NAMBE
Room Tamaya ABC - Session NAMBE1-MoA
Photonic Devices

Moderator: Thomas E. Vandervelde, Tufts University

1:30pm **NAMBE1-MoA-1 ErAs/Semiconductor Nanocomposites for 1.55 µm-Pumped and Hybrid Terahertz Photoconductive Switches***, **Angelique Gordon,** Wilder Acuna, Weipeng Wu, James Bork, Matthew Doty, Xi Wang, M. Benjamin Jungfleisch, Lars Gundlach, Joshua Zide,* University of Delaware

We present our latest results on the growth of ErAs/III-V semiconductor materials designed for photoconductive devices operating at 1.55 µm telecom-wavelength and for hybrid emitters. Terahertz (THz) technology holds significant promise across various fields, including biomedical imaging, communications, astronomy, and spectroscopy. Bridging the "Terahertz Gap" requires new materials engineered for high-performance and reliable technology. Photoconductive switches (PCS), key components for THz pulse generation and detection, face challenges under 1.55 µm excitation. ErAs:InGaAs and other nanocomposites have been explored for this purpose, but their high electron concentration, due to the Fermi level residing in the conduction band, limits dark resistivity. To address this, we propose ErAs:[$(InGaBiAs)_x(InAlBiAs)_{1-x}$)], a digital alloy with incorporated nanoparticles, as suitable PCS material for telecom-wavelength usage[1]. ErAs nanoparticles ensure sub-picosecond carrier lifetimes ensuring high temporal resolution while simultaneously pinning the Fermi level within the bandgap. The freedom offered by the InGaAlBiAs short-period superlattice enables tunable bandgap engineering—aluminum raises the conduction band edge while bismuth, incorporated through low-temperature, stoichiometric growth, maintains a bandgap suitable for 1.55 µm excitation. This approach achieves both low carrier concentration and high dark resistivity, enhancing the performance of THz photoconductive devices at telecom wavelengths. We also demonstrate a Hybrid THz emitter that integrates a sputtered Ta/CoFeB/Pt spintronic emitter and an MBE grown ErAs:GaAs photoconductive antenna (PCA) into a single device[2]. This device enables independent and tunable excitation of two THz emitters, facilitating control over emerging THz functionalities such as elliptical polarization and pulse shaping.

[1] W. Acuna, et al., Adv. Funct. Mater. 34, 2041853, (2024).

[2] W. Wu, et a.l, Adv. Opt. Mater. 2402374, (2024).

1:45pm **NAMBE1-MoA-2 Regrowth of Gasb Photonic Crystal Surface-Emitting Lasers by Molecular Beam Epitaxy***, Bradley J. Thompson,* Air Force Research Laboratory, Sensors Directorate*; Samuel M. Linser,* KBR & Air Force Research Laboratory, Sensors Directorate*; Sadhvikhas Addamane,* Sandia National Laboratories*; Thomas Rotter, Ganesh Balakrishnan,* University of New Mexico*; **Ricky Gibson**,* Air Force Research Laboratory, Sensors Directorate

The photonic crystal surface-emitting laser (PCSEL) is promising device for scaling power and brightness of semiconductor lasers [1]. Embedding a 2D photonic crystal near the active region of semiconductor laser defines the cavity and enables surface-emission. Not unlike distributed feedback (DFB) lasers this requires an epitaxial regrowth step, though for the PCSEL the feature sizes are smaller than those of the DFB laser and the lithographic features are closer to the active region. To operate a PCSEL in single-mode at the Γ-point a high-index contrast and appropriate symmetry of the photonic crystal are necessary. This requires control of the regrowth profile of the 2D photonic crystal. Output powers of 50W continuous-wave have been reported in GaAs-based devices operating around a wavelength of 1µm [2] utilizing metal-organic chemical vapor deposition (MOCVD). While these devices can be extended to longer wavelengths the necessary regrowth becomes challenging [3], particularly in antimonide-based devices due to the higher adatom mobility and the larger lattice constant required for the extend-short-wave infrared (e-SWIR) wavelengths. To date a maximum of 30mW from a 250µm aperture device have been reported [4]. Performance gains are expected with improved regrowth and the ability to optimize device based on high-fill factor air-void photonic crystals. Here we report on initial regrowth samples and devices exploring the molecular beam epitaxy (MBE) parameter space for devices emitting nominally at a wavelength of 2µm. Initial samples show higher uniformity and regularity in the embedded 2D photonic crystal, based on scanning electron microscope (SEM) images, than what have previously been reported. Limitations to optimization of GaSb-based devices based on the material and growth decisions will also be discussed.

