Application for EMC Oral Presentation Award
Electronic Materials Conference 2024

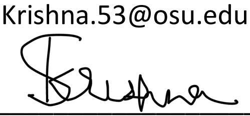
Student Name: Manisha R Muduli

Student Mailing Address: CL 374, 2024 Neil Ave, Columbus, OH, 43210

Student E-mail Address: muduli.1@buckeyemail.osu.edu

Advisor Name: Prof. Sanjay Krishna

Advisor E-mail Address: Krishna.53@osu.edu

Advisor Signature:  ____

Advisor signature certifies that the advisor has reviewed the award submission and finds that the work appears to be original and performed by the student.

Title of EMC Abstract: GaAsSb/Si heterojunction photodiodes fabricated with epitaxial layer transfer.

Name: Manisha R Muduli
Contact info: muduli.1@buckeyemail.osu.edu

a. Professional Preparation

Amity University, Noida, India	Nanotechnology	B.Tech.	2018
University of Pennsylvania, Philadelphia, PA	Nanotechnology	M.S.E.	2020
The Ohio State University, Columbus, OH	Electrical and Computer Engineering	Ph.D.	2025

b. Appointments

2024 – Superuser/trainer (cryogenic probe station), Nanotech West, The Ohio State University, Columbus, OH
2021 – Graduate Research Associate, Electrical and Computer Engineering, The Ohio State University, Columbus, OH
2020 – Teaching Assistant, Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, PA
2019 – 2021 – Graduate Student Fellow, Singh Center for Nanotechnology, University of Pennsylvania, Philadelphia, PA
2019 – 2020 – Research Assistant, Kagan group, University of Pennsylvania, Philadelphia, PA
2019 – Assistant Instructor, Quattrone Nanofabrication Facility, University of Pennsylvania, Philadelphia, PA

c. Publications
(i) Five most closely related to proposal project

Muduli, M., Schwartz, M., Gajowski, N., Lee, S. and Krishna, S., 2023, June. Investigation of Zn-diffusion in 2-micron InGaAs/GaAsSb superlattice planar diodes using atomic layer deposition of ZnO. In *Infrared Technology and Applications XLIX* (Vol. 12534, pp. 45-50). SPIE.
Schwartz, M., Jung, H., Lee, S., **Muduli, M.**, Ronningen, T.J., Ball, C., Grein, C. and Krishna, S., 2023, July. Development of Antimonide Based Avalanche Photodiodes for SWIR Remote Sensing Applications. In *IGARSS 2023-2023 IEEE International Geoscience and Remote Sensing Symposium* (pp. 4270-4273). IEEE.
Ball, C., Krishna, S., Ronningen, T.J., Lee, S., Jung, H., Schwartz, **M., Muduli**, M., Grein, C. and Fuller, E., 2022, December. Development of Avalanche Photodiodes with High Operating Temperatures to Enable Short-Wavelength Infrared Remote Sensing Applications. In *AGU Fall Meeting Abstracts* (Vol. 2022, pp. A15L-1383).

(ii) Five other significant publications

Zhao, T., Oh, N., Jishkariani, D., Zhang, M., Wang, H., Li, N., Lee, J.D., Zeng, C., **Muduli, M**., Choi, H.J. and Su, D., 2019. General synthetic route to high-quality colloidal III–V semiconductor quantum dots based on pnictogen chlorides. *Journal of the American Chemical Society*, *141*(38), pp.15145-15152.
Pise, M., **Muduli, M.**, Chatterjee, A., Kashyap, B.P., Singh, R.N. and Tatiparti, S.S.V., 2022. Instantaneous-Progressive nucleation and growth of palladium during electrodeposition. *Results in Surfaces and Interfaces*, *6*, p.100044.

Das, P.P., **Muduli, M.**, Borah, S. and Chaudhary, V., 2021. Principle of Green Chemistry: A modern perspective for development of sustainable textile fiber-based green nanocomposites. In *Green Chemistry for Sustainable Textiles* (pp. 121-136). Woodhead Publishing.

Lee, J., Zhao, T., Yang, S., **Muduli, M.**, Murray, C.B. and Kagan, C.R., 2024. One-pot heat-up synthesis of short-wavelength infrared, colloidal InAs quantum dots. *The Journal of Chemical Physics*, *160*(7).

d. Synergistic Activities

Collaborated with Yongkang Xia to develop a process for the transfer of III-V nanomembrane to Si as a part of the Intel CAFÉ project conducted at The Ohio State University. By participating in the Intel CAFÉ program project, we collaborate with the students, staff and faculties at The Ohio State University as well as the staff at Intel, which maximizes the impact of the project, not just to academic research, but also to the research done in the industry.

Train and assist students on the Lakeshore cryogenic probe station at the Nanotech West facility at The Ohio State University. In January 2024, I became the *superuser* of the tool, and I am responsible for the maintenance and the optimal functioning of tool. The title of a *superuser* helps me to train, troubleshoot and assist students on the probe station and transfer my knowledge about the tool to them.

Co-coordinated the Quattrone Nanofabrication Facility bootcamp (Fall 2019) with Dr. Gyuseok Kim at the Singh Center for Nanotechnology as an instructor for undergraduate and graduate students and high-school students, providing hands-on training in various cleanroom tools. For undergraduate and graduate students, the bootcamp aimed at providing a short cleanroom experience, and focused on different research activities that takes place in the cleanroom. For high-school students, the bootcamp aimed at nurturing students' interest in the STEM program by showing them the beauty of nanotechnology though lithography and oxide growth processes. The bootcamp attracted students from all age group and matured their interest in pursuing a degree in STEM.

Collaborated with Dr. Patrick Watson and Dr. Gyuseok Kim to design the solar cell module and assist the Nanofabrication of Electronic Devices course (ESE 336) for undergraduate students (Spring 2020). This course provided hands-on experience on the cleanroom fabrication processes to the students. They learnt about different cleanroom tools and the course piqued their interest in the device fabrication process. At the end of the course, several students voiced their interest in pursuing higher education in the semiconductor industry. The course continues to be actively developed and is currently administered by Dr. Patrick Watson and Dr. Gyuseok Kim at the University of Pennsylvania.

