Monday Morning, August 25, 2025

NAMBE
Room Tamaya ABC - Session NAMBE2-MoM
Bismuth-containing Alloys

Moderator: Corey White, University of Illinois at Urbana-Champaign

10:30am **NAMBE2-MoM-11 Molecular Beam Epitaxy Growth and Optoelectronic Properties of Droplet-Free Lattice-Matched GaInAsSbBi on GaSb with Photoluminescence Wavelength Exceeding 5 µm**, ***Preston T. Webster***, Air Force Research Laboratory, Space Vehicles Directorate; *Rigo A. Carrasco, Alexander T. Newell, Alexander W. Duchane,* Air force Research Laboratory, Space Vehicles Directorate; *Aaron J. Muhowski, Victor J. Patel, Samuel D. Hawkins,* Sandia National Laboratories; *Marko S. Milosavljevic, Shane R. Johnson,* Arizona State University; *Julie V. Logan, Christian P. Morath, Diana Maestas,* Air force Research Laboratory, Space Vehicles Directorate

While the performance of mid-wave infrared HgCdTe focal plane arrays are unparalleled, their relatively poor yield of manufacturing has motivated research into a multitude of III-V semiconductor alternatives. However, unlike HgCdTe which is tunable across the entire infrared spectrum with a lattice-matched (albeit *bespoke*) substrate, the III–V material and substrate options available present an MBE growth challenge. Type-II superlattice and metamorphic growth strategies have been the subject of a great deal of research to overcome the problem that, at present, there are no III-V random alloy solutions that can cover the full mid- to long-wave infrared spectral range on a commercially-available lattice-matched substrate. III-V alloys containing the heaviest group-V element Bi have long been known to offer the design freedom to achieve this degree of cutoff tunability with a lattice-matched substrate, however, they have historically proven to be very challenging to grow with smooth surface morphologies and high optoelectronic quality.

In this work, Ga is found to be the key to improving the incorporation quality of Bi in alloys of GaInAsSbBi. GaInAsSbBi alloys are grown lattice-matched on GaSb by molecular beam epitaxy demonstrating smooth surface morphologies, >5 µm wavelength photoluminescence emission, and minority carrier lifetimes > 1 µs [1]. At a growth temperature of 400 °C, the Ga flux is systematically increased, while the Bi flux is systematically decreased to identify GaInAsSbBi growth conditions that yield smooth droplet-free surface morphologies. The minority carrier lifetime is evaluated using time-resolved photoluminescence, where it is observed that GaInAsSbBi samples exhibit minority carrier lifetimes comparable to their Bi-free GaInAsSb counterparts, on the order of 1.5 - 2 µs. The bandgap and Urbach energy are evaluated from steady-state photoluminescence to gain insight into the impact of the incorporated Bi. Coupled with Rutherford backscattering spectrometry measurements of the Bi mole fraction, bandgap reduction rates of 97 meV/% Bi in InAsSbBi and 150 meV/% Bi in GaInAsSbBi are observed, significantly higher than previous experimental evaluations in InAsSbBi (35-55 meV/% Bi). The inclusion of Ga in the quinary alloy is effective in suppressing Bi's tendency to incorporate in clusters (which contribute to tail states that increase the Urbach energy slope) for Ga mole fractions > 9%, maximizing the bandgap reduction per unit Bi and overall optoelectronic quality.

[1] J. Appl. Phys. **137**, 065702 (2025).

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

10:45am **NAMBE2-MoM-12 Growth of InGaBiAs for Extended Short Wave Infrared Photodetectors**, ***Mrudul Parasnis***, *Md Toriqul Islam, Nuha Ahmed-Babikir, James Bork, Abhilasha Kamboj, Alimur Razi, Jamie Phillips, Joshua Zide,* University of Delaware

Dilute bismuthides are a class of highly mismatched alloys consisting of small amounts of bismuth incorporation in III-V semiconductors.[1] This incorporation of bismuth, due to its larger size compared to other elements within the host matrix, induces valence band anticrossing, thereby reducing the bandgap.[2] For this reason, dilute bismuthides are explored as a class of materials in optoelectronic devices such as infrared photodetectors.[2,3,4]