[1] S. Noda, et al., "High-power and high-beam-quality photonic-crystal surface-emitting lasers: a tutorial" Advances in Optics and Photonics, 15(4), 977-1032 (2023).

[2] M. Yoshida, et al., "High-brightness scalable continuous-wave single-mode photonic-crystal laser" Nature, 618(7966), 727-732 (2023).

[3] W. Lee, et al., "Comparison of Thermal and Atomic-Hydrogen-Assisted Oxide Desorption Methods for Regrowth of GaSb-Based Cascade Diode Lasers" J. Electron. Mater. 50, 5522–5528 (2021).

[4] L. Shterengas, et al., "Photonic Crystal Surface Emitting GaSb-based Type-I Quantum Well Diode Lasers" IEEE Journal of Selected Topics in Quantum Electronics, 31(2), 1-7 (2025).

2:00pm **NAMBE1-MoA-3 Growth and Optimization of Opto-electronic performance of InGaAsSb Photodetectors using Molecular Beam Epitaxy***, **Neha Nooman**, Nathan Gajowski, Punam Murkute, Vinita Rogers, Sanjay Krishna,* The Ohio State University

The quaternary alloy, $In_xGa_{1-x}As_ySb_{1-y}$, grown lattice-matched to GaSb substrates, is a promising alternative to extended InGaAs for Short-Wave Infrared (SWIR) detection due to its tunable wavelength range from 1.7 µm to 3 µm. This flexibility is essential for advanced imaging and sensing applications, positioning InGaAsSb as a key material for next-generation infrared devices. Yet, GaSb-based devices face challenges like high background doping and surface leakage, which hinder performance. Various growth techniques and architectures, including unipolar barrier designs, have been explored in the literature to mitigate these issues. Developing an optimal InGaAsSb-based structure requires a comprehensive understanding of the material's properties and key device performance metrics [1]. This work presents the molecular beam epitaxial (MBE) growth and characterization of the nominal composition $In_{0.29}Ga_{0.71}As_{0.25}Sb_{0.75}$ on a GaSb substrate. The growth temperature was estimated to be in the range of 450°C–460°C. Reflection High-Energy Electron Diffraction (RHEED) patterns confirmed that the InGaAsSb layer grows with a (4×2) surface reconstruction. Following MBE growth, the surface and structural properties of the alloy were characterized using High-Resolution X-Ray Diffraction (HR-XRD), Atomic Force Microscopy (AFM), Nomarski imaging, and photoluminescence (PL). Two structures were fabricated: a bulk structure with a 500 nm thick InGaAsSb layer and a homojunction p-i-n structure with a 1 µm thick intrinsic layer. The bulk InGaAsSb exhibited a lattice mismatch of 0.164% and a surface roughness of 1.02 A, indicating good crystalline quality. The PL peak was observed at approximately 2.33 µm. However, HR-XRD scans of the p-i-n structure revealed evidence of spontaneous superlattice formation in the active region, which is currently under investigation. This behavior may be attributed to growth near the miscibility gap (x~0.3). PL measurements showed no detectable peak shift despite the presence of the superlattice. Ongoing studies focus on optoelectronic properties like minority carrier lifetime and background doping to assess the superlattice's impact on performance.

1. K. Mamić, L. A. Hanks, J. E. Fletcher, A. P. Craig and A. R. J. Marshall, Semiconductor Science and Technology **39** (11), 115002 (2024).
2. I. P. Ipatova, V. A. Shchukin, V. G. Malyshkin, A. Y. Maslov and E. Anastassakis, Solid State Communications **78** (1), 19-24 (1991).

