Type-II Superlattice (T2SL) Barrier Infrared Detector (BIRD) for Earth Science Applications

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Outline

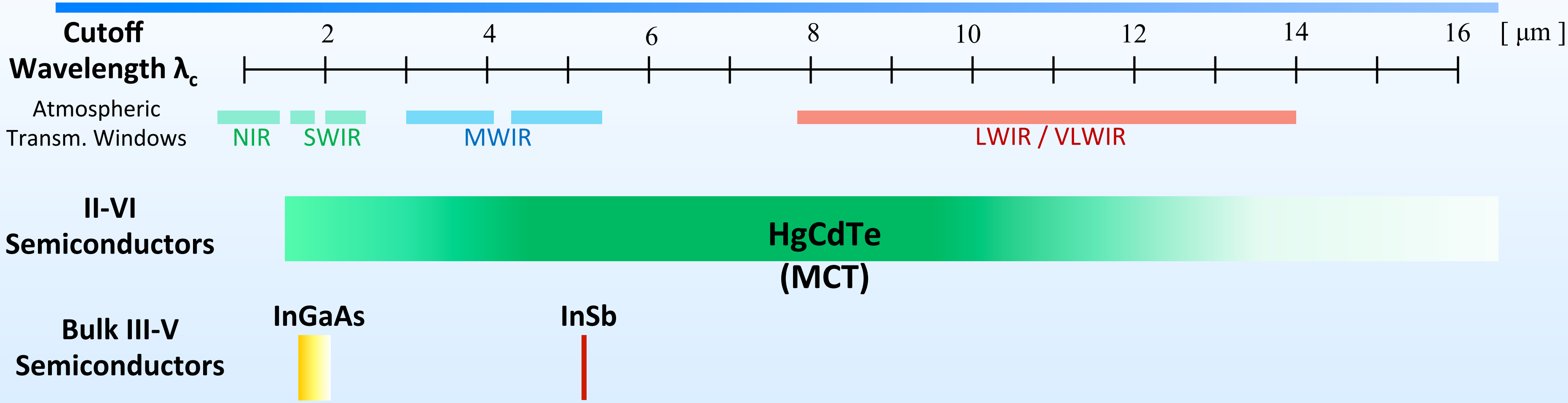
- Introduction
- Type-II Superlattice (T2SL) Barrier Infrared Detector (BIRD)
- Summary

Introduction

Thermal Infrared Focal Plane Arrays for Earth Science

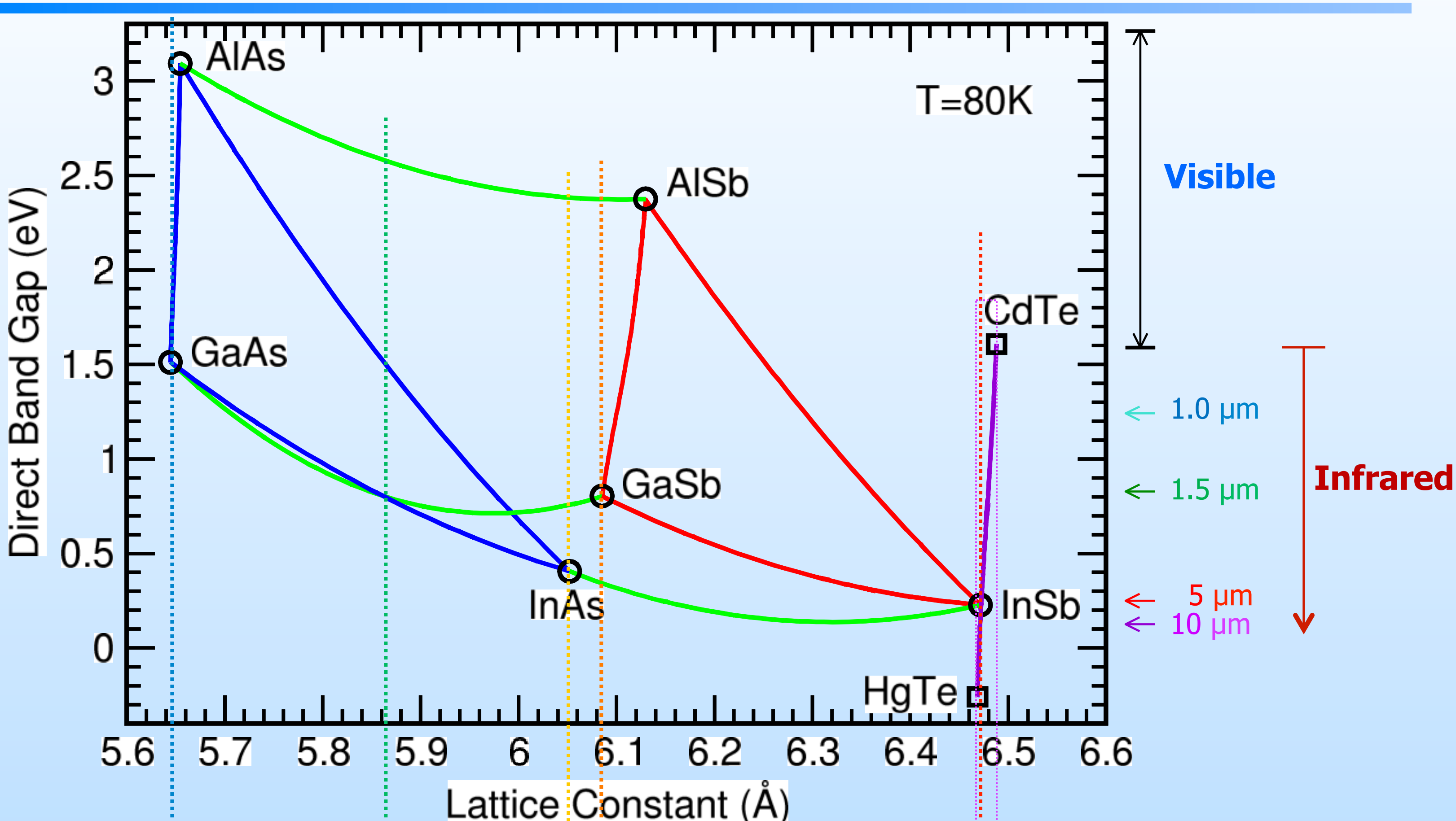
- Thermal infrared focal plane arrays (FPAs) for a variety of Earth Science related applications
  - Geology, ocean and ice changes, de-forestation, forest fires, soil moisture and plant health, weather, gas detection, pollution monitoring, …
- Infrared band of interests
  - 3 – 5 μm MWIR atmospheric transmission window
  - 8 – 14 μm LWIR atmospheric transmission window
  - Outside transmission windows, e.g., $\lambda_{cutoff} \sim 15.4$ μm for atmospheric sounding
- Focal plane arrays needed for
  - Imaging
  - Spectral imaging (more demanding)
- Desired infrared FPA properties
  - Customizable cutoff wavelength
  - High operability, spatial uniformity, temporal stability, scalability, and affordability
  - Low dark current and high QE
  - Higher operating temperature, less demanding cooler
  - Reduced mass, volume, power

