Tuesday Morning, September 19, 2023

Novel Materials
Room Ballroom A - Session NM-TuM1

Novel Materials, Optoelectronics

Moderator: Prof. Jason Kawasaki, University of Wisconsin - Madison

7:45am **NM-TuM1-1 Welcome and Sponsor Thank Yous***,*

8:00am **NM-TuM1-2 NAMBE Young Investigator Awardee Talk: Dislocation Dynamics in InGaSb Graded Buffers on GaSb Grown by MBE***, **Stephanie Tomasulo**, M. Twigg, S. Maximenko, I. Vurgaftman, J. Nolde,* U.S. Naval Research Laboratory **INVITED**

Conventional III-V materials possess a large range of bandgap energies (E_g) enabling their use in a wide variety of applications. However, researchers are typically constrained to the few lattice-constants available in commercial binary substrates, which greatly restricts access to the lowest-E_g (0.05-0.35 eV) options. Graded buffers can and have been used to bridge the gap between an available substrate and a bulk-like material with the desired E_g while mitigating excessively high threading dislocation densities (TDD). However, the dislocation dynamics in III-Sb materials is still poorly understood. Here, we explore the effects of substrate temperature (T_{sub}) on surface morphology and dislocation dynamics in $In_xGa_{1-x}Sb$ graded buffers. We grew two identical samples at T_{sub}=455 and 495 °C (pyro). These had 8 × 365 nm steps, increasing *x* by ~0.03 per step and capped with 1 µm of $In_{0.28}Ga_{0.72}Sb$ (grading rate of=0.58%/µm). Nomarski microscopy shows the lower T_{sub}=455 °C results in a rough surface, while T_{sub}=495 °C has a smooth, cross-hatched appearance as expected for a graded buffer. We then measured x-ray reciprocal space maps (RSMs) with the x-ray beam incident along both [110] and [1-10] to assess potential asymmetric strain relaxation. Such relaxation has been observed in other III-V graded buffers and explained by different dislocation formation energies/glide velocities along each direction, which results from the core structure of the dislocation being terminated with either a group-III (beta core) or a group-V (alpha core) element [1]. Thus, asymmetries in RSMs can be linked to dislocation glide behavior. We previously observed asymmetry in InAsSb graded buffer RSMs, finding minimal tilt when measured along [110] and significant tilt when measuring along [1-10], suggesting a preference for beta dislocation cores [2]. Interestingly, InGaSb graded buffers reveal the opposite asymmetry, i.e. measuring along [110] results in tilt while measuring along [1-10] shows little tilt, indicating alpha dislocation cores. Furthermore, in InGaSb, the tilt direction changes from positive (more glide on (111)) for T_{sub}=455 °C to negative (more glide on (-1-11)) for 495 °C revealing the significant role T_{sub} plays in dislocation dynamics. Additional samples will be explored, varying the V/III and grading rates, to build an understanding of how to control dislocation dynamics and TDD in InGaSb graded buffers. Etch pit density and transmission electron microscopy will be used to quantify TDD and supplement the understanding of dislocation dynamics gained from RSMs. [1] France et al. JAP 107, 103530 (2010). [2] Tomasulo et al., NAMBE 2019.

8:30am **NM-TuM1-4 Emergent Ferromagnetism in Altermagnetic Candidate MnTe Films Grown on InP (111)***, **Matthew Brahlek**,* Oak Ridge National Laboratory

To push into new generations of spintronic devices requires understanding new magnetic phenomena and also how to control both known and emerging material platforms as high-quality epitaxial thin films. Specifically, altermagnets are a new phase that is predicted to exhibit a strong spin splitting of the band structure, which can form the basis for new spintronic applications. MnTe, a candidate altermagnet, is a room-temperature antiferromagnet (TN ≈ 310 K) semiconductor (energy gap of order 1 eV) with a NiAs structure. Here, we present results on the molecular beam epitaxy growth and properties of MnTe/InP(111). Using polarized neutron reflectivity and magnetotransport, we find that there is emergent ferromagnetic behavior likely driven by a combination of charge transfer and strain. The ferromagnetic component is likely a slight canting of the bulk-like A-type antiferromagnetic state, as seen by neutron diffraction. This high level of tunabililty of MnTe opens the door to tailoring interlayer magnetic interactions in this layered material system. Together these results provide a potential mechanism of tuning antiferromagnetic ordering for applications in high-speed, next-generation spintronics.

