Novel Materials
Room Swan BC - Session NM-TuA1
Bismuthides

Moderator: Kevin Grossklaus, Tufts University

1:30pm **NM-TuA1-1 NAMBE Young Investigator Awardee Talk: Why do we Bother Using Costly MBE for Semiconductor Nanowires?***, Songrui Zhao*[1]*,* McGill University, Canada **INVITED**

Low-dimensional semiconductor nanowires has been an attractive material platform for both novel electronic and photonic devices as well as exploring new physics at low dimensions. Back to more than two decades ago, low-cost chemical vapor deposition (CVD) techniques had already been able to demonstrate devices based on single Si, Ge, InP, and GaN nanowires. Comparing to CVD, the operational cost of MBE is dramatically higher. So why do we bother using costly MBE for semiconductor nanowires? In this talk, I will discuss III-nitride nanowires grown by MBE as well as applying such nanowires to photonic devices. I will show that using such nanowires, quite a few underlying material challenges for III-nitride photonic devices can be greatly addressed, e.g., p-type doping into InN and AlN. This enables devices that were not possible previously, such as 207 nm emitting AlN LEDs with turn-on voltage only limited by the bandgap energy and a rectification ratio of more than 10^6, electrically injected AlGaN deep ultraviolet (UV) lasers down to 239 nm. Moreover, I will further show that such nanowires can be a useful template for the wafer-scale integration of ultrawide bandgap III-nitride epilayers (AlN and Al-rich AlGaN) on Si, and greatly relax the substrate requirement for the development of ultrawide bandgap III-nitride electronic and photonic devices. Vertical semiconductor deep UV LEDs down to 247 nm are demonstrated using such an approach.

2:00pm **NM-TuA1-3 Electrical Characterization of Doped GaSbBi Films Using High Resistivity AlGaSb Underlayers***, John McElearney, K. Grossklaus, T. Vandervelde,* Tufts University

Dilute III-V-Bi alloys, such as $GaSb_{1-x}Bi_x$, have garnered interest in recent years as useful materials for mid- to far-IR optoelectronic devices. This is primarily due to the dramatic reduction in bandgap energy caused by the interaction of the Bi impurity with the host valence band edge [1]. In $GaSb_{1-x}Bi_x$ specifically, reductions of up to 35 meV/%Bi [2] have been observed. Additionally, a predicted suppression of Auger recombination [3] and ability to be grown pseudomorphically on commercially available GaSb substrates makes $GaSb_{1-x}Bi_x$ a prime candidate for use in long wavelength photonics. Effective design of such devices will require a deeper understanding of the doping behavior of GaSbBi than is currently available. However, both GaSb substrates and MBE-grown GaSb buffer layers are intrinsically p-type (n_a ~ 1e16/cm^3), making the measurement of carrier concentrations or mobilities of any epilayers grown on them non-trivial. Following techniques previously employed in GaSb [4], we report on the electrical characterization of Bi-containing films grown on high resistivity Al-containing underlayers.

In this work we present carrier concentrations and mobilities for intentionally and unintentionally doped $GaSb_{1-x}Bi_x$ samples grown on highly resistive $Al_yGa_{1-y}Sb$ underlayers. Samples were grown on Zn-doped GaSb substrates (n_a ~ 1e18/cm^3) in a Veeco GENxplor system. Al, Ga and Bi, as well as dopant fluxes, were supplied by solid source effusion cells, while Sb was sourced from a valved cracker cell. Growth was monitored in-situ via RHEED and temperature was tracked by blackbody emission using a k-Space BandiT system. Hall effect measurements were conducted on Be and Te-doped GaSbBi films of low to moderate Bi-fraction, as well as on GaSb-capped AlGaSb layers to demonstrate their resistive behavior. High-resolution XRD was used to determine Bi and Al content, as well as confirm film quality and homogeneity. We also examine the effect the Al-underlayer, as well as any dopants present, has on Bi droplet formation and surface morphology via both Nomarski optical microscopy and atomic force microscopy. Results of this work will enable improved modeling and design of future GaSbBi-based optoelectronic devices.

[1] D.P. Samajdar, T.D. Das, S. Dhar, *Mater Sci Semicond Process*, **40**, 539-542 (2015).

[2] M. K. Rajpalke et al., *J. Appl. Phys*. **116**, 043511 (2014).

[3] S. Das, M. K. Bhowal, S. Dhar, *J. Appl. Phys.* **125**, 075705 (2019).

[4] M. G. Mauk, V. M. Andreev, *Semicond. Sci. Technol.* **18,** S191 (2003).

