MBE

Room Silver Creek - Session MBE-1MoM

Oxides and Nitrides

Moderator: Jason Kawasaki, University of Wisconsin Madison

8:00am **MBE-1MoM1 Oxide MBE Rocks!**, *Darrell Schlom,* Cornell University **INVITED**

MBE is renowned for preparing semiconductor heterostructures with high purity, high mobility, and exquisite control of layer thickness at the atomic-layer level. In recent decades it has become the definitive method for the preparation of oxide quantum materials as well, particularly when it is desired to perturb or exploit their properties. In this talk I will show examples of how the unparalleled synthesis precision of MBE can be used to tailor oxide quantum materials through the various approaches shown in Fig. 1 to expose hidden ground states [1]. The band structure is revealed by highresolution angle-resolved photoemission (ARPES) on pristine surfaces of these oxide heterostructures made possible by a direct ultra-high vacuum connection between MBE and ARPES [2].

[1] R. Ramesh and D.G. Schlom, "Creating Emergent Phenomena in Oxide Superlattices," *Nature Reviews Materials* **4** (2019) 257–268.

[2] D.G. Schlom and K.M. Shen, "Oxide MBE and the Path to Creating and Comprehending Artificial Quantum Materials," in M. Coll *et al.*, "Towards Oxide Electronics: a Roadmap," *Applied Surface Science* **482** (2019) 1–93.

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8:45am **MBE-1MoM4 RF-plasma MBE Growth and Characterization of β-Ga_2O_3/NbN$_x$ Heterostructures on SiC**, *Neeraj Nepal, D.S. Katzer, B. Downey, V.D. Wheeler,* U.S. Naval Research Laboratory; *L. Nyakiti,* Texas A&M; *E. Jin, V. Gokhale, M. Hardy, D. Storm, D. Meyer,* U.S. Naval Research Laboratory

Gallium oxide (Ga_2O_3) is an ultra-wide bandgap (UWBG) semiconductor with a bandgap of 4.5-4.9 eV and has higher figure of merit values than GaN and SiC for power and rf devices making it a candidate for next generation high-power/temperature electronics [1-3]. One disadvantage of β- Ga_2O_3 fordevice application is its low thermal conductivity [4]. Approaches to improve thermal performance are through heteroepitaxy directly on high thermal conductivity substrates (for instance β- Ga_2O_3 on SiC [5]), heat extraction from top side, or by transferring β- Ga_2O_3 to a high thermal conductivity substrate. While β- Ga_2O_3 nano-membranes have been transferred recently from a bulk substrate [6], it would be preferable to perform device processing and yield screening prior to transferring to a target substrate. To accommodate this approach, we present here our work investigating heteroepitaxial growth of Ga_2O_3 films on NbN$_x$, subsequent epitaxial lift-off, and transfer printing of Ga_2O_3 epilayers and devices. This work leverages our previous experience with demonstrated transfer printing of III-Nitride on NbN$_x$ devices [7].

Epitaxial NbN$_x$ films were grown on 6H-SiC in the PRO-75 rf-plasma molecular beam epitaxy (MBE) chamber, characterized *ex situ* and transferred to V80H oxide rf-MBE to grow β-Ga_2O_3. β- Ga_2O_3 layers were grown at 650 ° C on these NbN$_x$/6H-SiC templates. The baseline growth parameters were optimized with deposition of β- Ga_2O_3 films on c-plane sapphire substrates. Optimized MBE growth conditions were then used to grow 53 nm thick film on NbN$_x$, which has only (-201), (-402), (-603), and (-804) β- Ga_2O_3 peaks in the 2θ X-ray diffraction range of 10 - 90°. Transmission electron microscopy (TEM) shows that the Ga_2O_3 layer is crystalline and confirmed the XRD orientation relationship of (-201)$_{Ga2O3}$||(0001)$_{NbNx}$||(0001)$_{SiC}$. A high vertical breakdown field of ~2 to 3 MV/cm was found for MBE grown Ga_2O_3 on NbN$_x$. Finally, lateral XeF$_2$ etching of the buried NbN$_x$ layer to demonstrate lift-off capabilities and study transferability to foreign substrates.

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1. H.H. Tippins, Physical Review **140**, A316 (1965).

2. K. Akito et al., Jpn. J. Appl. Phys. **55**, 1202A2 (2016).

3. J.Y. Tsao, Adv. Electron. Mater. **4**, 1600501 (2018).

4. M. Santia et. al., Appl. Phys. Lett. **107**, 041907 (2015).

5. N. Nepal et al., 34th NAMBE Conference, MBE-MoA1, Banff, Canada October 1st, 2018.

6. H. Zhou et al., IEEE Electon Device Lett. **38**, 103 (2017).

7. D. J. Meyer et al., IEEE Trans. Semicond. Manuf. **29**, 384 (2016).

9:00am **MBE-1MoM5 Development of a High-Purity, High-Concentration Ozone Delivery System for MBE and Growth of β-Ga_2O_3**, *Mark O'Steen, T. Campbell, S. Farrell, E. Tucker, D. Hanser,* Veeco Instruments Inc.

Each year, research in oxide materials and devices increases and molecular beam epitaxy (MBE) serves as a critically important tool for the synthesis of these materials. The ever-increasing interest in oxide materials is attributable to the wide range of potential uses of these materials in applications including power electronics, structural buffer layers, gate dielectrics, superconductors, 2D electron gases, ferroelectrics, ferromagnetics, electrical isolators, and optically transparent conductive layers. For many of these applications, a key challenge for MBE growth is adequately oxidizing compounds to achieve desirable properties.

Molecular oxygen and oxygen plasma have been used extensively in the growth of oxide materials but have limitations including reactivity and growth rate. An alternative to these approaches is to use a stronger oxidizer such as ozone. However, using ozone as a source gas in MBE presents challenges related to generating, storing, and injecting ozone that is of both high purity and high concentration. Additionally, ozone has inherent challenges with toxicity and chemical instability.

To address these practical issues in safely implementing ozone in MBE, a distillation system has been integrated to a novel delivery system with key features including: delivery of high-purity, high-concentration ozone; wide-ranging, precise pressure control for the injected ozone gas; and comprehensive safety controls. Growth pressures have been actively controlled from 5x10^{-9} to 5x10^{-5} Torr with high precision and highly-linear ramp rate control. Additionally, to maximize process flexibility, this system provides for automated, rapid switching between injecting molecular oxygen, low-concentration ozone (15-25 wt%), and high-concentration ozone (~90 wt%).

Finally, this ozone system has been used in the growth of β-Ga_2O_3 epitaxial films. Details of the growth interactions will be discussed. The resulting epitaxial films were measured using techniques including RHEED, AFM, high-resolution XRD, and ellipsometry.

9:15am **MBE-1MoM6 Advancements in High Indium Content AlInN Grown Via Metal Modulated Epitaxy and Application Towards Polar/Non-Polar Optical Devices**, *Zachary Engel, E. Clinton, W.A. Doolittle,* Georgia Institute of Technology

AlInN has been a topic of recent study due to its unique property among III-nitrides of lattice matching to GaN at a composition of 18% indium, making it a strong candidate for power electronic and optoelectronic applications. A widely unexplored area is the application of AlInN towards visible/Near-IR optical devices. AlInN has a tunable bandgap, spanning the infrared to ultraviolet range, of 0.7 to 6.1eV. At a composition of about 70% indium AlInN has a perfect bandgap, 1.7eV, for tandem solar cells with silicon and for various optical communications applications. Challenges exist with the growth of AlInN as a result of the large lattice parameter mismatch and differences in growth regimes between the two binary components. At the low temperatures required for the growth of AlInN the aluminum adatoms have a low mobility, often leading to lateral phase separation in the film. Metal Modulated Epitaxy (MME) offers a good solution to the growth issues of AlInN. This flux modulated technique allows for growth under metal rich conditions, increasing surface diffusion lengths of the Aluminum while limiting droplet formation and terminating in a dry surface suitable for devices.

For comparison ~100 nm thick high indium content AlInN samples were grown using nitrogen rich (0.8 III/V ratio) MBE and MME using a III/V ratio of 1.3 with a dose designed to prevent surface segregation (details supplied at the conference). Both films were grown cold at 375 degrees C to limit phase separation The MME sample showed improvement over the MBE sample in crystal quality and surface roughness, with the XRD (0002) reflection FWHM improving from 783 arcsec to 184 arcsec, the XRD (10-15) reflection FWHM improving from 2456 arcsec to 1421 arcsec, and the AFM surface roughness improving from 1.52nm rms to 0.882nm rms between the MBE and MME samples respectively. The carrier concentrations of both samples were found to be about 1E19 cm-3 via hall measurement implying that like InN, In-rich AlInN may suffer from excessive residual electron concentrations and/or surface fermi-level pinning. Optical measurements will be presented at the conference.

The same MME growth conditions were used to grow 100nm of indium rich AlInN directly on a (111) p-silicon substrate. Simple indium contacts were used to contact the Si and AlInN. Vertical conduction and rectification between the silicon and AlInN layers were observed in this large area (~0.25x0.25 cm2) device. Understanding of the limitations of and physics

governing this promising vertical polar/non-polar heterojunction will be given at the conference. Additionally, results from various growth conditions will be detailed.

9:30am MBE-1MoM7 Structural and Electronic Properties of NbN and III-N/NbN Heterostructure Grown by Molecular Beam Epitaxy, *John Wright, G. Khalsa, H.G. Xing, D. Jena,* Cornell University

We have investigated the growth of NbN thin films and the incorporation of NbN into III-N semiconductor heterostructures using nitrogen plasma-assisted molecular beam epitaxy. We demonstrate how the structural and electronic properties of NbN vary as a function of the growth parameters including the substrate material, the substrate temperature, the nitrogen plasma conditions, and the Nb flux. NbN thin films possess a metallic state resistivity of around $100\mu\Omega$-cm and transition to the superconducting state below 17K. We demonstrate that atomically smooth epitaxial NbN thin films can be grown on both 6H-SiC and GaN. We have also investigated the epitaxial growth of GaN and AlN on NbN films with the goal of integrating NbN into heteroepitaxial III-N devices, creating new opportunities to utilize both the metallic and superconducting properties of NbN in III-N electronic devices.

We observe 2D layer-by-layer growth of NbN for over 100 monolayers on 6H-SiC substrate as evidenced by RHEED intensity oscillations during growth, yielding atomically smooth epitaxial NbN films with monolayer step heights. We show that when grown on GaN, NbN will grow in a layer-by-layer mode only below a critical thickness of between 6nm and 9nm, at which point the growth transitions to a 3D growth mode. When GaN films are grown on NbN using the metal rich growth conditions typically used in MBE growth of GaN it is observed that GaN will not form a continuous film but rather segregates into islands on the NbN surface. Our effort to optimize the growth of III-N thin films on NbN is ongoing.

We use X-ray characterization to assess the structure of NbN films and NbN/III-N heterostructures. We characterize the crystalline quality of the films using the rocking curve measurement technique, finding full width at half maximum of NbN on 6H-SiC of $0.05°$. We also investigate variation in the measured out of plane lattice parameter of NbN over a large range, from $2.50Å$ to $2.56Å$, a difference of 2.37%, depending on the MBE growth process.

9:45am MBE-1MoM8 Optically-induced 2DEGs in GaN/AlGaN Heterostructures, *Stefan Schmult,* TU Dresden, Germany; *S. Wirth,* Max-Planck-Institute for Chemical Physics of Solids, Germany; *V. Solovyev,* Institute of Solid State Physics RAS, Russia; *R. Hentschel, A. Wachowiak,* NaMLab gGmbH; *T. Scheinert,* TU Dresden; *A. Grosser,* NaMLab gGmbH, Germany; *I. Kukushkin,* Institute of Solid State Physics RAS, Russia; *T. Mikolajick,* TU Dresden & NaMLab gGmbH, Germany

In our MBE-grown ultra-pure GaN/Al$_{0.06}$Ga$_{0.94}$N heterostructures with barrier thickness of 16 nm, a 2-dimensional electron gas (2DEG) is absent in dark environment and at room temperature. However, illumination with ultra-violet light (UV, photon energies larger than the GaN band-gap) generates a conductive 2D channel at the GaN/AlGaN interface. An immediate consequence for lateral field-effect transistors (FETs) is their normally-off switching characteristics in the dark.

Upon UV illumination below 100 K the 2DEG persists after switching off the illumination, with a charge carrier density depending only weakly on the excitation power. Shubnikov-de Haas-oscillations and Zeroes in the longitudinal resistance recorded from Hall bars at T = 0.5 K clearly point at the 2D channel character with no parasitic current paths. The respective electron densities are extracted from Landau level filling factors.

Band diagram simulations point at the significance of the GaN surface potential value for the existence of a 2DEG in the dark. Two factors, namely the residual impurity background in the GaN/AlGaN layer stack as well as impinging UV radiation, appear to influence the surface potential, resulting in the difference between normally-on or -off FET operation. The reported characteristics demonstrate the technical feasibility of next-generation normally-off as well as light-sensitive GaN-based device concepts.

MBE
Room Silver Creek - Session MBE-2MoM

Heterogeneous Integration
Moderator: Zbigniew Roman Wasilewski, University of Waterloo

10:30am MBE-2MoM11 MBE Growth of High-Quality GaAs on C-plane Sapphire Substrate, *Samir Kumar Saha, R. Kumar, A. Kuchuk, Y. Maidaniuk, Y. Mazur, S.Q. Yu, G. Salamo,* University of Arkansas

Heteroepitaxy of III-V semiconductor is a well-established field. Generally, the term heteroepitaxy is used to denote the growth of dissimilar materials having similar crystal structure but different lattice constant. Very few examples exist in literature regarding single-crystal epitaxy of two semiconductors with dissimilar crystal structures such as cubic on wurtzite or cubic on trigonal. There have been a few works regarding cubic SiGe growth on a trigonal sapphire substrate. In this report, we discuss the growth of quality GaAs buffer on c-plane sapphire. Our motivation to grow GaAs on sapphire is based on its potential use in III-V microwave photonics, optoelectronics and electronics owing to the properties, such as, a large contrast in refractive index between GaAs and sapphire, the high resistivity of sapphire substrate and the transparency of the sapphire substrate near the III-As band gap.

When grown on c-plane sapphire, GaAs tend to grow along the [111] orientation. In our experiments we have observed that the growth of GaAs on sapphire has a small range of parameter for best quality material. In this window, our samples show a surface RMS roughness as low as 1.6 nm; a rocking curve linewidth comparable to the GaAs substrate at 90 arcsec, good photoluminescence efficiency, and suppression of twinning in GaAs to less 0.1%. The latter was accomplished by utilizing different growth strategies, such as, a low temperature initial layer, multiple annealing cycles and by optimizing growth parameters (growth temperature and arsenic flux).

10:45am MBE-2MoM12 Controlling Nucleation and Growth of IV-VI Rocksalt PbSe and PbSnSe on III-V Zincblende Substrates, *Brian Haidet, E. Hughes, K. Mukherjee,* University of California, Santa Barbara

Pb-rich PbSnSe is a rocksalt semiconductor with a conventional direct bandgap ranging from 0.3 eV to 0 eV, after which for alloy compositions >30% Sn, PbSnSe becomes a topological crystalline insulator with an inverted gap[1]. Recognizing that both infrared and potential quantum technologies require very high material quality, to us this system provides a fantastic opportunity to study heavily mismatched cross-materials-system heteroepitaxy. Previously, IV-VI growth has been dependent on fluorite substrates and buffer layers[1,2], but in this work, we explore PbSe growth on more conventional III-V substrates. This IV-VI/III-V interface incorporates a change in valency, surface charge, and crystal structure. GaSb and InAs are both nearly-lattice-matched to PbSe, but present chemically different surfaces, making this a model system for investigation.

We demonstrate that the nucleation behavior of PbSe can be controlled by modifying the III-V surface reconstruction and chemistry prior to growth. Specifically, by exposing arsenide surfaces to PbSe flux at high temperature, we can convert the surface into a suitable template for single-orientation nucleation of PbSe, resulting in a cube-on-cube epitaxial arrangement for both (001)- and (111)-oriented substrates. Interestingly, this result does not extend to antimonide surfaces or untreated arsenide surfaces, where the interfacial energy between substrate and film is so high as to make PbSe nucleation orientationally ambivalent. Uncontrolled nucleation results in a mixture of (001), (110), and {221}-type grains on (001) substrates, and rotations of (111) grains on (111) substrates. This behavior highlights the importance of surface chemistry in this heteroepitaxial system.

With this method, we have produced (001)-oriented PbSe films with 369 and 185 arcseconds of tilt about the [110] and [1-10] directions, respectively, in films only 80 nm thick. This result is on par with multi-micron-thick films from other studies[3]. The ability to recover higher-quality material in thinner layers has great implications for devices, especially those with electrically active heterojunctions. On (111)-oriented substrates, we further demonstrate for the first time growth of rocksalt compositionally (metamorphic) graded buffers in the PbSnSe alloy system, opening new avenues for fabrication of IV-VI devices.

[1] G. Springholz, G. Bauer. Semiconductors, IV-VI, in: Wiley Encycl. Electr. Elec. Eng. (2014)

[2] P. Müller, A. Fach, J. John, A. N. Tiwari, H. Zogg, and G. Kostorz. J. Appl. Phys. 79 (1996)

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11:00am MBE-2MoM13 On the Origin of Hillock Formation during the Growth of InGaAs/InAlAs Superlattice on InP(111) Substrates, *Ida Sadeghi,* University of Waterloo, Canada*; A. Pofelski, G.B. Botton,* McMaster University, Canada*; Z.R. Wasilewski,* University of Waterloo, Canada

InAlAs/InGaAs growth on polar InP(111) wafers offers physical properties of interest for optoelectronic devices. For instance, strain-induced internal piezoelectric field in the [111] orientated heterostructures can be useful for applications operating at the 1.55 μm wavelength [1]. However, growth on (111) substrates is much less understood than that on the conventional (001) substrates. Strong surface roughening with high density of hillocks and pits is the primary challenge for growth on (111) substrates.

Previous studies mainly focused on the surface morphology of the structures grown in [111] direction with less attention on the underpinning of the hillock formation [2]. In this study, scanning transmission electron microscopy (STEM) was used to elucidate the origin of the hillocks and surface roughening on singular and vicinal (111) surfaces. STEM analysis showed that the hillocks on singular (111) surfaces are formed due to the underlying stacking faults and twins. Observed strong suppression of twins and consequently hillocks on vicinal (111) surfaces (Fig. 1) is believed to result from minimizing (111) island formation through step flow promotion, as discussed in Ref. [3]. Since stacking faults and twins are caused by the local insertion of one monolayer of wurtzite (W) phase between two zinc blende (ZB) phases, suppression of phase instability between ZB and W structures is the most important challenge to overcome. Compared to the near lattice-matched growth of AlGaAs on GaAs(111) substrates [4], the difficulty is further compounded for (In,Al,Ga)As growth on InP(111) substrates due to the large bond length differences between InAs, AlAs, GaAs and InP.

[1] E.A. Caridi et al., Appl. Phys. Lett. **56** 659 (1990).

[2] C.D. Yerino et al., *J. Vac. Sci. Technol. B*, 35 010801 (2017).

[3] I. Sadeghi et al., *J.Vac.Sci.Technol. B* 37 031210 (2019).

[4] Y. Park et al., *J. Vac. Sci. Technol. B* **18** 1566 (2000).

11:15am MBE-2MoM14 Effectiveness of $In_{0.1}Ga_{0.9}As$ Dislocation Filters to Reduce Threading Dislocation Density, *Chen Shang,* J. Norman, A. Gossard, J. Bowers, University of California, Santa Barbara

Epitaxially grown semiconductor laser material on Si (001) with quantum dot (QD) active regions is important for lower cost optical interconnects. The projected QD laser lifetime is more than a million hours at 35 °C under continuous-wave (CW) operation [1]. The drastic reliability improvement is primarily due to the reduction of threading dislocation density (TDD) on the GaAs on Si buffer surface. Further reduction of TDD is needed for high temperature reliability and future integration with Si waveguides. Here, we investigate the effectiveness of $In_{0.1}Ga_{0.9}As$ dislocation filter layers grown on GaAs with different TDD. We investigate the filtering mechanism and provide insights to further lowering of TDD while also reducing total epitaxial thickness.

To generate GaAs surfaces with different TDD, a GaAs buffer layer (Fig. 1a) was grown on low defect density GaP on Si templates from NAsP$_{III/V}$, GmbH. Temperature cyclic annealing (TCA) was then performed with temperature ranging from 400 °C to either 700 °C or 735 °C, and 4, 8, or 12 cycles. The surface roughness of all 6 samples are similar, according to atomic force microscopy (AFM) measurements. 200 nm $In_{0.1}Ga_{0.9}As$ and 300 nm GaAs were then grown after TCA at 500 °C (Fig.1a). TDD was measured with electron channeling contrast imaging (ECCI) both before and after the growth of the filter layer. The results are summarized in Fig.1(c). Higher number of cycles reduced TDD with the effect being more prominent at lower maximum cycling temperature. The TDD is further reduced after the growth of the $In_{0.1}Ga_{0.9}As$ filter layer. The effectiveness of the filters, namely the percentage TDD reduction, on different TDD is shown in the inset of Fig.1(c). Although samples with maximum temperature of 700 °C have higher starting TDD, the filtering effectiveness is lower than the samples with maximum temperature of 735 °C. This implies that the filtering is facilitated not only by lateral motion of existing TDs, but also the formation of new glissile TDs as bridges between the existing TDs. The effect of initial GaAs thickness, filter layer structure, and relaxation asymmetry on the filtering effectiveness will be discussed.

11:30am MBE-2MoM15 Study of Pit Formation in MBE Grown GaP on Misoriented Si Wafers, *Srinath Murali, C. Zhang, R. King, C. Honsberg,* Arizona State University

Heteroepitaxial growth of III-V materials such as GaAs, InGaP, GaAsP on Si have been a subject of keen interest for several years due to its potential for high performance optoelectronic devices. However, the inherent difference in lattice constants between these compounds and silicon lead to the formation of large number of crystalline defects [1]. Additionally, the growth of polar films on non-polar substrates gives rise to the formation of antiphase domains at the interface that propagate throughout the film [2]. Some of these defects can be suppressed by the growth of a GaP buffer layer before growing the target structure, making GaP a key part of III-V integration with silicon [3]. The surface quality of GaP films will determine the quality of subsequent III-V layers grown and impact the electrical properties of these material systems.

In this work, the focus is on demonstration of epitaxially grown GaP on misoriented Si wafers using Molecular Beam Epitaxy. The GaP layer acts as a buffer between the Si substrate and a Dilute Nitride-GaNP material. The epitaxial GaP layers were grown on Si substrates of precise (001), 4° offcut in (110) and 6° offcut in (110) orientations by a combination of Migration Enhanced Epitaxy (MEE) and MBE methodologies. The reflection high energy electron diffraction (RHEED) patterns observed (fig. 1a) were a mixture of spots and streaks, indicating the presence of some islands in conjunction flat layers. Atomic force microscopy (AFM) imaging suggests the presence of pits on the GaP surface (fig. 1b and 1c). These pits could be a result of melt back etching on the Si substrate caused by the Ga adatoms impinging on the substrate during growth process. Pit formation due to melt back etching will be verified by removal of grown GaP layer and characterizing the Si substrate surface by further AFM imaging. The effect of substrate orientation and the growth technique on the pit formation along with methods to suppress them will be presented.

11:45am MBE-2MoM16 GaSb-Based Mid-Infrared Photonic Devices Monolithically Integrated onto Silicon, *Peter Carrington,* Lancaster University, UK

GaSb-based materials can be used to produce high performance photonic devices operating in the technologically important mid-infrared (MIR) spectral range (2 to 5 μm). Direct epitaxial growth of GaSb on silicon (Si) is an attractive method to reduce manufacturing costs and opens the possibility of new applications in lab-on-chip MIR photonic integrated circuits. However, the fundamental material dissimilarities including the large lattice mismatch, the polar-nonpolar character of the III-V/Si interface and differences in thermal expansion coefficient lead to the formation of threading dislocations (TDs) and antiphase domains (APDs) which effect the device performance. This work reports on the molecular beam epitaxial (MBE) growth of high quality GaSb-based materials and devices onto Si. This was achieved using a novel growth procedure consisting of; an efficient AlSb interfacial misfit array, a two-step GaSb growth temperature procedure and dislocation filters, resulting in a low defect density, anti-phase domain free GaSb buffer layer on Si. A nBn barrier photodetector based on a type-II InAs/InAsSb superlattice was grown on top of the buffer layer. The device exhibited an extended 50 % cut-off wavelength at 5.40 μm at 200 K which moved to 5.9 μm at 300 K. A specific detectivity of 1.5 x10^{10} Jones was measured corresponding in an external quantum efficiency of 25.6 % at 200 K. InAsSb p-i-n LEDs were also grown on the GaSb-on-Si buffer layer which showed bright room temperature electroluminescence (EL) peaking around 4.5 μm.

MBE
Room Silver Creek - Session MBE-1MoA

Novel Materials
Moderator: Kunal Mukherjee, University of California, Santa Barbara

1:30pm **MBE-1MoA1 MBE Innovator Award Winner**,

2:00pm **MBE-1MoA3 The Growth and Optical Properties of High Concentration of ErAs Embedded within GaAs**, *Yuejing Wang, D. Wei, C. Ni, S. Law, J. Zide,* University of Delaware
We report the MBE growth and the optical properties of ErAs:GaAs nanocomposites with high ErAs concentration. The study is motivated by looking for a novel composite III-V material as alternative plasmonic material in the short-wave to mid infrared range. ErAs, which is the most studied material in Lanthanide Arsenides (also referred as rare-earth arsenides), is interesting for a wide range of applications. The rock-salt crystal of ErAs shares common arsenic sublattices with many technologically important zincblende III-V semiconductors such as GaAs. High quality ErAs:III-V films can therefore be grown epitaxially on III-Vs with tunable properties by adjusting the ErAs concentration and growth conditions. In this work, we investigated the MBE growth of ErAs:GaAs nanocomposites with ErAs% up to ~52% using a co-deposition method. ErAs:GaAs films were grown at substrate temperatures ranging from 450°C to 600°C under As2 overpressure with various Er effusion cell temperatures in order to study the effects of both ErAs concentration and growth temperature on material properties. The high ErAs% is confirmed by Rutherford backscattering spectrometry. Fourier transform infrared spectroscopy was used to study the optical properties of the materials. Reflection data show that the as-grown ErAs:GaAs films have tunable plasma wavelength across the 2.68~6 μm window as higher ErAs% leads to shorter plasma wavelength. Higher growth temperature also tends to result in slight blueshift of the plasma wavelength. The shifts of plasma wavelength of these ErAs:GaAs films grown with different parameters are consistent with the changes in carrier concentrations studied from Hall Effect measurements, as higher ErAs% or higher growth temperature leads to larger electron concentration. Besides the influence on plasma wavelength, the scattering rate also decreases as the growth temperature increases either due to better crystallinity or change in morphology of ErAs nanoinclusions. A detailed TEM study is underway to understand the morphology and crystallinity of ErAs embedded in GaAs grown with various parameters, which potentially lead to tunable properties of the films. Furthermore, Drude formalism is applied to get preliminary modelling and understanding of the optical properties of these ErAs:GaAs films, and it agrees well with the experimental reflection data. The wide growth temperature range, plasmon response tunabililty and the ease of epitaxial combination of the ErAs:GaAs films with other conventional III–V semiconductors show a great potential for many novel optoelectronic and nanophotonic applications in the 2-5 μm range where there are very few plasmonic materials.

2:15pm **MBE-1MoA4 Varying MBE Growth Conditions to Limit Droplet Formation and Improve the Material Properties of TlGaAs Films**, *Kevin Grossklaus, J. McElearney, M. Stevens, T. Vandervelde,* Tufts University
TlGaAs may serve as a promising material for optoelectronic devices for the near to mid-IR range. $Tl_xGa_{1-x}As$ films of approximatley x=0.07 Tl have been achieved using solid-source MBE [1,2]. However, production of films with greater Tl content, device relevant thickness, and high material quality is limited by group III droplet formation, incorporation of excess arsenic, defect formation, and epitaxial breakdown. These detrimental effects result from the very low temperatures and high As fluxes needed for TlGaAs growth. Moving towards device quality TlGaAs films will require a better understanding of the trade-offs between conditions that produce high Tl incorporation and those that result in improved film quality.

In this work we have examined the structural, optical, and electrical properties of $Tl_xGa_{1-x}As$ films, with the goal of identifying process conditions that improve film properties. In particular, we focused on the conditions that led to the formation of Tl rich droplets on the film surface and the effects of those droplets on the film. TlGaAs films were grown at low temperatures in a Veeco GENxplor MBE system using a valved As-cracker and solid source effusion cells for the group-III elements. After growth the surface and structural properties of the films were examined by AFM, SEM, XRD and TEM. TlGaAs optical properties were studied by spectroscopic ellipsometry. Select samples were annealed after growth to examine the effect on their optical properties. Droplet formation was suppressed by decreasing growth temperature and increasing arsenic flux. When droplets do form they can produce a variety of different morphologies which depend on the film surface and growth conditions. TlGaAs films without droplets were found to be of uniform composition.

2:30pm **MBE-1MoA5 Adsorption-controlled Epitaxial Growth of the Hyperferroelectric Candidate LiZnSb on GaSb (111)**, *D. Du, P. Strohbeen, C. Zhang,* University of Wisconsin Madison; *H. Paik,* Cornell University; *P. Voyles, Jason Kawasaki,* University of Wisconsin Madison
A major challenge for ferroelectric devices is the depolarizing field, which competes with and often destroys long-range polar order in the limit of ultrathin films. Recent theoretical predictions suggest a new class of materials, termed hyperferroelectics [1], should be immune to the depolarizing field and enable ferroelectric devices down to the monolayer limit. Here we demonstrate the epitaxial growth of hexagonal LiZnSb, one of the hyperferroelectric candidate materials, on GaSb (111) substrates. Due to the high volatility of all three atomic species, we find that stoichiometric films can be grown in a thermodynamically adsorption-controlled window, using an excess zinc flux. Outstanding challenges remain in controlling the point defects of LiZnSb and in controlling polytypism. While the films primarily grow in a hexagonal "stuffed wurtzite" phase (space group $P6_3mc$), which is has the desired polar structure, there exists a competing cubic "stuffed zincblende" polymorph that is nonpolar (*F-43m*). We will discuss our strategy towards controlling defects and polytypism in LiZnSb, which is based in large part on the wurtzite – zincblende polytypism observed in InAs. We will also present preliminary electrical measurements on phase pure ferroelectric capacitor structures.

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2:45pm **MBE-1MoA6 Tuning the Electronic Structure of LuSb via Epitaxial Synthesis**, *Shouvik Chatterjee,* University of California, Santa Barbara; *S. Khalid,* University of Delaware; *H. Inbar, A. Goswami,* University of California, Santa Barbara; *F. Crasto deLima, A. Sharan, F. Sabino,* University of Delaware; *T. Brown-Heft, Y-H. Chang,* University of California, Santa Barbara; *A. Fedorov,* Lawrence Berkeley National Laboratory; *D. Read,* Cardiff University, UK; *A. Janotti,* University of Delaware; *C. Palmstrøm,* University of California, Santa Barbara
Observation of extreme magnetoresistance (XMR) in rare-earth monopnictides has raised enormous interest in understanding the role of its electronic structure. I present first demonstration of epitaxial synthesis of LuSb thin films on GaSb (001) substrates. Combining the techniques of molecular-beam epitaxy, low-temperature transport, angle-resolved photoemission spectroscopy, and hybrid density functional theory, we have unveiled the bandstructure of LuSb, where electron-hole compensation is identified as a mechanism responsible for XMR. In contrast to bulk single crystal analogues, quasi-two-dimensional behavior is observed in our thin films for both electron and holelike carriers, indicative of dimensional confinement of the electronic states. Introduction of defects through growth parameter tuning results in the appearance of quantum interference effects at low temperatures, which has allowed us to identify the dominant inelastic scattering processes and elucidate the role of spin-orbit coupling [1]. Furthermore, by fabricating ultra-thin films I show that it is possible to controllably create an imbalance in the band fillings of electron and hole-like carriers in this otherwise compensated semimetal. Moreover, magnetoresistance behavior can also be tuned by application of bi-axial strain by synthesizing thin films of LuSb on lattice mis-matched substrates. Our work demonstrates the efficacy of epitaxial synthesis of rare-earth monopnictides to control its electronic structure and thereby, its physical properties.

[1] S. Chatterjee *et al.,* Phys. Rev. B, **99**, 125134 (2019).

3:00pm **MBE-1MoA7 Programmable Magnetic Anisotropy in Ferromagnetic Semiconductor Films with Graded Composition**, *Jacek Furdyna, S.-K. Bac, S. Dong, X. Liu, S. Rouvimov,* University of Notre Dame; *Y. Wang,* Nanjing University, China; *S. Lee,* Korea University, Republic of Korea; *M. Dobrowolska,* University of Notre Dame
Developing strategies for manipulating magnetic properties of ferromagnetic semiconductors such as $Ga_{1-x}Mn_xAs$ is of interest both because of the basic science involved and of its potential for spintronic applications. In this presentation we explore the effects of compositional grading of such alloys on their ferromagnetic properties using MBE. For this

purpose, we chose the quaternary alloy $Ga_{1-x}Mn_xAs_{1-y}P_y$ grown by molecular beam epitaxy on a GaAs substrate, with Mn concentration kept constant at $x \approx 0.06$, while the concentration of P is graded along the growth direction, increasing stepwise from $y \approx 0.0$ to $y \approx 0.28$.

Note that in a graded $Ga_{1-x}Mn_xAs_{1-y}P_y$ film, grading the P concentration will result in a gradient of the concentration of holes that mediate the Mn-Mn exchange, and in a gradient of the strain in the film due to lattice mismatch with the substrate. Importantly, the existence of interfaces between layers in the graded sample will also lead to removal of inversion symmetry between successive layers along the gradient. One thus expects that the properties arising from graded strain and composition will result in an entirely new magnetic system, with novel ferromagnetic behavior. In fact, in an earlier study of magnetic domains in this system, it has already been found that domain walls in such a graded structure display an entirely new behavior [1], giving rise to speculation that Dzyaloshinskii-Moriya interactions may play a key and novel role in such systems.

Our magneto-transport studies of this graded structure revealed a series of new effects, the most conspicuous being the following: (1) Despite the fact that the specimen consists of distinct layers with different magnetic properties due to differences in the content of P, the entire structure behaves as a single magnetic domain; and (2) applying a strong magnetic field changes the magnetic anisotropy of this system by "imprinting" an internal field onto the system that persists after the initial field is removed, thus permanently changing the magnetic anisotropy of the graded specimen. While the mechanism causing such internal field to form is not presently understood, we speculate that its formation may be related to the removal of inversion asymmetry due to grading, which (along with spin-orbit coupling) leads to pronounced Dzyaloshinskii-Moriya interactions. On a practical end, such ability to permanently manipulate magnetic anisotropy of a ferromagnetic semiconductor holds out the possibility of novel magnetic memory applications.

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MBE
Room Silver Creek - Session MBE-2MoA

Bismuthides and Antimonides
Moderator: Joshua Zide, University of Delaware

3:30pm **MBE-2MoA9 LATE NEWS: Minority Carrier Lifetime and Photoluminescence Properties of Mid-Wave InAsSbBi**, *Preston T. Webster,* Air Force Research Laboratory*; P. Petluru,* University of Texas at Austin*; P.C. Grant,* Applied Technology Associates*; E.H. Steenbergen,* Air Force Research Laboratory*; D. Wasserman,* University of Texas at Austin

As lower cost infrared imaging goals drive research in alternatives to state-of-the-art HgCdTe, the unparalleled bandgap engineering flexibility afforded by the heaviest group–V element Bi offers a unique III-V analog to HgCdTe in InAsSbBi. By varying the mole fraction of constituent lattice-matched ternaries $InAs_{0.91}Sb_{0.09}$ (4 µm wavelength at 120 K) and $InAs_{0.93}Bi_{0.07}$ (12 µm wavelength), quaternary InAsSbBi spans the technologically relevant mid- to long-wave infrared spectrum and can be grown lattice-matched on large area GaSb substrates. Moreover, InAsSbBi's compositional likeness to conventional bulk InAsSb and the InAs/InAsSb superlattice put it in a unique position to take advantage of recent technological innovation discovered and implemented in these related infrared systems. Molecular beam epitaxy grown InAsSbBi alloys are examined using temperature-dependent steady-state and time-resolved photoluminescence spectroscopy, X-ray diffraction, reflection high-energy electron diffraction (RHEED), and Nomarski imaging. RHEED patterns show that the InAsSbBi layer grows with a droplet-free (2×3) surface reconstruction at 380 °C. The surface is observed to remain specular and droplet free during growth, and Nomarski imaging further verifies that a smooth surface morphology is obtained. The InAsSbBi layers are 1 µm thick sandwiched between lattice-matched InAsSb layers providing carrier confinement. Comparison of the tetragonal distortion measured by X-ray diffraction and the bandgap energy measured by steady-state photoluminescence provides an evaluation of the Sb and Bi content of each sample. The target InAsSbBi mole fractions yielding 5 µm wavelength emission are 6.0% Sb and 2.2% Bi, and detailed examination of the photoluminescence properties and molecular beam epitaxy growth conditions show the growth progression towards this goal. Bandgap characteristics and recombination dynamics evaluated from the photoluminescence experiments are compared to equivalent 5 µm

wavelength InAs/InAsSb superlattices and 4 µm wavelength lattice-matched InAsSb bulk samples.

3:45pm **MBE-2MoA10 Characterization of Thick GaAsBi Layers Grown with Strain-stabilization**, *Margaret Stevens, K. Grossklaus, J. McElearney, S. Lenney, T. Vandervelde,* Tufts University

$GaAs_{1-x}Bi_x$ alloys are challenging to grow by molecular beam epitaxy due to the surfactant-like nature and low solubility of bismuth (Bi) in this system. The key to good Bi incorporation in GaAsBi is to provide enough Bi flux to the surface to stabilize a surfactant layer, but not so much as to induce Ga-Bi droplet formation. The point at which Ga-Bi droplets form, or the Bi saturation point, limits the maximum Bi fraction obtainable with the growth conditions used. Samples grown with Ga-Bi droplets have reduced Bi composition and significant lateral and vertical phase separation. Strain-stabilization, by growing on partially relaxed InGaAs buffer layers, can be used to overcome Bi saturation in $GaAsBi_{0.07-0.09}$ films. We propose that reducing the compressive strain decreases the total energy of the system, allowing more Bi to incorporate and Ga-Bi droplet formation to be avoided. We have explored this trend for various GaAsBi epilayer thicknesses, as shown in Figure 1. By growing on $In_{0.105}GaAs$ buffer layers, droplet-free films >100 nm can be achieved for Bi fractions x<0.09. This is an improvement over samples grown with high compressive strain on GaAs, where films of >100 nm are limited to compositions of x<0.07.

In this work, we explore the connections between in-plane strain, Bi incorporation, droplet formation, and maximum GaAsBi film thickness. Samples were grown on a Veeco GENxplor MBE using a valved As_4 source and a solid source effusion cell for group-III elements and Bi. Bismuth fraction was determined by high-resolution x-ray diffraction combined with select samples confirmed through Rutherford Backscattering Spectrometry. Scanning transmission electron microscopy was used to characterize the phase separation brought on by droplet formation. Spectroscopic ellipsometry was used to characterize the absorption coefficient of thick GaAsBi films and identify Urbach tails associated with crystalline disorder. Lastly, initial doping studies comparing silicon vs. tellurium doping were explored to increase dopant incorporation in this material system. The ultimate goal of this study is to prepare the GaAsBi/InGaAs/GaAs system for optical device applications in the near-IR.

4:00pm **MBE-2MoA11 Comparing Droplet Formation and Phase Separation in Post-Saturation GaSbBi and GaAsBi**, *John McElearney, K. Grossklaus, M. Stevens, T. Vandervelde,* Tufts University

III-V semiconductors alloyed with dilute amounts of bismuth have been shown to have dramatically reduced bandgaps, making them well suited for optoelectronic applications in the mid- and far-infrared. Given that GaSb has a bandgap already in the near-IR range (Eg = 0.726 eV), $GaSb_{1-x}Bi_x$ has great potential for pushing out to these long wavelength regimes. Unfortunately, bismuth tends to surface segregate and form droplets at sufficiently high Bi flux rather than incorporate into the growing film. The highest Bi content $GaSb_{1-x}Bi_x$ reported to date had x=0.14, and only x=0.11 has been achieved without droplets forming on the film surface [1]. We have recently observed that droplets are also likely to form upon reaching some critical thickness for a given Bi content in GaAsBi films, and these droplets can lead to significant lateral and vertical phase separation in the GaAsBi system.

We have found the solubility of Bi in GaSb to be different than the solubility of Bi in GaAs. The same Bi flux that leads to x=0.0315 in $GaAs_{1-x}Bi_x$ (grown at 250°C) leads to negligible Bi incorporation in GaSb(Bi) (grown at 285°C). A comparison of the GaSb(Bi) and GaAsBi surfaces is shown in Fig. 1. This work seeks to determine the effect of increasing bismuth flux and film thickness on surface morphology and film homogeneity in GaSbBi films as compared to GaAsBi. Samples were grown on GaSb substrates in a Veeco GENxplor MBE system using a valved Sb cracker and solid source effusion cells for Ga and Bi, with growth monitored in-situ via RHEED. Bismuth content was determined via HRXRD and confirmed for select samples with Rutherford backscatter spectrometry. The presence/absence of droplets was determined via optical microscopy and SEM imaging, while cross-sectional film homogeneity and phase separation was examined via TEM

[1] O. Delorme, L. Cerutti, E. Tournie, J.-B. Rodriguez. J. Cryst. Growth, 447 (2017)

4:15pm MBE-2MoA12 Molecular Beam Epitaxy Growth and Bandgap Measurements of InAsSbBi, *Stephen Schaefer*, R.R. Kosireddy, S. Johnson, Arizona State University

The molecular beam epitaxy growth of the III-V semiconductor alloy InAsSbBi is investigated for growth temperatures ranging from 400 to 430 °C, As/In flux ratios of 0.91 and 0.94, Sb/In flux ratios of 0.10 and 0.12, and Bi/In flux ratios of 0.05 and 0.10. Bismuth readily incorporates at growth temperatures around 300 °C, but results in material with limited optical quality. Conversely, higher growth temperatures around 400 °C yield improved optical performance, but with limited Bi incorporation. The fraction of the Bi flux incorporated is observed to decay exponentially with a 17 °C characteristic temperature in the high temperature growth regime as shown in Fig. 1. Furthermore, when the As/In flux ratio is increased significantly above stoichiometry, the Bi incorporation decreases as As outcompetes Bi for group V lattice sites as shown by the solid square. Quaternary alloys such as InAsSbBi possess two degrees of freedom that allow the bandgap to be specified independently of strain. Photoluminescence spectroscopy is used to examine the temperature dependent bandgap and optical properties of InAsSbBi, while x-ray diffraction is used to determine strain. The bandgap as a function of temperature is shown in Fig. 2, where an Einstein single oscillator model fit to data (solid curves) provides the zero temperature bandgap energy. A bandgap bowing model is developed and employed to determine the InAsSbBi composition from the measured bandgap and strain.

4:30pm MBE-2MoA13 Microstructure, Chemical Composition, and Surface Morphology of InAsSbBi Grown on GaSb by Molecular Beam Epitaxy, *Rajeev Reddy Kosireddy*, S. Schaefer, S. Johnson, Arizona State University

The microstructure, chemical composition, and surface morphology of molecular beam epitaxy grown InAsSbBi is investigated using transmission electron microscopy (TEM), X-ray diffraction, and atomic force microscopy (AFM). The InAsSbBi layers are 210 nm thick and grown at temperatures between 400 and 430 °C on (100) GaSb substrates. The results indicate that the material is nearly lattice matched, coherently strained, and contains dilute Bi mole fractions. The bright field TEM image in Fig. 1 shows no visible defects in the material over large lateral distances. Lateral modulation of the Bi mole fraction is observed in the bright field image and in the chemical sensitive 200 dark field image shown in Fig. 2, where a line scan of the image intensity along the black rectangle is inset. Analysis of the ratio of the dark field image intensities indicates that the Bi mole fraction variation has about a 30 nm period and ranges from 0.42% to 0.58% with a 0.50% average value. A rough hazy surface with large Bi-rich droplets on the order of 1 μm diameter is observed when the InAsSbBi layer is grown with near stoichiometric As flux (see Fig. 3). Nevertheless, when the As flux is a few percent greater than stoichiometric, a smooth specular surface without large droplets is observed (see Fig. 4). The growth temperature and the As, Sb, and Bi over In flux ratios are listed in each figure. The results at higher growth temperature also show a similar dependence on the As flux. The surface interaction between As and Bi strongly affects the surface morphology and the incorporation of Bi into the InAsSbBi layer.

4:45pm MBE-2MoA14 Dislocation Dynamics as a Function of MBE Growth Conditions in Metamorphic InAsSb, *Stephanie Tomasulo*, Naval Research Laboratory; C. Affouda, M. Twigg, U.S. Naval Research Laboratory; M. Yakes, Naval Research Laboratory; E. Aifer, U.S. Naval Research Laboratory

Long wavelength IR III-V based devices have long been of interest for potential applications such as chemical sensing and large format IR imaging. Within the III-V family, extending to the longest wavelength requires the use of $InAs_{1-x}Sb_x$ ($x \leq 0.6$) which offers the lowest bandgap energy (E_g) ranging from 0.05-0.35 eV [1]. However, the lack of conventional substrate at the desired lattice constant has restricted progress on the growth and study of this material system. To overcome this limitation, we employ a metamorphic step-graded $InAs_{1-x}Sb_x$ buffer on GaSb, enabling the study of low-E_g $InAs_{1-x}Sb_x$ as a function of growth conditions. Using this method, we previously presented the effect of substrate temperature (T_{sub}) and V/III on Sb incorporation of the lowest-E_g cap layer [2]. Here, we investigate the effect of V/III on Sb incorporation as a function of x and use x-ray reciprocal space mapping (RSM) to examine the effect of growth conditions on strain and dislocation dynamics.

We grew several $InAs_{1-x}Sb_x$ step-graded structures in which the Sb/(As+Sb) flux ratio was varied from 0.05 to 0.50 in 0.05 increments, under various T_{sub} and V/III, and identified the Sb composition in each layer using RSM along [110] with (004) and (115) reflections. This allows comparison of Sb-content as a function of Sb/(As+Sb) for various V/III, given in Fig. 1. These

results suggest that V/III has little effect on Sb incorporation, in direct conflict with our previous photoluminescence (PL) results [2]. To understand the discrepancy between PL and RSM, we measured (004) RSM of the same three samples with the x-ray beam incident along [1-10], revealing extremely different strain relaxation compared to the [110] case. Asymmetric strain relaxation has been observed in other III-V graded buffer systems and has been explained by different dislocation formation energies and glide velocities along each direction resulting from the core structure of the dislocation being terminated with either a group-III or a group-V element [3]. To develop an understanding of this mechanism within $InAs_{1-x}Sb_x$ graded buffers, we will employ the x-ray analysis of Ayers [4] to quantify the threading dislocation density (TDD) in these films along both [110] and [1-10], thus enabling a comparison of TDD as a function of growth conditions, thickness, and propagation direction. AFM and TEM will further support these results. Taken together, we will develop a picture of dislocation dynamics during the growth of metamorphic $InAs_{1-x}Sb_x$.

Monday Afternoon Poster Sessions, September 23, 2019

MBE

Room Bar/Living Room - Session MBE-MoP

MBE-Poster Session

MBE-MoP1 Simultaneous Topographical And Electrochemical Mapping Using Scanning Ion Conductance Microscopy – Scanning Electrochemical Microscopy, *G. Mendoza,* Park Systems, Mexico*; Byong Kim, K. Lee,* Park Systems

Lately, scanning ion conductance microscopy (SICM), has emerged as a versatile non-contact imaging tool. To obtain spatially-resolved electrochemical information, scanning electrochemical microscopy (SECM), also known as the chemical microscope, has been developed [1]. In hybrid SICM-SECM techniques, the SICM compartment provides the accurate probe-sample distance control, while the SECM compartment measures the faradaic current for electrochemical information collection [2]. In this work, we demonstrate the use of an Atomic Force Microscopy (Park NX10) in combination with an ammeter for concurrent topography imaging and electrochemical mapping. The SICM-SECM probe consisted of a Au crescent electrode (AuE) on the peripheral of a nanopipette. High resolution probe-substrate distance control was obtained by the ion current feedback from SICM, while simultaneous electrochemical signal collection was achieved via the AuE from SECM. As a proof-of-concept experiment, an Au/Pyrex pattern standard sample was imaged with the SICM-SECM technique. The Au bar and the Pyrex substrate were clearly resolved from the SICM topography image, with the bar height and pitch width closely matching the actual values. In terms of the electrochemical property mapping, higher Faradaic current was seen when the probe was scanned over Au bar as a result of redox cycling, while lower Faradaic current was observed when the probe was over Pyrex substrate due to hindered diffusion (Figure 1). The capability of the SICM-SECM technique described here holds promise of many applications in the field of electrochemistry, material science and nanoengineering.

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MBE-MoP2 Doping and Surfactant Behavior of Gallium in Low-Temperature Silicon and Germanium Growth, *Amanda Lemire, J. Manninen, J. Chivers, K. Grossklaus, T. Vandervelde,* Tufts University

Silicon-germanium-tin (SiGeSn) compounds are interesting as potential direct bandgap CMOS compatible materials. Sn precipitation and surface segregation occur for growth and annealing temperatures substantially below standard Si and Ge growth temperatures [1]. Molecular beam epitaxy (MBE) growth at the low temperatures needed to achieve significant Sn incorporation can also result in a degradation in Si and Ge film quality. Understanding and improving the low temperature growth of Si and Ge may improve SiGeSn film quality for optoelectronic applications. Gallium has been investigated by crystallographic techniques as a dopant and surfactant in low-temperature Si epitaxial growth [2,3,4], and as a dopant in GeSn [1]. In this work we investigate the relationship between pyrometer calibrated MBE growth temperature (150°C - 600°C), growth rate, and the doping/surfactant behavior of Ga in low temperature Si, Ge, and SiGeSn epitaxy, paying particular attention to film electronic and optical properties. Changes in surface roughness as determined by AFM are used to indicate whether Ga provides a beneficial surfactant effect. Ga incorporation as a dopant is investigated by Hall Effect measurements. Film optical properties are measured by variable angle spectroscopic ellipsometry. Changes in crystalline structure and quality resulting from the presence of the Ga and from Sn incorporation are measured by XRD.

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MBE-MoP3 Buffer layer growth for Ⅲ-Ⅴ on Si substrates using Molecular Beam Epitaxy, *Geun-Hwan Ryu,* Inha University, South korea*; J.D. Song, S.Y. Ahn, N.G. Hong,* Korea Institute of Science and Technology, South Korea*; H.Y. Ryu,* Inha University, South Korea*; W.J. Choi,* Korea Institute of Science and Technology, South Korea

As we approach the physical limits of silicon in the semiconductor industry, there have been many attempts to overcome these obstacles. One of these attempts is to use III-V semiconductors due to its superior physical characteristics. However, epitaxial growth of III-V materials have been limited to III-V substrates such as GaAs and InP. In order to take advantage of Si substrates, which has been used for decades in the semiconductor industry due to its ease of use, low cost, availability in large areas and physical properties such as thermal conductivity, a well-constructed buffer layer is critical for heteroepitaxy of III-V materials. This buffer layer may overcome defects such as threading dislocation and anti-phase boundaries which are normally associated with heteroepitaxial growth. Here, we demonstrate the growth of a buffer layer using a seed layer and SPS to minimize defects.

Fig. 1(a) shows the structure of III-V on Si using a seed layer and Short-Period Superlattice (SPS). The AlAs seed layer is grown at a high temperature while the AlAs/GaAs SPS is grown at a low temperature. The buffer layer is terminated by an InGaAs/GaAs Defect Fiter Layer (DFL) structure. The surface roughness measured by Atomic Force Microscopy (AFM) was 2 nm (root mean square) (Fig. 1(b)). Fig. 1(c) shows the cross-section of the buffer layer using Transmission Electron Microscopy (TEM). It is apparent that the surface is improved in AlAs/GaAs SPS and the dislocation is decreased InGaAs/GaAs DFL. Fig. 1(d) shows the result of Etch-Pit Density (EPD) measurement using KOH solution and Optical Microscopy (OM). Average EPD value was 3,000 /cm^2. As a result, we expect to grow low-cost, high-efficiency devices by growing III-V compound semiconductor on Si substrates.

MBE-MoP4 Influence of Strain on InAsSb Composition, *Wendy Sarney, S. Svensson, A. Leff,* CCDC Army Research Laboratory*; D. Donetsky,* Stony Brook University

A mixed group-V semiconductor's composition results from a complex interaction of each group V element with each other and with the group IIIs. Furthermore, since group V fluxes are controlled thermally and by valves or flow controllers, precise control is overall very difficult in mixed group V alloys compared with mixed group III alloys.

MBE growth conditions, such as the group V absolute fluxes and flux ratios, substrate temperature, group III growth rates, and the presence of surfactants all affect the composition of InAsSb [1-4]. The co-dependence of each of these parameters on each other is not well established. The sign and degree of strain also influences incorporation.

In one example, we grew two series of InAsSb samples onto GaSb at a range of temperatures using flux ratios known to produce Sb compositions of ~50% and 9% (near lattice match) at 415° C. The higher composition samples are relaxed and unaffected by strain. The samples grown near lattice match resist the growth temperature-induced changes in composition, where the composition levels out for a range of ~75° in substrate temperature.

We also observed that the group V incorporation in InAsSb for the same Sb/As ratio varies depending on the degree and sign of the strain.