8:45am **NM-TuM1-5 Growth Parameters Impact on Electronic and Optical Properties of ErAs:InGaAlBiAs Materials***, **Wilder Acuna**, W. Wu, J. Bork, M. Jungfleisch, L. Gundlach, J. Zide,* University of Delaware

We present our work on the growth of ErAs:InGaAlBiAs through a digital alloy approach where a superlattice of thin layers of the quaternary InGaBiAs and InAlBiAs, behave as a quinary and allows tuning the bandgap with the gallium and aluminum composition just with layer thickness variation. We target InGaAlBiAs for 1550 nm optical excitation for photoconductive switches (PCS) that can generate and detect terahertz (THz) pulses. Semiconductors implemented in PCS need high dark resistance, subpicosecond carrier lifetime, and a high carrier mobility is desirable. Incorporating erbium above the solubility limit creates ErAs nanoparticles, decreasing the material's carrier lifetime. At the same time, ErAs nanoparticles have a strong pinning effect of the effective Fermi level on the material. In this narrow bandgap semiconductor, the Fermi level is close to the conduction band, i.e., there is a high electron concentration, which decreases the dark resistivity. Other authors have found that the size of ErAs nanoparticles affects the electron concentration in InGaAs, where bigger nanoparticles cause a lower electron concentration. Er can be co-deposited, forming nanoparticles at the same time the matrix is grown, which saves growth time; however, while the usual 490°C growth temperature could give enough adatom mobility to create sizeable nanoparticles, our structure of interest is a dilute bismuthide that requires lower temperature growth (~280°C). At this low temperature, we use interrupt growth and migration-enhanced epitaxy, which allows us to have lower carrier concentration. All these samples are characterized by different techniques to determine relevant properties. Dark resistance is obtained from Hall effect and Van der Pauw measurements, carrier lifetime from optical pump THz probe spectroscopy, optical band gap from spectrophotometry, material quality from high-resolution x-ray diffraction, and composition through Rutherford backscattering spectrometry.

9:00am **NM-TuM1-6 Heteroepitaxial Growth of Site-determined Quantum Emitters in 2D GaSe Films***, **Mingyu Yu**,* University of Delaware*; S. Law,* Pennsylvania State University

GaSe is an attractive van der Waals (vdW) material due to its intriguing bandgap behavior and is an ideal choice for quantum photonic technology. We will grow GaSe films on patterned substrates by molecular beam epitaxy (MBE) to obtain wafer-scale films with site-controlled localized quantum emitters (QEs). A proper substrate is critical as the substrate pattern is used to funnel electrons and holes to a local minimum to form emission. Unlike traditional epitaxy, vdW materials may grow on substrates with large differences in lattice constant/structure as the weak interlayer bonds make them less affected by substrate. However, it also means less control over the crystal structure and surface morphology of the deposited film. To achieve the goal—GaSe films with strain-localized QEs—we first need flat atomically-thin GaSe films with minimal twin boundaries. Our previous work[1] proved that Al_2O_3 was not suitable for the growth of GaSe films due to the poor wettability of Ga, so we turned to GaAs(111)B, which has the same cation as GaSe and a relatively small lattice mismatch (6%).

