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 \(10^5 \text{ n cm}^{-2} \text{ s}^{-1}\) => short period of time
• Total absorbed dose of ~ 1MRad/yr. => Total dose (TD) effects
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
Neutrons cause FPA degradation mainly through displacement damage effects. Damaged is characterized by Non-Ionizing Energy Loss (NIEL).

Non-Ionizing Energy Loss (NIEL) Si

![Graph showing NIEL for protons, neutrons, and electrons versus Particle Energy (MeV).](image)

\[ \text{NIEL} \times 1000 \text{ for keVcm}^2/\text{g} \]

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

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

![Graph showing Non-Ionizing Energy Loss for HgCdTe.](image)

C+E+I

Total Nuclear (Elastic & Inelastic)

Coulombic

Inelastic Nuclear

Elastic Nuclear

Proton on HgCdTe Non-Ionizing Energy Loss

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
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
- Contact metal deposition
- Passivation layer etch
- Passivation layer 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

Commercial grade devices in NIR to LWIR range

- NIR on Si, Room Temperature
- eSWIR on Si, 195K
- MWIR on CZT, 140K
- MWIR on Si, 110K
- LWIR on CZT, 85K
- LWIR on CZT, 110K
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.
At -100 mV bias

Simulation Results

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 $1 \times 10^8$ n/cm$^2$·s
- Maximum rate $\sim 2 \times 10^9$ 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

Maximum rate $\sim 2 \times 10^9$ n/cm$^2$·sec by mounting samples inside channel (without considering scattering)
### Energy Deposition in FPA: MCNP Calculation at FNAL

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Deposited Energy on HgCdTe FPA: Electron, Photon, Proton, and Neutron Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td></td>
</tr>
<tr>
<td>MCT</td>
<td></td>
</tr>
<tr>
<td>CdTe</td>
<td></td>
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<tr>
<td>e</td>
<td></td>
</tr>
<tr>
<td>Neutron</td>
<td></td>
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<tr>
<td>Photon</td>
<td></td>
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<tr>
<td>Proton</td>
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</tbody>
</table>

**Diagram:**

- **Deposited energy on HgCdTe FPA:**
  - Electron
  - Photon
  - Proton
  - Neutron

**Axes:**

- **Deposited energy (MeV/g/MeV)**
- **Particle energy (MeV)**
I-V Characterization (FPA_L) After Neutron Exposure

Before neutron flux

After neutron flux

Total: \( \sim 10^{12} \) n/cm\(^2\)
Although median $D^*$ was unchanged, the high noise tail side split into a separate peaks.

Total: $\sim 10^{12} \text{ n/cm}^2$, $10^5 \text{ n/cm}^2\text{s}$, 1/3 year, 24hrs
Imaging with EPIR-assembled IR Cameras

3-5μm MWIR

- before $1.5 \times 10^{13}$ n·cm$^{-2}$ neutron exposure

- HgCdTe

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

- after an extra temperature cycling from 100K to room temperature

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

- (b)

- (a)

- (c)

- Our T2SL nBn FPAs also shows good functionality, however Sb decay emits $\beta$ 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

- ... 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).


- Senseeker’s ROIC and ROIC mounted on PCB were tested under >1×10⁹ n/cm²/s (up to 2×10⁹ n/cm²/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 $1.5 \times 10^{13} \text{n} \cdot \text{cm}^{-2}$ neutron exposure and $2 \times 10^9 \text{n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ 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