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Development of Bandstructure Engineered Type-II Superlattice Antimonide Avalanche Photodiodes (BETA-APD) to Support Short-Wavelength Infrared Lidar Instruments

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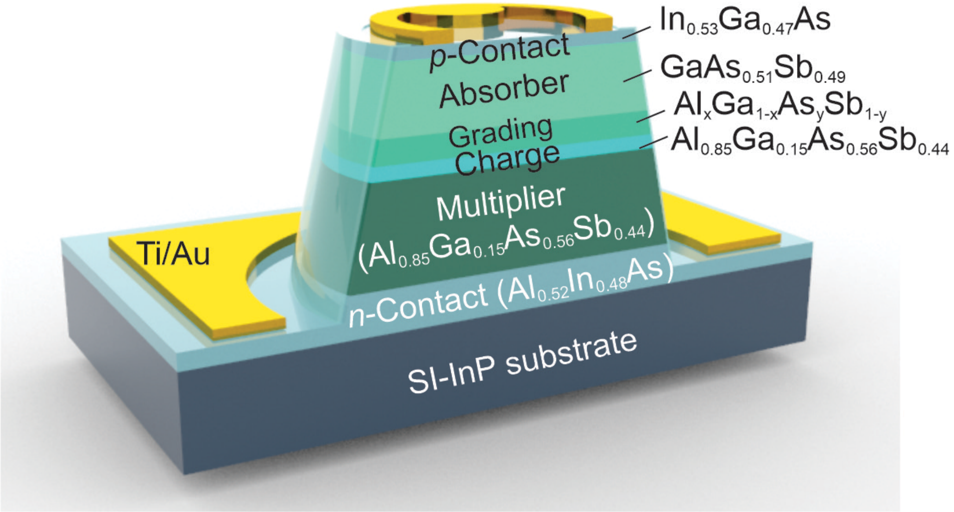
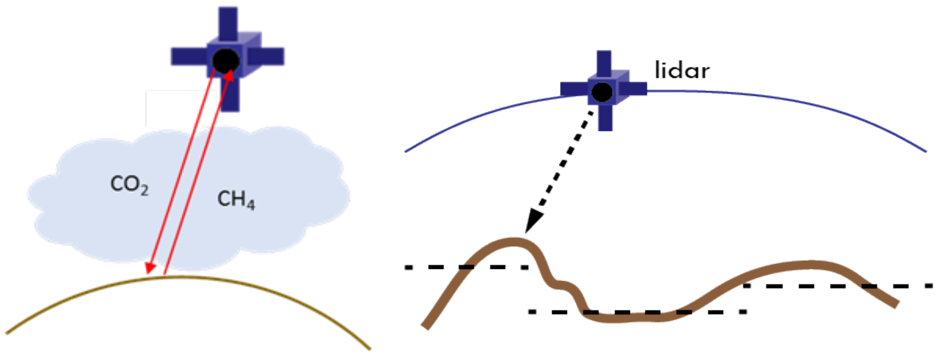
Introduction

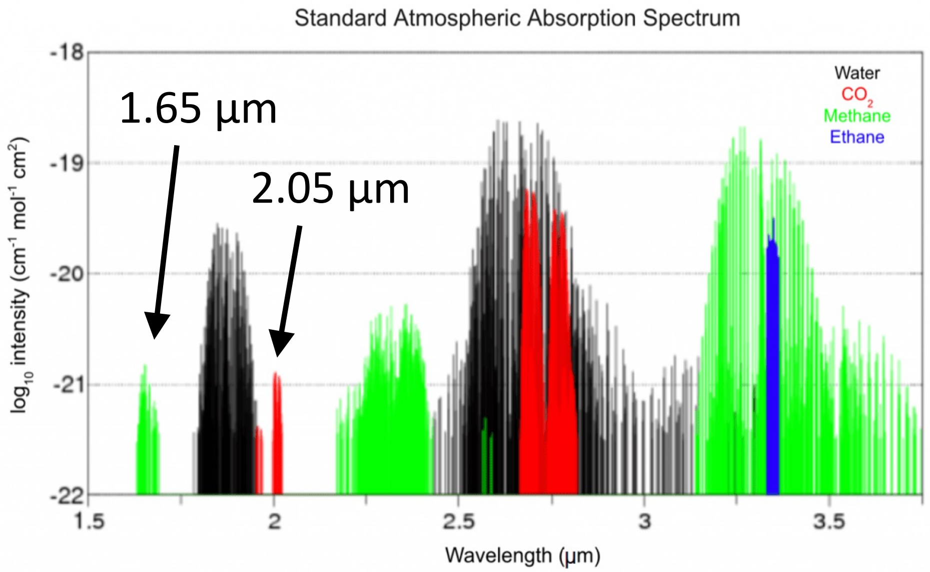
- Bandstructure Engineered Type-II Superlattice Antimonide Avalanche PhotoDiodes (BETA-APD)
- Develop short-wave infrared (SWIR) detectors (1-2 µm)
  - Enhance performance
    - High gain, high bandwidth
    - Low excess noise, low dark current
  - Enable high operating temperature (> 200 K)
    - Reduce SWaP of SWIR receivers/imagers
  - Mature from TRL 2 to 4
  - Funded under ACT 2020 (Amber Emory)



Mission Relevance

- Relevance to Earth science
  - Greenhouse gas sensing (CH_4, CO_2)
  - Topographic imaging
  - Wind sensing
- Two detector formats
  - Single element – GHG lidar
  - Small format (4x4) – precursor to large format array (imaging, hyperspectral, etc.)