Co-authored a book chapter (2021) with P. P. Das (NTU, Singapore) under the guidance of S. Borah (Amity University, Noida) and V. Chaudhary (Amity University, Noida) on the Principles of Green Chemistry for the book – *Green Chemistry for Sustainable Textiles*. The book was developed to spread awareness about the impact of textile industry on the environment and lay out the sustainable solutions for textile industry. This book is a small step in revolutionizing how the textile industry. Adoption of green chemistry principles and practices in the textile industry can lower water pollution and reduce greenhouse gas emissions.

Motivation and Novelty of the work.

Next generation high-bandwidth, energy-efficient connectivity for system-to-system and chip-to-chip communications in applications like data centers require semiconductor photonic devices that can handle data rates > 200 Gbps, well beyond the current standard of 112 Gbps. To address this, we propose the development of linear mode avalanche photodiodes (LmAPDs) using GaAsSb absorbers (high quantum efficiency at 1.55 μm), integrated with Si based avalanche multipliers (large gain, low excess noise). This work focuses on heterogeneous integration of GaAsSb with Si combines the strength from both materials, yielding a high-speed detector at short-wave infrared regime. One of the key science questions is related to exploring the structural, electrical and optoelectronic properties of the GaAsSb/Si interface. Several methods to integrate Si and III-V materials have been studied in the past including wafer bonding, epitaxial growth, epitaxial layer transfer, and micro-transfer printing. *In this work we demonstrate the first epitaxially transferred GaAsSb layers integrated with Si and demonstrate room temperature photocurrent.*

Unlike InGaAs which is the workhorse of 1550nm absorber, GaAsSb exhibits a low conduction band offset with Si (<0.1 eV) [1], which promotes electron transport between GaAsSb and Si and eliminates the need for a grading layer. We have integrated GaAsSb nanomembranes (NM) with Si using a poly(dimethylsiloxane) (PDMS) stamp to make the GaAsSb/Si PIN diodes (Fig. 1). Although Si NM have been transferred to GaAsSb/AlInAs/InP substrate before [2], transferring GaAsSb NM expands the possibility of photodetection along with the heterogeneous integration. The electronic properties of the PIN diodes were studied using capacitance-voltage (CV) measurements and current-voltage (IV) measurements. We report the first room temperature photocurrent obtained at 1550 nm for the GaAsSb-Si heterostructure, with a V_{oc} of 20mV (Fig. 2). Further, GaAsSb-Si interface is characterized through simulations and experimentation to quantify the conduction band offset and the sheet charge density at the interface.

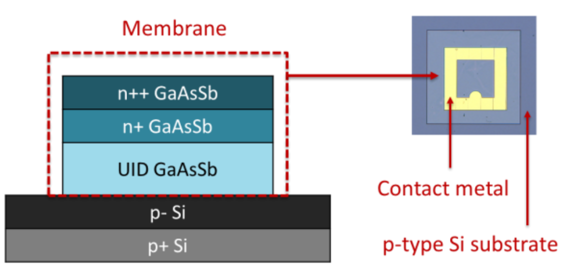


Fig. 1. (Left) GaAsSb/Si heterostructure after transfer. (Right) Microscopic image of GaAsSb/Si heterostructure photodiodes of sizes 300 μm x 300 μm after membrane transfer and metal deposition.

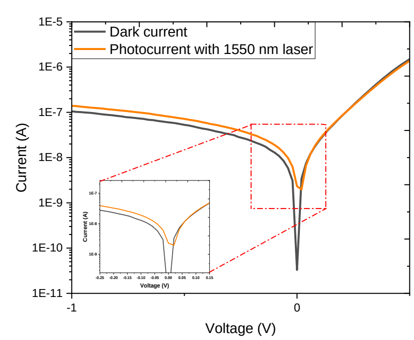


Fig. 2. Dark current and photocurrent (at 1550 nm) of the fabricated GaAsSb/Si PIN diodes measured at room temperature. (Inset) Enlarged image to show V_{oc} of the photocurrent.

[1] Naga Swetha Nallamothu, Yongkang Xia, Sk Shafaat S Nikor, Hyemin Jung, Nathan Gajowski, Seunghyun Lee, Shamsul Arafin, Sanjay Krishna, and Ronald M Reano. Direct bonding of GaAsSb to silicon for high-speed avalanche photodiodes. In *Laser Science*, pages JM7A–105. Optica Publishing Group, 2023.

[2] Yongkang Xia, Sk Shafaat Saud Nikor, Naga Swetha Nallamothu, Rachel L Adams, Hyemin Jung, Nathan Gajowski, Seunghyun Lee, Ronald M Reano, Sanjay Krishna, Steven Ringel, et al. Fabrication of Si/GaAs 0.51 sb 0.49 heterostructure diodes via transfer printing. In *2023 IEEE Photonics Conference (IPC)*, pages 1–2. IEEE, 2023.

Application for EMC Oral Presentation Award
Electronic Materials Conference 2024

Student Name: ___Pooja Reddy____

Student Mailing Address *(school address preferred)*:_________________________________

____476 Lomita Mall____

____Stanford, CA, 94305____

Student E-mail Address:

____poojadr@stanford.edu____

Advisor Name: ___Kunal Mukherjee____

Advisor E-mail Address:

____kunalm@stanford.edu____

Advisor Signature: ____

Advisor signature certifies that the advisor has reviewed the award submission and finds that the work appears to be original and performed by the student.

Title of EMC Abstract:
____*Expanded stability of layered SnSe-PbSe alloys and evidence of displacive phase transformation from rocksalt in heteroepitaxial thin films*________________________

Submission Requirements:
Items listed below should be submitted as a single pdf file by April 24th at 11:59pm EST. To submit, go to the EMC website, click "Submit Now" for Late News, choose the Student Awards section, and upload your pdf (this cover page, the NSF-style biosketch, and the one-page narrative).

