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Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

INFN LNF

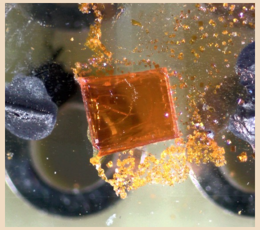
Missione 4 Istruzione e Ricerca

High Precision X-ray measurements

LNF

20-06-2026

Perovskite for X-ray detection: preliminary results from Micro-Perov and HyPoSiCX projects

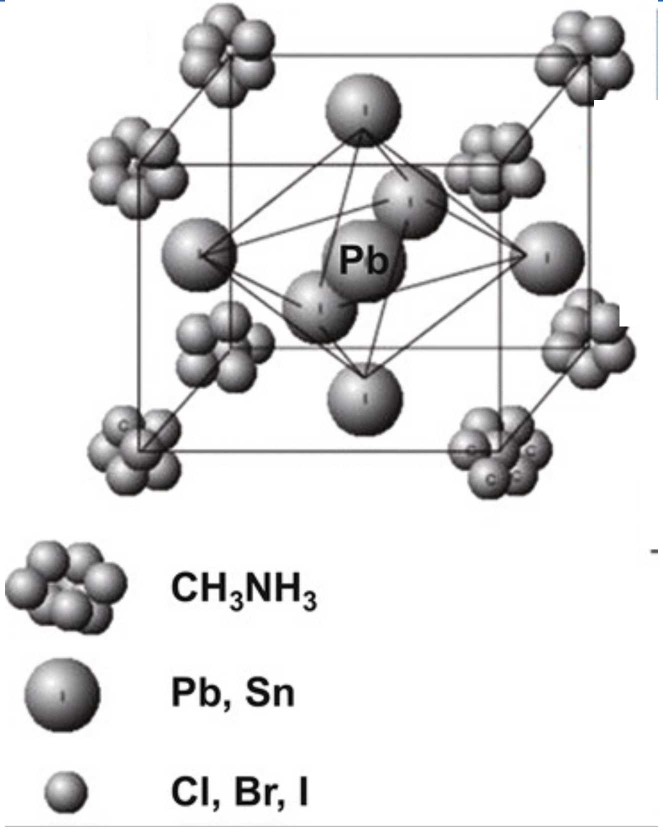


M. Testa (LNF-INFN) on behalf of:

- PRIN HyPoSiCX project : L.Pancheri (TIFPA), M. Testa, I. Viola (CNR-NANOTEC);
- MICROPEROV POC PNRR project : M. Testa, F. Matteocci, M. Auf der Maur (Dip. Ing. Elett. Tor Vergata), I. Viola, L. De Marco (CNR-NANOTEC)
- LNF-INFN: A. De Santis, A. Khan, G. Tinti, Z. Chubinidze, M. Beretta, G. Papalino, G. Felici, M. Gatta
- Univ. Trento: J. Endrizzi

Halide Perovskite

- **Organo Metal-Halide Perovskites (OMHP)** are a class of hybrid organic-inorganic semiconductor materials with a perovskite unit-cell structure **ABX_3** with A = $CH_3NH_3^+$, B = metallic cation (Pb^{2+}). X= halide anions (Cl^-, Br^-, I^-)
- OMHP are emerging as new generation photovoltaic material
- Band gap tunable changing halide (I,Br,Cl)
    - Opto-electronic properties combine **advantages from organic and inorganic semiconductors**

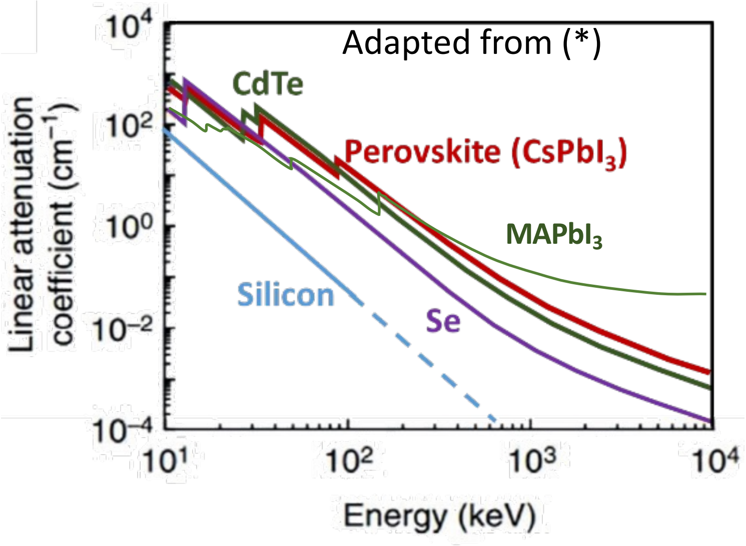


organic:
- Disordered system
- Localized electronic states
- Hopping transport ⇒ low mobility
- **Low cost, low temperature processing**
- **Can be solution processed**
- **Scalable to large area**

inorganic:
- **Ordered periodic crystal ⇒ band structure**
- **Delocalized Bloch states**
- **band transport ⇒ high mobility**
- Usually wafer based technology
- Costly, high temperature processes

- Disadvantage: contain ***highly mobile defects*** and have instabilities issues

Halide Perovskite for ionizing radiations



The typical composition of HP contains heavy elements (Cs, Pb, Ag, Bi, Sn, I, Br) with atomic numbers in the range of 47-82, larger in comparison to widely used X-ray absorber - CdTe (max atomic number is 52).

		Silicon	CH_3NH_3 (MA)$PbBr_3$
Density		2.33 g/cm^3	3.8 g/cm^3
Band gap (eV)		1.12 (indirect)	2.24 (direct)
Mobility μ (cm^2/Vs)	electrons	1400	25-140
	holes	450	13-220
Absorption (cm^{-1})		< 10^4	> $4x10^4$
Average energy for e/h creation (eV)		3.6	5.8
Radiation length X0 (cm)		9.36	2.33
Z_{eff}		14	62

- (μ x τ) product from 10^{-7} - 10^{-2} cm^2/V
- The typical values of the bulk resistivity >10^7 Ohm.cm (300K)
    - good signal/noise ratio
- **Self Healing** after radiation exposure

(*)Wei & Huang, J. Nat Commun 2019, 10, 1066; Del Sordo et al. Sensors 2009, 9; H.M. Thirimanne et al. Nature Comm 2018, 9, 2926

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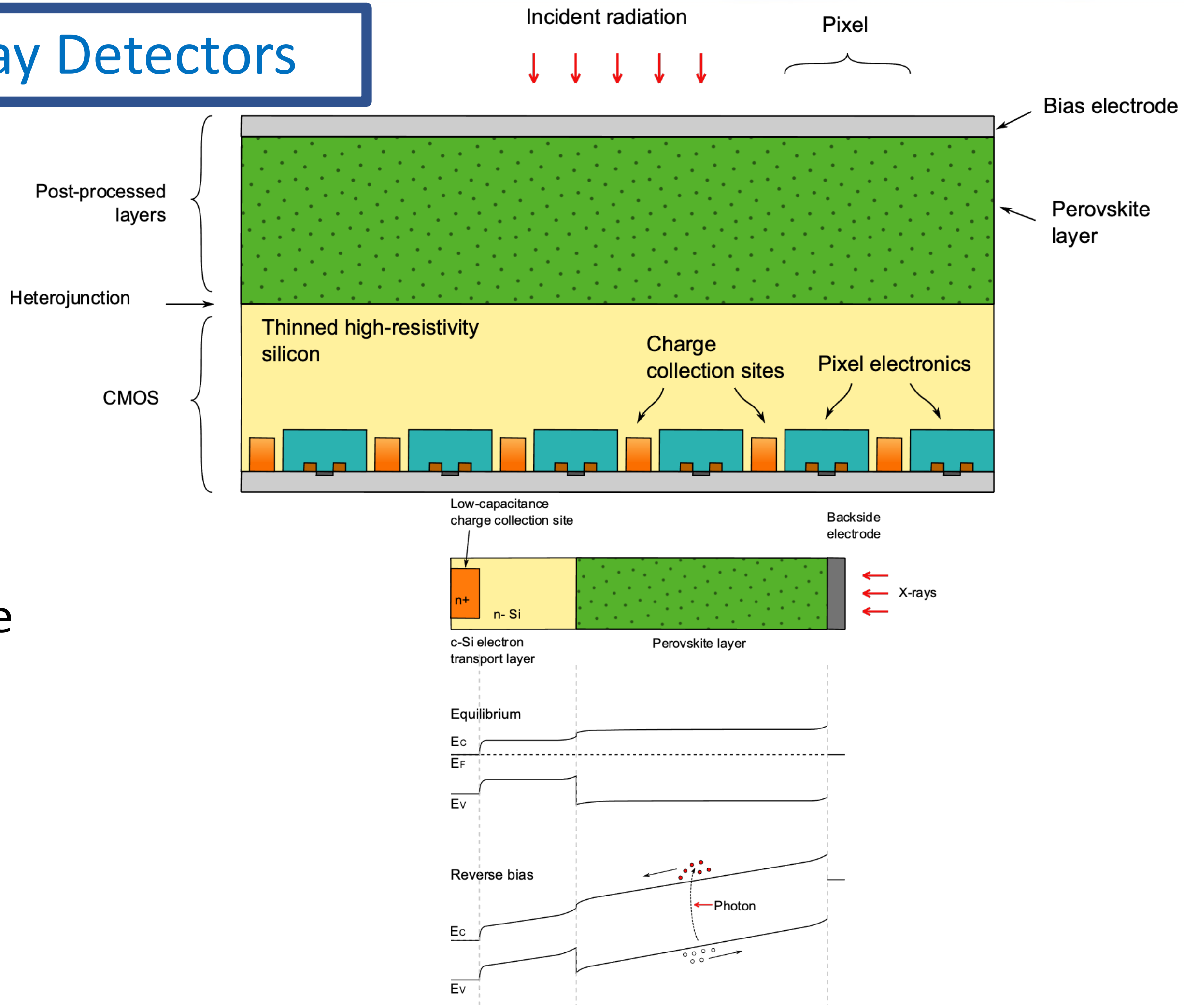
HyPoSiCX: Hybrid Perovskite on Silicon CMOS X-ray Detectors