2:15pm **NAMBE1-MoA-4 Growth-Temperature Effect on Group-V Compositions in 'W' Structured GaAsSb/InGaAs/GaAsP Quantum Wells***, **Zon Ma**,* National Chung Hsing University, Taiwan*; Chao-Chia Cheng, Chun-Nien Liu, Jenn-Inn Chyi, Charles W. Tu,* National Tsing Hua University, Taiwan

The display cutout area, "notch" or "Dynamic Island", of an iPhone is located at the top of the display and houses the front-facing camera, vertical-cavity surface-emitting lasers (VCSELs), and detectors for Face ID. These VCSELs use top and bottom AlAs/GaAs Distributed Bragg Reflectors (DBRs) as the vertical cavity, and the emission wavelength is limited to 980 nm, which cannot penetrate the display, and hence the "notch". It is desirable, however, to utilize the whole display, edge to edge, if the wavelength can be 1380 nm. Furthermore, the minimum permissible exposure for eye safety is about 500 times higher at 1380 nm than at 980 nm. Therefore, many groups are pursuing long wavelength emission on GaAs substrates for these two reasons. There have been several approaches. One is wafer bonding of InP-based lasers and GaAs-based DBRs, which is a more complicated process than simpler epitaxy. Other approaches are dilute nitrides and self-assembled InAs quantum dots, but they suffer from low output power due to material defects and small active volumes, respectively. This paper studies another approach: type-II

InGaAs/GaAsSb 'W'-quantum wells (QWs) with GaAsP strain compensating layers grown on GaAs (001) substrates by MBE. The schematic band diagrams are shown in Fig. 1. The control of group-V compositions in ternary and quaternary compounds, such as GaAsP, InAsP, GaAsSb, InAsSb, InGaAsP, and InGaAsSb, is a significant challenge. The growth temperature was varied from 450 to 540ºC while other growth parameters were kept the same. The designed QW thicknesses and material compositions (Sb, In, and P%) are 15 nm-GaAs0.9Sb0.1, 3 nm-In0.3Ga0.7As, and 15 nm-GaAs0.75P0.25, respectively. Fig. 2 shows the x-ray rocking curves (XRCs) and simulations of 'W'-QWs grown at five different growth temperatures. The extracted results from XRC analysis prove that the group-V compositions (As, Sb) and (As, P) are varied as a function of growth temperature. The phosphorus composition in GaAsP increases at growth temperature >500ºC. At higher temperatures, the group-V materials desorb readily and compete with each other during the growth. The desorption affects the growth rate and, consequently, QW thickness. Unlike the P incorporation behavior, the Sb composition in GaAsSb decreases with higher growth temperature. This can be attributed to the lower sticking coefficient of Sb at higher temperatures. The different incorporation behaviors of P and Sb were numerically extracted as shown in Fig. 3. Photoluminescence (PL) emissions are observed from shorter to longer wavelengths by increasing Sb incorporation. The very low Sb composition creates type I GaAsSb/InGaAs QWs, resulting in stronger PL at shorter wavelengths, as shown in Fig. 4. In summary, the different incorporation behaviors of group-V materials in GaAsSb/InGaAs/ GaAsP 'W'-QW affected by the growth temperature are experimentally investigated. XRC determines the material compositions, QW thicknesses, and crystalline quality. The emitted PL characteristics are in good agreement with XRC. The optimum growth temperature range of 450-500ºC for 'W'-QW is revealed to achieve better Sb incorporation and extend the PL emission wavelength.

2:30pm **NAMBE1-MoA-5 III-V Quantum Dot Lasers and Photodetectors Monolithically Integrated with Silicon Photonics by Two-Step Growth***,*

Alec Skipper*, Rosalyn Koscica,* UC Santa Barbara*; Bei Shi,* Aeluma Inc.*; Gerald Leake, Joshua Herman,* AIM Photonics*; Michael Zylstra,* Analog Photonics*; Kaiyin Feng, Chen Shang,* UC Santa Barbara*; David Harame,* AIM Photonics*; Jonathan Klamkin,* Aeluma Inc.*; John Bowers,* UC Santa Barbara

The integration of lasers with silicon photonics is required to produce highly-efficient low-footprint photonic integrated circuits (PICs) for applications in data communication, LIDAR, and biosensing. Monolithic integration through the direct growth of III-V semiconductor materials on patterned silicon photonics wafers would enable large-scale production of PICs by utilizing 300 mm silicon wafers and eliminating costly III-V substrates from the process. However, growth on patterned silicon photonics wafers introduces new challenges in material quality, coupling efficiency, and growth uniformity. In this work, we report a two-step growth approach using metal-organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) to create InAs quantum dot lasers and photodetectors coupled to silicon nitride waveguides on foundry-processed silicon photonics wafers.