Traditional Bulk Infrared Material Cutoff Wavelength Coverage



- MCT is the most successful infrared material to date
  - Adjustable band gap covering NIR to VLWIR. Long τ_{SRH}.
  - Soft and brittle. Requires expert handling in growth, fabrication, storage.
  - Longer λ_{cutoff} , high Hg fraction, progressively more challenging
- FPAs based on (near) lattice-matched bulk III-V semiconductors are highly successful in a few cases
  - SWIR InGaAs on InP performs at near theoretical limit
    - Single color, limited cutoff wavelength adjustability
  - InSb dominates MWIR market, despite lower operating temperature
    - Fixed cutoff wavelength, single color
  - Lacking the continuous cutoff wavelength adjustability of MCT

Semiconductor IR Material on Available Substrates



Substrates: GaAs InP InAs GaSb InSb CZT*

- MCT grown on CZT (CdZnTe) substrate covers full range of infrared
- $In_{0.53}Ga_{0.47}As$ grown on InP substrate has ~1.7 μm cutoff wavelength (covers SWIR)
- InSb grown on InSb substrate has 5.2 μm cutoff wavelength (covers MWIR)

Adjustable λ_c with III-V Quantum Structures
Development at JPL Center for Infrared Photodetectors

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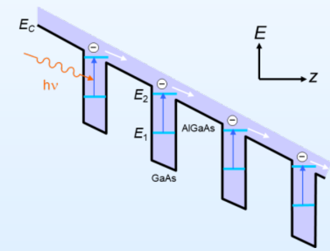
- Quantum well infrared photodetectors (QWIPs)

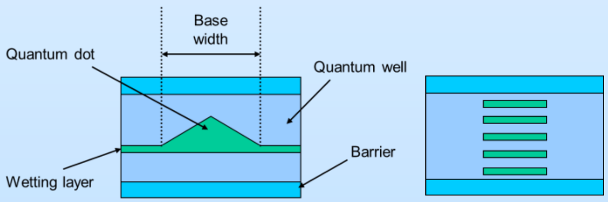
1Kx1K LWIR QWIP

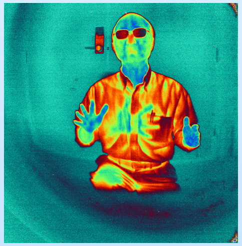


- Multi-band QWIPs

1Kx1K MW/LW Dualband QWIP

- Quantum dots (QDIPs)