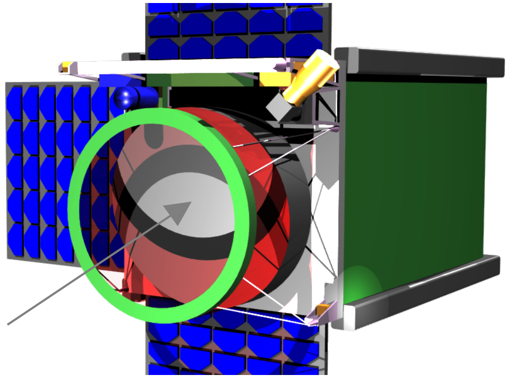




https://www.xenics.com/importance-of-methane-detection-and-the-use-of-infrared-to-detect-methane-leak/

Comparison to the State-of-the-Art

- Current SWIR detector technologies have limitations
  - HgCdTe: excellent performance, requires cryocooling (T_{op} ~100 K)
  - InGaAs APD: high operating temperature, high excess noise
- BETA-APD seeks to address these limitations
  - Previous APD development has demonstrated excess noise factor <2
  - High operating temperature reduces SWaP-C by eliminating cryogenic cooling
    - Reduce size and weight by two orders of magnitude
    - Reduce power by factor of 3-4



Key Advantages of BETA-APD

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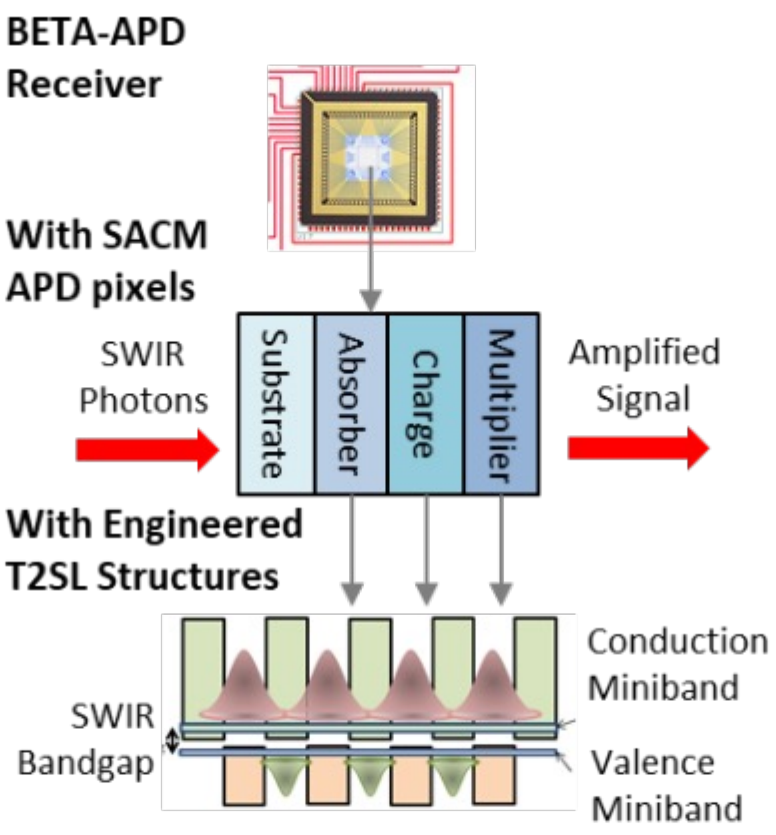
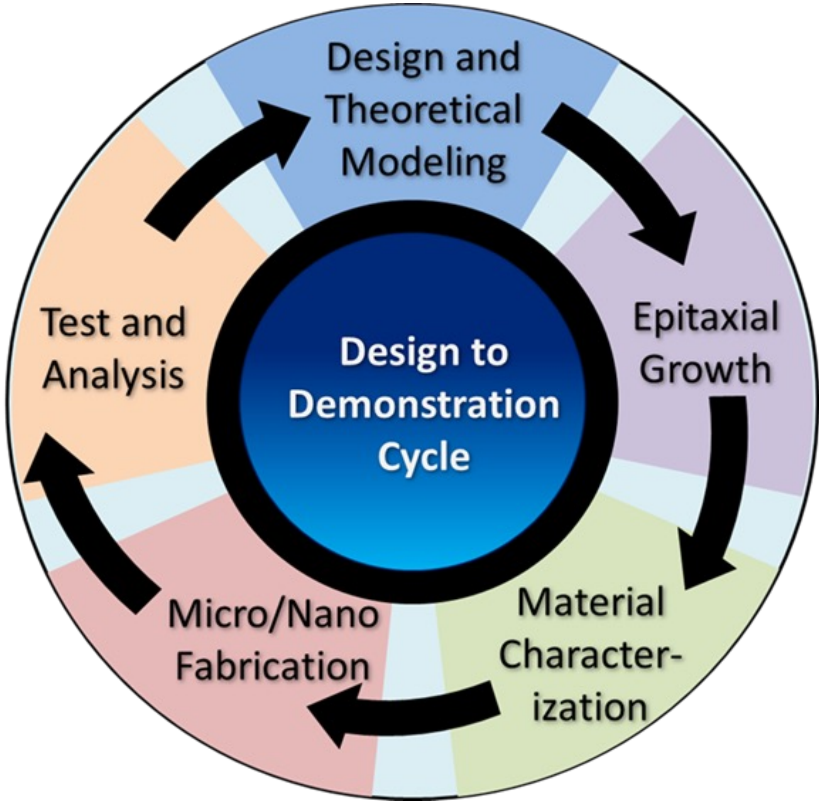
- Leverages advances in superlattice technology
  - Separate Absorption, Charge, Multiplication (SACM) structure enables independent optimization each layer
- Employs industry standard III-V materials on standard InP substrates
  - Rapid transition to manufacturing
- Builds on recent advances in APD performance
  - Low excess noise, high gain