By combining MOCVD's high-quality selective III-V buffers on silicon with MBE's precise control of growth parameters for quantum dots, we can mitigate many of the difficulties associated with III-V growth on patterned silicon photonics wafers. Photonic integrated circuits with silicon nitride couplers, silicon nitride waveguides, silicon ring resonators, and silicon nitride distributed Bragg reflectors all embedded in silicon dioxide were fabricated at AIM Photonics on 300 mm silicon-on-insulator wafers. Pockets were etched through the silicon dioxide leaving the silicon nitride couplers exposed on the silicon dioxide sidewalls. Anti-phase domain-free GaP, a GaAs buffer, and InGaAs strained layer superlattices were grown by MOCVD to reduce the defect density. Selective MOCVD growth was used in the exposed silicon pockets to prevent the deposition of polycrystalline III-V on the sidewalls containing the nitride couplers. A separate confinement heterostructure laser stack was then grown by MBE on diced 3.2 x 2.6 cm coupons with an InAs quantum dot active region aligned to the nitride couplers. This material was then fabricated into 4 mm long and 4 um wide ridge waveguide devices with contacts for electrical bias.

Using this method, we demonstrate waveguide-coupled lasers and photodetectors monolithically integrated with foundry-processed silicon photonics wafers. Lasers operate in the O-band for data communication applications and show mW-scale output powers measured in-fiber when coupled out of the chip. Photodetectors were characterized as a function of bias voltage when excited by 1.3 um input laser light coupled from off-chip. The photodetectors show a highly linear response with sub-nA dark current. Together with the integrated laser results, this represents a major step forward in creating scalable PICs with on-chip III-V devices.

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2:45pm **NAMBE1-MoA-6 Optical Enhancement of GaAsP Solar Cells on GaP/Si with Distributed Bragg Reflectors***,*

Bora Kim*, Adrian Birge, Brian Li, Corey White, Devon Lee, Minjoo Larry Lee,* University of Illinois Urbana-Champaign

Epitaxial III-V/Si tandem solar cells offer a path to high efficiency at lower cost[1]. 1.7 eV $GaAs_yP_{1-y}$ (GaAsP) is an optimal top cell for Si-based tandems, leveraging a GaP nucleation and a GaAsP graded buffer. Despite advances in dislocation control in GaAsP subcells on Si with two-step growth, strained layer superlattices, tailored doping profiles, and compositional grading[2], high threading dislocation density (TDD) still limits minority carrier diffusion lengths. Thinner GaAsP absorbers can mitigate challenges with low diffusion lengths but incur optical losses due to incomplete absorption. A distributed Bragg reflector (DBR) resolves this limitation by reflecting transmitted photons back into the absorber, enhancing effective optical path length and carrier collection while enabling thinner GaAsP. Here, we demonstrate the first GaAsP single-junction (1J) cell on Si with a 1.46% efficiency boost from a 20-period $Al_{0.20}Ga_{0.80}AsP/Al_{0.80}Ga_{0.20}AsP$ DBR, highlighting photon management for high-performance GaAsP/Si tandem solar cells.

We grew GaAsP solar cells via MBE on GaP/Si (001) templates with a 500 nm p-GaP buffer, a 1.8 µm p-GaAsP graded buffer and a 750 nm GaAsP absorber. Compared to our previous best GaAsP 1J devices[3], we reduced the cell thickness by 2.2 µm, allowing >2 µm for the DBR without exceeding the thermal expansion cracking threshold of ~6 mm.