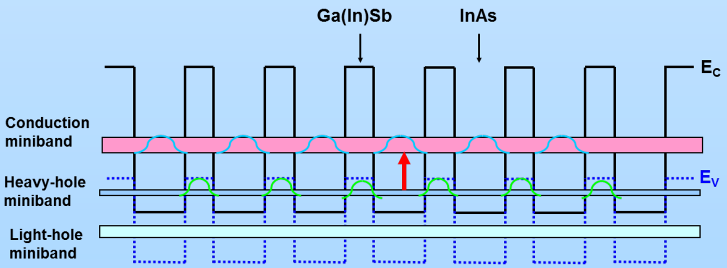


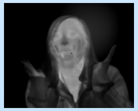


1Kx1K LWIR QDIP

640x512 LWIR QDIP

- Type-II superlattice (T2SL) Barrier IR Detector



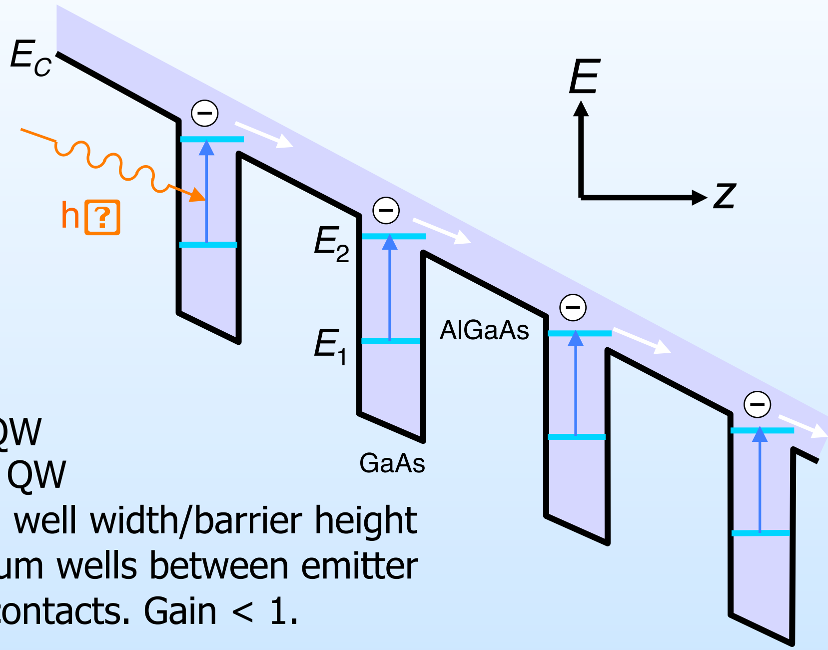


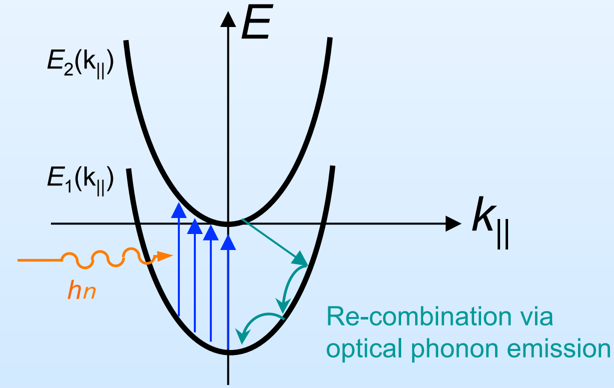
320x256 LWIR T2SL

1Kx1K MWIR T2SL

1Kx1K LWIR T2SL

Quantum Well Infrared Photodetector (QWIP)





- GaAs/AlGaAs QW
- InGaAs/InAlAs QW
- Adjust λ_c thru well width/barrier height
- Multiple quantum wells between emitter and collector contacts. Gain < 1.

- III-V semiconductor FPA "-ility" advantages
  - High operability, uniformity, large-format capability, producibility, affordability
  - **Temporal stability** (low 1/f noise). No need for frequent system recalibration.
- QWIP FPAs successfully deployed in LandSat-8, HyTES
- QWIP Challenges
  - Requires more cooling to control thermal dark current. Higher generation-recombination (G-R) rate from fast LO phonon scattering.
  - Low external QE. Needs light coupling structure for normal-incidence absorption.
    - Being addressed in R-QWIP by K. K. Choi - Resonator pixel concept.

Type-II Superlattice Barrier Infrared Detector

Concept and Theoretical Foundation of Superlattice Infrared Detectors - Caltech Connection

Schulman & McGill (Caltech)
Appl Phys Lett (1979)

MCT superlattice IR detector

Smith, McGill & Schulman (Caltech)
Appl Phys Lett (1983)

Advantages of **MCT superlattices** (SL IR detectors in general)

Smith & Mailhiot (LANL & Xerox)
J Appl Phys (1987)

InAs/GaInSb strained type-II superlattices IR detector

G. C. Osbourn (Sandia)
J Appl Phys (1982)

Strained layer superlattice from lattice matched materials

G. C. Osbourn (Sandia)
J Vac Sci Tech B (1984)

InAsSb Strained layer superlattice for LWIR detector

Darryl Smith: **Caltech** thesis advisor of Gordon Osbourn

Tom McGill: **Caltech** thesis advisor of Joel Schulman & Christian Mailhiot

- Originally proposed for HgTe/CdTe superlattice
  - Key advantages of superlattice for infrared detection pointed out in 1983 MCT SL paper
- Subsequent focus on superlattices based on the antimonides material system
  - Smith & Mailhiot 1987 paper considered the seminal work in T2SL infrared detectors

