Radiation Hardened Infrared Focal Plane Arrays

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Outline

- Introduction
- Experiments
  - Material choice, growth and characterization
  - Detector and focal plane array (FPA) modeling, design and fabrication
  - FPA and camera testing under high neutron flux
- Results and Discussion
- Summary

Introduction: Goal, Specifications and Challenges

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Goal:

Fabrication of cost-efficient video cameras using infrared sensors that have high resistance to radiation.

Specifications

- Target temperature: ~300°C
- Sensitive in the 5 µm and longer spectral range (MWIR)
- Operate at standard frame rates (>25 frames/s, hence the maximum sum of the integration time and the data transfer time up to 40ms)

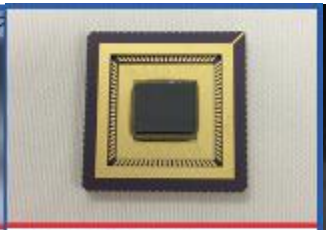
Challenges:

Radiation tolerance for prolonged operation

- Under neutron fluxes (10^5 n cm^{-2} s^{-1}) => short period of time
- Total absorbed dose of ~ 1MRad/yr. => Total dose (TD) effects

Company Overview

EPIR : R&D and Commercialization for II-VI based Material, Device and System Technologies



- ❖ **Pioneered molecular beam epitaxy (MBE) HgCdTe material growth**
- ❖ **Decades of experience with II-VI material and device fabrication and testing**
- ❖ **Headquartered in Bolingbrook, IL**
  - ➢ Commercial supplier of MBE materials and devices to a broad customer base
  - ➢ Provider of material, focal plane arrays, and sensors solutions
  - ➢ Close collaboration with two DOE National Labs from Chicago area: ANL (7 miles, CNM) and Fermilab (15 miles)

1. **II-VI Material Manufacturing**
   - ➢ Grow II-VI materials to enable standard and custom imaging products
   - ➢ HgCdTe on CdZnTe and Si-based substrates (using CdTe buffer layer)
2. **Focal Plane Arrays and Camera Development and Production**
   - ➢ Standard and specialty array detectors, FPAs and imaging sensors
3. **R&D Solutions using II-VI Technology**
   - ➢ Material, device & system modeling, optimization, fabrication and testing
   - ➢ Full process development to meet customer specifications

Project/R&D Objectives

1. HgCdTe material structural design, growth and characterization (QC)

2. Design devices and photomasks with sub-pixel pattern optimization

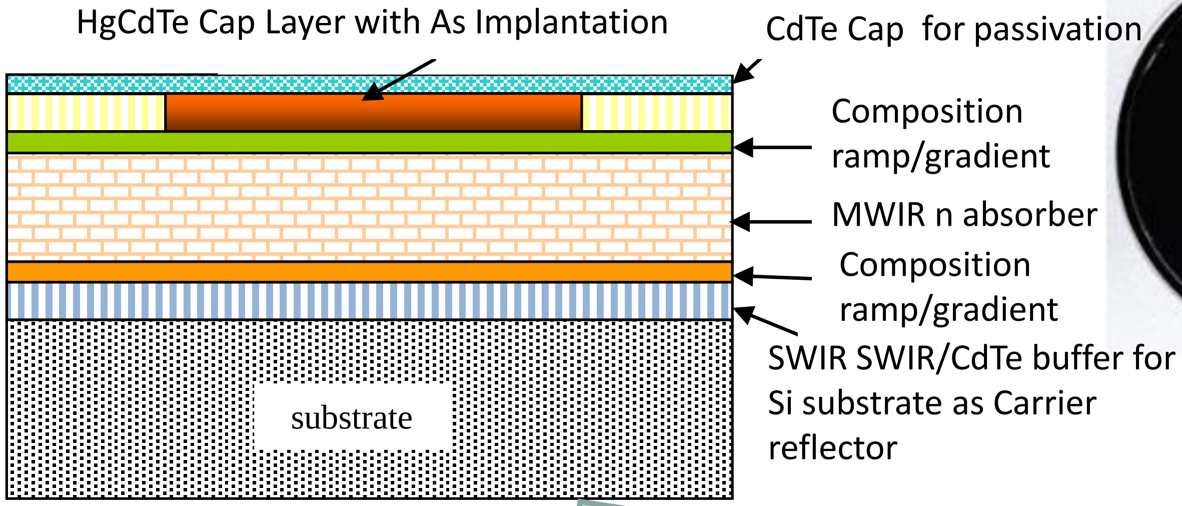
3. Fabrication of detectors with improved radiation hardness

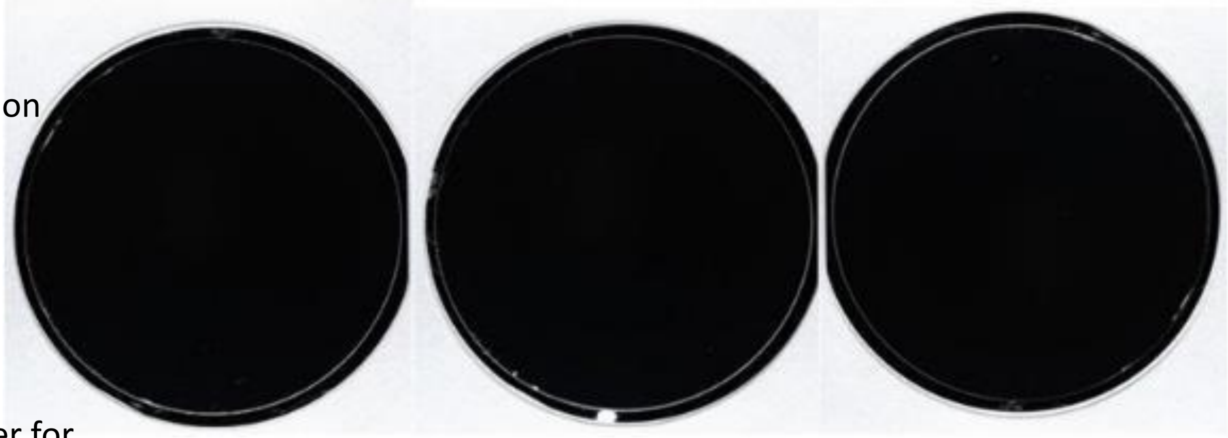
4. Integration of the detectors with radiation-hardened ROIC

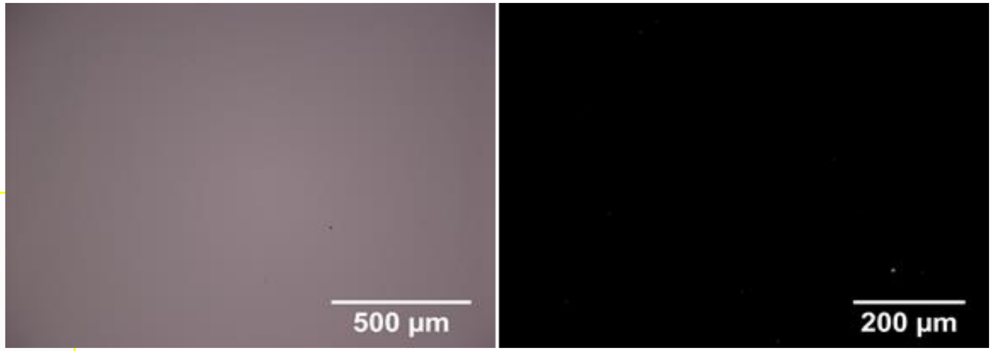
5. Packaging and testing detectors and cameras under neutron flux

Growth and Characterization of HgCdTe Heterostructures

1. Design double layer planar heterostructures (DLPH)

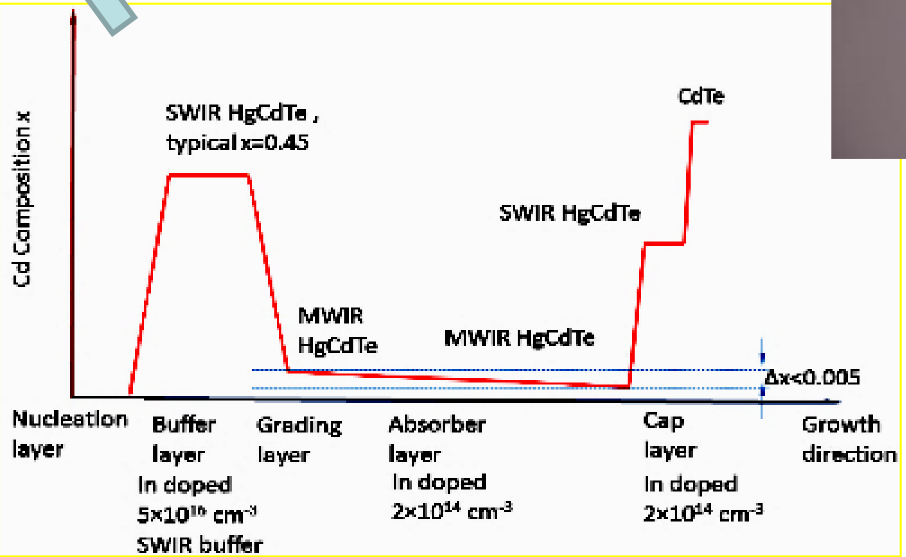






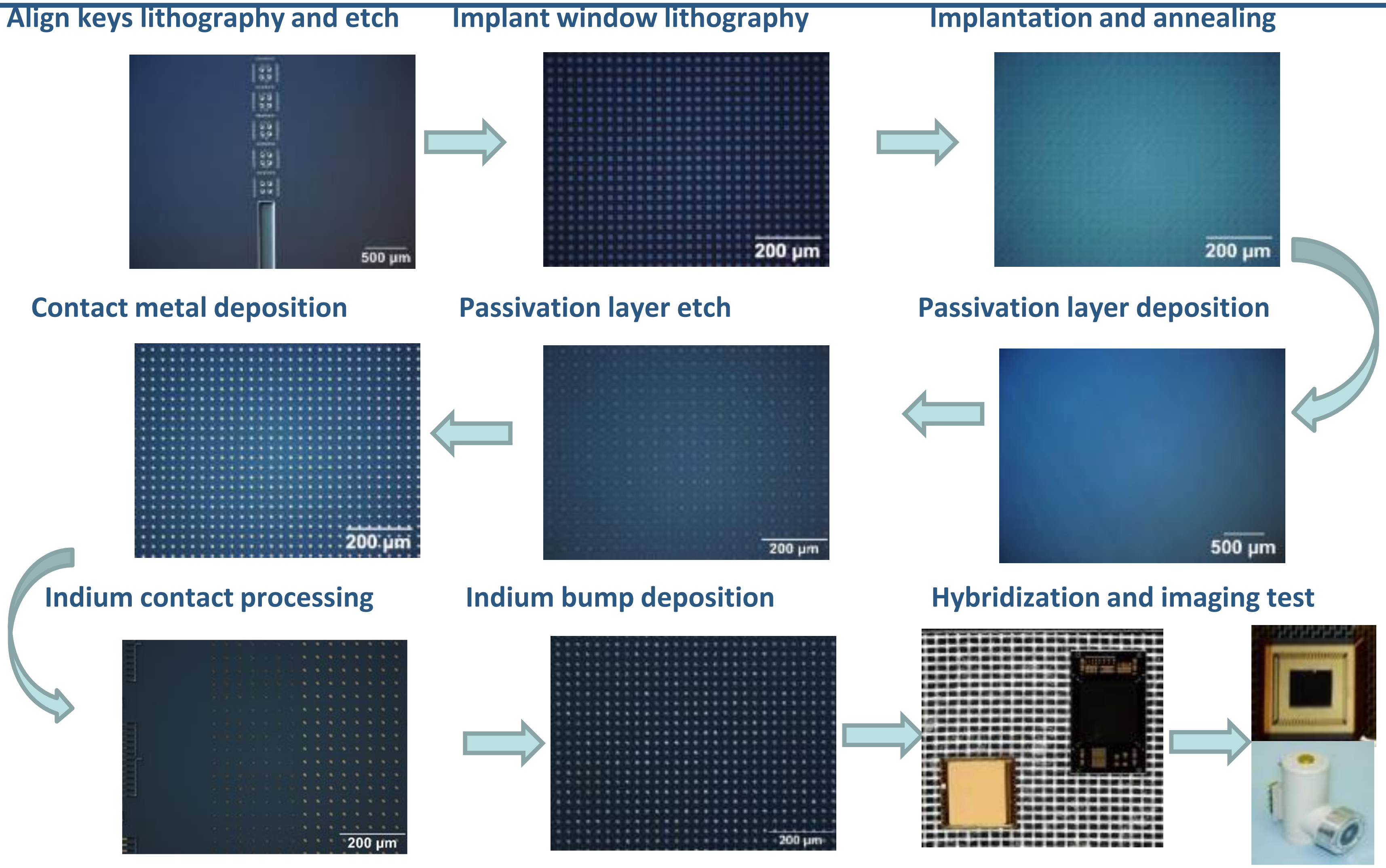
2. Precise composition and doping control (FTIR, Hall, SIMS)
3. Impurity reduction, low background doping:

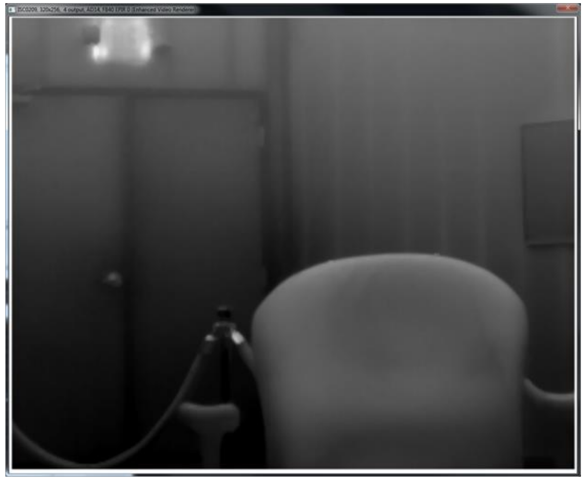
4. Defect reduction (EPD, surface defect counting, HRXRD)
5. Long carrier recombination lifetime (µs level) hence with long diffusion length

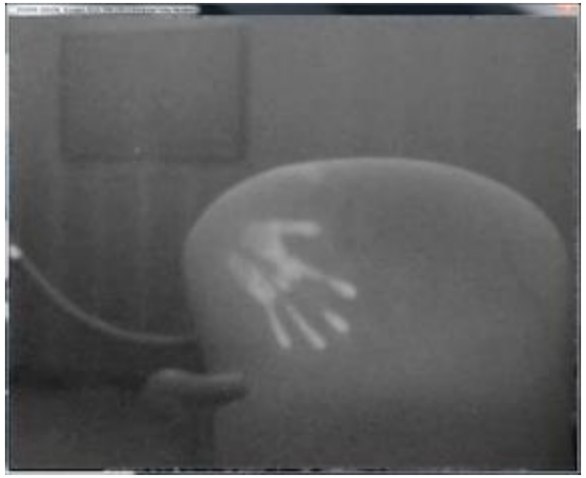


- MBE growth of high-quality HgCdTe layers achieved.
- Material tested under radiation flux.

Device Fabrication – Standard Process

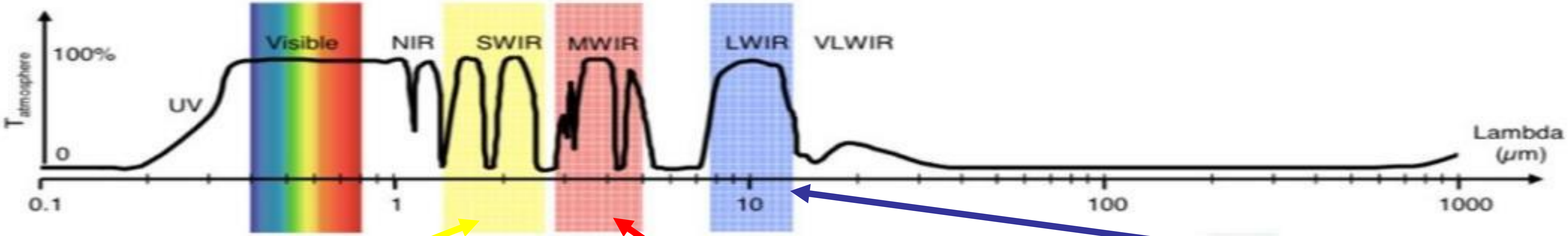






- EPIR optimized process control for array fabrication
- Background limited dark current performance achieved

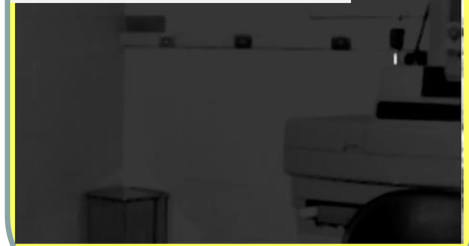
Infrared Focal Plane Arrays at EPIR



NIR-eSWIR

NIR on Si, Room Temperature

eSWIR on Si, 195K



MWIR

MWIR on CZT, 140K

MWIR on Si, 110K

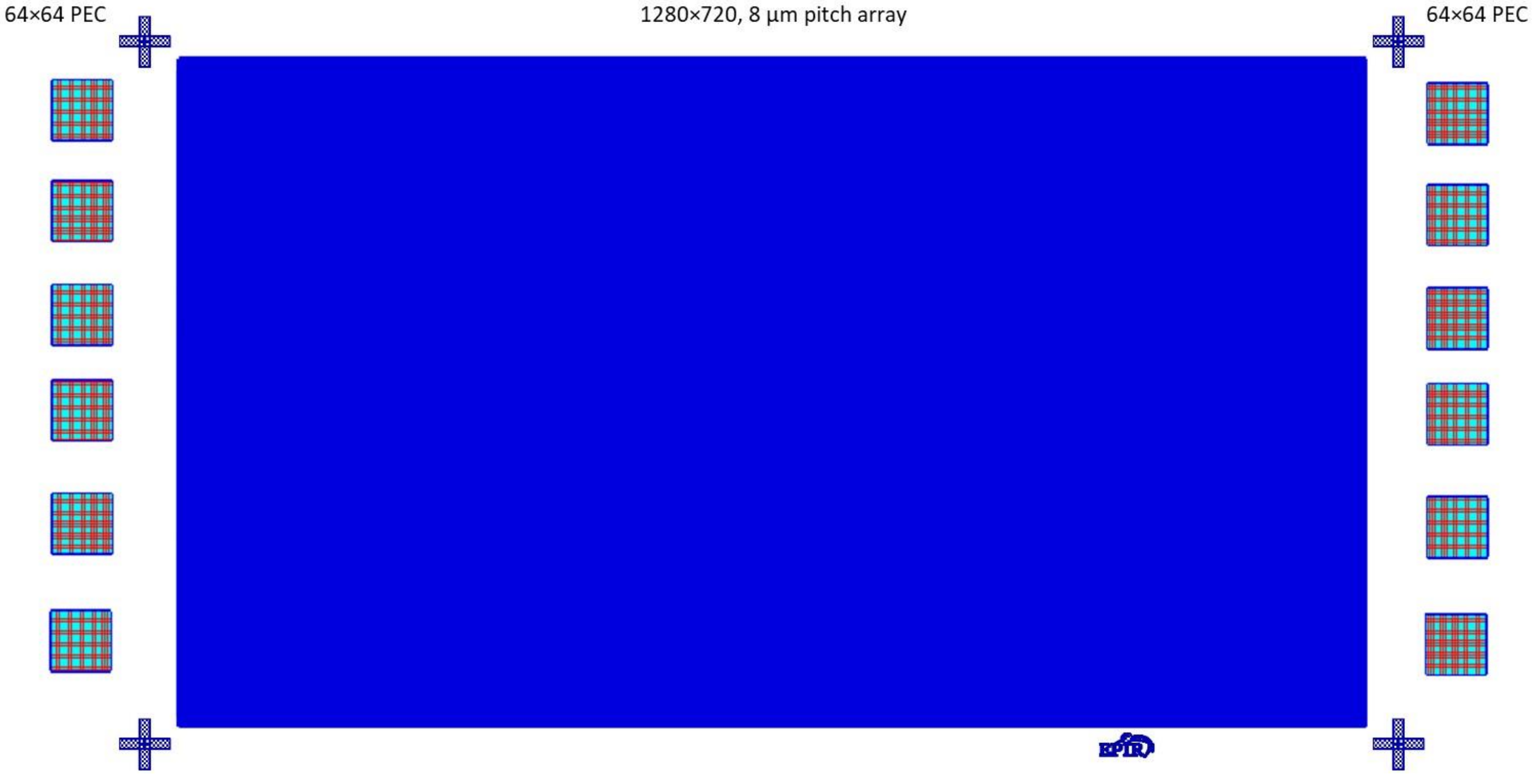
LWIR

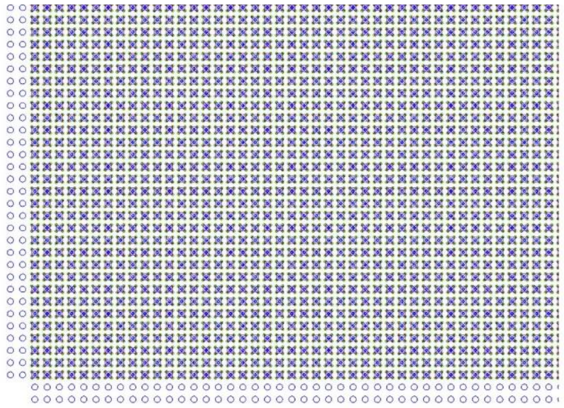
LWIR on CZT, 85K

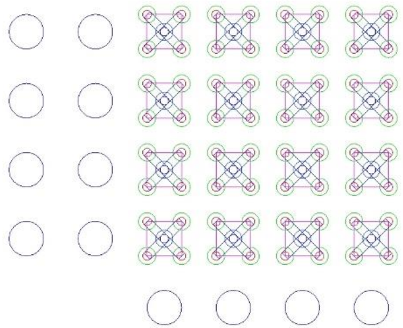
LWIR on CZT, 110K

- Commercial grade devices in NIR to LWIR range
- Can be fabricated on CdZnTe and Si substrates (using CdTe as buffer layers)

