Development of a CMOS Charge Sensing Pixel Array for the Selena Neutrino Experiment

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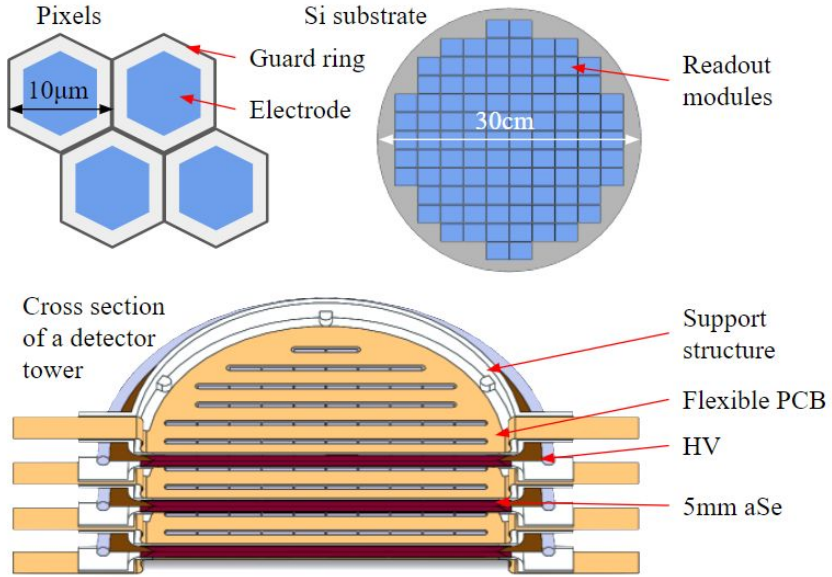
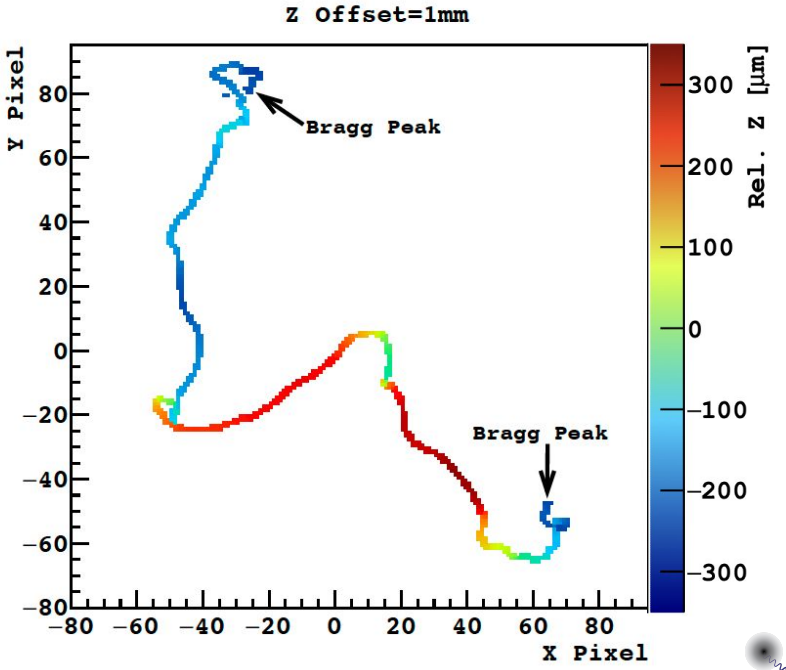
CPAD 2022

BERKELEY LAB

Introduction to Selena

A search for Neutrinoless Double Beta Decay in ^{82}Se using amorphous Selenium/CMOS [1]





[1] A. E. Chavarria et al. “Snowmass 2021 White Paper: The Selena Neutrino Experiment”. (2022). doi: 10.48550/ARXIV.2203.08779.

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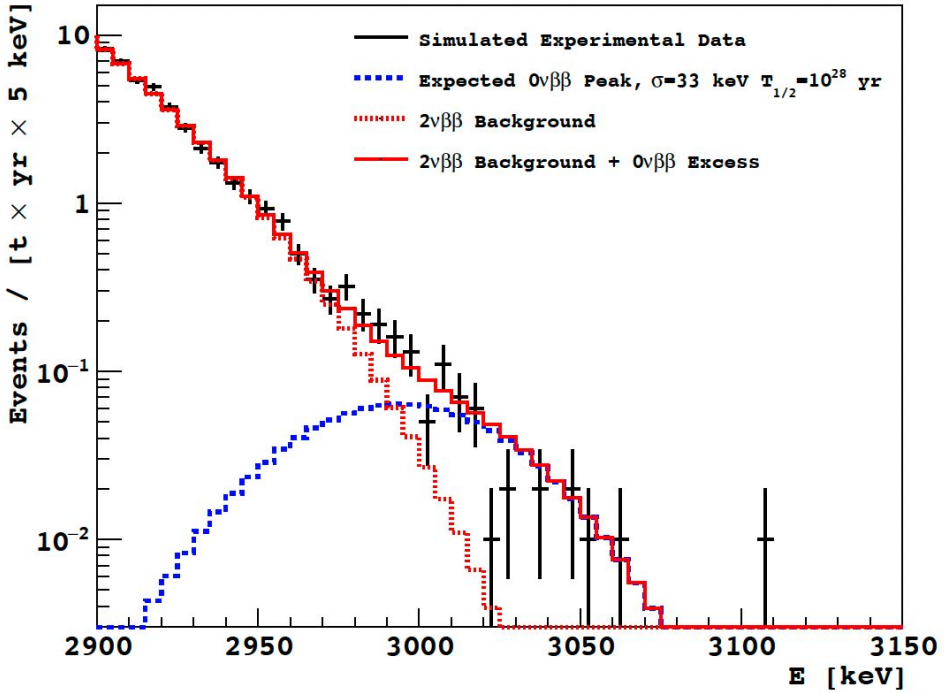
Science Goals

$0\nu\beta\beta$ search with ^{82}Se enriched aSe/CMOS:

- High $Q_{\beta\beta}$ (3MeV) protects from natural backgrounds in ROI
- Existing Industrial Capabilities to fabricate a ton-scale detector
- CMOS spatiotemporal resolution provides event classification and decay chain tagging

Science goals recently expanded to solar neutrino spectroscopy and an investigation into the "gallium anomaly," with implications for sterile neutrinos [1].