Typically, vdW materials cannot grow heteroepitaxially on 3D substrates unless the dangling bonds are terminated. We developed a process—annealing in Se at 680°C—to deoxidize GaAs(111)B in an As-free MBE while generating a Se-terminated surface smooth enough for subsequent growth (Fig. S1). Preliminary work has resulted in GaSe films with somewhat rough surfaces (Fig. S2a, 2d). Additional annealing of the substrate prior to growth can notably promote film coalescence and reduce roughness (Fig. S2b, 2e), probably because it facilitates a fully Se-terminated GaAs surface. Fig. S2e shows a surface comprised of twinned triangular domains, and the reflection high energy electron diffraction (Fig. S2g) confirms the coexistence of two GaSe orientations. In addition, the 2-step method (low-temperature nucleation followed by high-temperature growth) facilitates film coalescence (Fig. S2c, 2f), since high substrate temperature can enhance adatom mobility. Moreover, fresh GaAs(111)B wafers lead to more directional nucleation of GaSe (Fig. S3), implying that additional oxidation due to air exposure is detrimental to the growth of high-quality GaSe. We also found that the quality of vdW films had an opposite dependence on growth conditions (temperature and rate) in 2D/2D and 2D/3D growth modes. The next challenge is to achieve uniform coverage and unidirectional nucleation. The effects of growth parameters, substrate pretreatment, and uncracked/cracked Se will be examined to better understand the growth mechanics and morphology evolution of GaSe.

9:15am **NM-TuM1-7 Evaluating (001) and (111)A InAs Quantum Emitters at Telecommunication Wavelengths Grown by Droplet Epitaxy**, ***Margaret Stevens***, US Naval Research Laboratory; *W. McKenzie, G. Baumgartner,* Laboratory for Telecommunication Sciences; *J. Grim, A. Bracker,* US Naval Research Laboratory

Droplet epitaxy is a versatile growth method that can produce nanostructures with emission in the telecommunication wavelength ranges. The MBE growth conditions have a significant impact on the morphology of the nanostructures, and as a result, the emission of the quantum dots. Due to the low surface diffusion of In on InAlAs surfaces, conventional growth conditions in MBE lead to rings of small quantum dots on (001) surfaces that limit the emission to shorter wavelengths. Previously, we have shown that we can manipulate the crystallization stage of droplet epitaxy to create new morphologies on (001) surfaces and shift the resulting emission to 1300-1550 nm at 4 K [1]. By utilizing a two-stage As flux exposure, including a low flux exposure immediately after metal droplet deposition followed by a high flux exposure with a temperature ramp [2], we can create clusters of larger quantum dots at densities ~ 1/μm^2 surrounded by a higher density of smaller quantum dots. Further understanding of why the different morphologies form, and how we can better control quantum dot density, is needed.

In this work, we have expanded on the two-stage As flux exposure to further manipulate the morphology and density of InAs QDs grown on InAlAs/InP (001). We grew samples with different temperature ramps and different low-flux conditions to change the density and size of the different QD features that form. Atomic force microscopy (AFM) is used to study the quantum dot morphology and density and photoluminescence spectroscopy (PL) is used to study the resulting emission. Additionally, we grew InAs QDs via droplet epitaxy on InAlAs/InP (111)A surfaces to compare quantum dot size, density, and resulting emission to samples grown by the two-stage flux technique on (001) substrates. Finally, we incorporate our telecommunication range emitting quantum dots in diode structures to tune the QD charge state and study resulting emission properties.

[1] M. A. Stevens et al., JVST A, 41, 032703 2023

[2] S. V. Balakirev et al., Appl. Surf. Sci., 578, 152023, 2022

9:30am **NM-TuM1-8 Growth of InSb Quantum Well on InAs Using AlInSb Buffer Layer Assisted by Interfacial Misfit Dislocation Arrays**, ***Fatih Furkan Ince***, *A. Newell, T. Rotter, G. Balakrishnan,* University of New Mexico; *M. McCartney, D. Smith,* Arizona State University

Mid-wave infrared (MWIR) detectors are widely used in various fields, such as medical devices, remote sensing, and spectroscopy. InSb-based infrared focal plane arrays (FPAs) have emerged as a popular choice for their affordability, scalability, and temporal stability, as well as their spatial uniformity. However, achieving fully relaxed tunable absorber to cover MWIR and LWIR is challenging due to lack of binary substrates. Thus, type-II superlattices and metamorphic buffers are employed to cover the MWIR spectrum and extend into the long-wave infrared (LWIR) region [1], [2]. In this study, we propose using interfacial misfit dislocations to grow fully relaxed InSb on an InAs substrate, combined with direct growth of $Al_xIn_{1-x}Sb$ buffer layers on InAs, to develop tunable InAsSb absorbers for MWIR and LWIR applications. This approach is expected to lead to the production of high-performance MWIR and LWIR detectors, potentially opening new avenues for future applications.