- Goal: hybrid X-ray detectors with **perovskite** absorption layer and a **CMOS** silicon active layer
  - integrated readout electronics with array of pixels

- Direct generation in perovskite:
  - e^- (h) collected by silicon (backside electrode)
  - No barriers present for e^- and h :
    →fast collection and low recombination at interface

- Advantages with respect to flat panel technology and CdTe/CdZ
  - High Z perovskite →High efficiency in O(10) keV
  - CMOS pixel technology:
    - low-capacitance sensing sites→ low-noise readout
    - Spatial resolution of O(10) μm
  - Cost



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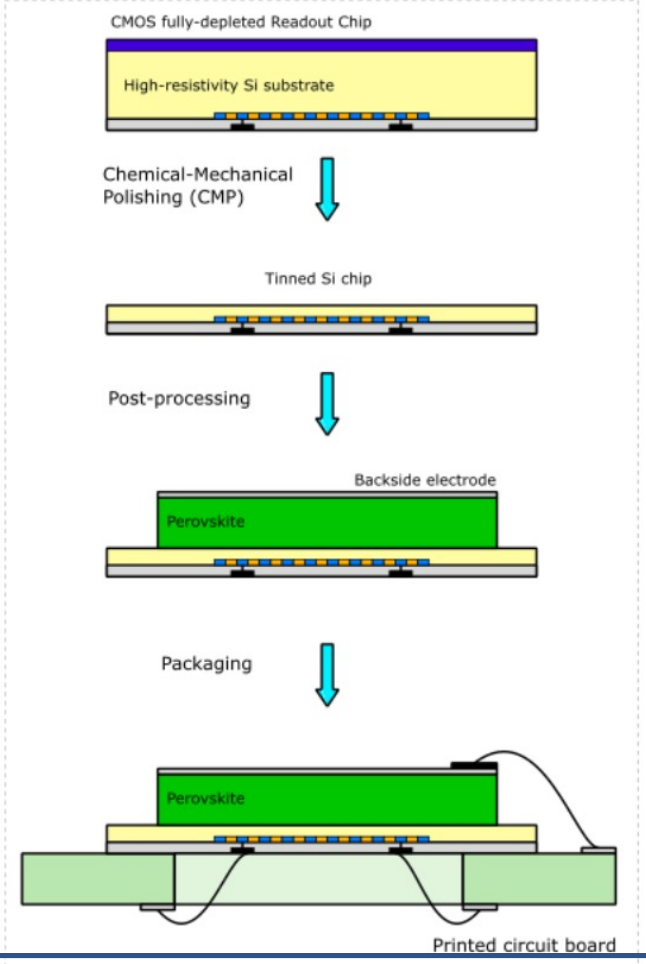
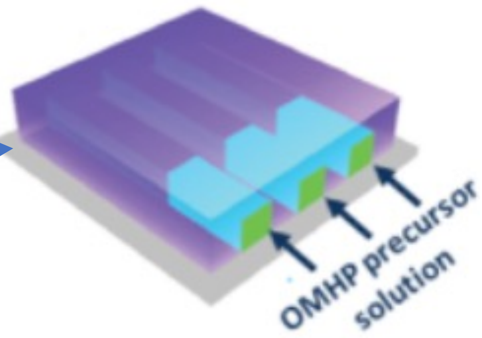
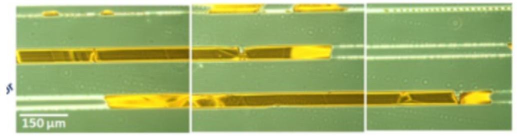
CMOS readout chip from ARCADIA INFN project



Micro-fluidics assisted direct growth on substrate

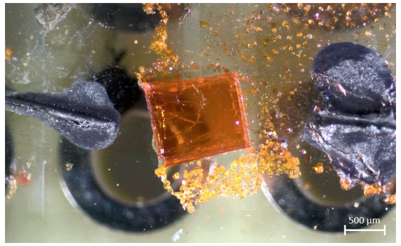


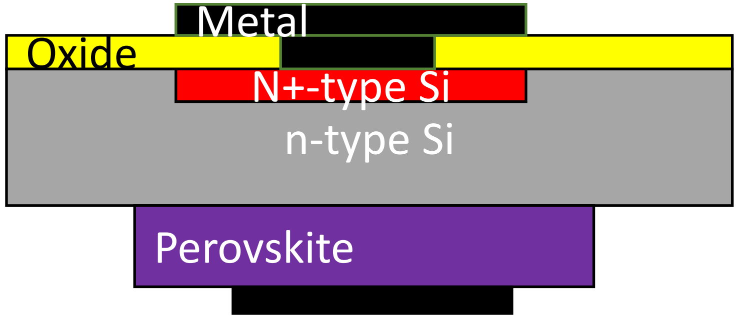


- single crystals in the form of microwires
  - →precise location and dimensions
  - → high aspect ratios (i.e. width/height)
- Target thickness of 100 μm, area of O(1) mm^2
- Bromide based OMHP will be used
  - expected to have less issues with mobile halide vacancies, compare to other compositions

- Type of prototype
  - Perovskite directly grown on **conductive glass**
  - Perovskite directly grown on **Silicon substrate**

    → Decouple the effect of interfaces with Silicon from pure perovskite





- Excitation sources for testing
  - X ray tubes
  - Minimum Ionizing Particles (MIP) from test beam
  - Visible Light

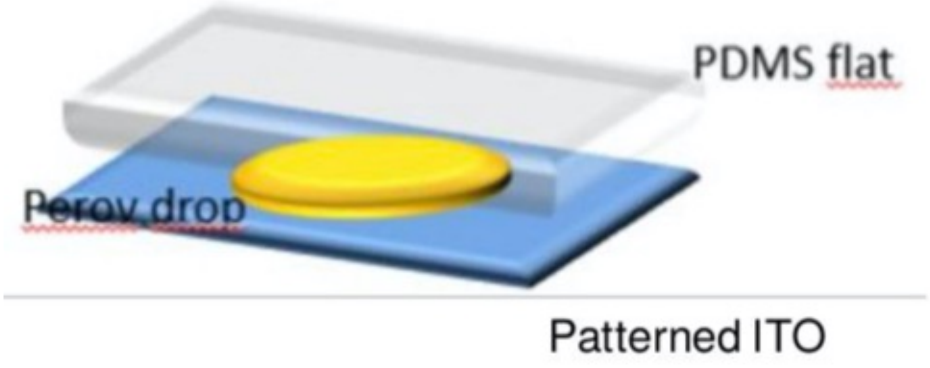
    → Cover different physical interactions (photons: photo-electric effect; MIP: ionization)

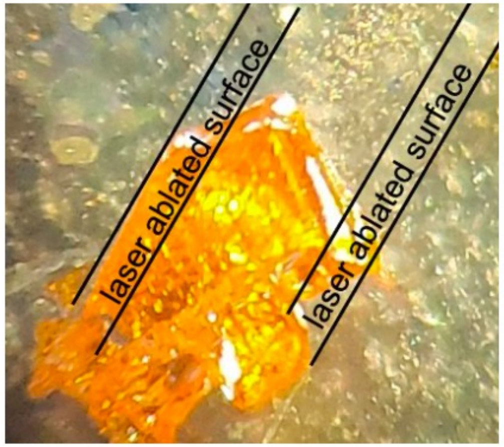
    → Cover different spatial distribution of the interactions: continuous (MIP) vs not continuous (photons)

