Antimonide-Based Planar Avalanche Photodiodes on InP Substrates for Short Wave Infrared Applications

Student: Mariah Schwartz

Student Email: Schwartz.1945@buckeyemail.osu.edu

Faculty: Dr. Sanjay Krishna

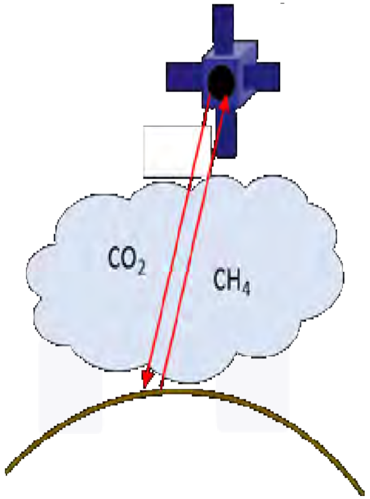
Faculty Email: Krishna.53@osu.edu

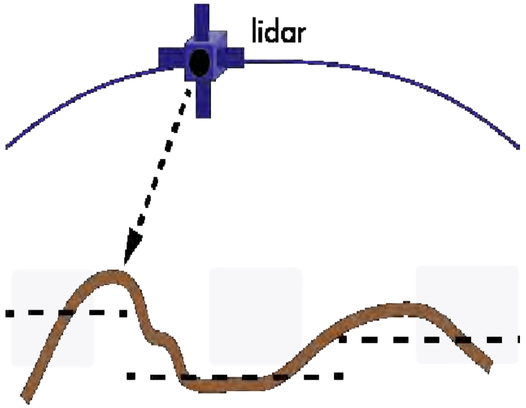
AFRL Sponsor: Dr. Charles Reyner

AFRL Directorate: AFRL/RY

PA #: AFRL-2023-5224

Background and Motivation





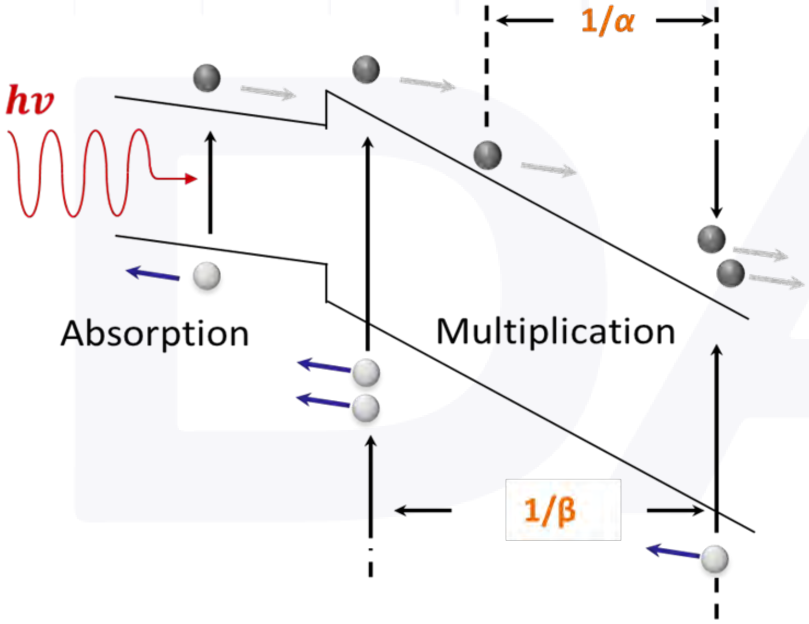
- 1-3 µm Remote Sensing at ≥ 200 K
  - Greenhouse gas imaging
  - Topographic imaging
  - Defense applications
- Current applications are motivated to reduce factors that increase the overall SWaP-C of a lidar system and significant cryogenic cooling is a contributor
- Linear mode Avalanche photodiodes (APDs) have demonstrated promising behavior due to their internal gain from impact ionization but further research is necessary to drive down the dark current mechanisms at high operating temperatures that impact the SWaP-C
  - Sb-based III-V alloy APDs may provide a solution to this with current investigations into mitigating the surface dark current