- NSF-style Biosketch *(up to 2 pgs, template attached)*
- One-page narrative *(inclusive of figures and references)* that highlights motivation and novelty of the work.

Pooja Reddy
poojadr@stanford.edu

a. Professional Preparation

Massachusetts Institute of Technology	Materials Science and Engineering	B.S., 2020
Stanford University	Materials Science and Engineering	4th yr, Ph.D.

b. Publications

(i) Five most closely related to proposal project

Reddy, P. D., Nordin, L., Hughes, L., Preidl, A. K., & Mukherjee, K. (2023). Expanded stability of layered SnSe-PbSe alloys and evidence of displacive phase transformation from rocksalt in heteroepitaxial thin films. *arXiv preprint arXiv:2311.01514*. accepted at *ACS Nano* 04/2024.

Haidet, B. B., Meyer, J., **Reddy, P.,** Hughes, E. T., & Mukherjee, K. (2023). Versatile strain relief pathways in epitaxial films of (001)−oriented PbSe on III-V substrates. *Physical Review Materials*, *7*(2), 024602.

Nordstrom, M. D., Garrett, T. A., **Reddy, P.,** McElearney, J., Rushing, J. R., Vallejo, K. D., Mukherjee K., Grossklaus K.A., Vandervelde T.E., & Simmonds, P.J. (2023). Direct Integration of GaSb with GaAs (111) A Using Interfacial Misfit Arrays. *Crystal Growth & Design*, *23*(12), 8670-8677.

(ii) Five other significant publications

Kossak, A. E., Huang, M., **Reddy, P.**, Wolf, D., & Beach, G. S. (2023). Voltage control of magnetic order in RKKY coupled multilayers. *Science Advances*, *9*(1), eadd0548.

Gregurec, D., Senko, A. W., Chuvilin, A., **Reddy, P. D.**, Sankararaman, A., Rosenfeld, D., ... & Anikeeva, P. (2020). Magnetic vortex nanodiscs enable remote magnetomechanical neural stimulation. *ACS nano*, *14*(7), 8036-8045.

Anikeeva, P. O., Senko, A. W., Gregurec, D., & **Reddy, P. D.** (2020). *U.S. Patent Application No. 16/427,911*.

Zhang Z., Hoang L., Hocking M., Hu J., Zaborski Jr G., **Reddy P.**, … & Mannix A.J. (2024). Chemically Tailored Growth of 2D Semiconductors via Hybrid Metal-Organic Chemical Vapor Deposition. *arXiv preprint arXiv:2403.03482*. in Review at *ACS Nano*.

Caretta L., Rosenberg E., Büttner F., Fakhrul T., Gargiani P., Valvidares M., Chen Z, **Reddy P.**, Muller D.A., Ross C.A., Beach G.S. (2020). Interfacial Dzyaloshinskii-Moriya interaction arising from rare-earth orbital magnetism in insulating magnetic oxides. *Nature communications*, *11*(1), 1090.

c. Synergistic Activities

FEI Helios NanoLab 600i DualBeam SEM/FIB Staff Trainer (2023- Present)

Train and qualify users from across campus on basic electron and ion beam use, on the Stanford Nano Shared Facilities Dual SEM/FIB tool.

Stanford Materials Research Society Executive Committee Member (2020 – Present)

Help plan community events to encourage connections between members of the graduate population in the Materials Science department.

Stanford Materials Research Society Art of Science Exhibition Chair (2022 - Present)

Lead a group of graduate students in organizing the largest student-run science-inspired art competition and exhibit at Stanford.

Stanford Materials Science Undergraduate Research Grant Program Co-chair (2022-Present)

Co-lead a team of graduate students organizing a paid research program during the academic year for undergraduates interested in Materials Science research.

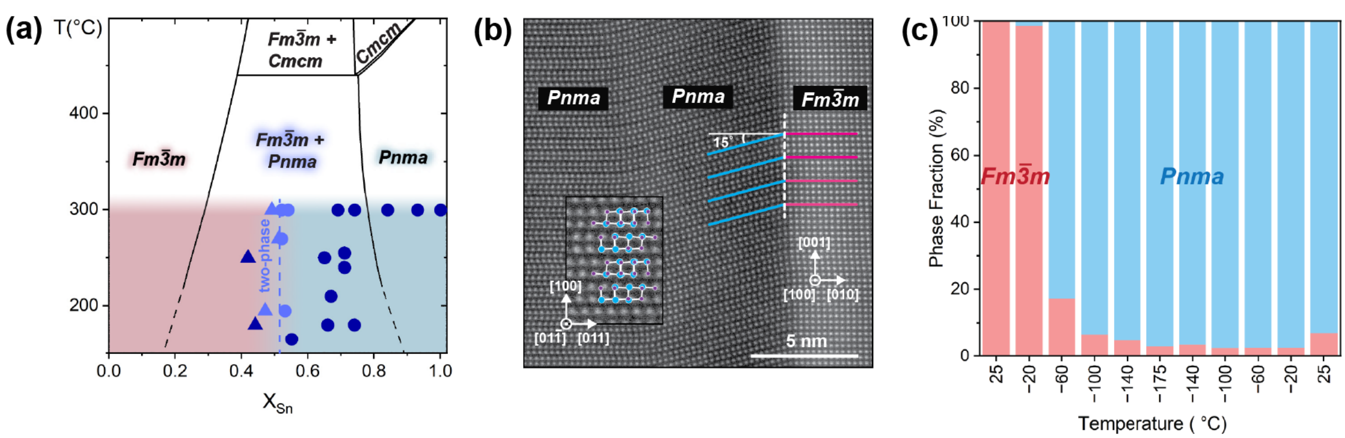
Stanford Materials Science and Engineering Student Advisory Board, (2022)

Represented PhD class year to provide feedback and action items to department faculty and administration on ways to improve student life in the department.