2:15pm **NM-TuA1-4 Influence of Growth Conditions on InAlBiAs Morphology and Electrical Properties***, James Bork, W. Acuna, J. Zide,* University of Delaware

We present on our recent progress in MBE-growth of InAlBiAs on (001) InP. As highly-mismatched alloys, quaternary bismuthides like InAlBiAs offer high degree of control over lattice constant, bandgap and band alignment, and spin-orbit coupling. This tuneabilty makes bismuthides of interest for use in infrared emitters and detectors, solar cells, and other (opto)electronic devices. [2,3,4,5] However, the high mismatch between the bismuthides' constituent elements make high quality, droplet-free growth difficult to achieve. [6] While previous work has explored the optical properties of InAlBiAs [7], a systematic study of the impacts of growth conditions on InAlBiAs morphology and electrical properties was still needed.

Through variation of the V/III and Bi/As flux ratios used during growth, we have constructed a growth-space diagram of Bi incorporation that demonstrates several key morphological regimes: V-rich (with droplets), III-rich (with droplets), and droplet-free. Using this diagram, we have demonstrated droplet-free growth of InAlBiAs w/ up to 5.1% Bi. The unintentional n-type doping concentration of these materials were measured to be between 10^{13}-10^{15} cm^{-3}.

[1] *Crystals.*17, 7, 63 (2017) [2] *Semicond. Sci. Technol.* 27, 094011 (2012) [3]*Appl. Phys. Lett.* 88, 201112 (2006) [4] *Sol. Ener. Mat. and Sol. Cells.* 155, 446-453 (2016) [5] *Jour. of Photovol.* 6, 1183-1190 (2016) [6] *Jour. of Appl. Phy.* 120, 125310 (2016) [7] *Jour. of Appl. Phy.* 126, 095704 (2019)

2:30pm **NM-TuA1-5 ErAs:InGaAlBiAs materials for 1.55 µm-pumped Terahertz Photoconductive Switches***, Wilder Acuna, J. Bork, J. Avenoso, L. Gundlach, J. Zide,* University of Delaware

Here, we present the study on the molecular beam epitaxy growth of ErAs nanoparticles embedded within an InP-based $(InGaBiAs)_x$ $(InAlBiAs)_{1-x}$ digital alloy for use in photoconductive switches (PCS) for terahertz (THz) generation and detection. Towards the aim of achieving PCs with desired properties, ErAs:$(InGaBiAs)_x$ $(InAlBiAs)_{1-x}$ digital alloy (henceforth: ErAs:InGaAlBiAs) offers several advantages. First, ErAs self-assembles as nanoparticles and can be incorporated by co-deposition or interrupt-growth. These nanoparticles pin the Fermi level and act as effective carrier traps, decreasing the carrier lifetime to sub-picosecond values [1]. Additionally, the InGaAlBiAs matrix allows band alignment to be engineered around the pinned Fermi level. When the matrix is InGaAs, ErAs pin the Fermi level close to the conduction band. Adding Bi and Al makes it possible to align the band to have a midgap Fermi level, thereby increasing the dark resistance while maintaining a bandgap below 0.8 eV. In the case of Bi, just a small amount narrows the bandgap by lifting the valence band due to valence band anti-crossing (VBAC) [2]; however, this increases the growth complexity as low temperatures and stoichiometric conditions are required. In addition, the semiconductor needs to be optically thick to absorb the majority of the optical pump pulse. Accordingly, the film must be lattice-matched to the InP substrate. In addition to discussing the growth, we present our progress in measuring material properties required for a high-performance PCS. [1] Appl. Phys. Lett. 75, 3548 (1999); [2] Phys. Rev. B 75, 045203 (2007).

2:45pm **NM-TuA1-6 Impact of Bi Surface Coverage During Growth on GaAsBi Diode Performance***, Robert Richards, N. Bailey, T. Rockett, M. Carr,* University of Sheffield, UK*; S. Hasegawa, H. Kawata, H. Nishinaka, M. Yoshimoto,* Kyoto Institute of Technology, Japan*; J. David,* University of Sheffield, UK

The dramatic effect of bismuth alloying on the band structure of GaAs makes GaAsBi a promising candidate material for a range of applications from telecommunication laser diodes [1] to solar cells [2]. Recently, the increased spin-orbit splitting energy in GaAsBi has been shown to dramatically reduce the “excess noise” associated with GaAsBi avalanche photodiodes [3], promising a new family of ultra-low-noise, Bi-engineered photodetectors. Further development of the MBE growth of this alloy is required to reduce dark currents and realise its potential.