[1-5]

SWaP-C: Size, weight, power and cost

Linear Mode APDs and Their Figures of Merit

Impact Ionization →Internal Gain



Important Equations

Signal-to-Noise Ratio (SNR)

$$SNR = \frac{(I_{ph}M)^2}{2q\left(I_{ph} + I_{dark}\right)BF(M)M^2 + \sigma_{circuit}^2}$$

Excess Noise Factor

$$F(M) = kM + (1 - k)\left(2 - \frac{1}{M}\right)$$

Keys to "High Performing" APDs:

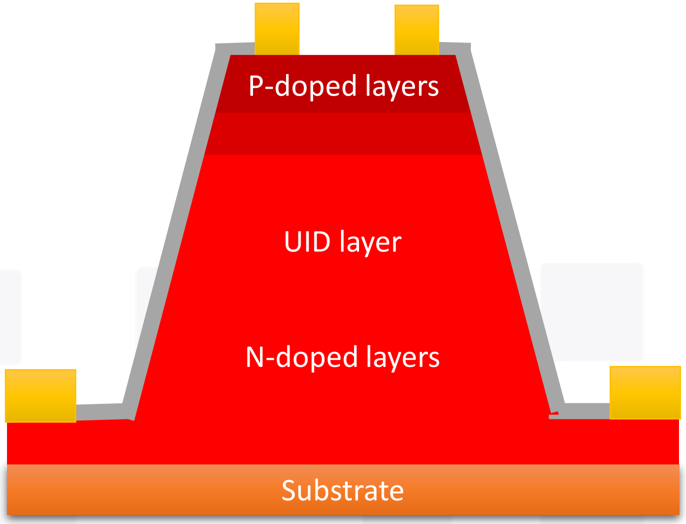
- Quantum Efficiency, QE ↑
- Multiplication Gain (M) ↑
- Dark Current (I_{dark}) ↓
- Excess Noise Factor F(M) ↓

Attractive for photon starved applications due to impact ionization resulting in gain but comes with the tradeoff of noise that must be mitigated to achieve high performance

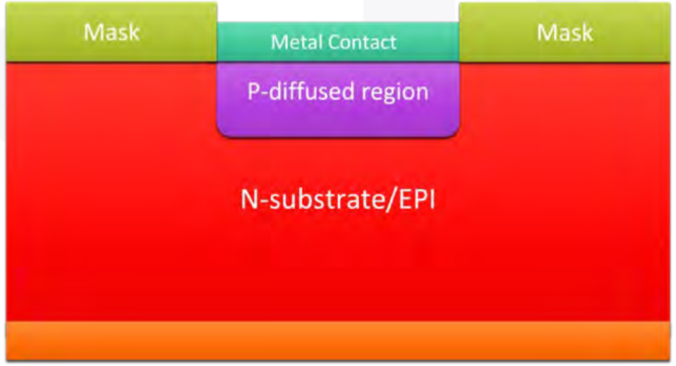
[6-8]

Defining the Dark Current Problem

- Dark current is component that contributes to the noise of a detector, thereby decreasing its overall signal-to-noise ratio (SNR)
  - Dark current can be broken into two components:
    - Bulk dark current: originates from material selection and the quality of its growth (presence of defects, etc)
    - Surface dark current: originates from the fabrication processing
- While much research has focused on the growth of materials to mitigate bulk dark current, it is likely that it cannot be removed entirely and there is benefit to explore the surface dark current portion. This is especially critical as devices get smaller.
- Since surface dark current is introduced during the fabrication processing, namely etching the material to form mesa devices, it is possible in theory to remove all surface dark current by forming devices without etching
- This is the motivation behind developing diffused planar APDs