Research Plan

- Design, grow, and test APD materials
  - Theoretical simulation by C. Grein (UIC)
  - Molecular Beam Epitaxy at OSU SEAL facility
- Fabricate and test detector devices
  - Design and fab by SK Infrared LLC
  - Use clean room facilities at OSU Nanotech West
- Independent device testing by NASA
  - Xiaoli Sun (GSFC) – general detector performance, benchmark against MCT
  - Amin Nehrir (LaRC) – swap out single element detector in lidar testbed



Separate Absorption, Charge and Multiplication (SACM)

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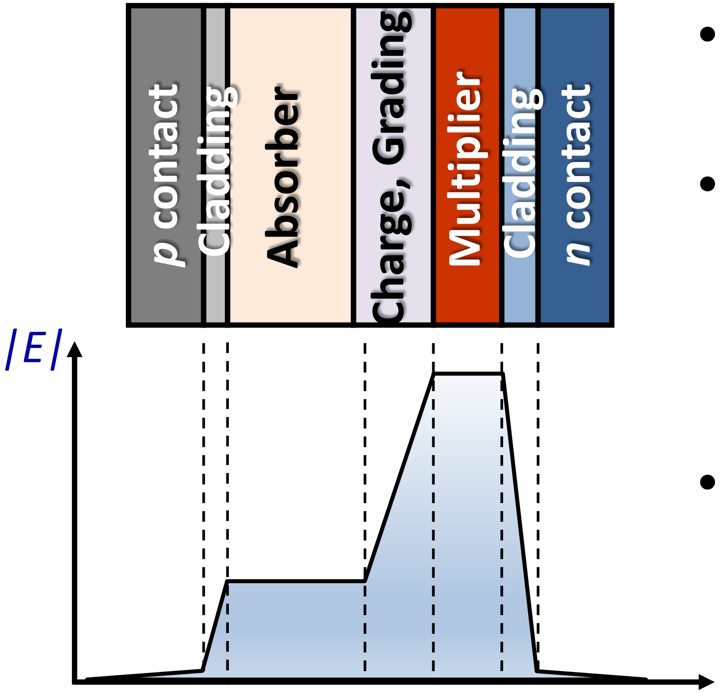
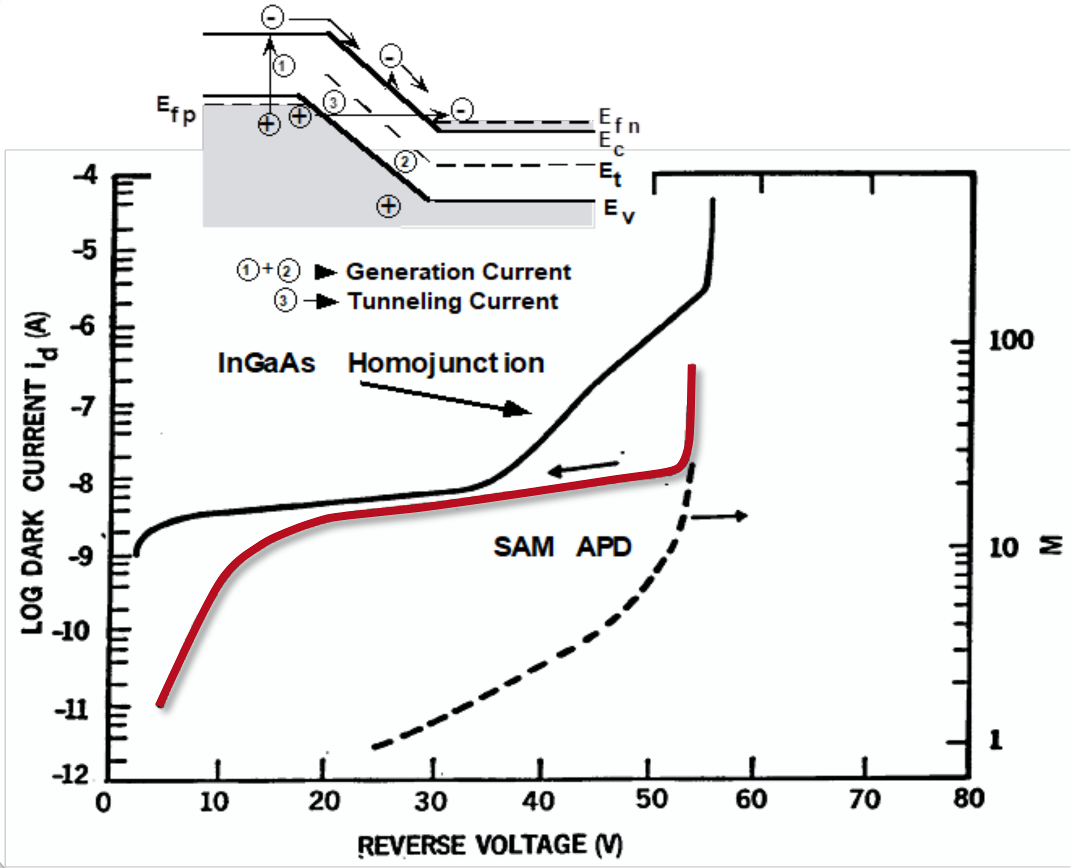


- Good absorber → High QE
- Good Multiplier →
  - High gain (M)
  - Low excess noise (F(M))
- Good Charge and Grading →
  - Low dark current (I)
  - No tunneling in Absorber



http://leos.unipv.it/slides/lecture/JPRD_Pavia_2003.pdf
Jones, A. H. (2020). Doctoral dissertation, University of Virginia.

