Radiation Hardened Infrared Focal Plane Arrays

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Overall Outline

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

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 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 (FPAs) 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

EPIR: Materials and Devices Development Timeline

Champions of Change
WINNING the FUTURE ACROSS AMERICA

Dr. Siva Sivananthan was named a "Champion of Change" by the **White House**.

EPIR was honored by the House Science and National Labs Caucus

BAE Selected EPIR to fabricate its FPAs and transferred IP to EPIR

EPIR obtain 10 Export Licenses to sell its infrared worldwide

Awards Winning

TECH 50 · NIGHT VISION · CRAIN'S CHICAGO BUSINESS CHICAGO'S TOP TECH TALENT · U.S. DEPARTMENT OF HOMELAND SECURITY

P32
3" Machine

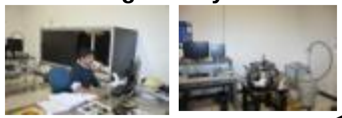
V100 #1
9" Machine

V100 #2
9" Machine

V100 #3
9" Machine

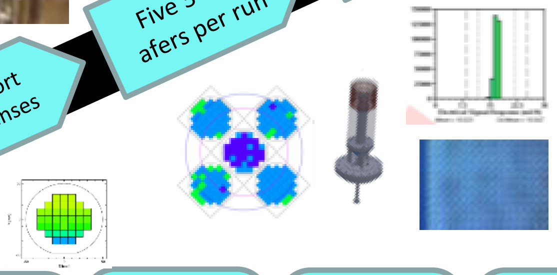
Device Fabrication

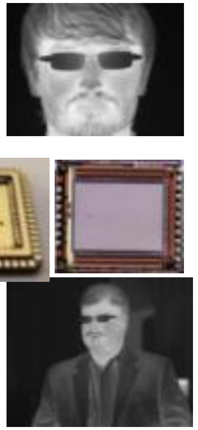
Focal Plane Arrays Testing Facility



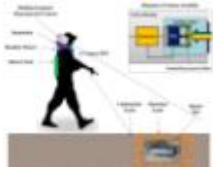
Expanding Portfolio
- Extended SWIR
- NIR
- HOT
- Hyperspectral
- APDs
- Thermoelectric
- Multicolor Devices

Timeline:
- 3 inch CdTe/Si
- 5 cm x 5 cm MCT/CdZnTe
- Export Licenses
- Five 3 inch afers per run
- 6 inch MCT and CdTe/Si wafers
- State of the art device lab
- 320x256 604x512 1024 x 1024





Our Technology in Space
HgTe material made at EPIR sent into orbit by NASA



High Performance Longwave Infrared (LWIR) HgCdTe on Silicon	Large Format Production of CdTe and CdZnTe on Si	SWIR HgCdTe Focal Plane Arrays for Urban Situational Awareness Superiority	Establish Capability for Low-Cost, High-Throughput and Large Format SWIR HgCdTe Production on CdTe on Si	Miniaturized Imaging Spectrometer Based on HgCdTe Infrared Focal Plane Arrays	Establish Capability for Low-Cost, High-Throughput Next Gen Multicolor HOT HgCdTe IRFPA	Near/Short Wavelength HgCdTe/Si-Based Infrared Focal Plane Arrays	High Operating Temperature, Broadband Visible/Infrared HgCdTe Photodetectors	**Most Recent Commercial Sales:** HgCdTe FPAs Solutions Prototyping

Infrared Material Products

- ❖ EPIR, as a horizontally integrated domestic infrared material supplier, enables:
  - ➢ Lower costs through the competitive nature of a horizontal supply chain
  - ➢ Manufacturing flexibility through rapid prototyping

Material	Spectral Band	Size
CdTe	-	3”
CdTe	-	6”
HgCdTe	SWIR/CZT	Up to 5 cm x 5 cm
HgCdTe	SWIR/Si	3”
HgCdTe	MWIR/CZT	Up to 5 cm x 5
HgCdTe	MWIR/Si	3”
HgCdTe	LWIR and MWIR/CZT	Up to 5 cm x 5cm
HgCdTe	MWIR/Si	3”

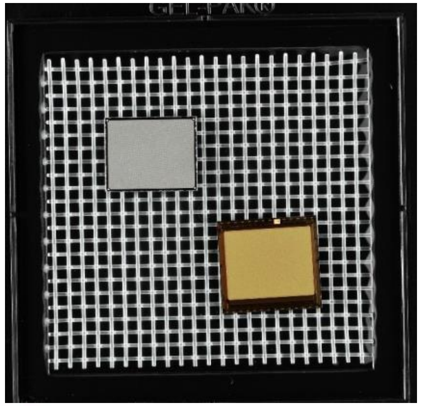
❖Also available:
- Custom HOT structures
- Avalanche photodiode structures
- Material for hyperspectral sensors
- nBn multilayers
- Two-color architectures

Infrared Device and System Products

1) Standard format, high performance IRFPAs

- ❖ Low format (320 x 256, 256 x 256) – mature technology, limited market
- ❖ Medium format (640 x 512, 512 x 512, 640 x 480) – large interest
- ❖ Large format (1024 x 1024, 1280 x 720) – emerging areas

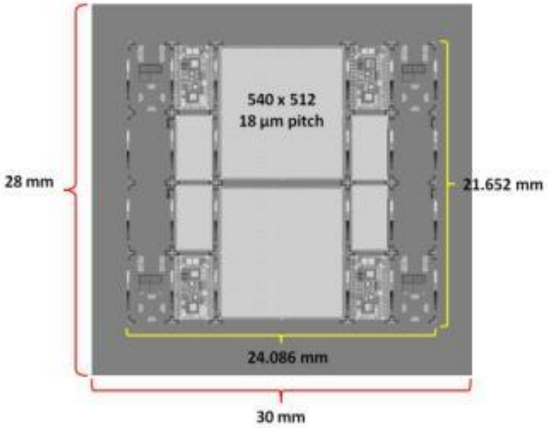
Use FLIR and SBFP ROICs
Customers: Brimrose, Brandywine, Photon Etc, Xenics, JHU, St. John Optical, IRCameras, Fibertek



2) Custom format detectors and IRFPAs

- ❖ Design, fabricate and integrate EPIR detectors and arrays with customer electronics and ROICs
- ❖ Implement new concepts and designs: APD, two-color, nBn, HOT

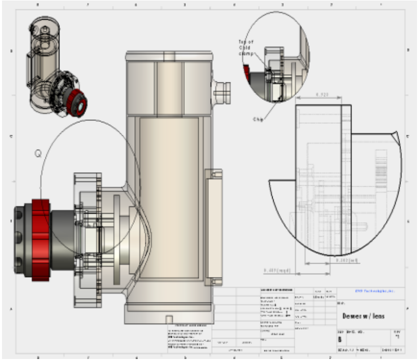
Customers: Black Forest Engineering, Brown University, Northrop Grumman, Raytheon, Lockheed Martin, Aselsan, Cyan, Imogin,, NASA Goddard, NASA JPL



3) EOIR systems

- ❖ Integrate EPIR detectors and IRFPAs in custom EOIR system (hyperspectral, polarization, active/passive, rad-hard)

Collaborate with system partners: Brimrose, Brandywine, Episensors
Current and potential customers: Army, NASA, DOE, Air Force, NVESD, BAE Systems, Lockheed-Martin, Northrop-Grumman



EPIR Material in Orbit

- ASTRO-H built by a major international collaboration led by Japan Aerospace Exploration Agency (JAXA) with over 70 contributing institutions in Japan, the US, Canada, and Europe
- Soft X-ray Spectrometer (SXS) consists of the Soft X-ray Telescope (SXT-S), the X-ray Calorimeter Spectrometer (XCS) and the cooling system

February 22, 20 BusinessWire
A Berkshire Hathaway Company

BOLINGBROOK, Ill.--(BUSINESS WIRE)--On February 17, 2016, Hitomi, (also known as ASTRO-H) successfully launched from the Tanegashima Space Center in Kagoshima, Japan. This satellite contains a state-of-the-art instrument, a Soft X-ray Spectrometer (SXS), built around HgTe calorimeter tiles developed by EPIR Technologies, Inc. (EPIR). The instrument achieves unprecedented energy resolution due to EPIR's processes to significantly reduce the tiles' specific heat. EPIR's technology provides a major contribution to the mission, which is an international collaboratio led by JAXA (the Japan Aerospace Exploration Agency), and includes NASA.

"Working with this outstanding team to send our technology into space for the first time is an important milestone for EPIR, and we look forward to continuing to develop next generation imaging technology for space observation"

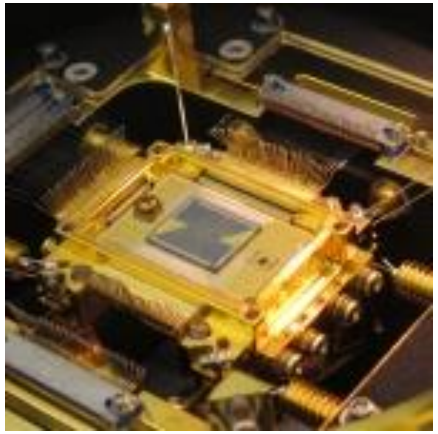
Tweet this

The Hitomi satellite will observe distant galaxies and black holes, and it is expected to provide new insights on the mysteries of the universe through X-rays. The NASA-developed SXS sees X-ray "colors" with unparalleled spectral resolution by measuring the heat produced when X-ray photons strike the HgTe calorimeter tiles made by EPIR.

"Working with this outstanding team to send our technology into space for the first time is an important milestone for EPIR, and we look forward to continuing to develop next generation imaging technology for space observation," said Dr. Sivalingam Sivananthan, Founder and Chairman of EPIR.

EPIR's HgTe material layers are the detectors in the XCS

-XCS was fabricated with NASA Goddard team



From Design to FPAs

EPIR

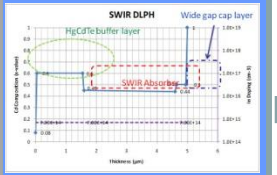
Customer Requirements

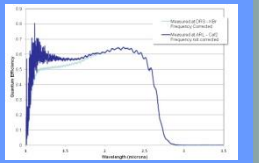
Modeling

Detector Architecture

Material Optimization

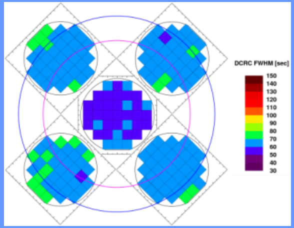
Mask Design

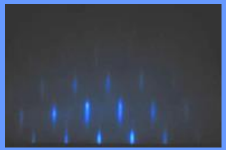




MBE Material Growth

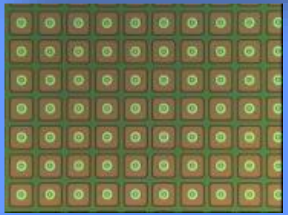
Substrates Preparation
Material Growth
Characterization

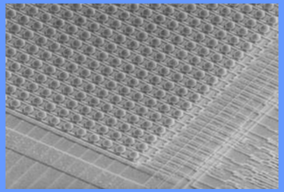


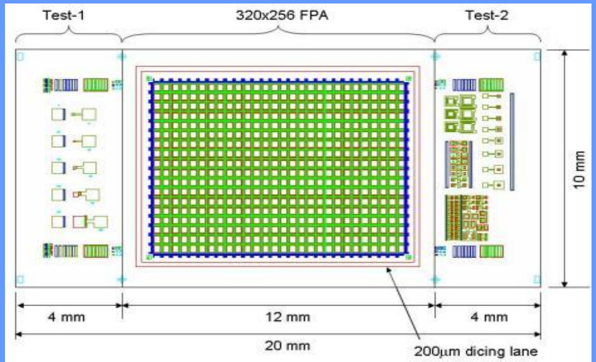


Detector Array Processing

Wafer Dicing
Lithography
Annealing
Passivation
Contact Deposition
Metal Liftoff
PAD Metal
Indium Bumps
Die Singulation





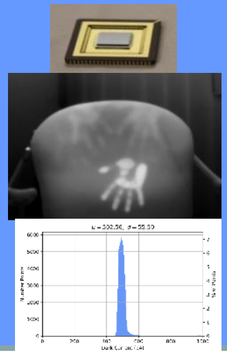


FPA Characterization

Array Hybridization, Packaging, and Bonding

Die-by-die
AR Coating

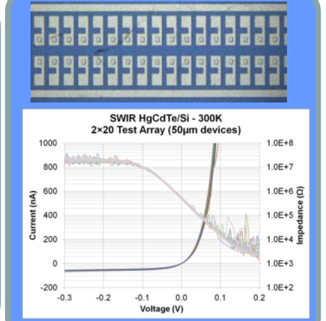
FPA Radiometric Characterization



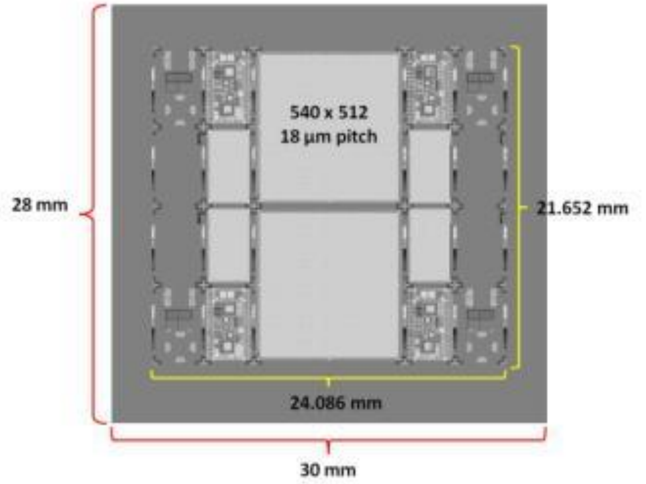
Test Array Characterization

Mount PECs on a LCC

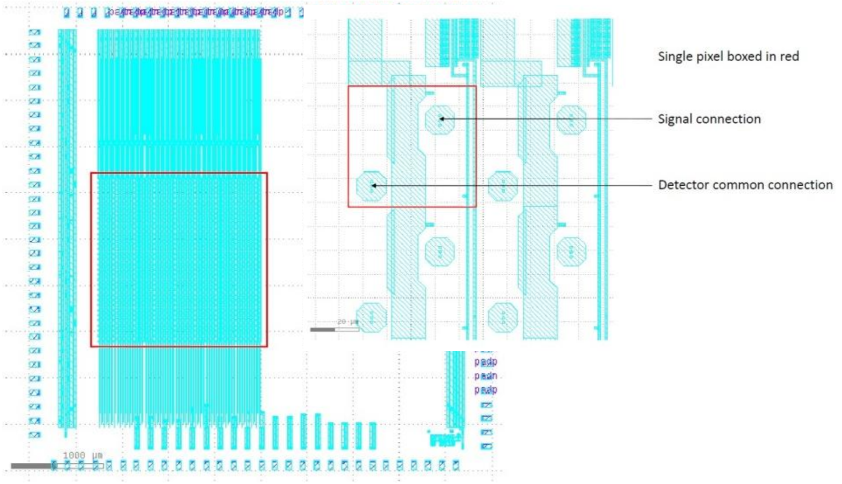
Detailed Device Characterization Using IVs, QE, Spectral Noise, etc



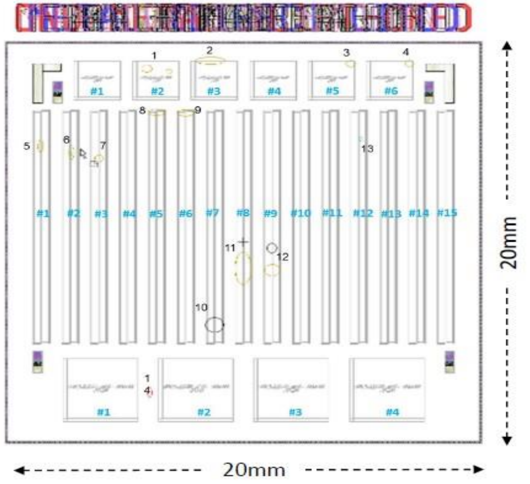
Custom Detectors and Arrays



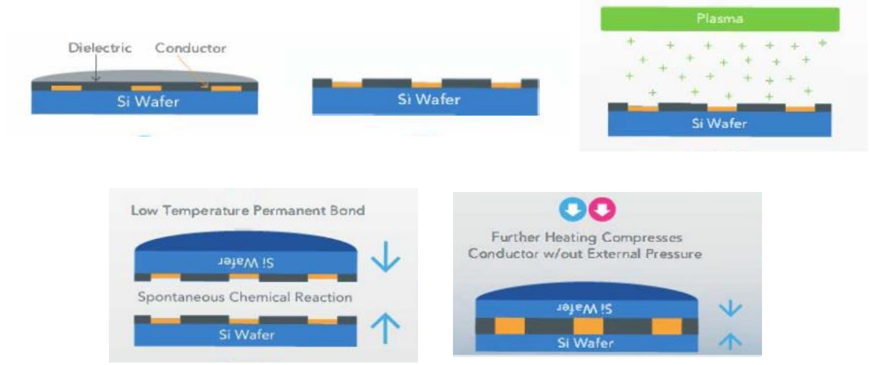
Large area process demonstration for LWIR FPAs



Custom LWIR arrays with two bumps per pixel



Linear MWIR and LWIR arrays for custom ROICs



Direct bond interconnect development

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Introduction: Goal, Specifications and Challenges

EPIR

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
- Operate at standard frame rates (>25 frames/s)
- Resolutions of 640 × 480 pixel

Challenges:

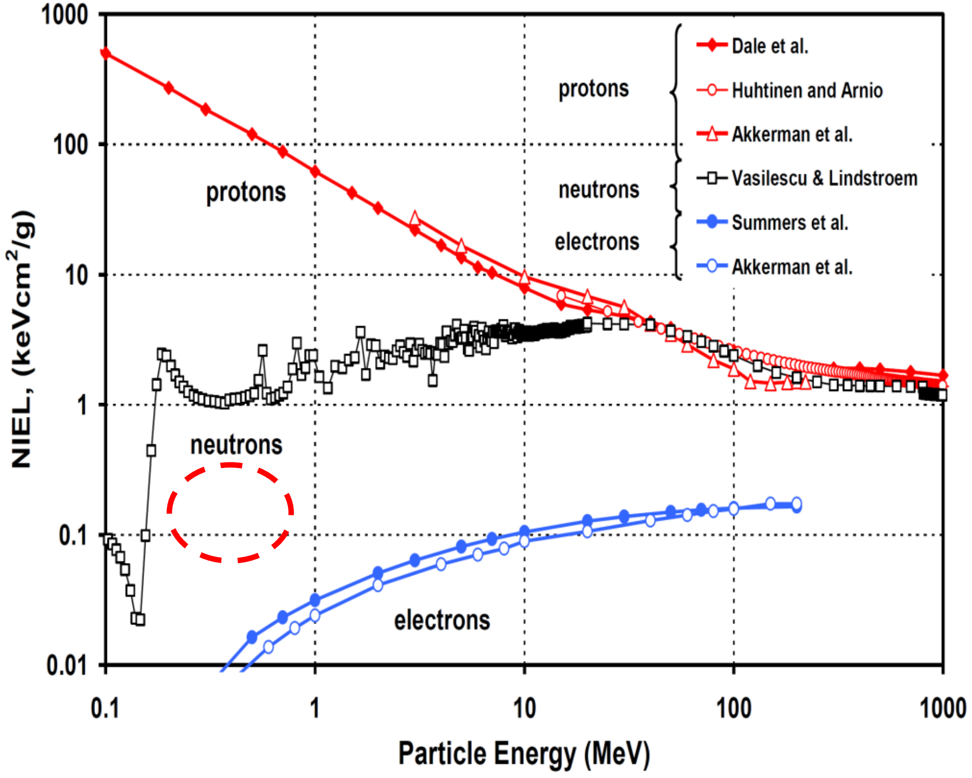
Radiation tolerance for prolonged operation

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

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).

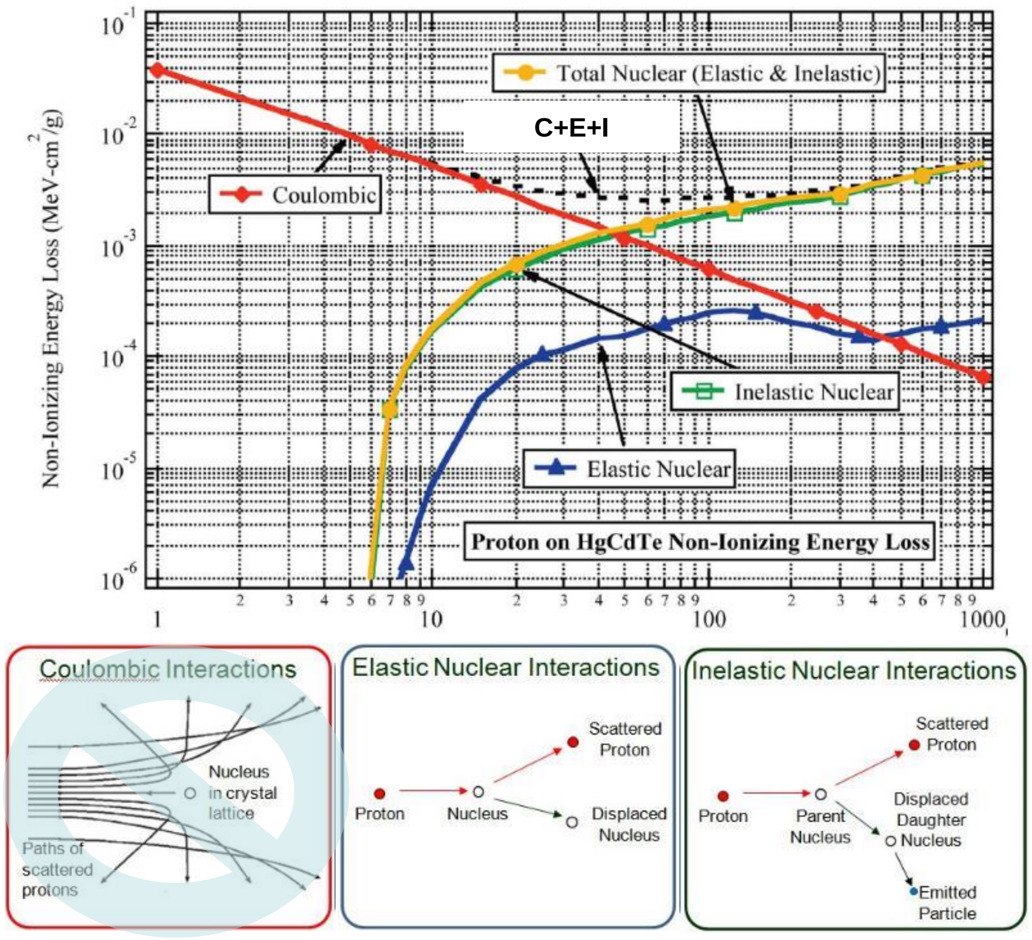
Non-Ionizing Energy Loss (NIEL) Si



×1000 for $keVcm^2/g$

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

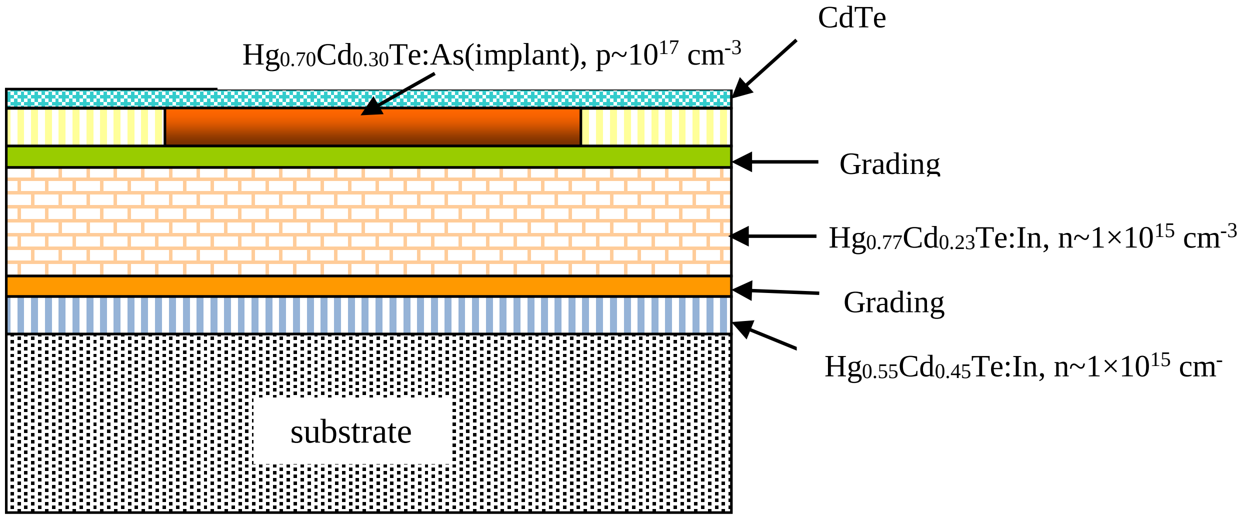
3. Fabrication of detectors with improved radiation hardness

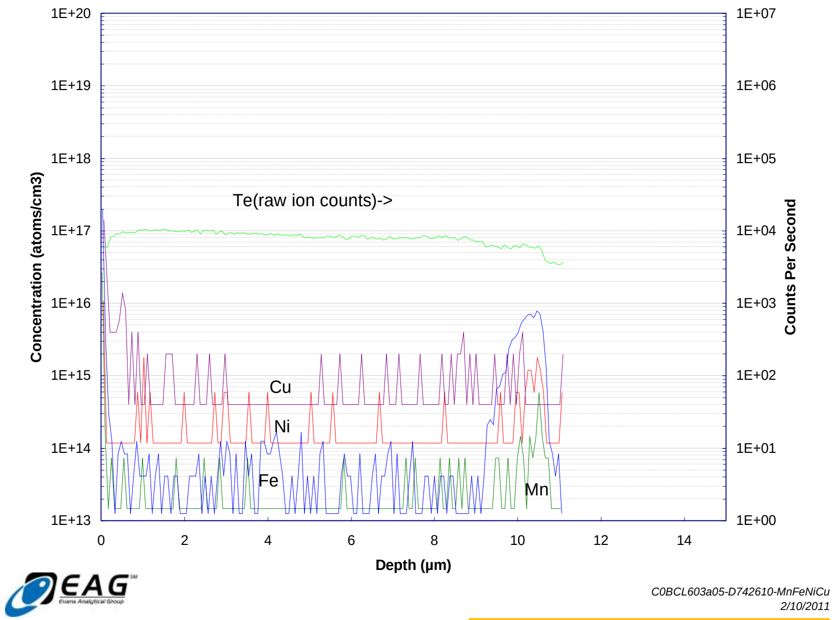
4. Integration of the detectors with radiation hardened ROIC

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)

200x

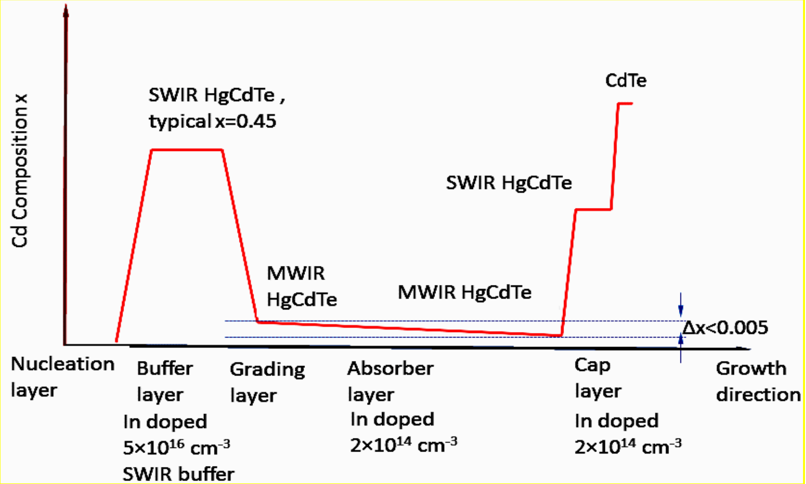
1000x

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

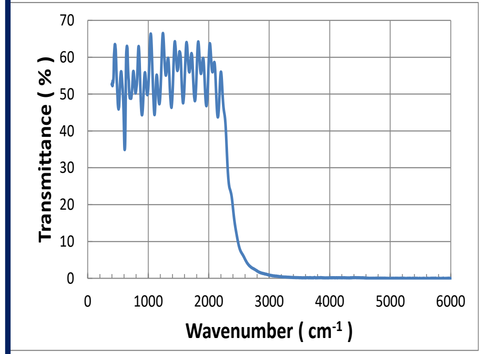
MBE Material growth and characterization

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

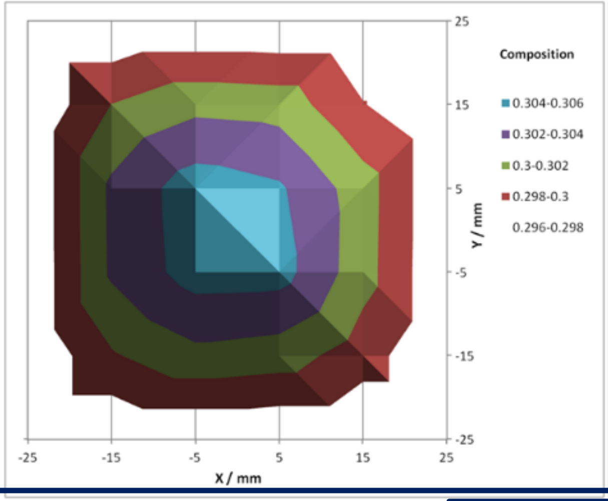
Designed material structure



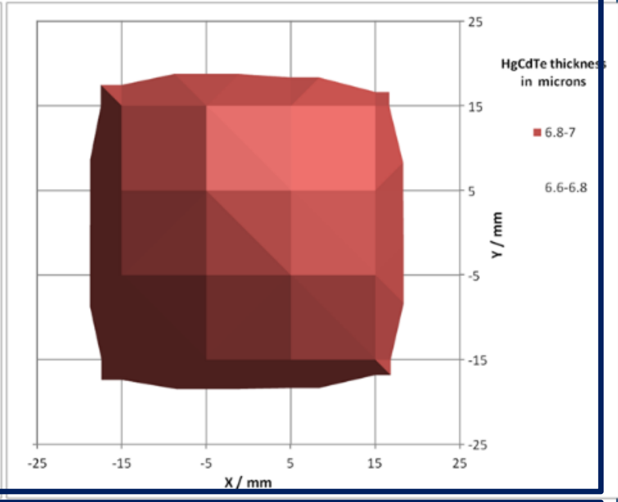
FTIR



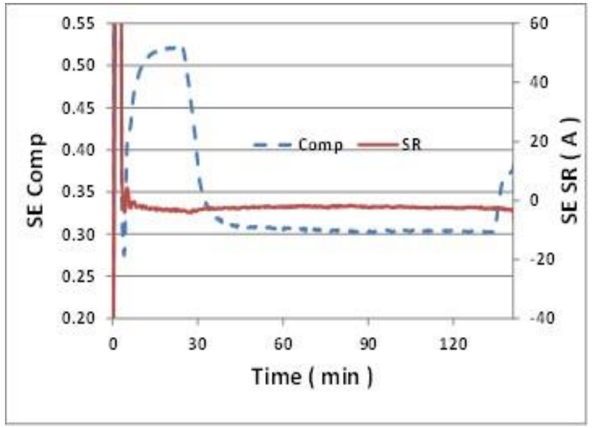
Composition mapping



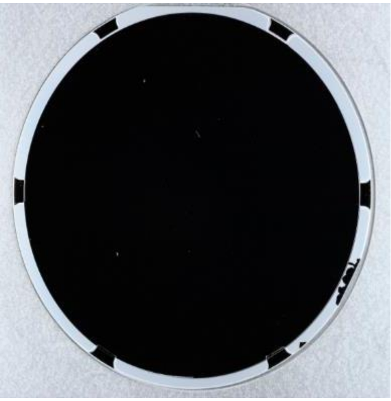
Thickness mapping



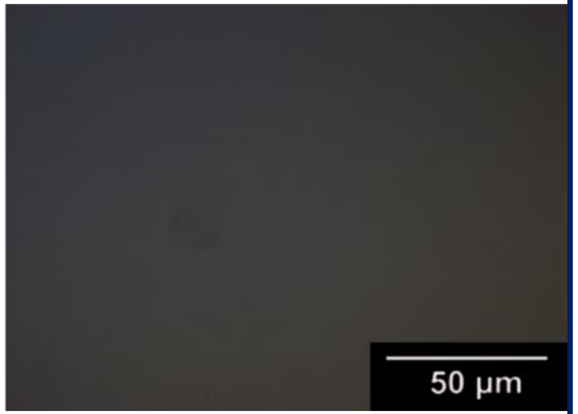
In situ SE



Whole Wafer Imaging

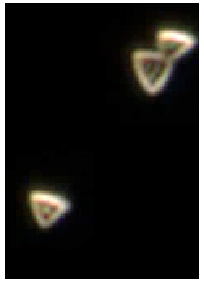


1000x



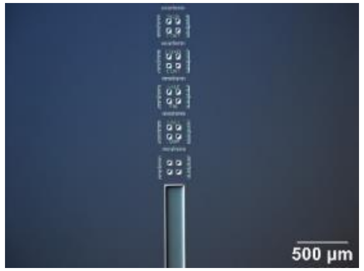
After EPD, DF

Etch Pits

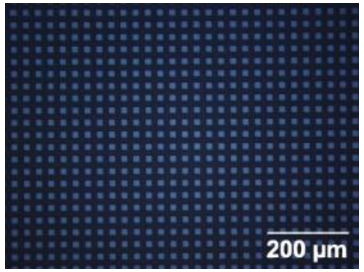


Device Fabrication – Standard Process

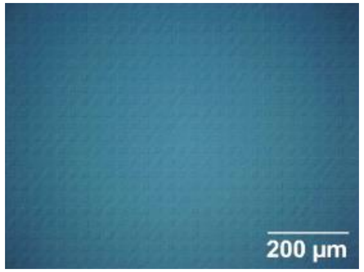
Align keys lithography and etch

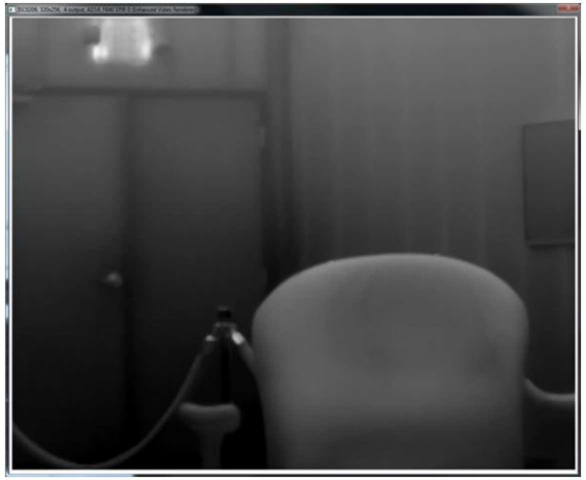


Implant window lithography



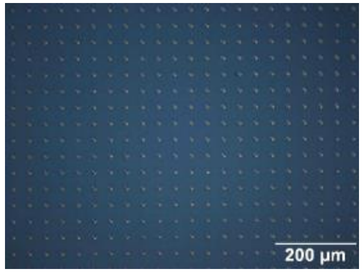
Implantation and annealing



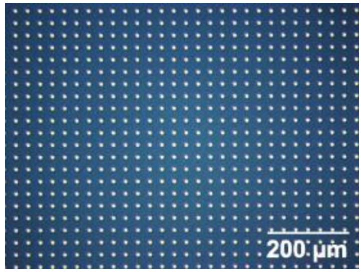


Passivation layer deposition

Passivation layer etch

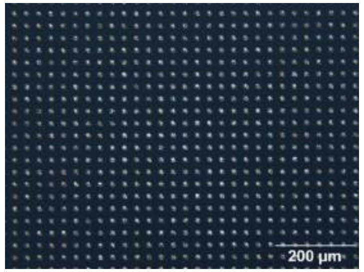


Contact metal deposition

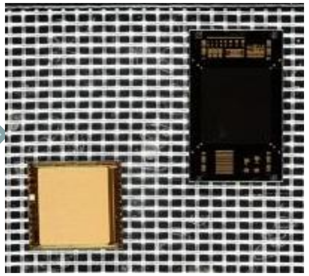


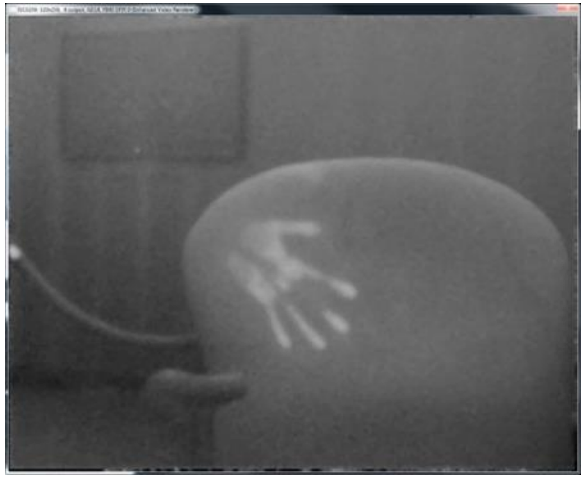
Indium contact processing

Indium bump deposition



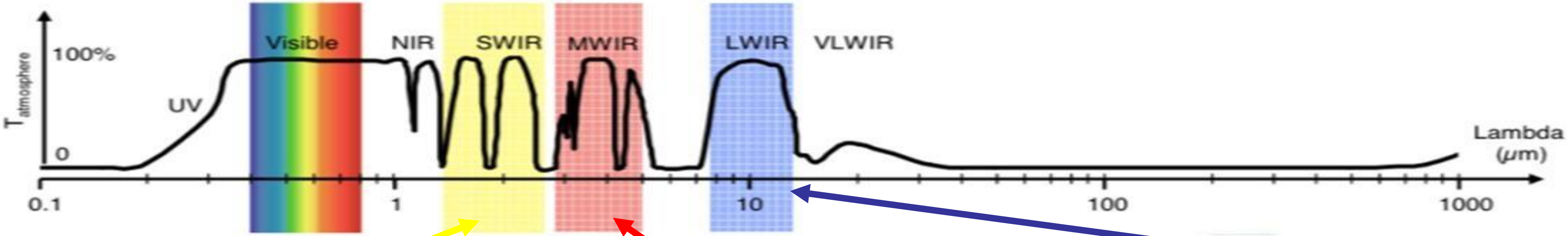
Hybridization and imaging test





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

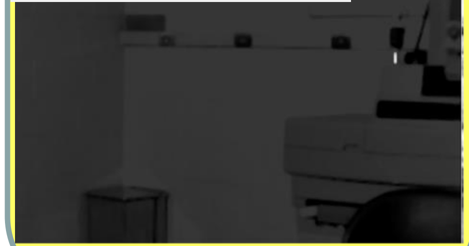
Infrared Focal Plane Arrays at EPIR



NIR-eSWIR

NIR on Si, Room Temperature

eSWIR on Si, 195K



MWIR

MWIR on CZT, 140K

MWIR on Si, 110K

LWIR

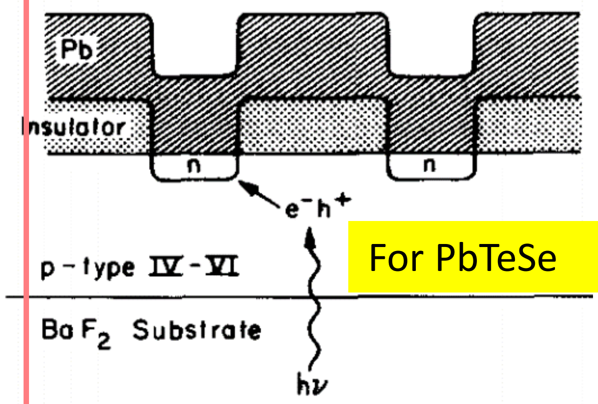
LWIR on CZT, 85K

LWIR on CZT, 110K

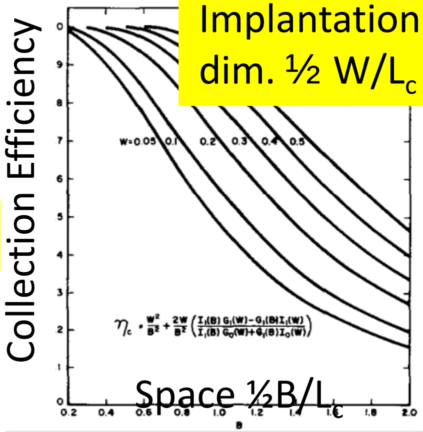
Commercial grade devices in NIR to LWIR range

Lateral Collection Diodes

EPIR



For PbTeSe

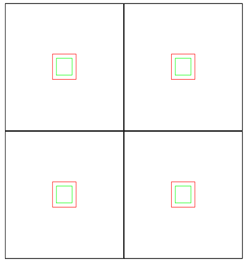


Implantation dim. ½ W/L_c

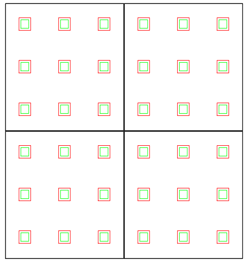
H. Holloway, M. D. Hurley, and E. B. Schermer, V-VI semiconductor lateral-collection photodiodes Appl. Phys. Lett. 32, 65 (1978)

*L_c: carrier diffusion length

Device architecture optimization: reduce G-R current using lateral collection configuration



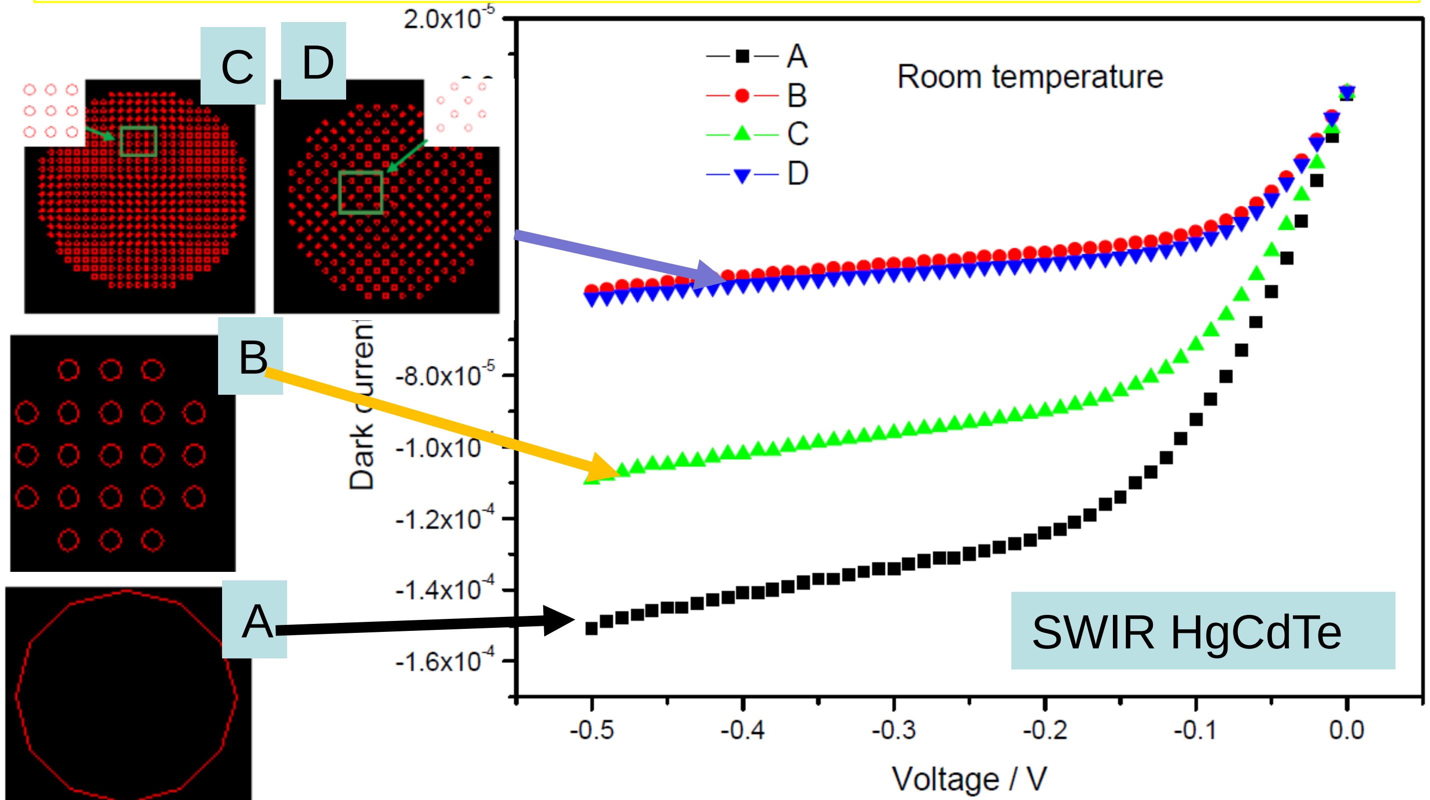
-High lateral diffusion
-Low J_d
-High operability



-Optimized performance
-Insensitive to displacement damage

Advantages:

- Reduced dark current
- Relatively high dynamic resistance
- Relatively low capacitance
- **<u>Reduced the chance of radiation damages occurred at the junction area, hence reduced GR/TAT leakage current</u>**

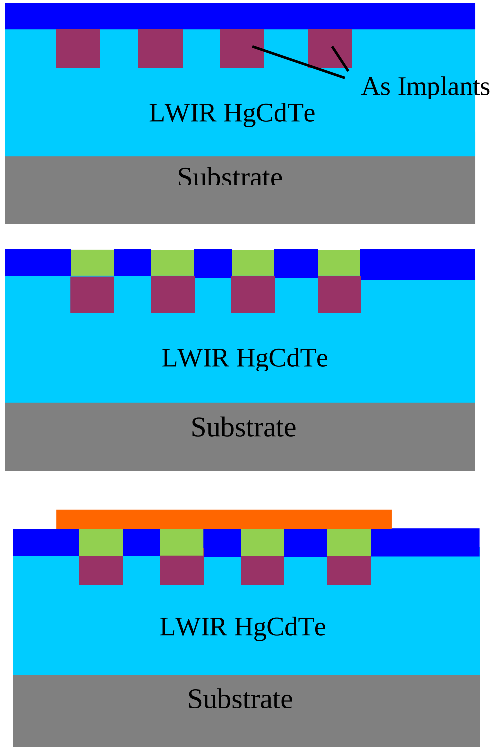


Hui Qiao, Xiangyang Li, Infrared Technology, 39(6) 489(2017)

Device Fabrication Process Development

• Mature capability to fabricate PECs and FPA

• Modify standard device geometry to enhance radiation hardness: multiple implants and additional metal interconnect to provide parallel connection between the multiple contacts on each pixel area



a) CdTe passivation

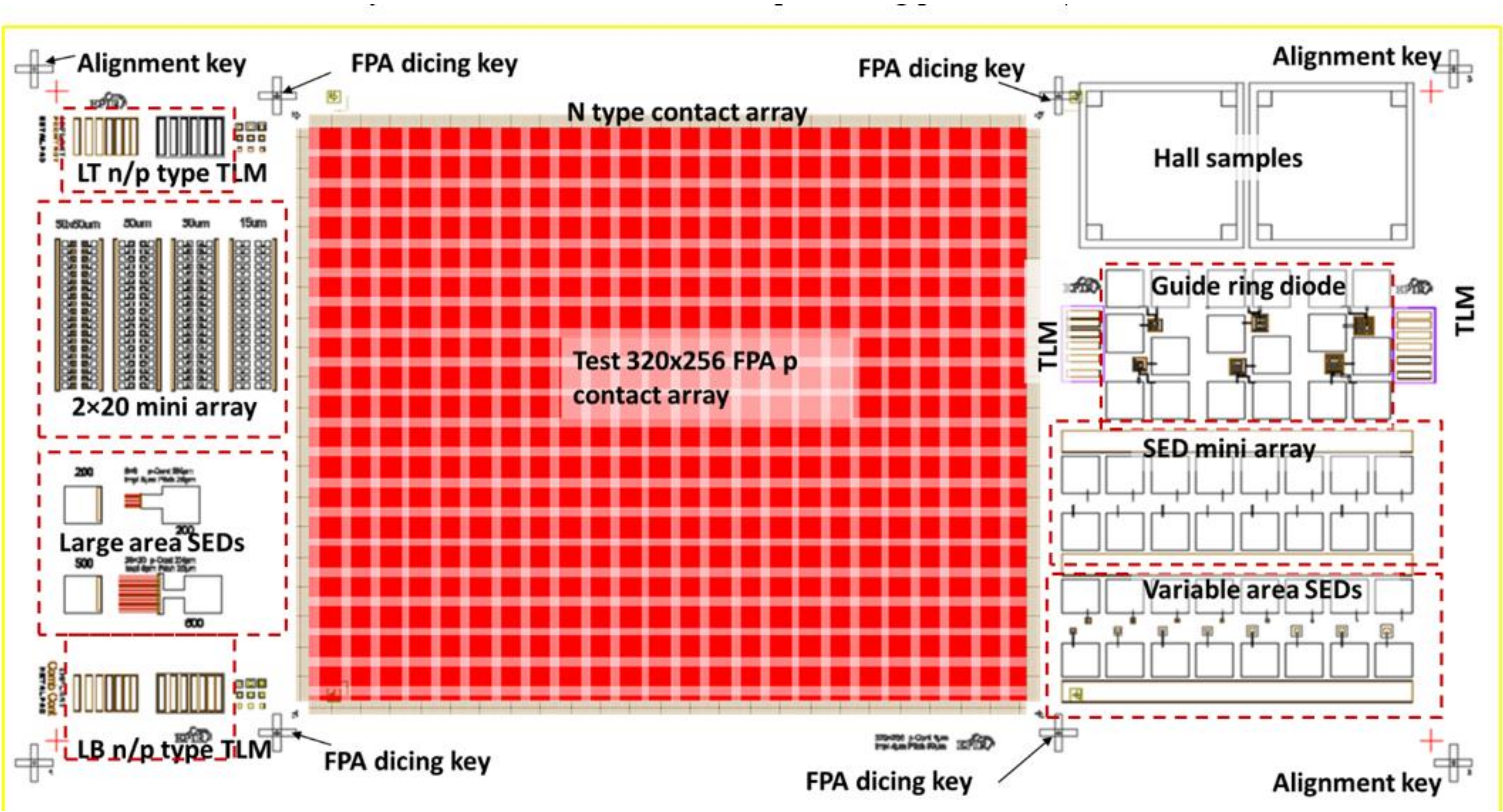
b) Photolithography, etch and metallization for p-type contacts

c) Photolithography and metallization for p-type contacts interconnect

- Small implantation/processing windows require better control in device processing
- Run trial processes to assess the impact of these additional steps on the overall device quality,

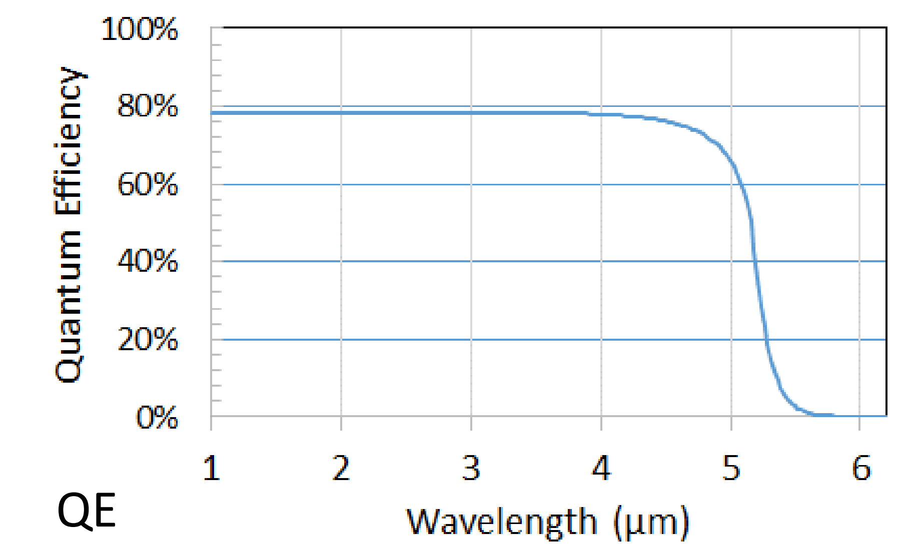
Optimized device fabrication processes for radiation hardened detectors

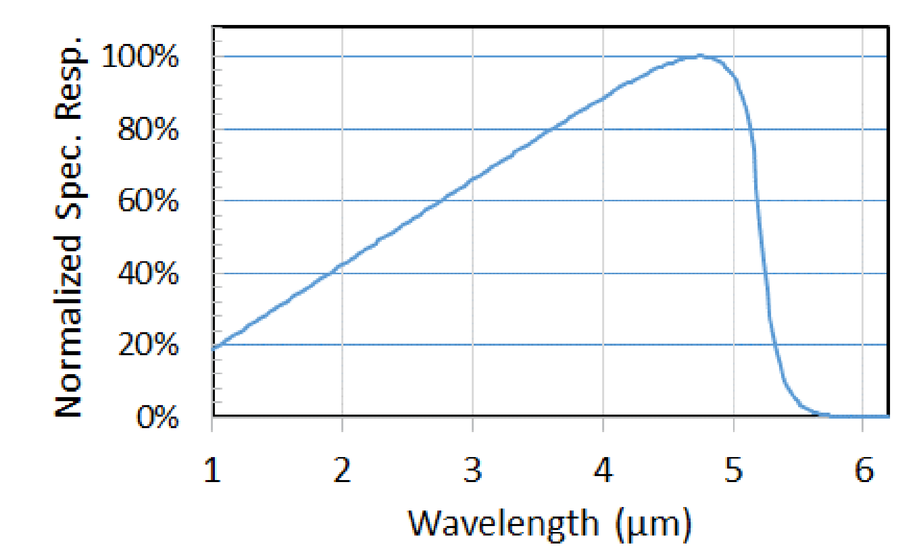
Mask Design for Radiation Hardened Arrays and Test Elements



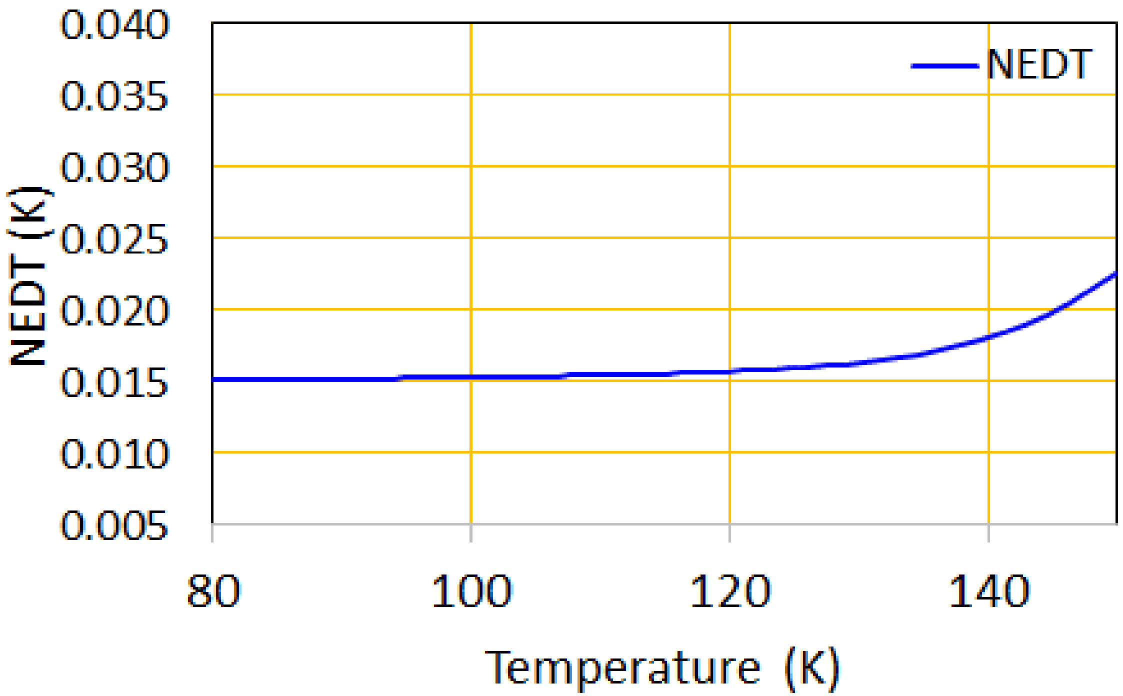
Simulation Results

At -100 mV bias





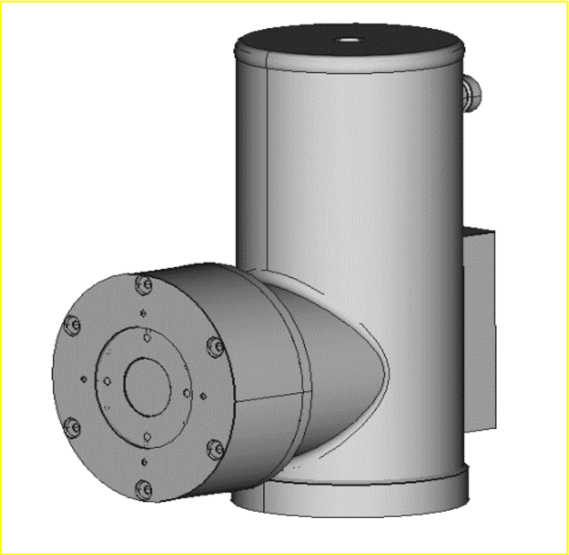
Relative spectral response

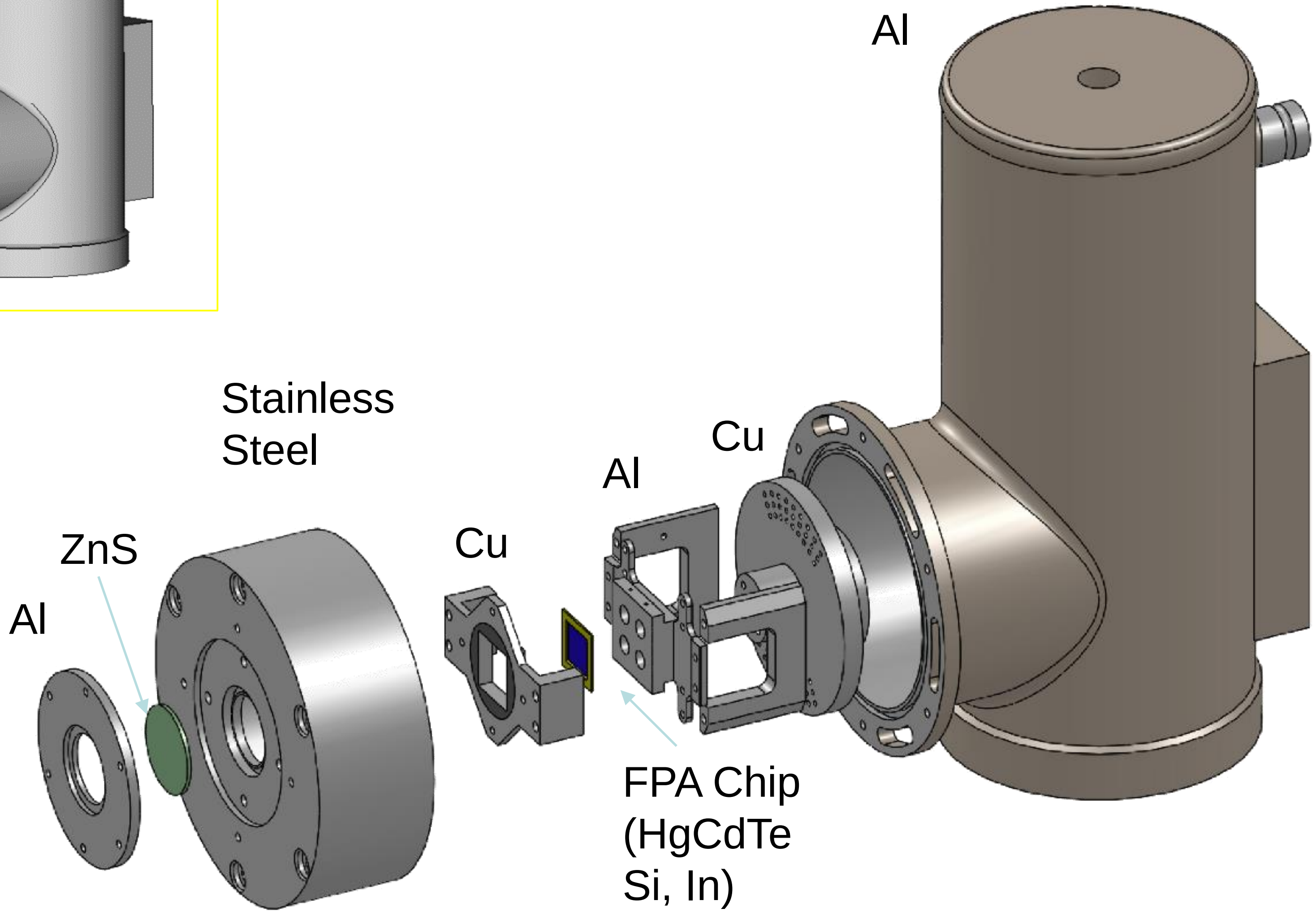


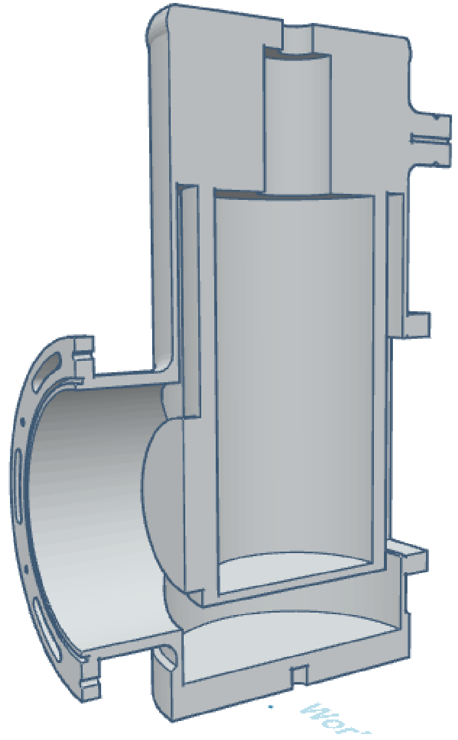
NEDT simulation results for 30-µm pitch size, 1-ms integration time, 100 mV reverse bias

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

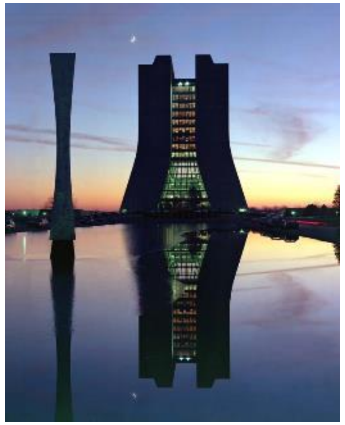
3D Model Construction for the MCNP Radiation Simulation

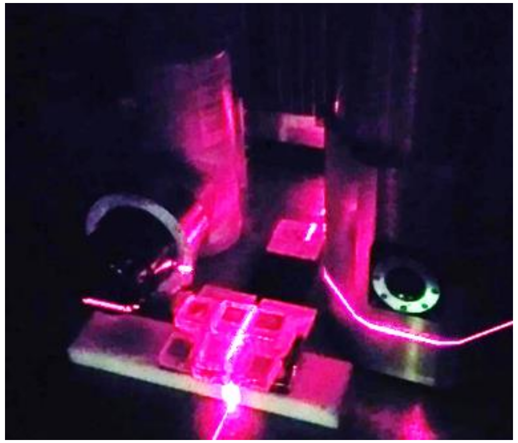


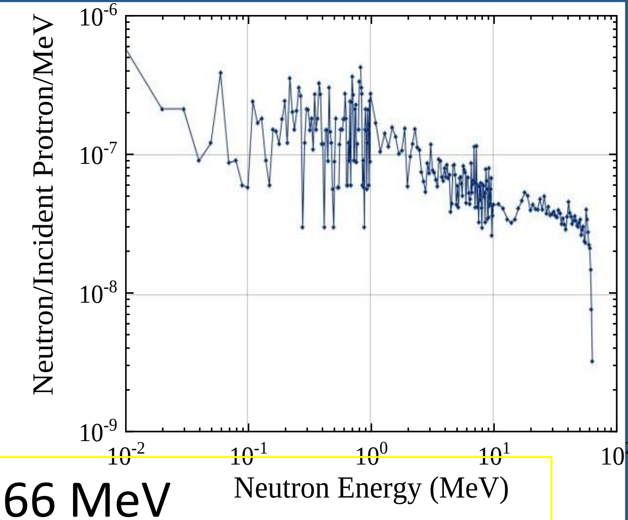


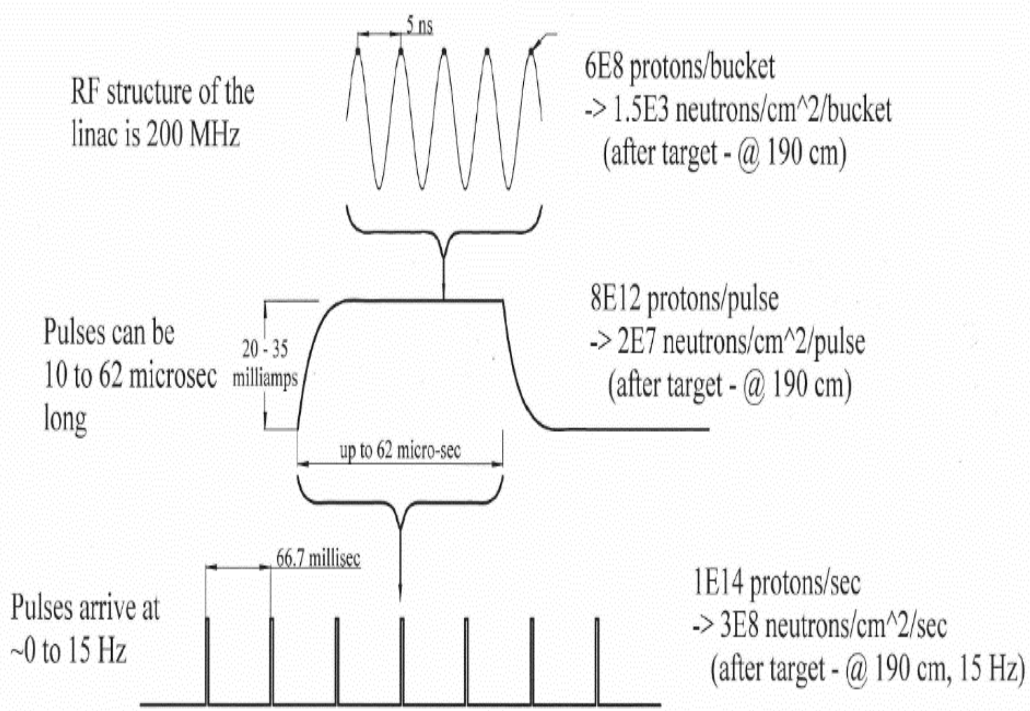


EPIR's FPAs under neutron flux at FNAL





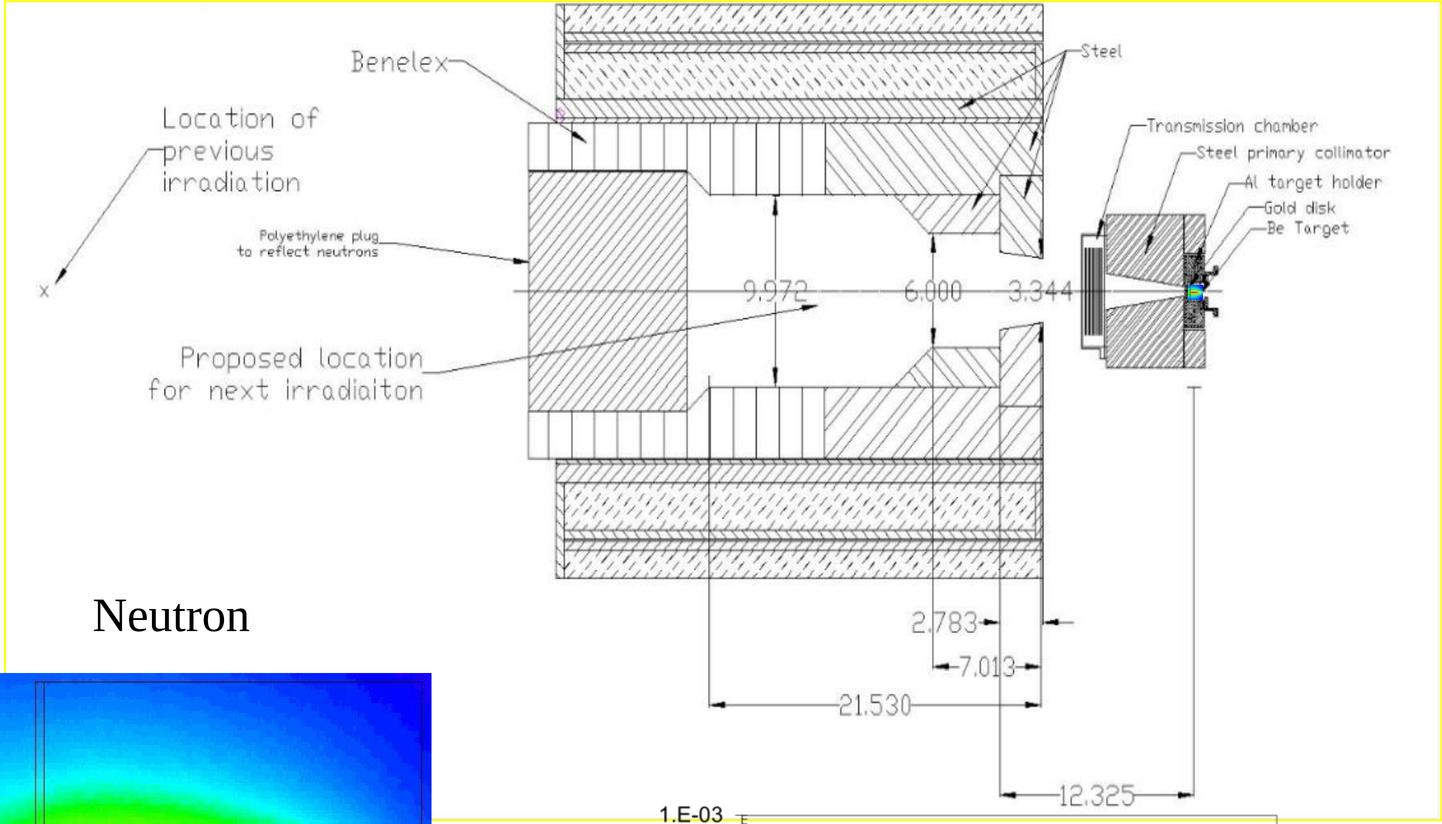




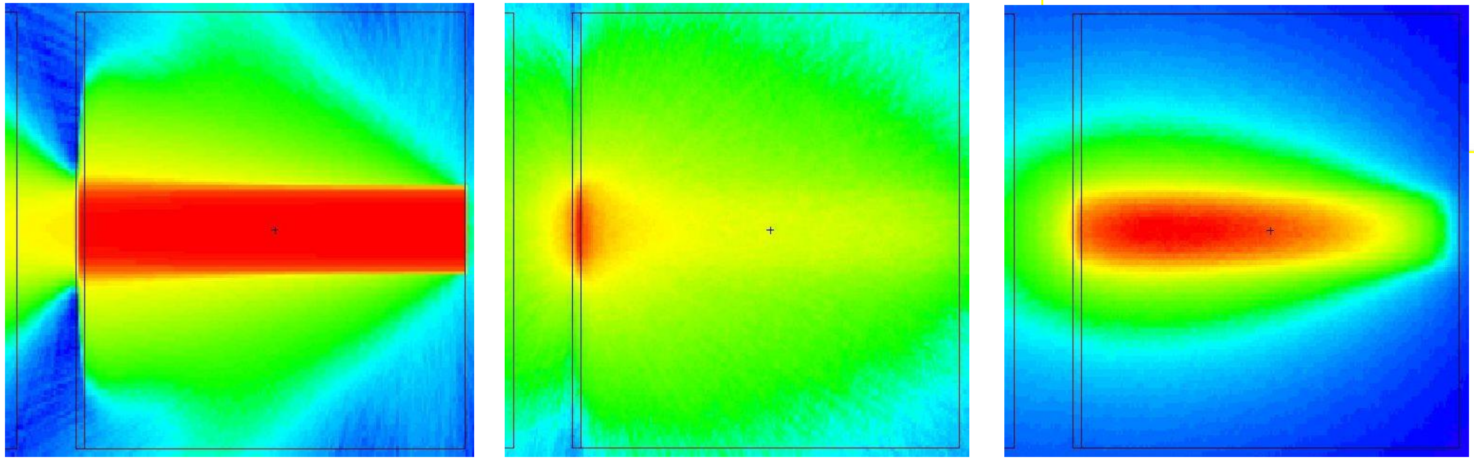
- The maximum neutron energy was 66 MeV
- Irradiated at a typical rate of 1×10^{8} n/cm$^{2}\cdot$s
- Maximum rate ~2×10^{9} n /cm$^{2}\cdot$sec by mounting samples inside channel (without considering scattering)
- ~35 days of exposure are needed to reach the total dose of 1 Mrad at the flux of 1×10^{8} n/cm$^{2}\cdot$s
- ~42 hours of exposure are needed to reach the same cumulative dose at the flux of 2×10^{9} n/cm$^{2}\cdot$s

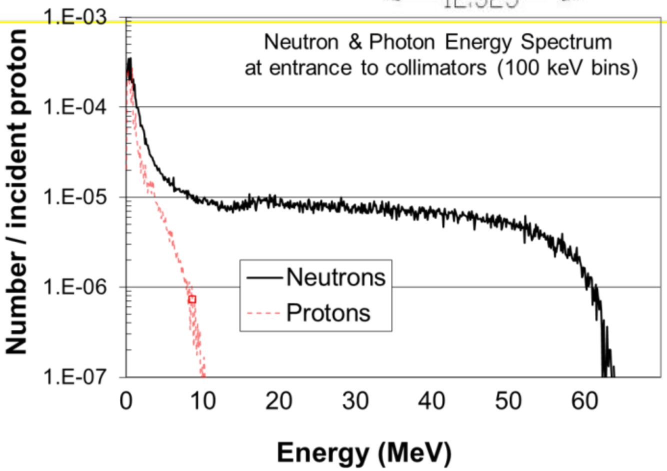
Dose rates were calculated based on the "theoretical" maximum in FNAL's standard configurations. Operational constraints may significantly lower rates and maximum doses. We will investigate alternative configurations in order to mitigate the operational reductions.

Approaches to increase neutron flux



Proton | Photon | Neutron





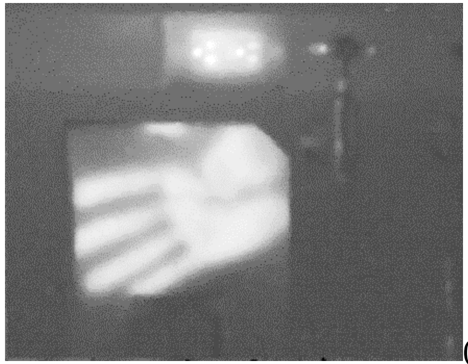
MWIR FPA Before and After Neutron Exposure

(a) before neutron exposure

(b) after 1-hour neutron exposure under flux 2.59×10^{8} n/cm^{2}·s

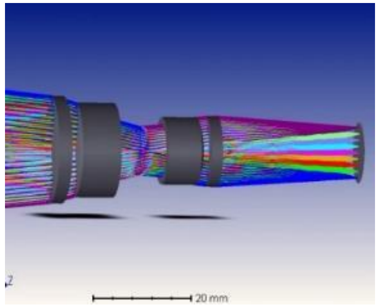
(c) after one extra temperature cycling from liquid nitrogen to room temperature

MWIR_FPA_F:
Mounted in an IR camera directly facing neutron beam.
Irradiated at 77K

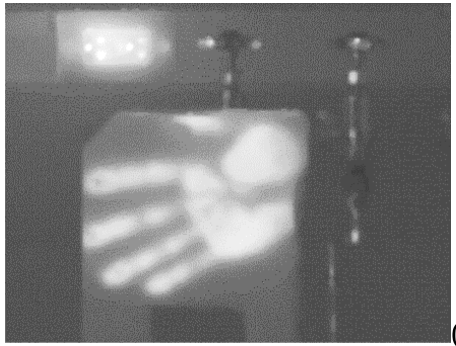

(a)

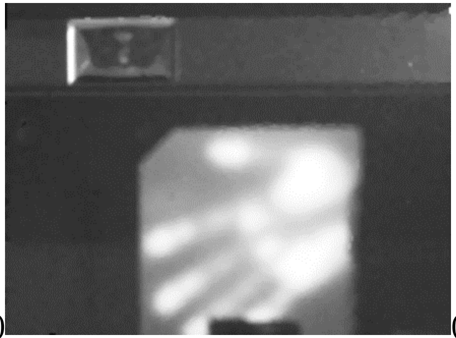

(b)


(c)

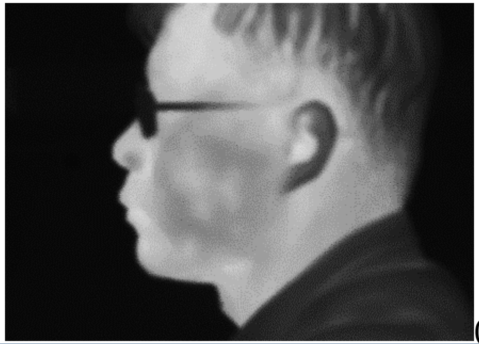


MWIR_FPA_B:
Mounted in a cryostat parallel with the beam direction.
Irradiated at 77K


(a)

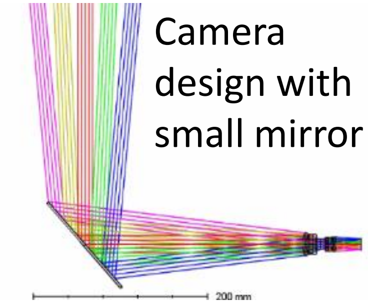

(b)

MWIR_FPA_L:
Mounted behind a 1-inch-thick polyethylene bar at the edge of the neutron beam and parallel to the beam.
Irradiated at room temperature.


(a)

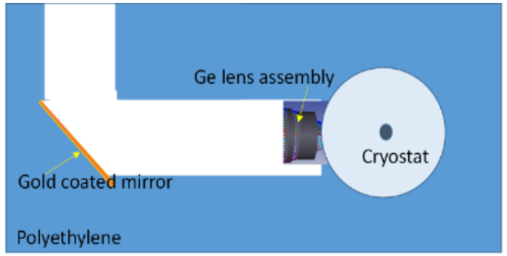

(b)

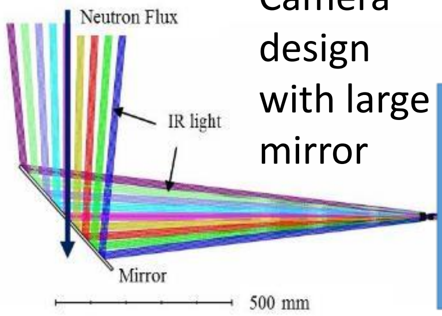
Camera designed for high flux radiation environments



Camera design with small mirror

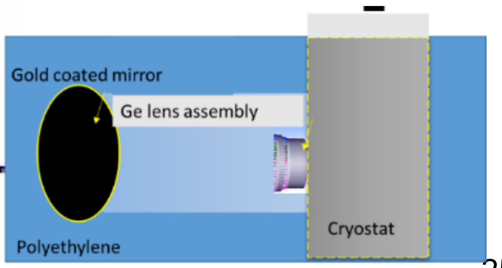
Camera bottom view



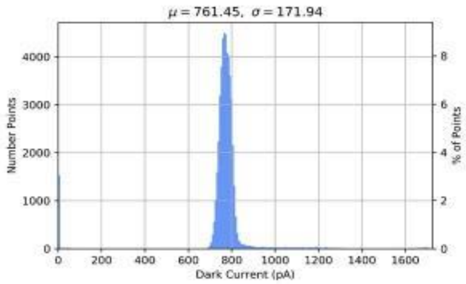
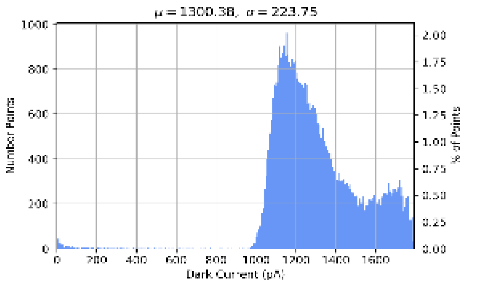
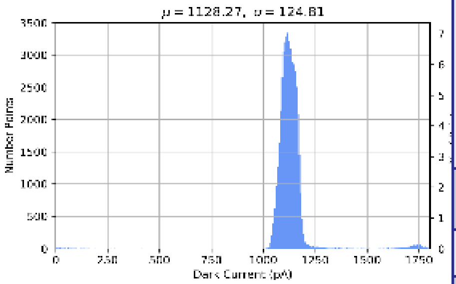
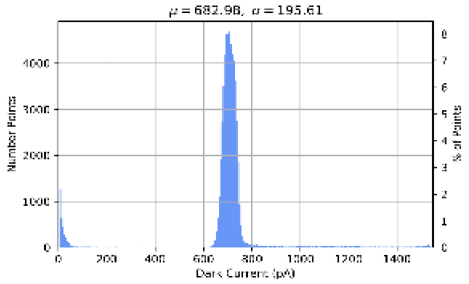
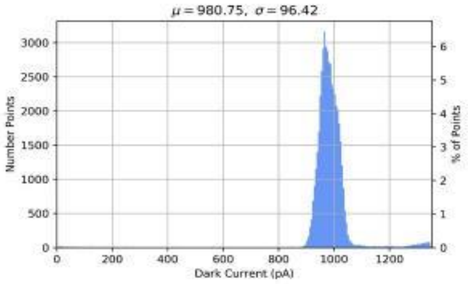
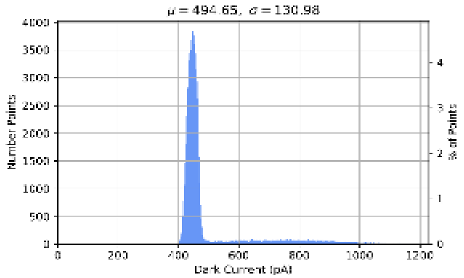
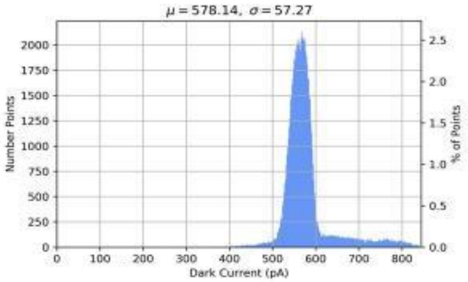


Camera design with large mirror

Camera side view



Dark Current Histograms Before and After Neutron Exposure

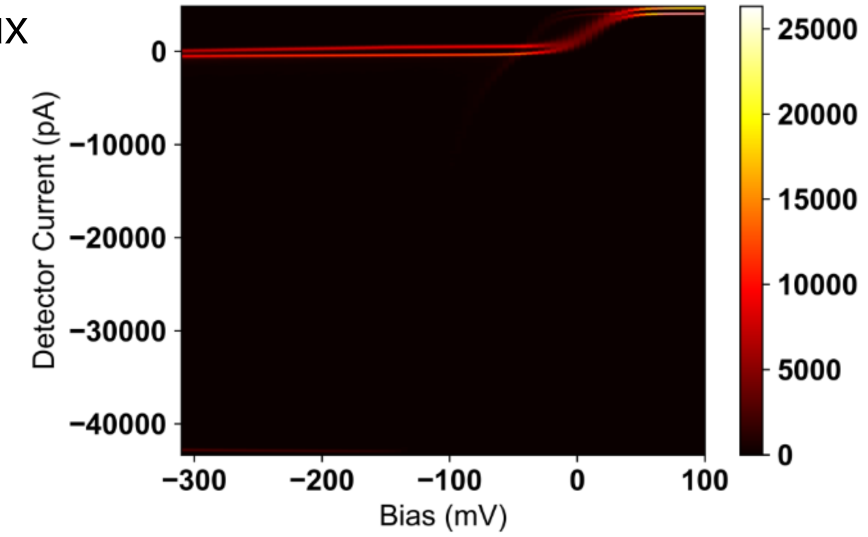
	Before exposure	After exposure	After extra 1 temperature cycle
MWIR FPA _F	 μ= 761 pA, σ= 172 pA	 μ= 1300 pA, σ= 224 pA	 μ=1128 pA, σ=124 pA
MWIR FPA _B	 μ=683pA, σ=196pA	 μ=981pA, σ=96pA	
MWIR FPA_ L	 μ=495pA, σ=131pA	 μ=578 pA, σ=57 pA	

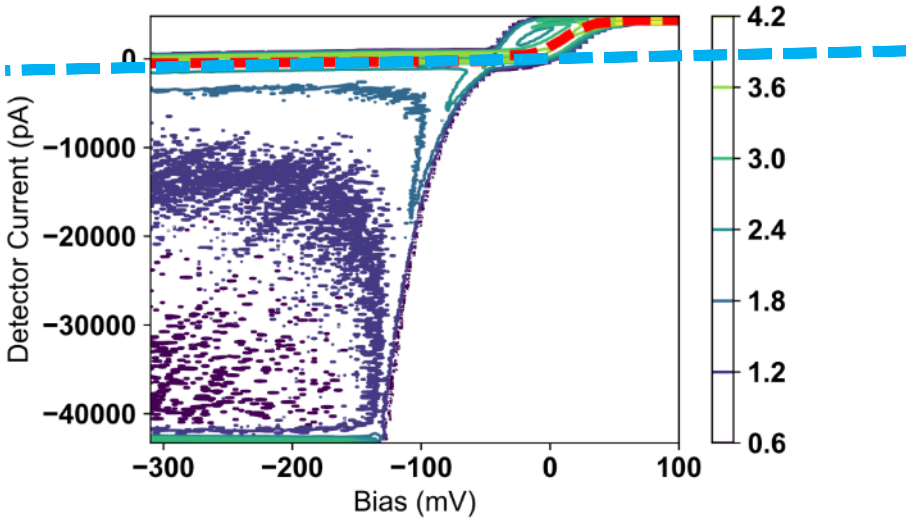
FPA#	NEDT before exposure	NEDT after exposure	NEDT after extra temp. cycling
MWIR_FPA_F	21mK	162mK	33mK
MWIR_FPA_B	16mK	18mK	
MWIR_FPA_L	28mK	26 mK	

- MWIR FPAs directly facing the neutron flux ($2.59\times10^8 n/cm^2s$)degraded after irradiation
- Performing another temperature cycle can recover the original characteristics.
- MWIR FPAs mounted parallel to the neutron flux show little change after neutron radiation exposure.

I-V Characterization (FPA_L) After Neutron Exposure

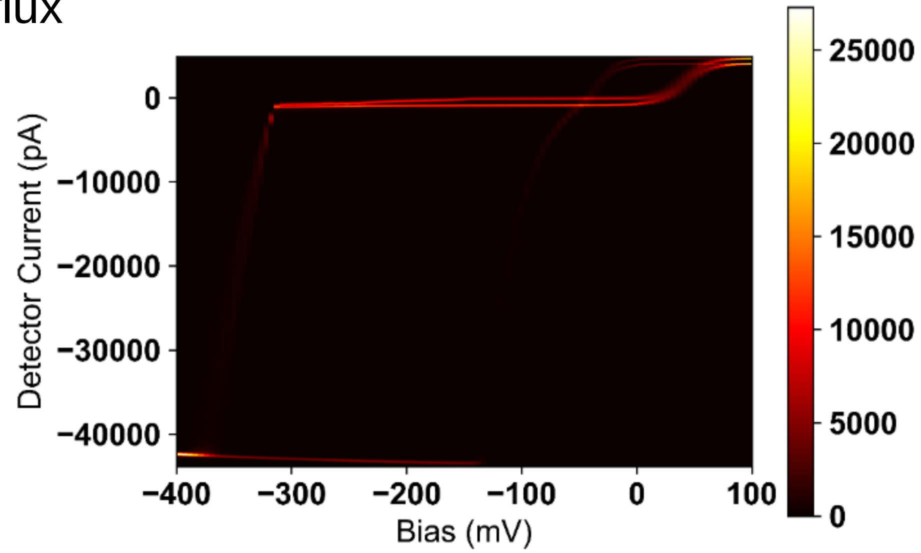
Before neutron flux

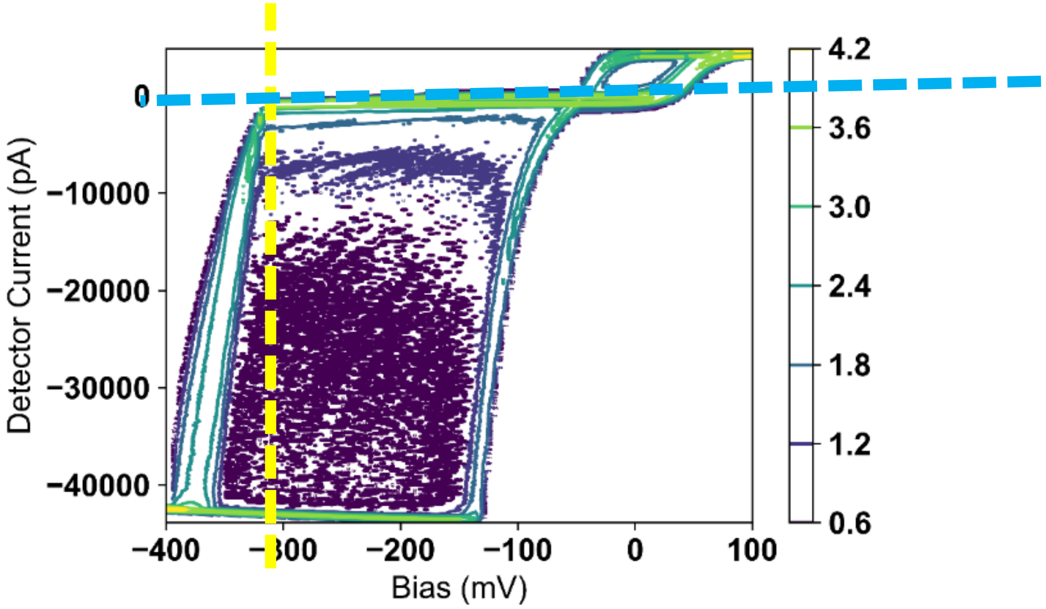




After neutron flux

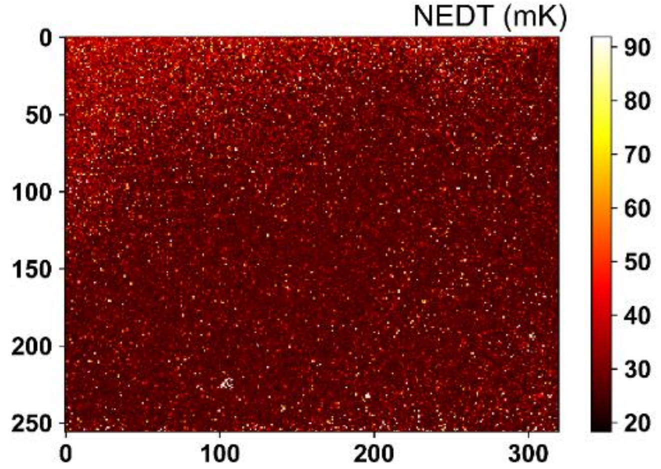
Total: ~10^{12} n/cm^2

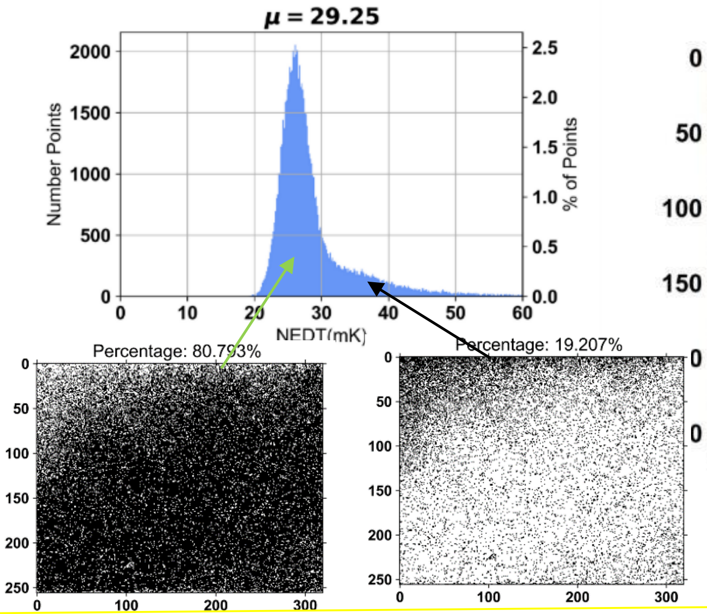


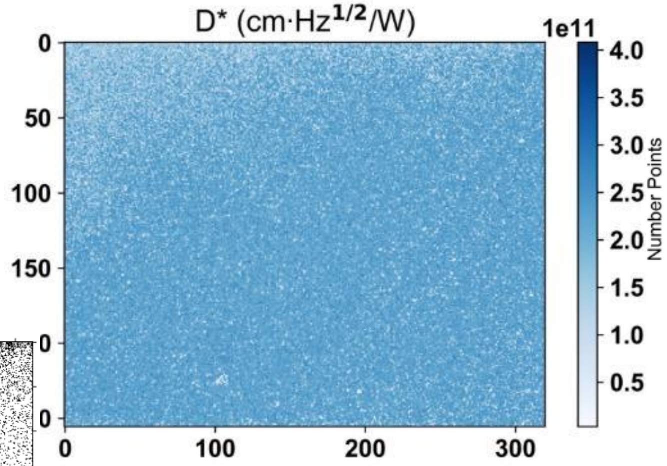


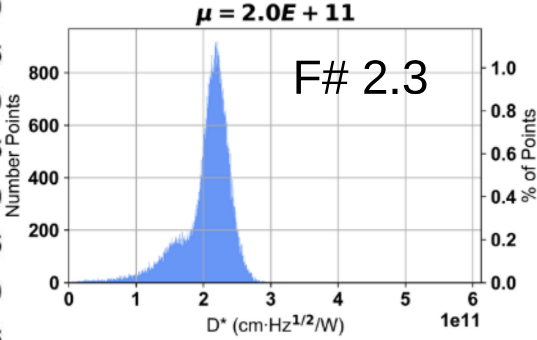
NEDT/Detectivity Before and After Neutron Flux Exposure (~10^{12} n/cm^2)

Before Neutron flux



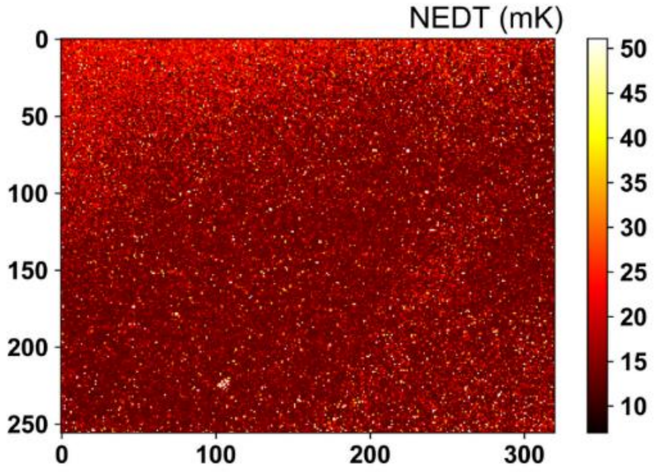


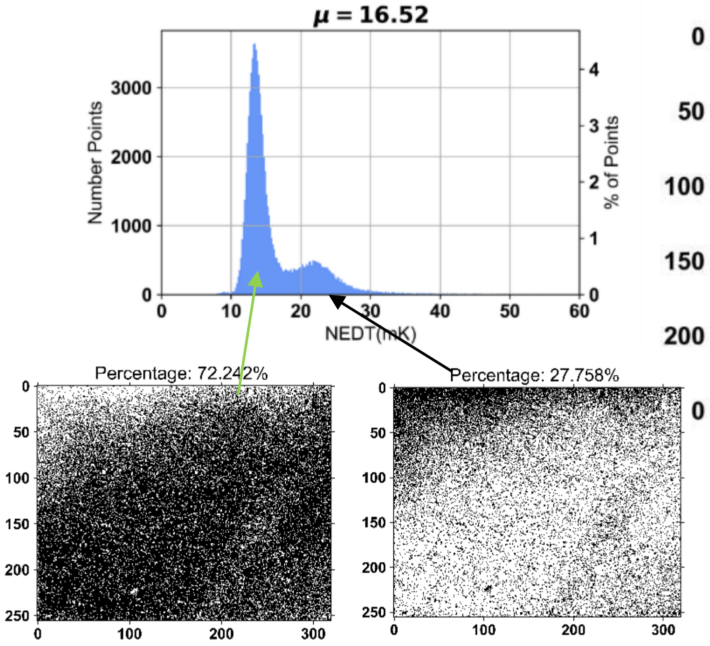


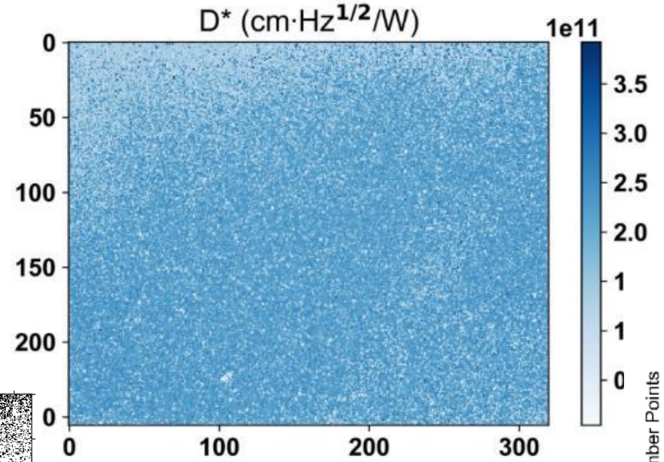


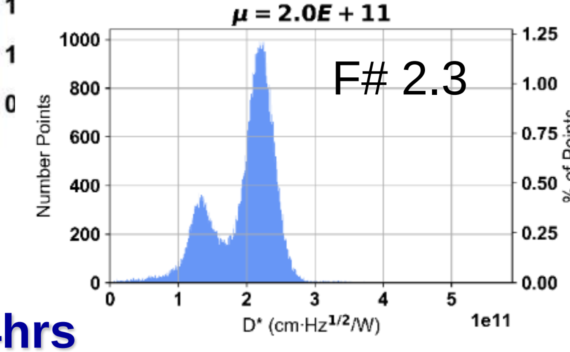
Although median D* was unchanged, the high noise tail side split into a separate peak.

After Neutron flux









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

Summary

- HgCdTe is the preferred material for use in high radiation environment applications. EPIR has grown the HgCdTe with desired performances using MBE
- Lateral collection architectures could reduce the radiation induced dark current in implantation-formed p-n junctions. Photomasks (including e-masks) were designed.
- FPA device processing procedures were established at EPIR
- HgCdTe FPAs under irradiation showed minimal performance degradation
- MWIR FPAs directly facing 10^8 n/cm^{2}s neutron flux got degraded performances after irradiation. However, performing another temperature cycle recovered and restored the original performance
- MWIR FPAs mounted parallel with neutron flux show little change after 2.59×10^8 n/cm^{2}s neutron flux irradiation, more than 2000 times higher than the typical high neutron flux working environment with 10^5 n/cm^{2}s, under a total dose ~10^{12} n/cm^2.
- Working with Fermilab to further increase the flux to ensure the 1MRad/year dose can be tested in a relatively short period of time.

THANK YOU