Mesa architecture devices



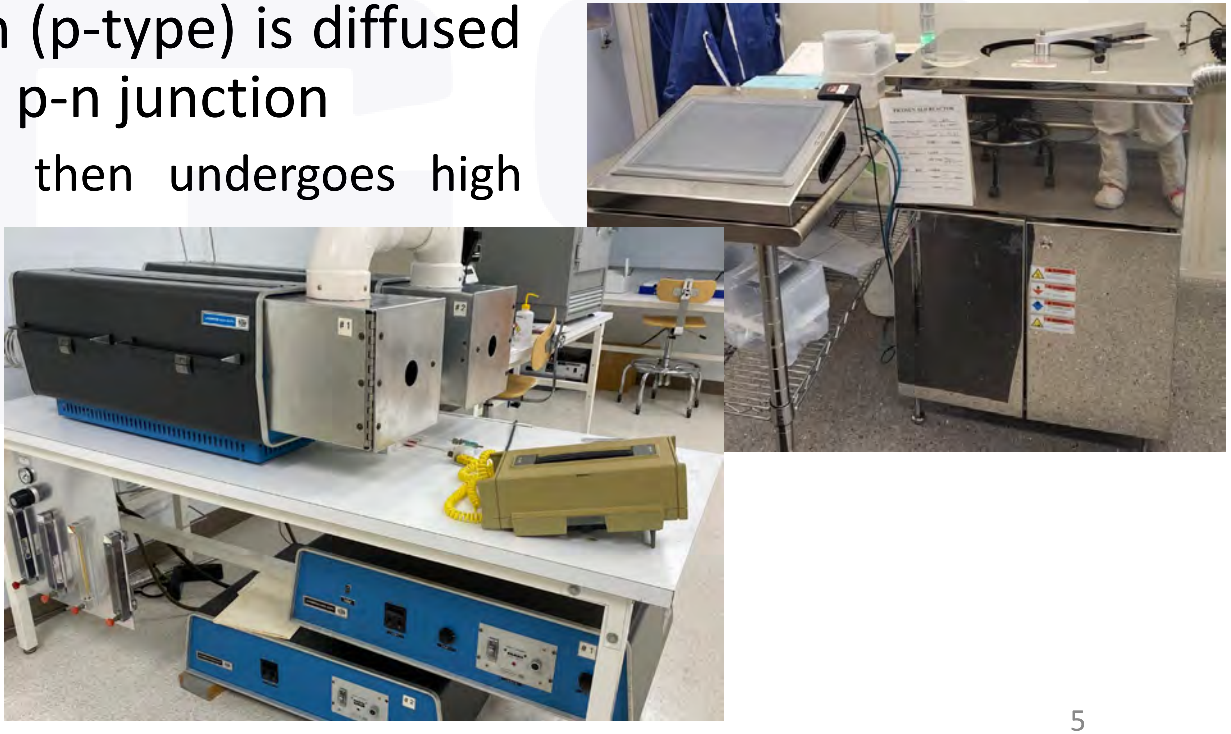
Planar architecture devices

[9-10]

Planar APDs and Novel Diffusion Processing


https://imr.osu.edu/research/core-facilities/nanotech-west-laboratory/

- Planar APDs are unique as they do not require etching which introduces surface dark current and thus can influence premature breakdown
- Recently, our work has centered on the development of planar APDs through diffusion processing whereby Zn (p-type) is diffused into a n-type Sb-based material stack to form a p-n junction
  - ZnO is deposited onto the material stack and then undergoes high temperatures to diffuse the Zn into the structure



