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UNIVERSITÉ JEAN MONNET SAINT-ÉTIENNE

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4–11: A CMOS Image Sensor with A Stacked Photon Absorber for Wide-spectral Imaging

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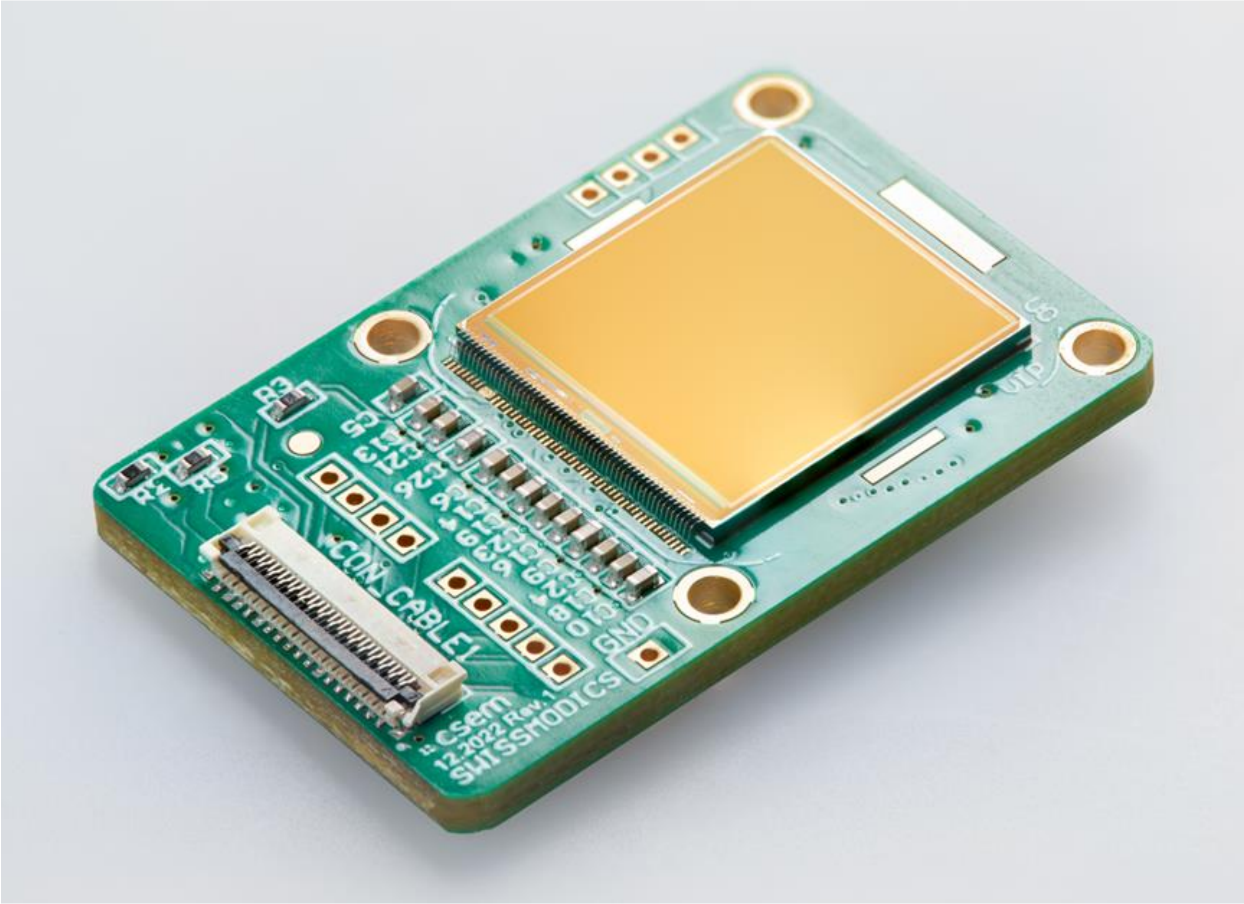
Outline

- Context
- Proposed approach
- Step 1: readout chip design
- Step 2: Sensor development
- Conclusions



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Context

Image Credit: News on Cornell.Edu

Impact on composite structures can generate long-distant delamination. → **Defect detection requires immobilizing the aircraft.** → **How about more efficient diagnostic tools?** → **Inserting miniaturized cameras would ease the detection.**

Context

Swissmodics: Development of a **S**ensor with **Wi**de-**S**pectral **S**ensitivity for **MO**nitoring of **D**amage and Defects **I**n **C**omposite Structures

- State-of-the-art

  3D connection of photon absorbers to readout chips via bonding techniques

- Trend

  Going towards monolithic detectors to reduce cost and increase resolution

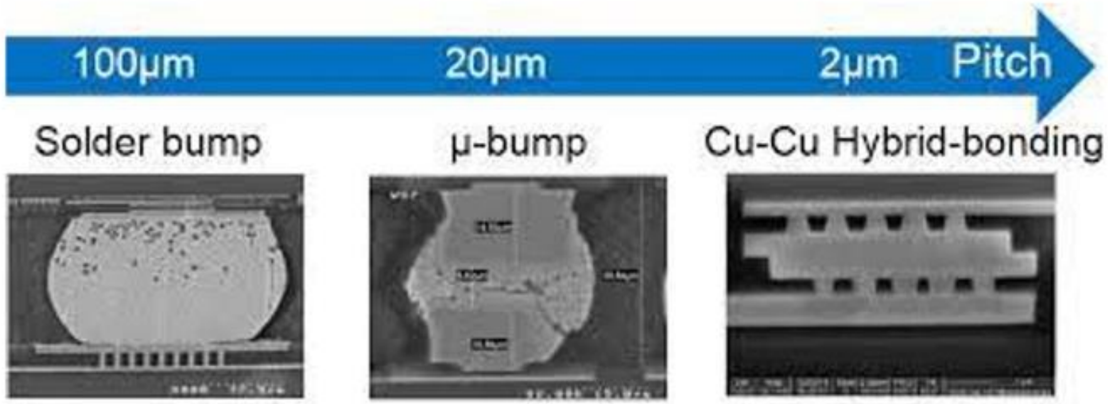
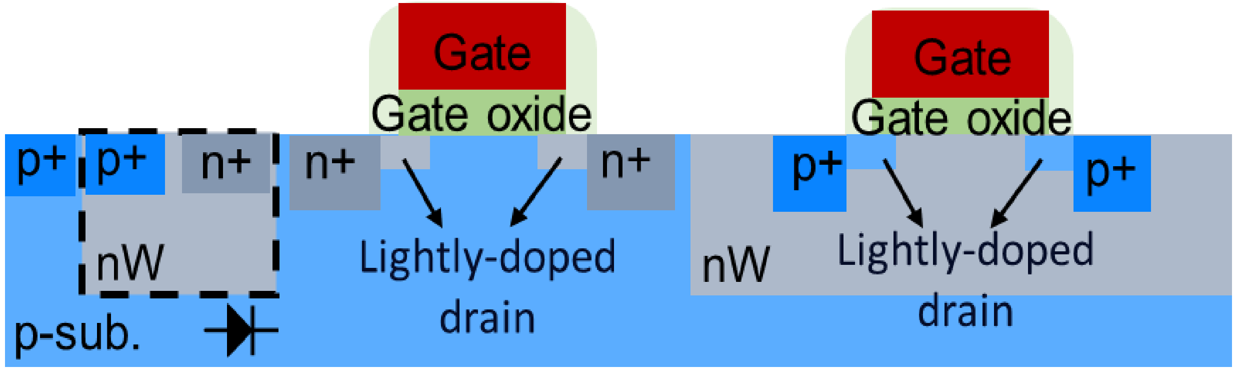


Image Credit: Imed Jani. Uni. Grenoble Alpes, 2019.

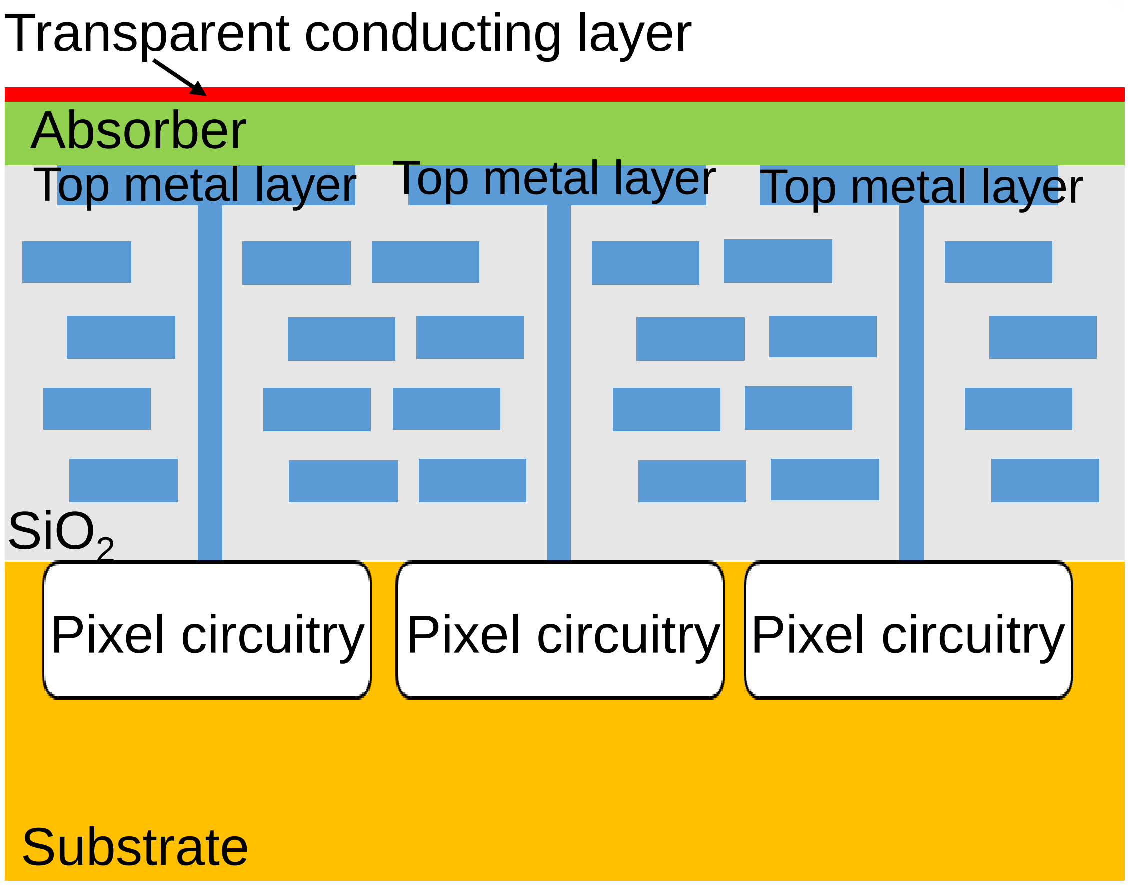


A simple sketch for a CMOS image sensor.

Proposed approach

3-D monolithic detectors with exotic sensing materials for X-ray, visible, and near-infrared (NIR) imaging

- Absorber on top of a pixel array for a 100 % fill factor
- Entire pixel area available for circuitry
- Top metal layer of the CMOS process as the in-pixel electrode
- Transparent conducting layer on top of the absorber as the global counter electrode
- Configurable pixel architecture to cope with various photon energies
- Compatible with different sensing materials (perovskite, quantum dots(QDs), …)



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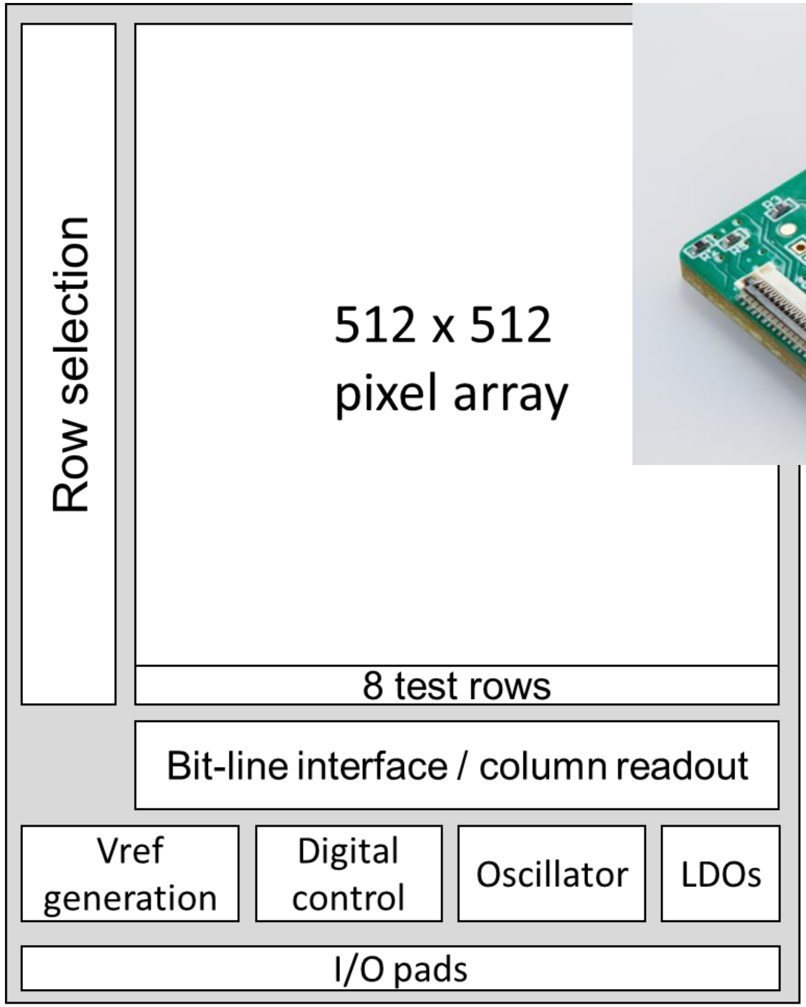
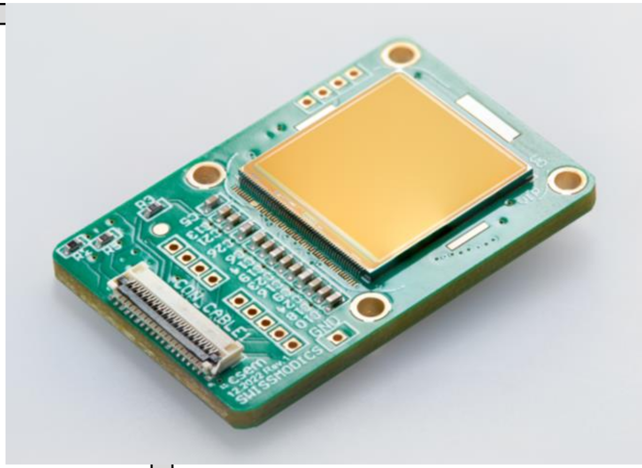
Readout chip design: design features





Features	Values
Supply voltage	3.3 V, 1.8 V
Pixel resolution	512 x 512
Pixel pitch	22.5 µm
Sensitivity (C_{min})	50 µV/e-
Full-well capacity (C_{max})	8.5 Me-
Dynamic range	> 100 dB
Maximum frame rate	50 fps
Hole and electron collection	√
Global shutter	Similar

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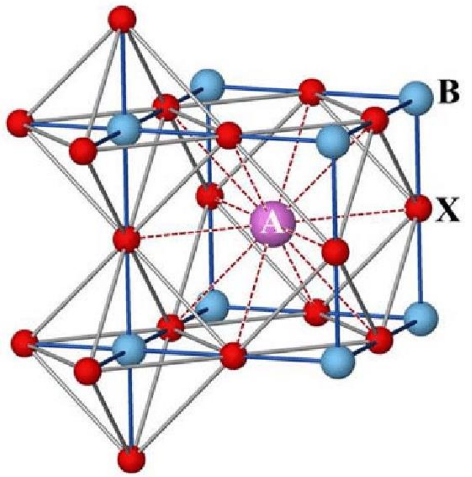
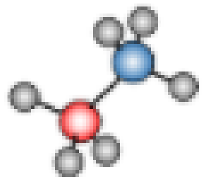
- **Step 2: Sensor development**
  - **Sensors based on hybrid perovskites**
  - **Sensors based on quantum dots**
- Conclusions

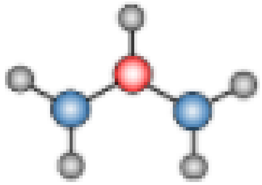
Sensors based on hybrid perovskites

- General structure formula
  - ABX_3
  - A=cation (Inorganic Cs^+; organic MA^+,FA^+)
  - B= Pb^{2+}, Sn^{2+}
  - X= I^-, Br^-, Cl^-





Methylammonium
$MA^+(CH_3NH_3)^+$



Formamidinium
$FA^+(CH_3NH_3)^+$

- Material properties
  - A high tolerance of defects even by solution processing
  - Low temperature budget up to 100 °C of annealing
  - Long diffusion lengths
  - Ambipolar (hole and electron) charge transport
  - A high carrier mobility
  - **An adjustable bandgap**
  - **Strong optical absorption**

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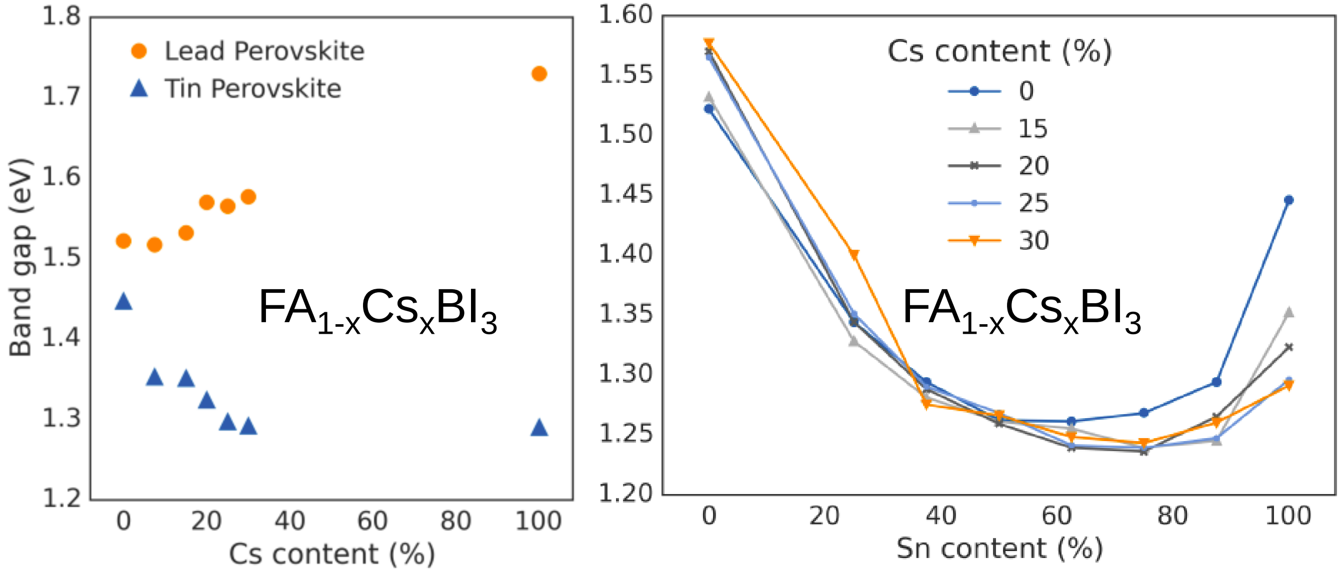
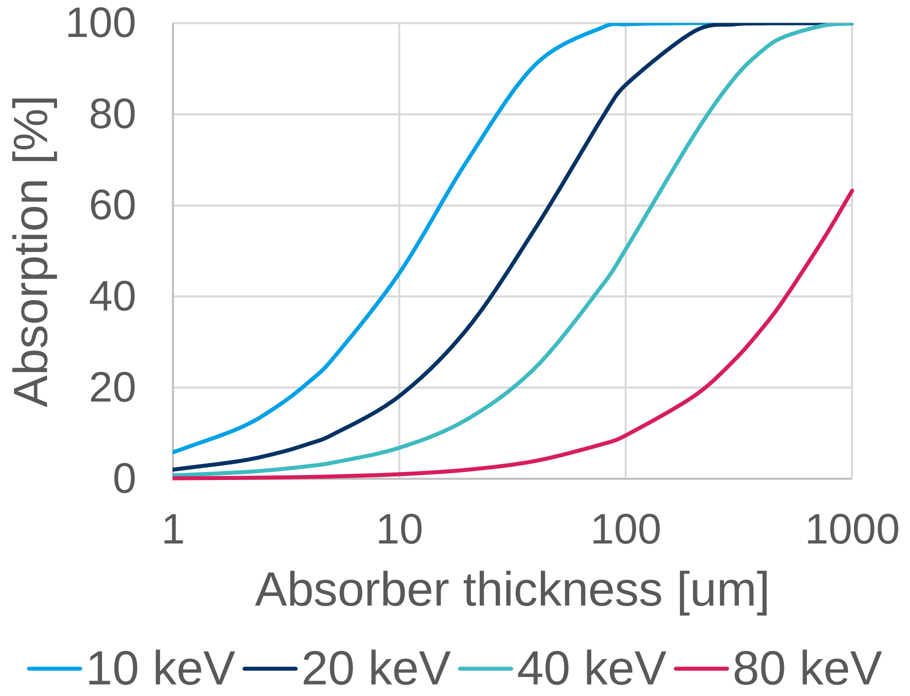
Sensors based on hybrid perovskites

- Near-infrared detection
  - $FA_{0.83}Cs_{0.17}Pb_{0.5}Sn_{0.5}I_3$ with a bandgap down to 1.24 eV



📖 R. Prasanna, et al., "Band Gap Tuning via Lattice Contraction and Octahedral Tilting in Perovskite Materials for Photovoltaics," J. Am. Chem. Soc. 2017, 139, 32, 11117–11124.

- X-ray detection
  - $FA_{0.83}Cs_{0.17}Pb(I_{0.83}Br_{0.17})_3$ with a high absorption coefficient even for a thin film



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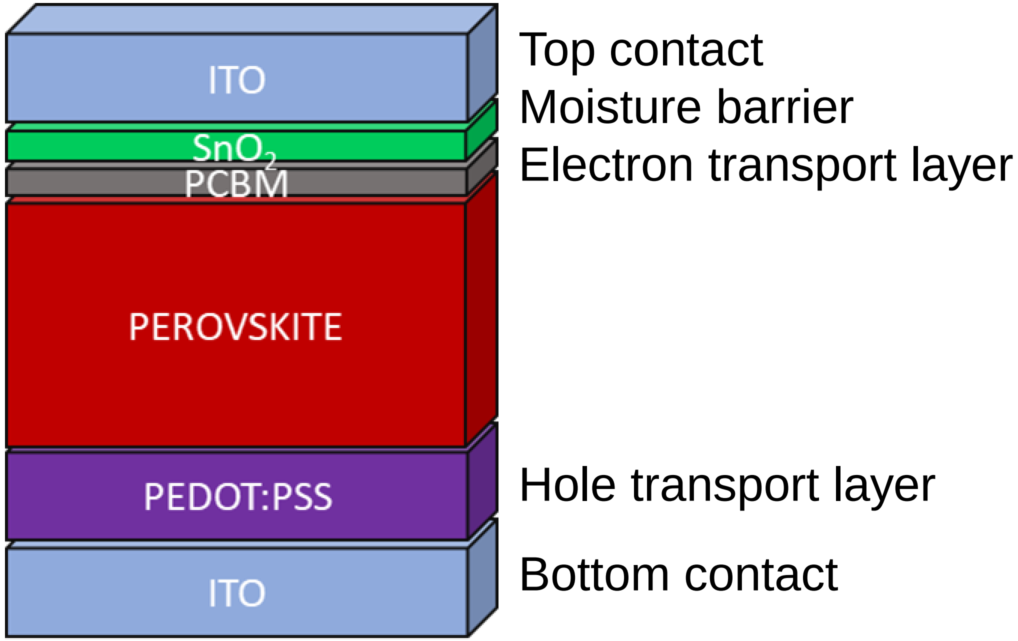
Sensors based on hybrid perovskites

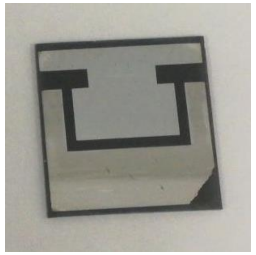
Sensor fabrication on a glass substrate

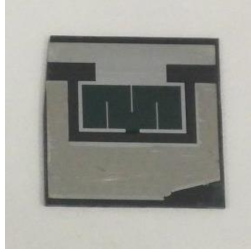
- Perovskite deposition by spin or blade coating
- First characterization to be shown

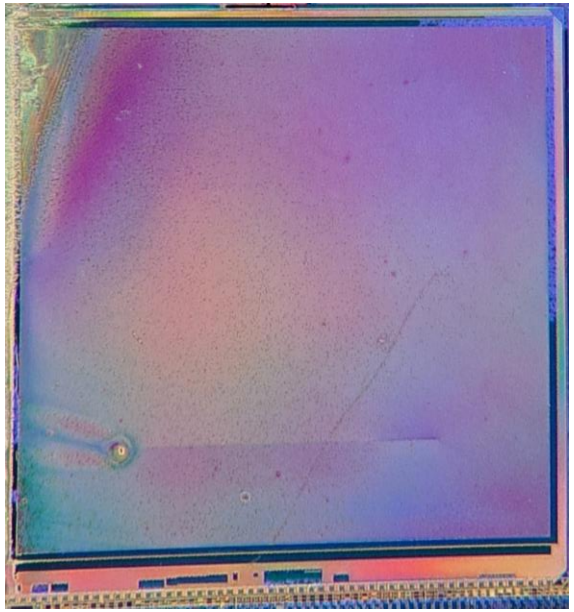
Sensor integration on our readout chips

- Challenge with stability to moist
- Processed samples to be characterized









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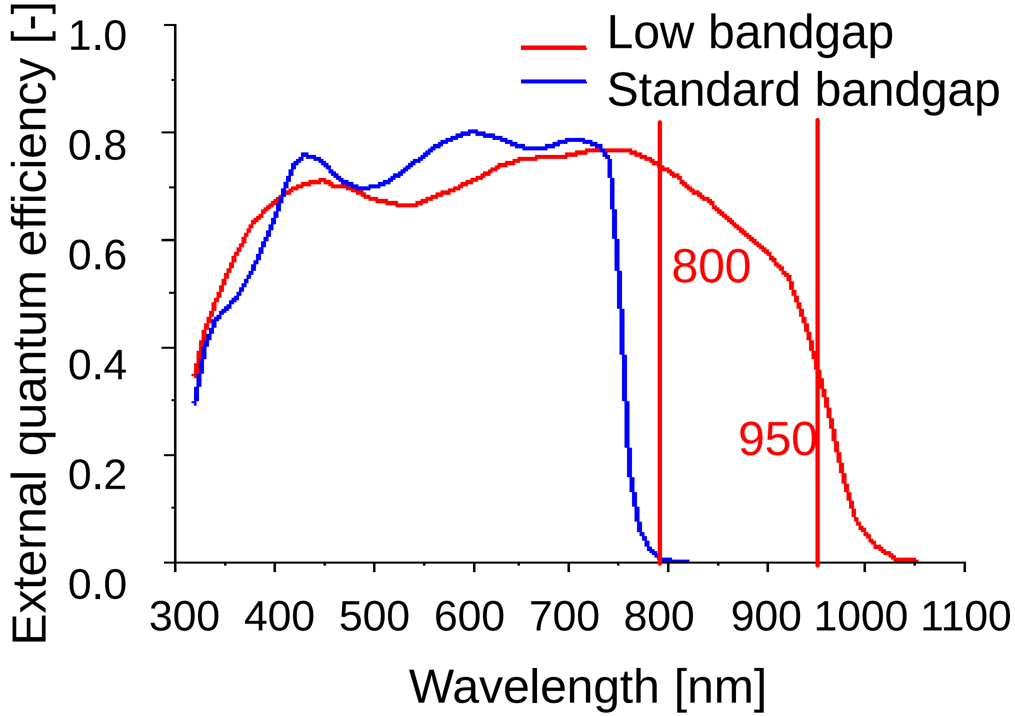
Sensors based on hybrid perovskites using a glass substrate

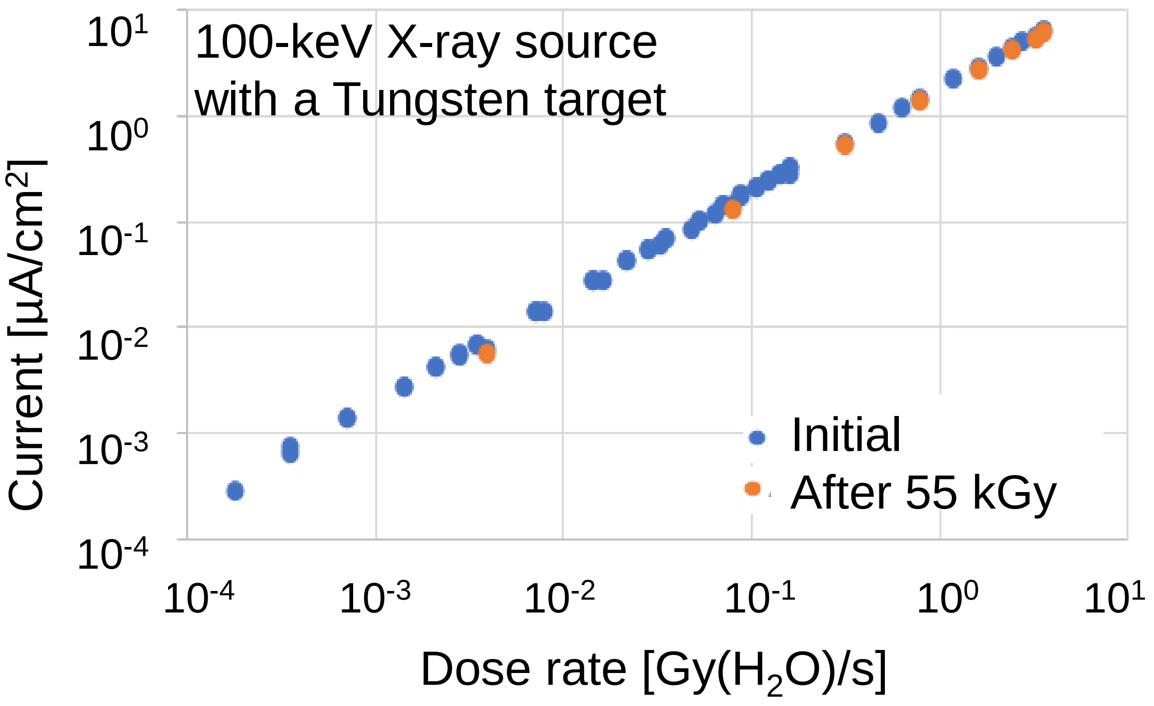
Characterization for near-infrared imaging

- Quantum efficiency above 70 % at 800 nm and 40 % up to 950 nm



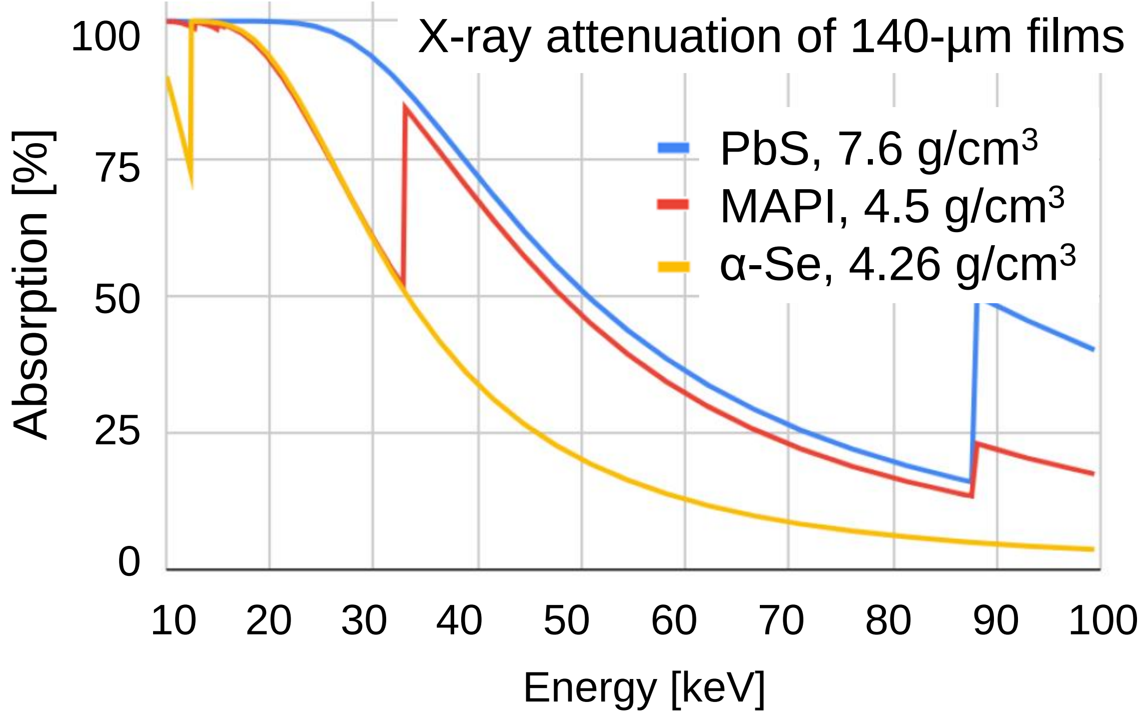
Characterization for X-ray imaging

- Good linearity over four decades
- Low response degradation after 55 kGy



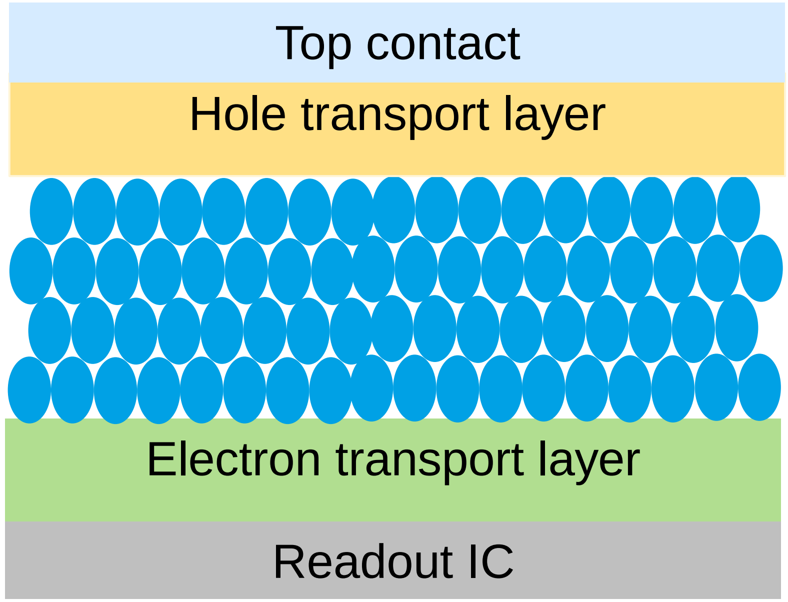
X-ray sensors based on quantum dots

- Material property
  - High absorption over a wide energy range of X-rays



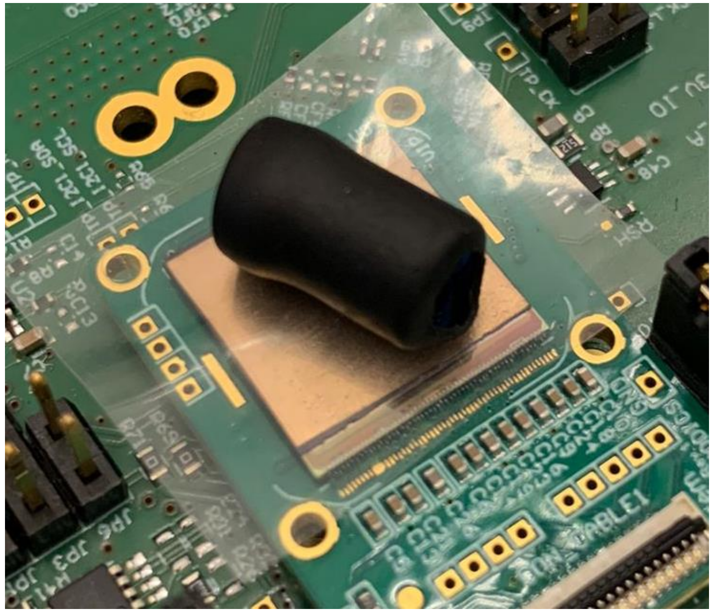
📖 This X-ray absorption plot is made from the NIST database.

- Device structure
  - Material deposition by spray coating
  - 120-um film of PbS quantum dots

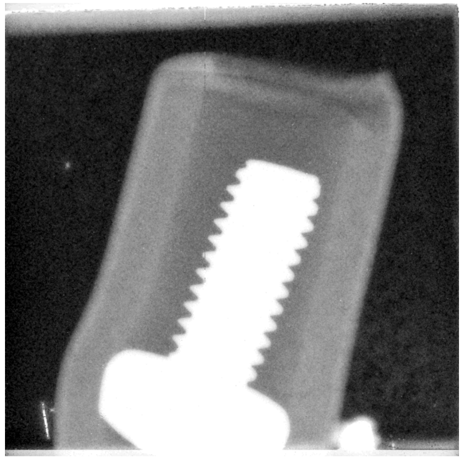


X-ray sensors based on quantum dots

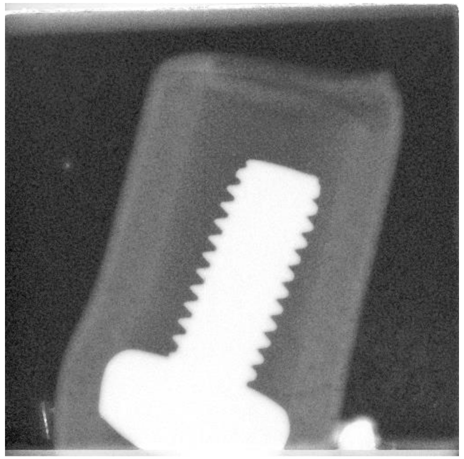
- Diode bias: 11 V



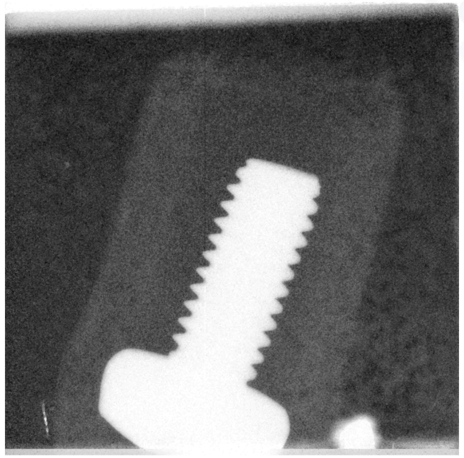
Screw in a plastic tube



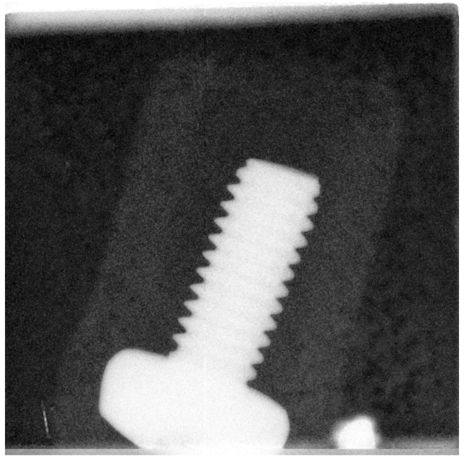
28 keV



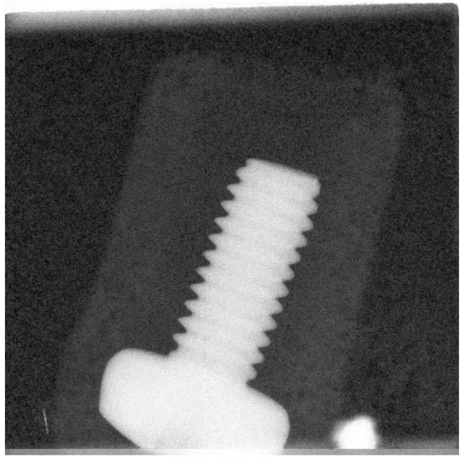
40 keV



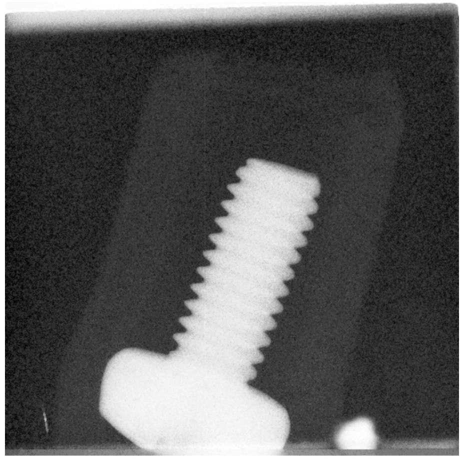
60 keV + 2-mm Al



80 keV + 2-mm Al



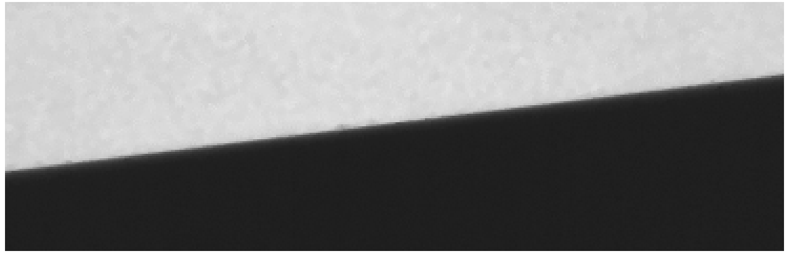
100 keV + 2-mm Al

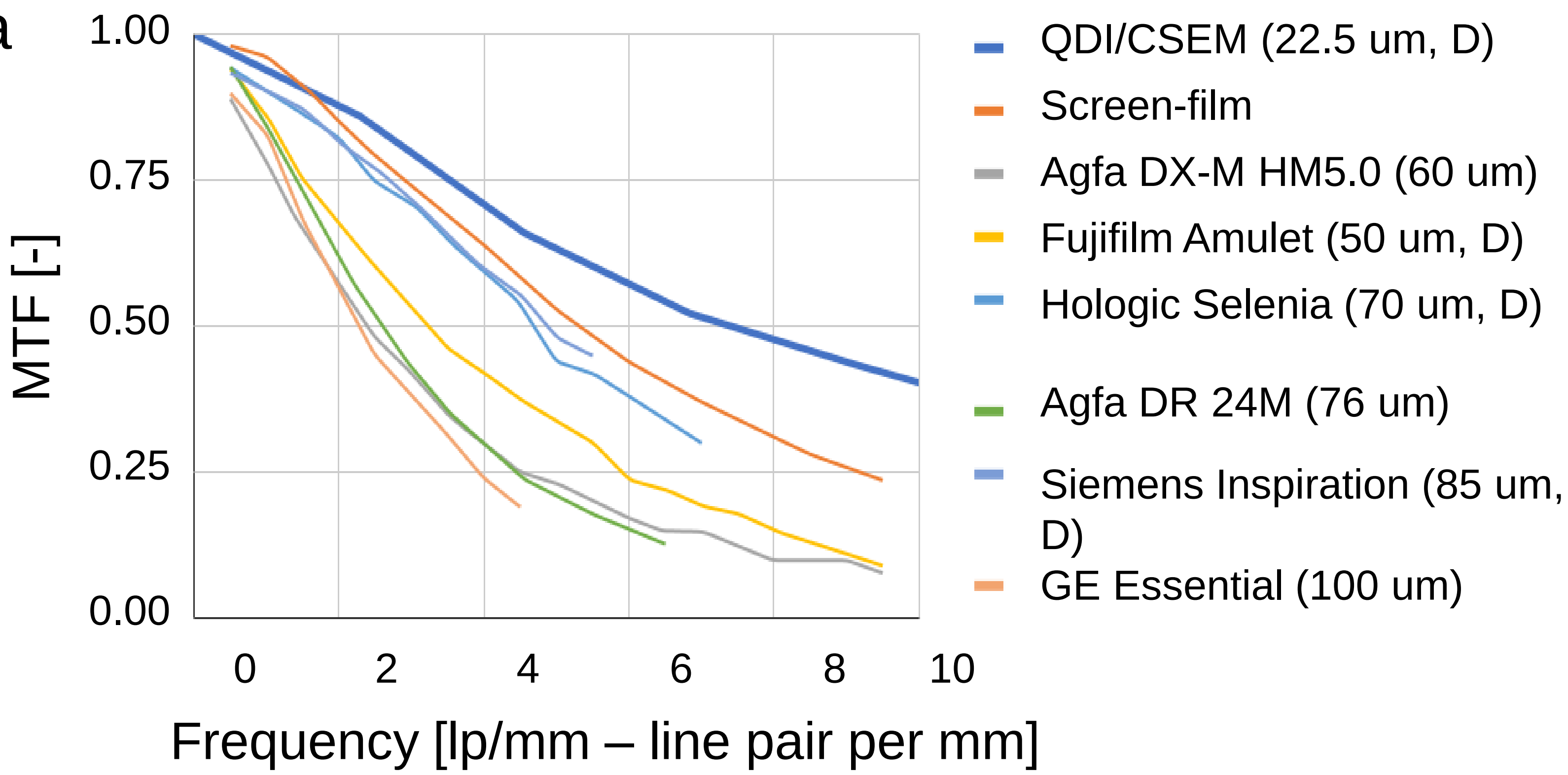


115 keV + 2-mm Al

X-ray sensors based on quantum dots: modulated transfer function (MTF) comparison

Image of an edge taken with a 5-V bias across the diode





📖 Modified from the white paper of Agfa, "Does the pixel size of a full-field digital mammography detector matter for early detection of breast cancer?," Copyright 2019.

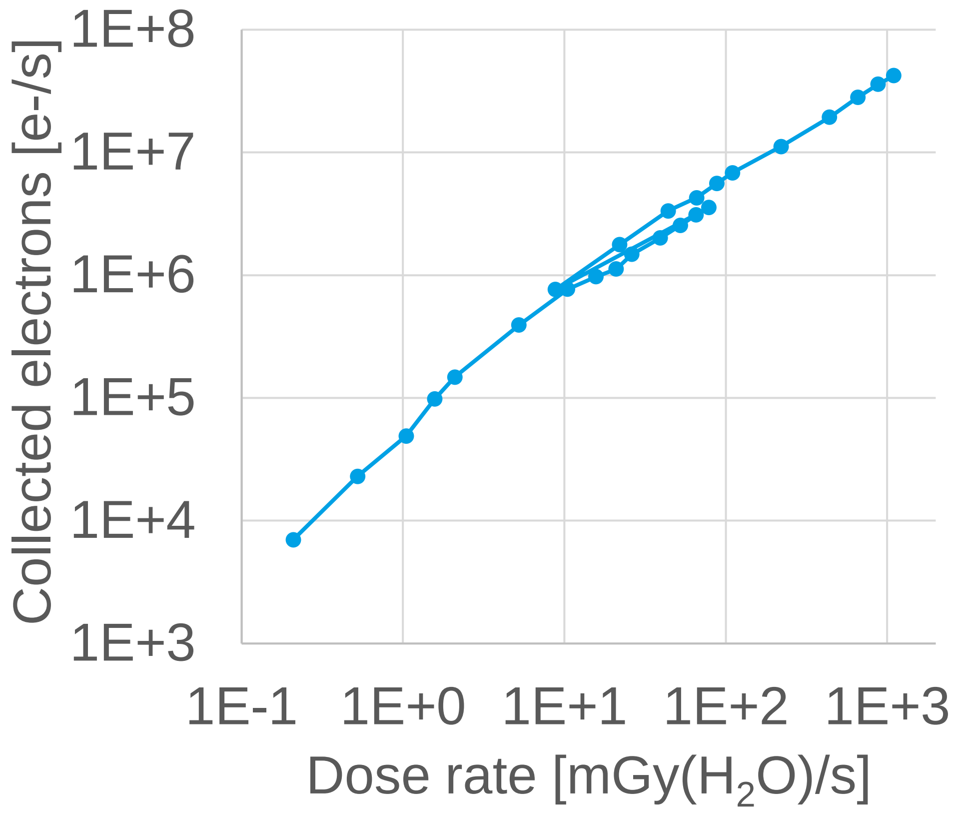
X-ray sensors based on quantum dots: noise equivalent dose (NED) comparison

Brand	Model	Pixel pitch	Technology	NED, uGy
Varex	PaxScan® 2530W	139	a-Si/GADOX	0.5
Varex	PaxScan® 2530W	139	a-Si/CsI	0.25
Trixell	Pixium® 4343 RC-e	148	a-Si/CsI	0.25
Trixell	Pixium® 4343 RC-e	148	a-Si/GADOX	0.64
Newheek	Ma1012X	85	IGZO/CsI	0.3

Brand	Pixel pitch	Technology	NED, 28 kV, uGy	NED 40kV, uGy	NED 60kV, uGy
QDI/CSEM	22.5	CMOS/QDs	**1.00**	**0.35**	**0.41**
QDI/CSEM	67.5 (3x3 binning)	CMOS/QDs	**0.33**	**0.12**	**0.14**

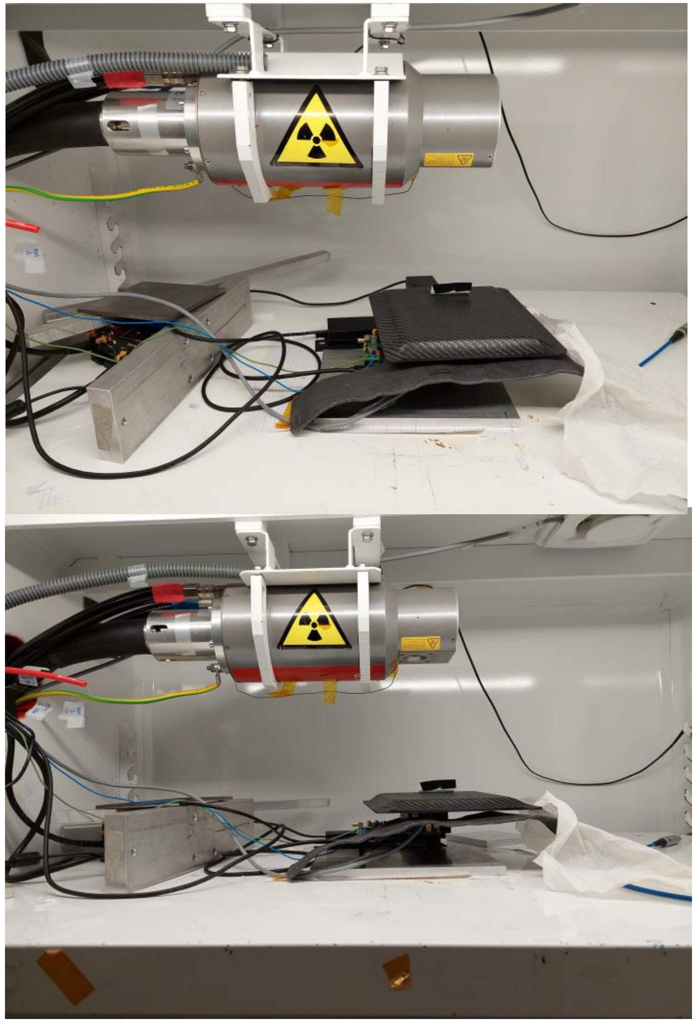
📖 Data is taken from product datasheets available on the website.

X-ray sensors based on quantum dots

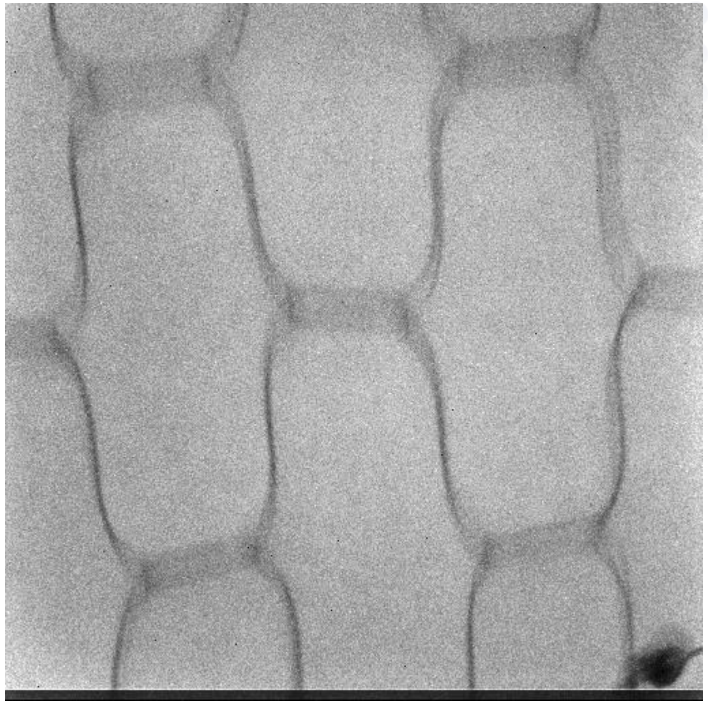


Electron flux w.r.t. dose rate

Bias only across the absorber: 5 V



X-ray setup in UJM



X-ray image of a 1.5-cm thick carbon composite

Tube voltage: 40 kV

Diode bias: 10 V

QDI systems

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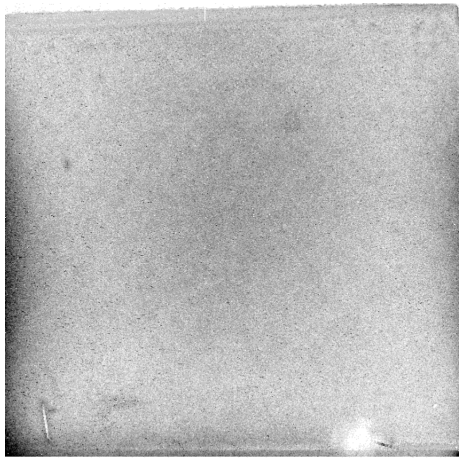
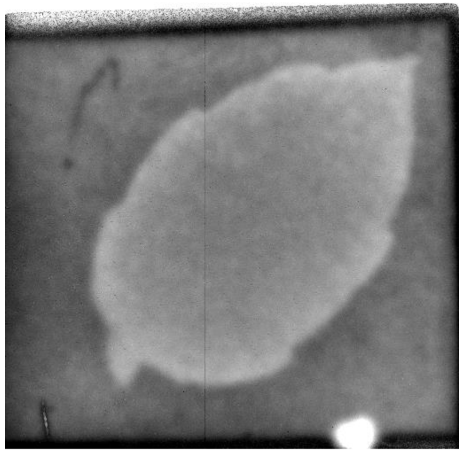
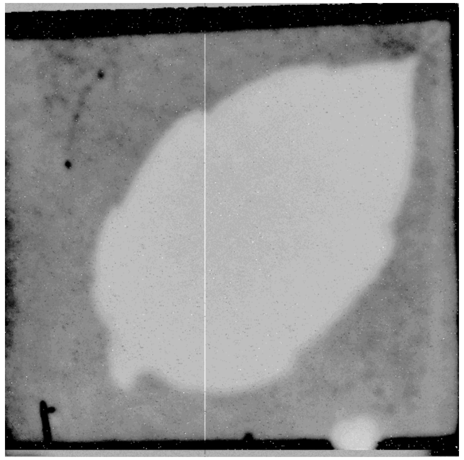
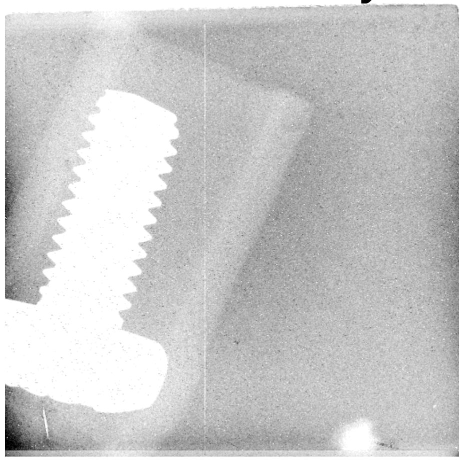
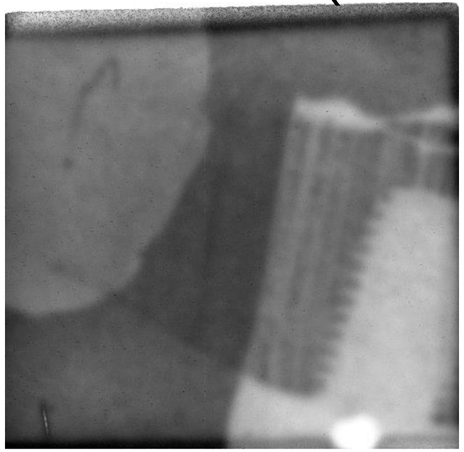
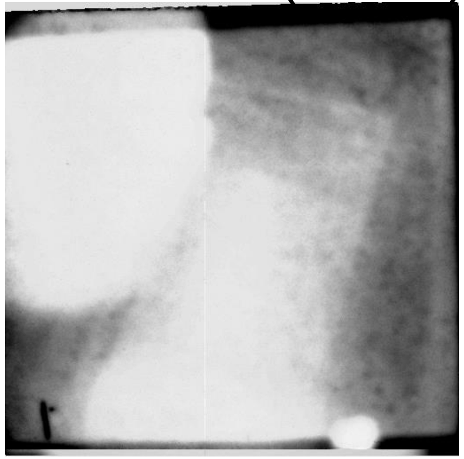
QD-based X-ray sensors sensitive to visible and short-wavelength infrared (SWIR) photons

Leaf | 28-keV X-ray | 1300-nm LED (SWIR) | White LED (visible)

Screw in a tube and leaf

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Conclusions

- We have developed CMOS readout chips compatible with different sensing materials.
- We have realized the first X-ray sensor based on direct conversion through PbS quantum dots.
- Our X-ray sensor achieves state-of-the-art sensitivity.
- Our X-ray sensor demonstrates potential for visible and near-infrared imaging.

- Next step
  - Detailed characterization of our exotic image sensors
  - Radiation measurements on our CMOS readout chips

Acknowledgement

Clean Sky 2
JOINT UNDERTAKING

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A CMOS Image Sensor with A Stacked Photon Absorber for Wide-spectral Imaging

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FACING THE CHALLENGES OF OUR TIME