We will discuss using interfacial misfit dislocations to form instantly relaxed buffer layers on InAs substrates, and analyze the directly grown AlInSb and InSb epilayers using HR-XRD ω-2θ scans and reciprocal space mapping. TEM analysis showed misfit dislocation arrays at the AlInSb/InAs interface. We investigated InSb quantum wells grown with different AlxIn1-xSb barrier layers using PL and present a detailed analysis of the InSb quantum wells based on PL and TRPL results. These findings provide a better understanding of the properties of these materials and their potential for MWIR and LWIR applications.

[1] W. L. Sarney, S. P. Svensson, Y. Xu, D. Donetsky, and G. Belenky, “Bulk InAsSb with 0.1 eV bandgap on GaAs,” J. Appl. Phys., vol. 122, no. 2, p. 025705, Jul. 2017.

[2] A. Rogalski, “Next decade in infrared detectors,” in Electro-Optical and Infrared Systems: Technology and Applications XIV, Warsaw, Poland, 2017.

+Author for correspondence: incef@unm.edu

9:45am **NM-TuM1-9 Molecular Beam Epitaxy of Kagome Antiferromagnetic Mn_3GaN grown on MgO(001)**, ***Ali Abbas***, *A. Shrestha, A. Smith,* Ohio University

There have been very few studies of antiperovskite structure Mn_3GaN in general and it was seen in MBE growth mainly as a second-phase precipitate when growing MnGaN [4]. However, this material is very interesting since it can support the Kagome antiferromagnetic spin structure [3]. And so, we grow thin films of Mn_3GaN on cubic MgO(001) substrates using rf N–Plasma MBE. In our work, Mn_3GaN is deposited at 250 ±10°C with a Mn:Ga:N flux ratio of 3:1:1. We keep the Ga:N ratio fixed using an RF plasma nitrogen source. The sample surface is continuously monitored throughout the growth using reflection high energy electron diffraction. During the growth, the RHEED pattern was observed to be highly streaky, indicating an atomically smooth surface. In addition, we observed half-order fractional streaks (2x pattern) in the [100] direction. The calculated *in-plane* lattice constant based on RHEED is 3.89 ±0.06 Å. This value is very close to the lattice constant *a* of Mn_3GaN according to theory (3.898 Å) [1] and with the *in-plane* experimental value for sample growth by sputtering (3.896 Å); and in that work, the authors also observed a 2x pattern [2]. We also measure the *out-of-plane* lattice constant using X-ray diffraction. For the major 002 peak, the value calculated is 3.84 ±0.06 Å which also agrees well with the theoretical value (3.898 Å) [1] and with the experimental reported *c* value [2] (3.881 Å). Since we did not observe significant second-phase peaks, the phase purity of the sample is quite high, and Rutherford backscattering confirms a stoichiometry of 3:1:1.

This work is supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under Award No. DE–FG02–06ER46317.

References:

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[2]T. Hajiri, K. Matsuura, K. Sonoda, E. Tanaka, K. Ueda, & H. Asano, (2021). Spin–Orbit–Torque Switching of Noncollinear Antiferromagnetic Antiperovskite Manganese Nitride Mn 3 Ga N. *Physical Review Applied*, **16(2)**, 024003.

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[4] KH. Kim, KJ. Lee, HS. Kang, FC. Yu, JA. Kim, DJ. Kim, KH. Baik, SH. Yoo, CG. Kim, YS. Kim, (2004).Molecular beam epitaxial growth of gan and gamnn using a single precursor. physica status solidi (b), 241(7):1458–1461

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