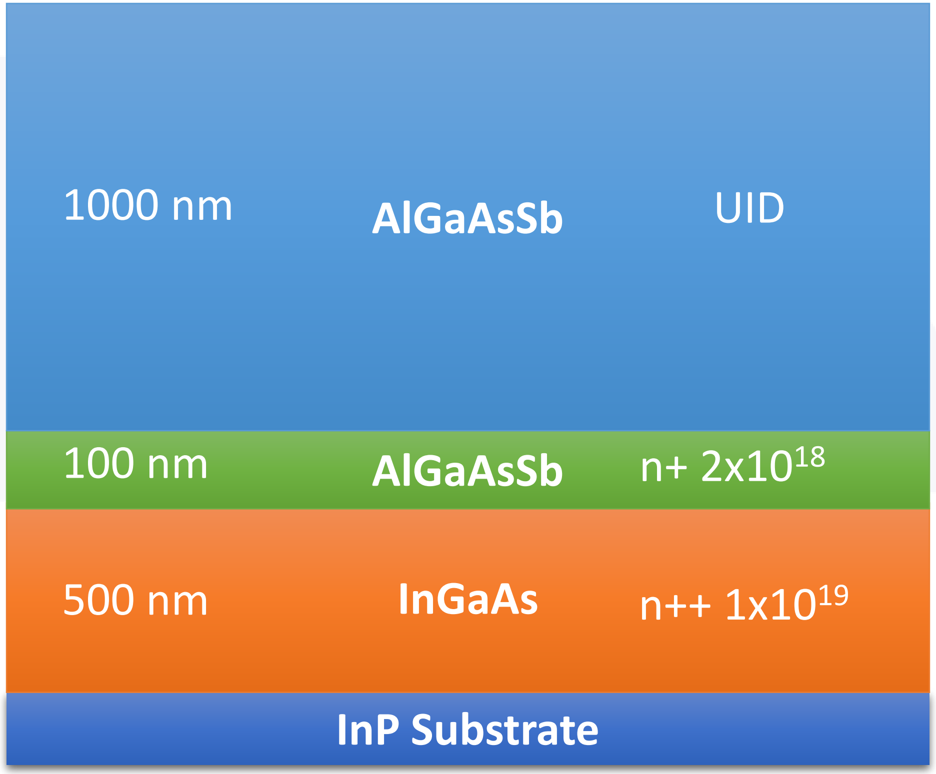
Zn diffusion into our material systems via ALD has not been published in literature

[11-15]

Sb-based APDs for Diffused Planar Investigation

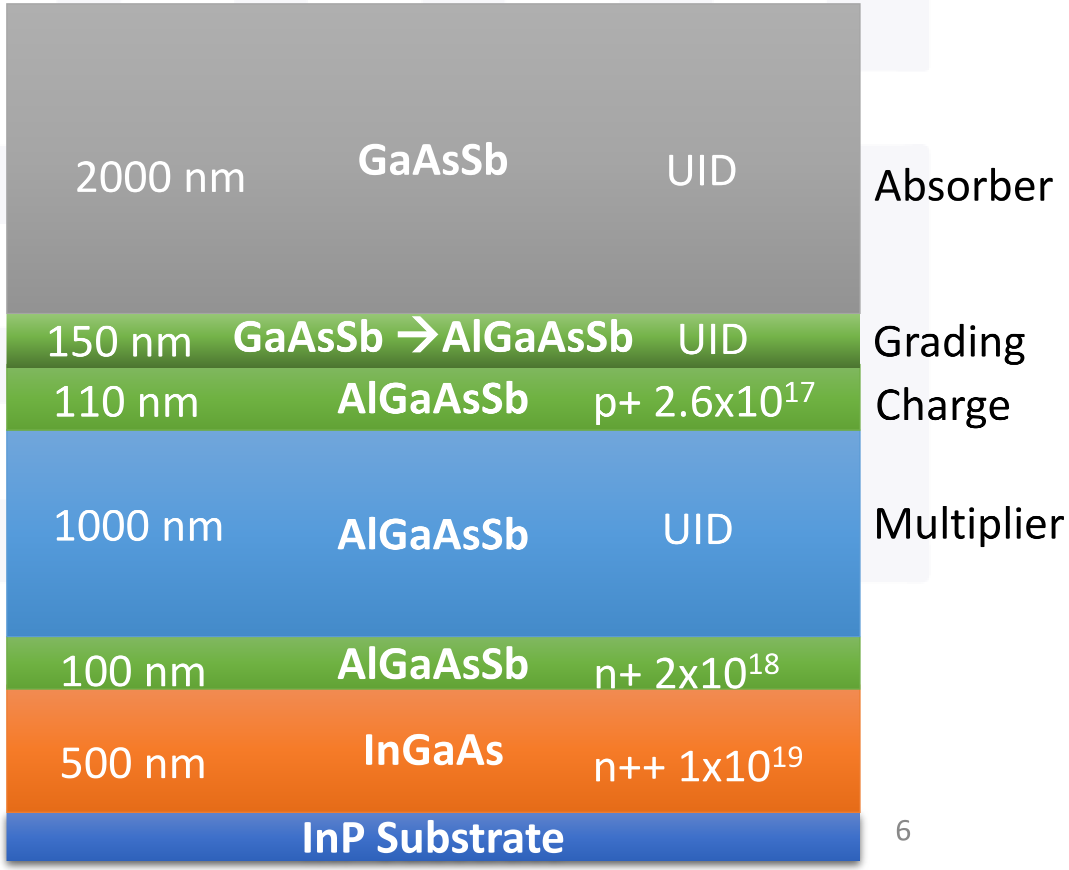
- We have developed a two-pronged study to investigate the diffusion conditions into two materials of interest for our group. These materials serve as the multiplier and absorber of more complex separate absorption, charge, and multiplication (SACM) APDs that have demonstrated high gain (*M=278*)[16] previously

