MBE
Room Max Bell Auditorium - Session MBE-SuM
Nanowires/Novel III-V Compounds and Growth Techniques

Moderators: Richard Ares, Université de Sherbrooke, Amy Liu, IQE Inc.

8:45am **MBE-SuM-1 Optically Active Dilute-Antimonide Ga(In,Sb)N Nanostructures for Deep-visible Optoelectronics and Solar Fuel Applications***, **Faqrul A. Chowdhury**, Q Shi, H Guo,* McGill University, Canada*; Z Mi,* University of Michigan

The bandgap of GaN alloy can be reduced to ~2 eV by introducing very small amount (1-5%) of antimony (Sb). This is equivalent to incorporation of >30% of In in GaN, however, with substantially reduced lattice mismatch between GaSbN and GaN, compared to that between InGaN and GaN. The reduction of GaN energy bandgap with Sb incorporation is primarily due to upward shift of the valence band-edge [1], which is in direct contrast to downward shift of the conduction band-edge by alloying with In [2]. Therefore, precise tuning of the band-edges can be obtained with simultaneous incorporation of In and Sb in GaN, and the energy bandgap can be drastically reduced to deep visible and near-infrared spectral range, while maintaining a relatively small lattice mismatch to the underlying GaN template/substrate. We have recently shown [3-4], both theoretically and experimentally, that MBE grown GaSbN nanostructures are optically active, exhibiting strong, tunable photoluminescence (PL) emission at room temperature from UV to deep visible range in dilute Sb limit (<1%). Subsequently, we have demonstrated GaSbN dot-in-nanowire devices as an archetype for In-free visible LEDs. Herein, we have successfully synthesized InGaSbN nanowire heterostructures and explored their properties using X-ray diffraction, micro-Raman, and X-ray photoelectron spectroscopy. We have demonstrated that the emission wavelengths can be readily varied from blue, green to red spectral range with very small amount of Sb into InGaN. For example, the emission wavelength of InGaN (with ~28.9% of In) can be extended from 574 nm to 630 nm by incorporating only ~0.3% of Sb in InGaSbN under identical growth condition, which would otherwise require ~39% of In incorporation in InGaN. The outcomes of this study can have a profound impact on the development of high-efficiency, phosphor-free LEDs and a broad impact on solar energy conversion, including solar cells, solar fuels, and various electrochemical devices and systems [5].

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9:00am **MBE-SuM-2 The Effects of N Incorporation in GaAsSb based Core-shell Nanowires***, **Prithviraj Deshmukh**, M Sharma, S Nalamati,* North Carolina A&T State University*; C Reynolds, Y Liu,* North Carolina State University*; S Iyer,* North Carolina A&T State University

Bandgap tuning beyond 1.3 µm in GaAsSb nanowires (NWs) can be achieved using dilute amounts of nitrogen. Incorporation of nitrogen in the GaAsSb shell is studied in order to reduce the bandgap energy for realizing nanoscale optoelectronic devices in the telecommunication wavelength region. In this report, varying N incorporation in the GaAsSbN shell is realized by changing the N-plasma pressure. High density of vertical GaAsSb(N) core-shell configured nanowires are grown on Si (111) substrates using plasma assisted molecular beam epitaxy. The growth duration of the nitride shell was optimized to produce high photoluminescence (PL) intensity. Effects of N incorporation on the morphology of NWs were studied to optimize a closely lattice-matched core-shell material configuration. Evolution of N-induced band tail states in the PL emission has been correlated with increase in growth duration under N-plasma. Rapid thermal annealing at different temperatures was carried out to understand the nature of N-induced defects. Changes in peak positions and line shapes in the Raman spectra of annealed samples have been used to ascertain the nature of the defects being annihilated during the growth. Study of structural quality of dilute nitride NWs using transmission electron microscopy will also be presented. This systematic study reveals that the morphology and optical characteristics of the nitride nanowires can be significantly improved by appropriate lattice matching with the non-nitride core.

9:15am **MBE-SuM-3 Growth of GaAsSb Axial Nanowires on Graphene by Molecular Beam Epitaxy***, S Nalamati, M Sharma, **Prithviraj Deshmukh**,* North Carolina A&T State University*; D Snyder, J Kronz,* Pennsylvania State University*; M Zugger, L Reynolds, Y Liu,* North Carolina State University*; S Iyer,* North Carolina A&T State University