Phase change materials often transition between amorphous and crystalline states. There are few systems which transition between crystal structures at accessible temperatures, and even fewer which maintain semiconducting characteristics, rather than transitioning to and from an insulator. The PbSe-SnSe materials system is a unique example of both: a Sn-rich 2D-bonded layered orthorhombic structure (*Pnma*), and a Pb-rich 3D-bonded rocksalt structure ($Fm\bar{3}m$), which have an indirect and direct band gap respectively, require a fraction of a unit cell displacement to transform between phases [1]. This huge change in bonding drives a large contrast in the electrical, optical, and thermal properties. The unusual combination of large property contrast between the phases while retaining close proximity in structure has the potential for important phase-change devices, if the bulk two-phase region can be avoided.

Recently, results in PbSnSe show a direct switch between these two crystal structures, but require high temperature synthesis (>600 °C) and rapid quenching to maintain metastable phases [1,2]. In contrast, we realize direct low-temperature synthesis (165–300 °C) of epitaxial PbSnSe thin films on GaAs via molecular beam epitaxy (MBE) using an *in situ* PbSe surface treatment. We show a significantly reduced two-phase region, stabilizing the *Pnma* layered structure out to $Pb_{0.45}Sn_{0.55}Se$, beyond the bulk-limit at around $Pb_{0.25}Sn_{0.75}Se$ at low temperatures [3]. We are also able to directly access metastable two-phase films of layered and rocksalt grains that are nearly identical in composition around $Pb_{0.50}Sn_{0.50}Se$, entirely circumventing the two-phase region. In these films, we find evidence of an incomplete displacive transformation from rocksalt to layered phases, which we believe occurs when the film cools from growth temperature to room temperature. Microstructural characterization reveals that there are two flavors of interfaces between phases that have specific orientation relationships and show novel strain-relief mechanisms. Interestingly, the 3D to 2D transformation occurs with minimal lateral strain, which gives this materials system great promise for heterostructure devices where optical, electronic, and thermal properties are switched. Cryogenic Hall measurements of a rocksalt film show property change with a temperature-induced phase transition that also may enable highly doped layered phase PbSnSe films. This thin film growth method on GaAs provides new avenues to both tune the energetic landscape using alloys, and to couple these materials with existing photonic schemes for next generation phase-change devices.

[1] T. Katase et al. ... T. Kamiya, *Science advances*, ***7***(12), (2021).
[2] Y. Nishimura et al. ... T. Kamiya, *Adv. Electron. Mater*, ***8***(9), (2022)
[3] H. Krebs et al. ... D. Kallen, *Z. Für Anorg. Allg. Chem*, *312* (5–6), 307–313, (1961)



(a) Pbse-SnSe phase space. Black lines mark the bulk phase diagram. Growth conditions of MBE samples are overlaid. Layered phases are marked by circles and rocksalt phases are marked by triangles. Single-phase samples are marked in dark purple, while the approximate compositions of each phase in two-phase samples are marked in light purple. Shaded color shows the metastable phases accessed with MBE grown thin films. The dashed purple line denotes the two-phase displacive transformation region at growth temperatures below 300 °C. (b) $Pb_{0.5}Sn_{0.5}Se$ two-phase film. High resolution scanning transmission electron microscopy image of a vertical grain boundary with an inset of the layered phase orientation. Here select lattice planes (blue and red) and the grain boundary (dashed white) are marked. (c) Phase fraction as a function of temperature of an as grown single-phase rocksalt X_{Sn}=0.42 film when cycled from room temperature to -175 °C.

Application for EMC Oral Presentation Award
Electronic Materials Conference 2024

Student Name: (Rachel) Corey White

Student Mailing Address *(school address preferred)*:

10100 Burnet Road, Bldg. #160

Austin, TX 78758

Student E-mail Address:

coreywhite@utexas.edu

Advisor Name: Dr. Seth Bank

Advisor E-mail Address:

sbank@ece.utexas.edu

Advisor Signature:

Advisor signature certifies that the advisor has reviewed the award submission and finds that the work appears to be original and performed by the student.

Title of EMC Abstract:

Bismuth Incorporation into InSb Towards Long-Wave Infrared Photodetectors

Submission Requirements:

Items listed below should be submitted as a single pdf file by April 24th at 11:59pm EST. To submit, go to the EMC website, click "Submit Now" for Late News, choose the Student Awards section, and upload your pdf (this cover page, the NSF-style biosketch, and the one-page narrative).

- NSF-style Biosketch *(up to 2 pgs, template attached)*
- One-page narrative *(inclusive of figures and references)* that highlights motivation and novelty of the work.

R. Corey White
10100 Burnet Road, Bldg. #160, Austin, TX 78758 • *coreywhite@utexas.edu* • (336) 340-8587

Professional Preparation

North Carolina State University	Electrical Engineering	B.S. 2019
North Carolina State University	Computer Engineering	B.S. 2019
The University of Texas at Austin	Electrical Engineering	M.S. 2021
The University of Texas at Austin	Electrical Engineering	*(Expected)* Ph.D. 2024

Appointments

2021, 22 Research Experience for Undergraduates (REU) Mentor, UT Austin
2021, 23 Teaching Assistant, Electrical Engineering, UT Austin
2021-24 X-ray Diffractometer Trainer & Superuser, UT Austin
2019-24 National Science Foundation Graduate Research Fellow (NSF GRFP)
2019-24 Graduate Research Assistant, UT Austin
2019-23 Cockrell School of Engineering Fellow, UT Austin
2019-21 Society of Women Engineers "Brown Bags with Grads" Mentor, UT Austin
2017-19 Teaching Assistant, Computer Engineering, NCSU
2019 National Science Foundation Research Experience for Undergraduates, NIMS Japan
2018 National Science Foundation Research Experience for Undergraduates, UT Austin
2017 National Science Foundation Research Experience for Undergraduates, Duke