In this work, the influence of growth conditions on the performance of GaAsBi diodes is investigated across a large number of p-i-n diode devices grown at the University of Sheffield and the Kyoto Institute of Technology, as well as other devices reported in the literature. The results show that increasing bismuth content leads to an increase in the device dark currents due to the resultant reduction in the device band gap. The rate of change in saturation current density with respect to band gap is broadly in line with the findings of earlier work [4]; however, the temperature dependence of

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the saturation current density is not trivial. The results suggest that growth temperature is not the only key parameter for high-quality device production and that control of the bismuth surfactant layer during growth is critical to maintaining good material quality and the attendant low dark currents. For the most heavily strained devices, low temperatures appear to reduce the effect of plastic strain relaxation on the device properties [5]. By relating the dark currents to the low temperature photoluminescence properties of GaAsBi layers, the importance of the bismuth surface coverage during growth is highlighted.

[1]S. J. Sweeney and S. R. Jin, "Bismide-nitride alloys: Promising for efficient light emitting devices in the near- and mid-infrared," J. Appl. Phys., 113(4), 043110, (2013).

[2]R. D. Richards et al., "Photovoltaic characterisation of GaAsBi/GaAs multiple quantum well devices," Sol. Energy Mater. Sol. Cells, 172, 238-243, (2017).

[3]Y. Liu et al., "Valence band engineering of GaAsBi for low noise avalanche photodiodes," Nat. Commun., 12(1), 4784, (2021).

[4]R. D. Richards et al., "Temperature and band gap dependence of GaAsBi p-i-n diode current–voltage behaviour," J. Phys. D: Appl. Phys., 54(19), 195102, (2021).

[5]N. Bailey et al., "Effect of MBE growth conditions on GaAsBi photoluminescence lineshape and localised state filling," Sci. Rep., 12(1), 1-8, (2022).

3:00pm **NM-TuA1-7 Towards Lattice-Matched Narrow Bandgap $InAs_ySb_{1-x-y}Bi_x$ Photodetectors***,* ***Corey White****, M. Bergthold,* The University of Texas at Austin*; I. Okoro,* Texas State University*; Y. Wang,* The University of Texas at Austin*; L. Nordin,* Stanford University*; A. Muhowski,* Sandia National Laboratories*; D. Wasserman, S. Bank,* The University of Texas at Austin

Bismuth incorporation in III-V alloys induces a desirable bandgap reduction, however, III-V-Bi alloys have struggled to achieve high material quality due to the dramatic difference between the ideal growth temperature of the host III-V matrix and the relatively cold growth temperatures necessary for promoting significant bismuth incorporation.[1,2] In-SbBi, however, is a particularly promising material system for accessing the longwave-infrared (LWIR) with high performance optoelectronic devices due to the relatively similar ideal growth windows for InSb and III-Bi materials. Recently we demonstrated the growth of high quality InSbBiwith unity sticking Bi incorporation and demonstrated the first photoluminescence (PL) measurements from this alloy. By incorporating As into InAsSbBi, the quaternary can be lattice-matched to InSb substrates enabling the growth of thick layers, which is vital for strong absorption in photodetectors. Here we report the growth and optical properties of the first dilute-bismide films lattice-matched to InSb. Films exhibited highly substitutional bismuth incorporation enabling the first room temperature PL, as well as progress towards LWIR photodetection.

InAsSbBi films were grown on InSb substrates by solid-source MBE. Low substrate temperatures and V/III flux ratios near unity promoted high substitutional bismuth incorporation. Following similar high-quality GaAsBi growth,[3] a relatively fast growth rate was used to kinetically suppress bismuth segregation during growth.

X-ray diffraction measurements confirmed lattice-matching of InAsSbBi to InSb and Rutherford backscattering spectrometry measurements were performed to quantify the 1.3% Bi content in the film. Ion channeling measurements demonstrated highly substitutional bismuth incorporation (~95%), which is a prerequisite for high optical quality.[4] We observed room temperature PL at ~7.6 um from InAsSbBi demonstrating a considerable redshift in emission wavelength beyond InSb. To evaluate the potential of this material family for optoelectronic devices, a prototype MSM photodetector was fabricated on InSbBi and preliminary light and dark I-V characteristics demonstrated the first photodetection from InSbBi grown in the unity sticking regime.

[1]S. Francoeur et al., *Appl. Phys. Lett.* **82** (2003).

[2]S. Tixier et al., *Appl. Phys. Lett.* **82** (2003).

[3]A. Ptak et al., *J. Cryst. Growth***338** (2012).

[4]S. Spruytte et al., *MRS Internet J. Nitride Semicond. Res.* **5** (2000).

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