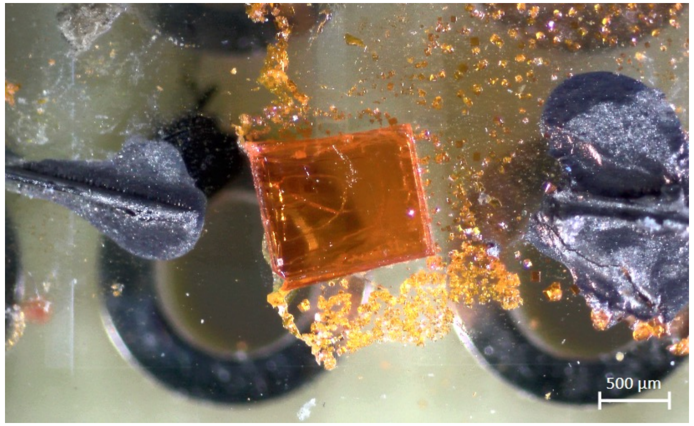
- ***Crucial for material and interfaces understanding***
- ***Input for Modelling***

Devices with perovskite grown on patterned glass

- Micro pad MAPbBR$_3$ crystal:
  - Directly grown on patterned ITO substrate (*)
  - ITO top contact
  - Typical height 100 μm
  - Active area ~ 500 μm x 500 μm







(*) Deposited patent
102022000010469, EU extensions :
"Confined growth of perovskite single-crystal on patterned conductive substrate for optoelectronic devices"

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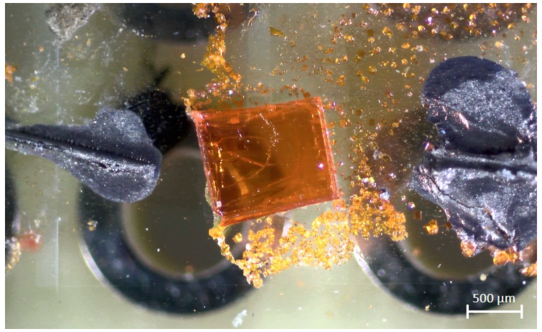
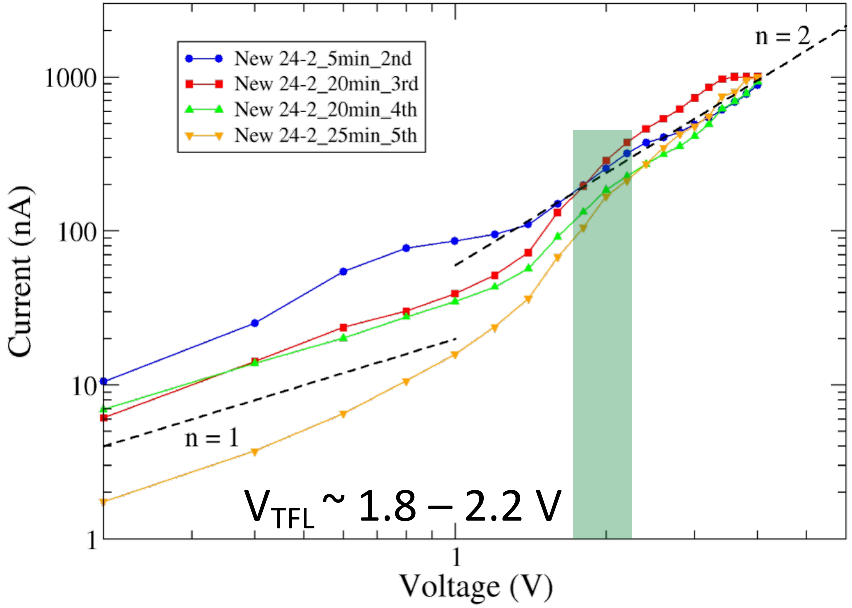
Devices with perovskite grown on patterned glass



Dark JV for material characterization



Space charge limited current:

$$J = \frac{9\varepsilon_r \varepsilon_0 \mu V^2}{8L^3}$$

Fit with n = 2: $I = 6\times10^{-8}\,\frac{\mathrm{A}}{\mathrm{V}^2}\cdot V^2$

⇨ $\mu \approx 14\ \mathrm{cm^2/Vs}$,
compatible with μ of bulk
1-mm thick single crystals

Trap filled limit:

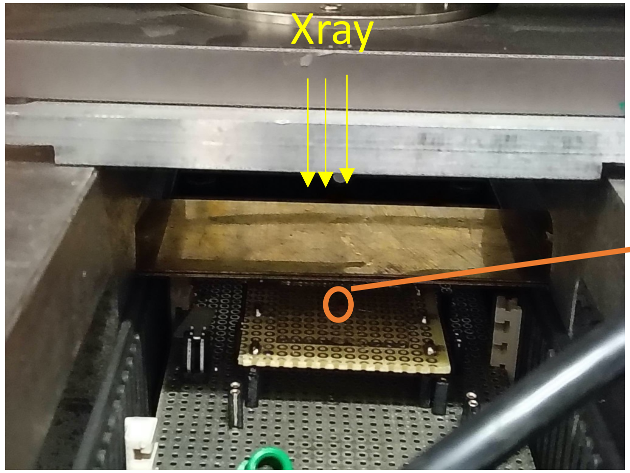
$$V_{TFL} = \frac{e n_t L^2}{2\varepsilon_r \varepsilon_0}$$

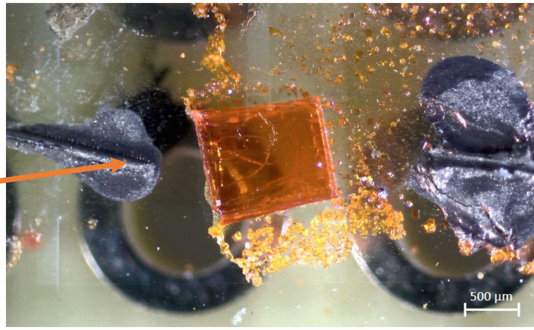
⇨ $n_t \approx 9.6\times10^{11}\ \mathrm{cm^{-3}}$
with $V_{TFL} = 2$ V

Perovskite grown on patterned glass: X ray response

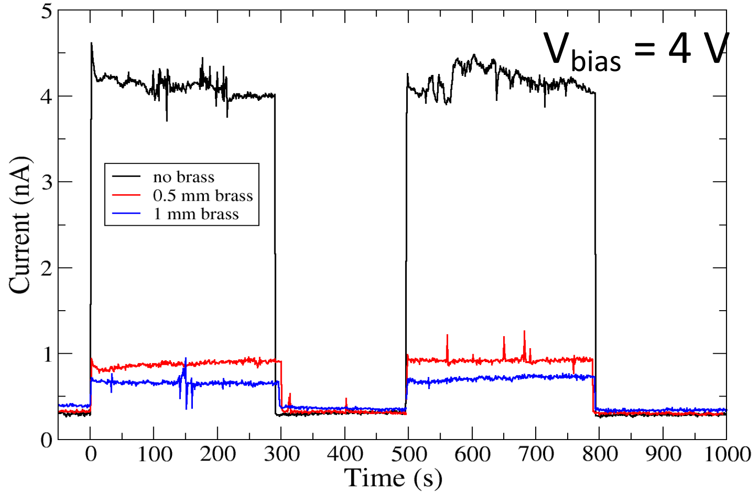
(*) Thanks to A. Scordo, S. Manti, F. Sgaramella

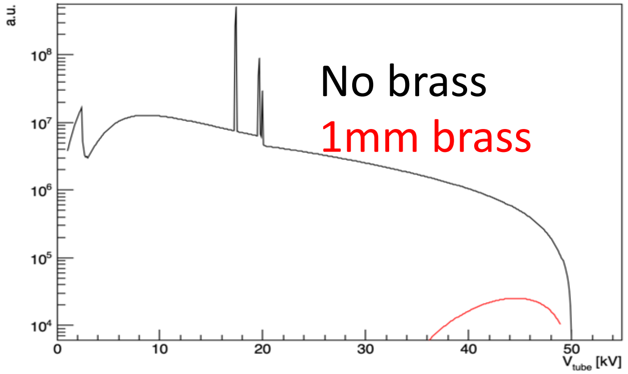
- X-ray WINDCHILL TUBE Molibdenum (*)
- 300 uA, 60 keV
- Use brass to filter energies > 30 KeV → Signal observed
- Measured ratio of current w/wo brass larger than expected ratio of fluxes → Under investigation