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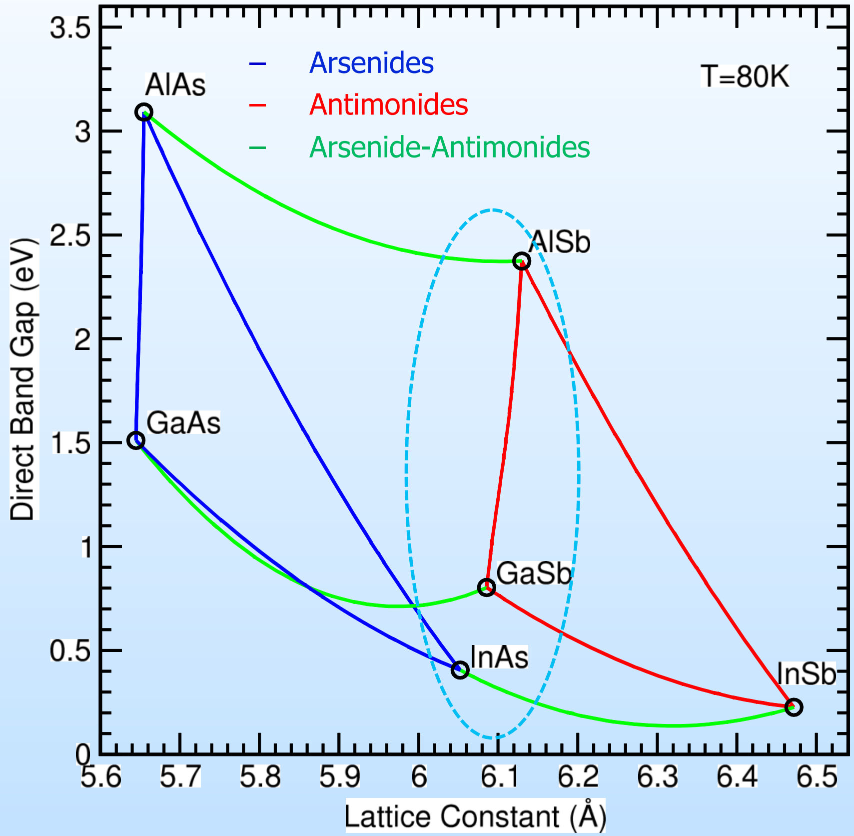
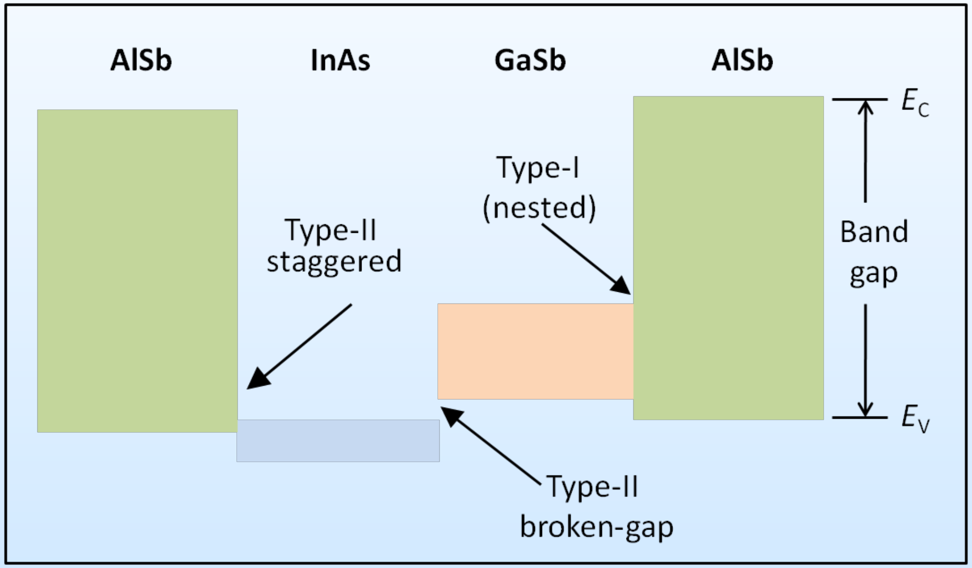
Antimonides Material System for Type-II Superlattices

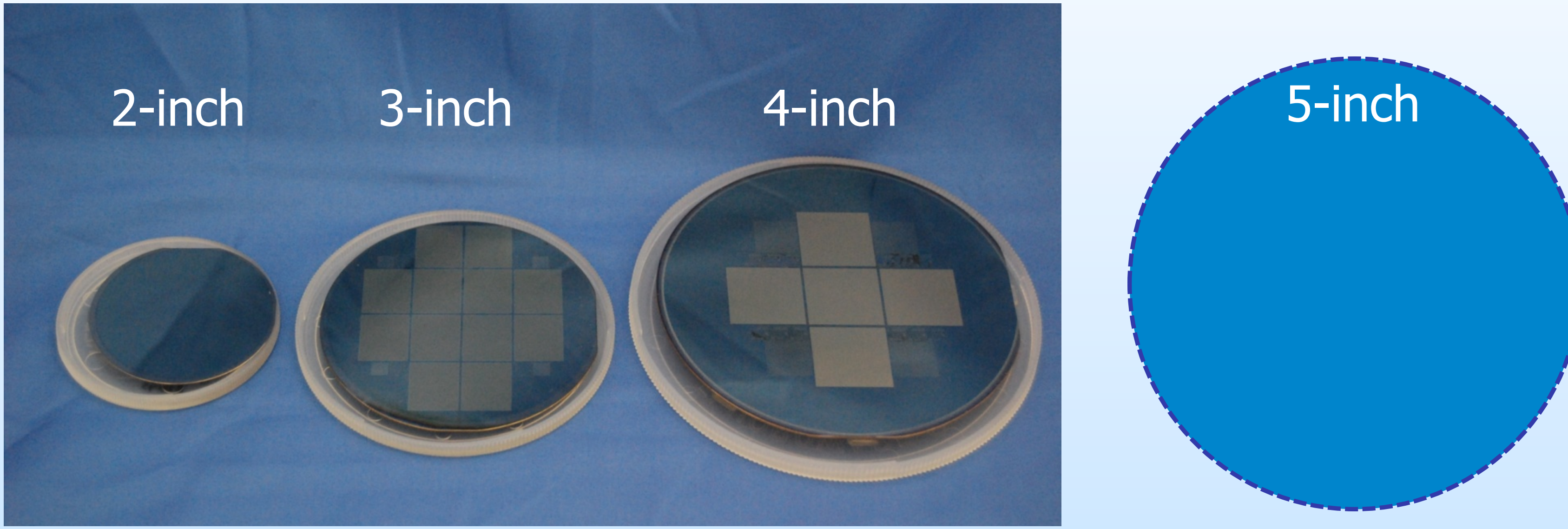




- Material system includes InAs, GaSb, AlSb and their alloys
  - Nearly lattice matched (~6.1 Å)
- Alloys with GaAs, AlAs, and InSb adds even more flexibility
- GaSb (2″,3″,4″, …) and InAs substrates