Material Considerations: Bandgap, Lattice Constant, Substrates

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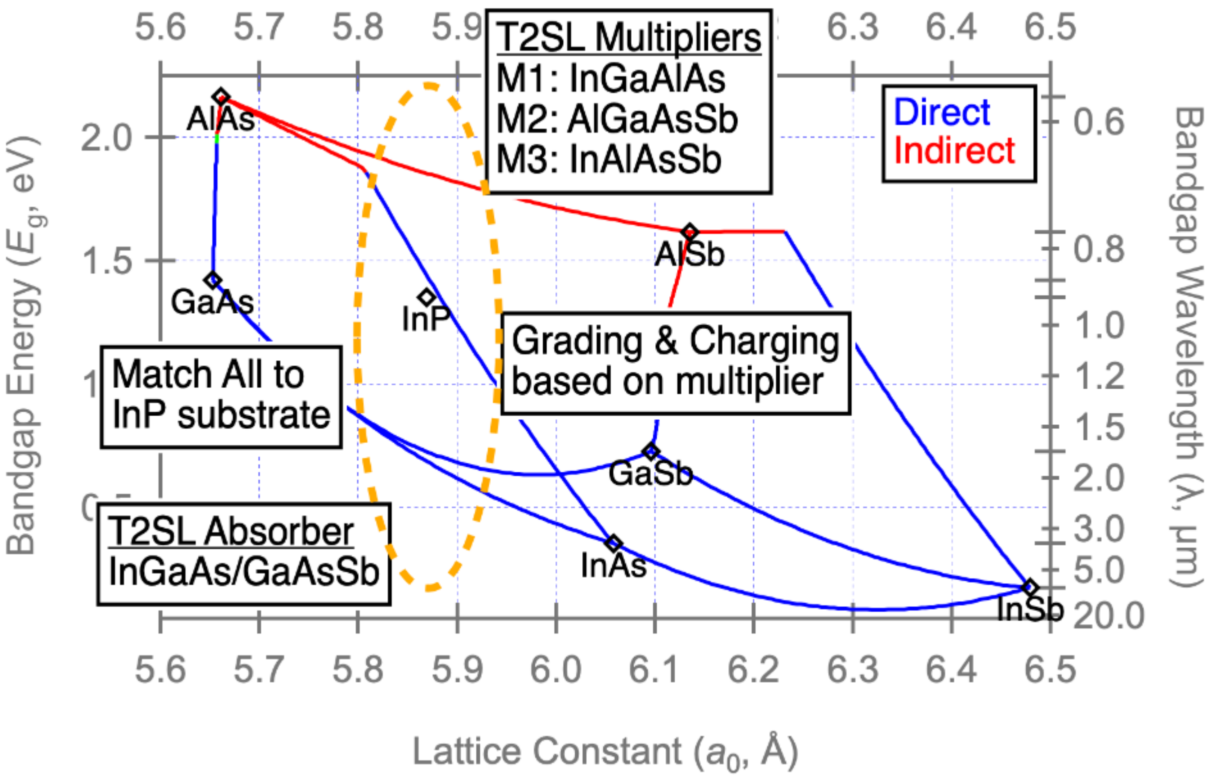

- SLS: Strained Layer Superlattice
- DA: Digital Alloys
- T2SL: Type II Superlattice

- **Choice of Substrates (InP, InAs and GaSb)**
  - InP is available in large area (6-inch), is transparent in the SWIR, and facilitates scalability and manufacturability
  - InAs has bandstructure similar to HgCdTe and could lead to high gains
  - GaSb based APDs have potential to reach MWIR/LWIR

Modeling of Impact Ionization Properties

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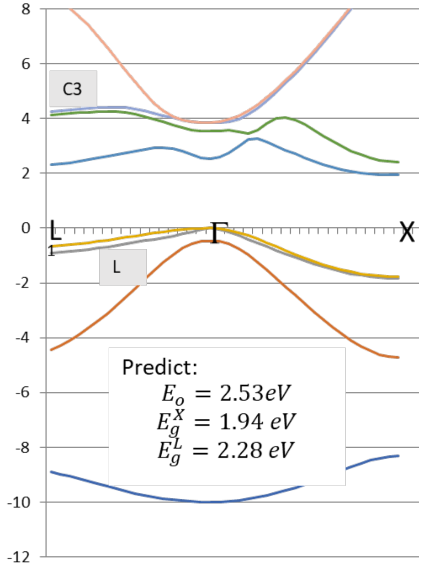
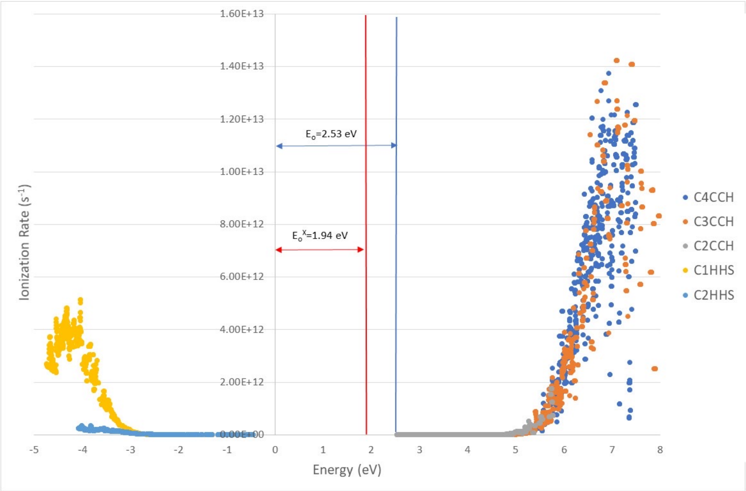
- Methods
  - Full zone electronic band structures using empirical pseudopotential method plus spin-orbit interactions
  - Computed $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ and $Al_{0.79}In_{0.21}As_{0.74}Sb_{0.26}$ using virtual crystal approximation
  - Predict hot carrier impact ionization rates in those band structures
  - Predict impact ionization coefficients for transport in those band structures