Detector R&D -> 100 kg Demonstrator -> 10 ton target



Simulated spectrum for 100 ton-yr exposure

[1] A. E. Chavarria et al. "Snowmass 2021 White Paper: The Selena Neutrino Experiment". (2022). doi: 10.48550/ARXIV.2203.08779.

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Hybrid aSe/CMOS sensors

Medical imaging industry:

aSe target coupled to thin film transistor array

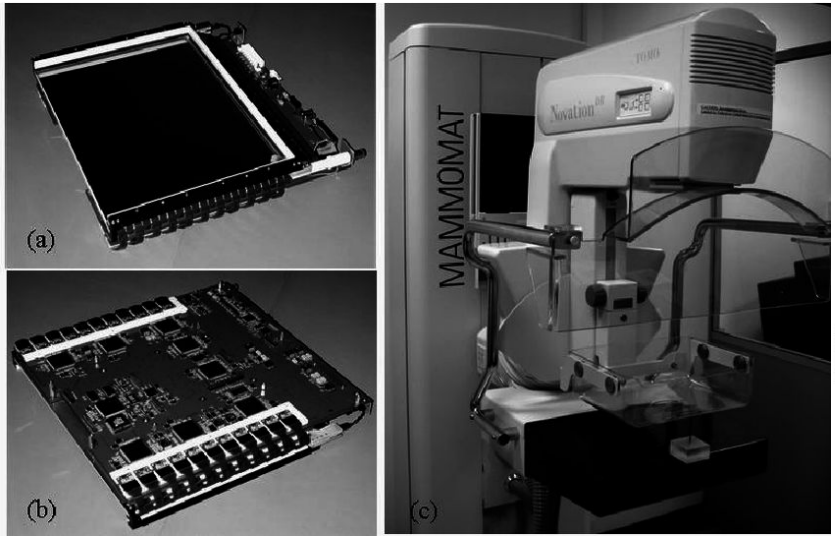
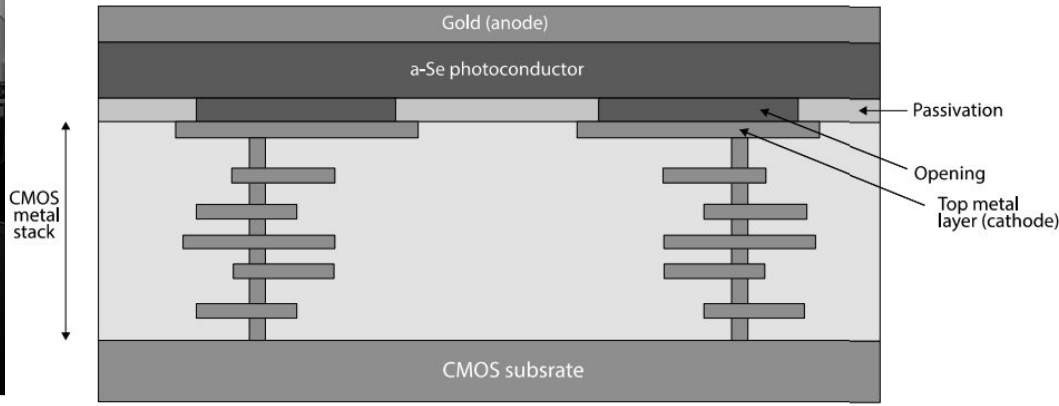


Image from [2] M Bissonnette et al. “Digital breast tomosynthesis using an amorphous selenium flat panel detector”. In: Proc. SPIE 5745 (Apr. 2005). doi: 10.1117/12.601622

CMOS

- Active area of research [3]
- Low noise, fast readout
- Room temperature operation
- High voltage ~ 5-50v/um



[3] Kaitlin Hellier et al. “Recent Progress in the Development of a-Se/CMOS Sensors for X-ray Detection”. In: Quantum Beam Science 5.4 (2021). issn: 2412-382X. doi: 10.3390/qubs5040029.

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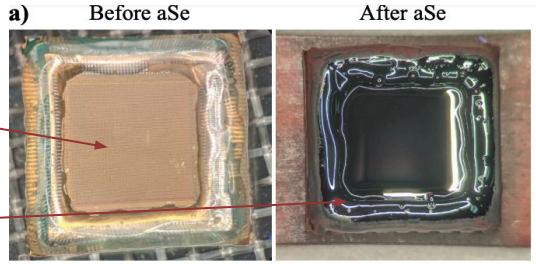
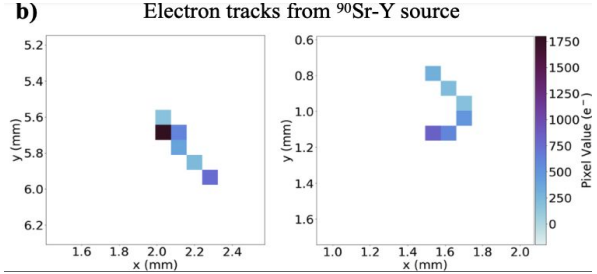
Selena Initial Prototype Results

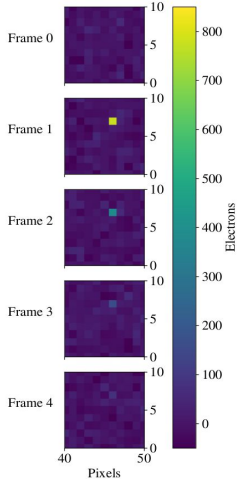
topmetal-II⁻ APS[1]
- 84x84 um pixel pitch
- Rolling shutter readout