Previous studies have demonstrated that $In_{0.53}Ga_{0.47}As$ photodetectors have a wavelength of 1.7µm. Incorporation of bismuth into $In_{0.53}Ga_{0.47}As$ reduces the bandgap by 56 meV per %Bi, thereby extending the detection wavelength. In this work, we show that InGaBiAs can be used as a promising material for short wave infrared (SWIR) photodetectors and extend the operational wavelength beyond 1.7µm. The structure of SWIR photodetectors consist of Be doped InGaAs as a p-type capping layer and Si doped InGaAs as n-type region, both grown at 490°C and lattice matched to InP substrate. InGaBiAs acts as an active region and is grown at low temperatures of 265°C (Band edge thermometry). Diodes with this p-i-n structure are fabricated into mesa devices using standard photolithography, chemical etching, and metallization processes. Our findings show that incorporating 1.5% Bi into InGaBiAs successfully extends the wavelength up to 2µm.

The device properties have a strong dependency on the Bi/As flux ratio. We have observed that the dark current density, capacitance and spectral response are influenced by the growth conditions and flux ratios. A 5% increase in arsenic shows an increase in carrier lifetime by two orders of magnitude. The devices grown with about 7% higher arsenic flux showcased reduced dark current density ($1.55x10^{-3}A/cm^2$ at -0.1V) and enhanced spectral response compared to stoichiometric conditions. We identified two distinct activation energies for each growth condition, in order to analyze factors limiting dark current in stoichiometric, low As and high As flux growth conditions.

[1] Crystals 17, 7, 63 (2017) [2] J. Vac. Sci. Technol. A 40, 042702 (2022) [3] Appl. Phys. Lett. 99, 031110 (2011) [4] Appl. Phys. Lett. 100, 112110 (2012)

11:00am **NAMBE2-MoM-13 Performance of Mid-Wave Infrared GaInAsSbBi nBn Photodetectors Before and as a Function of High Energy Proton Exposure**, ***Julie Logan***, *Alex Newell, Rigo Carrasco, Christopher Hains, Gamini Ariyawansa, Joshua Duran, Diana Maestas, Christian Morath, Preston Webster,* Air Force Research Lab

There are presently no III-V random alloy detector solutions that can cover the full mid- to long-wave infrared spectral range on a commercially-available lattice-matched substrate. This technology gap forces compromise through either the management of defects introduced in metamorphic growth, use of strain-balanced InAs/InAsSb type-II superlattice which has reduced absorption and transport performance, or use of InSb which lacks design flexibility at this single cutoff wavelength of 5.5 µm. To overcome these limitations, the bulk random alloy GaInAsSbBi material system is being developed which can simultaneously be grown lattice-matched on GaSb substrates while obtaining cutoff tunability due to the bandgap reduction rate of 150 meV/% Bi in GaInAsSbBi. The incorporation of Ga into the random alloy suppresses Bi's tendency to cluster and allows full exploitation of Bi's strong influence on bandgap to provide future tunability throughout the infrared spectral range.

Molecular beam epitaxy grown GaInAsSbBi *n*B*n* photodetectors are produced which exhibit a 4.8 µm cutoff wavelength at 130 K (0.3 µm longer than its Bi-free GaInAsSb counterpart *nBn* detectors), and these variable-area detector arrays are radiometrically characterized before and as a function of proton irradiation to evaluate anticipated operation in the space radiation environment. These photodetectors are produced with varied composition of the AlGaAsSb barrier to optimize the valence band alignment to the absorber material. It is shown that group-V composition in the barrier is more impactful than group-III composition in determining the photo-current turn-on and quantum efficiency (thus controlling the valence band alignment). The shot-noise limited noise equivalent irradiance for the most optimized structure characterized is 14× above the expectation for a hypothetical detector with unity quantum efficiency and Rule 07 dark current. Upon exposure to 63 MeV protons, defects generated in the crystal structure of the photodetector result in an increase in dark-current and reduction in quantum efficiency. These both result in an increase in noise equivalent irradiance, with a damage factor of 3.6×10^{-2} photons/p^+, which is notably lower than the 10^{-1} photons/p^+ reported for MWIR SL-based *n*B*n* detectors. Most of the improved radiation hardness is attributable to a lower rate of degradation in the dark current and minority carrier lifetime with irradiation. This could indicate that the incorporation of heavy Bi atoms enhances the radiation hardness of the material in a way analogous to Hg in HgCdTe, making them more suitable for space applications than other III-V detector solutions.