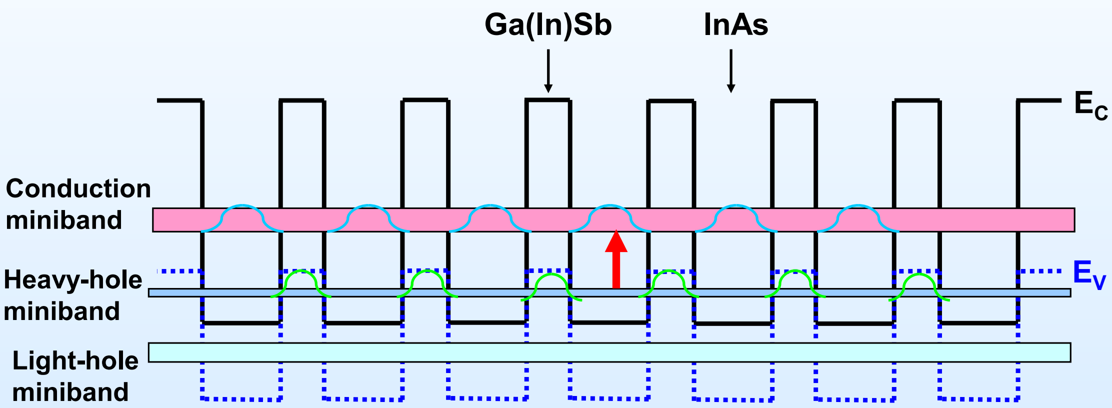
- Three types of band alignments
  - Type-I (nested, straddling)
  - Type-II staggered
  - Type-II broken gap (misaligned, Type-III)
    - Unique among common semiconductor families
    - Overlap between InAs CB and GaSb VB enables interband devices
- Tremendous flexibility in artificially designed materials / device structures

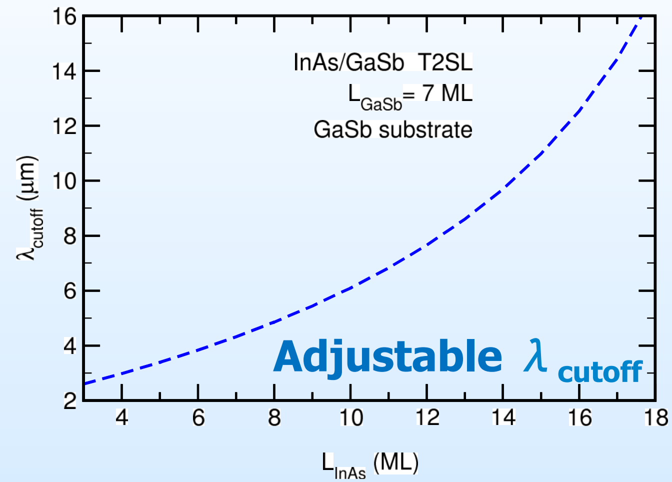
GaSb Substrate Development



- GaSb substrate available commercially in 2, 3, and 4-inch formats
  - Cost: <$1,000 for a 3-inch substrate
  - US and UK suppliers
- Detector results demonstrated on 5 and 6-inch substrates
- Low defect density

Antimonide Type-II Superlattices



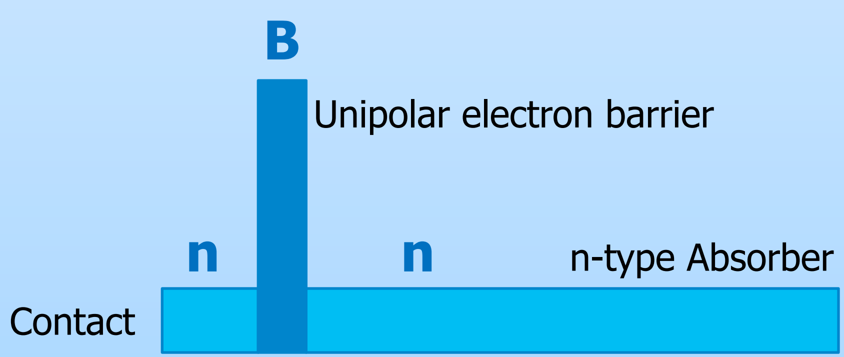


- Band gap can be made smaller than constituent bulk semiconductors
- Continuously adjustable band gap / λ_{cutoff} by varying layer widths
  - Covering SWIR, MWIR, LWIR, and VLWIR
- Sufficiently large absorption coefficient to achieve ample QE
- Dark current reduction in superlattice
  - Can be engineered for Auger suppression
  - Less susceptible to tunneling reduction
- III-V semiconductor challenges
  - Generation-recombination (G-R) dark current due to SRH processes
  - Surface leakage dark current without good passivation

Review Book Chapter:
"Type-II Superlattice Infrared Detectors",
D. Z. Ting, A. Soibel, L. Höglund, J. Nguyen, C. J. Hill, A. Khoshakhlagh, and S. D. Gunapala, Semiconductors and Semimetals **84**, pp.1-57 (2011).