Study I:Planar AlGaAsSb PIN APD



1000 nm	AlGaAsSb	UID
100 nm	AlGaAsSb	n+ $2x10^{18}$
500 nm	InGaAs	n++ $1x10^{19}$
InP Substrate		

Study II: Planar GaAsSb/AlGaAsSb SACM APD

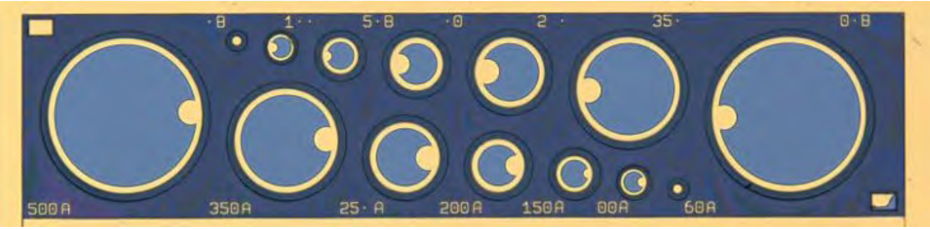


2000 nm	GaAsSb	UID	Absorber
150 nm	GaAsSb → AlGaAsSb	UID	Grading
110 nm	AlGaAsSb	p+ $2.6x10^{17}$	Charge
1000 nm	AlGaAsSb	UID	Multiplier
100 nm	AlGaAsSb	n+ $2x10^{18}$	
500 nm	InGaAs	n++ $1x10^{19}$	
InP Substrate			