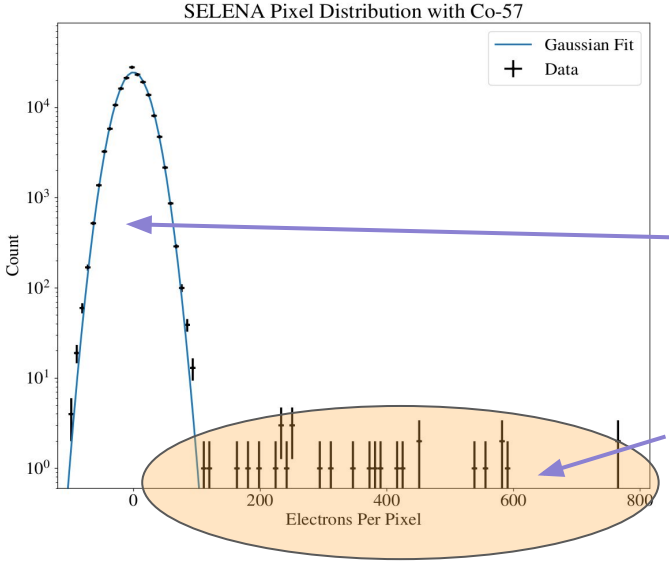
500um aSe
- Deposited by Hologic Inc.





Single Photon Response





Noise distribution, σ=23 e⁻

Pixels with charge

[1] Mangmang An et al. A Low-Noise CMOS Pixel Direct Charge Sensor, Topmetal-II-.Nucl. Instrum. Meth. A, 810:144–150, 2016

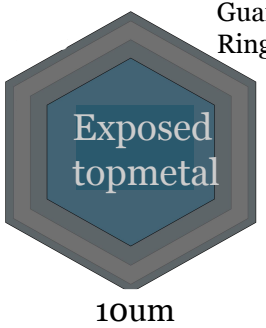
Towards a CMOS for Charge Readout of aSe

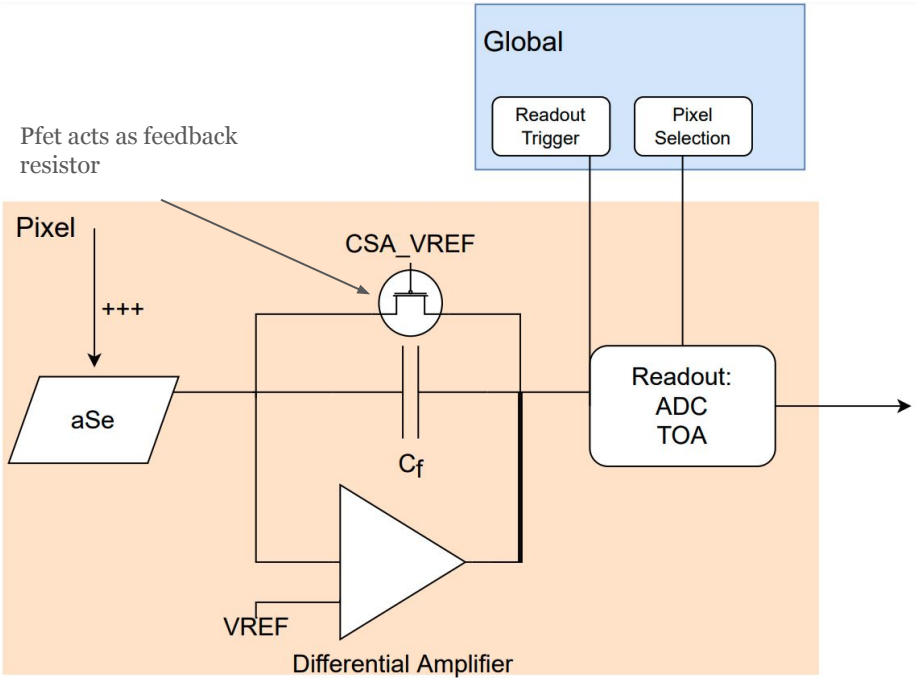
The TopmetalSe, designed for Selena

Technical Goals:

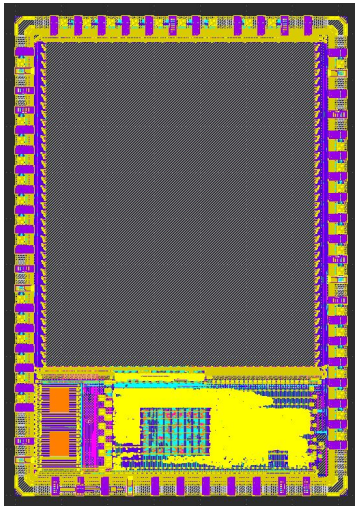
- 10um pixel pitch
- Charge Sensitive Amplifier Frontend
- Hexagonal pixel geometry optimized for collection efficiency
- 10 e^- noise
- Time of Arrival (TOA) measurement

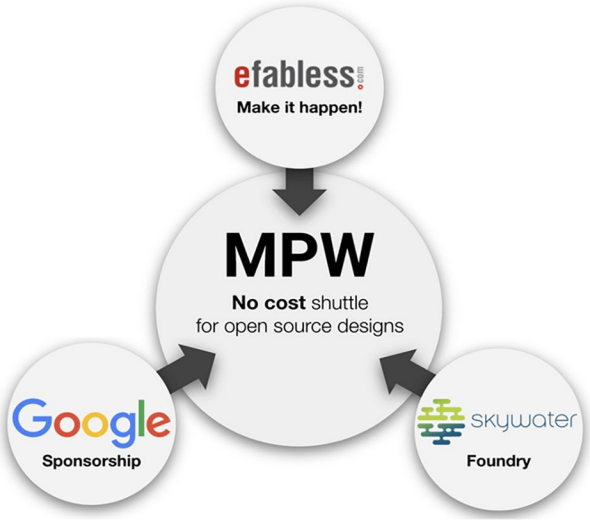
Example Pixel Geometry:





Open Source ASIC Design





Digital & Analog Open Source Tooling

Magic VLSI Layout Tool
Current distribution version 8.2

NGSPICE

StefanSchippers/
xschem_sky130

XSCHEM symbol libraries for the Google-Skywater 130nm process design kit.

The-OpenROAD-Project/
OpenLane

OpenLane is an automated RTL to GDSII flow based on several components including OpenROAD, Yosys, Magic, Netgen and custom methodology...

First ever fully free and open-source process design kit (**Sky130nm PDK**), released June 2020.