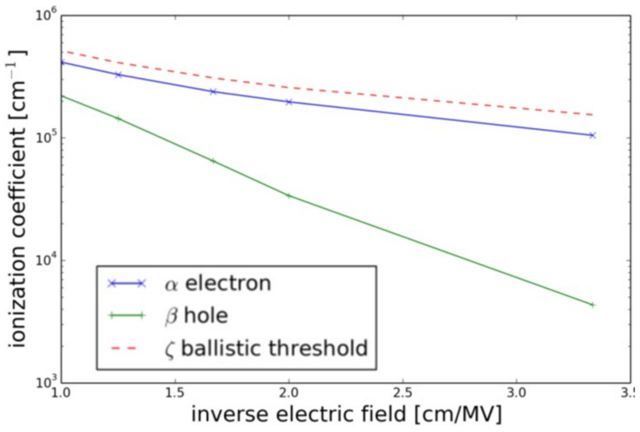
Electronic Band Structure



Impact Ionization Rates



Impact Ionization Coefficients



Calculations predict $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ on InP to be good electron APD

(Modeling by Prof. Grein, University of Illinois)

Design, Growth and Fab of GaAsSb/AlGaAsSb SACM

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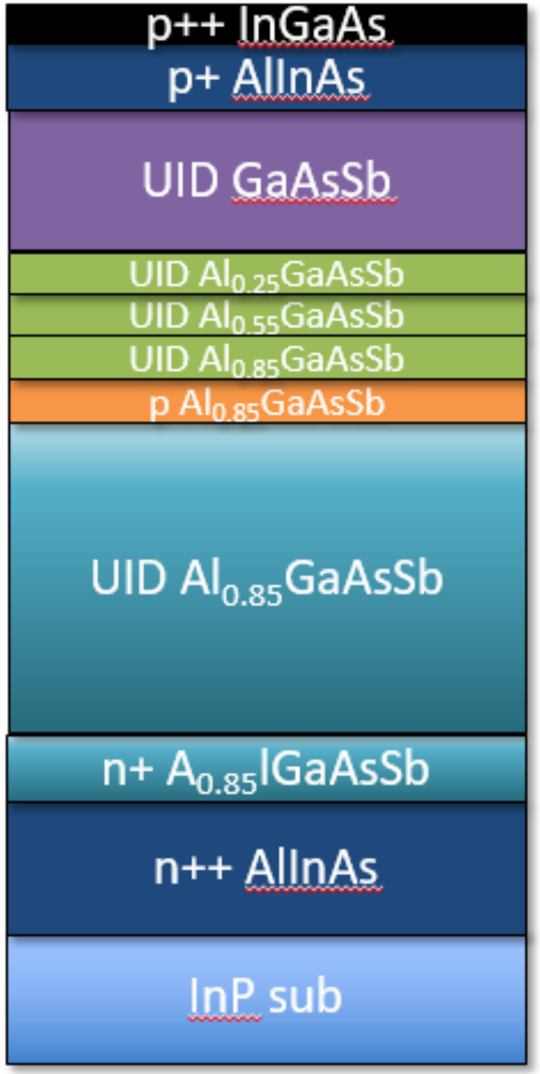

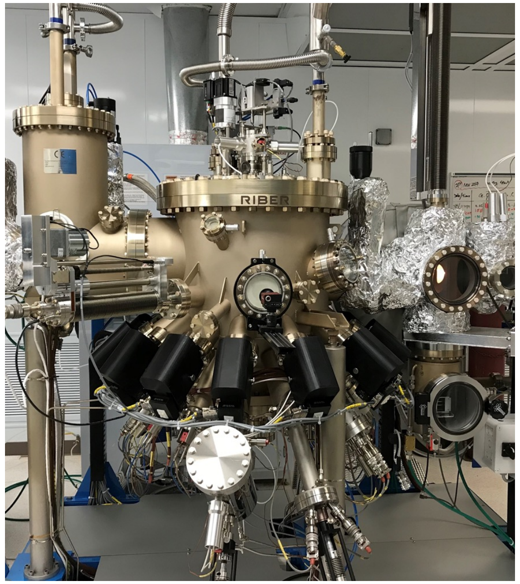

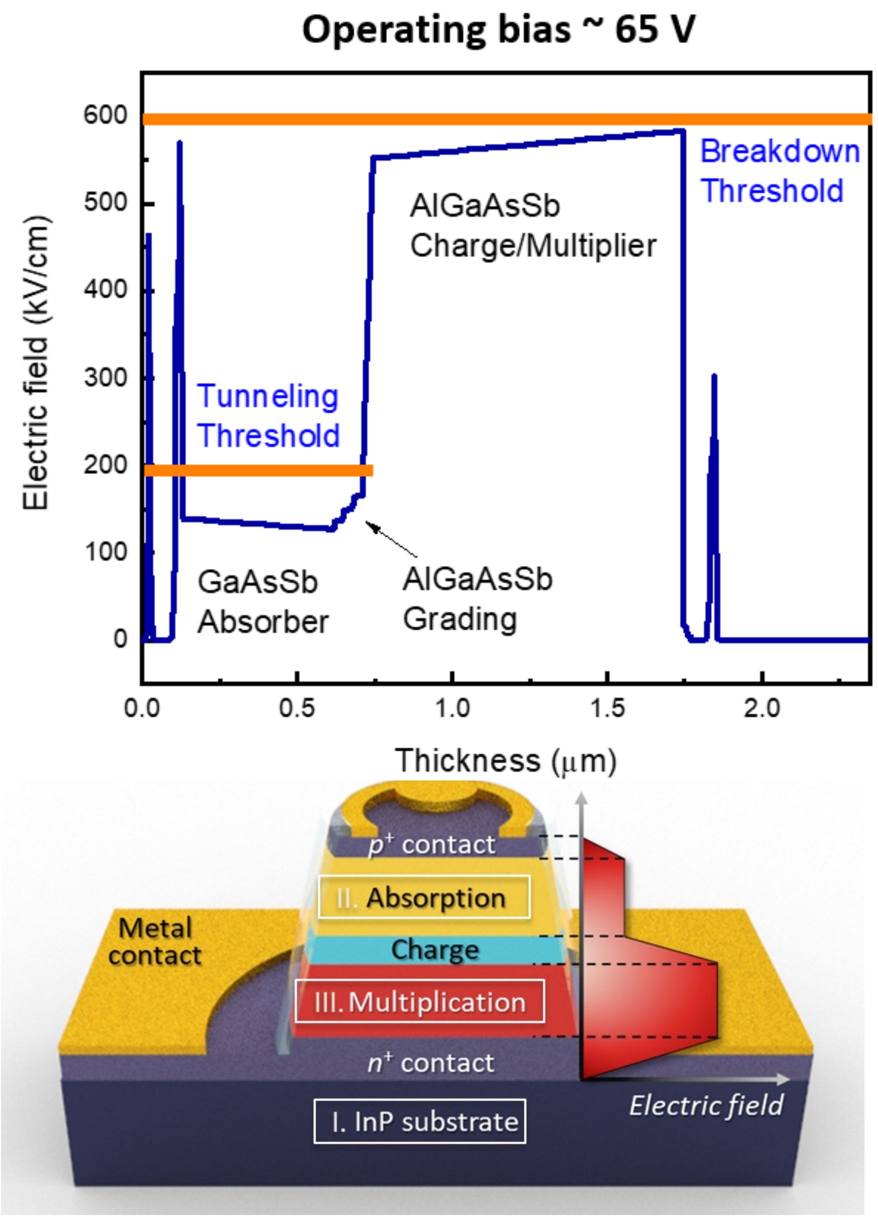

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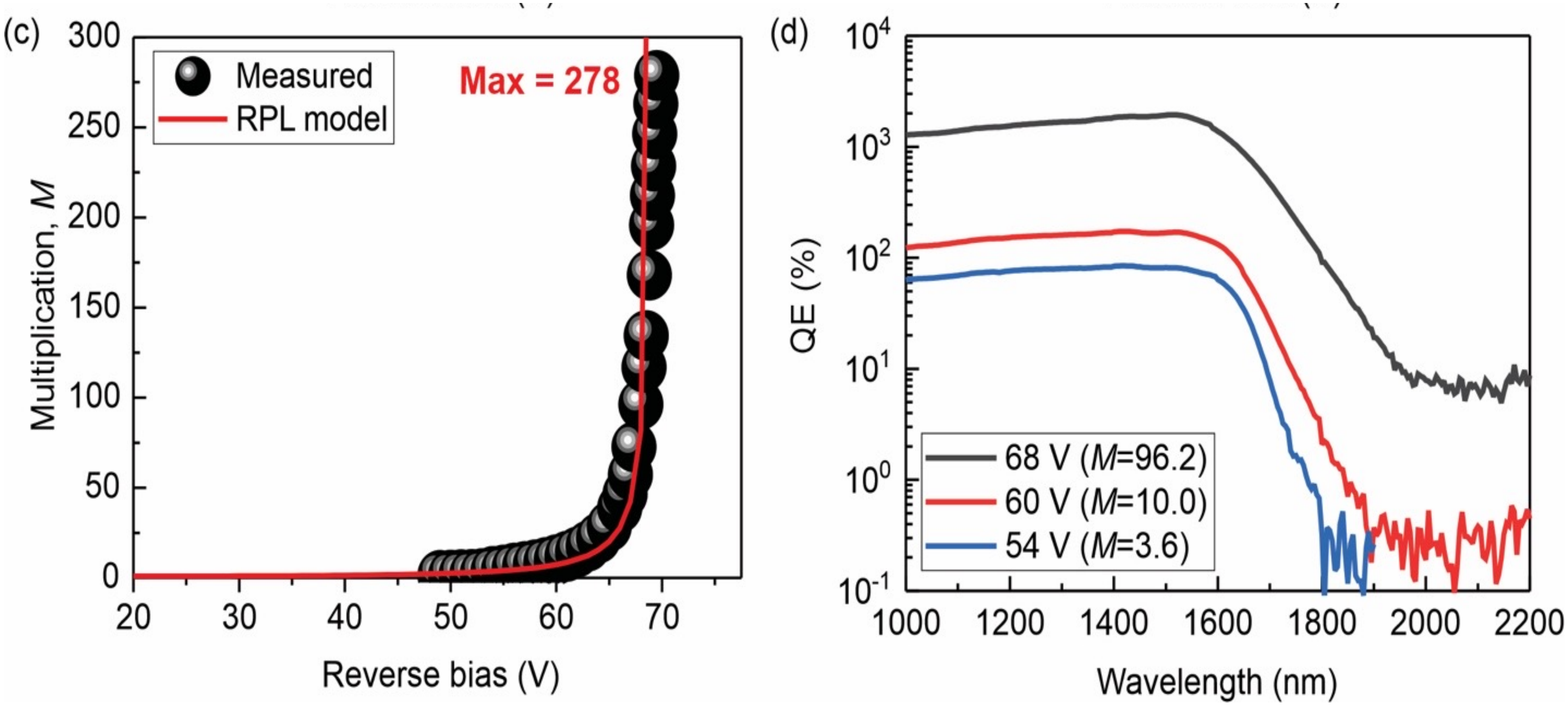
Multiplication and Spectral QE