Unipolar Barrier Detector Architecture: Addressing III-V Challenges

- Maimon & Wicks "**nBn** detector, an infrared detector with reduced dark current and higher operating temperature", *Appl Phys Lett*. (2006)
  - 240 citations on Web of Science as of June 2017
    - Arguably the most influential paper in infrared detectors in the past decade
  - The nBn and, in general, unipolar barrier infrared detectors (XBn, pBp, DH, CBIRD, …) have been implemented in a wide variety of materials systems by research groups world-wide.
- The unipolar barrier in nBn blocks electrons but not holes
  - Leads to G-R and surface leakage dark current suppression



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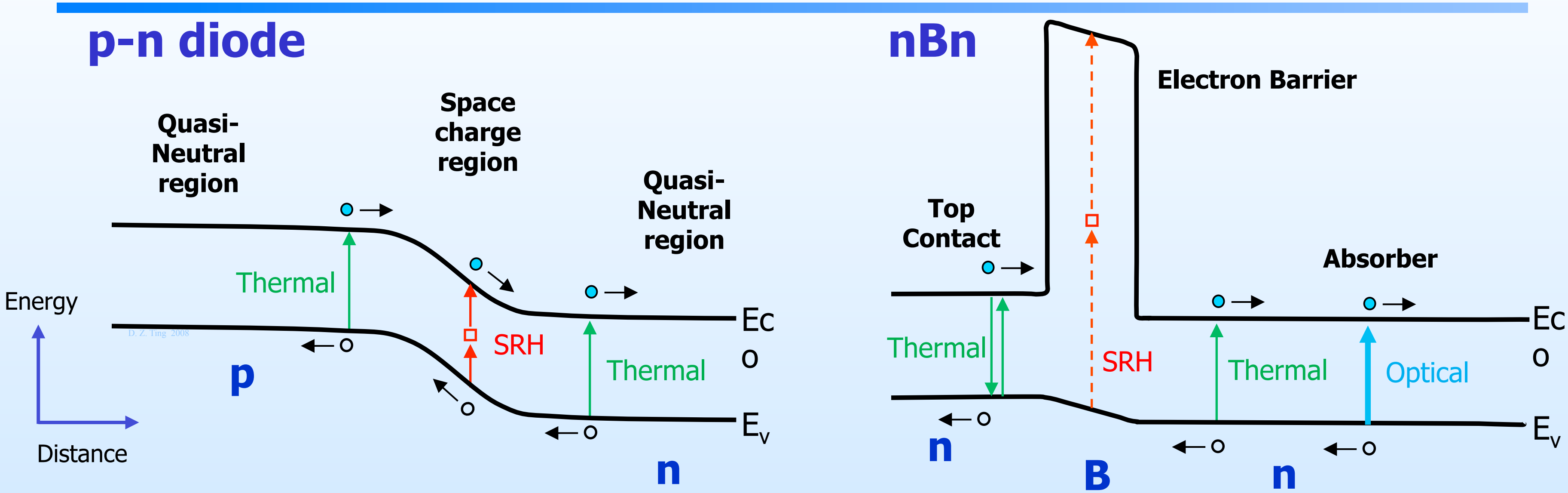
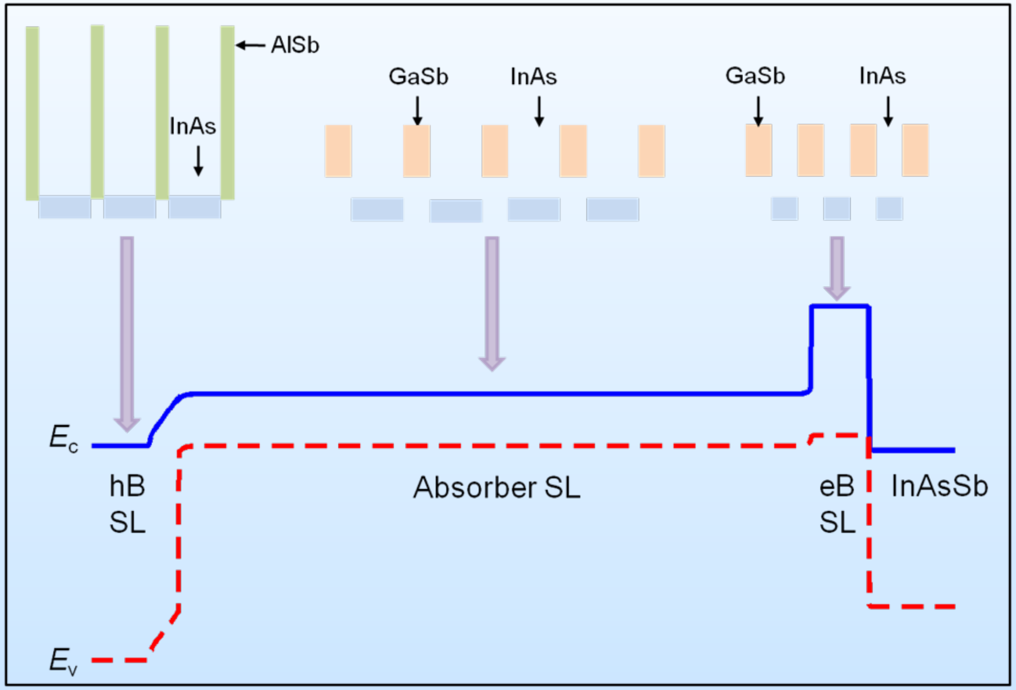
G-R Dark Current Suppression in nBn