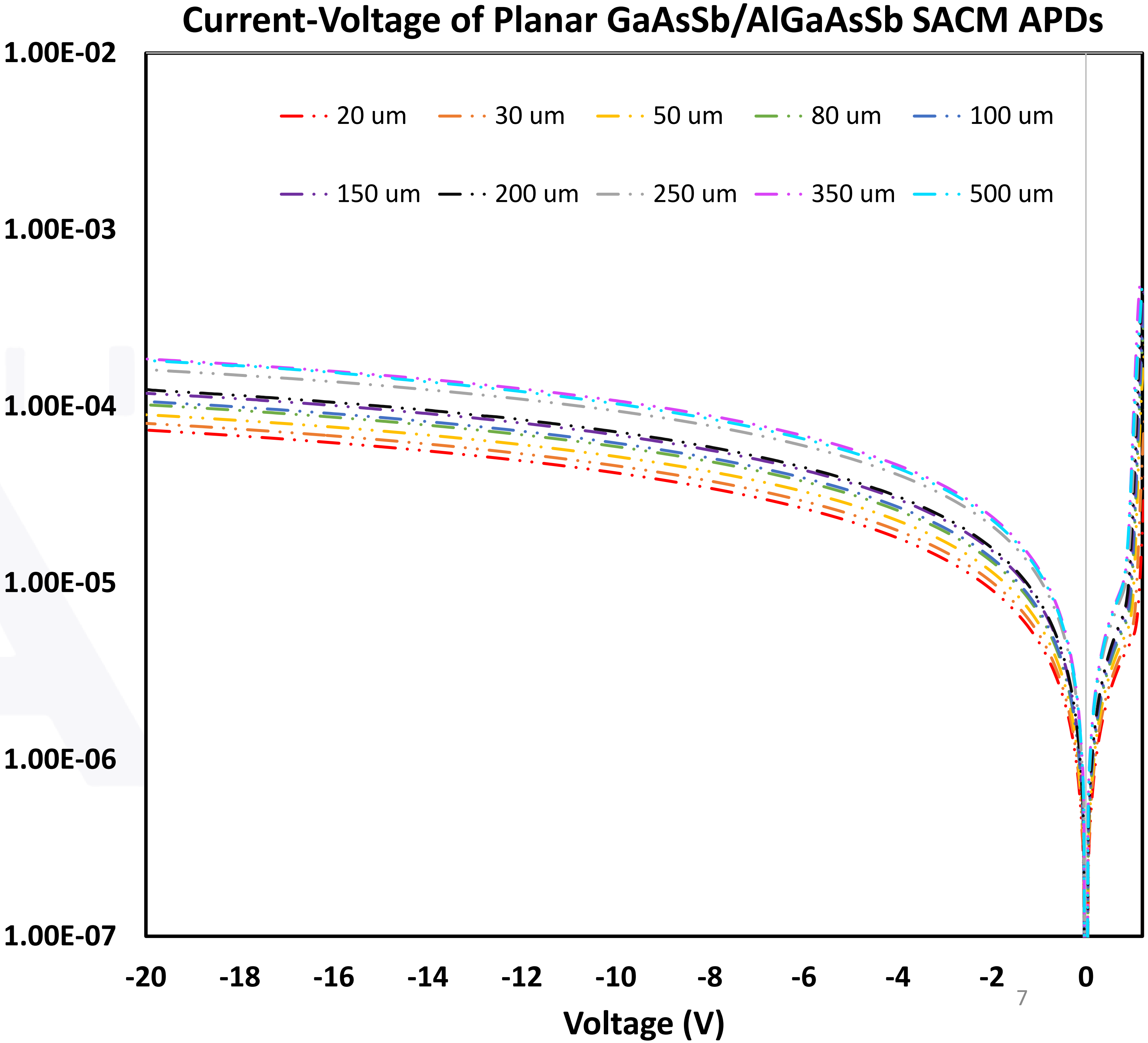
[16]

Preliminary Work

- Preliminary current-voltage measurements of planar GaAsSb/AlGaAsSb SACM APDs show promise with visible rectifying behavior
- Follow-on work will focus on the further reduction of the dark current by optimizing the planar processing



Devices fabricated with varying diameters



Technical Challenges and Future Work

- The development of planar APDs gives rise to additional fabrication challenges that must be addressed to mitigate the surface dark current
- These include optimization of the processing to reach sufficient Zn diffusion depths for producing a p-n junction
- Follow on work will be investigating the incorporation of guard rings into the design to serve as an alternative conductive pathway and further lower the surface dark current
  - Significant research can be addressed with optimization of guard rings in addition to the diffusion planar fabrication processing
  - Secondary diffusion can also be considered

Diffused Planar Sb-based APDs on InP Substrates

Advantages	Disadvantages
Potential to eliminate surface leakage current	Method of diffusion requires optimization
Potential for high gain (>100)	Additional considerations may be required such as guard rings or secondary diffusion

Acknowledgements

Thanks to the support and guidance of colleagues at OSU as well as the team at AFRL on this work:

OSU: Manisha Muduli, Hyemin Jung, Dr. SeungHyun Lee, Sophie Mills, Dr. T. J. Ronningen, Dr. Tyler Grassman, Dr. Wu Lu, and Dr. Sanjay Krishna

AFRL: Dr. Charles Reyner, Dr. Gamini Ariyawansa, Dr. Joshua Duran, and Brent Webster