$GaAs_xSb_{1-x}$ semiconductor nanowire (NW) arrays are of great interest for the next generation infrared (IR) photodetectors due to the ability to tune the bandgap in this material system from 0.73 eV to 1.42 eV, encompassing the important communication wavelength range. Graphene as a substrate is very attractive due to its favorable material characteristics, namely, high electrical conductivity, optical transparency, mechanical flexibility along with it being cheaper, making it a potential alternative to conventional III-V substrates. Hence, $GaAs_xSb_{1-x}$ NWs on graphene provides a pathway for fabricating next-generation flexible and cheaper SWIR photodetectors. In this work, epitaxial growth of $GaAs_xSb_{1-x}$ (x=0.1) axial NWs by using Ga-assisted molecular beam epitaxy on monolayer graphene/SiO_2/Si has been demonstrated. Growth optimization that leads to minimal 2D growth, vertical NWs with good spatial distribution across the sample will be presented. Micro-photoluminescence (µ-PL) measurements on the NWs thus grown under optimized conditions exhibited an emission peak at 1.35eV with full width half maxima (FWHM) of 69 meV. Further, NWs grown on monolayer graphene substrate manifest higher intensity and lower FWHM compared to nanowires grown on Si/SiO_2 substrate with similar growth recipe, suggesting the superior optical quality of nanowires. The existence of only (111) and corresponding higher-order reflections in x-ray diffraction spectra attest to the vertical alignment of NWs. The Raman spectra of these NWs exhibit sharp LO and TO modes at 260.7cm^{-1} and 282.2cm^{-1}, which are redshifted with respect to the corresponding reference peaks of GaAs peaks due to Sb incorporation. High-resolution transmission electron microscopy and selective area diffraction pattern confirmed the zinc-blende structure of the NWs. These preliminary results on the use of graphene as the substrate for the growth of vertical and high-quality GaAsSb NWs are promising and shows high prospects for improving the performance of single nanowire-based devices.

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9:30am **MBE-SuM-4 Cylindrically Confined Superparamagnetic MnAs Nanocrystals Embedded in Wurtzite (In,Ga)As-(Al,Ga)As Core-shell Nanowires***, **Janusz Sadowski**,* Linnaeus University, Sweden*; S Kret, A Kaleta, B Kurowska, M Sawicki,* Institute of Physics, Polish Academy of Sciences, Poland

The nanometer-size superparamagnetic MnAs nanocrystals confined in the nanotube geometry have been fabricated by high-temperature annealing of the MBE-grown core-shell nanowires comprising (Ga,Mn)As dilute ferromagnetic semiconductor. The annealing induced decomposition of (Ga,Mn)As, has already been studied, but only for layered structures based on the native zinc-blende (Ga,Mn)As parent phase. We have demonstrated before, that it is possible to obtain (Ga,Mn)As in the wurtzite structure, by low temperature MBE growth at the side-walls of wurtzite (In,Ga)As nanowires [1,2]. Because of the well-known thermal instability of (Ga,Mn)As [3] the moderate-to-high temperature (300 – 600 ºC) post-growth annealing of NWs with (Ga,Mn)As shells causes decomposition of (Ga,Mn)As solid solution into ensemble of MnAs nanocrystals embedded in the GaAs host matrix. MnAs is a ferromagnetic metal with interesting properties, e.g. strong magnetocaloric effects, ferromagnetic phase transition combined with structural phase transition (hexagonal to orthorhombic phase) at a critical temperature T_C of about 40ºC. In the nanocrystals embedded in wurtzite GaAs matrix, the hexagonal MnAs phase can be stabilized by strain, hence the T_C in this case can possibly be enhanced with respect to T_C of MnAs in the bulk or layered form.

We have studied different kinds of samples with parent (Ga,Mn)As NW shells grown either directly on (In,Ga)As core NWs, or surrounded by (Al,Ga)As shells. The latter are blocking Mn diffusion during the post-growth annealing process, supporting cylindrical confinement of the nanocrystals. Annealing processes have been performed both *ex-situ* after the MBE growth of initial (In,Ga)As-(Al,Ga)As-(Ga,Mn)As core shell NWs, and *in-situ* in the transmission electron microscope, with use of the specially designed holders enabling annealing up to 700ºC. Beside radial confinement of MnAs nanocrystals, we have observed their preferential location at the vicinity of the stacking faults defects (typical for III-V nanowires). This effect enables adjusting the axial distribution of MnAs nanocrystals.

This work has been supported by the research projects granted by Carl Tryggers Stiftelse för Vetenskaplig Forskning (Sweden) CTS 16: 393, and by the National Science Centre (Poland) - project no. 2014/13/B/ST3/04489.

[1] A. Siusys, J. Sadowski, et. al., Nano Lett. 14, 4263 (2014).

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Nanoscale, **9**, 2129 (2017).

[3] H. Ohno, Science **281**, 951(1998).

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9:45am **MBE-SuM-5 Bright Single InAsP Quantum Dots at Telecom Wavelengths in Position-Controlled InP Nanowires***, **Philip Poole**, S Haffouz,* NRC, Canada*; K Zeuner,* KTH Royal Institute of Technology, Sweden*; D Dalacu, J Lapointe, D Poitras, K Mnaymneh, X Wu, M Couillard, M Korkusinski,* NRC, