Antimone Barrier Infrared Detector Focal Plane Arrays for Earth Science Applications

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Motivation

- NASA successfully deployed long-wavelength **QWIP** (quantum well infrared photodetector) FPAs
  - LandSat-8 TIRS (Thermal Infrared Sensor) – Multispectral IR Imager
  - HyTES (Hyperspectral Thermal Emission Spectrometer) – Hyperspectral IR Imager
    - [https://hytes.jpl.nasa.gov/](https://hytes.jpl.nasa.gov/)

- QWIP FPA advantages
  - Made from robust III-V semiconductors, providing FPA “-ility” advantages
    - High operability, large-format capability, producibility, temporal stability, spatial uniformity, affordability
  - **Temporal stability** (low 1/f noise). No need for frequent system recalibration - **More science return**.

- QWIP FPA challenges
  - Higher dark current due to larger generation-recombination (G-R) rate; photoconductor architecture
  - Low conversion QE. No intrinsic normal-incidence absorption; sub-unity photoconductive gain (~0.1)
  - Requires more cooling to control thermal dark current to achieve needed sensitivity
  - Low operating temperature: TIRS ~ 43 K; HyTES ~ 40 K (both with ~12 µm response)

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**Can we achieve higher operating temperature to reduced cooler demand for lower size, weight, and power (SWaP), and still retain the FPA ‘ility’ advantages?**
Advances in III-V Semiconductor IR Photodetectors

Antimonide infrared absorbers

- InGaAsSb alloy: 2 - 4 µm cutoff wavelength
- Type-II superlattices (artificial IR material)
  - Continuously adjustable bandgap provides cutoff wavelength coverage from 2 µm to >15 µm
  - Tunneling and Auger dark current suppression
- All can be grown on GaSb substrates
  - 2”, 3”, 4” diameter format commercially available.

Unipolar barrier detector architecture

- Unipolar barrier detector architecture
  - Unipolar Barriers block electrons but not holes (or vice versa)
  - Examples: nBn, XBn, XBp, CBIRD
- Can suppress G-R and surface leakage dark current, w/o impeding photocurrent
- Higher operating temperature / sensitivity

The confluence of these two developments has led to a new generation of versatile, cost-effective, high-performance infrared detectors and focal plane arrays based on robust III-V semiconductors.
JPL Type-II Superlattice Barrier IR Detector (T2SL-BIRD)

- Antimonide T2SL high operating temperature barrier infrared detector (**HOT-BIRD**)
  - Customized cutoff wavelength to match InSb
  - Excellent FPA imaging performance at 160K
  - Comparison with InSb FPA
    - Planar InSb (ion implant) ~ 80K. MBE epi InSb ~ 95-100K (can image up to 110-120K). **HOT-BIRD FPA operates at much higher T.**
    - InSb FPA is a major incumbent technology; leads all photodetector FPA market in volume, with >50% market share (units sold) in 2018.

- Low dark-current MWIR FPA for spectral imaging
  - For NASA CubeSat Infrared Atmospheric Sounder (CIRAS)
  - Achieved low dark current of $J_{dark}(111 \text{ K})=1.8 \times 10^{-8} \text{ A/cm}^2$ required for spectral imaging application

**JPL antimonide alloy and superlattice BIRD FPA demonstrated high uniformity & operability, with cutoff wavelengths covering SWIR to VLWIR.**

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*Antimonide bulk alloy/T2SL barrier IR detectors $\lambda_{Cutoff}$

All can be grown lattice-matched to, or pseudomorphically on, GaSb substrates

| Wavelength $\lambda$ | SWIR | MWIR | LWIR | VLWIR |...
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(Very) Long Wavelength Infrared FPA for Land Imaging

- Developing type-II superlattice (T2SL) barrier infrared detector (BIRD) FPAs to meet NASA Sustainable Land Imaging (SLI) interests in thermal IR bands in the 8 – 12 µm range.

- Initial Round FPA: $\lambda_{c\text{utoff}} \sim 11$ µm
  - SBF-193 ROIC, 640x512, 24 µm pitch
  - FPA with $\lambda_{c\text{utoff}} \sim 11.2$ µm T2SL absorber material
  - $J_{\text{dark}}(60K) \sim 7 \times 10^{-5}$ A/cm²; QE $\sim 37\%$, no A/R coating.
  - FPA operability $\sim 99.4\%$

- Second Round FPA: $\lambda_{c\text{utoff}} > 12$ µm
  - Longer cutoff; improved dark current; SBF-193 ROIC
  - FPA with $\lambda_{c\text{utoff}} \sim 12.6$ µm T2SL absorber material
  - $J_{\text{dark}}(65K) \sim 3 \times 10^{-5}$ A/cm²; QE $\sim 27\%$, no A/R coating.
  - FPA operability $\sim 99.98\%$
  - Estimated 20K operating temperature advantage over QWIP FPA. Reduce cooling demand for favorable SWaP.

Long wavelength type-II superlattice (T2SL) barrier infrared detector (BIRD) FPAs can provide an estimated 20 K operating temperature advantage over existing QWIP FPAs.
Long-wavelength T2SL BIRD for “Silicon Sandwich” FPA

- L3 Cincinnati Electronics patented “silicon sandwich” process favorable for large-format FPA
- JPL/L3 collaboration to implement long-wavelength T2SL barrier IR detector silicon-sandwich FPA
- Detector material wafers designed, grown, and characterized at JPL
  - L3 process requires bonding III-V semiconductor wafer to silicon wafer first (transfer detector layer to silicon wafer)
  - Stringent wafer-bow requirements for the detector wafer
  - Material/wafer characterization: very good X-ray diffraction, surface roughness, wafer bow
  - Four 4-inch diameter wafers sent to L-3 for FPA fabrication
- A sister wafer used for detector fabrication/characterization at JPL
  - Demonstrated good LWIR detector characteristics
  - At 60 K, $\lambda_{\text{cutoff}} = 11.6 \, \mu\text{m}$; QE ~30% at 8.6 $\mu$m (no A/R coating); dark current density ~ $6 \times 10^{-6} \, \text{A/cm}^2$

Wafer bow measurement

Surface roughness

Spectral QE

Dark Current

Peak to valley = 15.6 $\mu$m (4-inch diameter wafer)

RMS roughness = 1.12 Å
LW T2SL BIRD “Silicon Sandwich” FPA Demonstration

Conventional FPA
- Fabricate detector arrays on III-V semiconductor detector wafer
- Hybridize detector array to silicon ROIC
- Remove III-V substrate to avoid thermal mismatch with silicon ROIC

L3 “Silicon Sandwich” FPA
- III-V detector wafer bonded to silicon wafer
- Remove III-V substrate (leaving detector layer on silicon)
- Fabricate detector arrays on silicon wafer
- Hybridize detector array to silicon ROIC.

- Successfully demonstrated “Silicon Sandwich” FPA with LW T2SL BIRD
  - L3 fabricated FPAs using FLIR ISC-1308 ROIC (1280×1024, 12 µm pitch)
  - Dark current density: $J_{\text{dark}}(69.4K) = 1.9 \times 10^{-5} \text{ A/cm}^2$; QE=29% (8-10 µm)
  - NEDT = 29.2 mK at 69.4K (27.5 °C background, F/2 optics, 7.7-10 µm filter)
  - Operability: 99.5%
- An integrated dewar cooler assembly (IDCA) is being built at L3

The successful demonstration of silicon sandwich FPA paves the way to multi-megapixel long-wavelength T2SL BIRD FPAs for high-resolution applications.
References /Acknowledgement

TIRS QWIP

epi-InSb FPA
- “Recent progress in InSb based quantum detectors in Israel”, P. Klipstein et al., Infrared Physics & Technology 59 (2013) 172–181

Unipolar barrier IR detectors – nBn, XBn, CBIRD

Type-II superlattice barrier IR detectors

L3 silicon-on-silicon FPA
- “Indium antimonide large-format detector arrays”, Mike Davis and Mark Greiner, Optical Engineering 50(6), 061016 (2011)

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