Contract# RY9-OSU-21-2-AFRL2

References

1. H. Riris, K. Numata, S. Wu, and M. Fahey, “The challenges of measuring methane from space with a LIDAR,” *CEAS Space Journal*, vol. 11, no. 4, pp. 475–483, Sep. 2019, doi: https://doi.org/10.1007/s12567-019-00274-8.
2. U. N. Singh *et al.*, “Feasibility study of a space-based high pulse energy 2 µm CO2 IPDA lidar,” *Applied Optics*, vol. 56, no. 23, p. 6531, Aug. 2017, doi: https://doi.org/10.1364/ao.56.006531.
3. P. Mcmanamon, *LiDAR Technologies and Systems*. Bellingham, Washington, Usa Spie Press, 2019.
4. B. Pal, *Frontiers in Guided Wave Optics and Optoelectronics*. IntechOpen, 2010.
5. J. S. Franks, “What is eye safe?” Apr. 1991, doi: https://doi.org/10.1117/12.43840.
6. G.M. Williams, “Optimization of eyesafe avalanche photodiode lidar for automobile safety and autonomous navigation systems,” *Opt. Eng.,* vol. 56, no. 3, pp. 031224, Mar. 2017, https://doi.org/10.1117/1.OE.56.3.031224.
7. J. D. Vincent, S. Hodges, J. Vampola, M. Stegall, and G. Pierce, *Fundamentals of Infrared and Visible Detector Operation and Testing*. John Wiley & Sons, 2015.
8. R. J. McIntyre, “Multiplication noise in uniform avalanche diodes,” *IEEE Transactions on Electron Devices*, vol. ED-13, no. 1, pp. 164–168, Jan. 1966, doi: https://doi.org/10.1109/t-ed.1966.15651.
9. A. Rogalski, P. Martyniuk, and M. Kopytko, “Challenges of small-pixel infrared detectors: a review,” *Reports on Progress in Physics*, vol. 79, no. 4, p. 046501, Mar. 2016, doi: https://doi.org/10.1088/0034-4885/79/4/046501.
10. B. T. Marozas, W. D. Hughes, X. Du, D. E. Sidor, G. R. Savich, and G. W. Wicks, “Surface dark current mechanisms in III-V infrared photodetectors [Invited],” *Optical Materials Express*, vol. 8, no. 6, p. 1419, May 2018, doi: https://doi.org/10.1364/ome.8.001419.
11. A. W. Walker, S. Moisa, A. J. SpringThorpe, and O. J. Pitts, “Zn diffusion depth effect on photoresponse uniformity in InP/InGaAs avalanche photodiodes,” *Optical and Quantum Electronics,* vol. 54, no. 9, Jul. 2022, doi: https://doi.org/10.1007/s11082-022-03931-1
12. D. Wu, A. Dehzangi, J. Li, and M. Razeghi, “High performance Zn-diffused planar mid-wavelength infrared type-II InAs/InAs$_{1-x}$Sb$_x$ superlattice photodetector by MOCVD,” *Applied Physics Letters*, vol. 116, no. 16, p. 161108, Apr. 2020, doi: https://doi.org/10.1063/5.0005326.
13. R. K. Saroj, Van Tang Nguyen, Steven Boyd Slivken, G. J. Brown, and Manijeh Razeghi, “Demonstration of Zn-Diffused Planar Long-Wavelength Infrared Photodetector Based on Type-II Superlattice Grown by MBE,” *IEEE Journal of Quantum Electronics,* vol. 58, no. 5, pp. 1–6, Oct. 2022, doi: https://doi.org/10.1109/jqe.2022.3172772.
14. J. Burm *et al.*, “Edge Gain Suppression of a Planar-Type InGaAs–InP Avalanche Photodiodes With Thin Multiplication Layers for 10-Gb/s Applications,” *IEEE Photonics Technology Letters,* vol. 16, no. 7, pp. 1721–1723, Jul. 2004, doi: https://doi.org/10.1109/lpt.2004.829546.
15. Manisha Muduli, M. Schwartz, N. Gajowski, S. Lee, and S. Krishna, “Investigation of Zn-diffusion in 2-micron InGaAs/GaAsSb superlattice planar diodes using atomic layer deposition of ZnO,” Jun. 2023, doi: https://doi.org/10.1117/12.2663602.
16. S. Lee *et al.*, “High gain, low noise 1550 nm GaAsSb/AlGaAsSb avalanche photodiodes,” *Optica*, vol. 10, no. 2, p. 147, Jan. 2023, doi: https://doi.org/10.1364/optica.476963.