- Maximum gain ~ 278 at 69.5 V
- Maximum measurable QE was ~ 2270 % at 68 V

Reading Reference

Research Article Vol. 10, No. 2 / February 2023 / Optica 147

OPTICA

High gain, low noise 1550 nm GaAsSb/AlGaAsSb avalanche photodiodes

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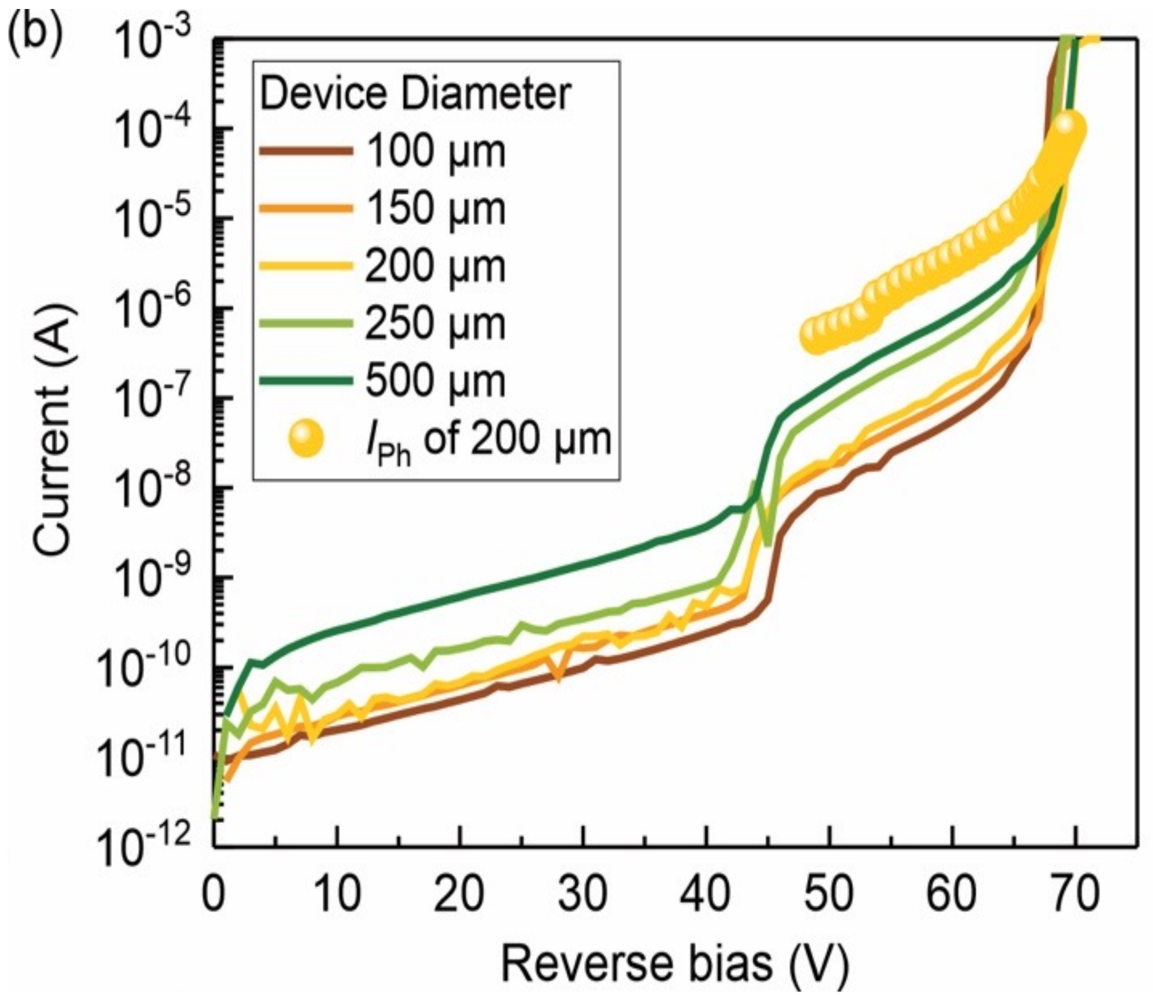
Received 29 September 2022; revised 27 November 2022; accepted 6 December 2022; published 24 January 2023

High sensitivity avalanche photodiodes (APDs) operating at eye-safe infrared wavelengths (1400–1650 nm) are essential components in many communications and sensing systems. We report the demonstration of a room temperature, ultrahigh gain ($M = 278$, $\lambda = 1550$ nm, $V = 69.5$ V, $T = 296$ K) linear mode APD on an InP substrate using a $GaAs_{0.5}Sb_{0.5}/Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ separate absorption, charge, and multiplication (SACM) heterostructure. This represents ~10× gain improvement ($M = 278$) over commercial, state-of-the-art InGaAs/InP-based APDs ($M \sim 30$) operating at 1550 nm. The excess noise factor is extremely low ($F < 3$) at $M = 70$, which is even lower than Si APDs. This design gives a quantum efficiency of 5935.3% at maximum gain. This SACM APD also shows an extremely low temperature breakdown sensitivity (C_{bd}) of ~11.83 mV/K, which is ~10× lower than equivalent InGaAs/InP commercial APDs. These major improvements in APD performance are likely to lead to their wide adoption in many photon-starved applications.

https://doi.org/10.1364/OPTICA.476963 S. Lee et al https://doi.org/10.1364/OPTICA.476963 (2023)