Mask Design for HD Radiation Hardened Arrays and Test Elements

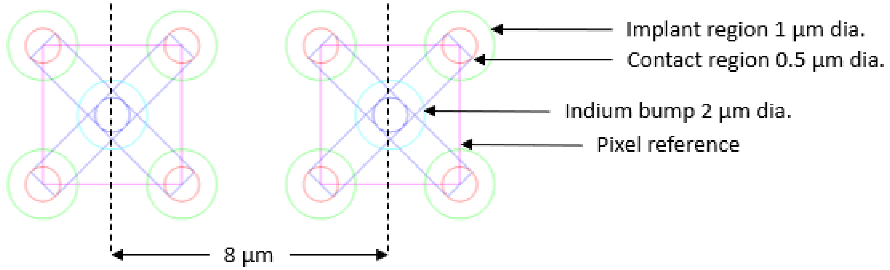






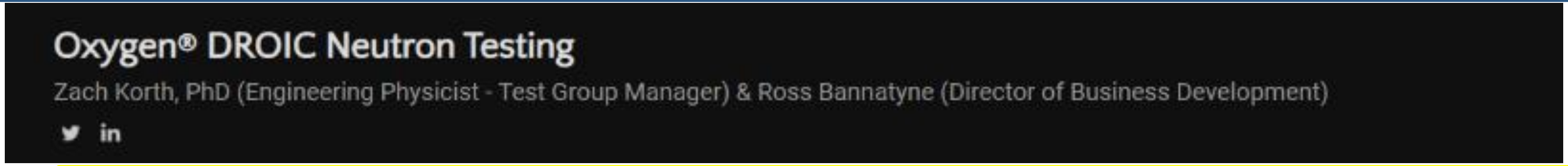
1080x720 FPA with Senseeker's ROIC

8µm pitch



Under bump metal (UBM) and indium bumps are positioned away from the p-n junction area, reducing the impact of the hybridization force on FPA characteristics

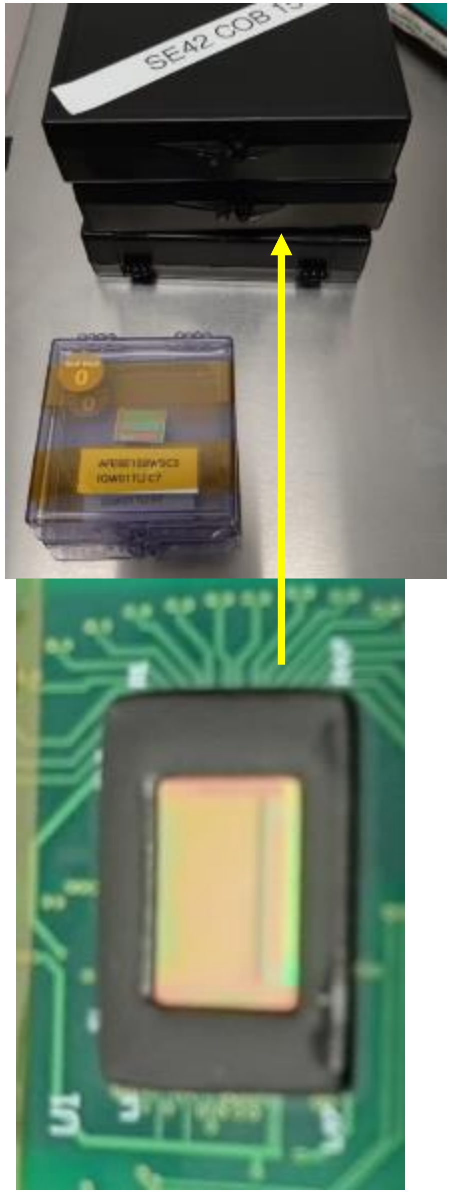
Choice of ROIC and other Electronic Components



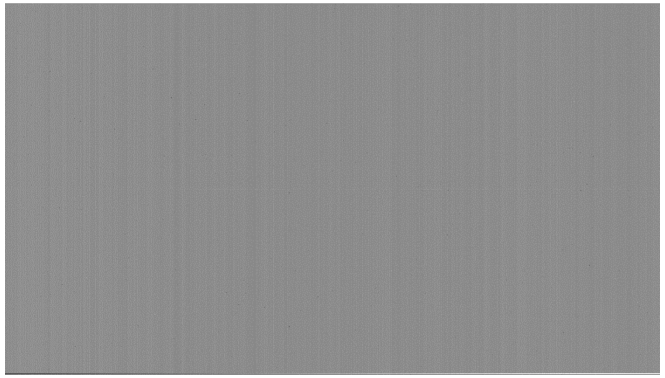
- … the devices were re-tested at Senseeker's facility in Santa Barbara to observe any effects that may have occurred due to displacement damage. We were delighted to find that **not a single pixel was 'lost'** and **all of the samples were fully functional**. Each Oxygen DROIC has an array size of 1280 x 720 pixels - that is 921,600 pixels per device. Although the post-radiation leakage characteristics were slightly elevated, they **were still within product specifications**.

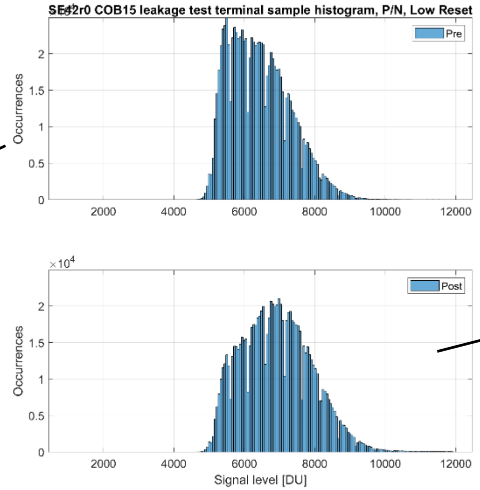
From: https://senseeker.com/news/IS-20210527-01.htm

- Senseeker's ROIC and ROIC mounted on PCB were tested under >1×10 ^{9} n/cm^{2}/s (up to 2×10 ^{9} n/cm^{2}/s) neutron irradiation for 2 hours
- We also tested electronic components from Alphacore under similar neutron irradiation conditions. All components maintained full functionality after the neutron irradiation

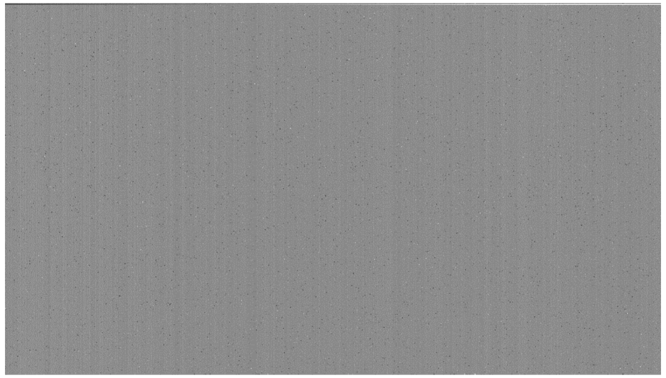


Before neutron irradiation

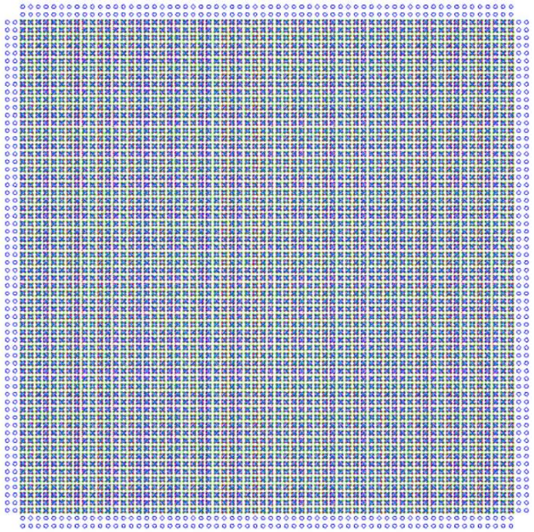


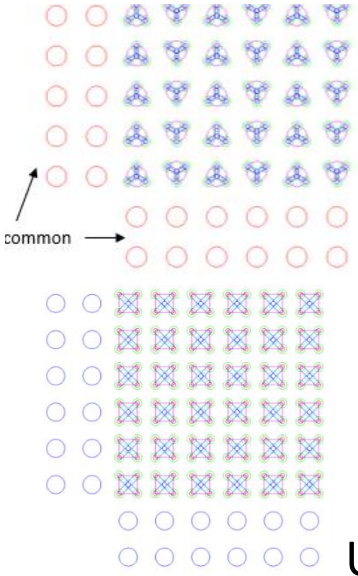


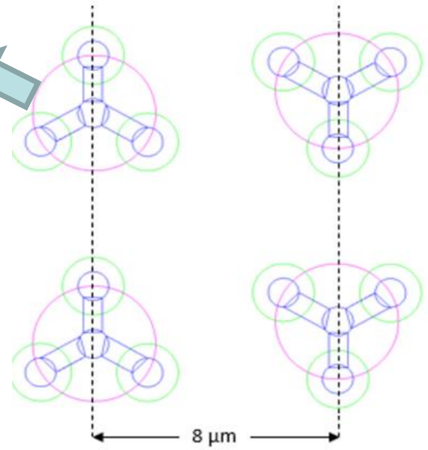
ROIC after neutron irradiation

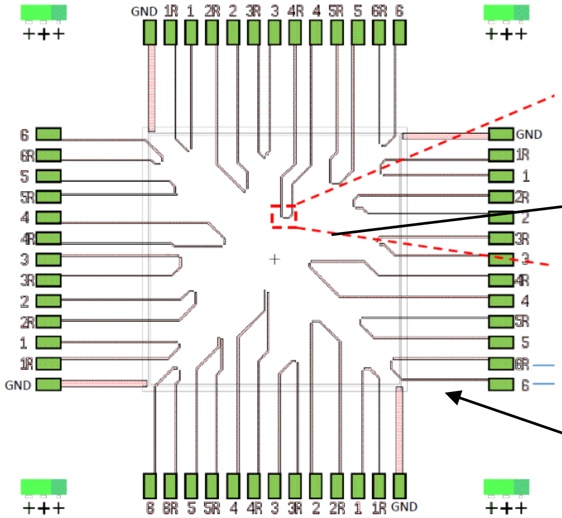


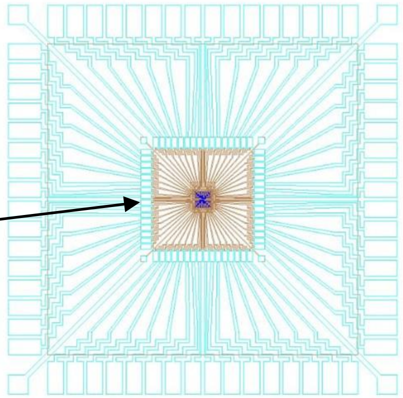
64x64 Testing Array with 2x2 or 3 Subpixel Arrays



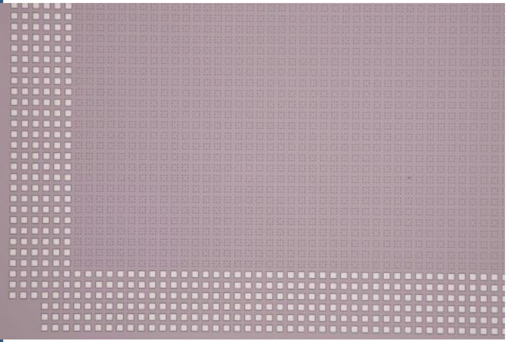


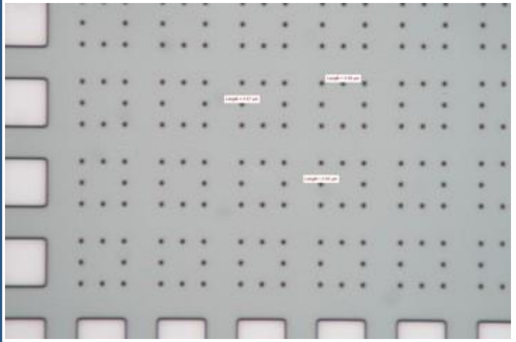


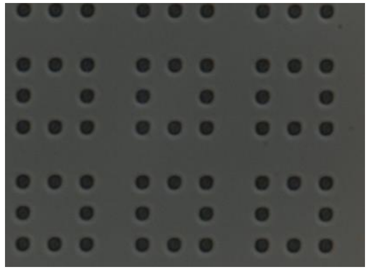




Fanout circuit for testing:

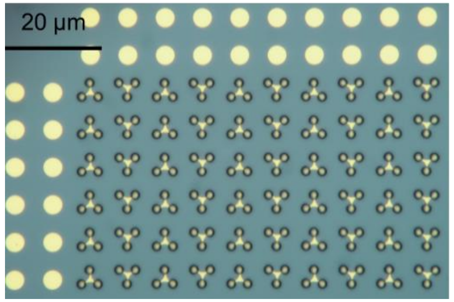




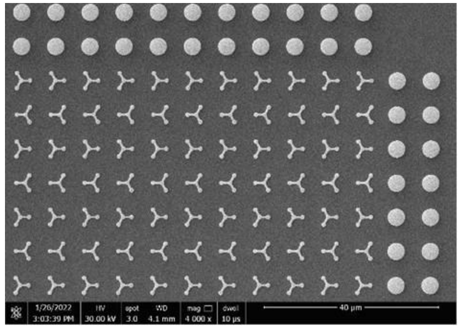


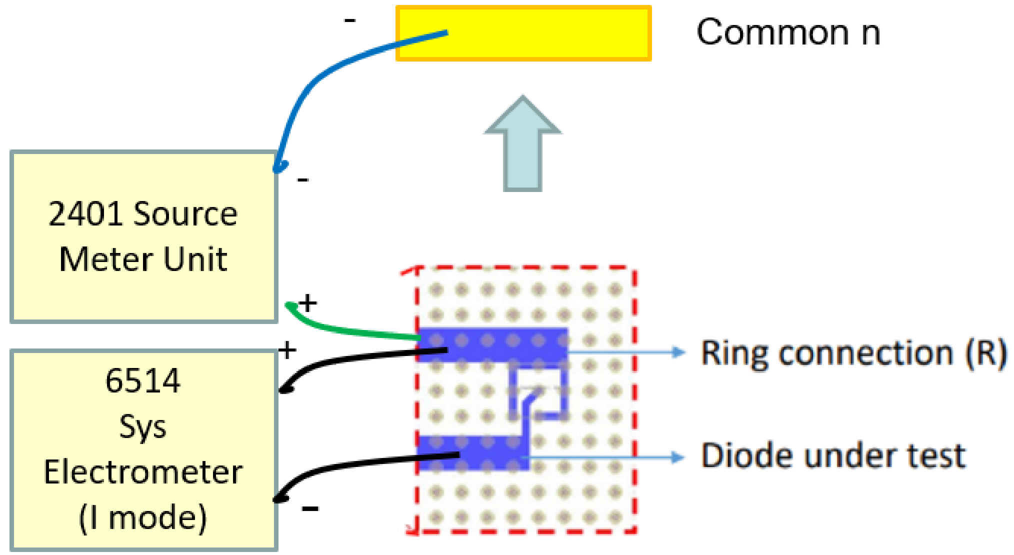
- ✓2x2 per pixel array with a 15µm pitch
- ✓2x2 per pixel array with an 8 µm pitch
- ✓3 subpixel per pixel array with an 8µm pitch

Under optical microscope:



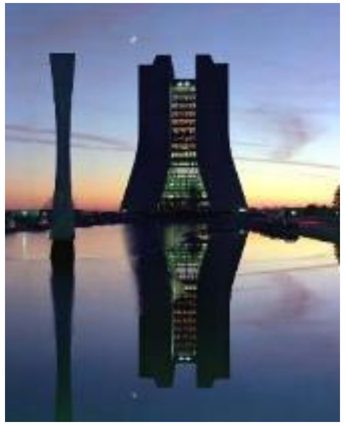
Under SEM:

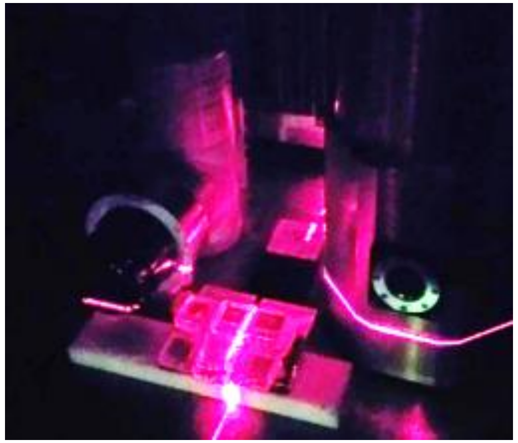


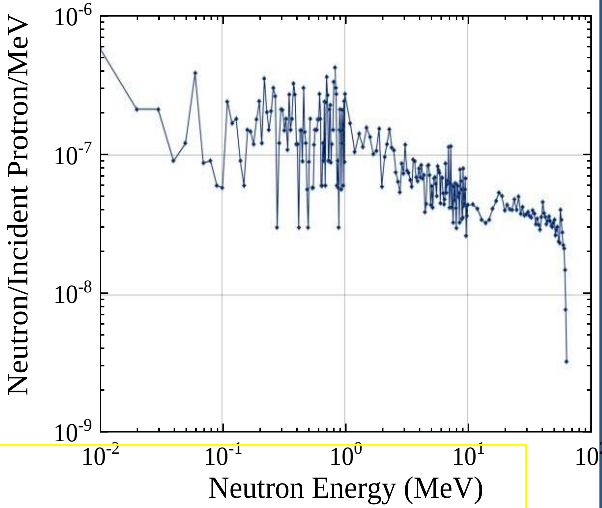


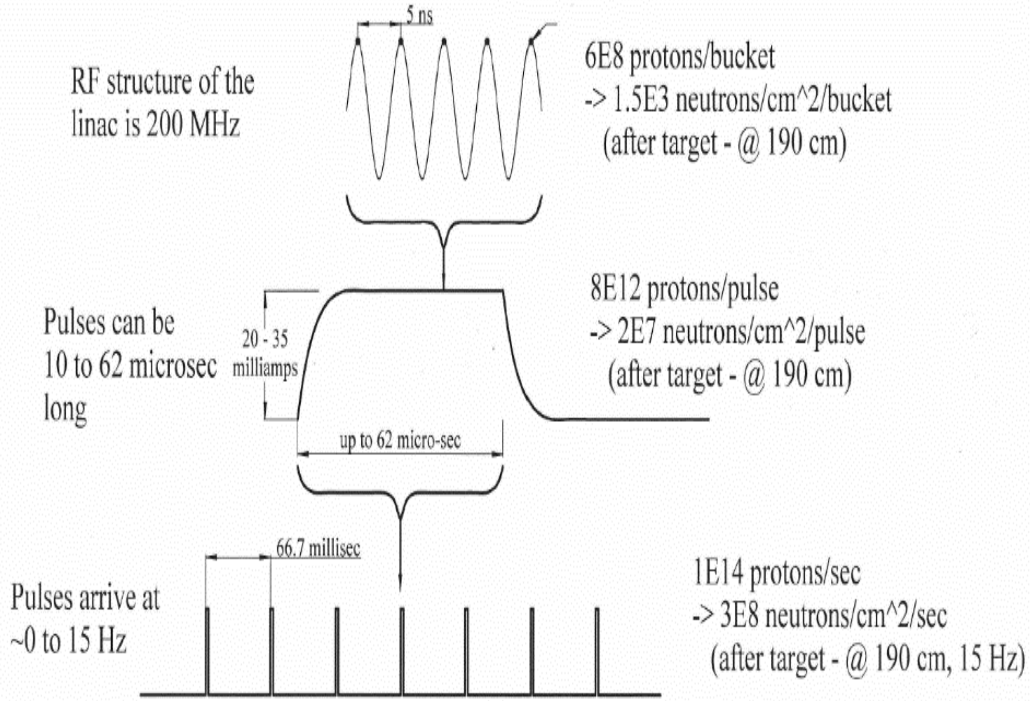
Fanout circuit mounting and test configuration on chip carrier PCB through wire-bonding

EPIR's FPAs under Neutron Flux at FNAL







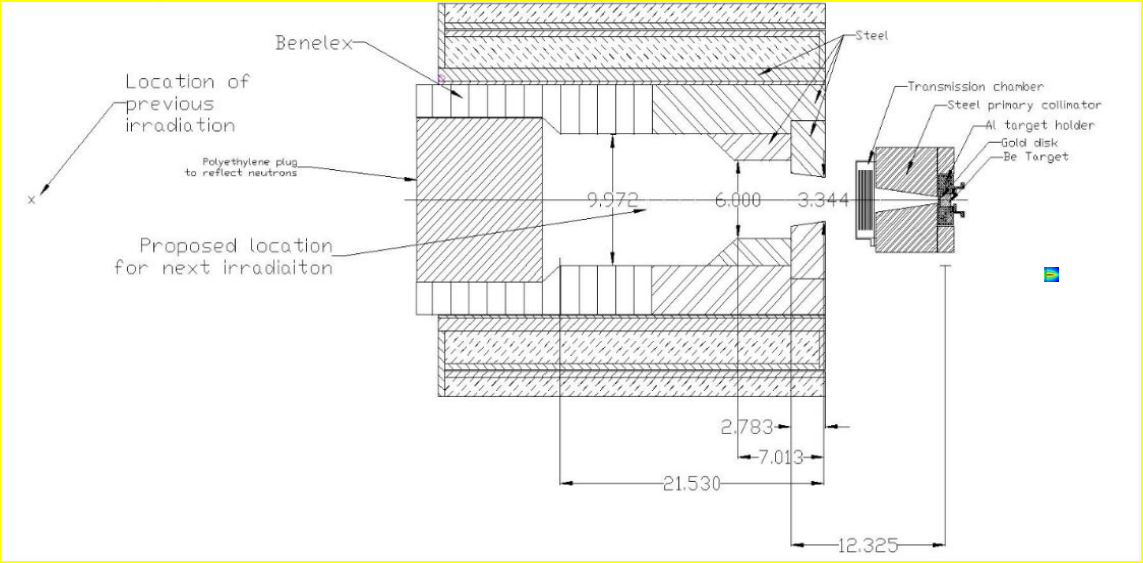


Standard Testing condition:

- Maximum neutron energy was 66 MeV
- Irradiated at a typical rate of 1×10^{8} n/cm$^{2}\cdot$s
- Maximum rate can achieve ~2×10^{9} n /cm$^{2}\cdot$sec by mounting samples inside the channel (without considering scattering)

Dose rates were calculated based on the theoretical maximum in FNAL's standard configurations. Operational constraints may significantly lower rates and maximum doses. We will investigate alternative configurations in order to mitigate the operational reductions.