11:15am **NAMBE2-MoM-14 Improving Bi Incorporation in InSbBi and AlInSbBi**, ***Amberly Ricks***, University of Texas at Austin; *Corey White,* University of Illinois at Urbana Champaign; *Seth Bank,* University of Texas at Austin

InSb-based alloys are a promising alternative to HgCdTe for long-wave infrared (LWIR) operation.1,2 Adding small amounts of Bi into InSb leads to large bandgap reductions extending the infrared response,3 where most of the bandgap change occurs in the valence band.4,5 The integration of Bi into wide-bandgap alloys like AlInSb can decouple the lattice parameter from band alignments, offering a novel solution to dark currents in InSbBibased devices (e.g. as barriers). A challenge associated with growing Bi-containing III-V alloys is Bi forming droplets on the film surface instead of integrating into the alloy, requiring specific growth conditions.6,7 Thus, it is essential to investigate the growth space for InSbBi and AlInSbBi due to their combined potential as active and barrier layers for LWIR devices.

To explore Bi incorporation kinetics, InSbBi films were grown with a modulated Bi flux by solid-source MBE on n-InSb. Growth parameters promoting Bi incorporation3 were used: a 300°C substrate temperature, a 0.975x V/III flux ratio, and a ~1 μm/hr growth rate. Bi dose was modulated from 4 ML (for a 7.5 ML period) to 25 ML (for a 45 ML period). ω-2θ X-ray diffraction (XRD) measurements suggested similar Bi concentrations for all films, but atomic force microscopy (AFM) showed smooth surfaces (RMS roughness of ~1 nm) for the two shortest period samples. This indicates that Bi can be incorporated without droplets by utilizing the kinetics of Bi atoms and perhaps suppressing the formation of Bi nuclei. Experiments are underway to study higher Bi fluxes and other duty cycles.

To explore the solubility limits of Al, AlInSbBi films were grown by MBE at Al concentrations from 1-5%. The same growth parameters used for InSbBi were applied to enhance Bi incorporation, but with a continuous supply of Bi. ω-2θ XRD measurements showed a 0.5% Bi limit was reached for all AlInSbBi films, and AFM showed there were no droplets. Growths are underway with higher Bi fluxes to verify if the upper limit was reached, and future experiments will further investigate the interplay between Al and Bi. Understanding the growth space for both InSbBi and AlInSbBi will provide opportunities to create enhanced nBn devices lattice matched to InSb substrates that access the LWIR.

This work was supported by the NSF (DMR-2119302).

1 S. Svensson et al., Appl. Opt., 56, 2017

2 P. Martyniuk, M. Kopytko, and A. Rogalski, Opto-Electron. Rev., 22, 2014

3 R. White et al., Apply. Phys. Lett., 121, 2022

4 R. Kudrawiec et al., Semicond. Sci. Technol., 30, 2015

5 S. Francoeur et al., Appl. Phys. Lett., 82, 2003

6 M. Rajpalke et al., Appl. Phys. Lett., 105, 2014

7 A. Ptak et al., J. Cryst. Growth, 338, 2012

11:30am **NAMBE2-MoM-15 Impact of Hydrogenation on the Minority Carrier Lifetime of InAsSbBi and the Sensitivity of InAsSbBi nbn Photodetectors***, **Mach Michaels**,* Georgia Institute of Technology*; Mangal Dhoubhadel, Khalid Hossain,* JP Analytical, LLC*; Alexander Duchane, Rigo Carrasco, Luke Helms,* Air Force Research Laboratory*; Christopher Hains,* A-Tech, LLC, a BlueHalo Company (ATA BlueHalo)*; Julie Logan, Christian Morath, Diana Maestas, Preston Webster,* Air Force Research Laboratory

As decreasing rocket launch costs continually reduce the barrier to access space, space-based surveillance missions previously performed using a small quantity of exquisite sensing assets are being re-envisioned as larger constellations of satellites, necessitating the production of more sensors. The current state-of-the-art for mid- to long-wave infrared detection is HgCdTe-based, however, there has been a growing interest in more manufacturable III-V alloys to support these larger sensing constellations of tomorrow. III-V alloys incorporating the heaviest group-V element Bi, such as InAsSbBi, can be tuned to span the entire infrared spectral range with a lattice-matched commercially available substrate, however, the growth of these alloys is challenging. Relatively low growth temperatures conducive to incorporating higher mole fractions of Bi necessary to reach long-wave infrared cutoffs results in relatively higher defect content that degrades the minority carrier lifetime, a critical parameter governing the overall photodetector sensitivity. It has recently been shown that post-growth hydrogenation is effective in passivating these defects and improving the minority carrier lifetime in InAsSbBi [1], motivating the study of its effects on InAsSbBi *nBn* photodetectors.