Thickness ~ 100 µm





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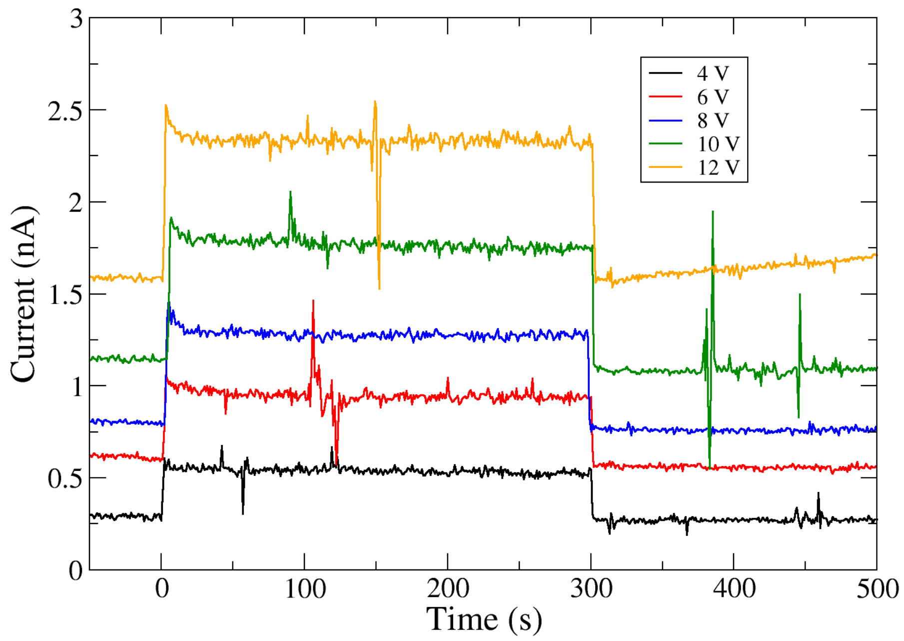
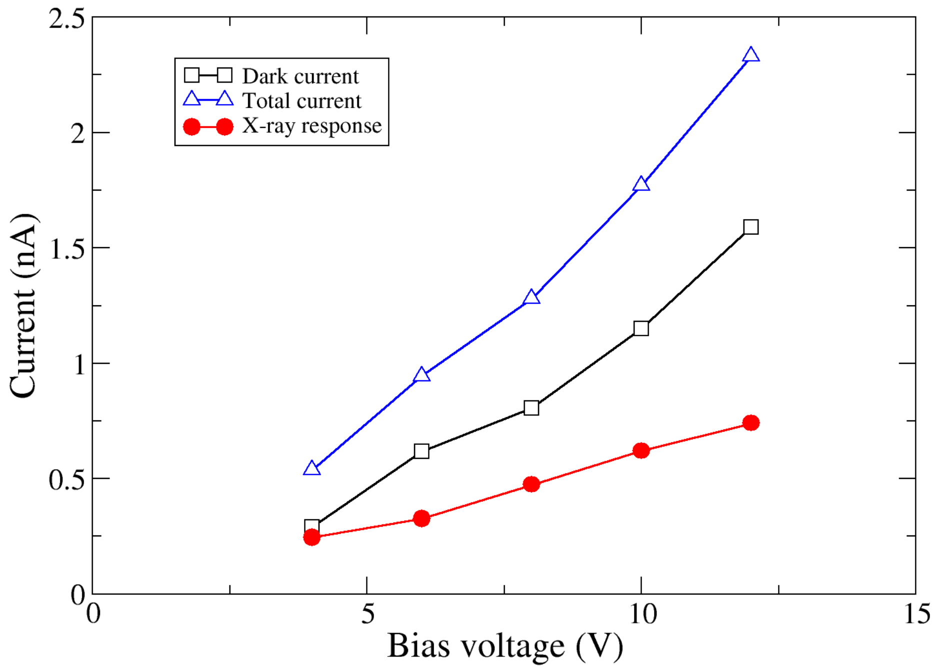
Perovskite grown on patterned glass: X ray response





Increase of response and dark current with increasing V_{bias}

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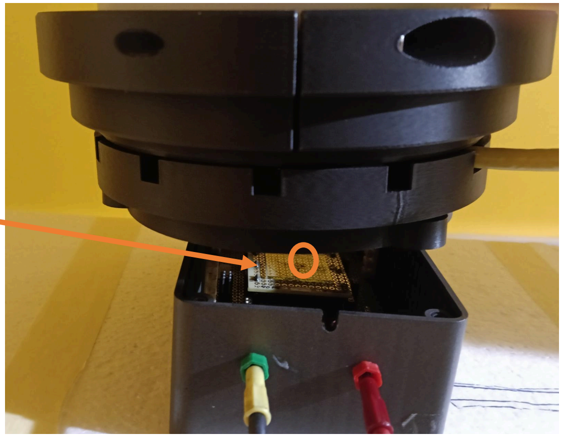
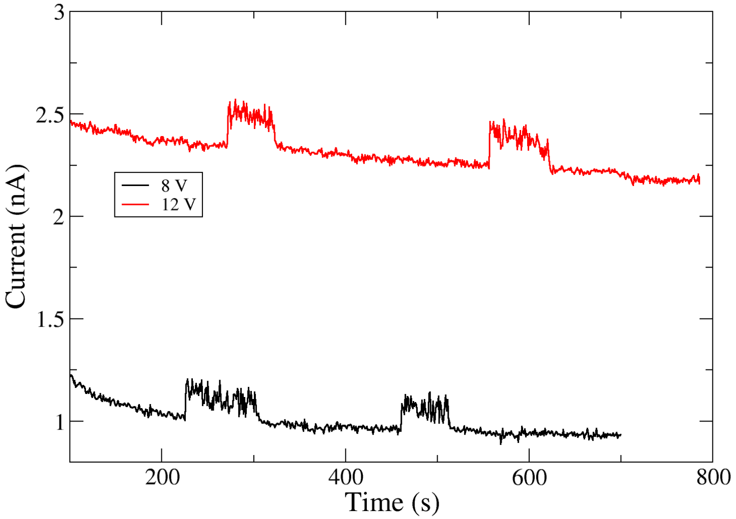
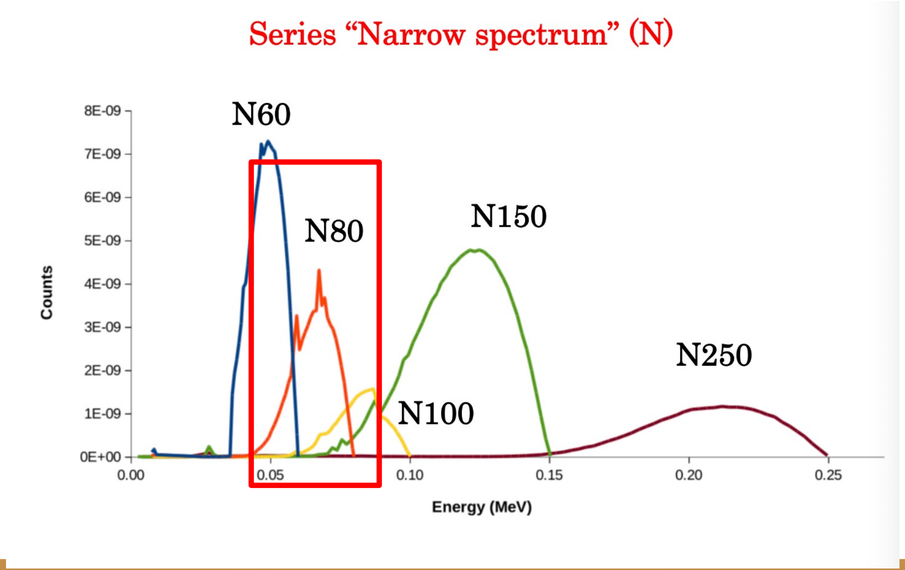
Perovskite grown on patterned glass: X ray response@<E>=80 keV

- W anode (*)
- 80 keV , 1mA
- spectrum N-80 ISO 4037 mm Al + 2mm Cu
  → negligible contribution below 30 keV
- Clear current signals from the device