Tapeout options include free lottery-based OS shuttle (OpenMPW) and $10k reserved shuttle (ChipIgnite)

Shuttles offered ~3 month cycle

Lowers barrier of entry to ASICs, improves design sharing and iteration

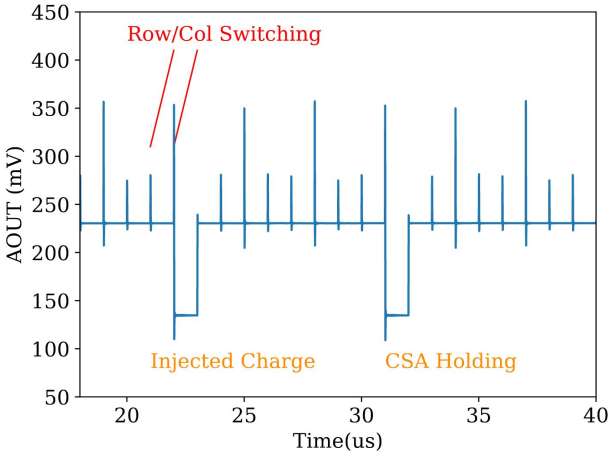
Status of TopmetalSe Designs (1)

TopmetalSe-V1: Submitted for tapeout in June, expected delivery in ~~Fall '22~~ February '23

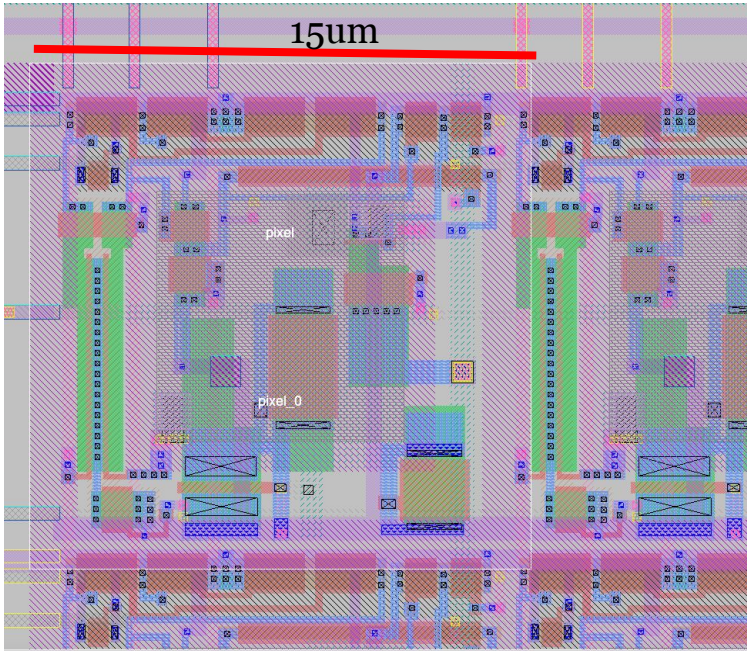
15 x 15 um pixels, 25 e- noise (simulation), 100x100 pixel array, <uW per pixel

Charge conversion gain: 25uv/electron

Rolling shutter readout:



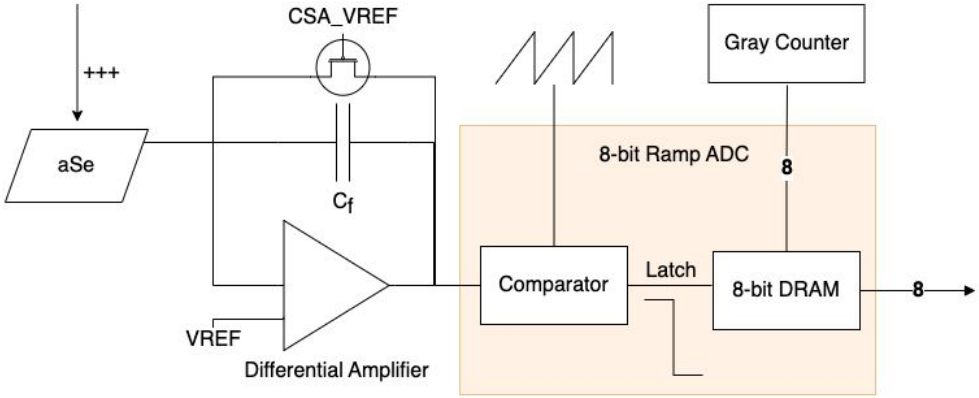
SPICE simulation of 3x3 pixel array with an injected signal

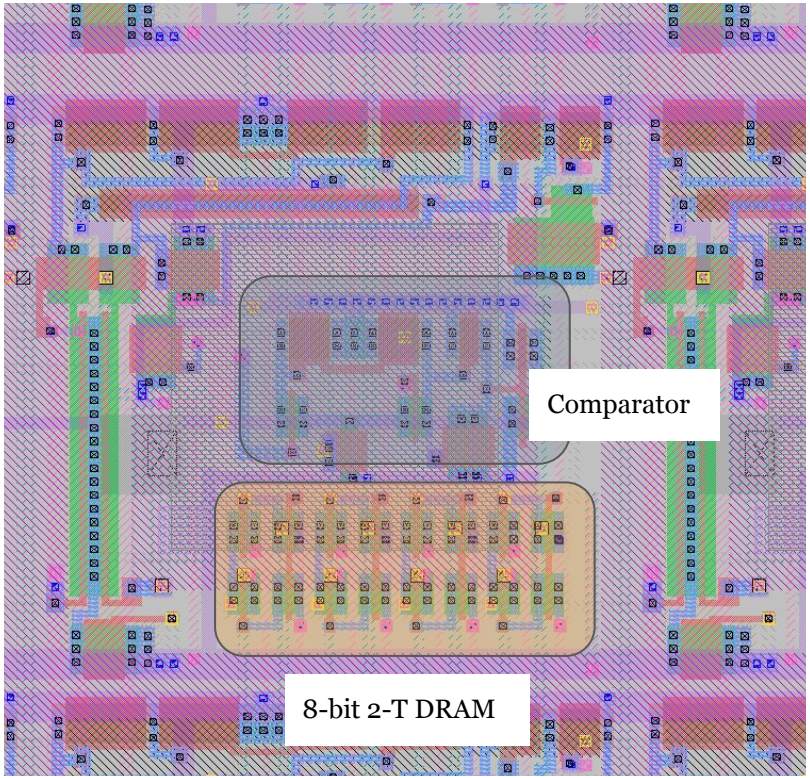


Status of TopmetalSe Designs (2)

TopmetalSe-DPS: pending successful tapeout

Digital Pixel Sensor readout [5] implements per-pixel ADC





[5] S. Kleinfelder et al. A 10000 frames/s cmos digital pixel sensor. IEEE Journal of Solid-State Circuits, 36(12):2049–2059, 2001.

