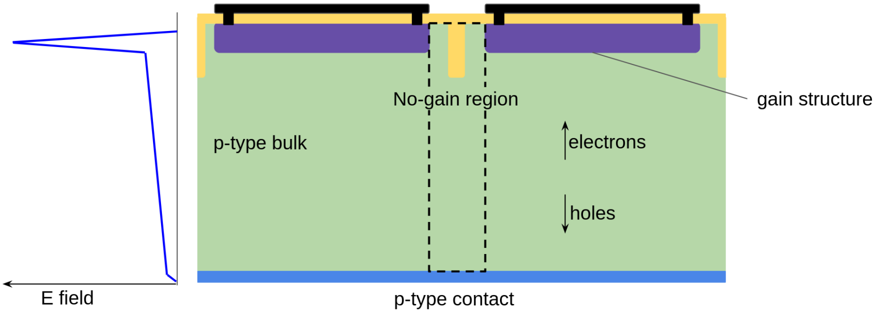




Future (short term)

[innovatorsmag.com]

Trench Isolated LGADs

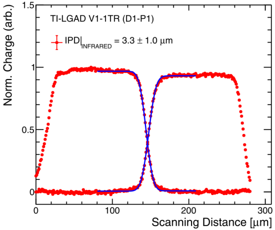


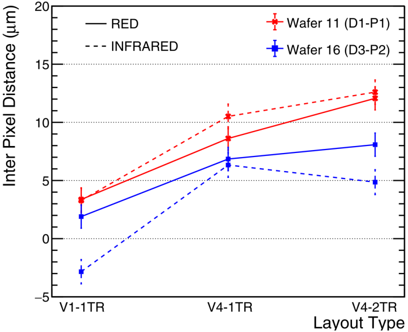
- Gain structure on readout side
- Trenches used to isolate channels
- Trench width about 1 μm $\Rightarrow$ narrower no-gain area than standard LGADs

[G. Paternoster et al. IEEE EDL Vol 41 Issue 6 (2020) 884-887]

Trench Isolated LGADs

[A. Bisht et al. NIMA 1048 (2023) 167929]



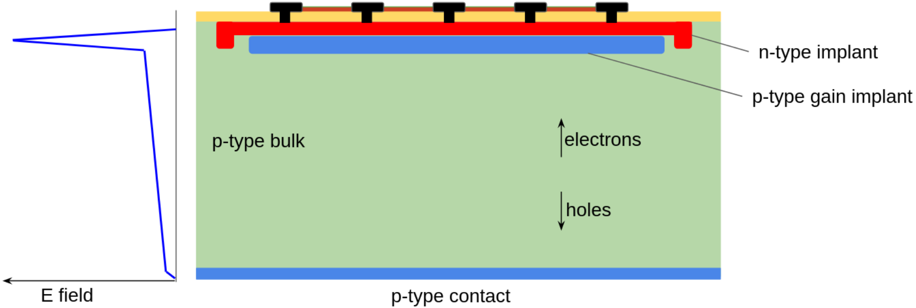


- No-gain area of 3-5 μm on 50 μm substrate
- One production for high energy physics and a second ongoing
- See also M. Senger et al. NIMA 1039 (2022) 167030

For x-ray applications:

- All photons get full e^- gain
- “Fill factor” of 94% for 100 μm pixels
- Is the no-gain area for 50 μm preserved for thicker sensors?
- How to scale trench lithography for large sensors?

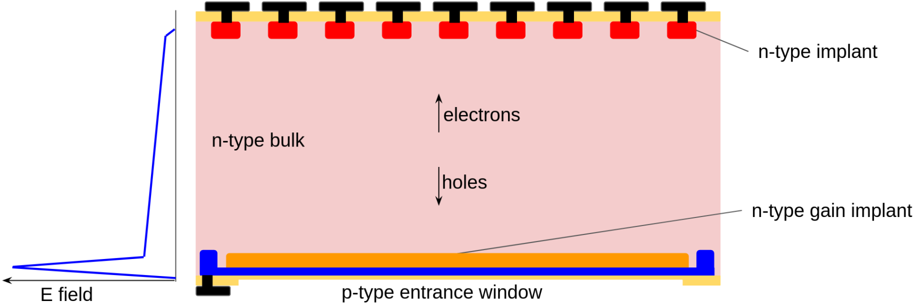
DC Resistive Silicon Detectors (LGADs)



- Resistive charge sharing between pixels $\Rightarrow$ improved spatial resolution
- Channel isolation can be an issue depending on electronics
- Planned first experimentation for high energy physics (thin substrates, single sided)

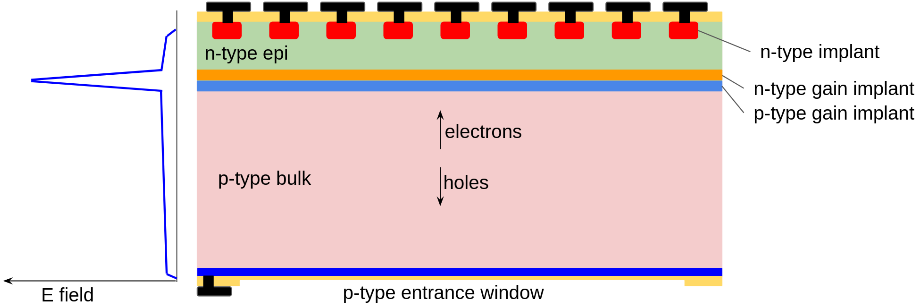
[L. Menzio et al. NIMA 1041 (2022) 167374]

N-type Inverted LGADs



- Inverted LGAD inverting all doping types
- Process to be developed
- More superficial interactions get e^- gain, deeper interaction h^+ gain
- No plans to produce this form
- Planned first experimentation for high energy physics (thin substrates, single sided)

Deep Junction LGADs

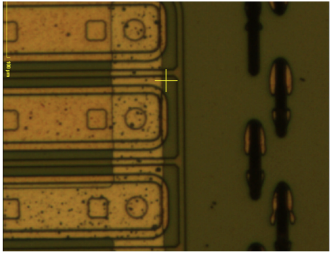


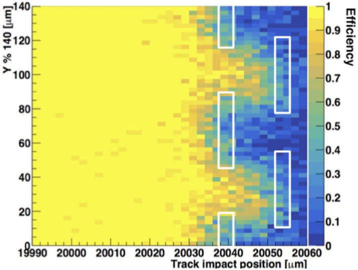
- Contiuous gain layer
- Pixel segmentation separated from gain segmentation
- Process to be developed
- All photons get full e^- gain
- Submitted an RD50 project for high energy physics

[S. Mazza RD50 workshop 2023]

Active Edges

[G. Calderini et al. 2019 JINST 14 C07001]

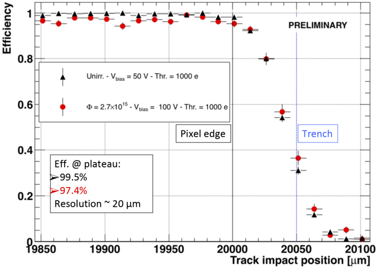




- Produced on thin active substrates $\sim$130 μm
- Trench-to-pixel distance 50 μm
- Other options: continuous trench, columns

For x-ray applications:

- Thicker substrates (deeper trenches)
- Integrate process with TEW
- INFN funding application for x-ray sensors for astrophysics



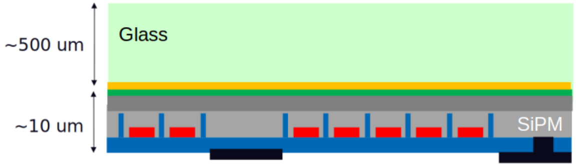
3D Integration Clean Room

New clean room under commissioning at FBK

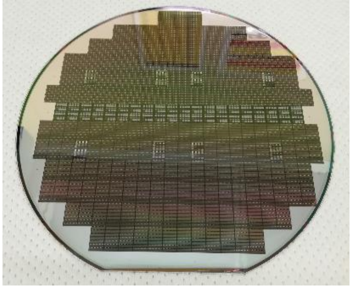
- 187 m^2 ISO class 4 and 5
- Wafer Temporary Bonding/Debonding
- Metal and Fusion Direct Bonding
- Grinding and Polishing
- Metrology for 3D stacked wafers
- Atomic Layer Deposition

Backside (Post-)Processing

BackSide Illuminated SiPM for IR



SiPM side



Glass side

- Bonding
- Grinding
- Chemical Mechanical Polishing
- Debonding

- 8 inch capability for grinding, CMP, bonding, debonding
- TEW to be tested for BSI SiPM for UV
- TEW on x-ray sensors for astrophysics in INFN funding request

Future (medium term)

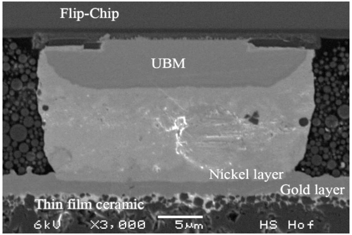
[Tumblr]

A New Clean Room and Equipment

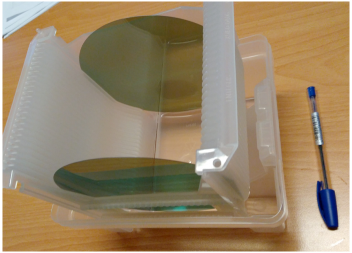
Capabilities being defined

- Bump bonding
- SiC
- SiGe, Ge on Si
- Packaging
- Improved lithography
- ...

[S. Härter et al. IEEE 2012]



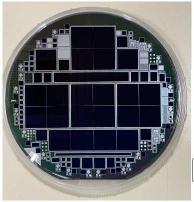
[Wikimedia]

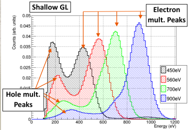


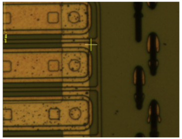
[Wikimedia]

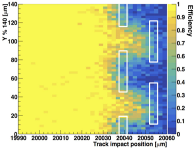
Summary

- Several activities at FBK for soft x-rays
- Performances close to requirements document
- TEW and LGAD technologies being developed
- Future projects push these technologies
- Upgrades of the clean rooms open new possibilities
- New processes and materials
  $\Rightarrow$ new sensors and applications





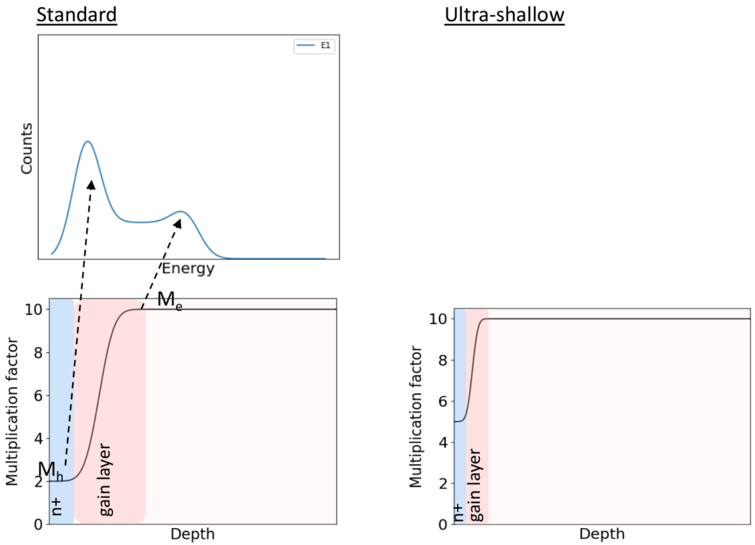




Backup Material

Charge Spectra iLGAD

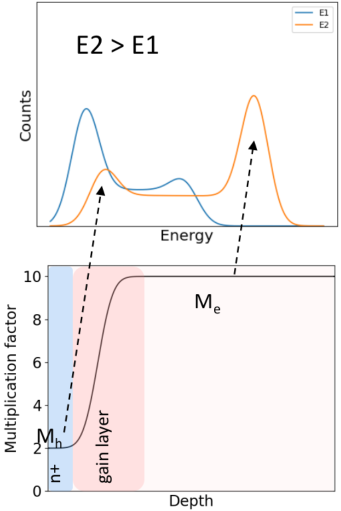
[M. Carulla HPXM 2023]



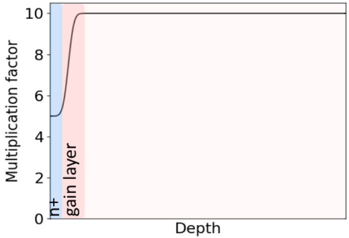
Charge Spectra iLGAD

[M. Carulla HPXM 2023]

Standard

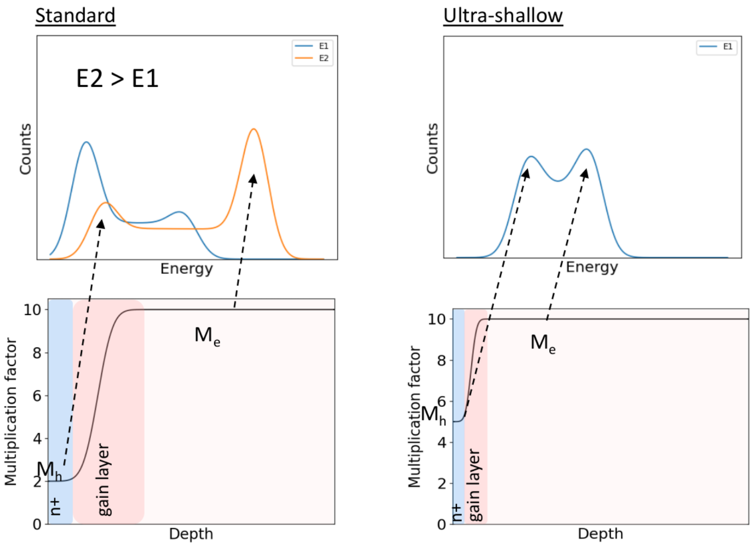


Ultra-shallow



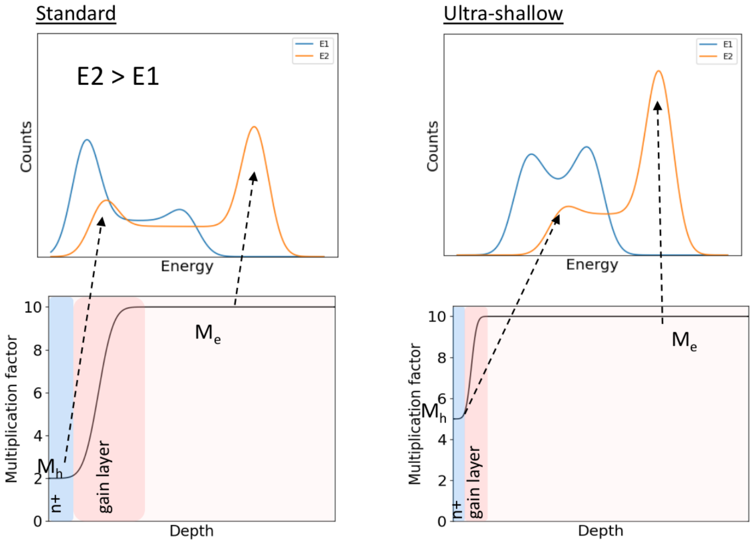
Charge Spectra iLGAD

[M. Carulla HPXM 2023]