The 20-period AlGaAsP DBR calibration shows a 95.7% peak reflectance with a 55 nm bandwidth, closely matching calculations (97.2%, 60 nm). Electron channeling contrast imaging reveals similar TDD (~7-8×10^6 cm^{-2}) in cells with or without a DBR, indicating negligible impact from DBR growth. External quantum efficiency (EQE) measurements show enhanced carrier collection at 660-730 nm due to DBR reflection, increasing EQE-calculated short-circuit current density (EQE-J_{SC}) by 1.42 mA/cm^2. EQE at 450-550 nm was lower than expected, likely due to elevated window/emitter interface recombination loss. Nevertheless, the DBR cell exhibits a 1.46% absolute efficiency gain due to increased J_{SC} and a 12 mV open-circuit voltage (V_{OC}) boost. Additionally, V_{OC} and fill factors closely match our previous best n+/i/p cells[3].

This work demonstrates 15%-efficient GaAsP solar cells on Si with an AlGaAsP rear DBR, where DBR reflection improves near-bandedge EQE and J_{SC}. Our results show the promise of DBRs for high-efficiency, low-cost GaAsP/Si tandems, with potential for enhanced radiation hardness in space applications with a thin absorber.

[1] J. F. Geisz et. al., *Semicond. Sci. Technol.* **17** (2018). [2] J. T. Boyer et. al., *Cryst. Growth Des.*, **20** (2020). [3] S. Fan et. al., *Cell Rep. Phys. Sci*., **1** (2020).

3:00pm **NAMBE1-MoA-7 Interface Fermi-Level Engineering for Selective Hole Extraction Without P-Type Doping in CdTe Solar Cells to Reach High Open Circuit Voltage (>1 V)***,*

Zheng Ju*, Xin Qi, Xiaoyang Liu,* Arizona State University*; Jiarui Gong,* Texas A&M University*; Razine Hossain, Nathan Rosenblatt, Tyler McCarthy, Allison McMinn, Martha McCartney, David Smith,* Arizona State University*; Zhenqiang Ma,* University of Wisconsin - Madison*; Yong-Hang Zhang,* Arizona State University

Solar cells, along with other optoelectronic devices such as photodiodes, light-emitting diodes (LEDs), and lasers, rely on p-n junctions to either collect photogenerated carriers in absorber regions or inject carriers into the active region. The use of p-n junctions in solar cells is advantageous because the electric field within the device yields the efficient extraction of photogenerated carriers for high power conversion. The doping levels in the p- and n-regions set the built-in voltage (V_{bi}) across the device, which in turn limits the maximum achievable open circuit voltage (V_{oc}). A higher V_{bi} is preferred as it creates a stronger electric field in the absorber region, reducing the transit time for photogenerated carriers, enhancing their collection at the contacts, and improving overall conversion efficiency.

Solar cells with a V_{oc} exceeding 1 V have been developed using an n-type CdTe/MgCdTe double-heterostructure (DH) absorber with an n-type indium tin oxide (ITO) transparent layer forming a hole-selective contact. No p-type doping is used in the devices. The ITO layer is directly deposited atop the MgCdTe barrier layer. Charge transfer from the ITO and the n-type absorber to the interface states between the ITO and the top MgCdTe barrier results in a Fermi level near the valence band edge of the CdTe layer. This charged interface functions effectively as a "p-region," achieving a V_{bi} of up to 1.01 V. A straightforward model is proposed to explain the relationship between Mg composition in the barrier layer and the corresponding V_{bi}. The modeling results are in good agreement with experimental results obtained from capacitance-voltage (*C-V*) measurements.X-ray photoelectron spectroscopy (XPS) measurements on samples having a MgCdTe top barrier layer with different Mg compositions confirm the correlation between the interface Fermi-level position and the observed V_{bi}. The devices, tested by the National Renewable Energy Laboratory (NREL), show a V_{oc} over 1 V (1.0164 ± 0.0026 V), consistent with the V_{bi} derived from *C-V* measurements, thereby confirming that V_{bi} limits V_{oc} in these devices. The integrated J_{sc} from EQE is 24.88 mA/cm^2, attributed to the absence of an absorptive hole-selective contact layer, such as a-Si:H. The efficiency of this device reaches 17.3%.

This innovative approach to addressing the challenge of low p-type doping in CdTe solar cells can potentially be applied to other interfaces involving semiconductors, transparent conductive oxides (TCOs), and certain metals, offering broad applications not only in photovoltaics but also in photodetectors, LEDs, and lasers.

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