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MBE-MoP5 Grading for Control of the Lattice Constant and Bandgap, as well as the Charge Distribution and Band Offsets at Interfaces, *Wendy Sarney, S. Svensson, A. Leff,* CCDC Army Research Laboratory*; D. Donetsky, G. Kipshidze, L. Shterengas, G. Belenky,* Stony Brook University

Compositional grading allows growth of bulk unstrained, unrelaxed InAsSb across the composition spectrum onto GaSb [1, 2]. Transmission electron microscopy (TEM), for example in Fig 1, shows that GaAlInSb grades behave as an ideal illustration of the principles outlined by Tersoff [3]. This mitigates the grade's residual strain, and the in-plane lattice constant at the top of the graded region equals the native unrelaxed lattice constant of the epilayer. Proper grading allows for virtual substrates with x-ray peak widths that are on the same order as the substrate and are coincident to the active epilayer peak (example, Fig 2).

There is limited work for the optimization of grading rates, strain offsets at the grade/virtual substrate interface, and grading species selection. TEM and x-ray diffraction data that demonstrate how these choices affect the epilayer quality. We also studied the practicality of extending Tersoff's methodology to other materials, such as InGaAs, and group V grades such as InAsSb and GaAsSb.

Another application of composition grading is maintaining a constant lattice constant while controlling charge distributions and band offsets at interfaces. Such grading requires precise composition control, and unlike the Tersoff grades, ideally occurs without dislocation formation. We will discuss our findings related to such grades.

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MBE-MoP6 Estimation of the Lateral Dimensions of Epitaxial CdSe/ZnSe Fractional Monolayer Quantum Dots, *Carlos Basilio*, Cinvestav-IPN, México; *I. Hernández-Calderón,* CINVESTAV, México

CdSe fractional monolayer quantum dots (FMQDs) are formed by the epitaxial deposit of a submonolayer (coverage $\Theta<1$), they present 3D confinement, and their emission is in the blue spectral range. The photoluminescence (PL) spectra of these FMQDs present excitonic features that need a clear explanation [1, 2]. Their structural properties are not well known; its characterization by transmission electron microscopy, to determine their lateral dimensions, represents a great experimental challenge, due to their ultra-thin thickness of just one monolayer (ML) and the relatively low contrast between ZnSe and CdSe. Therefore, it is very important to use indirect methods that allow estimating the lateral sizes and density of these FMQDs.

In this work, we present the PL characterization and theoretical modeling of CdSe/ZnSe FMQDs with a nominal coverage of ≈ 0.5 ML. The quantum dots were grown by atomic layer epitaxy within a ZnSe matrix grown by molecular beam epitaxy on a GaAs (001) substrate at $\approx 275\ °C$ growth temperature. The low temperature (19 K) PL spectra show an intense excitonic emission which typically consists in a double peak in the 2.752 to 2.760 eV energy range, with narrow full widths at half maximum, as shown in Figure 1. The excitonic spectra suggest small distributions in form, size, and composition of the CdSe/ZnSe FMQDs. To model the FMQDs we employed the factorized envelope approximation [3]. For simplicity, we considered that the FMQDs have a rectangular shape with L_x and L_y of similar sizes due to the C_4 symmetry of the (001) substrate surface. The calculations indicate that the excitonic emission can be correlated to lateral dimensions in the 4 to 5 nm range, see Figure 2, which result in a FMQDs density of 3×10^{12} cm^{-2} for a CdSe coverage of ≈ 0.5 ML.

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MBE-MoP7 Study of Conduction Mechanism using Temperature-Dependent Current-Voltage Measurements for GaAsSb Nanowire and Effect of In-situ Annealing, *Mehul Parakh, S. Johnson, R. Pokharel, S. Devakoa, P. Ramaswamy, J. Li, S. Iyer,* North Carolina A & T State University

This work presents the first observation of space charge limited conduction (SCLC) mechanism in intrinsic GaAsSb nanowires (NW) grown by Ga-assisted molecular beam epitaxy and the effect of post-growth in-situ annealing in an ultra-high vacuum on the conduction mechanism in the NWs. Current-voltage (I-V) measurements on single NW (using Conductive Atomic Force Microscopy) and ensemble NWs (using two probe method) exhibited linear behavior at lower bias transitioning to a power law behavior at higher bias, where the dominance of injected carriers over thermally generated charge carriers was observed. Temperature-dependent analysis on as-grown ensemble NW device in SCLC region yielded a wide trap density of 1016 cm-3 distributed over a wide energy range in the band gap compared to the reduced trap density of 7 * 1014 cm-3 in in-situ annealed NW ensemble at a trap energy level of 0.12 eV located below the band edge, suggesting annealing in ultrahigh vacuum is an effective approach for the annihilation of the traps. The trap density is attributed to be originating from Ga vacancy and GaSb defect level in III-V ternary material system. Increased PL intensity and red shift with reduced full-width half maxima at 4K were observed for in-situ annealed NWs compared to as-grown NWs. This can be correlated to better compositional homogeneity and annihilation of traps in the annealed NWs. Asymmetrical broadening and decreased TO/LO mode observed in the room temperature Raman spectra of as-grown NWs correlates well to more strain incorporation and presence of disorder, leading to the higher density of traps compared to the in-situ annealed NWs.

MBE-MoP8 N-type Doping of GaAs Nanowires using GaTe Source Grown by Self Assisted Molecular Beam Epitaxy, *Shisir Devkota, M. Parakh, P. Ramaswamy,* North Carolina A & T State University; *L. Reynolds,* North Carolina State University; *S. Iyer,* North Carolina A & T State University

N-type doping of GaAs nanowires (NWs) grown by molecular beam epitaxy (MBE) on (111) Si substrate using gallium telluride (GaTe) as a dopant source is successfully reported. A detailed study has been carried out to assess the impact of variation of GaTe source cell temperature on morphology, electrical and optical properties of NWs. Tellurium (Te) doping in the NWs was investigated for GaTe cell temperatures ranging from $200\ °C$ to $570\ °C$. The variations in the optical, electrical and morphological characteristics with cell temperature were investigated using low-temperature photoluminescence (PL), atomic force microscopy (AFM) and scanning electron microscopy (SEM). Te incorporation in our NWs was attested by the presence of 4K PL shoulder peak, which is· 0.18 eV red shifted with respect to GaAs band to band transition at 1.50 eV. Moreover, a shift in the PL peaks, variation in their full width maxima and corresponding variation in the I-V characteristics from AFM were used to ascertain the increase in Te incorporation in the NWs with increasing cell tempature. Best fitting of the simulated I-V curves with the experimental data on a single NW obtained from AFM yielded the highest carrier concentrating of 2.2×10^{17}/cm^3 with a carrier mobility of 7500 cm^2/ Vs. The highest responsivity of Te doped NW/p-Si was found to be 64 mA/W. Transmission electron microscopy (TEM) investigations of these NWs will also be presented.

MBE-MoP9 Effect of Gold Coatings on Quantum Dot Emission, *Ariel Weltner, C. Schuck, K. Vallejo, K. Sautter, T. Garrett, D. Tenne, P. Simmonds,* Boise State University

We grow tensile strained quantum dots (TSQDs) by depositing GaAs on InAlAs(111)A buffer layers lattice-matched to InP(111)A substrates. Tensile strain of 3.7% is imposed due to the difference in lattice constant between the two materials. The unusual presence of tensile strain in these GaAs QDs lowers their band gap and red-shifts their light emission further into the infrared. The outcome is TSQDs that emit light at energies below the bulk band edge of GaAs.

One of the applications for these high symmetry TSQDs on (111)-oriented surfaces is as entangled photon sources. The single photon spectroscopies used to demonstrate entanglement require that the photon collection efficiency of our measurements be as high as possible. During photoluminescence (PL), our TSQDs emit photons in all directions. One way to increase photon collection efficiency is to insert a mirror below our TSQDs to reflect the photons emitted downward (towards the substrate) back to the sample surface, where they can be collected in the spectrometer.

For conventional InAs/GaAs(001) QDs, this mirror is typically a distributed Bragg reflector (DBR), consisting of a superlattice of alternating GaAs/AlGaAs layers. To create a similar DBR in our InP-based structures would be challenging for two reasons. First, the GaAs TSQDs emit light at $\lambda = 1000$–1100 nm (at 11 K). Second, our samples would require lattice-matched InGaAs and InAlAs, which do not have a particularly strong index contrast. The combination of these factors means that each period of the InGaAs/InAlAs superlattice would need to be significantly thicker than conventional GaAs/AlGaAs DBRs, with even more periods required to reach even low reflectivity. High quality InGaAs/InAlAs growth on InP(111)A requires growth rates of ~170 nm/hr, which estimates a total growth time for DBRs of 8-10 hours.

A cheaper, easier, and less time-consuming approach is to take advantage of the long-wavelength emission from our GaAs TSQDs. At 11 K, the TSQD photon emission energy (<1.24 eV) is less than the band gap of either InAlAs (1.53 eV) or InP (1.42 eV), allowing us to simply use a gold reflective coating on the backs of the substrate. The InAlAs barriers and InP substrate are transparent to the TSQD emission, allowing photons to be reflected by the gold coating, back up through the sample, and into the PL collection optics.

Preliminary results on GaAs TSQDs show a clear increase in PL intensity for coated vs uncoated samples. We will present results showing how gold deposition thickness affects PL intensity and how the gold-InP interface may be optimized to maximize reflectivity.

Monday Afternoon Poster Sessions, September 23, 2019

MBE-MoP10 Nanostructure Mapping of GaAs and Ge (111)A Quantum Dots using Island Scaling and Radial Distribution Scaling Analysis, *Trent Garrett*, H. Henry, K. Sautter, K. Vallejo, C. Schuck, A. Weltner, E. Jankowski, P. Simmonds, Boise State University

Tensile strained quantum dot (TSQD) nanostructures present new and exciting properties, including a reduction in the band gap [1], Type I and II carrier confinement [2], and an opportunity for entangled photon emission due to low fine structure splitting [1]. These interesting TSQD properties enable potential applications in quantum, optic, and information devices [1]. We utilized molecular beam epitaxy (MBE) to synthesize self-assembled GaAs and Ge TSQDs on InAlAs(111)A surfaces. We control TSQD structural properties (i.e. volume, height, and diameter) by changing basic MBE parameters such as growth temperature, rate, and deposition amount [2]. Understanding how these parameters affect QD properties is key to successfully integrating these nanostructures into future devices. We use island scaling (IS) and radial distribution scaling (RDS) to determine how variations in MBE growth parameters and materials affect TSQD structural properties. RDS enables us to qualitatively determine the diffusion coefficient; as well as the probability of finding TSQDs at a certain distance from an arbitrary origin [3]. Although RDS has been used extensively to study traditional compressively strained QDs [4], this represents the first use of IS and RDS to explore the growth of Ge and GaAs TSQDs on InAlAs(111)A. We have seen marked differences between Ge and GaAs TSQD self-assembly, despite the fact that from the point of view of tensile strain, these two TSQD systems are similar.

We will present IS and RDS curves for Ge and GaAs TSQDs grown at 535 °C with depositions ranging from 0.2–0.6 bilayers and 3–4.5 monolayers, respectively. Compared to GaAs TSQDs, our IS results suggest narrower size distributions for Ge TSQDs, while RDS displays higher probabilities of finding Ge TSQDs closer to an arbitrary origin. This investigation will allow us to more fully understand the differences in the processes by which Ge and GaAs TSQDs self-assemble, leading to even closer control over their structural properties.

MBE-MoP11 Optical Properties of InAs/GaAsSb Sub - Monolayer Quantum Dots with Various Sb Compositions, *Minseak Kim*, H.J. Jo, J.S. Kim, Yeungnam University, Republic of Korea; Y. Kim, S.J. Lee, Korea Research Institute of Standards and Science, Republic of Korea; C. Honsberg, Arizona State University

We have investigated optical properties of the InAs/GaAsSb sub-monolayer (SML) quantum dots (QDs) by photoreflectance (PR) and photoluminescence (PL) spectroscopy. To form SML-QDs, a 0.5 ML-thick InAs layer was grown on the GaAs buffer layer and subsequently a 2.5 ML-thick GaAsSb layer (Sb compositions; 0 ~ 19.4%) was followed to cover the InAs layer. The SML-QDs layer consists of 5 cycles of InAs (0.5 ML)/GaAsSb (2.5 ML). After formation of the SML-QDs, 10 nm-thick GaAs layer was used as a spacer layer. 8 periods of SML-QD layers were embedded in each sample.

Fig. 1 and 2 showed the low temperature PL and PR spectra for InAs/GaAsSb (0.5 ML/2.5 ML) SML-QDs, respectively. As increasing the Sb composition, PL emission peak position drastically red-shifted due to the decreasing of the potential barrier height. In the PR spectra, we observed not only QDs related optical transitions but also GaAs band-to-band (E_{GaAs}) and unidentified transitions (UT) as shown in Fig. 2. The amplitude of PR spectra related to SML-QDs transitions are relatively larger than those of the GaAs. This phenomenon can be attributed to the fact that the photo-generated carriers efficiently confined in the SML-QD region. In Addition, we observed sharp transition features between GaAs and QDs due to the interface electronic states of InAs/GaAsSb/GaAs.

MBE-MoP12 LATE NEWS: Epitaxial Growth of Relaxed InGaN Films on ZnO Substrate by Plasma-Assisted Molecular Beam Epitaxy, *Kamruzzaman Khan*, E. Ahmadi, University of Michigan

InGaN alloys are attractive for optoelectronic and electronic applications and have been studied extensively for light emitting diodes and lasers in the last two decades. Varying In content in ternary InGaN alloys allows band gap engineering in a wide range of energies from 0.7 eV to 3.4 eV. Nonetheless, growth of large In content InGaN alloys have been challenging due to significant difference in thermal stability of InN and GaN, in addition to large lattice mismatch between InGaN and GaN. The latter limits the critical thickness of InGaN films grown on GaN after which InGaN relaxes plastically via formation of defects.

The above-mentioned challenges have motivated scientists to develop relaxed InGaN as pseudo-substrate. Growth of $In_zGa_{1-z}N$ on relaxed $In_xGa_{1-x}N$ substrate (z>x) is favorable due to smaller lattice mismatch which will result in larger critical thicknesses. Multiple groups have studied growth of relaxed InGaN films on GaN substrates. It has been shown that achieving full or even partial relaxation of an InGaN layer via an abrupt transition results in high density of V-defects and pits that degrade the structural and optical quality of the layer. A fully relaxed $In_{0.1}Ga_{0.9}N$ layer has been achieved on GaN by grading InGaN [1]. However, it has been shown that the relaxation occurs through formation of threading dislocations.

In this work, we have investigated growth of InGaN on ZnO substrates using plasma-assisted molecular beam epitaxy (PAMBE). InGaN and ZnO possess same stacking order. Moreover, based on Vegard's law $In_{0.2}Ga_{0.8}N$ is lattice matched to ZnO in c-plane [2] which is promising for growth of high quality relaxed InGaN buffer layers. Also, PAMBE is a relatively low temperature growth technique which should suppress the formation of unwanted In_2O_3 interlayer because of reaction between O and InGaN at the interface enabling smooth growth on these lattice-matched but chemically dis-similar materials. Here, the impact of In and Ga metal fluxes and substrate temperature on ZnO-InGaN interface quality, InGaN surface morphology and InGaN composition have been studied. We have also compared the ZnO substrate polarity (Zn-face vs O-face) on the InGaN film quality.

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MBE-MoP13 LATE NEWS: Molecular Beam Epitaxy of AlN and GaN Nanocrystals: Towards High Efficiency Deep Ultraviolet LEDs, *Yuanpeng Wu*, A. Pandey, D.A. Laleyan, X. Liu, P. Wang, C. Ahn, M. Kira, Z. Mi, University of Michigan

To date, it has remained difficult to achieve efficient LEDs operating in the ultraviolet (UV)-C band due to several critical challenges: 1) poor p-type conduction of AlN and the resulting extremely low carrier (hole) injection efficiency, 2) very low quantum efficiency due to the presence of high densities of defects, and 3) poor light extraction efficiency associated with transverse-magnetic (TM) polarized emission for Al-rich AlGaN. Dislocation-free AlGaN nanocrystals have recently shown great promise to address these critical challenges. With the use of plasma-assisted molecular beam epitaxy (MBE), we have performed extensive studies of Mg-doped AlN nanocrystals. We show that, the use of N-rich conditions can significantly enhance Mg-dopant incorporation while suppressing N-vacancy related defect formation. The formation of Al-vacancy related defects, on the other hand, can be minimized by optimizing the growth temperature. Under optimized growth conditions, we demonstrate that large densities Mg-dopant ($\sim 1 \times 10^{20} cm^{-3}$) can be incorporated in AlN. The resulting high concentrations of Mg-dopants lead to the formation of Mg impurity band and efficient hole hopping conduction. At room temperature, we measured free hole concentrations up to $6 \times 10^{17} cm^{-3}$, which is nearly seven orders of magnitude higher than that of Mg-doped AlN epilayer.

We have further investigated the epitaxy, fabrication, and characterization of large area AlN nanocrystal LEDs. The device exhibits strong electroluminescence emission at ~210 nm and excellent current-voltage characteristics, with a turn-on voltage ~6 V. The ideality factor is estimated to be ~4 and further increases with applied voltage, due to the tunneling of holes from the Mg impurity band to the valence band. We have also demonstrated deep UV LEDs by incorporating single and double monolayer GaN active regions, respectively. Such dislocation-free GaN monolayer structures can exhibit transverse-electric (TE) polarized emission in the deep UV spectrum and have reduced quantum-confined Stark effect. The controlled formation of single and double monolayer GaN was further confirmed by HAADF-STEM analysis. AlN nanowire LEDs with GaN monolayers incorporated were further fabricated. For the monolayer GaN sample, the emission peak is at 238 nm. The light intensity increases near-linearly with increasing current. The peak emission wavelength stays nearly invariant with increasing current, due to the extreme quantum-confinement. Work is currently in progress to achieve deep UV LEDs with high power operation by enhancing the light extraction efficiency utilizing AlGaN photonic nanocrystals and by optimizing fabrication process.

MBE-MoP14 LATE NEWS: Graphene/III-V Hybrid Diodes and Optical Devices by Heteroepitaxy, *R. Yao, B. Zheng*, University of Massachusetts Lowell; H. Kum, Y. Kim, S. Bae, J. Kim, Massachusetts Insititute of Technology; H. Zhang, University of Massachusetts Lowell; S. Xia, Georgia Institute of Technology; *Wei Guo*, University of Massachusetts Lowell

Graphene, an atomic monolayer formed by carbon hexagons, has recently emerged as a novel material with unique electrical and optical properties. In order to change the optical properties of graphene, a gate voltage applied to this capacitor causes carriers to accumulate or deplete on the

graphene sheet, change the graphene optical conductivity and switch the intraband absorption of the graphene. This change in absorption modulates the intensity of light travelling through it. Operation speed can be increased by using a thicker gate oxide, but the resulting lower capacitance leads to a smaller graphene optical conductivity change and reduced modulation depth and efficiency.