Perovskite thickness ~ 100 μm



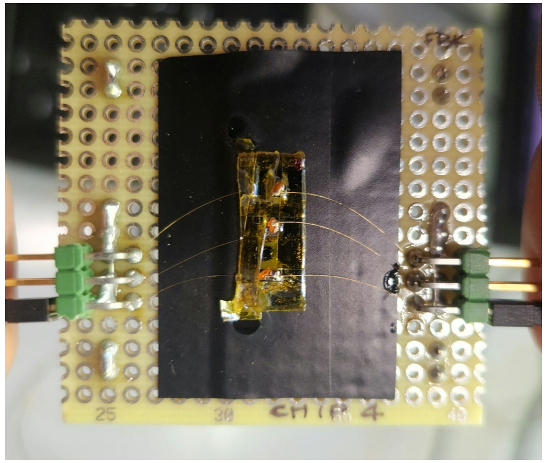


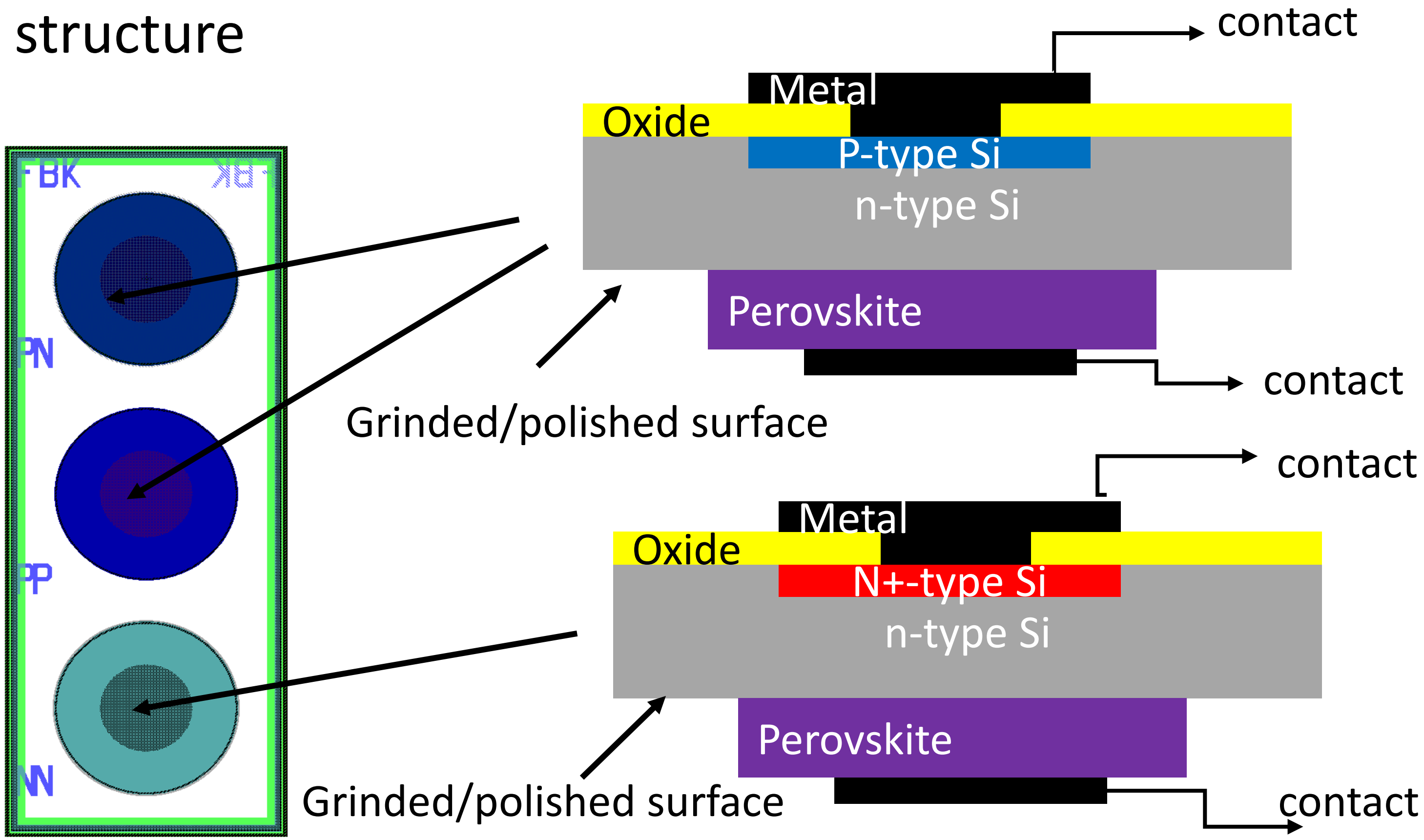
(*) Thanks to R. Bedogni, L. Russo

Devices with perovskite on Silicon

- Micro pad $MAPbBR_3$ crystal:
  - *Directly grown* on silcon PN and NN structure

- ITO top contact
- Typical thickness 100 μm
  Typical active area ~ 500 μm x 500 μm





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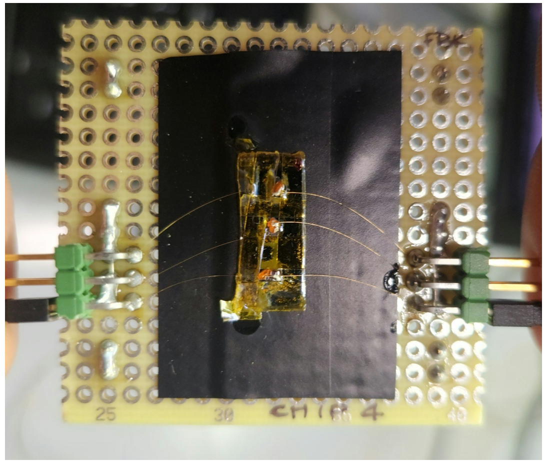
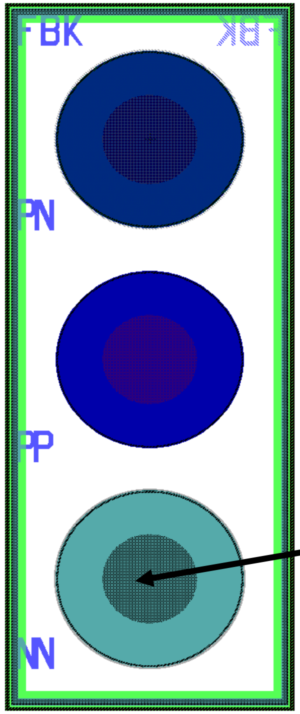
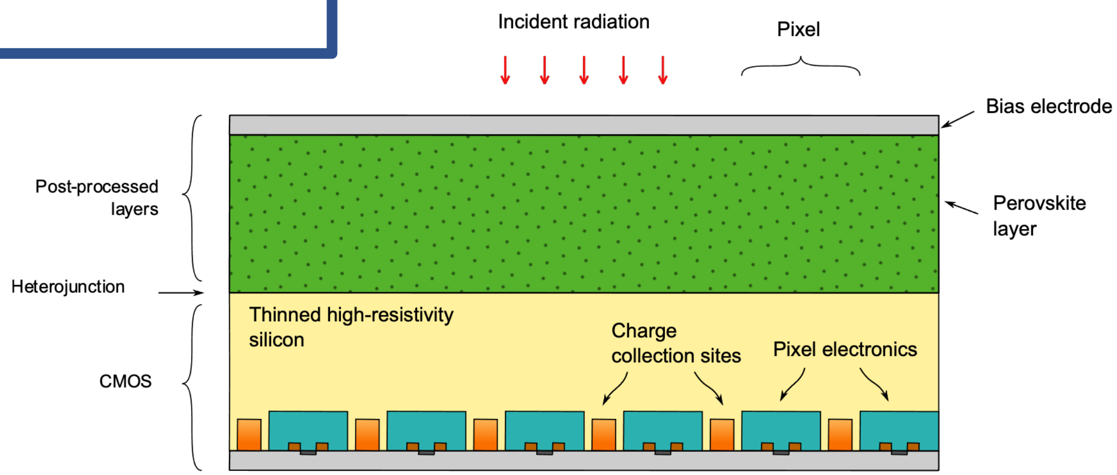
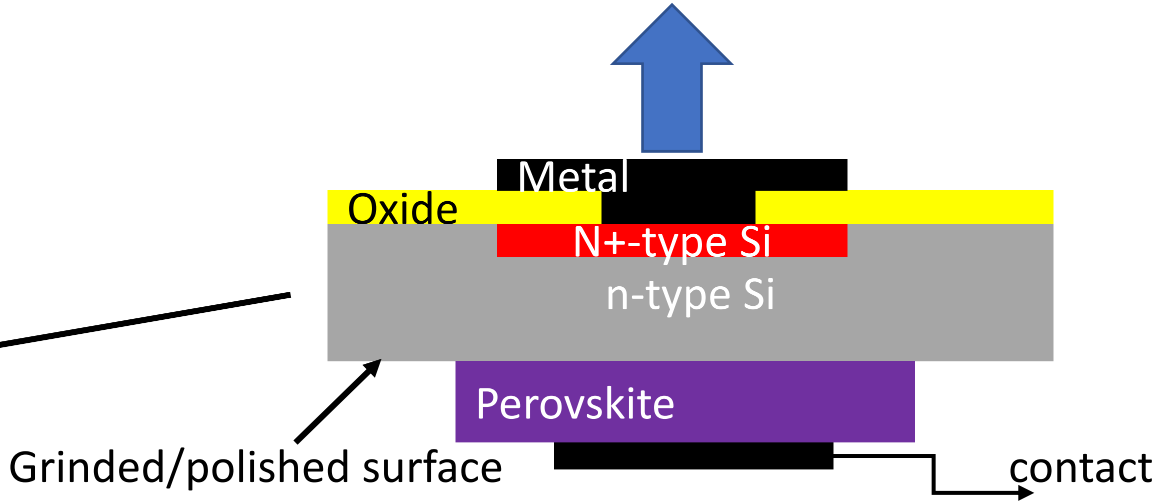
Devices with perovskite on Silicon