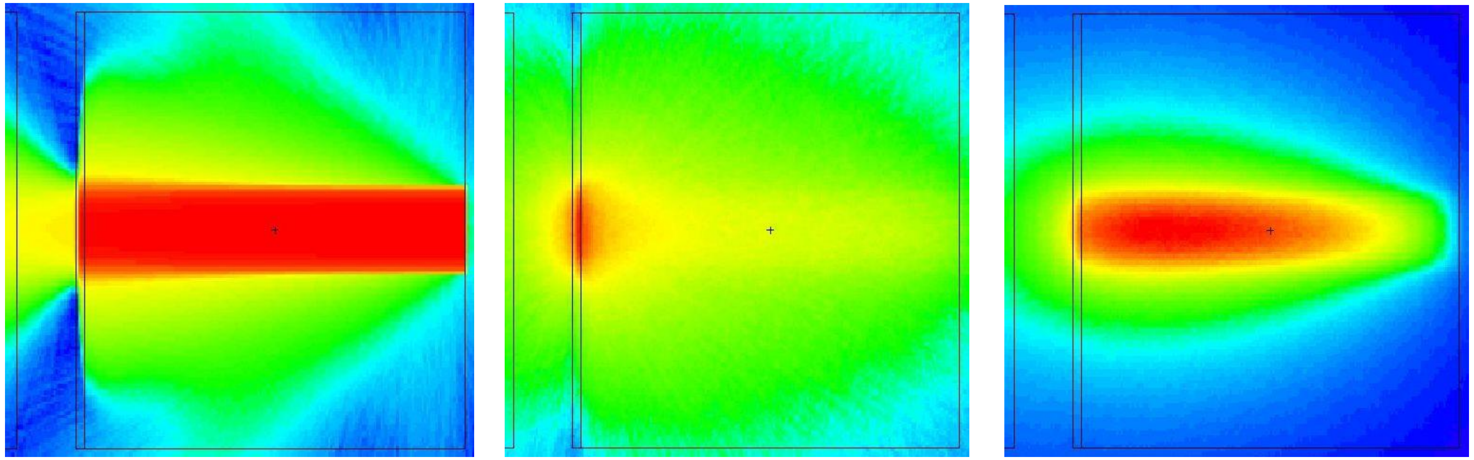
Approaches to Increase Neutron Flux

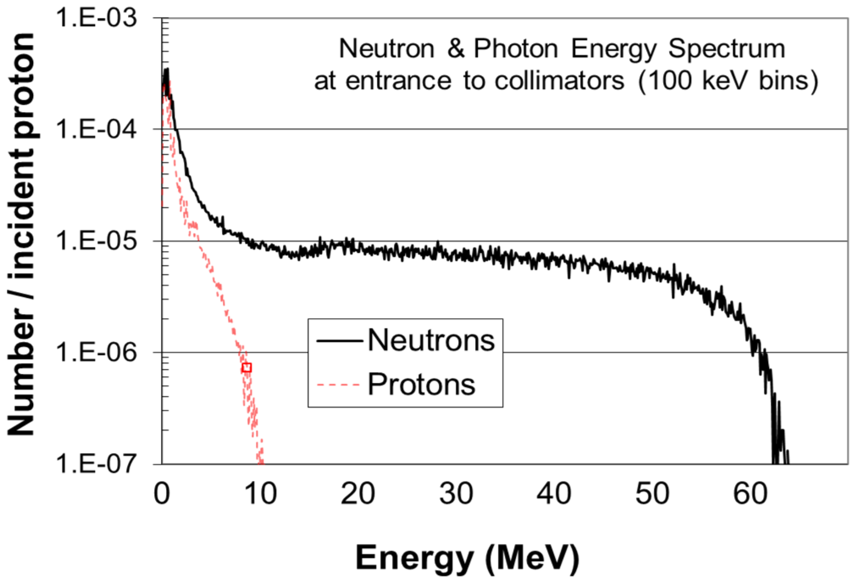


Proton

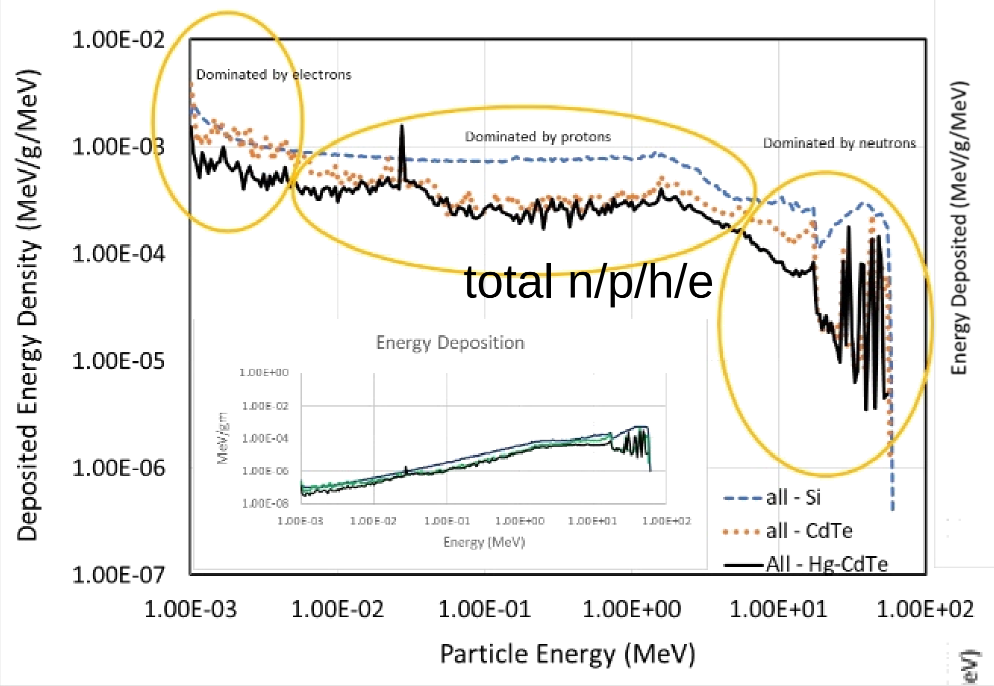
Photon

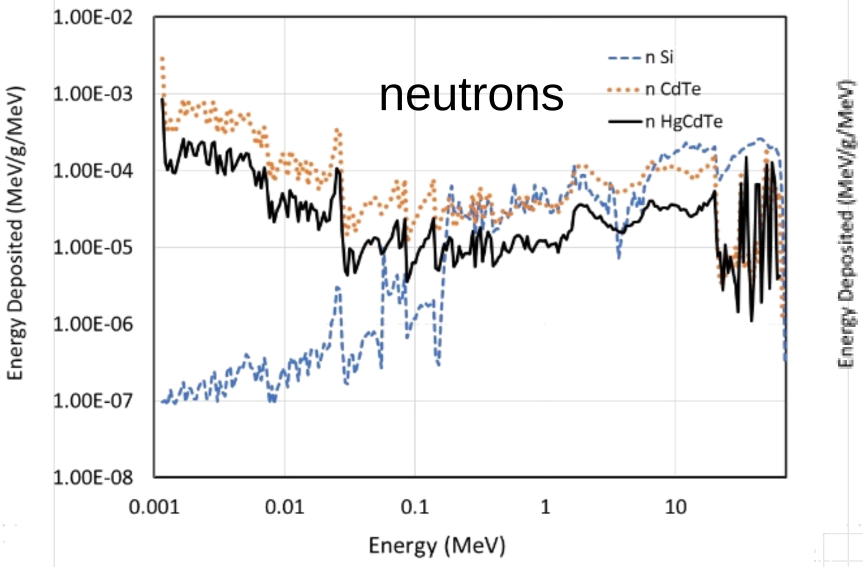
Neutron

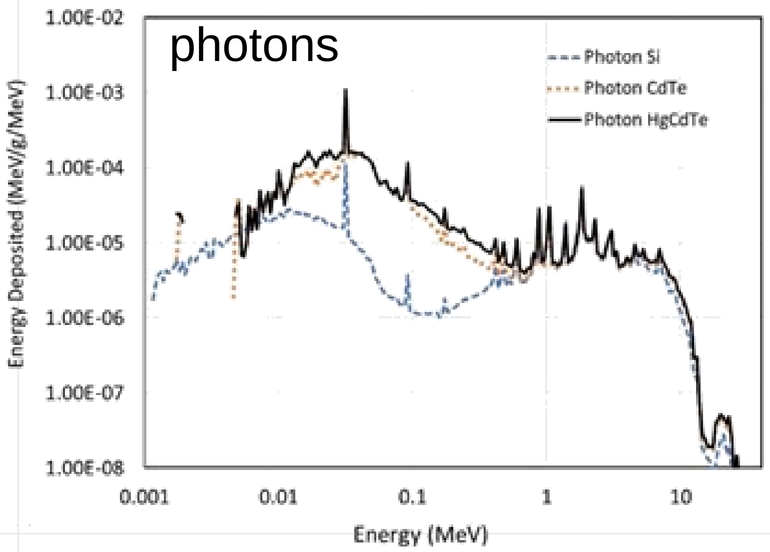


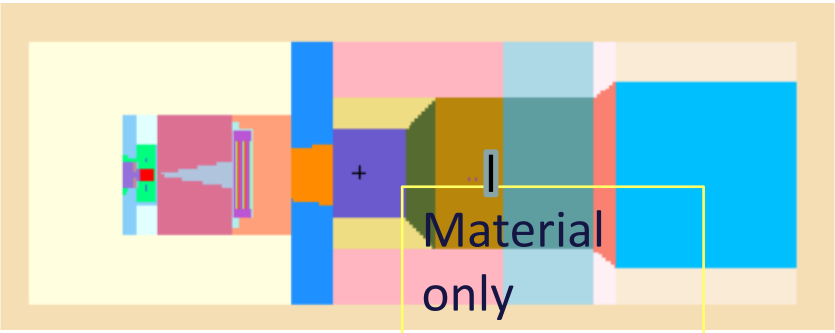


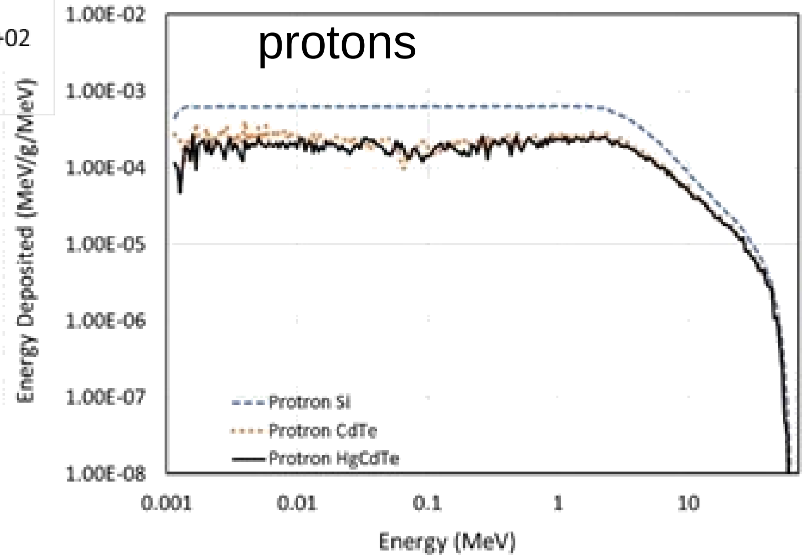
Energy Deposition in Material: MCNP Calculation at FNAL

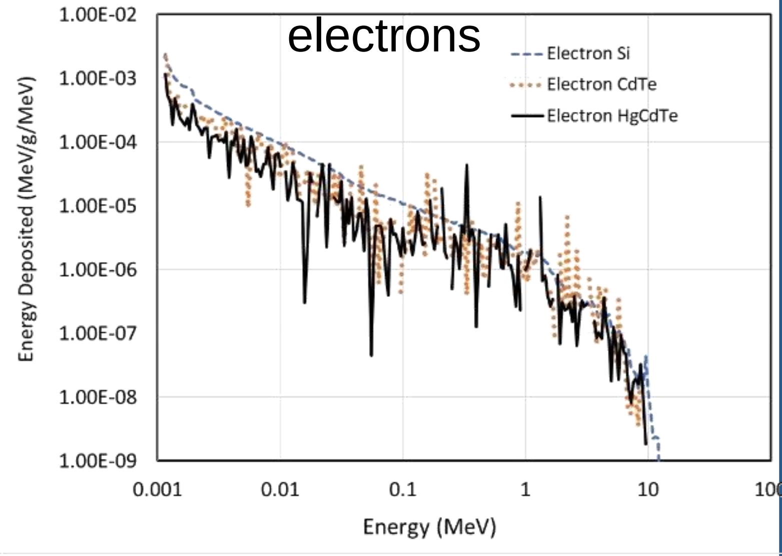






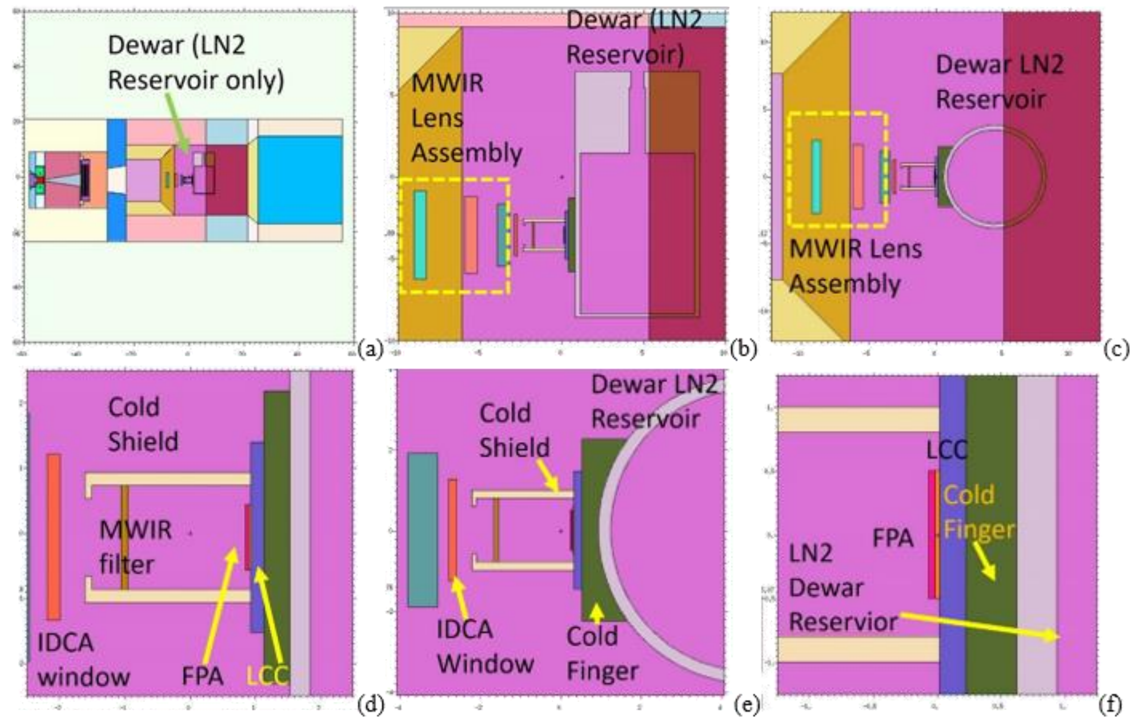


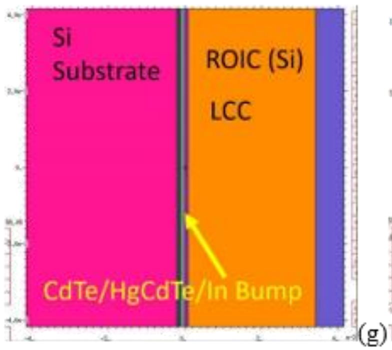


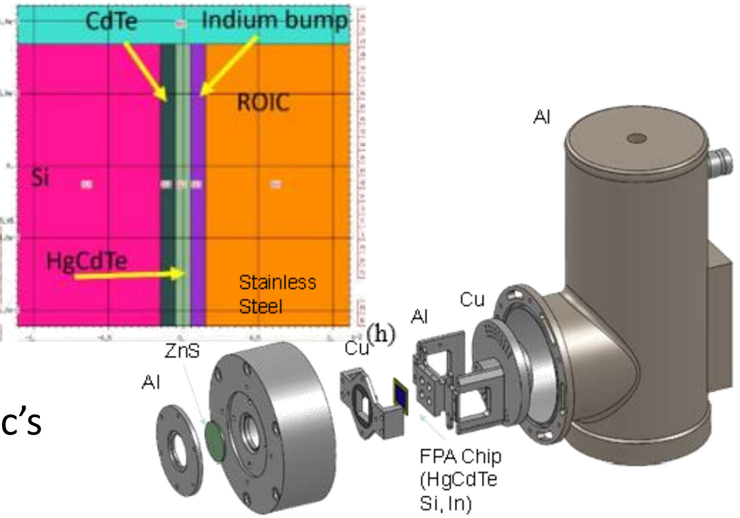


Deposited energy on HgCdTe material: through all electron, photon, proton and neutron mechanisms

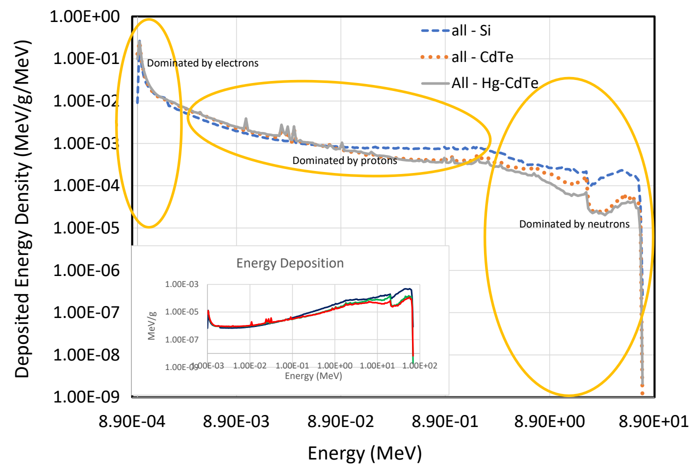
MCNP Camera Modeling



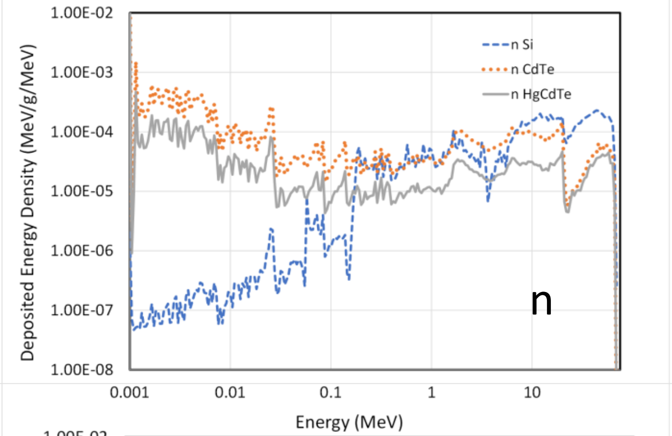


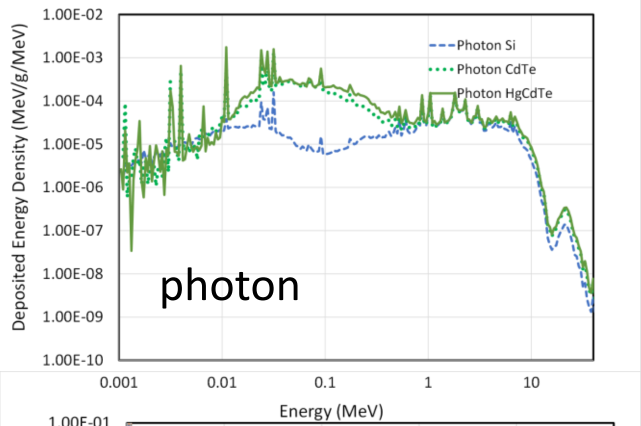


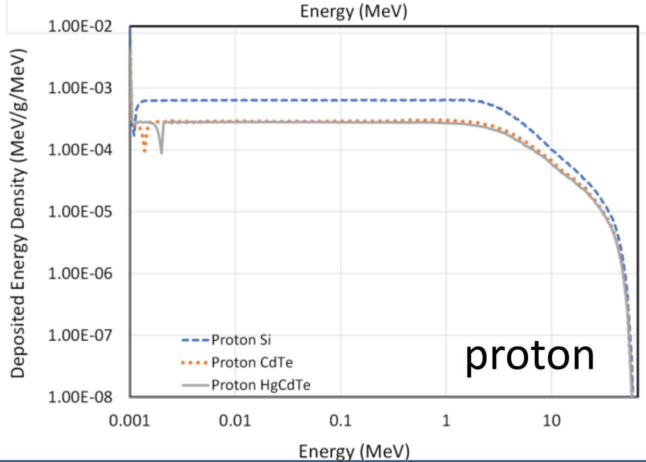
Supported by Dr. Kroc's group at FNAL

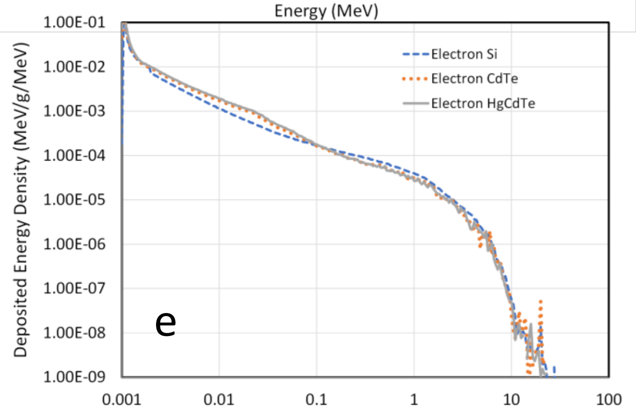


- Energy density deposited (F6 Tally) in the FPA chip.
- Include energy deposited in Si, CdTe and HgCdTe

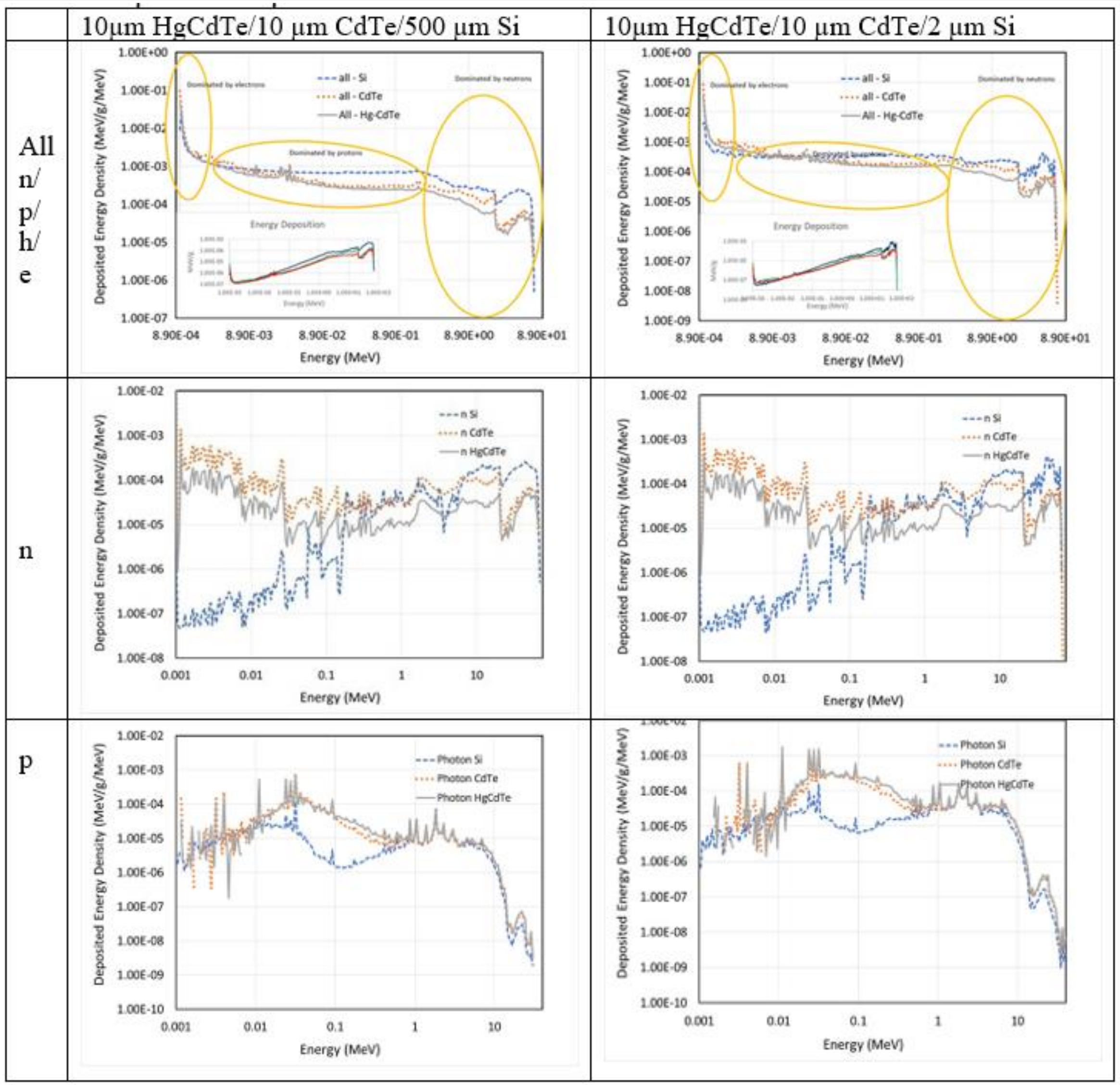


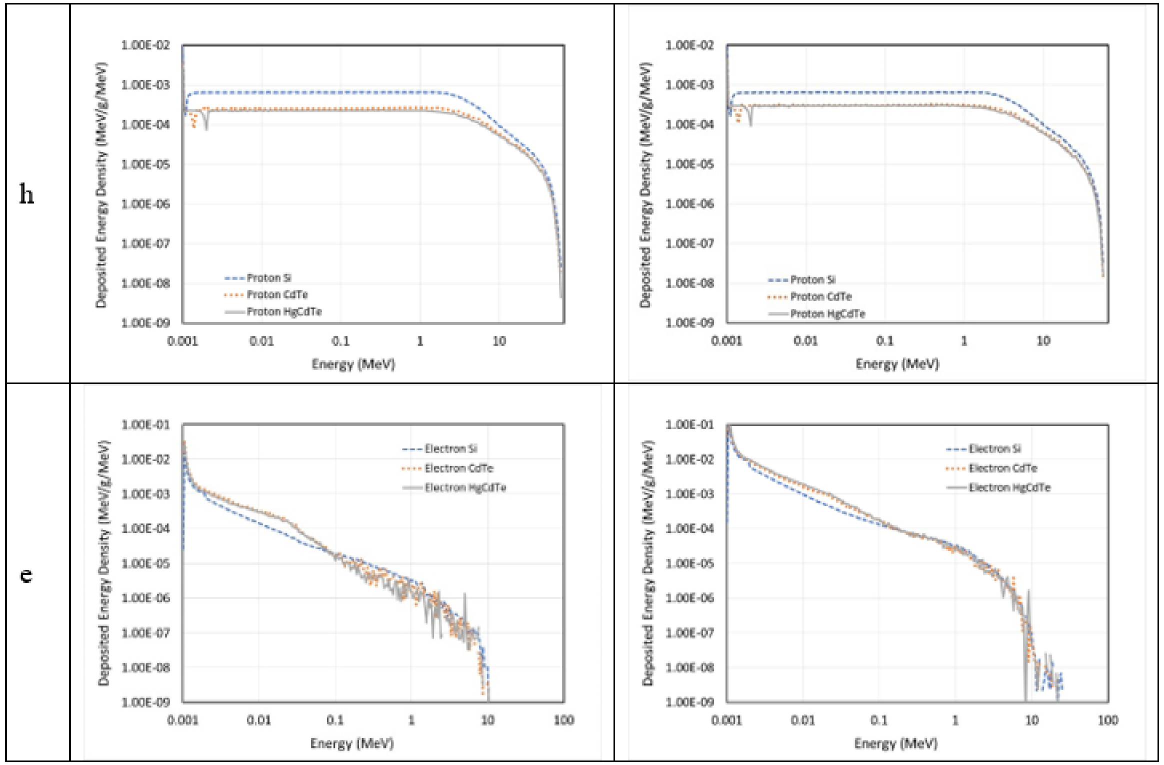






Effect of Thinning Si Substrate





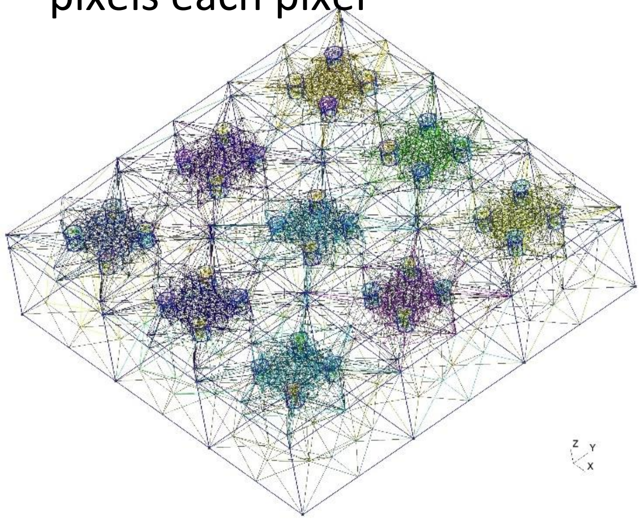
- Almost identical behavior with normalized mass.
- Thin substrate samples have less energy deposited directly through neutrons while more energy through h/p/e, especially through e with energy less than 10keV.
- Low energy electrons deposited in Si Si may have less influence on HgCdTe FPAs as long as a proper grounding is present.

Python Base Opensource Device Simulation

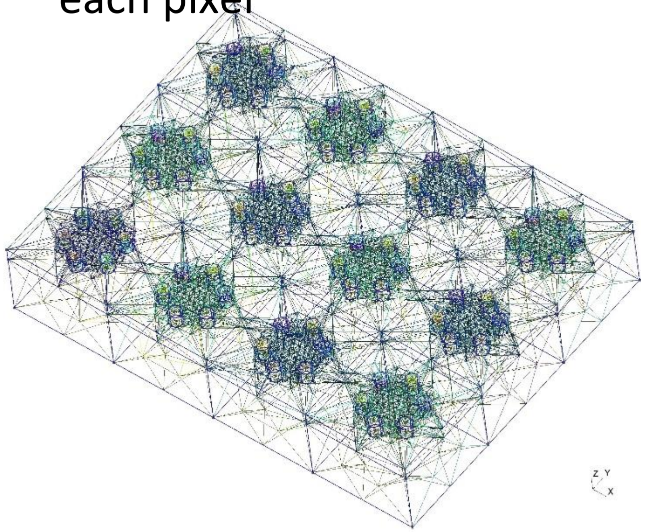
EPIR

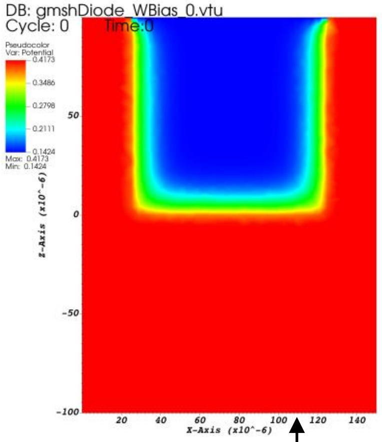
- Supported by DoE NP diversity program for encouraging women and other under-represented group students to get involved in STEM research
- Used opensource DevSim Python package, partially supported by DoE, to conduct 3-dimensional device simulation
- Enhanced diode model will include not only photon current generation, and diffusion but also generation-recombination, impurity/defect-assisted tunneling, and band-to-band tunneling current generation mechanisms
- Specifically developed for adapting the sub-pixelated lateral collection pixels designed for this project

3x3 pixels with 2x2 sub-pixels each pixel

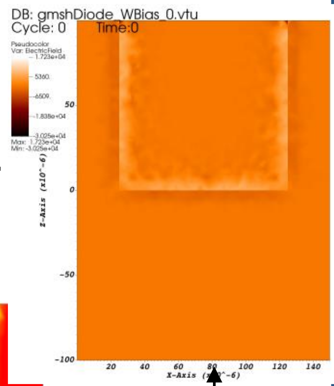


3x4 pixels with 6 sub-pixels each pixel

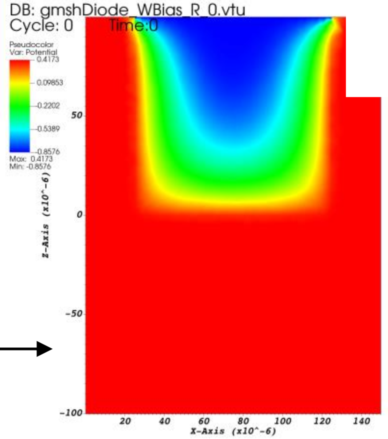




Example of potential inside a n-on-p subpixel



0-biased potential plot

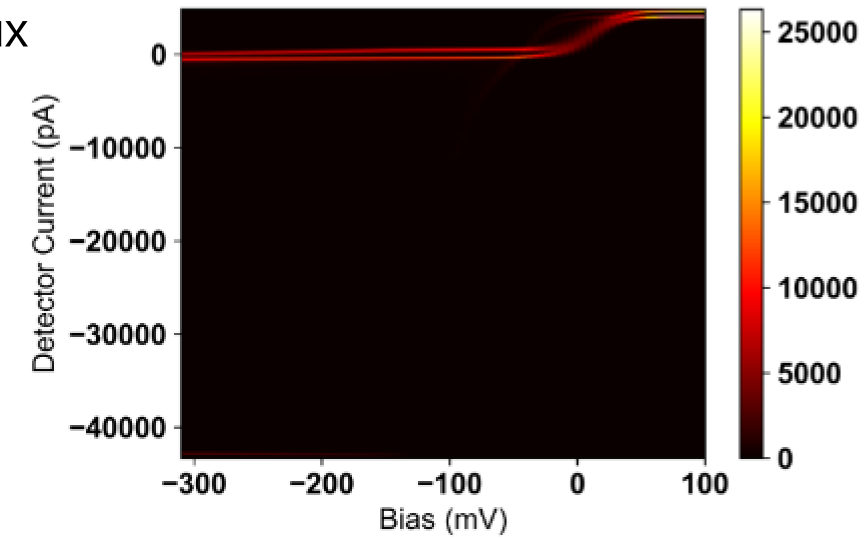


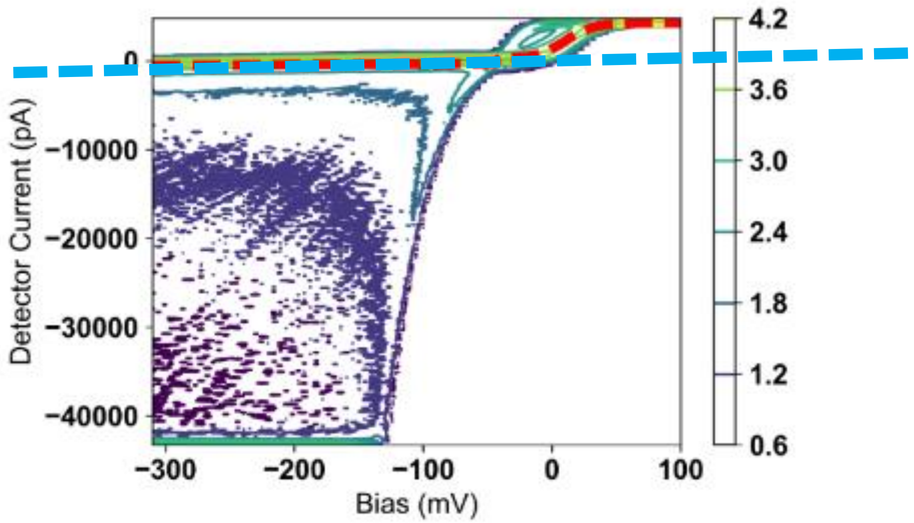
Biased potential plot

Built-in E-field plot

I-V Characterization (FPA_L) After Neutron Exposure

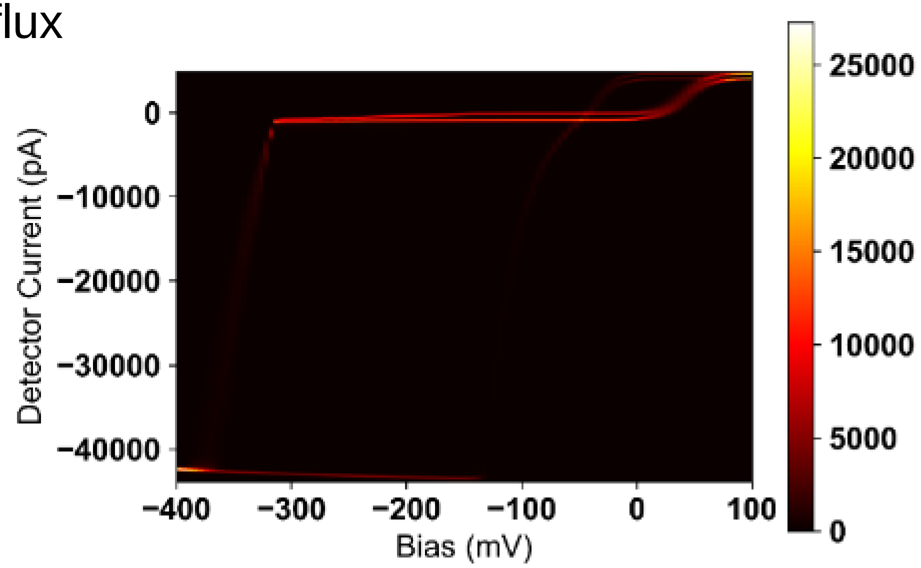
Before neutron flux

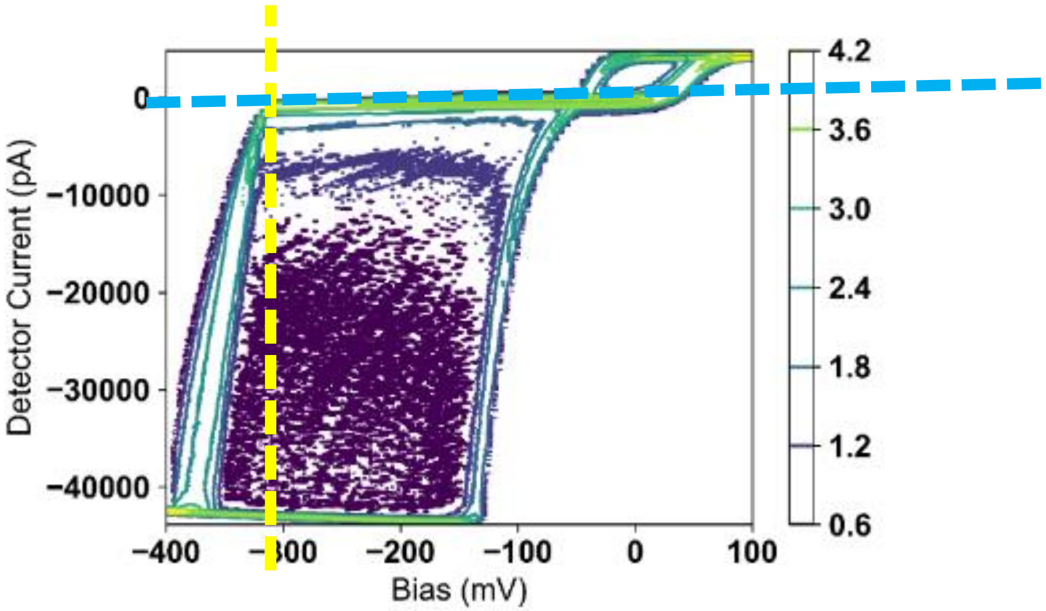




After neutron flux

Total: ~10^{12} n/cm^2





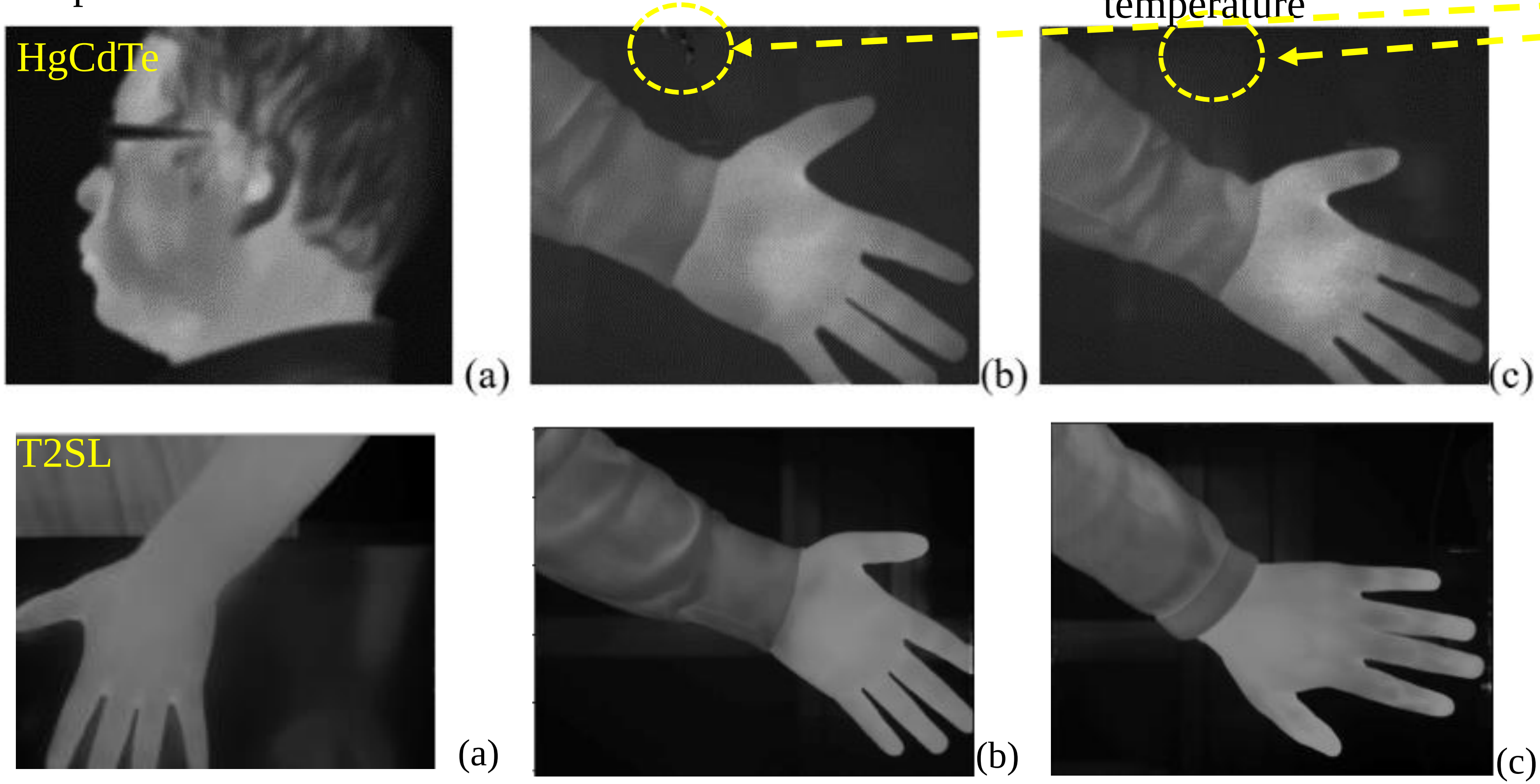
Imaging with EPIR-assembled IR Cameras

3-5µm MWIR

before 1.5×10^{13} $n\cdot cm^{-2}$ neutron exposure

after 1.5×10^{13} $n\cdot cm^{-2}$ neutron exposure under an instant flux of 2×10^{9} $n\cdot cm^{-2}\cdot s^{-1}$

after an extra temperature cycling from 100K to room temperature



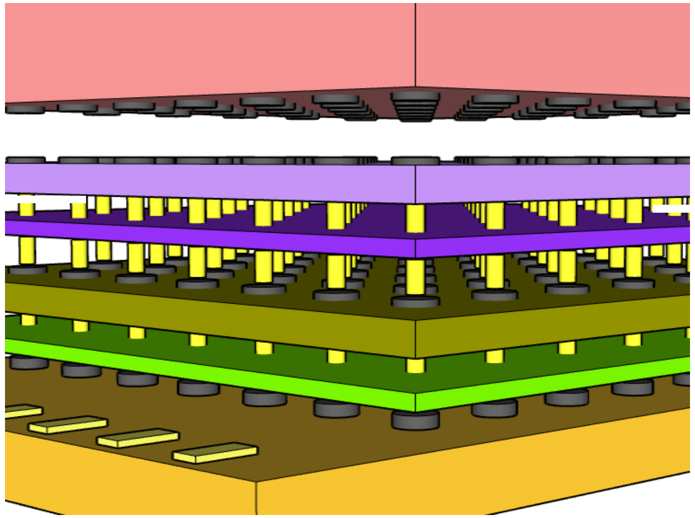
The circled area shows the defective pixels recovered after temperature circling.

Our T2SL nBn FPAs also shows good functionality, however Sb decay emits β particles and the FPA required ~**4 Months** “cooling down” period before being released from FNAL’s neutron facility

Summary and Future Works

- HgCdTe is the preferred infrared material for use in high radiation environment applications. EPIR has grown the HgCdTe wafers with desired characteristics using MBE
- Lateral collection device architectures were used to reduce the dark current in implantation-formed p-n junctions. Photomasks were designed and 64x64 small PEC array and 1080x720 HD FPAs were being fabricated and tested
- Testing at Fermilab: HgCdTe FPAs maintained functionality after 1.5×10^{13} $n\cdot cm^{-2}$ neutron exposure and 2×10^{9} $n \cdot cm^{-2} \cdot s^{-1}$ instant irradiation flux with only minor performance degradation. Equivalent to >2-year of continuous peak operation.
- Most of the sub-optimal FPA pixels after irradiation can be recovered and restored to the original condition after the temperature cycle (77 K to 300 K)
- Working with ROIC and other electron component manufacturers enables the fabrication of HD IR cameras with high radiation resistance capabilities
- We will continue to work with Fermilab for further testing of existing components and for testing new FPAs and cameras
- Will employ direct bonding to reduce cost and improve FPA operation stability
- Commercialization of the camera product

Thermo-mechanically reliable vertically integrated chip



- In collaboration with Fermilab
- ASICs under development for NP detectors (RHIC, CBAF)
- Conducting radiation hardened design

THANK YOU