In this work, we demonstrate a hybrid graphene/GaAs diode and efficient modulation of THz radiations. The hybrid modulator diode is achieved by heterogeneous integration of graphene with GaAs heterojunctions enabled by the remote epitaxy technology, where graphene is placed at the depletion region of the GaAs p-n junctions, sandwiched between n-type GaAs top junction and p-type GaAs bottom junctions. The operation principle of the hybrid modulator diodes is similar to the modern semiconductor electro-absorption modulators (EAM), where the active quantum well (QW) region in placed in the III-V p-n junctions and p-n junction is electrically biased to change the absorption spectrum of the active QW region. In the hybrid modulator diode, the bias voltage of the GaAs p-n junction diode can effectively tune the Fermi level in the hybrid junction by using the depletion electric field or current injection. Figure 1b shows the reflection high-energy electron diffraction (RHEED) pattern of the GaAs layers grown on 2D graphene, it is found that a streaky GaAs 2x RHEED pattern is obtained after 400 nm GaAs remote epitaxy growth on graphene. The streaky and sharp pattern indicates smooth GaAs (100) surfaces resulted from the remote epitaxy growth. A micrograph image of the as-grown sample is shown in the inset of Figure 1b, and a mirror-like surface is obtained in the graphene region.

The details of the device characterizations over the broad spectrum from NIR to THz will be presented.

MBE-MoP15 LATE NEWS: The Role of Intervalley Phonons in Hot-Carrier Transfer and Extraction in InAs/AlAs$_{0.16}$Sb$_{0.84}$ Quantum-Well Solar Cells, *V.R. Whiteside, H. Esmaielpour, **Kyle R. Dorman**, T.D. Mishima,* University of Oklahoma*; D.K. Ferry,* Arizona State University*; M.B. Santos, I.R. Sellers,* University of Oklahoma

Much of the recent work in hot-carrier solar cells has focused on inhibiting hot-carrier relaxation through the creation of a phonon bottleneck, whereby the reabsorption of LO phonons at high excitation power reduces hot-carrier thermalization rates. We present a different approach in which the band structure of the constituent materials is utilized to store and transfer hot electrons in the upper L and X valleys of InAs quantum-well layers in a superlattice absorber, and then extract the carriers via energy selective n-Al$_{0.35}$In$_{0.65}$As and p-AlAs$_{0.16}$Sb$_{0.84}$ contact layers [1].

The electro-optical properties of p-i-n diodes with an InAs/AlAs$_{0.16}$Sb$_{0.84}$ superlattice absorber were characterized with simultaneous continuous-wave photoluminescence and monochromatic current density-voltage measurements. The experiments revealed a stable hot-carrier population not only at a relatively low excitation power, but which was nearly independent of excitation power. This behavior is attributed to preferential scattering of high-energy electrons from the Γ valley to the upper metastable satellite valleys of the InAs conduction band, which inhibits carrier thermalization via LO phonon emission. Both a high electric field and optical excitation are shown to enable hot-carrier generation in the InAs quantum wells. However, the extraction of electrons from the absorber to the n-Al$_{0.35}$In$_{0.65}$As layer is inhibited by the mismatch in the L to Γ valley degeneracy across the InAs/Al$_{0.35}$In$_{0.65}$As interface. A strength of this approach is that hot-carrier extraction is facilitated by well-established physical effects, namely intervalley scattering and the Gunn effect. Luminescence data provide evidence of a stable hot carrier population, which is shown to impact the performance of the device under practical operating conditions without the need for a phonon bottleneck. As such, this approach provides a viable route towards a hot-carrier solar cell.

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MBE

Room Silver Creek - Session MBE-1TuM

Technology of MBE

Moderator: Sanjay Krishna, The Ohio State University

8:15am **MBE-1TuM1 Epitaxy: State of the Art & and Future Trends**, *Manijeh Razeghi,* Northwestern University   **INVITED**

Nature offers us the periodic table—a full assortment of atoms. Through science and engineering we can put them together in elegant ways to realize functional structures. One of the most transformative structures we have discovered is the semiconductor. It has become one the most pervasive and powerful inventions in human history, ranked fourth in the list of top innovations since the wheel, behind the printing press, electricity, and penicillin, but ahead of eyeglasses, paper, and the steam engine.

As our growth tools have improved we have gained the ability to manipulate atoms on ever-smaller lengths scales. With an understanding of quantum mechanics these growth techniques allow us to harness the power of the semiconductor to create new structures never before found in nature. This has been an enabling technology and through our manipulation of these structures we have developed a whole host of new applications that are shrinking the World and fostering the rapid advancement of human society.

We are able to create quantum devices that allow us to see invisible light from deep UV to THZ. We can probe the human body to find cures and treat diseases. We can communicate with each other faster over ever-larger distances, sharing even more information, thanks to quantum technologies. A particularly rich playground for quantum technology is the so-called III-V semiconductors made of atoms from columns III and V of the periodic table, and constitution compounds with many useful optical and electronics in their own right.(having direct band gap, Strong Covalent bonding with Zinc blend symmetry) Guided by highly accurate simulations of the electronics structure, modern semiconductor optoelectronic devices are literally made atom by atom using advance growth technology such as MBE and MOCVD in ways to give them new properties that neither material has on its own.

In this talk I will review the growth of state of the art semiconductor materials for high performance and quantum devices ranging from the deep UV (200 nm) all the way up to THZ (300 micron) based on MBE MOMBE, Gas-MBE,LPE, VPE , and MOCVD. I will cover the advantages and disadvantages of each technique and discuss the need for future epitaxial techniques to allow us to continue expanding our atomic control of quantum materials.

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8:45am **MBE-1TuM3 Growth-Induced Temperature Changes During Transition Metal Nitride Epitaxy on Transparent SiC Substrates**, *D. Scott Katzer, M. Hardy, N. Nepal, D. Storm, B. Downey, E. Jin, D. Meyer,* U.S. Naval Research Laboratory

Accurate non-contact substrate temperature monitoring and control during MBE growth has been a topic of continued interest for more than 25 years [1-3]. While accurate temperature control is well understood for homoepitaxial growth, large substrate temperature changes that are not accurately sensed by the substrate heater thermocouple can be induced by high carrier densities [4-5], reduction of the effective bandgap of the substrate/epitaxial layer stack [1-2], and changes in the surface reflectivity (e.g. induced by the accumulation of gallium droplets in GaN MBE) [6] during growth. In general, any change of the thermal cavity that partially encloses the substrate can also be expected to lead to a change in substrate temperature.

An experimental case that exemplifies the one of most extreme examples of growth-induced temperature changes is the MBE growth of metallic films on transparent semi-insulating SiC. Integration of epitaxial metal layers are technologically important as they will enable substantial performance benefits, design flexibility, and novel device structures such as metal-base transistors [7] and integrated epitaxial superconductor/semiconductor heterostructures [8]. Metals are highly reflective, have very high carrier densities, and have very small or zero band gaps compared to the ~ 3 eV gap of SiC. All of these factors mean that even very thin epitaxial metal layers can be expected to lead to large substrate temperature changes during growth.

In this presentation, we will discuss the use of in-situ SiC band-edge thermometry and pyrometry to quantify and control the substrate

temperature excursion during the MBE growth of transition metals and transition metal nitrides on transparent 3" diameter 4H- and 6H-SiC substrates.

This work was funded by the Office of Naval Research.

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9:00am **MBE-1TuM4 Using the Desorption Mass Spectrometry Technique to Optimize Sb Flux in GaSbBi Growth**, *Jedidiah McCoy, C. Lu, R. Kaspi,* Air Force Research Laboratory

Bismuth incorporation into GaSbxBi1-xis of interest because the bandgap is substantially reduced within manageable levels of strain. However, MBE growth of this alloy has yet to mature. This is because achieving substantial (>10%) Bi incorporation while maintaining good crystal quality is challenging. To assist Bi competition over Sb in group V incorporation, growths must be conducted at relatively low substrate temperatures (<300 °C) with near-stoichiometric V/III flux ratios [1]. Because these conditions are outside of the typical GaSb growth window, it becomes imperative to precisely establish the Sb/Ga flux ratio as it is observed to have a large effect on Bi incorporation.

In this study, we utilized the desorption mass spectrometry (DMS) technique to establish a near-stoichiometric Sb/Ga flux ratio at the growth temperature of interest. The DMS technique allows for in-situ monitoring of desorbed Sb so that fine-tuning of the Sb/Ga flux ratio can be accomplished. Using this methodology, GaSb1-xBix layers were deposited at temperatures ranging from as low as 125 °C to 300 °C. Bismuth incorporation exceeding 15% was achieved as well as room temperature luminescence approaching 4 µm, as shown in figure 1.

The DMS technique was also used to explore the GaSb1-xBixgrowth surface. This was done by interrupting the growthsequence and raising the substrate temperature thereby releasing any unincorporated Bi at the surface, which could then be quantified using the desorption spectra, see figure 2. A correlation between this steady-state concentration of unincorporated Bi with growth conditions such as substrate temperature and Bi flux will be discussed.

9:15am **MBE-1TuM5 BBr₃ as a B Source in Plasma Assisted MBE**, *Richard Cramer, B. Bonef, J. Speck,* University of California, Santa Barbara

Boron is a difficult material to use in MBE due to its high melting point. Traditionally group III molecular beams are generated by vaporizing samples of pure metal at temperatures well above their melting points. For B which has a melting point of 2076° C this is not currently feasible as even high temperature effusion cells max out around 2000° C. Due to this limitation there is interest in exploring other B sources for MBE such as ion-beam, electron-beam, and gas sources including BBr₃. In this talk we will present BGaN growth experiments which serve as a proof of concept for BBr₃ as a B source for plasma assisted MBE.

We will present data from our experiments in which we grow fully coherent, random alloy, $B_xGa_{1-x}N$ thin films with x up to 3% and thickness up to 280 nm.[1] High resolution XRD was used to characterize the film quality and determine the strain state of the films. On axis ω-2θ scans were used to determine the c parameter of the films and the presence of thickness fringes in these scans is indicative of high crystal quality and was used to measure thickness. Reciprocal space maps around off axis peaks were used to determine that the films were fully coherent to the GaN on sapphire substrates. Using the elastic coefficients of GaN and standard stress-strain relations we calculated the relaxed c parameter and from that the B composition using Vegard's law and theoretical values for wurtzite phase BN lattice constants.

Tuesday Morning, September 24, 2019

Atom probe tomography (APT) was performed on samples to demonstrate that they had a random, binomial, distribution of B and Ga atoms and are therefore true random alloys.[2] APT and secondary ion mas spectroscopy (SIMS) results were also used to characterize the impurity levels in the films and it was found that our initial growth conditions lead to high levels of O, C, and Br impurities.

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9:30am MBE-1TuM6 Assessing MBE Regrowth Quality on Transfer Printed Virtual Substrates, *Michael Yakes,* Naval Research Laboratory*; M. Lumb, M. Bennett,* George Washington University*; J. Nolde, S. Tomasulo,* Naval Research Laboratory*; C. Haughn,* Army Research Laboratory*; S. Mack, S. Maximenko, K. Schmieder,* Naval Research Laboratory

III-V semiconductor devices provide the highest performance in many optoelectronic applications, including solar cells. However, the large cost to produce these devices can make them very expensive compared to lower quality counterparts. One key factor driving the cost of III-V devices is the high cost of high quality, single crystalline substrates. To address this issue, we have been developing a new technique which we call transfer printed virtual substrates (TPVS). In this technique, shown in Figure 1, a large number of virtual substrate layers, separated by epitaxial release layers, are grown on a source substrate. From this source substrate, virtual substrate layers are moved to separate low cost handles using micro-transfer printing. By iterating through many layers of the source substrate stack, one source substrate can be used to produce a large number of low-cost, epi-ready virtual substrates, which can in turn be used to produce a variety of microscale devices.

In this presentation, we will illustrate the quality of epilayers grown on TPVS by MBE [1,2]. To evaluate surface morphology and optical quality we grew a GaAs/AlGaAs MQW structure on a GaAs TPVS and control wafer. We observed similar surface roughness, XRD peak width and PL linewidths on both the TPVS and the control samples. We've also produced a device demonstration using identical GaAs solar cell structures grown on a native substrate and a TPVS. The efficiency of devices grown on a TPVS is degraded by less than 2% absolute efficiency from the control structures (Figure 2), both under one-sun conditions and under concentration. The experiments suggest that with further process enhancement, TPVS should be able to produce identical performance devices with much lower cost.

9:45am MBE-1TuM7 LATE NEWS: Mechanism of Si Doping in O_2 Plasma-Assisted MBE Growth of β-Ga_2O_3, *Nidhin Kurian Kalarickal, Z. Xia, J. McGlone, S. Krishnamoorthy, W. Moore, M. Brenner, A.R. Arehart, S.A. Ringel, S. Rajan,* The Ohio State University

Si has been shown to be a shallow donor in β-Ga_2O_3 and the MBE growth of Si-doped β-Ga_2O_3 thin films is of extensive importance for realization of electronic and optoelectronic devices based on this promising ultra-wide bandgap material. The dependence of Si flux on effusion cell temperatures have been found to be significantly higher in oxygen environments when compared to non-oxide growth chambers, suggesting that the mechanism of Si flux generation is different from sublimation [1]. *In this work, we report on understanding the mechanism of Si doping during oxygen plasma-assisted MBE (PAMBE) growth of β-Ga_2O_3.*

We studied the dependence of Si deposition as a function of oxygen chamber pressure, Si cell temperature, plasma power and shutter time using Secondary Ion Mass Spectroscopy analysis.Our studies show that (a) Si flux is not limited by Si vapor pressure but by the formation of SiO species on the Si surface, (b) the low sublimation energy of SiO leads to weak dependence of the SiO flux on Si cell temperature and strong dependence on the background oxygen pressure and (c) extended exposure to activated oxygen can lead to passive oxidation of Si surface to SiO_2 leading to reduction in SiO flux.

The work reported provides key understanding for incorporating Si into future oxide-based semiconductor heterostructure and device MBE growth. This work was funded by AFOSR GAME MURI (Grant FA9550-18-1-0479, Program Manager Dr. Ali Sayir).

[1] Xia, Zhanbo, et al." *IEEE Electron Device Letters* 39.4 (2018): 568-571 .

MBE
Room Silver Creek - Session MBE-2TuM
MBE Devices
Moderator: Songrui Zhao, McGill University

10:30am MBE-2TuM10 Development of AlAsSb Digital Alloys on GaSb and InP Substrates for Photo-Detector Applications, *Baolai Liang, B.C. Juang, M. Debnath, D. Huffaker,* University of California, Los Angeles

The III-(As, Sb) ternary or quaternary materials are commonly limited by spontaneous formation of clusters and phase separations during alloying. In particular, due to the wide miscibility band gap, growth of thick high-quality and lattice-matched AlAsSb alloy on GaSb or InP substrates is extremely challenging because of the non-unity sticking coefficient of group-V species. In this research, digital alloy growth by molecular beam epitaxy (MBE) has been adopted in preference to conventional random alloy growth because of the extra degree of control.

The AlAsSb structures are grown on epi-ready InP (001) and GaSb (001) substrates, respectively, via digital alloy growth technology by a Veeco GEN930 MBE reactor, in which both As_2 and Sb_2 fluxes are supplied using valved cracker cells. In order to get the precise lattice-matched AlAsSb alloy with high crystalline quality, digitally grown AlAsSb is realized by periodically alternating the As and Sb shutter to obtain the desired alloy composition. The AlAsSb epi-layers grown by digital alloy technique showed stronger photoluminescence intensity, narrower peak linewidth, and larger carrier activation energy than that grown via the random alloy technique, indicating an improved optical quality with lower density of non-radiative recombination centers for the AlAsSb digital alloy samples. In addition, a relatively long carrier lifetime was observed from the digital alloy samples, consistent with the results obtained from the photoluminescence study.

Finally, the AlAsSb epi-layers have been applied to constructed PIN and Separate Absorption and Multiplication Avalanche Photodiodes (SAM-APD) structures. The devices show optimized detection performance.

Figure (a) High-resolution cross-sectional TEM of the AlAsSb/GaSb interface and corresponding diffraction pattern of the AlAsSb digital-alloy epi-layer. (b) Low-temperature (7 K) PL emission from AlAsSb/GaSb digital-alloy epi-layer.

[1] E. Hall, H. Kroemer, L.A. Coldren, *J. Cryst. Growth* 203, 447 (1999).

[2] M. C. Debnath, B.L. Liang, R. B. Laghumavarapu, G.D. Wang, A. Das, B.C. Juang, D. L. Huffaker, *J. Appl. Phys.* 121, 214304 (2017).

[3] B.C. Juang, B.L. Liang, D.K. Ren, D.L. Prout, A.F. Chatziioannou, D. L. Huffaker, *Crystal* 7, 313 (2017).

[4] B.C. Juang, A. Chen, D.K. Ren, B.L. Liang, D.L. Prout, A.F. Chatziioannou, D. L. Huffaker, *Adv. Optical Mater.* 2019, 1900107

10:45am MBE-2TuM11 Structural and Optical Properties of Bulk nBn InAsSb Metamorphic Detector, *Vinita Dahiya, Z. Taghipour, A. Blumer,* The Ohio State University*; D. Lubyshev, J. Fastenau, A. Liu,* IQE Inc.*; T. Grassman, S. Krishna,* The Ohio State University

With the availability of GaSb substrates, 6.1Å family based III-antimonide material system has shown enormous potential in the infrared detectors due to high design flexibility of various heterostructures. However, to compete with the incumbent HgCdTe technology, fabrication of large format focal plane arrays (FPAs) is required for higher throughput and yield. One promising path to larger FPAs and higher volumes includes the epitaxial growth on mismatch large area substrates, which includes the drawback of the generation of deleterious threading dislocations (TDs). The TDs impedes the minority carrier lifetime which in turn increases the dark current, hence noisy photodetector. Thus, it is important to minimize the TD density (TDD) and study its effect on the minority carrier lifetime.

For this purpose, InAsSb nBn photodetectors with a room temperature 50% cut-off wavelength of 4.2 μm are grown on three substrates, including GaSb itself, semi-insulating GaAs, and Ge/Si substrates using appropriate metamorphic buffer layers. To study the correlation between TDD and the minority carrier lifetime,t techniques including electron channel contrast imaging (for TDD measurement) and time resolved microwave reflectance (for minority carrier lifetime measurement) are employed.

The preliminary results indicated that the sample with lowest TDD (grown on GaSb substrate) has the highest minority carrier lifetime and the magnitude of minority carrier lifetime is reduced to half when grown on Ge/Si. Although, the nBn detector on Ge/Si has higher lifetime compared to the GaAs substrate. Interestingly, the difference in lifetime does not have a

direct correlation with the diode performance measured on large-area devices, as the quantum efficiency measured ~60% on all three samples. Thus, Ge/Si can be used as an alternative approach to grow virtual substrates, enabling large format FPA processing with direct integration of the III-V devices with Si microelectronics read-out and processing architectures.

11:00am MBE-2TuM12 All-Epitaxial Mid-Wavelength Infrared Resonant Cavity-Enhanced Photodiodes, *Gregory Savich*, G. Wicks, J. Shao, K. Jamison, L. Fredin, T. Golding, Amethyst Research Inc.; *M. Carmichael*, Amethyst Research Ltd., UK; *A. Craig, F. Al-Saymari, A. Marshall,* Lancaster University, UK

III-V semiconductor-based mid-wavelength infrared (MWIR) detectors have reached a point of diminishing returns in the drive towards reduced dark current. To realize a significant improvement in dark current magnitude, new concepts and approaches must be explored. One approach is to reduce the thickness of the optical absorber of the detector. Typical MWIR detectors require several micron thick absorbers in order to absorb most of the light and obtain high quantum efficiency. This results in elevated dark current as dark current is directly proportional to optical absorber thickness [1]. One approach to reducing optical absorber thickness is to place a thin optical absorber within a resonant cavity between high reflectivity mirrors, similar to vertical-cavity surface emitting laser (VCSEL) structures. This resonant cavity-enhanced photodiode (RCE-PD) architecture creates many optical passes through the absorber, allowing an absorber which is 50-100x thinner than conventional MWIR detectors while offering other unique features including: narrow spectral linewidth, reduced dark and background current, and enhanced detection at cavity resonance.

We report on all-epitaxial MWIR RCE-PDs via MBE. Distributed Bragg reflector upper and lower mirrors are deposited on either side of an optical cavity containing a thin MWIR optical absorber via a single growth. Results show dark current magnitudes near or below Rule07 [2] at the cut-off wavelength of the absorber, spectral linewidths <40 nm, and a 300K D* > 1×10^{10} cm Hz$^{1/2}$ W^{-1}. Creating an all-epitaxial RCE-PD requires careful epitaxial design and exact control of MBE growth parameters which will be discussed.

[1] G. R. Savich, *et al,* Applied Physics Letters 106(17), 173505 (2015).

[2] W. E. Tennant, Journal of Electronic Materials 39(7), 1030-1035 (2010).

11:15am MBE-2TuM13 Molecular Beam Epitaxy of Coalesced AlGaN Nanowires: Ultraviolet Transparent Electrodes for Large-Area LEDs, *Brelon May*, National Renewable Energy Laboratory; *E. Hettiaratchy, B. Wang, C. Selcu, B. Esser, D. McComb, R. Myers,* The Ohio State University

Nanowire based AlGaN optoelectronics have the advantage of providing high crystalline quality material on a variety of different substrates. However, the efficiency of nanowire-based LEDs is not on par with similar thin film devices. This is in part because each individual nanowire must be wired in parallel. Typical heterostructures have a p-type up design, requiring a conformal metal top contact which is highly opaque in the ultraviolet (UV) wavelengths. This work uses plasma assisted molecular beam epitaxy (PAMBE) to demonstrate coalesced n-AlGaN nanowires as a transparent semiconductor electrode top contact to improve the light extraction efficiency of UV nanowire LEDs on Si. Electron microscopy reveals coalescence of nanowire tops into a continuous top electrode. Conductive atomic force microscopy (cAFM) is used to measure the uniformity of the resistance of the coalesced nanowire LEDs. Direct imaging of operational devices is used to investigate the homogeneity of the current spreading in the coalesced nanowire LEDs at the sub-micron scale. Compared with conformal semi-transparent metallic contacts, the UV transparent n-AlGaN coalesced layer results in efficiency improvement of about 37×. Additionally, the coalesced contact avoids the direct wiring of electrical shorts resulting in a greatly increased yield of working large-area (>1 mm^2) nanowire UV LEDs.

11:30am MBE-2TuM14 High Peak-current Density AlN/GaN Resonant Tunnel Diodes Grown by rf-MBE on GaN Templates, *David Storm,* U.S. Naval Research Laboratory; *T. Growden,* Naval Research Laboratory; *E. Cornuelle, L. Whitaker,* The Ohio State University; *P. Peri,* Arizona State University; *W. Zhang,* Wright State University; *J. Daulton,* Massachusetts Institute of Technology; *D.S. Katzer, M. Hardy, N. Nepal,* U.S. Naval Research Laboratory; *R. Molnar,* Massachusetts Institute of Technology; *E. Brown,* Wright State University; *P. Berger,* The Ohio State University; *D. Meyer,* U.S. Naval Research Laboratory; *D. Smith,* Arizona State University

AlN/GaN resonant tunnel diodes (RTD) exhibiting peak current density (J$_P$) as high as 930 kA/cm^2 and peak-to-valley current ratios (PVCR) of 1.1 have been grown by rf plasma-assisted MBE on MOCVD-grown GaN templates on sapphire. The threading dislocation density of the GaN templates was estimated to be 3×10^8 cm^{-2} by atomic force microscopy (AFM). Nominally identical structures were grown at temperatures between 760 °C and 860 °C under growth conditions identical to those used to demonstrate repeatable, stable, room-temperature negative differential resistance (NDR) and high J$_P$ in AlN/GaN RTDs grown on freestanding GaN substrates [1, 2]. The device structures were characterized by AFM, high-resolution x-ray diffractometry (HR-XRD), and transmission electron microscopy (TEM). AFM revealed increasing surface roughness with increasing temperature. HR-XRD of similarly-grown samples indicated a constant, N-limited growth rate of 3.21 nm/min. TEM revealed sub-surface pits below the active region and corroborated the previous estimate of the dislocation density. Stable, repeatable, room-temperature NDR was observed from all samples. In general, higher growth temperatures resulted in higher J$_P$ but with fewer devices exhibiting proper NDR. In particular, the sample grown at the highest temperature, 860 °C, yielded the highest J$_P$ (930 kA/cm^2), but only the smallest-area devices exhibited NDR. Conversely, samples grown at lower temperature yielded a higher fraction of devices exhibiting NDR, including larger area devices, but the J$_P$ and PVCR were much reduced. Thermal modeling indicates these devices exhibit NDR despite active region temperatures in excess of 400 °C, and that for a given J$_P$ this temperature increases markedly with increasing device area, suggesting device performance is thermally limited.

[1] T.A. Growden *et al.*, Appl. Phys. Lett. **109**, 083504 (2016)

[2] T.A. Growden *et al.*, Appl. Phys. Lett. **112**, 033508 (2018)

+ Author for correspondence: david.storm@nrl.navy.mil

11:45am MBE-2TuM15 Optimized Material for Intermediate Band Solar Cells: Type-II CdTe Quantum Dots in a ZnCdSe Matrix, *Vasilios Deligiannakis,* The City College of New York/Graduate Center of CUNY; *M. Begliarbekov,* CUNY Advanced Science Research Center; *S. Alsheimer,* City College of New York, City University of New York; *I. Kuskovsky,* Queens College; *M. Tamargo,* City College of New York, City University of New York

Intermediate band solar cells (IBSCs) based on quantum dots (QDs) have the potential to overcome the Schockly-Quisser limit for single junction soar cells. By forming an intermediate band (IB) within a host material with a larger band gap, QDs can ultimately increase light absorption of the solar spectrum without compromising the open circuit voltage of the device. This is achieved by a two-step photon process that occurs from the valence band (VB) to the IB and from IB to the conduction band (CB), while the conventional band to band transitions from the VB to CB of the host material is still allowed.

Type-II ZnCdSe/Zn(Cd)Te sub-monolayer QDs have been explored by our group for their promising properties as IBSCs. However, it was recently shown that at the interface between the ZnCdSe host material and the QDs an unintentional highly strained interfacial layer (IF) is formed comprised of ZnSe[1]. The presence of this layer can affect the band structure of the device and result in an accumulation of strain, which can lead to the formation of defects, reducing the device performance. Here we pursue a new material system: sub-monolayer CdTe QDs embedded in the ZnCdSe host material. Besides providing a platform in which the ZnSe IF layer is highly suppressed, this system has several advantages over the ZnCdTe QD

system previously studied. Two main advantages are: 1) the binary composition of the QDs which makes them more easily controlled and more uniform, and 2) its larger valence band offset with the matrix material (ZnCdSe) which allows for better device bandstructure engineering.

The ZnCdSe/CdTe QD superlattice (SL) is grown by a combination of conventional molecular beam epitaxy (MBE) and migration enhanced epitaxy (MEE). A spacer region of ~3nm was grown made of ZnCdSe nearly lattice matched to InP. The formation of CdTe QDs was achieved by using a shutter sequence of alternating Cd and Te fluxes with short wait times between them. A triple cycle of this alternating shutter sequence was used, and the spacer and QD layers were repeated 100 times. High resolution XRD data illustrates the high quality of the IB absorption material and shows that the superlattice (SL) structure is under high compressive strain due to the CdTe QDs and indicates no evidence of a ZnSe IF layer. Calculations indicate that only sub-monolayer quantities of CdTe are required for the observed SL mismatch. Both IB absorption layers and full solar cell device structures will be discussed.

Tuesday Afternoon, September 24, 2019

MBE

Room Silver Creek - Session MBE-1TuA

Layered Materials

Moderator: Stephanie Tomasulo, Naval Research Laboratory

1:30pm **MBE-1TuA1 MBE Young Investigator Award Winner: TBD**,

2:00pm **MBE-1TuA3 Band Engineering to Achieve a Wide Band Gap Topological Insulator**, *Ido Levy, C. Youmans, T. Garcia, H. Deng, S. Alsheimer, L. Krusin-Elbaum, P. Ghaemi, M. Tamargo,* City College of New York, City University of New York

Three dimensional topological insulators (3D TIs) are being widely researched today for their attractive and unique transport properties [1]. These materials present a bandgap in the bulk and highly conducting metallic surface states. Heterostructures of these TIs are predicted to show promising properties [2]. We have recently shown that a short period superlattice of two TI materials, such as Bi_2Se_3 and Sb_2Te_3, can present promising electrical properties, for example a decrease in carrier concentration in the bulk and an increase of resistance as a function of the superlattice period. This can be explained by the formation of a bulk bandgap in the superlattice due to confinement effects in each of the layers, as a result of their "broken gap" band alignment. A question remains as to the presence of the topological surface states in such a short period superlattice structure. To investigate this, magnetoconductance measurements were performed for the superlattice structure with the smallest periodicity; one that showed the reduced bulk conductivity previously observed. Fitting these data to the typically used Hikami-Larkin-Nagaka theory [3] suggests the presence of two two-dimensional conduction channels in the small period superlattice as expected for a 3D TI layer. Angle dependent magnetoresistance measurements and a fit of the dephasing length (l_ϕ) dependence on temperature both give further supporting evidence of the preservation of the topological surface states. Thus, we conclude that this short period Bi_2Se_3-Sb_2Te_3TI-TI superlattice behaves as a designer 3D TI with different properties to the two individual TI constituents, which are conducting in the bulk. Tight binding calculation for such short period TI-TI superlattices were performed and the results suggest that for the appropriate combination of materials, it may be possible to achieve a "designer" 3D TI with a bulk bandgap that is larger than the gaps of either of the component TI materials.

[1] Y. Xia et al., Nat. Phys. 5, 398 (2009)

[2] K.M. Masum-Habib et al., Phys. Rev. Lett. 114, 176801 (2015)

[3] S. Hikami et al., Prog. Theor. Phys. 63, 707 (1980)

2:15pm **MBE-1TuA4 Van der Waal Epitaxy of Bi_2Se_3 on GaAs: A Morphological Playground**, *Theresa Ginley, S. Law,* University of Delaware

Molecular beam epitaxy of layered van der Waal (vdW) materials is a promising avenue for improving optic, optoelectronic, spintronic, and valleytronic technologies. These materials are characterized by strongly bonded layers in the *a-b* plane and weak vdW bonds between layers in the *c*-direction. During thin film growth the weak vdW bonds translate to weak interaction with the substrate. Unlike in strongly bonded traditional epitaxy, vdW materials can grow on substrates with vastly different lattice constants and crystal structures. However, the weak substrate interaction means that vdW epitaxy cannot be fully understood via the well-known mechanics of traditional MBE, and morphological control has proven challenging; vdW materials tend to grow in terraced "wedding cake" morphologies rather than the desired atomically smooth layers. These materials also preferentially grow in the (001) orientation with the vdW gaps parallel to the growth surface. Other orientations have proven elusive and require extensive pretreatment or patterning of the substrate. An in-depth exploration of vdW phase space is required to understand the growth dynamics of these material systems.

In this study we look at the topological insulator (TI) Bi_2Se_3 as a prototypical vdW material. Previous work on $(Bi_{1-x}In_x)_2Se_3$ (a trivial insulator for x>0.3) revealed a complex phase space with features ranging from ultra-smooth surfaces to nanowires.[1] Here, we focus phase space exploration on Bi_2Se_3 in order to discover novel morphologies that could take advantage of the TI behaviors in Bi_2Se_3. It has been found that using a seed layer plays a major role in the final morphology of the films. A film grown on a 10nm $(Bi_{0.5}In_{0.5})_2Se_3$ seed layer results in the formation of Bi_2Se_3 nanowires perpendicular to the substrate (film A). A film grown on a 5nm Bi_2Se_3 seed layer results in a smooth film (film B). Finally, growth with no seed layer results in needles of Bi_2Se_3 in the (105) orientation (film C). All three morphologies show some degree of orientation along the [110] axis of the GaAs substrate, known to be the fast diffusion direction for bismuth. Based on this research it is believed that vdW growth dynamics are dominated by the relative strength of film/adatom and substrate/adatom interactions. The growth to anneal ratio, substrate temperature, and film thickness have also been explored to better understand the growth mechanics and nanowire evolution in the Bi_2Se_3 material system.

2:30pm **MBE-1TuA5 Growth of GeTe and Sb2Te3 Interlayer Structures for Interfacial Phase Change Devices via Molecular Beam Epitaxy**, *Adrian Podpirka, D. Shrekenhamer, C. Zgrabik, J. Pierce, J. Gagnon,* JHU/APL

Phase change memories (PCMs) are based on the bad glass forming ability and metastability of the thermodynamic and kinetic transition in chalcogenide materials. This relies on the electrical and optical properties changing substantially when the atomic structure of the materials is altered. This transition, between a significant electrical resistance in the amorphous phase and a highly conductive state in the crystalline phase, has lent itself to numerous applications that include optical storage (i.e. blue ray and CDs) to electronic devices (i.e. Intel x-point technology). A novel subset of these materials uses the superlattice structure in order to greatly reduce the switching current and total energy required, thereby overcoming the joule heating constraint common to conventional PCMs. These are known as interfacial phase change materials (iPCM). Though currently unsettled as to the origins of the mechanism, they have shown promise for use in microwave devices based on interlayer switching by reducing the thermal loads required. In this presentation, we investigate the growth of interfacial GeTe-Sb_2Te_3 structures via Molecular Beam Epitaxy (MBE) with differing orientations and various substrates (GaAs, Si, Al_2O_3) and report on the electro-optical properties associated with the morphological and structural changes in this material system. By varying the elemental flux and novel heating method, we are able to stabilize the superlattice structure in a 2D growth regime. The ability to grow via MBE on transparent substrates allows us to incorporate the iPCMs into next-generation optical devices.

2:45pm **MBE-1TuA6 Molecular Beam Epitaxy of Hexagonal Boron Nitride on HOPG**, *Ping Wang, E.T. Reid, D.A. Laleyan, J. Gim, Q. Wen, Z. Liu, Z. Zhong, M. Kira, R. Hovden, Z. Mi,* University of Michigan

As a member of the III-nitrides as well as the two-dimensional (2D) material families, hexagonal boron nitride (hBN) has received tremendous attention in recent years, and has emerged as a promising candidate for many applications, including deep ultraviolet (UV) and 2D optoelectronics, 2D transistors, and quantum emitters. In the 2D materials group, graphite, graphene, and hBN are lattice-matched to within 2% and exhibit complementary electronic properties, with hBN having a wide bandgap and graphene being a gap-less semimetal [1]. Multilayer hybrid heterostructures based on graphene and hBN have been intensively studied by stacking layers exfoliated from highly-ordered pyrolytic graphite (HOPG) and hBN crystals. To realize well-stacked vertical 2D heterostructures and to achieve scalable devices, epitaxial growth of such configuration would be highly beneficial [2].

In this context, we have investigated the epitaxy of hBN on HOPG utilizing ultra-high temperature molecular beam epitaxy (MBE) equipped with a plasma-assisted nitrogen source. We have demonstrated the formation of hBN quantum dots (QDs) and flakes at different growth conditions. The initial nucleation of hBN takes place primarily at the HOPG atomic steps, where the height fluctuation provides nucleation sites on low surface energy planes, whereas nucleation rarely formed on the bare terraces. Auger electron spectroscopy (AES) confirms the presence of boron and nitrogen elements from the QDs and flakes with a B/N ratio nearly 1, indicating both of the dot- and flake-like nanostructures are BN. Atomic force microscopy (AFM) shows that most of the flakes are 1 ML hBN with a thickness of 3.5 Å, while the QDs have lateral sizes ~5-10 nm and heights ~2-5 nm. Strong excitonic emission at ~215 nm has been observed using a 193 nm excitation laser at room temperature. A detailed study of the structural and optical properties of hBN quantum dots is currently in progress and will be reported.

MBE
Room Silver Creek - Session MBE-2TuA

Quantum Dots
Moderator: Paul Simmonds, Boise State University

3:30pm MBE-2TuA9 InAs Chirped Quantum Dot Growth on Si for Broadband Spectral Gain Mode--locked Laser, *Daehwan Jung,* Korea Institute of Science and Technology, Republic of Korea*; J. Norman, C. Shang, S. Tao, Y. Wan, A. Gossard, J. Bowers,* University of California, Santa Barbara

Monolithic integration of an efficient and reliable III-V light source onto Si has been heavily studied for the past decades. Recently, quantum dot (QD) lasers directly grown on Si have shown tremendous improvements in performance and device reliability, primarily due to the effective carrier localization of QDs. [1] Furthermore, QD lasers are promising for generation of ultra-short pulses by operating them in the passively mode-locking regime. We have shown that QD lasers epitaxially grown on Si could be used as a source for a dense wavelength-division multiplexing (DWDM) system. [2] The monolithically integrated mode-locked QD laser consisted of five layers of InAs/In$_{0.15}$Ga$_{0.85}$As dot-in-a-well (DWELL) structure and showed an optical gain spectrum full-width at half-maximum (FWHM) of 3.56 nm. The relatively small optical spectrum width can be further increased by considerably designing the QD active region on Si.

For conventional low threshold current QD lasers, growing the multiple QD layers in an identical growth condition (i.e. temperature) is crucial. Doing so, a full epitaxial laser structure will have narrow photoluminescence (PL) linewidth. However, for broadband gain mode-locked lasers, growing the QD layers at slightly different QD structures is important so that the ensemble of individual PL spectra possesses broad PL spectrum while maintaining a high intensity.

Here, we report growth of chirped InAs/GaAs QDs by solid state molecular beam epitaxy. The InAs/InGaAs DWELL structures vary as shown in the Table I. Five samples were grown on native GaAs substrates to investigate their PL properties. The DWELL active region was grown at 495 °C by an optical pyrometer. The InAs QD deposition rate was 0.1132 monolayer (ML) per second. Figure 1 shows PL spectra of the five different samples. The PL peaks are well spaced to have a broadened optical gain. Full laser structures were grown on Si to compare the FWHMs of a broadband gain laser with chirped QD growth and a conventional laser. Figure 2 shows the two different lasers grown on Si have similar PL intensities. However, the broadband gain laser possesses a much wider PL linewidth (FWHM= 43 meV) than the reference laser in which the linewidth is 28.6 meV). More optimizations on the chirped QD growth could lead to further broadened PL widths. We believe that the chirped InAs DWELL structure is a promising method to realize passively mode-locked QD lasers with broadband optical gain spectrum.

[1] Daehwan Jung *et al.* Appl. Phys. Lett. 111 (12), 122107

[2] Song Tao *et al.* Appl. Phys. Lett. 113 (4), 041108

3:45pm MBE-2TuA10 InP Quantum Dots for Dislocation-tolerant, Visible Light Emitters on Si, *Pankul Dhingra,* University of Illinois Urbana-Champaign*; Y. Sun,* Yale University*; S. Fan, R. Hool, M.L. Lee,* University of Illinois Urbana-Champaign

We present the first demonstration of InP quantum dots (QDs) on Si showing room-temperature, visible photoluminescence (PL) intensity nearly identical to samples grown on GaAs. The past few years have seen tremendous progress in the development of 1.3 μm InAs quantum dot (QD) lasers on Si with low threshold current density and high reliability despite threading dislocation densities (TDD) of 10^7 cm^{-2} [1]. The high luminescence efficiency of InAs QDs on Si can be attributed to lateral carrier confinement of the QDs and high QD density, 3 orders of magnitude higher than the TDD. Epitaxial InP QDs embedded in (Al$_x$Ga$_{1-x}$)$_{0.52}$In$_{0.48}$P can also be grown on GaAs and have recently been used to demonstrate red and near-infrared lasers with low threshold current density [2]. Here, we show that the apparent dislocation-tolerance of InAs QDs on Si also extends to InP QDs on Si, making them an ideal candidate for low-cost visible and near-infrared lasers and light emitting diodes (LEDs).

We grew InP/AlGaInP QD PL structures on bulk GaAs and GaAs/Si virtual substrates using MBE. GaAs/Si virtual substrates were grown on commercially available GaP/Si (001) templates using a 3.6 μm thick GaAs$_x$P$_{1-x}$step-graded buffer. Cross-sectional transmission electron microscope (XTEM) images of samples grown on both GaAs and GaAs/Si were nearly identical, showing coherently strained InP QDs capped by a smooth InGaP QW. Planar-view cathodoluminescence (CL) maps showed essentially no dislocations for the sample grown on GaAs, as expected. In contrast, a TDD of 3.3×10^7 cm^{-2} was observed for the sample grown on GaAs/Si. Atomic force microscopy (AFM) showed a high QD density of 1.3×10^{11} cm^{-2} on both substrates, which is several orders of magnitude greater than the TDD in the active region. We performed room-temperature PL measurements to characterize the emission wavelength and intensity of InGaP QWs and InP QDs grown on both GaAs and GaAs/Si virtual substrates. The integrated intensity of the InGaP QW sample grown on GaAs/Si is ~9× lower than the QW on GaAs due to the high TDD. In contrast, the integrated intensity of InP QDs on Si is ~16× higher than the InGaP QW on Si and within 15% of InP QDs grown on GaAs, showing the high dislocation tolerance of InP QDs. In conclusion, we show that high density InP/AlGaInP QDs can be grown on Si with similar structural and optical properties as growth on bulk GaAs, paving a pathway towards low-cost, integrated light emitters with potential applications ranging from micro-LEDs to optogenetics.

[1] Jung, ACS Photonics, **5**, 1094 (2018)

[2] Lutti, Electron Lett., **5**, 247 (2005)

+ Author for correspondence: mllee@illinois.edu

4:00pm MBE-2TuA11 Gallium-assisted Deoxidation for Spatially and Spectrally Controlled InAs Quantum Dot Molecules, *Lauren McCabe, J. Zide,* University of Delaware

InAs quantum dots (QDs) have long been considered as possible qubits and numerous proof-of-concept quantum operations have been performed [1, 2]. However the random nucleation for these self-assembled QDs and the spectral inhomogeneity that arises from variations in size, composition, and shape have made it impossible to produce arrays of identical QDs that are desired for scalable production of devices. Other material platforms for quantum device technologies face similar problems with inhomogeneity [3, 4]. To overcome these challenges we are engineering a new, molecular beam epitaxy (MBE) grown III-V QD material platform with built-in spectral tunability and site control. We present on using improved gallium-assisted deoxidation [5, 6] of patterned GaAs substrates for InAs QD growth used in photonic crystal cavities.

Typical patterned growth of QDs produces low optical quality structures [7]. To address this we are implementing a column of QDs in between the patterned GaAs surface and the optically active QD. This maintains the spatial location but creates a buffer layer away from defects at the growth interface. However in the fabrication of the patterned substrates surface oxide forms. Conventional thermal deoxidation leaves the surface pitted due to the stable surface oxide Ga$_2$O$_3$ reacting to form a volatile oxide Ga$_2$O. These surface pits compete with the fabricated nano-holes of the pattern for QD nucleation. A previous study by Atkinson et. al. successfully investigated gallium-deoxidation for patterned nano-holes [5, 6]. The nano-holes were spaced 500 nm apart and used a gallium deposition rate of 1 ML per minute to deposit 6 to 8 ML in 30-second intervals with 30-second growth interrupts. This study achieved 60% doubly and 40% singly occupied QDs in nano-holes. For implementation into our photonic crystal cavities we require a 10-μm spacing of nano-holes for the devices, single QD occupancy in nano-holes, and higher gallium flux for continued growth of the QD column in a GaAs matrix. We have shown 89% single QD occupancy in our pattern using a 12 ML per minute gallium deposition rate to deposit 4 to 6 ML in 1-second intervals with 30-second growth interrupts. The growth parameters and oxide removal for this system will be discussed.

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4:15pm MBE-2TuA12 Influence of the Growth Conditions on the Performance of InAs Sub-Monolayer Quantum Dot Infrared Photodetectors, *Kevin Vallejo,* Boise State University*; A. Zeidan, T. Cantalice, A. Quivy,* University of Sao Paulo, Brazil*; P. Simmonds,* Boise State University

Semiconductor devices that can efficiently emit or detect infrared radiation (IR) are in ever increasing demand for applications in fields as diverse as medicine, agriculture, astronomy and national security. A common type of

IR detector is the quantum well infrared photodetector (QWIP), which relies on intraband carrier transitions between the confined states of the quantum wells. Although QWIPs perform well under certain conditions, these devices are not sensitive to normal incident radiation, have high values of dark current and require cryogenic temperature to operate, making them bulky and expensive. In contrast, quantum dot infrared photodetectors (QDIPs) offer higher sensitivity to normal incidence light, longer photoexcited carrier lifetime, and lower dark current values. Quantum dots for QDIP devices are often grown via the Stranski-Krastanov growth mode, but this self-assembly process places limits on how closely we can control QD size and composition. However, sub-monolayer quantum dots (SML-QDs) offer enhanced height and composition uniformity, higher surface density of nanostructures, the absence of a wetting layer and improved 3-dimensional confinement [2].

The nucleation of InAs islands on GaAs(001) is influenced by our choice of MBE growth parameters, leading to SML-QDs with different shapes, sizes and compositions that can impact QDIP performance. In the present work, we have explored the effects of growth rate and arsenic flux on the growth and performance of InAs/GaAs SML-QD structures for QDIPs. We consider the influence of these variables on the formation and stacking of the small 2D InAs islands, verifying their structure with x-ray diffraction (Fig. 1). We tested the QDIP devices optically and electrically at 10 K (Fig. 2), measuring specific detectivities in the 10^{11} cm $Hz^{1/2}$ W^{-1} range. We will discuss differences in QDIP performance as a function of the MBE conditions used.

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4:30pm MBE-2TuA13 Effect of Annealing on Structure and Luminescence of InP/AlGaInP Quantum Dots, *Pankul Dhingra,* University of Illinois Urbana-Champaign; *Y. Sun,* Yale University; *E. Moog, M.L. Lee,* University of Illinois Urbana-Champaign

Lasers based on self-assembled quantum dots (QDs) have attracted widespread interest due to their unique characteristics that include low threshold current density and resistance to threading dislocations. While most work to date has focused on 1.3µm InAs/GaAs QDs, InP QDs have also aroused interest for low threshold lasers in the visible and near-infrared regime. For example, electrically injected room-temperature InP QD lasers showed a J_{th} of 190 A/cm² with emission at 740 nm [1]. Growth of phosphides by MBE typically requires a relatively low substrate temperature (500°C) compared to MOVPE (≈700°C), which leads to degraded optical properties and makes post-growth annealing a crucial step to improve the material quality [2]. For InAs/GaAs QDs grown using MBE, thermal annealing leads to a significant blueshift of emission wavelength due to the interdiffusion of In between the QDs and the surrounding matrix [3]. In contrast, little is known about the effects of annealing on InP/AlGaInP QDs. Here we report the exceptional thermal stability of InP/AlGaInP QDs, showing ≈50X improvement in room temperature photoluminescence intensity without signs of structural degradation or blueshifting for annealing temperatures T < 875°C.

We found that annealing improves the optical properties of InP QDs, InGaP QWs and AlGaInP DHs, with QDs showing the greatest benefit and up to 50X enhancement in the integrated PL intensity. While high-T rapid thermal annealing (RTA) of InP QDs led to > 50X intensity increase, the emission spectra showed an abrupt blueshift of ≈20 nm for T > 875°C. Cross-sectional transmission electron microscopy (XTEM) of such QD samples showed a reduction in strain contrast, indicating strong interdiffusion between the matrix and the QDs. Given the lack of blueshift for T < 875°C, we next investigated the effect of furnace annealing for longer times (≈10-100 minutes) at lower T and found that similar PL intensity improvements of ≈50X could be attained while avoiding any blueshift. XTEM and HAADF-STEM of furnace-annealed samples showed clear strain and composition contrast from individual QDs, similar to the as-grown structure. The remarkable improvement in emission intensity without significant structural changes at T < 875°C proves thermal annealing to be a crucial step towards the development of visible InP QD LEDs and low-threshold lasers using MBE.

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+ Author for correspondence: mllee@illinois.edu

4:45pm MBE-2TuA14 Structural and Optical Properties of GaAs(111)A Tensile-strained Quantum Dots using As₂ and As₄, *Christopher Schuck,* University of Delaware; *K. Vallejo, T. Garrett,* Boise State University; *Q. Wang, Y. Wang, B. Liang,* Hebei University, China; *P. Simmonds,* Boise State University

GaAs(111)A tensile-strained quantum dots (TSQDs) are the first optically active materials system to combine the benefit of epitaxial self-assembly, (111)-orientation, and tensile strain[1]. They are structurally and optically tunable, dislocation-free, exhibit low fine structure splitting (FSS), and have a tunably reducible bandgap[2,3]. To outline the full capabilities of this promising new material system, we recently presented a comprehensive study on the customization and optimization of GaAs(111)A TSQD properties[2]. However, all (111) TSQDs were grown using tetrameric arsenic (As₄) for consistency with previous (111) growths[1–4], since much of the original growth optimization on (111) surfaces was done before the advent of valved crackers. However, research shows that dimeric arsenic (As₂) often provides better material properties. Here we present the impact of arsenic species choice on the growth and properties of GaAs/InAlAs(111)A TSQDs.

Using As₂ or As₄ in the growth of GaAs(111)A TSQDs results in different TSQD structure and photon emission behavior. Structural differences with different arsenic species provide a greater ability to tailor TSQDs and reveal different nucleation and growth kinetics. Depending on the substrate temperature and arsenic species, GaAs(111)A TSQDs have a triangular base, with two possible crystallographic orientations, or a hexagonal base (Fig. 1 (a,b)). We attribute these different morphologies to differences in step edge growth rates. For all morphologies, As -grown TSQDs exhibits improved photoluminescence (Fig. 1 (c)). Additionally, the higher symmetry of the hexagonal TSQDs may result in lower FSS, which may further improve entangled photon emission.

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5:00pm MBE-2TuA15 Comparing the Self-assembly of Tensile-strained Ge and GaAs Quantum Dots on InAlAs(111)A, *Kathryn Sautter, C. Schuck, T. Garrett, K. Vallejo, A. Weltner,* Boise State University; *J. Smith, C. Ratsch,* University of California, Los Angeles; *P. Simmonds,* Boise State University

Compressively strained quantum dots (QDs) grown on (001) surfaces have been explored widely for optoelectronic applications. A recently developed process, tensile-strained self-assembly enables the tunable synthesis of defect-free QDs on non-(001) surfaces, opening up many potentially novel applications. For example, theory predicts that Ge will become a direct band gap semiconductor when grown on (110) surfaces under ~3% biaxial tensile strain and a semimetal on (111) surfaces under ~4% tensile strain.[1–4] (111)-oriented GaAs QDs are a promising source for entangled photons due to their high symmetry and low fine-structure splitting.

The development of tensile-strained self-assembly has chiefly focused on the growth of Ge and GaAs QDs on the (110) and (111)A surfaces of In$_{0.52}$Al$_{0.48}$As. With almost identical lattice constants, these Ge and GaAs QD systems are very similar from the point of view of tensile strain, with ~3.7% lattice mismatch. However, while exploring the self-assembly of tensile-strained Ge and GaAs QDs, we discovered significant differences between these two systems. Although both show excellent tunability in terms of QD size and areal density with growth conditions, Ge and GaAs QDs exhibit different shapes and nucleation behaviors. To understand these differences, we used a combination of experimental characterization and computational modelling. We compare experimentally derived island scaling and radial distribution functions to predictions from density functional theory and kinetic Monte Carlo simulations of potential energy surfaces (PES). We use this data to explore the surface diffusion behavior of the Ge and Ga adatoms on InAs(111)A.

Under the same MBE growth conditions, Ge QDs have a higher critical cluster size than GaAs QDs, although in both cases these critical clusters seem to adopt a three-fold symmetry consistent with the (111)A surface. Our models indicate that the InAlAs surface has an As-trimer reconstruction, and preliminary results show marked differences in the migration behavior of Ge and Ga adatoms on this surface. The potential barriers to Ge adatom surface diffusion appear to be lower than for Ga

adatoms, resulting in longer diffusion lengths. We will discuss our experimental and computational results from both a kinetic and thermodynamic perspective.

MBE
Room Silver Creek - Session MBE-1WeM

Superconductor/Semiconductor Interfaces

Moderator: Christopher Schuck, University of Delaware

8:15am **MBE-1WeM1 Towards Topological Qubits with MBE-grown Heterostructures**, *Michael Manfra,* Purdue University   **INVITED**
Decoherence through sensitivity to local perturbations is a key impediment to many current generation qubit technologies. The topological properties of emergent non-local degrees of freedom in condensed matter systems are conjectured to protect quantum states from environmental noise. Numerous material systems are now under investigation to explore topological properties, several of which are amenable to fabrication into complex heterostructures using molecular beam epitaxy techniques. In this talk I will review our efforts to exploit the power of MBE to build systems capable of hosting topological qubits.

The best controlled topological phase is the quantum Hall effect in AlGaAs/GaAs heterostructures. Here the notion of dissipationless edge modes and Abelian and non-Abelian braiding statistics were first theoretically developed and can be systematically studied in experiments. Recent innovations in heterostructure design (see Fig. 1) have allowed for exploration of these properties in small electronic Fabry-Perot interferometers. I will discuss MBE's crucial role enabling these experiments.

Hybrid heterostructures of s-wave superconductors with semiconductors possessing strong spin-orbit coupling are conjectured to behave as topological superconductors and host Majorana zero modes. Using a multi-chamber MBE we have developed Al/InAs heterostructures that display experimental signatures consistent with Majorana zero modes. I will describe some of the opportunities and challenges for epitaxy presented by this approach.

Figure 1: new heterostructure design facilitates operation of interferometers in the fractional quantum Hall regime.