Dark and Photocurrent with 1.55 µm Illumination



- Punch through at 45 V and breakdown at 70 V
- Dark IV does not completely scale with area
- Further reduction in dark current is needed

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Comparison - Current

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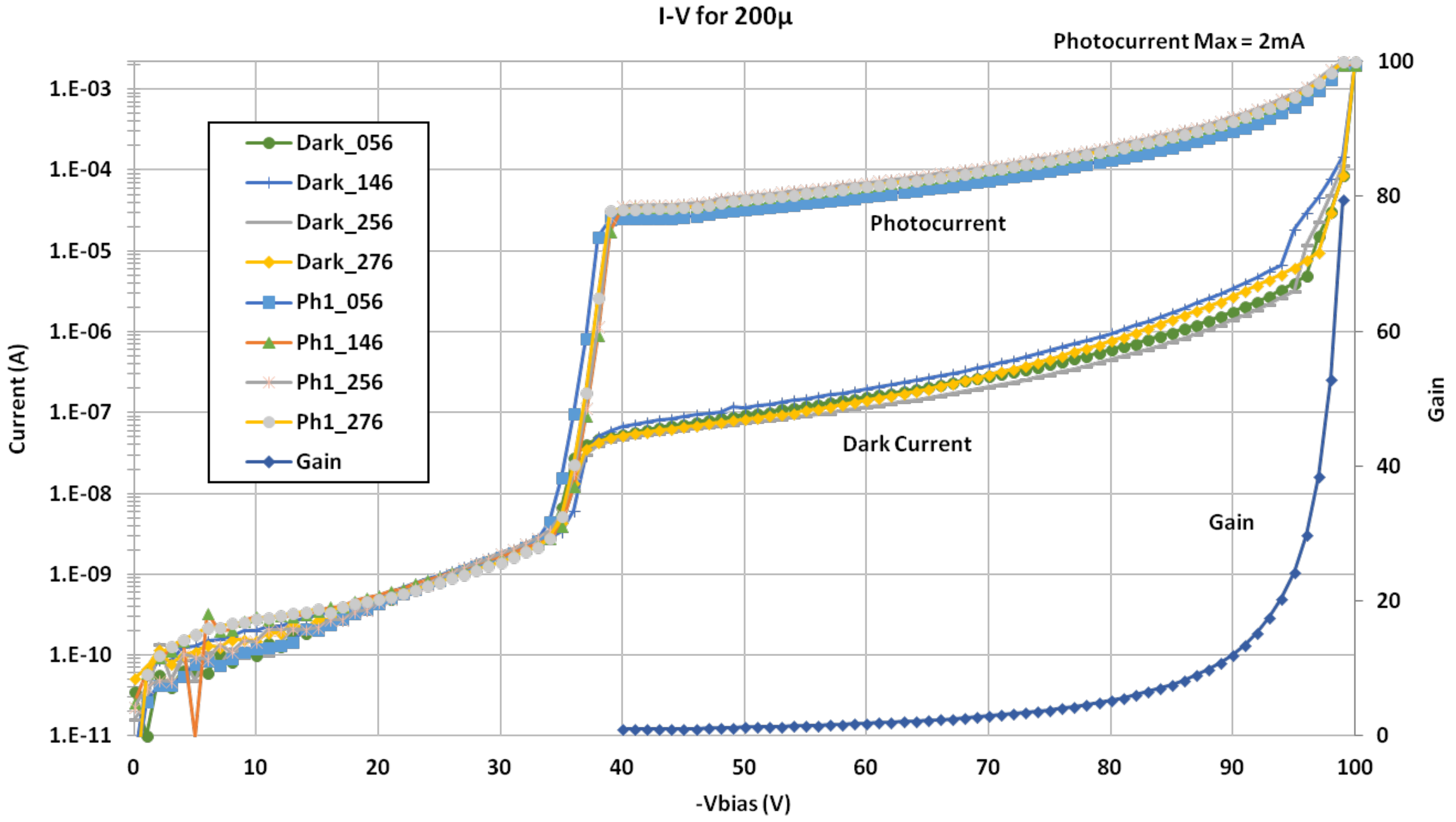

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Target Specifications

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Key Question: How to rapidly advance the TRL level of this technology and make it better than SoA (Laser Components) for operation at 1.65 µm (incorporation into methane lidar testbed)

Detector Characteristic	BETA-APD Design Target	Laser Components APD
Large single element detector	200 µm diameter	205 µm diameter
Operating Temperature (T_{op})	> 200 K	295 K
Linear gain	≥ 100	10
Responsivity	> 0.94 A/W (M=1)	0.94 (M=1)
Excess noise factor	≤ 3.2 (M=30)	≤ 3.2 (M=10)
Dark current	< 25 nA (M=30)	< 25 nA (M=10)
Noise Equivalent Power	< 0.02 pW/Hz$^{1/2}$ (M=30)	< 0.07 pW/Hz$^{1/2}$ (M=10)
Bandwidth	> 1 GHz (M=30)	> 1 GHz (M=10)

Summary and Next Steps

- Summary of Progress
  - Developed a fabrication process ready for pre-production of 1.65 μm APDs
    - – Maximum useful gain is 73x for low light levels at room temperature
  - High operating bias and dark current observed in the GaAsSb/AlGaAsSb SACM APD
- Next steps
  - Execute test and measurement plan for benchmarking APD performance
  - Investigate source of dark current using IVT measurements
  - Redesign, grow epitaxial structure and fabricate single element detectors to reduce operating bias, punchthrough and dark current
  - Develop small format 4x4 mini-arrays to test spatial uniformity
  - Continue to develop 2 μm APD (InAs-based detectors)