- NN/perovskite structure is a prototype of the final device
- Other PN structures aimed for modeling validation









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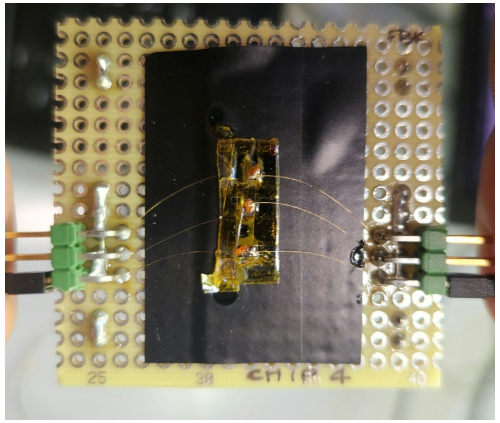
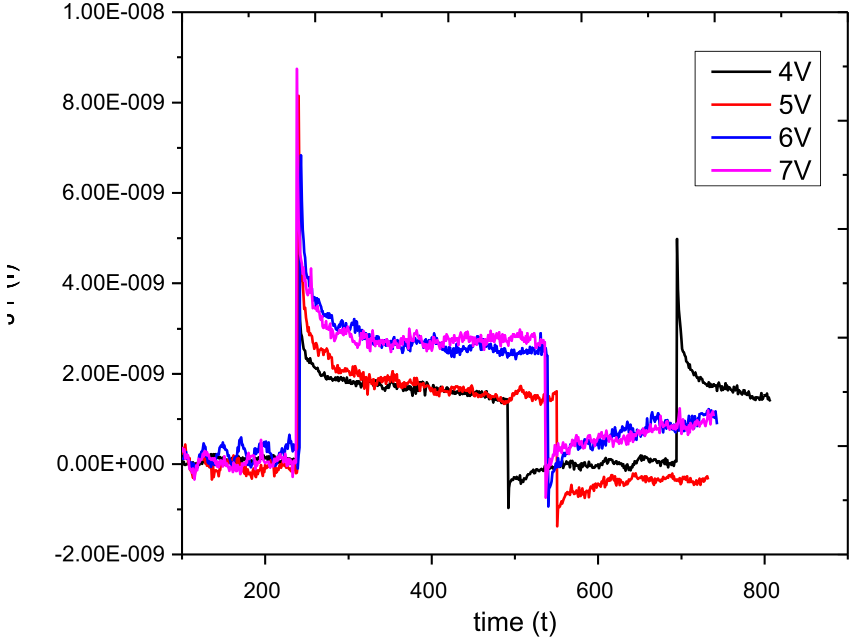
Devices with perovskite on Silicon: X ray response

- Collimated X-ray tube (Mo) (*): 850 uA, 48.5 kV
- Measured photon flux ~ 1.2×10^5 photons/s

- Beam spot of ~100 μm
  → response due to Perovskite, not to nearby Silicon
- Silicon-only NN sample provides much higher dark-current, being photo-conductor
  → Silicon + perovskite interface working qualitatively as expected

Demonstration of functional NN - perovskite interface

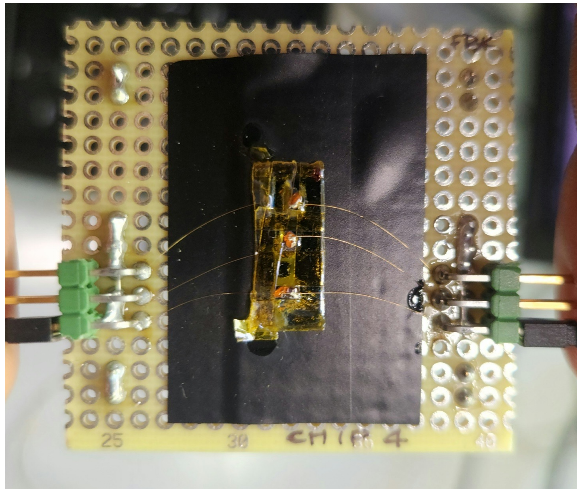




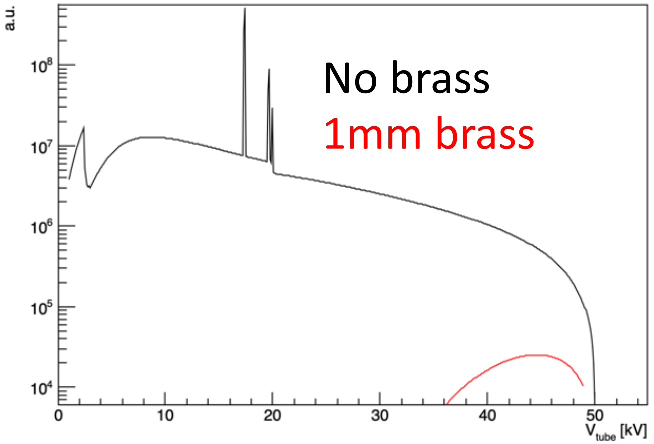
(*)Many thanks to D. Hampai

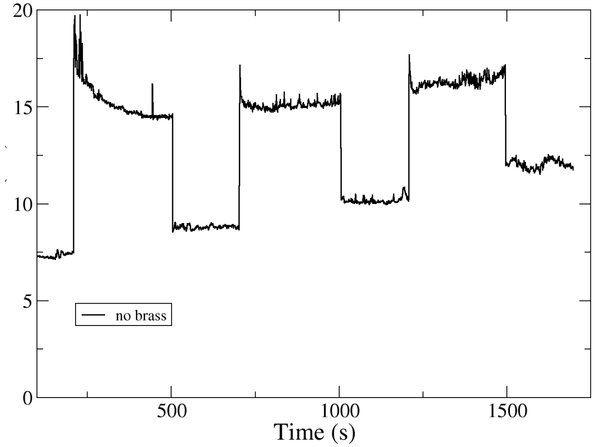
Devices with perovskite on Silicon: X ray response

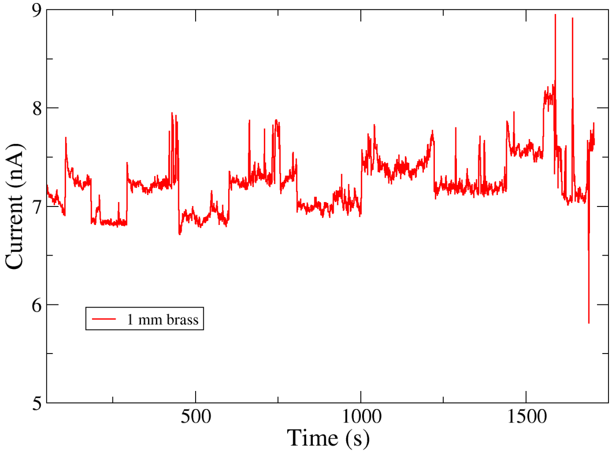
- X-ray WINDCHILL TUBE Molibdenum (*)
- 300 uA , 60 keV
- Use brass to filter energies > 30 KeV
- → Signal observed even at high energies
- Observed ratio of currents w/wo brass larger than expected ratio of fluxes
    - Under investigation



$V_{bias} = 4V$



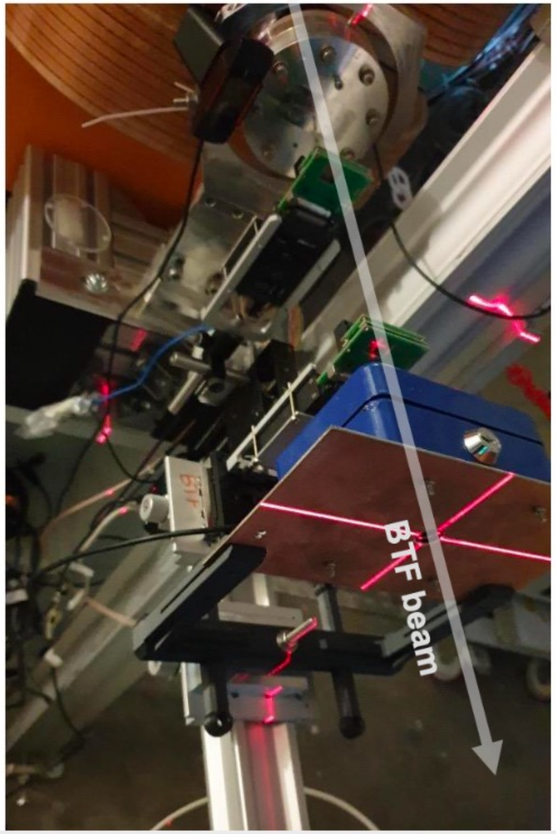


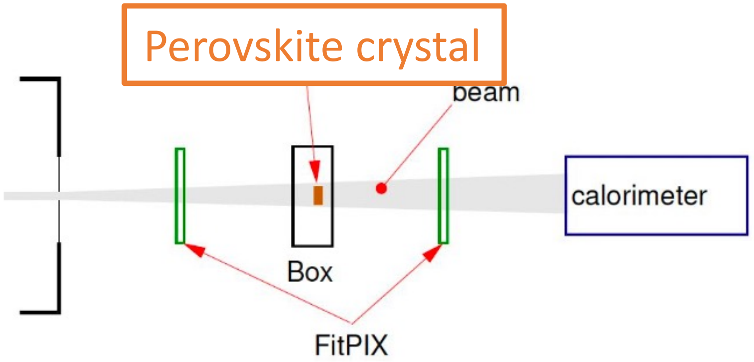


https://spekpy.smile.ki.se
https://xrfcheck.bruker.com/FilterTransmissions

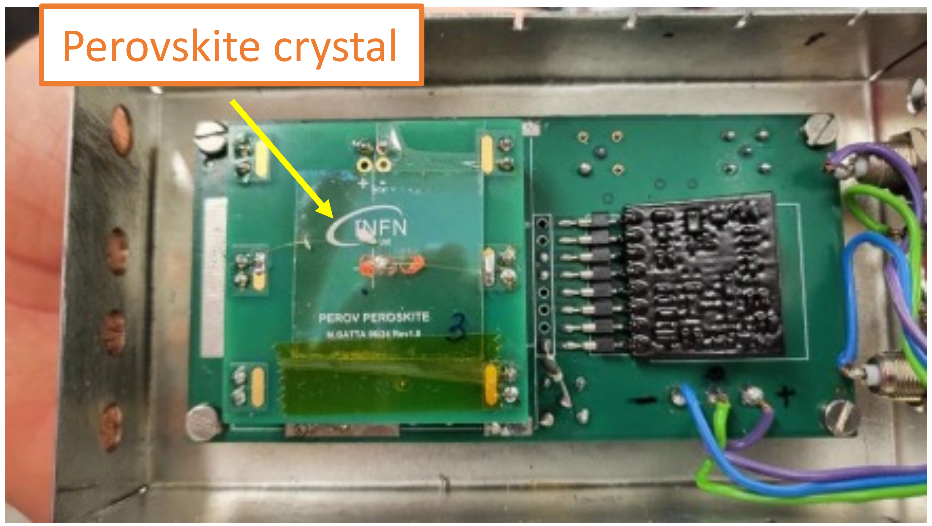
(*)Thanks to A. Scordo, S. Manti, F. Sgaramella

Test beam results





- Test beam performed at the **Beam Test Facility** @LNF (Nov 24)
- Electron beam with 300 MeV energy behaves as minimum ionising particles on small size crystal



Dedicated eletronics with pre-amplificator and shaper with shaping time ~ 6 μs
Z. Chubinidze, G. Felici, M. Gatta, G. Papalino

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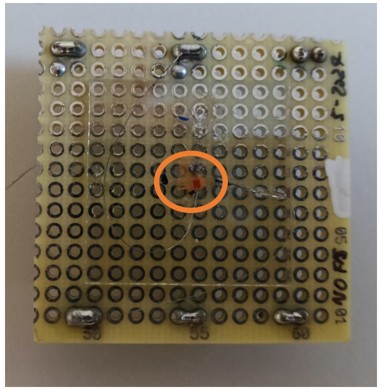
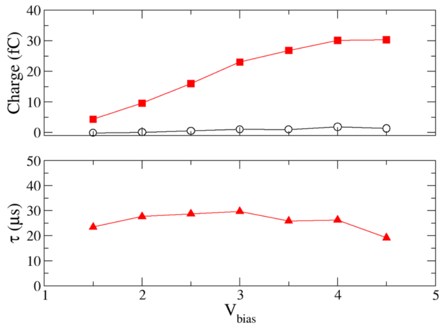
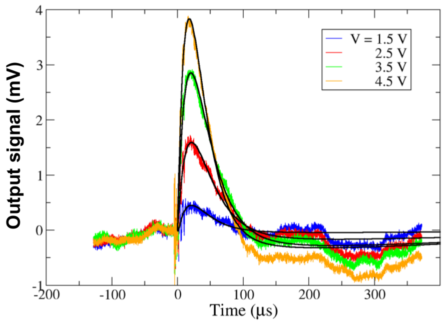
Test Beam: perovskite grown on patterned glass



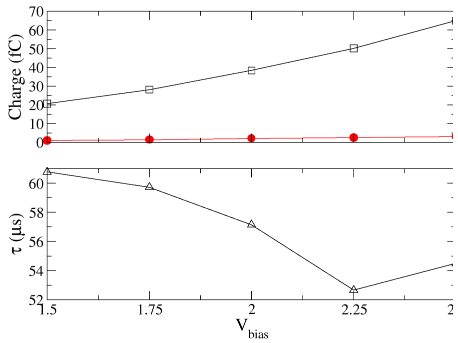
- e^- beam multiplicity around 20k per bunch
  - Effective mult. on the active area under evaluation
- ***First observation of MIP signal on 100 μm-thick perovskite***
  - Previosly, observation of MIP signal on 1mm thick $MaPbBR_3$ Crystal with single particle sensitivity [*Nanoscale*, 2024,16, 12918-12922]

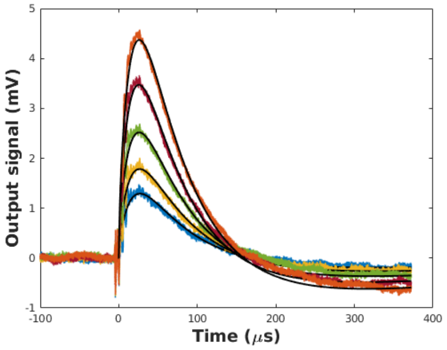
Sample 1





Sample 2





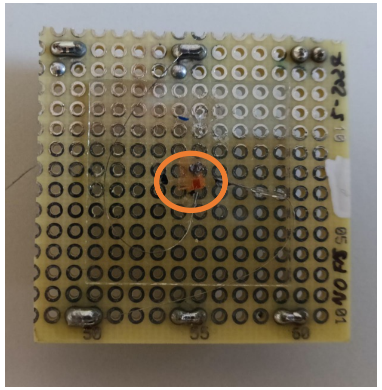
- Fit to

$$i_i(t) = q_1\delta(t) + \frac{q_2}{\tau_s}e^{-t/\tau_s}$$

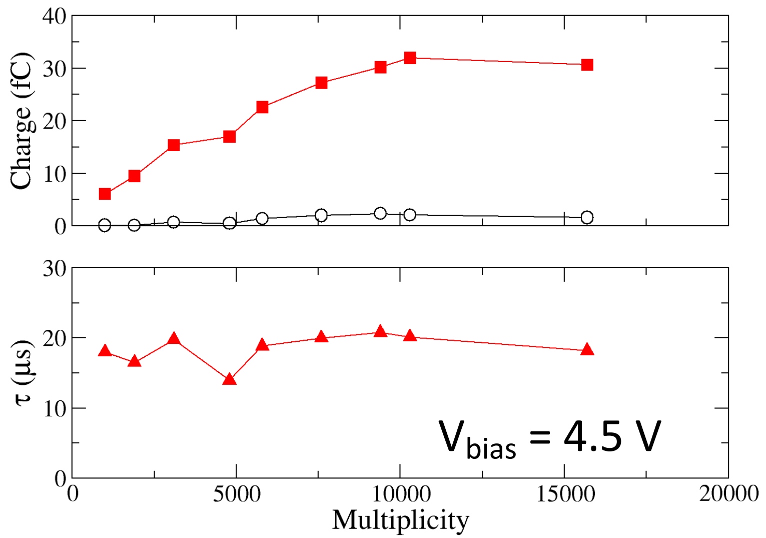
after electronics response deconvolution

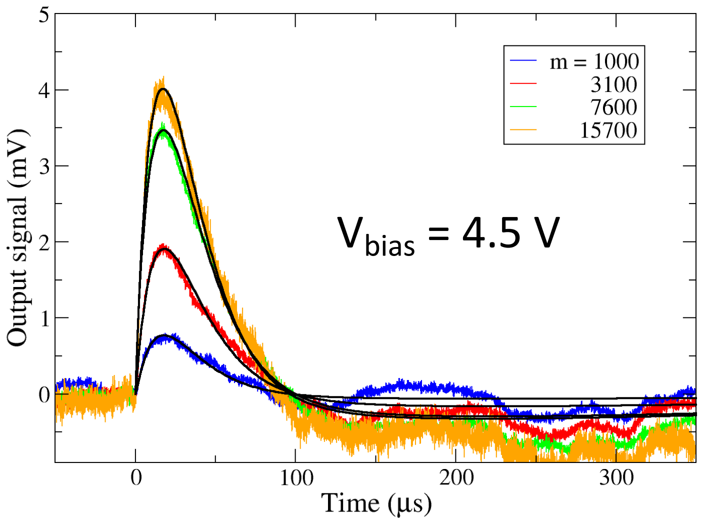
- Fast component $q_1 \sim 0$
- Slow component with characteristic time of O(10) μs