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8:45am **MBE-1WeM3 Aluminum Metallization of III-V Semiconductors for the Study of Proximity Superconductivity**, *Wendy Sarney, S. Svensson, A. Leff,* CCDC Army Research Laboratory; *J. Yuan, W. Mayer, K. Wickramasinghe, J. Shabani,* New York University
Reactivity issues and the required mitigating growth conditions encumber molecular beam epitaxy of precise superconductor/semiconductor interfaces. In this work we study metallurgical transitions between Al and various III-As(Sb) binary and ternary semiconductors. To minimize reactivity, we deposit Al at slow growth rates onto cold (less than 0 °C) substrates. Since the interface's crystallinity affects the electronic/optical properties, i.e. Schottky barrier heights [1], etc., we conduct extensive structural characterization studies with transmission electron microscopy (examples shown in Figure 1). The close proximity of the superconductor may negatively affect the neighboring semiconductor [2], compelling the use of very thin intermediate layers. Certain intermediate layers have a secondary desirous effect of preventing the Al metal layer from interacting with the underlying semiconductor [3], and may control electrostatic potentials and local carrier densities.

Our primary semiconductor of interest is InAsSb. Over recent years, we demonstrated unstrained, unrelaxed InAsSb grown on virtual substrates and metamorphic buffer layers [4] - [5]. For compositions near 50%, InAsSb exhibits a very strong g-factor [6]. In hybrid InAsSb-Al structures, we observed superconducting proximity effect in InAsSb films where the product of supercurrent and normal resistance reaches the Al superconducting gap, as expected from theory. In this paper, we discuss the tradeoffs between different Al deposition conditions and the selection and optimization of intermediate layers.

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9:00am **MBE-1WeM4 Epitaxy and Characterization of Superconducting Aluminum Films on InAs Quantum Well Heterostructures**, *Tiantian Wang,* Purdue University
The epitaxial coupling of superconductors and high spin-orbit coupled semiconductors has recently been of growing interest for topological quantum computation applications [1]. Reducing disorder at the superconductor-semiconductor interface and in the superconducting layer is of main importance to improve device performance [2]. In this study, we focus on the in-situ molecular beam epitaxial deposition of Al superconducting layers on top of high spin-orbit coupled InAs planar heterostructures [3, 4].

The structural properties of the Al epitaxial layer will be reported relying on transmission electron microscopy (TEM). The determination of the predominant Al growth orientation, of the presence of grains and their properties and the characterization of the defects present in the Al layer are important parameters that we will present.

Figure 1 reports high resolution TEM data associated to Al-InAs hybrid planar hetero-structures with different strain profile in the quantum well. A clear impact of the strain on the Al growth orientation is observable in Figure 1(b) with the transition of the Al growth orientation from (111) to (110). The impact of Al growth temperature will also be analyzed.

Figure 1. The layer stack of two types of Al-InAs quantum well heterostructures (a) and the high-resolution TEM images of the aluminum layer in the two structures (b). The red lines represent one Al unit cell, indicating that the growth orientation is (111) for structure I and (110) for structure II. The zone axis is along InGaAs.

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9:15am **MBE-1WeM5 Transport Properties of Superconductor-Ferromagnetic- Semiconductor Heterostructures**, *Kaushini Wickramasinghe, J. Yuan, K. Sardashti, M. Dartiailh, W. Mayer,* New York University; *M. Jiang, L. Anh, M. Tanaka, S. Ohya,* University of Tokyo, Japan; *V. Manucharyan,* University of Maryland; *J. Shabani,* New York University
The rising interest in superconducting quantum computation has led to the exploration of topological superconductors. One of the schemes to achieve a topological superconductor is to use hybrid superconductor-semiconductor structures [1]. We are studying MBE grown InAs surface 2DEGs coupled with Al as a potential candidate. In addition to the good epitaxial contacts, spin texture of the induced current governs the nature of superconductivity. Using dilute magnetic semiconductors $In_xMn_{1-x}As$, we can filter the triplet states over the singlets. The Al-InAs heterostructures have been characterized and studied using Josephson junctions. We also report on structural analysis of MBE epitaxy of Al-InMnAs-InAs and corresponding magnetic and electronic measurements.

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9:30am **MBE-1WeM6 LATE NEWS: Van der Waals Epitaxy of High Quality AlN towards Deep Ultraviolet Light Emitting Diodes on Monolayer Graphene**, *Ping Wang, A. Pandey, E.T. Reid, J. Gim, W.J. Shin, D.A. Laleyan, D. Zhang, Y. Sun, Z. Zhong, R. Hovden,* University of Michigan
Van der Waals epitaxy of III-nitrides on two-dimensional (2D) materials has attracted significant attention, as it promises significantly reduced dislocation densities compared to conventional heteroepitaxy on lattice mismatched substrates.[1] The resulting epilayers can also be readily exfoliated and transferred to arbitrary substrates for subsequent device processing and integration.[2] To date, however, controlled nucleation of adatoms on the sp2-hybridized 2D surfaces has remained difficult, due to the extremely low surface energy, which limits the formation of large-area single-crystalline epilayers.

Here, we have investigated the epitaxy and characterization of AlN and AlGaN-based heterostructures on monolayer graphene by using plasma-assisted molecular beam epitaxy (MBE). Commercial one monolayer graphene was transferred on sapphire and AlN template substrates to explore the effects of crystallographic information underneath graphene

on the epitaxial relationship. The initial adatoms stacking manner and nucleation orientation can follow the epitaxial registry of the AlN template beneath graphene, whereas it is more challenging for graphene covered sapphire to maintain the epitaxial relationship. Without using any pretreatment and buffer layer, we have demonstrated that single-crystalline AlN can be achieved on monolayer graphene covered AlN template (Figure 1). Such AlN has comparable crystal quality and band edge emission with the commercial AlN template. We have further investigated the epitaxy and fabrication of AlGaN-based deep ultraviolet light emitting diodes (DUV-LED) on monolayer graphene. The as-fabricated devices exhibit excellent current-voltage characteristics and strong electroluminescence emission at ~260 nm with a maximum external quantum efficiency (EQE) of ~4%. The device performance is comparable to identical structures grown directly on commercial AlN template.

9:45am **MBE-1WeM7 LATE NEWS: Determination of Background Doping Type in Type-II Superlattice using Capacitance-Voltage Technique with Double Mesa Structure**, *Seunghyun Lee, D.R. Fink, S.H. Kodati, V. Dahiya, T.J. Ronningen,* The Ohio State University; *M. Winslow, C.H. Grein,* University of Illinois at Chicago; *A.H. Jones, J.C. Campbell,* University of Virginia; *J.F. Klem,* Sandia National Laboratories; *S. Krishna,* The Ohio State University

The background doping in superlattice absorber is one of the most important material parameters for the design and evaluation of infrared detectors. Due to the highly conductive substrates of these narrow-bandgap materials, it is difficult to conduct Hall measurements to verify the doping type of unintentionally doped materials [1]. This is especially true in Type -II superlattice (T2SL) InAs/AlSb where one of the constituents has a background doping that is n-type (InAs) and the other is background doped p-type (AlSb). Here, we demonstrate a novel technique that uses capacitance-voltage (C-V) measurements using a double mesa structure. Two p-i-n and n-i-p homojunction diodes were grown using 10 ML InAs/10ML AlSb were grown by molecular beam epitaxy. The top, intrinsic, and bottom layers are 300, 1000 and 500 nm thick, respectively. Double mesa devices were then fabricated using standard semiconductor fabrication processes. The first etch was a shallow etch that went past the top contact into the absorber layer. The second etch was a deeper etch that reach the bottom contact. CV measurements were undertaken on devices in which the radius of the deep etch was varied while the radius of the shallow etch was kept constant. The double mesa devices have two built-in junctions at the interfaces: the first is in the shallow mesa between the top contact, and intrinsic layer (1st junction), and the second in the deep mesa between the intrinsic layer and the bottom contact (2nd junction). For the PIN device, the device's capacitance will scale with the deep etch radius if the intrinsic layer is p-type. However, if the intrinsic doping is n-type the capacitance will not scale with the deep etch radius. Figure 1 shows capacitance as a function of deep etch radius. For p-i-n device, the capacitance scales with the deep etch radius, but for n-i-p device the capacitance is independent of the radius. This comparison clearly indicates that the doping type of this unintentionally doped InAs/AlSb T2SL is p-type ($\sim 3 \times 10^{16}$ cm^{-3}). We plan to perform temperature studies on the doping type of the T2SL. These additional results will be discussed at the presentation.

MBE
Room Silver Creek - Session MBE-2WeM

Heterostructures and Quantum Dots
Moderator: Stephanie Law, University of Delaware

10:30am **MBE-2WeM10 Vertical Hole Transport in InAs/InAs$_{1-x}$Sb$_x$ Type-II Superlattices**, *Cheng-Ying Tsai, Y. Zhang, Z. Ju, Y.-H. Zhang,* Arizona State University

This abstract reports the study of the vertical hole transport in InAs/InAs Sb strained layer type-II superlattice . The low hole mobility in InAs/InAs$_{1-x}$Sb$_x$ superlattice is considered as the main reason for the low internal quantum efficiency of its mid-wave and long-wave infrared photodetectors, compared with that of its HgCdTe counterparts. Optical measurements using time-resolved photoluminescence (TRPL) and steady-state photoluminescence (SSPL) are implemented to extract the diffusion coefficients and mobilities of holes in the superlattices at various temperatures.

The structure of the samples consists of a mid-wave infrared superlattice (MWSL) absorber region grown atop a long-wave infrared superlattice

(LWSL) probe region by using MBE. When the sample is illuminated by laser light, the photogenerated carriers in the MWSL region will diffuse into the LWSL probe region and give photoluminescence, which is used to measure the time of flight of the holes that vertically transport through the entire MWSL region. The hole diffusion coefficients and mobilities in the MWSL can be determined by fitting the TRPL decay profile with the diffusion and rate equations, or by the ratio of the integrated SSPL intensities from LWSL and MWSL.

The carrier dynamics in LWSL and MWSL can be described by rate equation and diffusion equation, assuming no external electric field, respectively. The diffusion in the LWSL is negligible due to its thin thickness compared with that of MWSL. The extracted mobilities from SSPL at various temperatures are illustrated in Figure 1, which shows a hole mobility of 56 cm^2/Vs at 70 K. Besides, the extracted mobility from TRPL fitting (Figure 2) gives a hole mobility of 54 cm^2/Vs at 70 K, which is in excellent agreement with the result measured by using SSPL.

10:45am **MBE-2WeM11 Room Temperature THz Intersubband Transitions in Continuously-graded Al$_x$Ga$_{1-x}$As Parabolic Quantum Well Arrays**, *C. Deimert,* University of Waterloo, Canada; *P. Goulain, J.-M. Manceau, A. Bousseksou,* CNRS and University of Paris-Sud, France; *W. Pasek, T. Yoon, N.Y. Kim,* University of Waterloo, Canada; *R. Colombelli,* CNRS and University of Paris-Sud, France; *Zbigniew Roman Wasilewski,* University of Waterloo, Canada

While conventional THz optoelectronic devices operate in the weak coupling regime between light and matter, the strong coupling regime provides an attractive alternative. For such devices, parabolic quantum wells (PQWs) will be critical in enabling operation up to room temperature. Unlike the more ubiquitous square wells, PQWs have equal intersubband (ISB) spacing, which provides a strong, unified absorption line independent of thermal occupation.

PQWs in Al$_x$Ga$_{1-x}$As can be grown with molecular beam epitaxy (MBE) using digital alloys, however this technique only approximates the parabolic potential, and it also generates many interfaces. We instead generate a smooth composition gradient, employing a linear dynamical model of our Al cell to smoothly vary the flux at standard growth rates [1].

Using this technique, we grow a stack of 54 PQWs with Al varying between 2-30%. We demonstrate the quality of this sample using multipass transmission spectroscopy. The measured transmittance in Figure 1 demonstrates a clear THz ISB absorption at both 300K and 8K with minimal shift of the peak. The temperature dependence of the linewidth is particularly noteworthy – below 100K, the linewidth is exceptionally small, reaching a record-low value of 5.7% of the center frequency.

Further work will aim at incorporating these PQW arrays into THz devices operating in the strong coupling regime at around 100K, obtaining performance levels presently only achievable at liquid helium temperature.

[1] C. Deimert, Z. R. Wasilewski, *Journal of Crystal Growth* **514**, 103-108 (2019).

11:00am **MBE-2WeM12 Excitonic Properties of Asymmetric Triple CdSe Quantum Wells**, *F. Hernández-García,* Cinvestav-IPN, México; *F. Sutara, Isaac Hernández-Calderón,* CINVESTAV, México

Asymmetric triple quantum wells (ATQWs) present interesting optical properties that can be modulated as a function of the separating barriers thicknesses. The number of excitonic transitions and their energies will depend on the degree of overlap of the exciton wave functions in the quantum wells. If the barriers are thick enough, we will observe three fundamental optical transitions, one for each (single) QW. If the barriers are very thin, which allow strong quantum well coupling, the ATQW will present only one fundamental transition because the three QWs constitute a *single quantum system*. ATQWs with barrier thicknesses within those extremes can present two or three emission peaks with energies and intensities depending on the thickness of each separating barrier. A previous study on asymmetric double ultra-thin quantum wells of CdSe within ZnSe barriers demonstrated that the thinner QWs required several tens of nm to decouple the QWs and that ZnSe barriers of around 5 nm caused a strong coupling of the ultra-thin CdSe QWs [1].

Here, we present the results of the epitaxial growth and the low temperature photoluminescence characterization of the excitonic emission of three different ATQW heterostructures, two made with thin ZnSe barriers of 5 nm that produce strong coupling, and one heterostructure with thick 100 nm ZnSe barriers. Each heterostructure contains three CdSe QWs, with thicknesses of 1, 2 and 3 MLs. In the coupled heterostructures the QWs were grown in two sequences 1-2-3 and 3-2-1; the uncoupled

heterostructure was grown with the sequence 3-2-1; the first QW is always closer to the GaAs(001) substrate. The QWs were grown by atomic layer epitaxy within ZnSe barriers grown by molecular beam epitaxy, all samples were grown at 275 °C. For the coupled ATQW heterostructures we observed only one optical transition around 2.34 eV, for the uncoupled ATQW we observed three excitonic peaks around 2.32, 2.48 and 2.67 eV, as expected. The electronic structure of each ATQW system as well as the peculiarities of their excitonic spectra will be explained in terms of the structural properties of the heterostructures and the degree of coupling of the QWs.

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11:15am MBE-2WeM13 Gain Measurements of Se-based II-VI Multiple Quantum Well Structures for Vertical-External-Cavity Surface-Emitting Laser Applications, *K. Zhao,* The City College of New York*; G. Chappell, J. Hastie,* University of Strathclyde, UK*; S.K. Gayen,* The City College of New York/Graduate Center of CUNY*; **Maria Tamargo**,* City College of New York, City University of New York

Vertical-external-cavity surface-emitting lasers (VECSELs), also known as semiconductors disk lasers (SDLs), have captured the interest of many researchers due to their unique features, such as high output power, ultrashort pulse operation, thin gain region, and wide spectral coverage. VECSELs based primarily on III-V quantum wells structures have been well developed. However, it is still challenging to achieve devices working in the yellow and green wavelengths. Se-based II-VI materials such as ZnCdSe and ZnCdMgSe grown lattice matched to InP are attractive materials for this application. Recently our groups have reported some initial results pertaining to the optically pumped lasing potential of these materials. However, optimizing the materials for the very stringent structural requirements of the VECSEL requires a better understanding of the optical properties of the Se-based II-VI materials.

We report on the growth by molecular beam epitaxy of multiple quantum well (MQW) ZnCdSe/ZnCdMgSe structures for application as VECSELs devices operating at 565 nm. X-ray diffraction (XRD) 2θ-ω scan obtained along the (002) reflection, with clear evidence of thickness fringes, confirms the excellent crystalline quality of the samples. The structures were characterized using a pump probe technique from which the optical gain of the material could be estimated. For these measurements it was necessary to remove the absorbing InP substrate by a selective chemical etching technique. Gain values of ~9% were obtained for near-lattice matched samples. We will present results of the effect on gain of structural parameters, such as strain. The results will inform the design of the optimum VECSEL structure.

11:30am MBE-2WeM14 Structural and Optical Properties of PbTe/CdTe/InSb Heterostructures Grown using Molecular Beam Epitaxy, *Tyler McCarthy,* Arizona State University

Rock-salt lead chalcogenides are of much current interest for several reasons, including their direct band gap in the infrared (IR) wavelength range [1]. Integrating II-VI and IV-VI chalcogenides with III-V compounds into epitaxial heterostructures combines the advantages of wide-band gap II-VI binaries and alloys, good for electrical and optical confinement, with narrow-band gap III-V and IV-VI compounds. IV-VI active layers are also of interest for room temperature operational IR devices because IV-VI materials have significantly smaller Auger coefficients than the III-V or IIVI materials [2]-[4], a property that could be utilized to enhance IR laser and photodetector performance [5]. Thus, the heterocrystalline epitaxial integration of rock-salt lead chalcogenides with zincblende II-VI and III-V semiconductors on commercially available III-V semiconductor substrates can potentially enable a wide range of novel material properties and device applications.

In this study, heterovalent and heterocrystalline structures composed of InSb, CdTe, and PbTe layers were grown on ¼ 2" (001) InSb substrates in a single-chamber MBE system. High-quality materials were achieved using careful control of the growth conditions at the interface between two different crystal structures with matched lattice constants in plan. For the PbTe/CdTe heterostructures (Fig. 1), CdTe growth was initiated on the Cd-terminated InSb surface by opening the Te cell shutter, whereby a (2×1) surface reconstruction was observed immediately. The surface reconstruction during the PbTe growth on CdTe, which eventually transitioned to a streaky (1×1) pattern during the PbTe growth when a Te surface soak of 60 seconds was used between the bottom CdTe buffer and the PbTe layer, suggests that the common Te atoms at the interface help to promote layer-by-layer growth of PbTe. This contrasts the case of PbTe grown directly on InSb, where the use of a Te overpressure on InSb resulted in a spotty surface reconstruction throughout the growth. PL properties of the samples were tested between 13 to 300 K, with an increase in peak emission energy with temperature. Crystal quality was determined from XRD and TEM.

Author Index

Bold page numbers indicate presenter