Publications

[1] **R. C. White**, A. J. Muhowski, M. K. Bergthold, L. J. Nordin, I. Okoro, H. Hijazi, D. Wasserman, and S. R. Bank, "Molecular beam epitaxy of $InAs_ySb_{1-x-y}Bi_x$ lattice-matched to InSb towards long-wave infrared detectors," *Under Review at Journal of Crystal Growth and Design.*
[2] **R. C. White**, L. J. Nordin, A. J. Muhowski, D. Wasserman, and S. R. Bank, "Photoluminescence from $InSb_{1-x}Bi_x$ alloys at extended wavelengths on InSb," *Applied Physics Letters*, vol. 121, no. 19, pp. 191901, Nov. 2022.
[3] Q. Meng, R. H. El-Jaroudi, **R. C. White**, T. Dey, Md. S. Reza, S. R. Bank, and M. A. Wistey, "Effects of B and In on the Band Structure of BGa(In)As Alloys," *Journal of Applied Physics*, vol. 132, no. 19, pp. 193104, Nov. 2022.
[4] J. Kopaczek, F. Dybala, S. J. Zelewski, N. Sokolowski, W. Zuraw, K. M. McNicholas, R. H. El-Jaroudi, **R. C. White**, S. R. Bank, and R. Kudrawiec, "Photoreflectance studies of temperature and hydrostatic pressure dependencies of direct optical transitions in BGaAs grown on GaP," *Journal of Physics D: Applied Physics*, vol. 55, no. 1, pp. 015107, Oct. 2021.

Presentations

[1] **(Best Student Talk Award) R. C. White**, M. K. Bergthold, T. A. Leonard, A. F. Ricks, D. Wasserman, and S. R. Bank, "InSb-Based Dilute-Bismide Alloys Towards Long-Wave Infrared Sensing," *37th North American Conference on Molecular Beam Epitaxy*, Madison, WI, Sept. 2023.

[2] **R. C. White**, M. K. Bergthold, A. J. Muhowski, Y. Wang, A. F. Ricks, D. Wasserman, and S. R. Bank, "Lattice-Matched InAsSbBi Photodetectors for Long-Wave Infrared Sensing," *81st Device Research Conference*, Santa Barbara, CA, June 2023.
[3] **R. C. White**, M. K. Bergthold, T. A. Leonard, A. F. Ricks, D. Wasserman, and S. R. Bank, "Optical and Structural Properties of InSb-Based Dilute-Bismide Alloys Grown by Molecular Beam Epitaxy," *65th Electronic Materials Conference*, Santa Barbara, CA, June 2023.
[4] **(Best Student Talk Award) R. C. White**, M. K. Bergthold, I. Okoro, Y. Wang, L. J. Nordin, A. J. Muhowski, A. F. Ricks, D. Wasserman, and S. R. Bank, "Towards Lattice-Matched Narrow Bandgap $InAs_ySb_{1-x-y}Bi_x$ Photodetectors," *36th North American Conference on Molecular Beam Epitaxy*, Rehoboth Beach, DE, Sept. 2022.
[5] **(Best Student Talk Award) R. C. White**, M. K. Bergthold, A. J. Muhowski, L. J. Nordin, A. F. Ricks, D. Wasserman, and S. R. Bank, "Growth of InAsSbBi on InSb Towards Lattice-Matched Longwave Infrared Optoelectronics," *64th Electronic Materials Conference*, Columbus, OH, June 2022.
[6] **R. C. White**, Q. Meng, M. Lopez, A. Ponnekanti, L. J. Nordin, A. J. Muhowski, D. Wasserman, S. R. Bank, and M. A. Wistey, "Growth and Characterization of $InSb_{1-x}Bi_x$: A (Potentially) Not So Highly Mismatched Alloy for Wavelength Extension on InSb," *21st International Conference on Molecular Beam Epitaxy*, Virtual, Sept. 2021.
[7] **R. C. White**, A. J. Muhowski, L. J. Nordin, D. Wasserman, and S. R. Bank, "Growth and Optimization of InSbBi Alloys for Wavelength Extension on InSb," *63rd Electronic Materials Conference*, Virtual, June 2021.
[8] **R. C. White**, R. H. El-Jaroudi, Q. Meng, P. Dhingra, M. L. Lee, S. R. Bank, and M. A. Wistey, "Mechanism for Blueshift with Annealing in Near-Infrared B-III-V- Alloys on GaAs," *62nd Electronic Materials Conference,* Virtual, June 2020.

Synergistic Activities

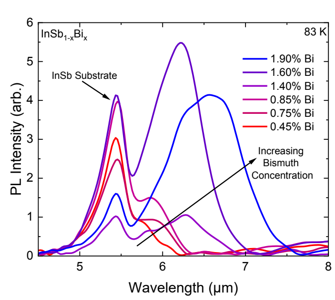
Founder of Women in Fab Club	UT Austin	2023-Present
Vice Chair & Treasurer of IEEE Photonics	UT Austin	2021-Present
REU Program Mentor	UT Austin	2021, 2022
President & Member of IEEE Eta Kappa Nu	NCSU	2016-2019
Founder of out in STEM Club	NCSU	2016-2019

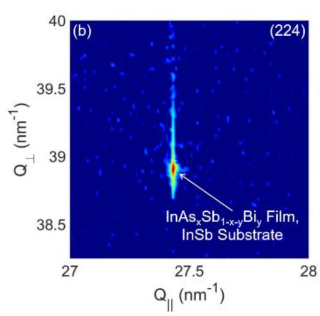
Narrative: Bismuth Incorporation into InSb Towards Long-Wave Infrared Photodetectors