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Summary:

- Selena proposes the use of aSe/CMOS for next generation neutrino physics
- CMOS sensors for aSe charge readout are actively being developed and characterized
- Open Source ASIC design increases accessibility and will continue to grow

Thanks to:
the GIRA Committee,
my advisor Alvaro Chavarria,
and group members/collaborators Yuan Mei (LBL) , Alex Piers (UW) and Xinran Li (LBL)

Backup

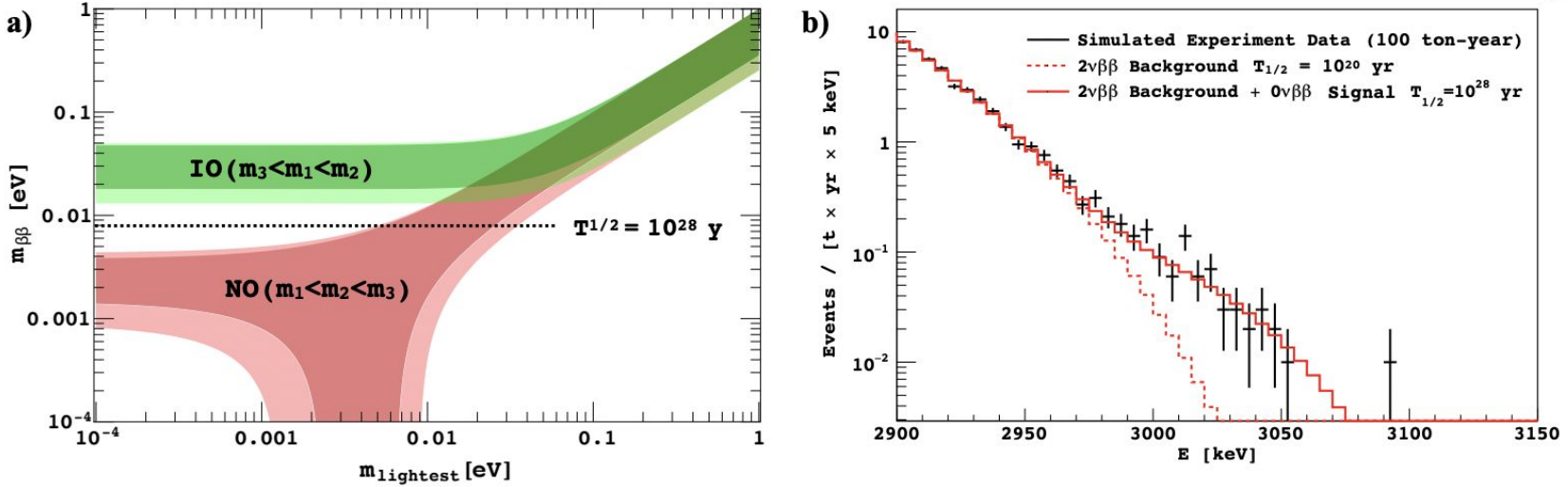
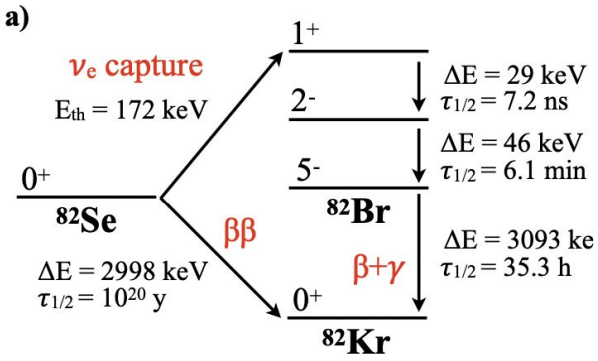
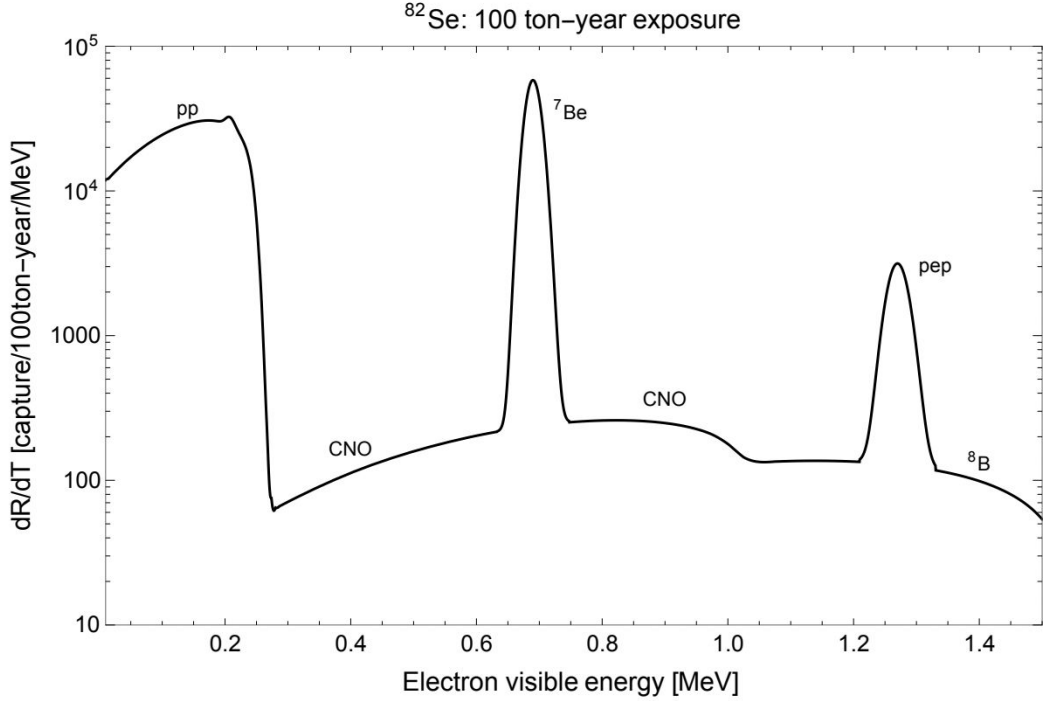