In this work, molecular beam epitaxy grown InAsSb/InAsSbBi/InAsSb photoluminescence test structures and 4.32 μm cutoff InAsSbBi *nBn* photodetectors are examined before and after hydrogenation treatments using deuterium. In the photoluminescence test structures, the hydrogenation process yields a 4× improvement in the minority carrier lifetime, up to 1.2 μs. However, the lifetime of the *nBn* photodetectors remains unchanged following hydrogenation, as does the shot noise equivalent irradiance evaluation of their overall sensitivity. Instead, the hydrogenated *nBn* photodetectors exhibit a significantly higher reverse vias turn-on, suggesting that the hydrogenation process has modified the valence band alignment across the barrier/absorber interface. Secondary ion mass spectrometry measurements confirm that the deuterium delivered by the hydrogenation process is trapped in the overlying AlGaAsSb barrier layer in these structures and as such, cannot passivate the InAsSbBi absorber volume below. This result motivates future work to prioritize the so-called inverted *nBn* structure wherein the InAsSbBi active region is grown on the AlGaAsSb barrier.

[1] Appl. Phys. Lett. **124**, 021104 (2024).

11:45am **NAMBE2-MoM-16 Synthesis of Epitaxial $Bi_{1-x}Sb_x$ Nanomembranes***, **Saad Mohammad Bhuiya**,* University of New Mexico, Bangladesh

Bismuth-antimony ($Bi_{1-x}Sb_x$) alloys with x = 0.07–0.22 are known to host topologically protected states, making them promising candidates for quantum information processing. Establishing robust processes for synthesizing single-crystalline $Bi_{1-x}Sb_x$ compounds compatible with widely used substrates is crucial for materials and device characterization. In this work, we demonstrate the synthesis of $Bi_{1-x}Sb_x$ nanomembranes (NMs), structural elements that can be epitaxially grown on semiconductor substrates and transferred onto different hosts. These NMs present exciting opportunities for integrating topological states with additional functionalities. Furthermore, due to their elastic deformability, they offer a unique platform for investigating the effects of strain on $Bi_{1-x}Sb_x$ topological insulators.

Our synthesis approach involved epitaxial growth via molecular beam epitaxy (MBE), selective substrate removal, and NM transfer. We grew $Bi_{1-x}Sb_x$ layers with a target Sb composition of 8% on GaAs (111)A substrates (AXT Inc.). The substrates were degassed at 500 °C and deoxidized at 620 °C under As overpressure before deposition. The epitaxial films, designed to be ~100 nm thick, were grown at temperatures between 150–200 °C across different runs, with a deposition rate of ~4 nm/min. In situ reflection high-energy electron diffraction (RHEED) provided real-time monitoring, while ex situ characterization was conducted via x-ray diffraction (XRD), Raman spectroscopy, and electron microscopy. XRD revealed sharp diffraction peaks corresponding to $Bi_{1-x}Sb_x$, and Raman spectroscopy confirmed the presence of characteristic vibrational modes. Scanning electron microscopy (SEM) showed a relatively smooth film surface with some randomly distributed regions of increased thickness, whose structural properties remain under investigation.

We isolated the $Bi_{1-x}Sb_x$ NMs by selectively etching the GaAs (111)A substrate in an $NH_4OH:H_2O_2$ solution. To preserve NM integrity, the films were capped with a photoresist and mounted onto a glass substrate using crystal bond adhesive, with the GaAs surface facing upward. A customized jet etcher facilitated precise substrate removal. Following etching, the NM was released by dissolving the crystal bond and photoresist in acetone. The freestanding NM was then transferred onto an oxidized silicon substrate, although this method allows for versatile host selection. Optical imaging, SEM, and Raman spectroscopy confirmed the NM's structural integrity and the complete removal of GaAs. Profilometry measurements indicated a final NM thickness of ~98 nm, closely matching the intended epitaxial layer thickness.

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