Radiation Hardened Infrared Focal Plane Arrays

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Overall Outline

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

Introduction: Goal, Specifications and Challenges

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)

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

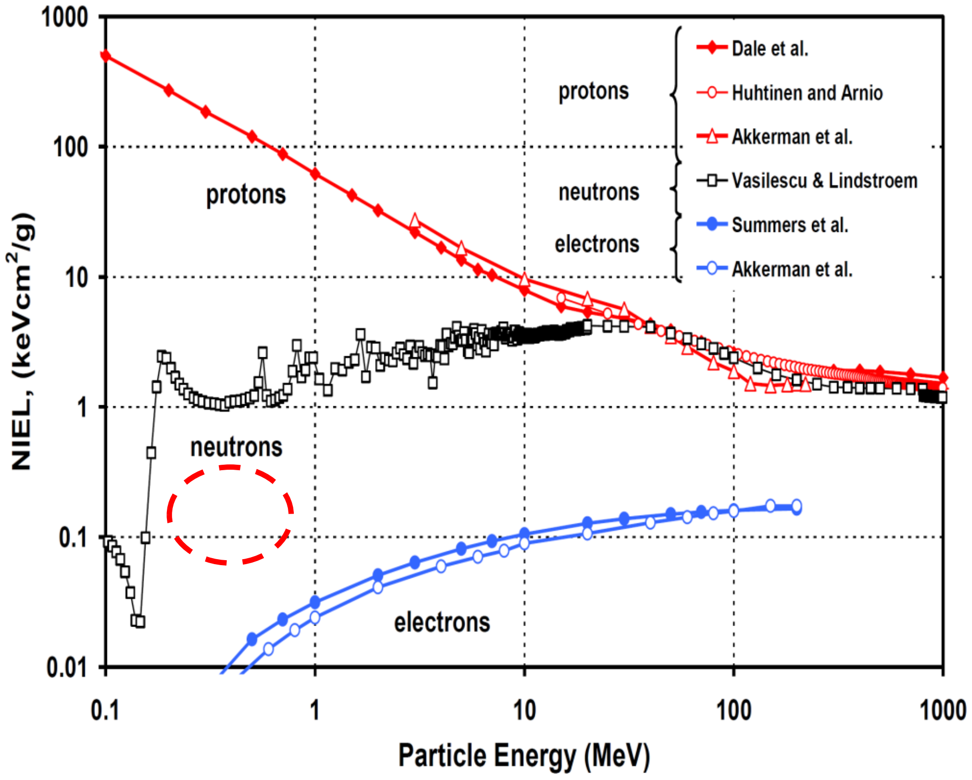
- ❖ **Pioneered molecular beam epitaxy (MBE) HgCdTe growth**
- ❖ **Decades of experience with II-VI material and device fabrication and testing**
- ❖ **Headquartered in Bolingbrook, IL**
  - ➢ Commercial supplier of MBE materials and devices to a broad customer base
  - ➢ Provider of material, focal plane arrays and sensors solutions

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

Displacement Damage Effects in HgCdTe and Related Materials

Neutrons cause FPA degradation mainly through displacement damage effects. Damaged is characterized by Non-Ionizing Energy Loss (NIEL).

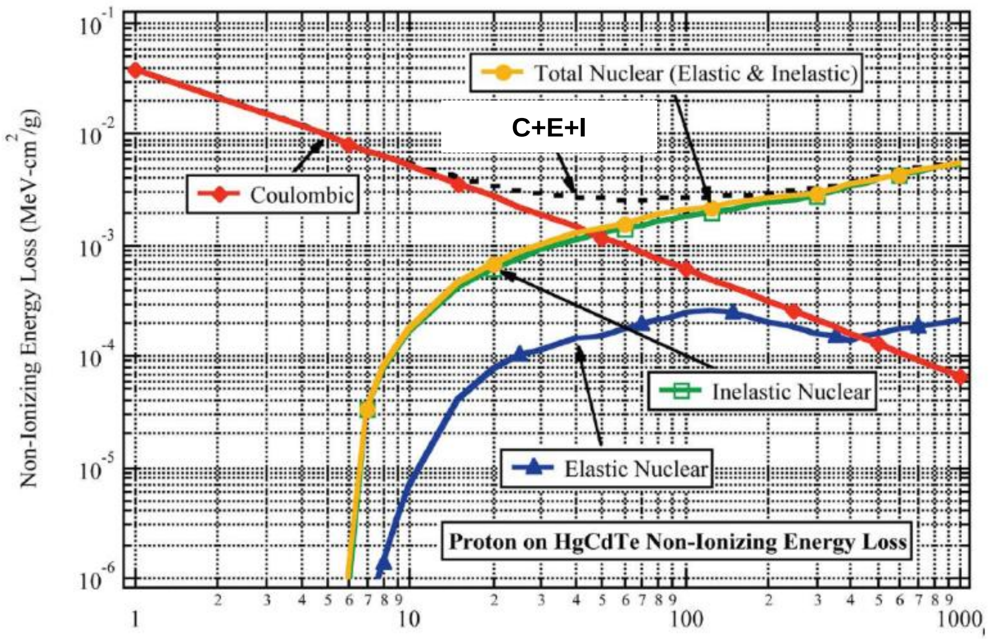
Non-Ionizing Energy Loss (NIEL) Si

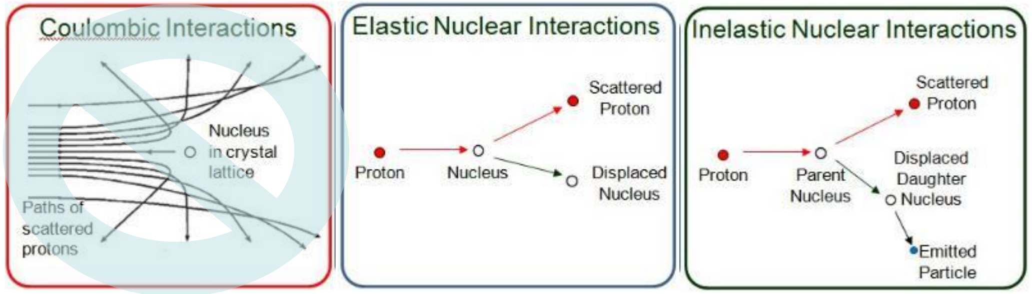


×1000 for keVcm²/g

Final Test Guideline from Surrey Satellite Technology Limited, Guildford, Surrey GU2 7YE, UK (2014)

Non-Ionizing Energy Loss (NIEL) HgCdTe (proton)





J.E. Hubbs, et al., IEEE Trans. Nucl. Sci. **54**, 2435 (2007)
V. M. Cowan, C. P. Morath, J. E. Hubbs, Appl. Phys. Lett. **101**, 251108 (2012)

Project/R&D objectives

1. HgCdTe material growth and characterization

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

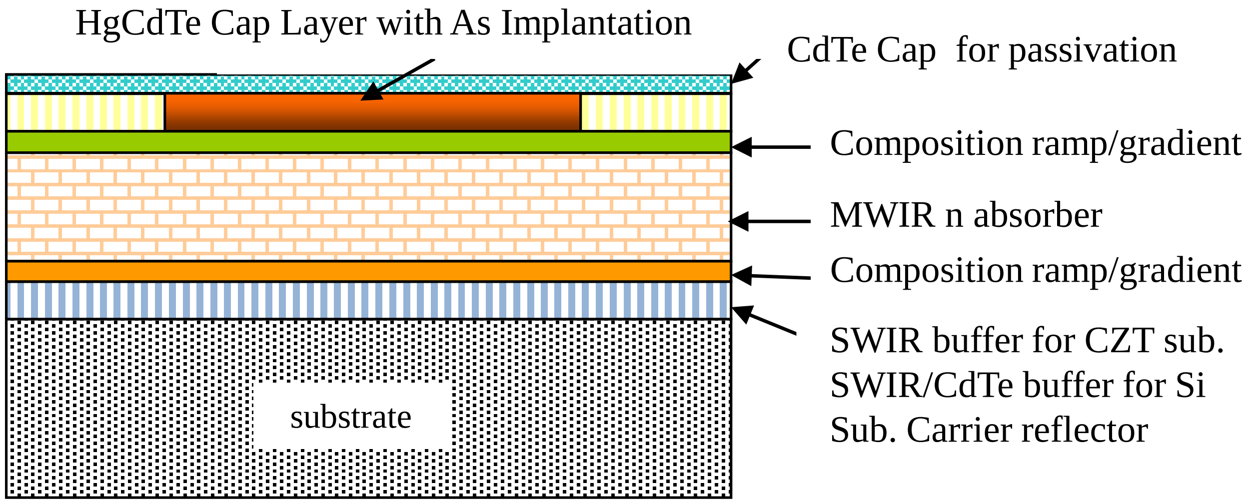
3. Fabrication of detectors with improved radiation hardness

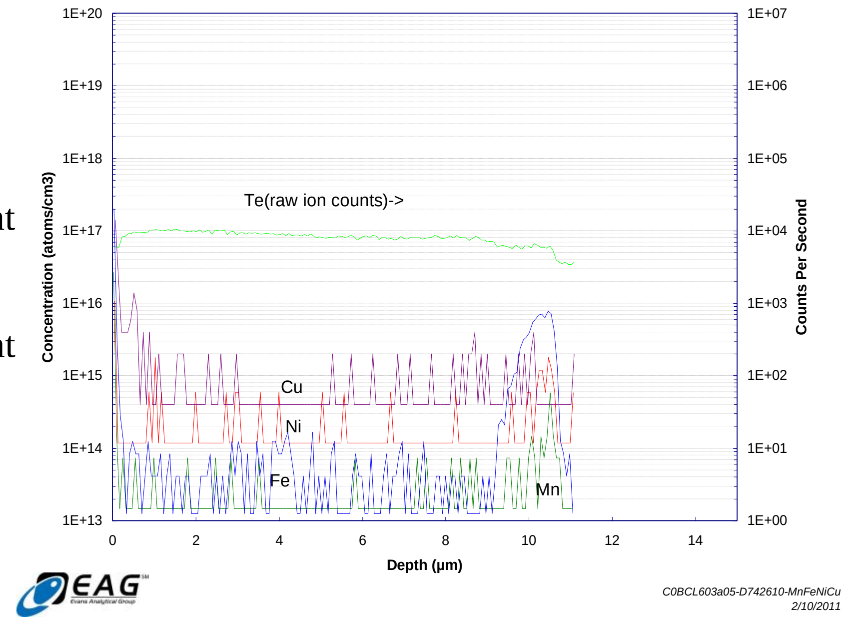
4. Integration of the detectors with radiation hardened ROIC

5. Packaging and testing detectors and cameras under neutron flux

Growth and Characterization of HgCdTe Heterostructures

1. Design double layer planar heterostructures (DLPH)

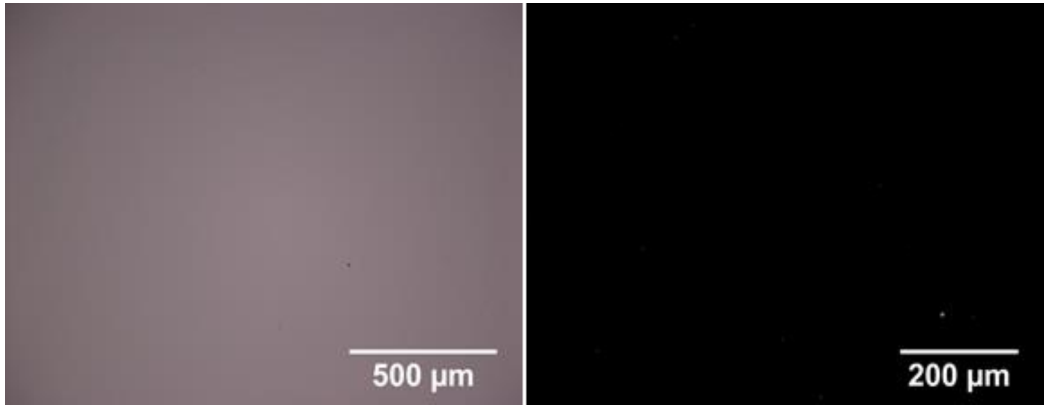




2. Precise composition and doping control (FTIR, Hall, SIMS)

3. Impurity reduction, low background doping:

4. Defect reduction (EPD, surface defect counting, HRXRD)

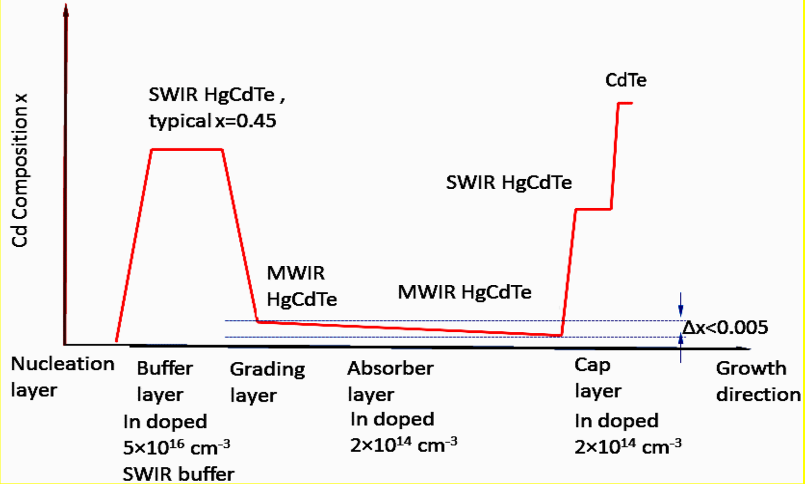


MBE growth of high-quality HgCdTe layers achieved. Material tested under radiation flux.

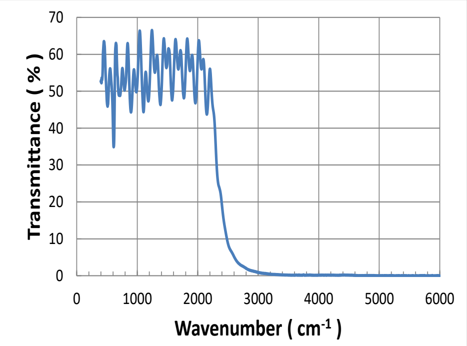
MBE Material growth and characterization

HgCdTe hetero-structures designed and subsequently grown at EPIR using MBE

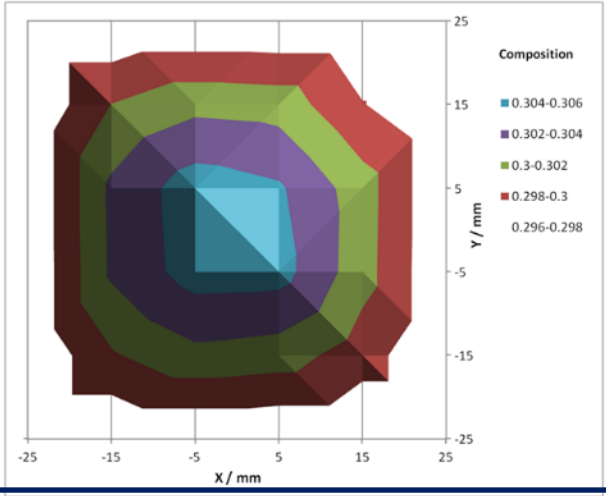
Designed material structure



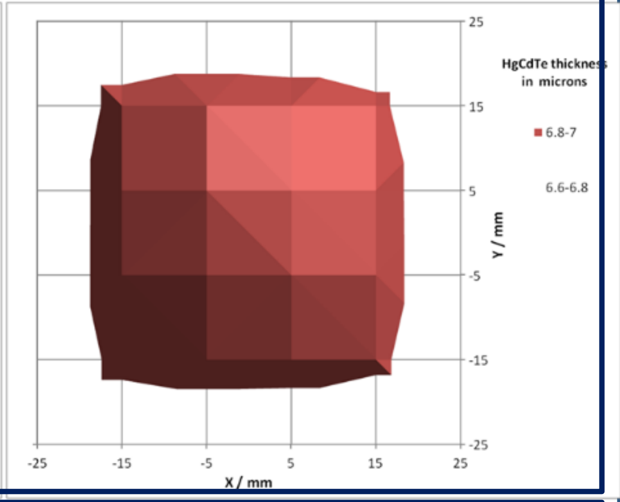
FTIR



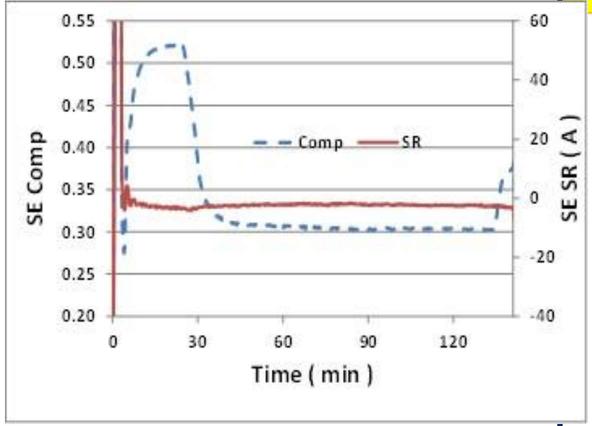
Composition mapping



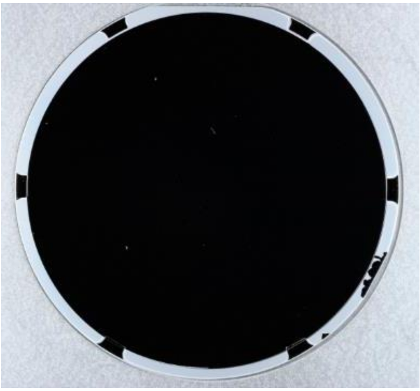
Thickness mapping



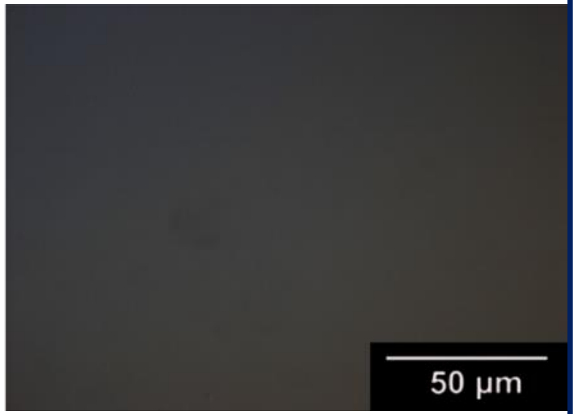
In situ SE



Whole Wafer Imaging

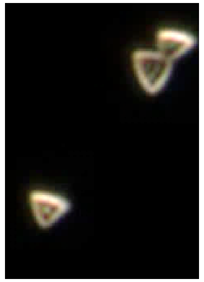


1000x



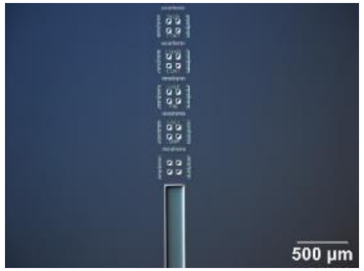
After EPD, DF

Etch Pits

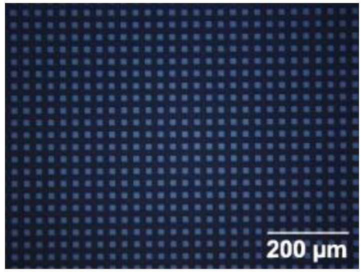


Device Fabrication – Standard Process

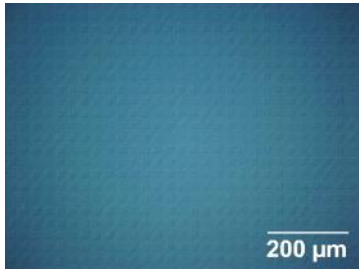
Align keys lithography and etch

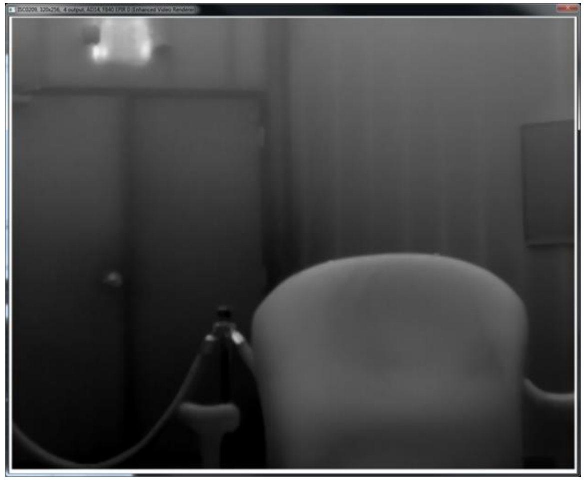


Implant window lithography



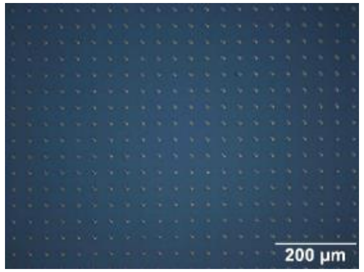
Implantation and annealing



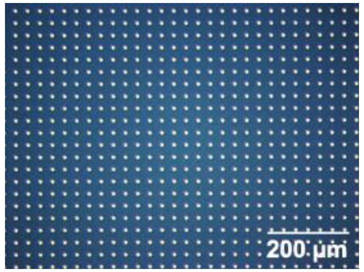


Passivation layer deposition

Passivation layer etch

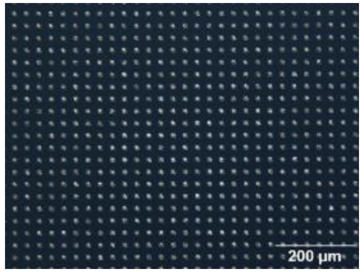


Contact metal deposition

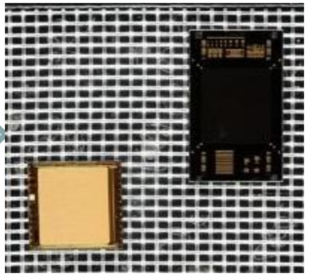


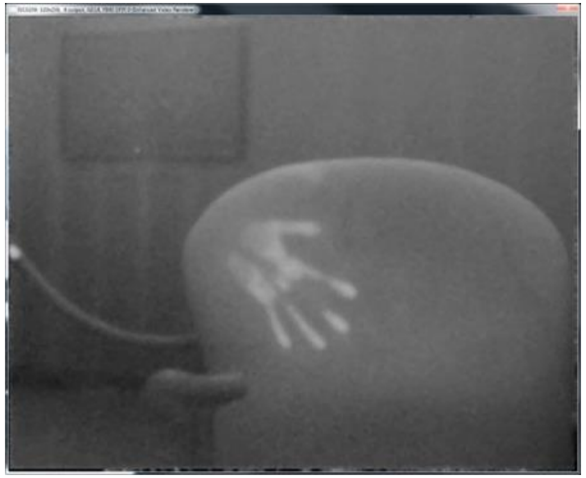
Indium contact processing

Indium bump deposition



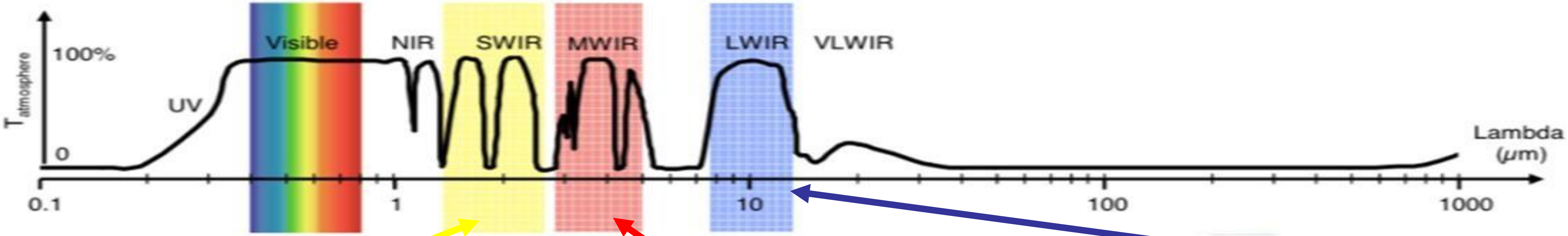
Hybridization and imaging test





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

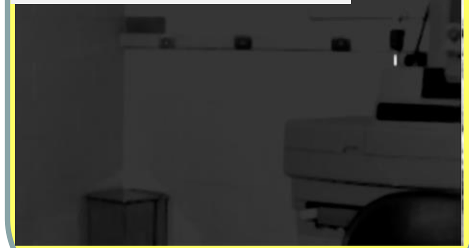
Infrared Focal Plane Arrays at EPIR



NIR-eSWIR

NIR on Si, Room Temperature

eSWIR on Si, 195K



MWIR

MWIR on CZT, 140K

MWIR on Si, 110K

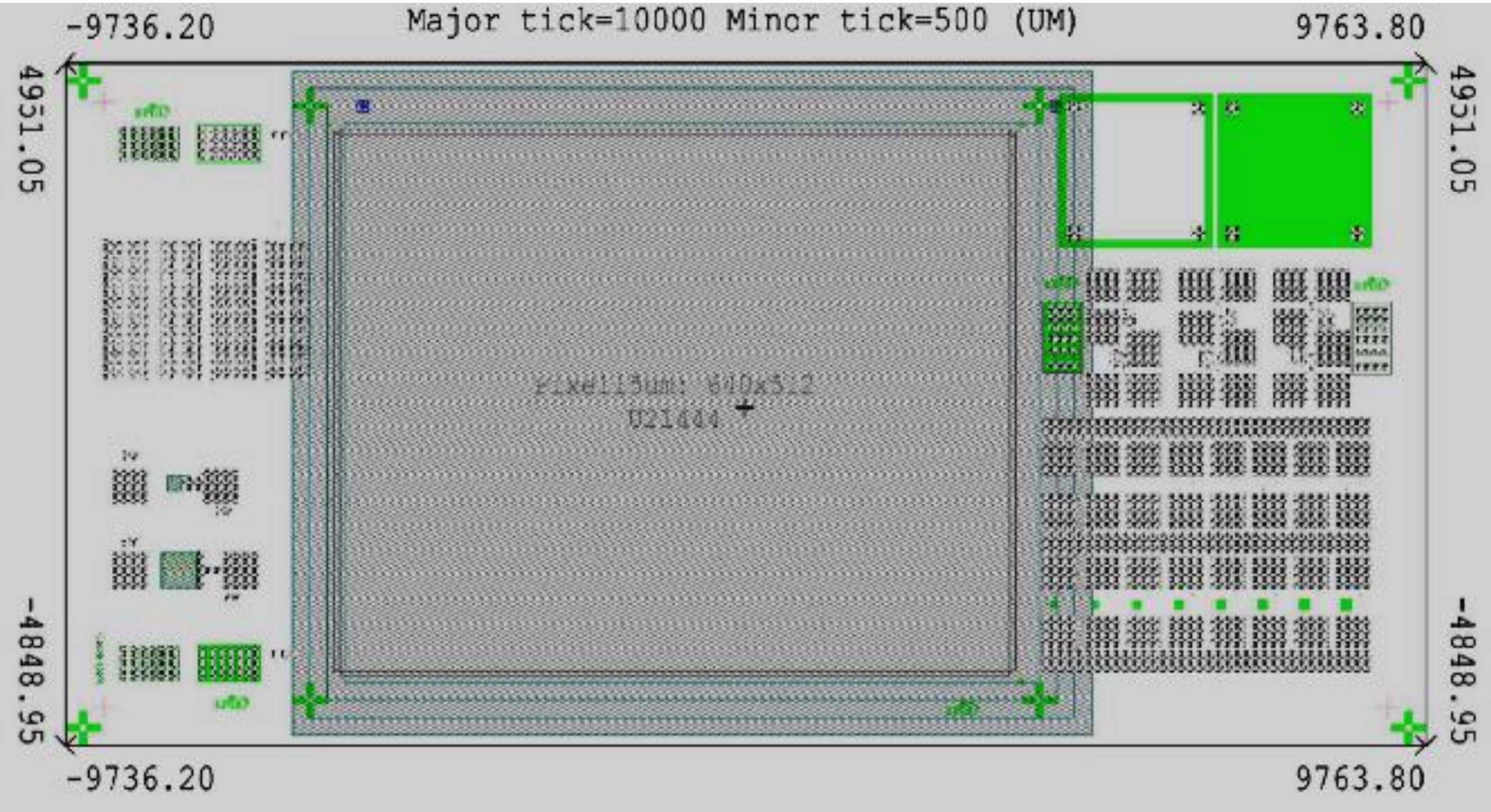
LWIR

LWIR on CZT, 85K

LWIR on CZT, 110K

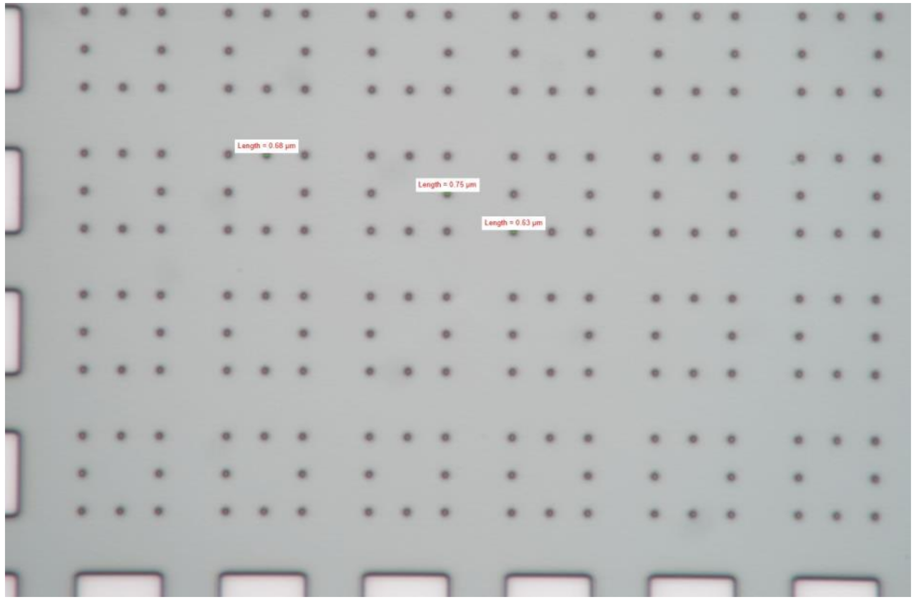
Commercial grade devices in NIR to LWIR range

Mask Design for Radiation Hardened Arrays and Test Elements



640x512 FPA with ISC0403 ROIC

15µm pitch

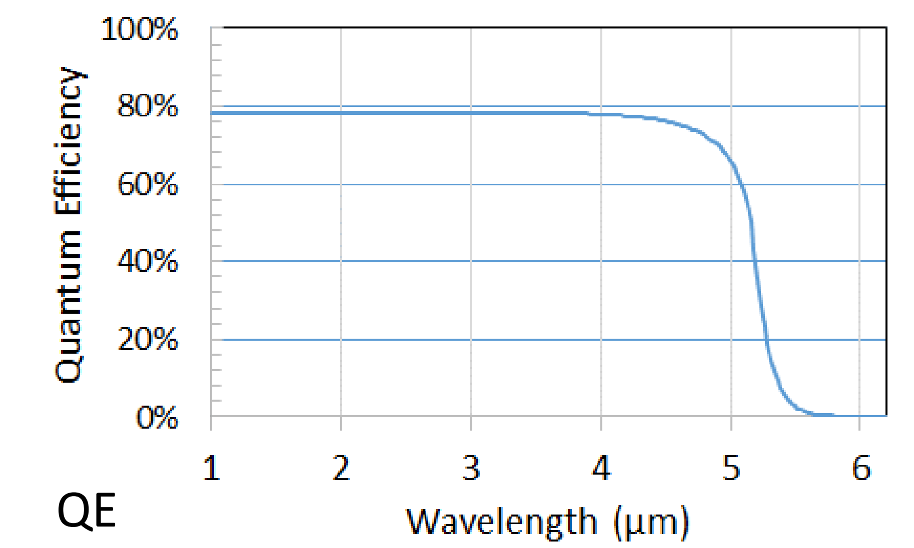


FPA section before metal contact deposition

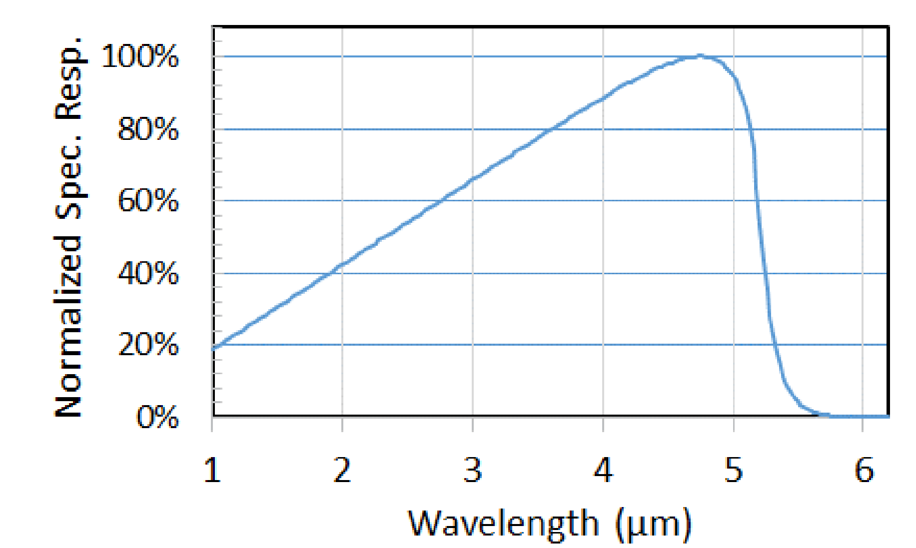
Under bump metal (UBM) and indium bumps are positioned away from the p-n junction area, reducing the impact of the hybridization force on FPA characteristics

Simulation Results

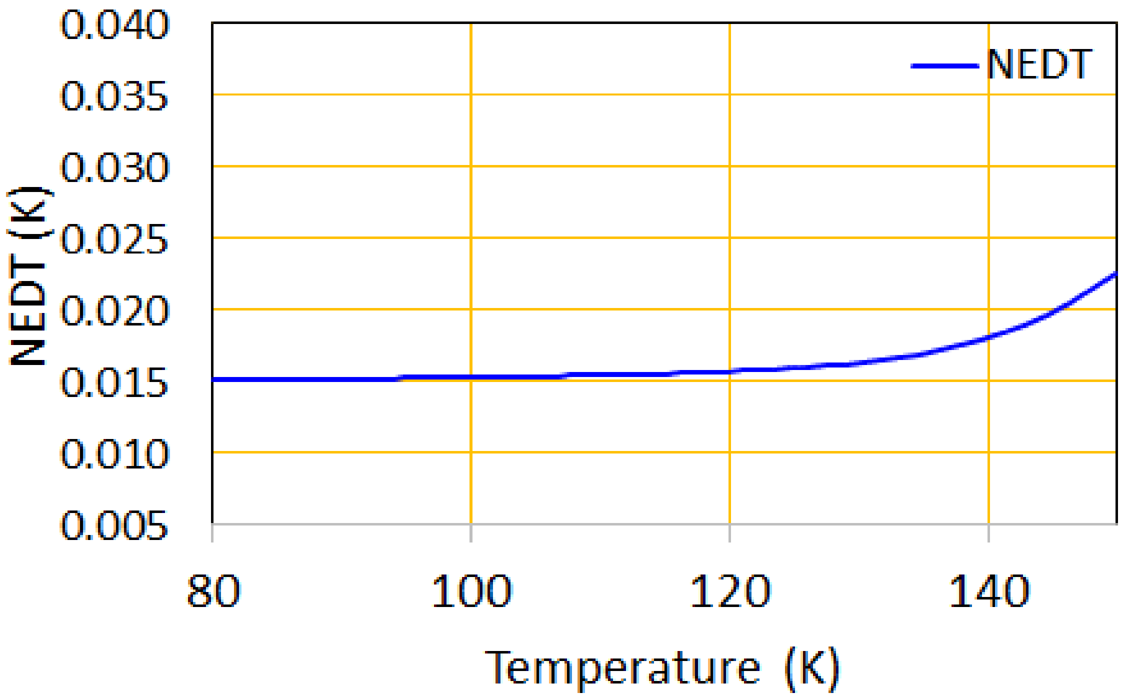
At -100 mV bias



QE



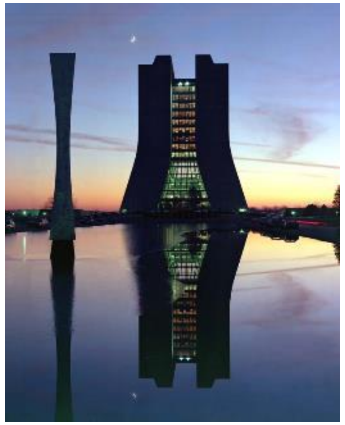
Relative spectral response

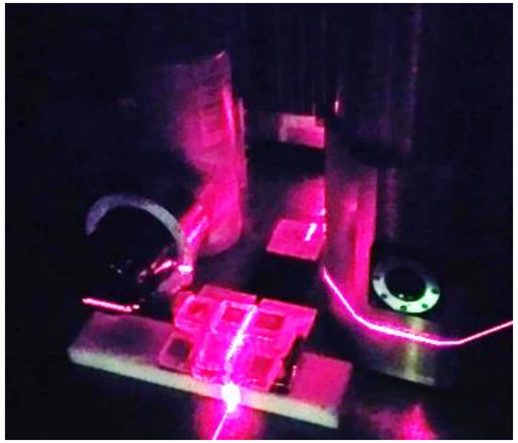


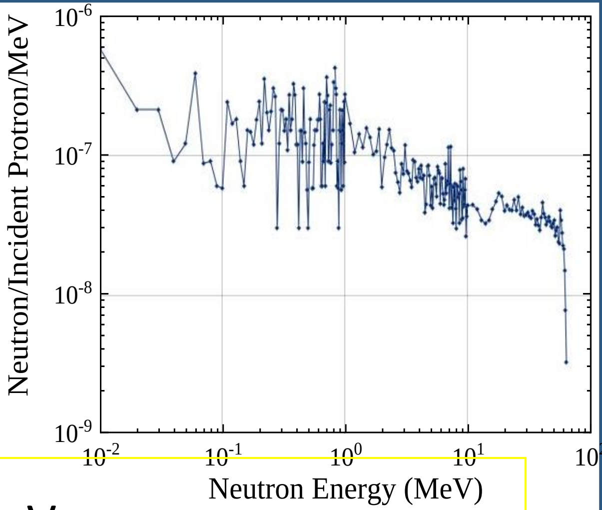
NEDT simulation results for 30-μm pitch size, 1-ms integration time, 100 mV reverse bias

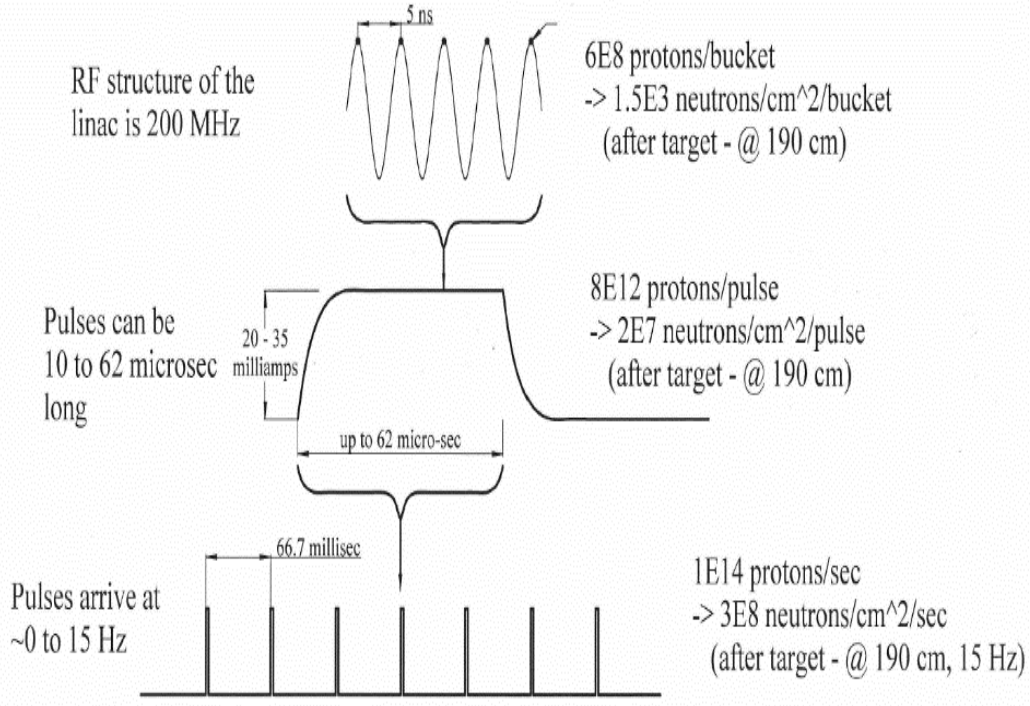
Simulation calculation confirmed that our material and detector design will meet the requirements.

EPIR's FPAs under Neutron Flux at FNAL





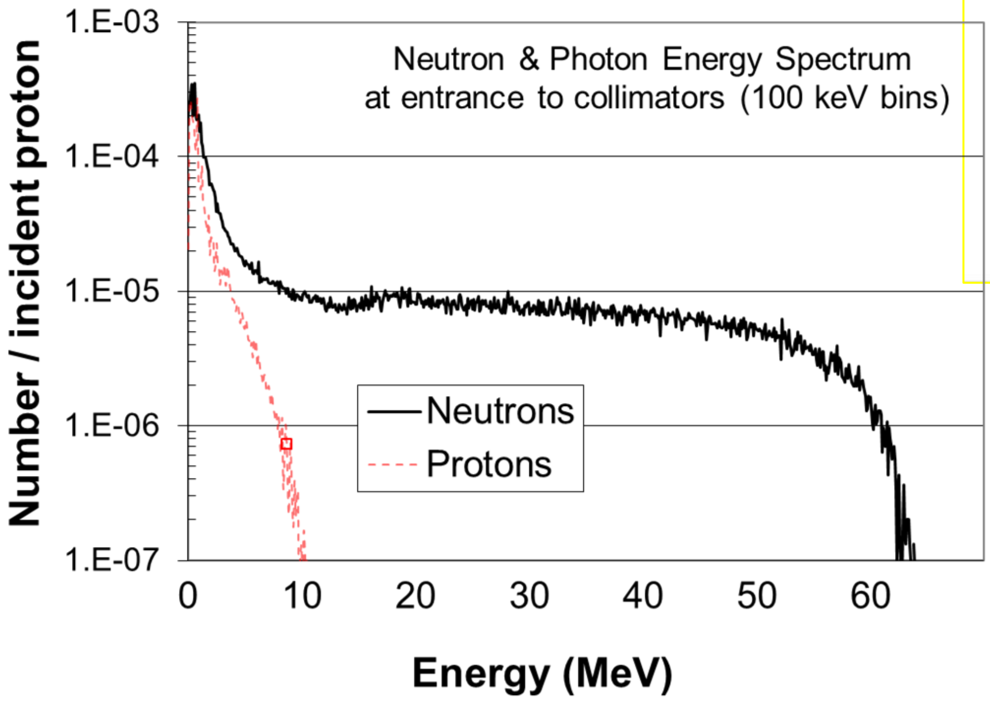


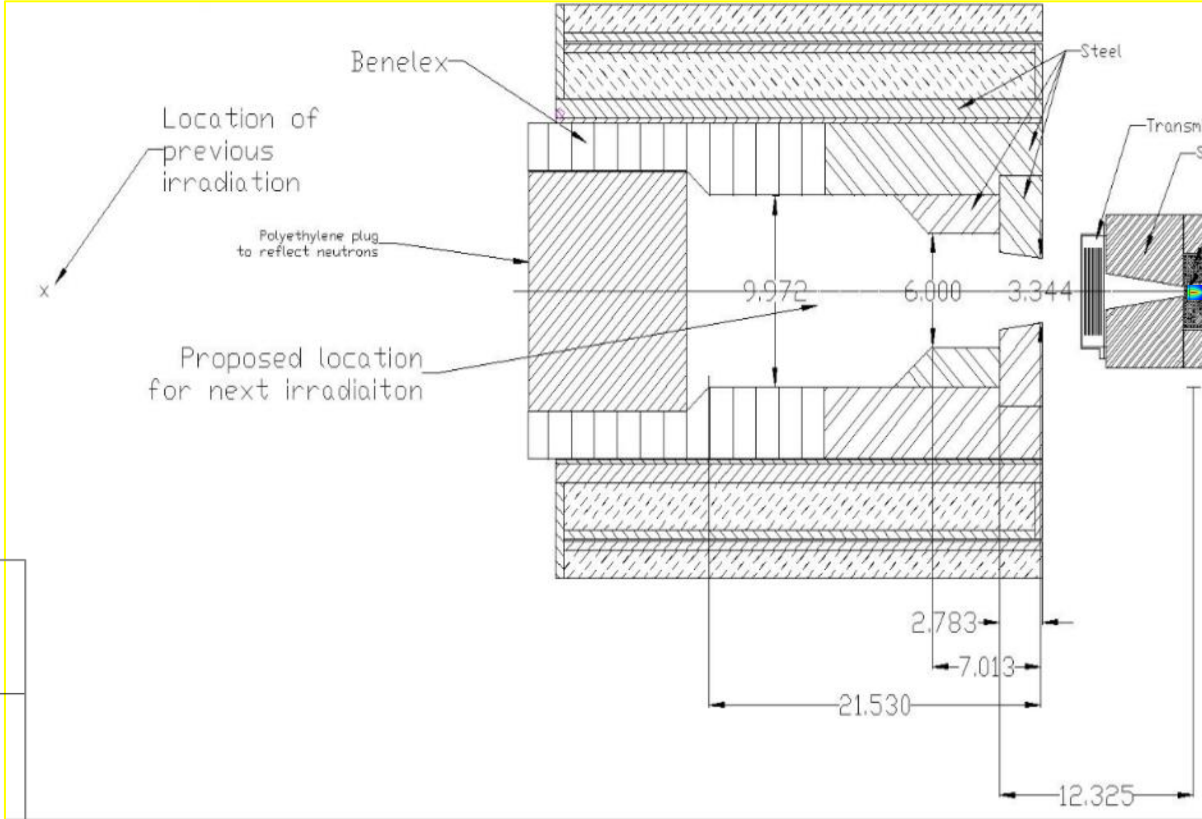


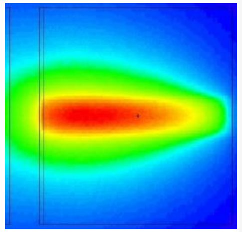
- Maximum neutron energy was 66 MeV
- Irradiated at a typical rate of 1×10^{8} n/cm^{2}·s
- Maximum rate ~2×10^{9} n /cm^{2}·sec by mounting samples inside channel (without considering scattering)

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





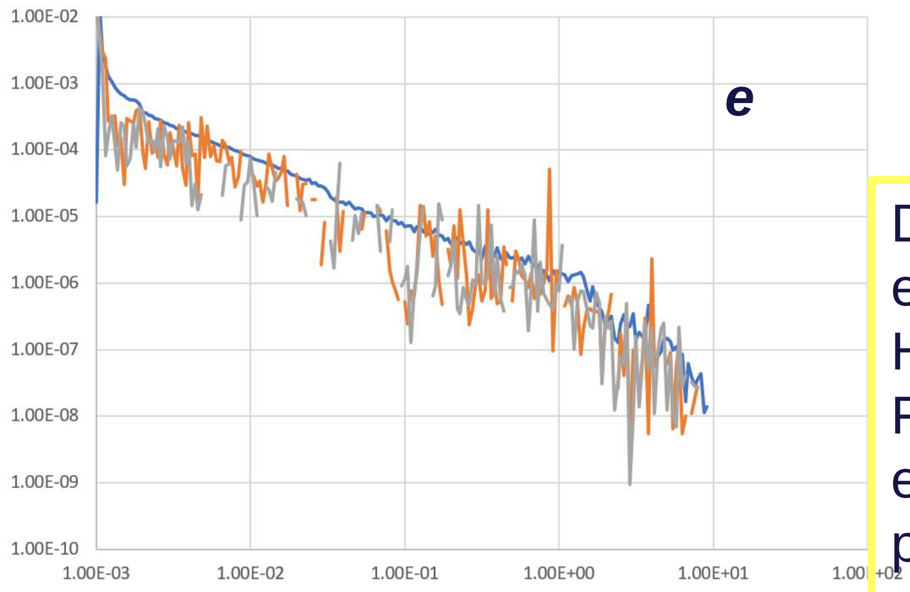


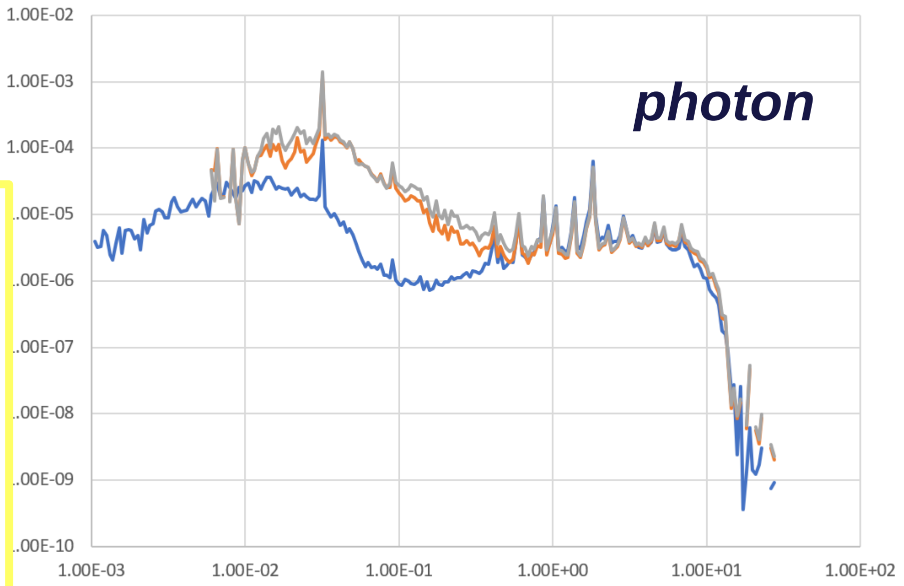
Neutron

Maximum rate ~2×10^9 n /cm^2·sec by mounting samples inside channel (without considering scattering)

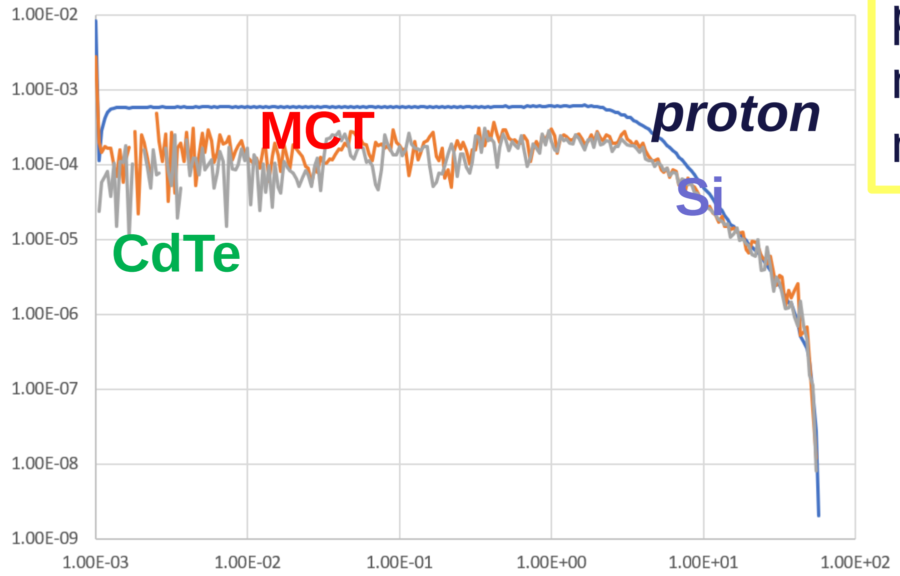
Energy Deposition in FPA: MCNP Calculation at FNAL

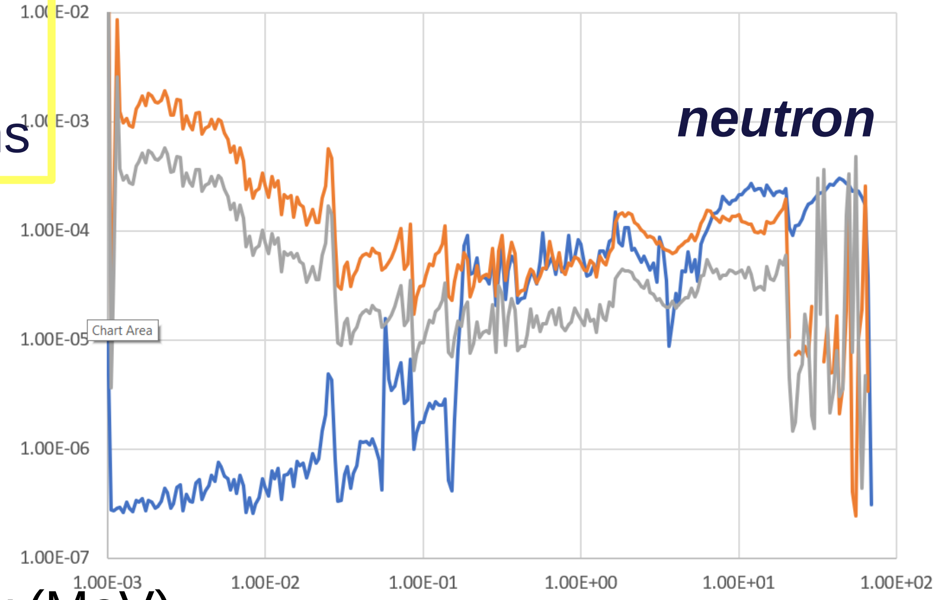
Deposited energy (MeV/g/MeV)





Deposited energy on HgCdTe FPA: electron, photon, proton and neutron mechanisms

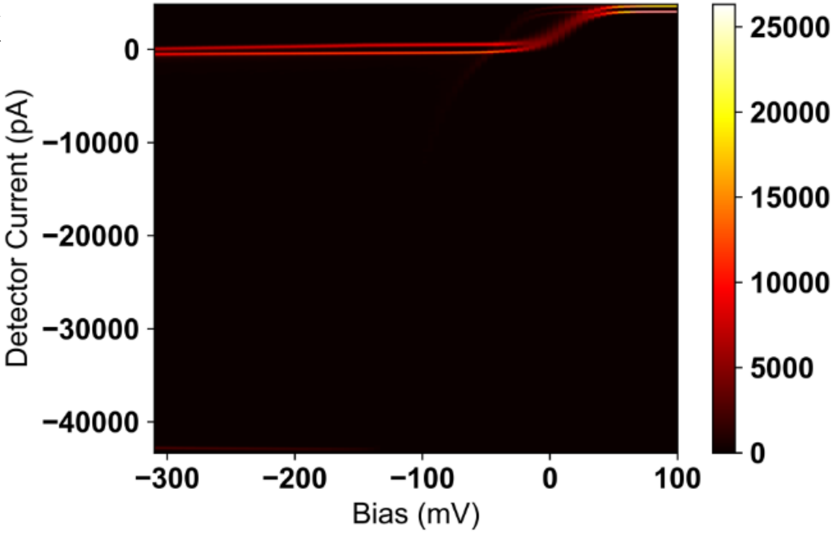


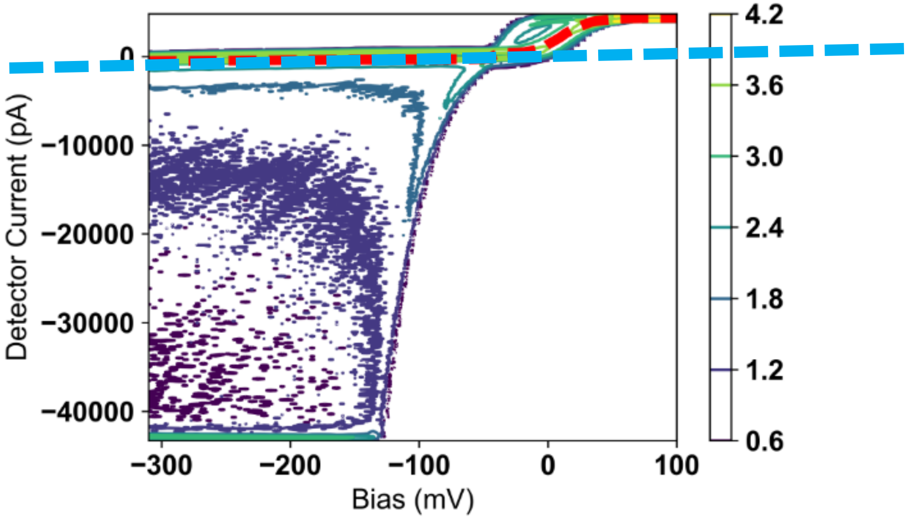


Particle energy (MeV)

I-V Characterization (FPA_L) After Neutron Exposure

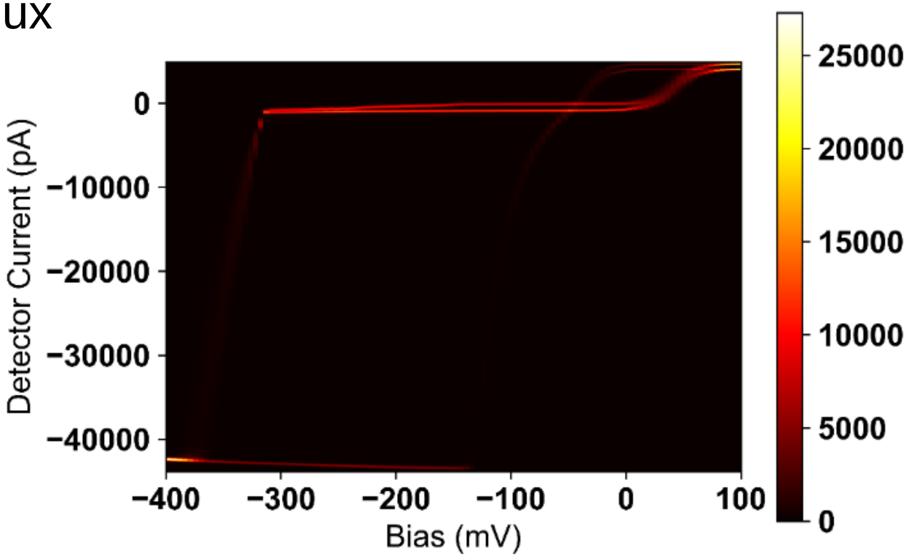
Before neutron flux

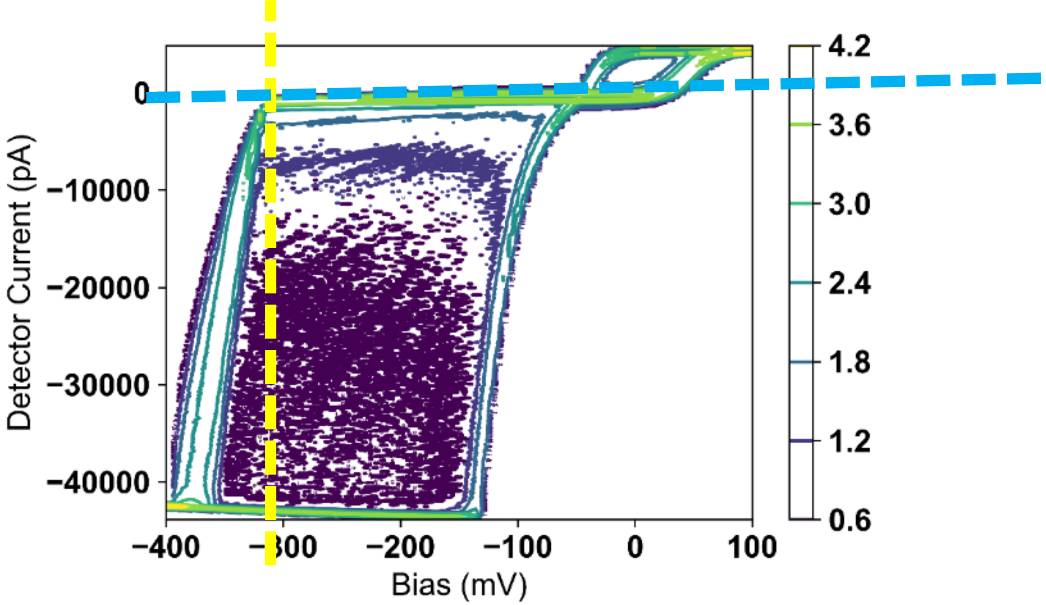




After neutron flux

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

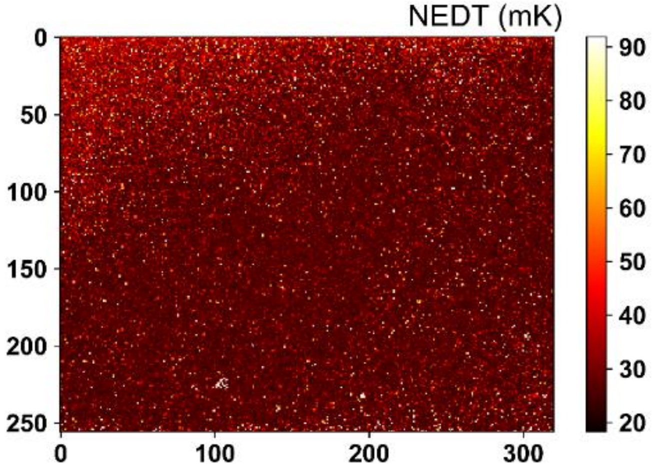


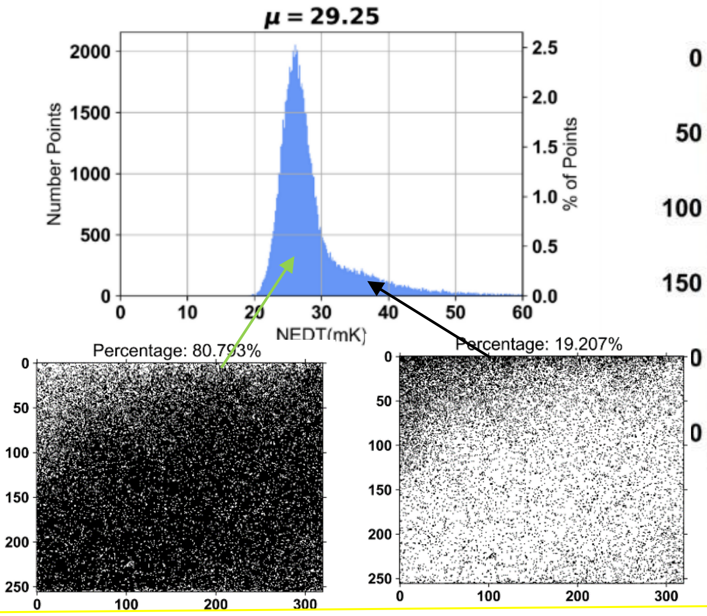


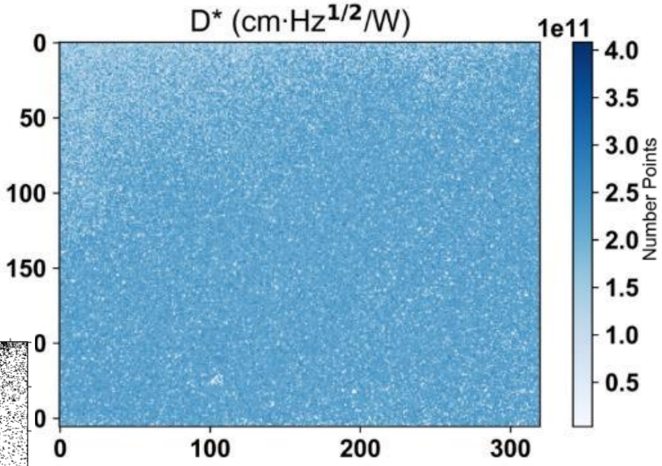
NEDT/Detectivity Before and After Neutron Flux Exposure (~10^{12} n/cm^2)

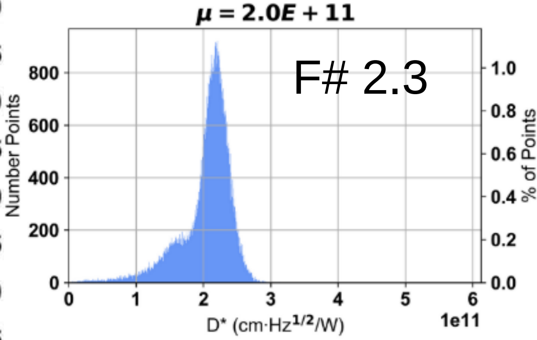
EPIR

Before neutron flux exposure



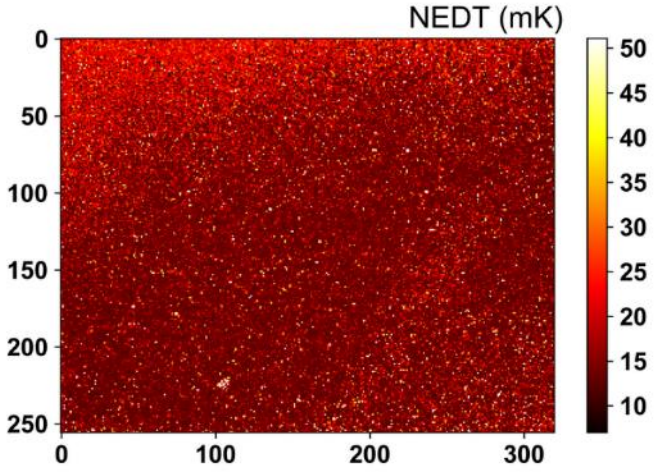


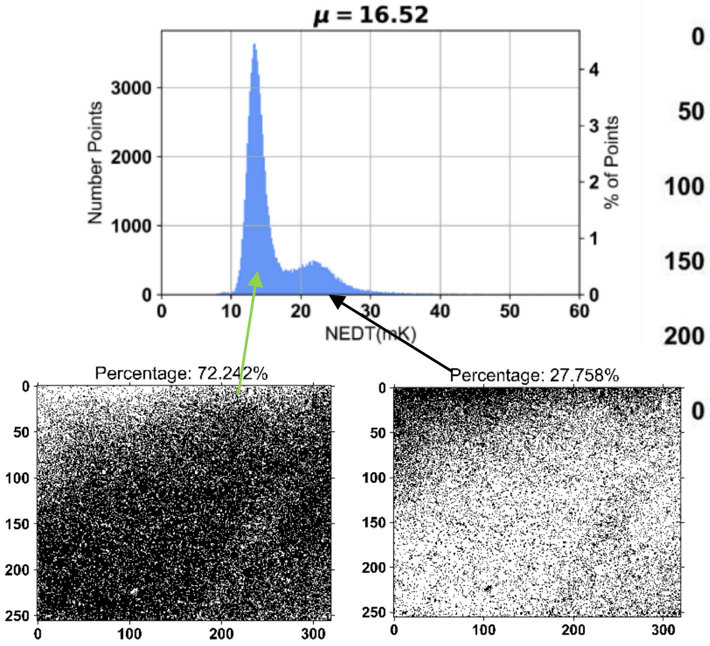


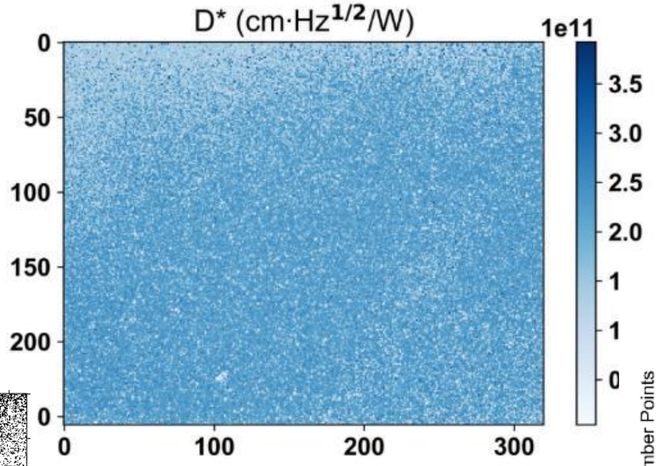


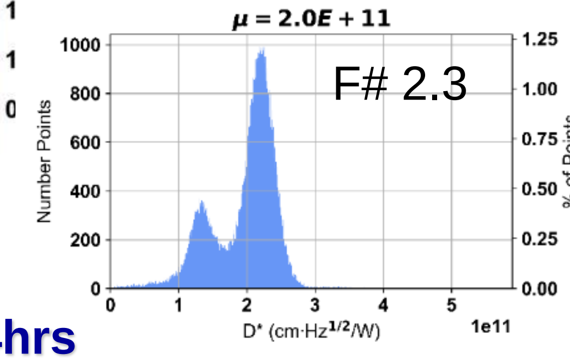
Although median D* was unchanged, the high noise tail side split into a separate peaks.

After neutron flux exposure









Total: ~10^{12} n/cm^2,
10^5 n/cm^{2}s, 1/3 year, 24hrs

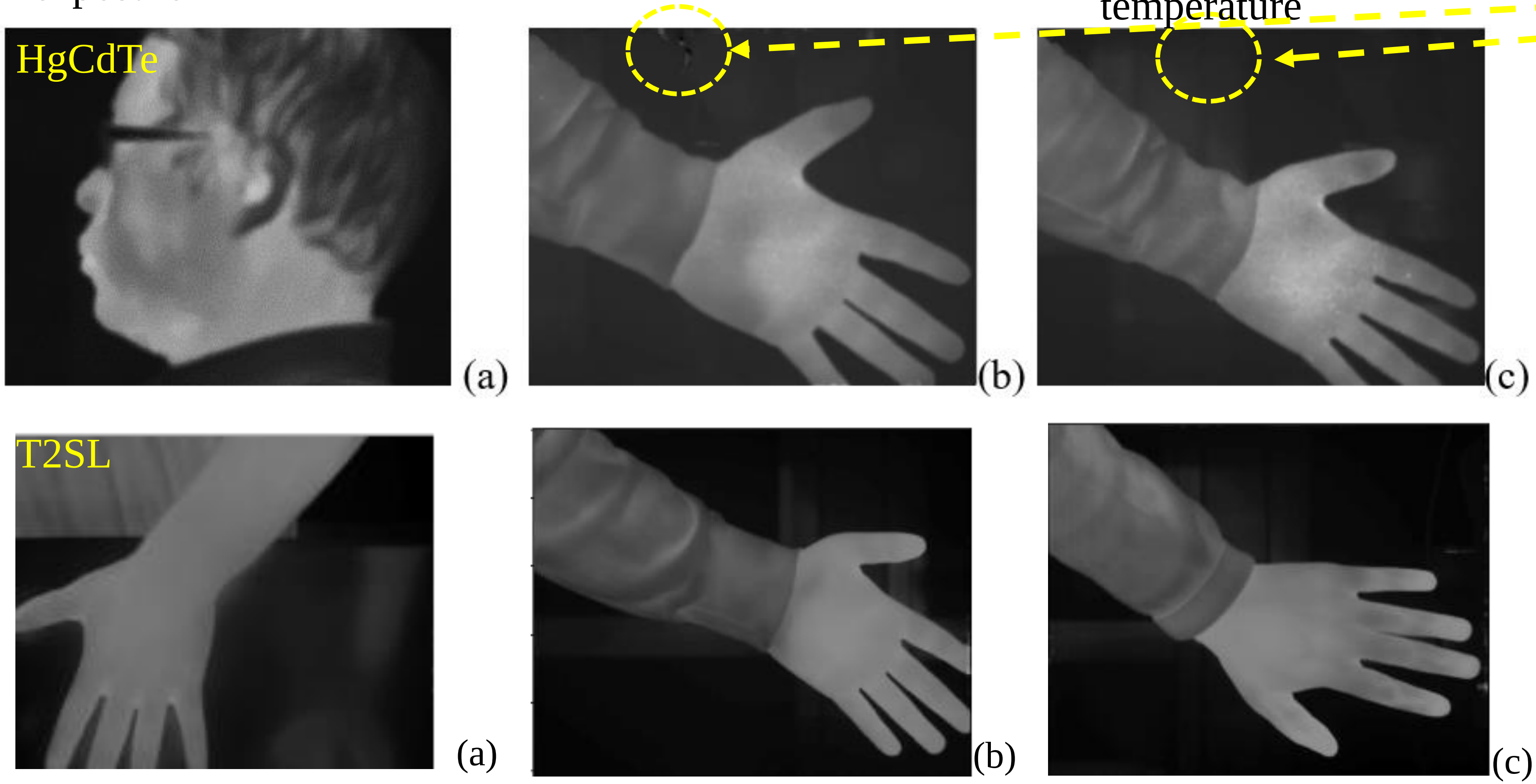
Imaging with EPIR-assembled IR Cameras

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

Test of ROIC and other Electronic Components

Oxygen® DROIC Neutron Testing

Zach Korth, PhD (Engineering Physicist - Test Group Manager) & Ross Bannatyne (Director of Business Development)

- … 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**.
- … Our takeaway is that the neutron testing activity appears to indicate that the circuit design and IC fabrication process implementation of Oxygen are pleasingly robust.
- … We would typically implement Triple Modular Redundancy (TMR) to mitigate against Single Event Upsets (SEU), and make other specialized design tweaks to mitigate against Single Event Latch-up (SEL) and to extend the ability to withstand a higher level of Total Ionizing Dose (TID).

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
- Alphacore's components maintained full functionality after the neutron irradiation

Summary

- HgCdTe is the preferred infrared material for use in high radiation environment applications. EPIR has grown the HgCdTe with desired characteristics using MBE
- Lateral collection device architectures were used to reduce dark current in implantation-formed p-n junctions. Photomasks were designed and FPAs were fabricated
- 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
- Most of the sub-optimal FPA pixels after irradiation can be recovered and restored to the original condition after we performed a temperature cycle (77 K to 300 K)
- Working with ROIC and other DoE-sponsored radiation hardened electron component manufactures will enable us to fabricate IR cameras with larger scale FPA (million pixels) and high radiation resistance capabilities.
- We will continue to work with Fermilab for further testing of existing components and for testing new FPAs and cameras

THANK YOU