R. Corey White | Advisor: Dr. Seth Bank | The University of Texas at Austin

There is strong motivation for developing high-performance detectors that operate within the long-wave infrared (LWIR, 8-14 μm) as such devices are of critical importance to numerous applications including gas sensing, thermography, and astronomical imaging. Historically, however, the corresponding narrow bandgap energies have proven particularly challenging to access with conventional III-V alloys. For this reason, devices operating in this spectral region continue to be dominated by $Hg_{1-x}Cd_xTe$ even though such devices are plagued by low yield and poor uniformity.[1] More importantly, though, the constituent elements Hg, Cd, and Te are all highly toxic leading to recent restrictions on the production of such devices due to safety concerns.[2]

Dilute-bismide alloys, due to the dramatic bandgap reductions introduced by bismuth incorporation in traditional III-V alloys,[3,4] have the potential to enable a new route to lattice-matched bulk III-V alloys with tunable bandgap energies spanning the LWIR. InSb-based dilute-bismide alloys are a particularly promising candidate material system due to the relatively narrow bandgap energy that InSb possesses enabling LWIR bandgap energies with minimal bismuth incorporation. Furthermore, InSb and III-Bi materials share remarkably similar ideal growth conditions,[5] which potentially facilities the incorporation of bismuth into InSb without the degradation in material and optical quality so often seen in wider bandgap III-As-Bi alloys. Surprisingly, InSb-based dilute-bismide alloys are relatively experimentally underexplored and many important material parameters have yet to be investigated. Previously, we realized the first ever photoluminescence from $InSb_{1-x}Bi_x$ demonstrating increasing wavelength extension with increasing bismuth incorporation, which is extremely promising for high-performance optoelectronic devices. Then, by achieving the first lattice-matching of $InAs_ySb_{1-x-y}Bi_x$ to InSb substrates, we established a route towards lattice-matched photodetectors with strong absorption from thick, high-quality active regions. At this year's conference, I am excited to present how our growth advances have enabled the first lattice-matched, bulk III-V photodetectors with cutoff wavelengths extended beyond that of native InSb. Altogether, this work showcases the strong device potential for InSb-based dilute-bismide alloys.





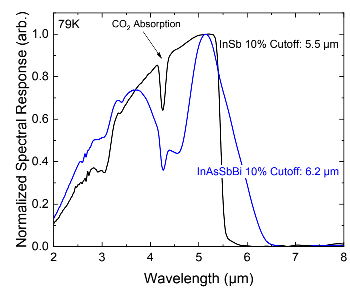


Fig. 1 (Left) Photoluminescence from InSbBi films with up to 1.9% bismuth incorporation demonstrating significant wavelength extension with minimal bismuth incorporation. Notably, the PL intensity does *not* drop off with increasing bismuth content (as is often seen in highly mismatched alloys) suggesting InSbBi PL strength is *not* dominated by bismuth concentration, which may be very promising for InSbBi-based optoelectronic devices operating at extended wavelengths. **Fig. 2 (Middle)** Reciprocal space map of a lattice-matched InAsSbBi film with 1.3% bismuth incorporation grown on an InSb substrate showing no signs of relaxation or phase separation in the quaternary alloy. **Fig. 3 (Right)** Normalized spectral response from prototype InAsSbBi (blue) and InSb (black) photodetectors demonstrating an extension in cutoff wavelength from 5.5 μm for InSb to 6.2 μm for InAsSbBi due to the arsenic- and bismuth-induced bandgap reductions.

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Application for EMC Oral Presentation Award
Electronic Materials Conference 2024

Student Name: Yiteng Wang

Student Mailing Address *(school address preferred)*: 1107 W. Green St., Apt. 634, Urbana, IL, 61801

Student E-mail Address: yitengw2@illinois.edu

Advisor Name: Minjoo Larry Lee

Advisor E-mail Address: mllee@illinois.edu

Advisor Signature: ______________________________

Advisor signature certifies that the advisor has reviewed the award submission and finds that the work appears to be original and performed by the student.

Title of EMC Abstract: Heteroepitaxial Integration of Embedded Visible InP Quantum Dot Lasers on SiN/Si Photonic Integrated Circuits

Yiteng Wang
yitengw2@illinois.edu

a. Professional Preparation

Georgia Institute of Technology	Materials Science and Engineering	B.S.,	2019
University of Illinois Urbana-Champaign	Materials Science and Engineering	Ph.D., In Progress	

b. Appointments

2021- Graduate Research Assistant, University of Illinois Urbana-Champaign
2018-2019 Undergraduate Research Assistant, Georgia Institute of Technology

c. Publications

(i) Conference Presentations

[1] Wang, Y., Hool, R. D., North, W. K., Pandey, S., Raftery, E. M., Choquette, K. D., Lee, M. L. (2023). InP lateral epitaxial overgrowth by solid-source molecular beam epitaxy. The 37th North American Conference on Molecular Beam Epitaxy, Madison, WI, USA

[2] Wang, Y., Dhingra, P., Sorace-Agaskar, C., Heidelberger, C., Lee, M. L. (2022). Monolithic integration of III-Vs with silicon nitride integrated photonics by MBE. The 64th Electronic Materials Conference, Columbus, OH, USA

(ii) Publications

[1] Xu, S., Zhang, S., Kirch, J. D., Gao, H., Wang, Y., Lee, M. L., Tatavarti, S. R., Botez, D., Mawst, L. J. (2023). 8.1 μ m-emitting InP-based quantum cascade laser grown on Si by metalorganic chemical vapor deposition. Applied Physics Letters, vol. 123 pp. 031110 1-5.

[2] Wang, Y., Watanabe, A. O., Ogura, N., Raj, P. M., Tummala, R. R. (2020). Sintered Nanocopper Paste for High-Performance 3D Heterogeneous Package Integration. Journal of Electronic Materials, vol. 49, pp. 6737–6745.