- Conventional p-n diode
  - Defects in the band gap leads to SRH processes and G-R dark current in depletion region
  - In many cases (e.g., InAs), surface of p-type layer inverts to n-type, leading to surface leakage current path
- The nBn
  - SRH processes are drastically reduced in wide-band-gap barrier region
  - Suppresses G-R dark current
  - Photocurrent flows un-impeded
  - Barrier also blocks electron surface leakage current
  - Resulting in higher operating temperature / sensitivity

Example of T2SL based Unipolar Barrier Detector: Complementary Barrier Infrared Detector (CBIRD)



- Complementary Barrier Infrared Detector (CBIRD)
- p-type LWIR superlattice absorber
- **unipolar hole barrier** (hB)
  - widely adopted
- **unipolar electron barrier** (eB)
- Both barriers are superlattice-based

- Electron and hole barrier functions
  - Careful control of doping profile and placement of electrical (N-P) junction inside hB suppresses G-R dark current without disrupting the extraction of minority carriers
  - eB suppresses minority carrier injection (exclusion)
  - eB serves as a BSF layer; also suppresses electron surface leakage

Ting et al., *Appl. Phys. Lett.* **95**, 023508 (2009); **102**, 121109 (2013)

CBIRD Device Characteristics

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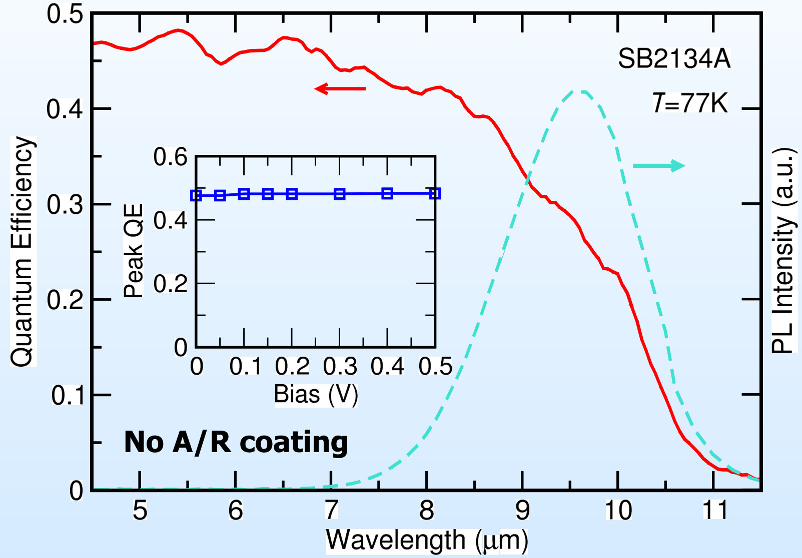
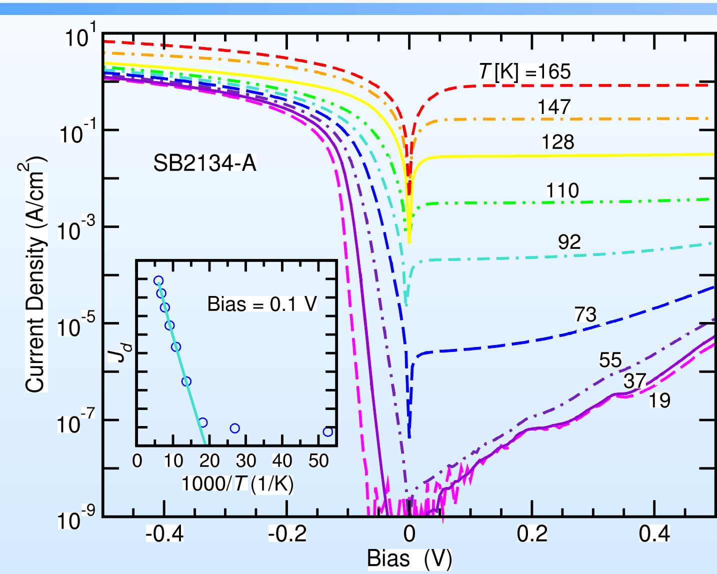


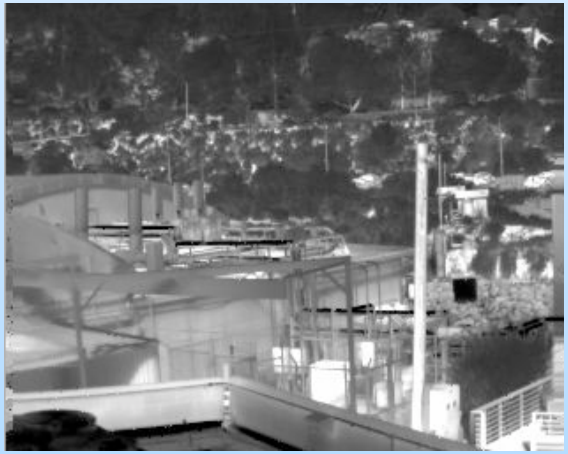
Ting et al., *Appl. Phys. Lett.* **102**, 121109 (2013)



- Discrete 200 µm × 200 µm devices
- 9.8 mm cutoff (50% peak QE)
- QE=40% (λ =8.5 µm, no AR coating)
- Zero-bias turn-on
- J_d(0.1V, 77K) = 0.8x10^{-5} A/cm^2
- Near-diffusion-limited dark current behavior to below 77K

Additional studies:

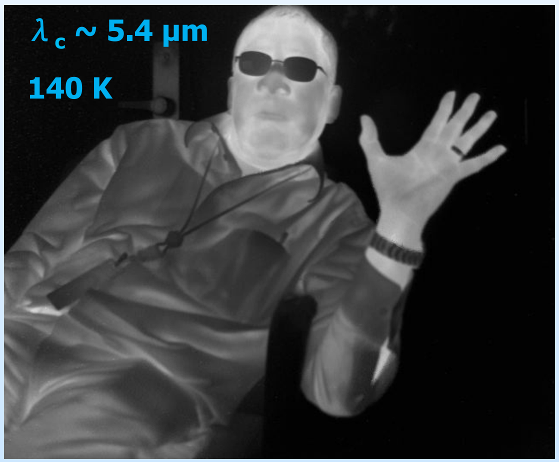
- Gain and noise: Soibel et al., *Appl. Phys. Lett.* **96**, 111102 (2010)
- Proton radiation effect: Soibel et al., *Appl. Phys. Lett.* **107**, 261102 (2015)



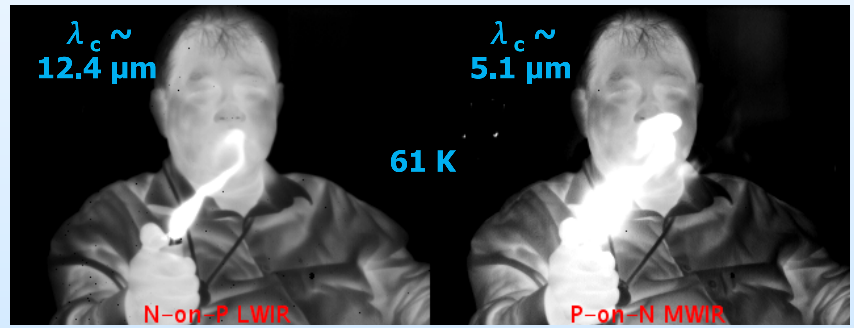
ISC 0903 DI, 320x256, 30 mm pitch
NEDT – 18.6 mK (f/2, 300K)
[Rafol et al., *JQE* **48**, 878 (2012)]

JPL T2SL Barrier Infrared Detector (BIRD) FPAs

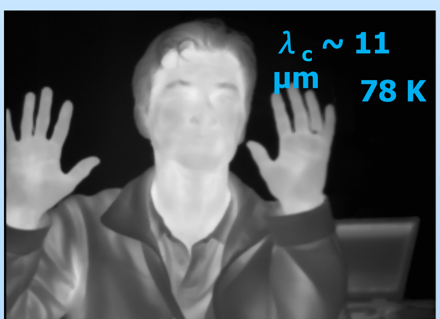
- Successfully implemented FPAs with a variety of λ_{cutoff} and formats
- High operability/uniformity routinely achieved, MWIR to VLWIR.



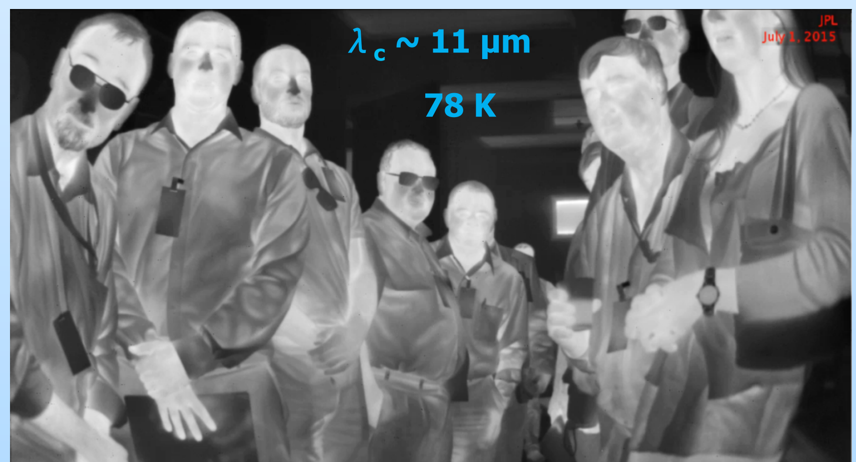
99.1% operability (640 x 512)



99.94% / 99.95% operability (320 x 256 switchable)



99.8% operability (320 x 256)



99.4% operability (1280 x 720 format)

Ting et al., *Proc SPIE* **10177**, 101770N (2017)

T2SL BIRD FPA Development for Earth Science Applications

- CubeSat Infrared Atmospheric Sounder (CIRAS)
  - High Operating Temperature (HOT) BIRD MWIR (λ_{cutoff} ~5.3 µm) FPA

- Hyperspectral Thermal Emission Spectrometer (HyTES)
  - LWIR (λ_{cutoff} ~12 µm) BIRD FPA to replace existing QWIP FPA
  - Higher QE, lower dark current, <u>higher operating temperature</u>
  - Retaining uniformity, operability, temporal stability …
- SLI-T: Long Wavelength Infrared FPA for Land Imaging
  - VLWIR (λ_{cutoff} ~13 µm) BIRD FPA
  - Goal: Significantly higher operating temperature than QWIP FPA
  - Plans for demonstrating a small sensor core as well as a very large format FPAs in collaboration with industry partner

Summary

- Recent advances in III-V semiconductor IR detectors
  - Type-II superlattice (and bulk alloy) provides continuously adjustable cutoff wavelength from SWIR to VLWIR
  - Unipolar barrier device architecture enhances detector performance

- MWIR to VLWIR type-II superlattice barrier infrared detector (BIRD) FPAs routinely achieve high operability and uniformity

- Meeting a variety of Earth Science infrared FPA needs