FIG. 2. **a)** Allowed values for $m_{\beta\beta}$ as a function of the mass of the lightest neutrino for different orderings of the neutrino masses [6]. The width of the bands represent the uncertainties in the parameters of the PMNS matrix. The dashed line shows the value of $m_{\beta\beta}$ that corresponds to $\tau_{1/2} = 10^{28}$ y in ^{82}Se. **b)** Predicted $\beta\beta$-decay spectrum of ^{82}Se about $Q_{\beta\beta}$ in a 100 ton-year exposure if $\tau_{1/2} = 10^{28}$ y.





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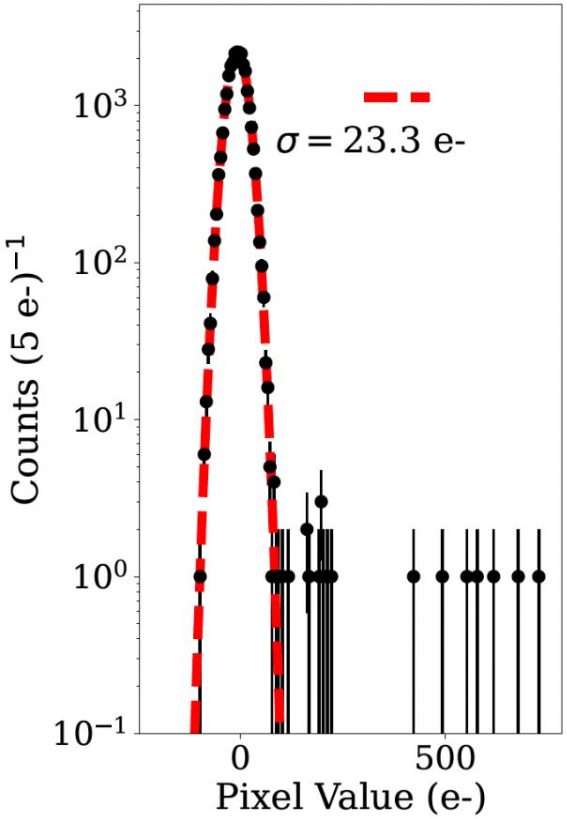