Test Beam: perovskite grown on patterned glass II



- Variation of e^- beam multiplicity
  - Effective mult. on the active area under evaluation
  - Dynamic range up to ~10^4
- *Promising application as beam monitoring*





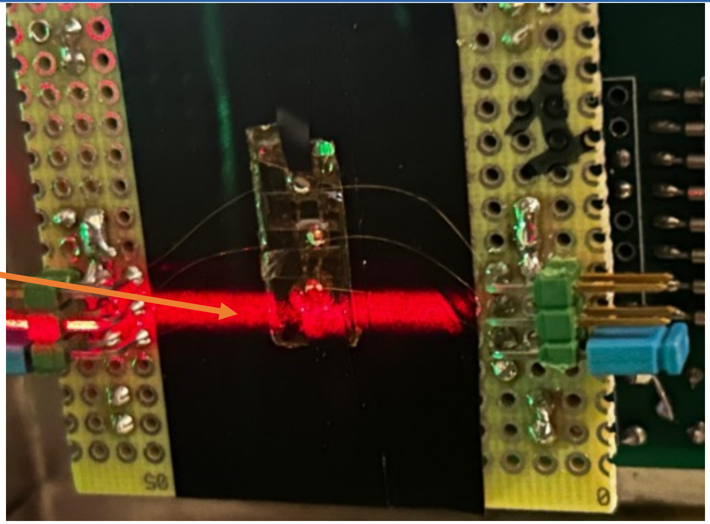
- Fit to
$$i_i(t) = q_1\delta(t) + \frac{q_2}{\tau_s}e^{-t/\tau_s}$$
after electronics response deconvolution

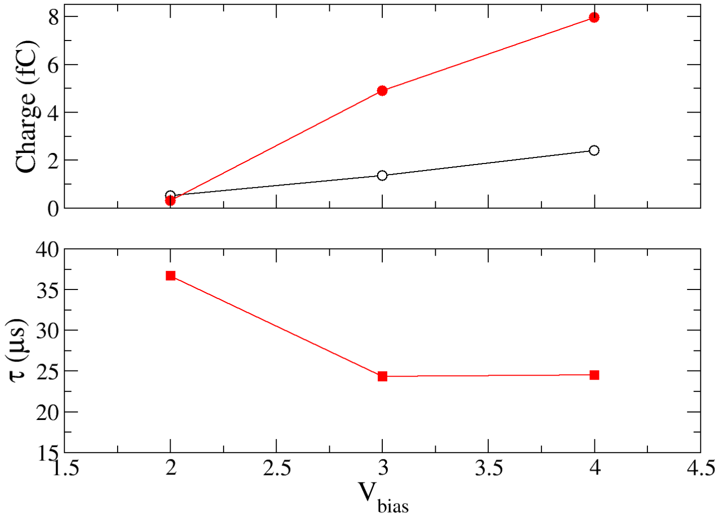
- Fast component q_1 ~ 0
- Slow component with characteristic time of O(10) µs

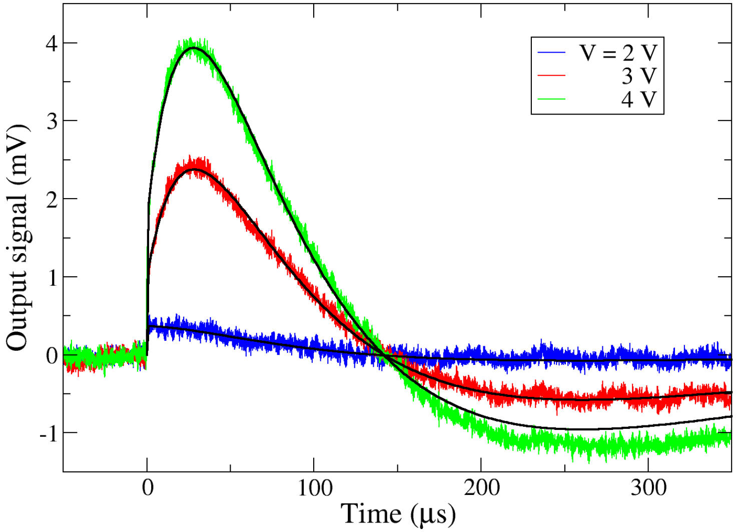
Test Beam: perovskite grown Silicon

- e^- beam multiplicity around 20k per bunch
  - Effective mult. on the active area under evaluation
- ***First observation of MIP signal on NN+perovskite***

Beam aligned on NN structure







- Fit $i_i(t) = q_1\delta(t) + \frac{q_2}{\tau_s} e^{-t/\tau_s}$ after electronics response deconvolution
  - Fast component q_1 *!= 0* likely due to Silicon
  - Slow component with characteristic time of O(10) μs

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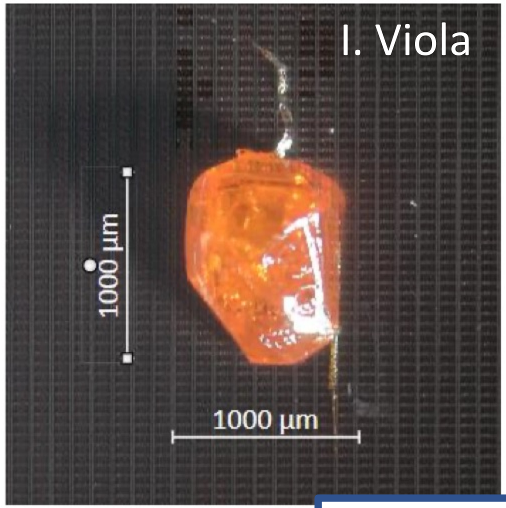
Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

INFN LNF

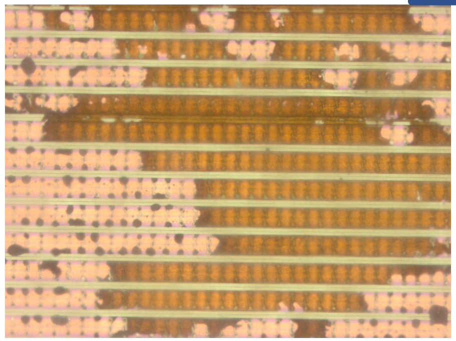
Recent developments

- Perovskte direct growth on **Timepix** ASIC
- Timepix ASIC : 55µm x 55µm pixel pitch, ideal for **X ray imaginig**
- Advantages
  - no need of bump bonding and flip chip (cost) of Si/CdTe sensors
  - direct grown of perovskite on the ASICS substrate: Aluminium pads sorrunded by oxide
- Challenge: growth of 100 µm thick single crystals on full area
  Alternative: deposition of 1µm-thick film on full area, but sensitivity only to high flux

~100 µm thick crystals on TIMEPIX2



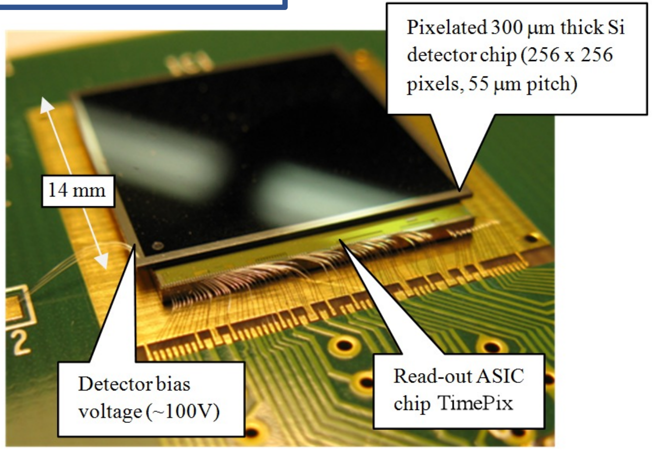
Timepix2 by CERN



~1 µm thick film

F. Matteocci

TIMEPIX with Silicon Sensor



Under study how to reduce roughness (eg plasma treatment , UV Ozon)

Conclusions

- Demonstrated sensitivity to X ray of O(10) keV by **100 μm-thick single crystal** perovskite **directly grown**
  - on patterned glass
  - on **N silicon** substrate
- Next steps:
  - Direct growth of 100 μm-thick single crystal perovskite
    - on CMOS substrate
    - on Timepix ASIC