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[4] Watanabe, A. O., Wang, Y., Ogura, N., Raj, P. M., Smet, V., Tentzeris, M. M., Tummala, R. R. Low-Loss Additively-Deposited Ultra-Short Copper-Paste Interconnections in 3D Antenna-Integrated Packages for 5G and IoT Applications. (2019). IEEE 69th Electronic Components and Technology Conference (ECTC), Las Vegas, NV, USA, pp. 972-976

d. Synergistic Activities

Student volunteer of the 102nd Engineering Open House (EOH) at University of Illinois Urbana-Champaign 2024

One-Page Narrative for EMC 2024 Student Oral Presentation Award

[redacted]

Figure 1. (a) False-colored XSEM of embedded edge-emitting laser. (b) Photograph of laser emission under CW electrical pumping. (c) RT CW laser spectrum of 4.6-µm ridge laser at injection current below and above threshold.

Heterogeneous integration of visible lasers with Si- or SiN-based photonics is attractive for on-chip photonic applications such as quantum computing, biosensing and near-eye displays.[1-3] Although wafer- and chip-scale bonding are commercially available for heterogeneous integration, direct epitaxial growth of III-V devices on complementary metal–oxide–semiconductor (CMOS)-compatible Si photonic integrated circuits (PICs) leverages the advantages of the Si IC industry and enables a high density of integration and high scalability. To address the challenges of growing III-V on lattice-mismatched Si substrates, particularly the formation of threading dislocation defects, quantum dots (QDs) are considered as a great candidate for active layers of III-V lasers on Si photonics due to their high dislocation tolerance, in addition to their thermal stability and optical feedback immunity.[4-5] With such unique properties, a wide variety of epitaxial III-V QD lasers have been demonstrated on planar or v-grooved Si at a wide range of wavelengths from blue to infrared.[6-11] Moving a step further, several groups have demonstrated near- to mid- infrared lasers on patterned Si PICs by direct epitaxial growth.[12-14] However, to date, no visible spectrum lasers on Si PICs have been reported.

With collaboration with C. Heidelberger et al. from MIT Lincoln Laboratory, we are able to fill the gap by integrating an InP QD laser emitting in the red spectrum on SiN/Si PICs via direct epitaxial growth by molecular beam epitaxy. The novelty of our work lies in the first demonstration of visible spectrum InP QD lasers directly grown on CMOS foundry-compatible SiN/Si PICs with CW operation at low threshold current density (< 800 A/cm^2) and mW-level power output. The work can further pave the wave to realize visible integrated photonics on chip for applications such as quantum information, near-eye displays, and bio-sensing.

[1] Wang, Jianwei, et al. *Nature Photonics*, vol. 14, no. 5, May 2020, pp. 273–84. **[2]** De Vos, Katrien, et al. *Optics Express*, vol. 15, no. 12, 2007, p. 7610. **[3]** Hamada, Hiroki. *Fiber and Integrated Optics*, vol. 34, no. 5–6, Nov. 2015, pp. 259–81. **[4]** Dhingra, Pankul, et al. *Applied Physics Letters*, vol. 117, no. 18, Nov. 2020, p. 181102. **[5]** Huang, H., et al. *APL Photonics*, vol. 5, no. 1, Jan. 2020, p. 016103. **[6]** Sun, Yi, et al. *Light: Science & Applications*, vol. 7, no. 1, June 2018, p. 13. **[7]** Luo, Wei, et al. *Optics Letters*, vol. 46, no. 18, Sept. 2021, p. 4514. **[8]** Lin, Qi, et al. *Optics Express*, vol. 31, no. 10, May 2023, p. 15326. **[9]** Shang, Chen, et al. *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 25, no. 6, Nov. 2019, pp. 1–7. **[10]** Tournié, Eric, et al. *Light: Science & Applications*, vol. 11, no. 1, June 2022, p. 165. **[11]** Xu, S., et al. *Applied Physics Letters*, vol. 123, no. 3, July 2023, p. 031110. **[12]** Shang, Chen, et al. *Light: Science & Applications*, vol. 11, no. 1, Oct. 2022, p. 299. **[13]** Wei, Wen-Qi, et al. *Light: Science & Applications*, vol. 12, no. 1, Apr. 2023, p. 84. **[14]** Remis, Andres, et al. *Light: Science & Applications*, vol. 12, no. 1, June 2023, p. 150.

Application for EMC Oral Presentation Award
Electronic Materials Conference 2024

Student Name: Shagorika Mukherjee

Student Mailing Address: University of Delaware
Rm 201, 127 The Green
DuPont Hall
Newark, Delaware, 19716
United States

Student E-mail Address: shagrika@udel.edu

Advisor Name: Dr. Stephanie Law

Advisor E-mail Address: slaw@psu.edu

Advisor Signature: Stephanie Law

Advisor signature certifies that the advisor has reviewed the award submission and finds that the work appears to be original and performed by the student.

Title of EMC Abstract: Shadow Mask Molecular Beam Epitaxy

Shagorika Mukherjee
shagrika@udel.edu

a. Professional Preparation

Independent University, Bangladesh	Electrical & Electronic Engineering	B.S., 2016
University of Delaware	Materials Science & Engineering	Ph.D. Candidate

b. Appointments

2021- Graduate Research Assistant, University of Delaware, USA
2017-19 Lab Instructor, North South University, Bangladesh
2016-17 Lab Instructor, Independent University, Bangladesh
2014-15 Undergraduate Teaching Assistant, Independent University, Bangladesh

c. Publications

(i) Mukherjee, S., Sitaram, S. R., Wang, X., Law, S., "Shadow Mask Molecular Beam Epitaxy", NAMBE 2023, Madison, Wisconsin (conference poster presentation)

…

(ii) Chatratin, I., Mukherjee, S., Janotti, A., "Revisiting the role of group-V acceptor impurities and their AX centers in CdTe", APS March Meeting 2022 (Link)

(iii) Chatratin, I., Mukherjee, S., Janotti, A., "Hybrid Functional Calculations for Antimony Doping in CdTe", IEEE PVSC 2022 (Indexed in IEEE, Link)