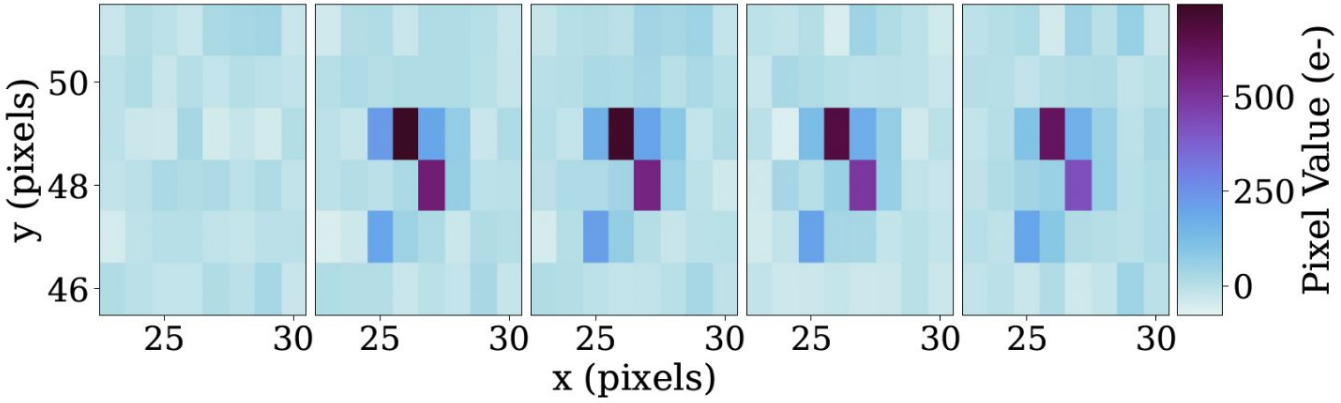

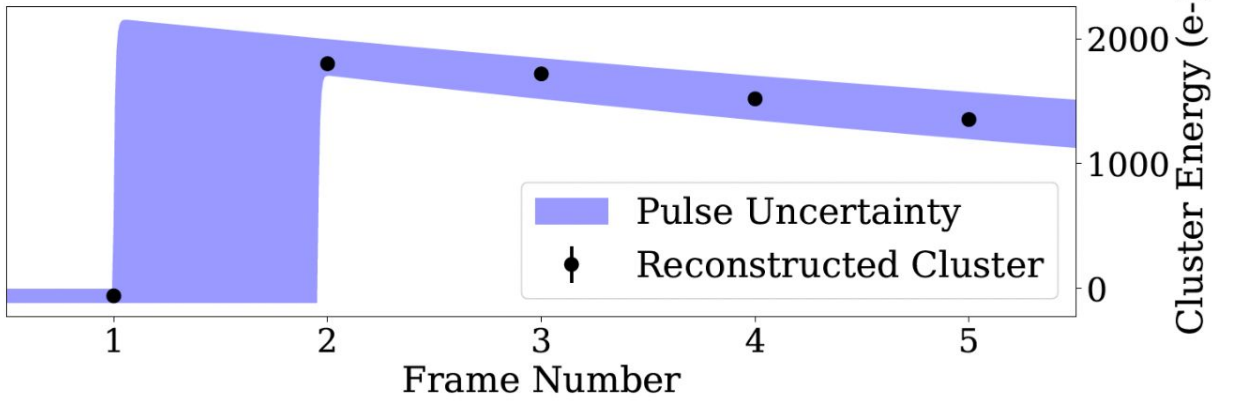

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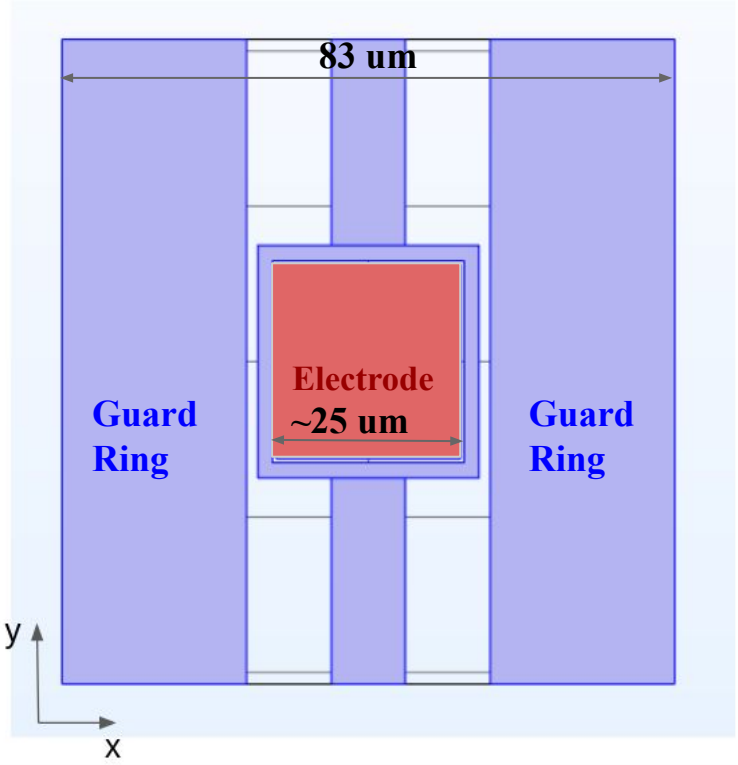
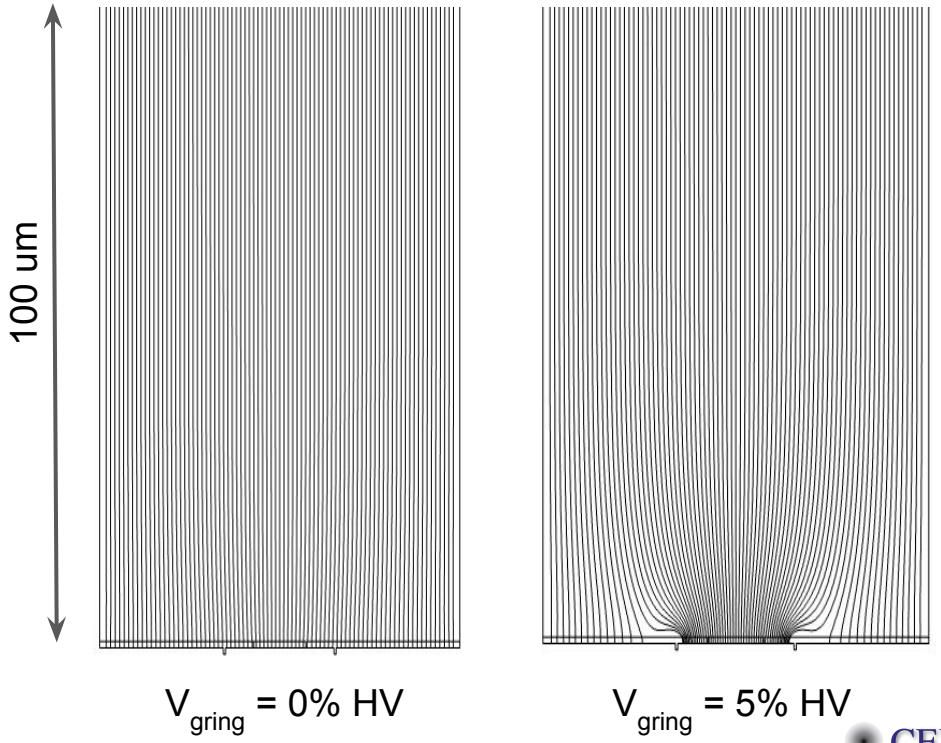
Electrostatic Detector Simulations