Charge Spectra iLGAD

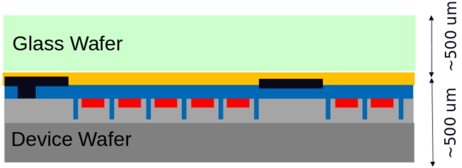
[M. Carulla HPXM 2023]



BSI SiPM Process

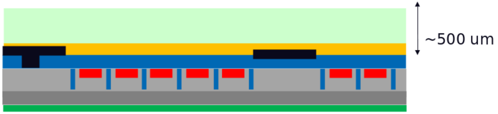
1. SiPM Wafer

2. Temporary Bonding

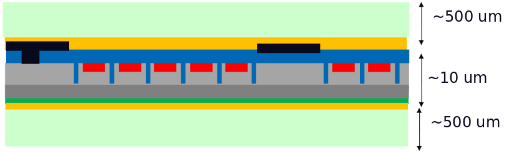


3. Grinding & Polishing

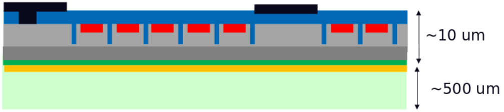
4. Backside processing



5. Permanent Wafer Bonding



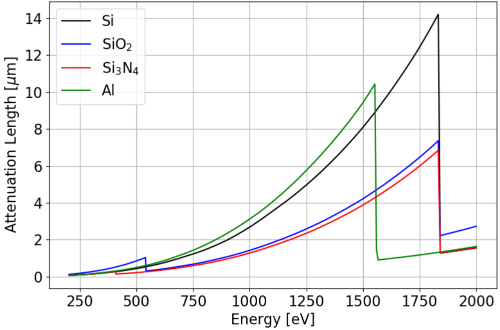
6. Wafer Debonding

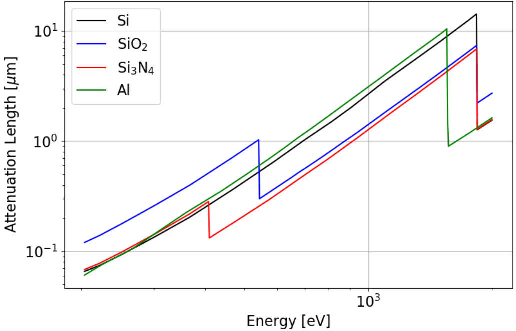


See also L. Parellada-Monreal et al. NIMA 1049 (2023) 168042

Soft X-rays Attenuation

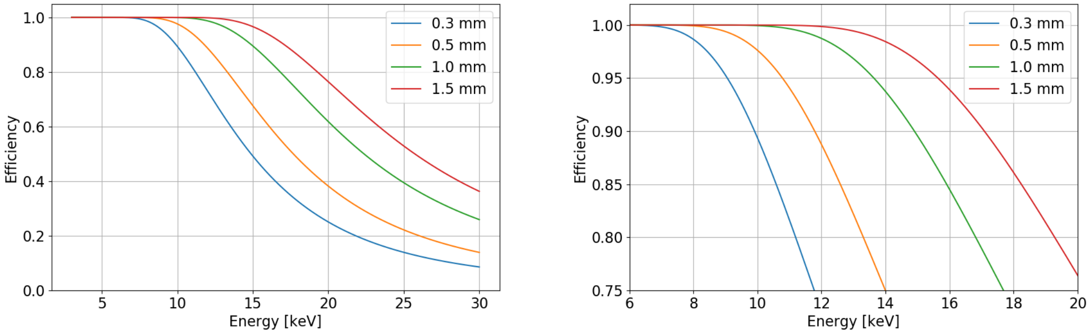
Data from http://henke.lbl.gov/optical_constants/atten2.html





“Hard” X-rays Efficiency Si

Attenuation length data from http://henke.lbl.gov/optical_constants/atten2.html



DC-RSD

[L. Menzio et al. NIMA 1041 (2022) 167374]