(iv) Mukherjee, S., Razzak, M. A., "Analysis of 100 kW Grid-Connected Solar Photovoltaic System Developed on the River Deltas of Eight Divisions of Bangladesh Using RETScreen ", ECCE 2017, (Indexed in IEEE, Link)

(v) Mukherjee, S., Razzak, M. A., "Design, Analysis & Optimization of Grid-Connected Solar Photovoltaic System Using RETScreen in Eight Divisions of Bangladesh", iCEEiCT 2016, (Indexed in IEEE, Link)

d. Synergistic Activities

EmPower Mentor to new incoming graduate students (2022), University of Delaware

Secretary (2022), Materials Research Society (MRS) student chapter, University of Delaware

First Year Representative (2021), Materials Research Society (MRS) student chapter, University of Delaware

Shagorika Mukherjee
University of Delaware

Motivation

The motivation of our research lies in creating ***in-plane gradient permittivity materials (in-plane GPMs)***, the foundation to develop ***ultracompact spectrometers (UCSs)*** working in the mid-infrared (mid-IR) regime. IR spectroscopy is known for its applications in chemical sensing, environmental monitoring, thermal imaging, healthcare, security and atmospheric studies[1]. The available conventional IR spectroscopy systems are expensive and bulky. Even the existing on-chip configurations either need a large footprint and have low resolution or are limited to short working wavelengths (< 2 μm)[2-5]. We are motivated to solve all these problems by making a compact, low cost, and furthermore, a spectrometer with higher and wider working wavelength range (~6-16 μm). The mid-IR is of interest as various fundamental molecular absorption resonances take place in this wavelength range[6]. In an in-plane GPM, different wavelengths of light can be confined at different in-plane locations at the nanometer scale. Hence, the proposed UCS based on an in-plane GPM will be an innovative way to collect spectral information from incident light on a chip, resulting in significantly reduced size and cost of a spectrometer. This can potentially reduce the dimensions of the chip to ~10-20 μm, significantly smaller than other available IR spectrometers.

Novelty

Our aim is to synthesize in-plane GPMs, in which the permittivity varies in the lateral/in-plane direction. The novelty of this research work lies in developing an easy to replicate and reliable technique to fabricate in-plane GPMs. Current methods of in-plane GPM fabrication involve etching[7] of materials after growth, ion implantation patterning[8], and RF magnetron sputtering[9]. These techniques have a variety of downsides such as contamination/damage to the films, diminished film quality, etc. We will address these issues by using an old technique called ***shadow mask molecular beam epitaxy (SMMBE)*** [10,11]. As the name suggests, SMMBE uses a mask either directly fabricated on the substrate or placed in contact with the substrate. During film deposition, epitaxial layers are grown on the substrate through apertures in the mask. In this way, the film grows only in the desired areas, eliminating the need for post-growth etching and the concomitant damage to the film. The use of the shadow mask results in a gradient of film thickness and/or composition near the mask edges. The steepness of the gradient can be controlled by varying the mask thickness and/or the angle of the mask edges. In this research, we demonstrate the potential of the SMMBE technique in developing in-plane GPMs, which, to the best of our knowledge, has not been explored before. We are interested in working in the IR regime, hence our GPMs are comprised of Si:InAs, a good IR plasmonic material. By creating flux gradients of both indium and silicon near the edges of the mask, we can control the permittivity of Si:InAs in the in-plane direction. Each location on the material surface thus has a different carrier density, leading to a different plasma frequency, and ultimately to a different permittivity. Furthermore, another innovation of this project lies in the idea of incorporating our in-plane GPMs to develop on-chip IR spectrometer devices. The figure below represents (a) the schematic of in-plane GPM development process using SMMBE; (b) nano-FTIR spectrum from an in-plane GPM showing a gradient of field enhancement from ~650 cm^{-1} to 900 cm^{-1} over a sample width of ~13 μm, indicating the successful creation of an in-plane permittivity gradient; and (c) schematic of the proposed spectrometer.

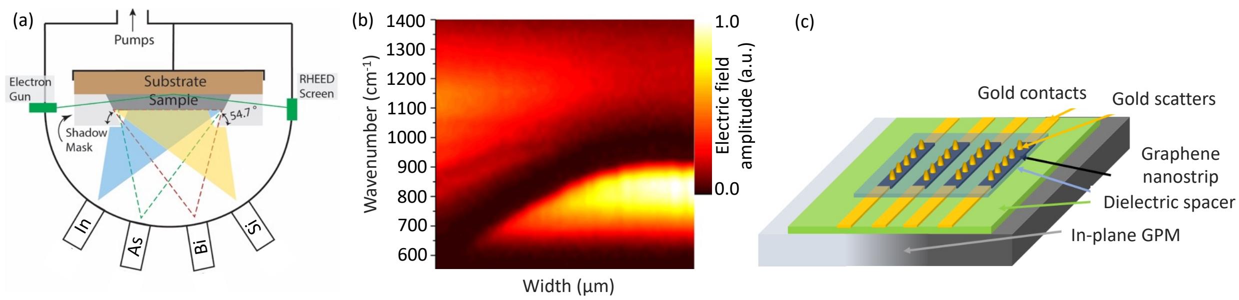

Fig. 1. (a) schematic of in-plane GPM development process using SMMBE (reproduced)[12]; (b) nano-FTIR spectrum from an in-plane GPM showing a gradient of field enhancement; (c) schematic of the proposed ultracompact spectrometer using an in-plane GPM.

References:
1. S. S. Dhillon et al. 2017; 2. D. M. Kita et al. 2018; 3. X. Wu et al. 2004; 4. R. F. Wolffenbuttel et al. 2004; 5. Private communication: UCS proposal; 6. S. Law et al. 2012; 7. C. Ionescu-Zanetti et al. 2006; 8. A. J. Cleri et al. 2022; 9. Herbert Dittrich et al. 2009; 10. W. T. Tsang et al. 1977; 11. Y. Luo 2000; 12. T.P. Ginley et al. 2020.