Single pixel structure



Simulated field lines

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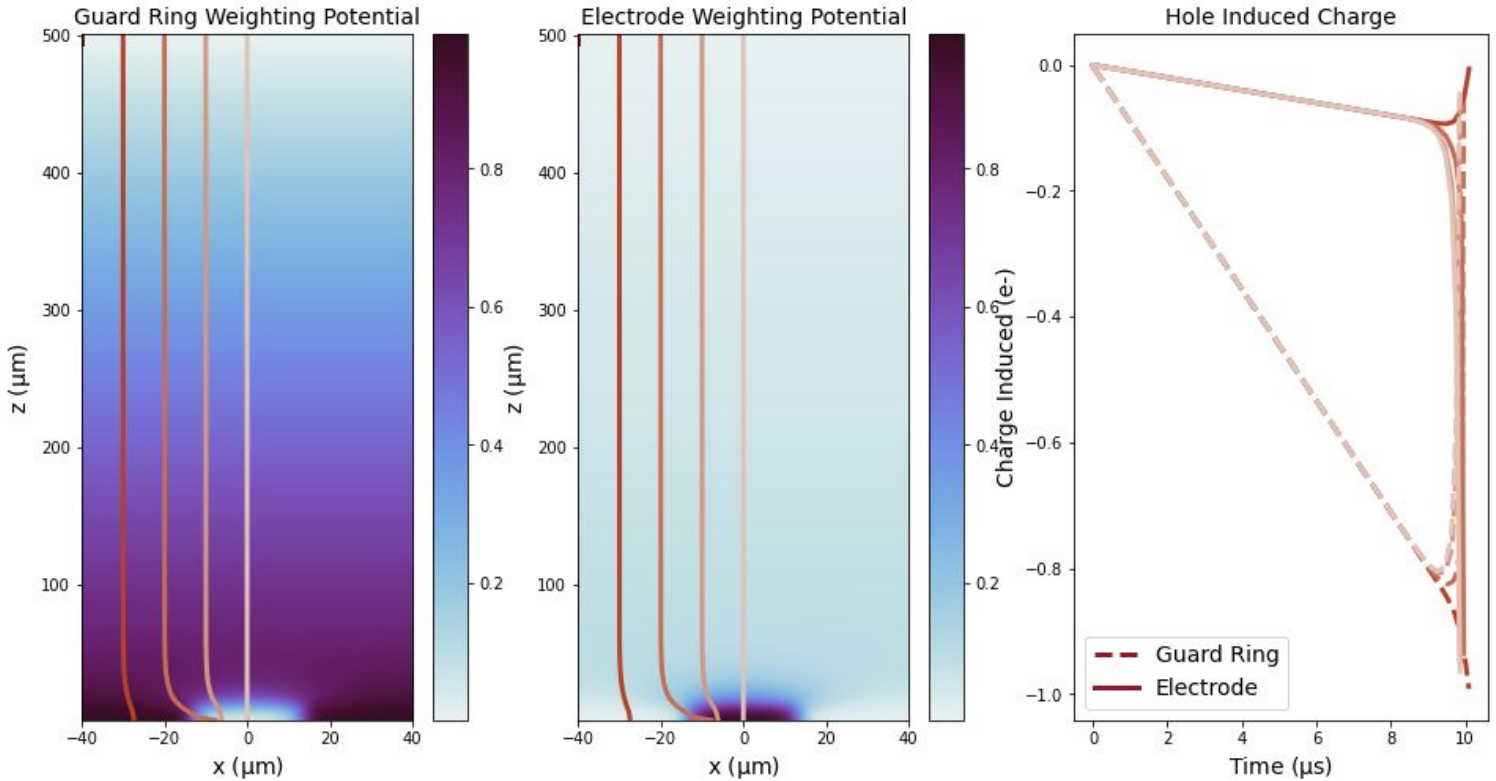
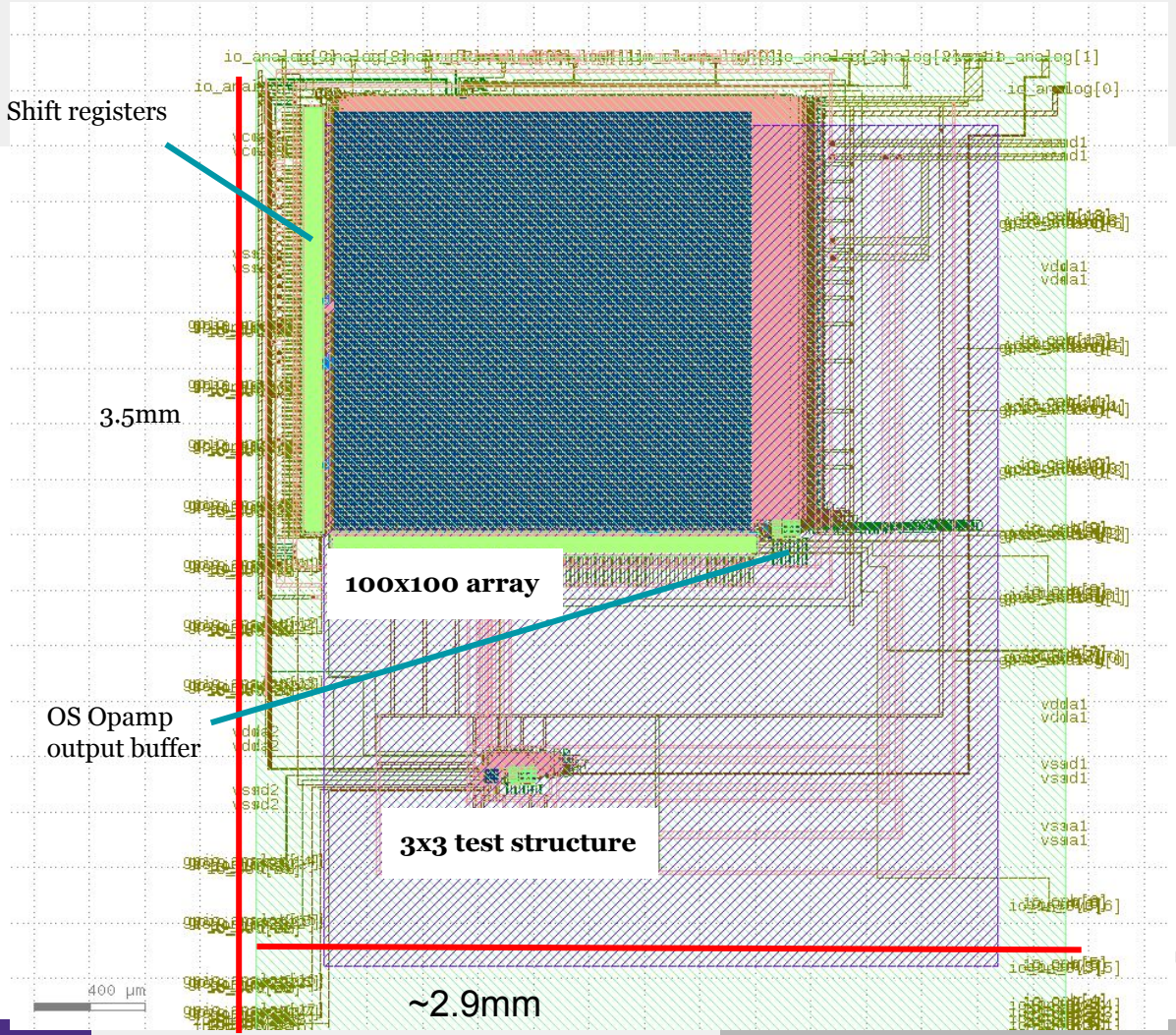
Detector Simulations--Point Source Response



Tapeout date: June 8th

Delivery date original in October, delayed to February



Example Pixel Geometry: