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

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 \((10^5 \text{ n cm}^{-2} \text{ s}^{-1})\) => 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 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

- 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
- 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.
... 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.


• Senseeker’s ROIC and ROIC mounted on PCB were tested under $>1 \times 10^9$ n/cm$^2$/s (up to $2 \times 10^9$ 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
64x64 Testing Array with 2x2 or 3 Subpixel Arrays

Under optical microscope:
- 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 SEM:
- 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

Fanout circuit for testing:

Fanout circuit mounting and test configuration on chip carrier PCB through wire-bonding
Standard Testing condition:

- Maximum neutron energy was 66 MeV
- Irradiated at a typical rate of \(1 \times 10^8\) n/cm\(^2\)-s
- Maximum rate can achieve \(\sim 2 \times 10^9\) n/cm\(^2\)-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

Neutron & Photon Energy Spectrum at entrance to collimators (100 keV bins)
Energy Deposition in Material: MCNP Calculation at FNAL

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

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

Supported by Dr. Kroc's group at FNAL
**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**

- 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: $\sim 10^{12}$ n/cm$^2$
Imaging with EPIR-assembled IR Cameras

3-5μm MWIR

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

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.

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 $1.5 \times 10^{13}$ n·cm$^{-2}$ neutron exposure and $2 \times 10^9$ n·cm$^{-2}$·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.

In collaboration with Fermilab

- ASICs under development for NP detectors (RHIC, CBAF)

- Conducting radiation hardened design.
THANK YOU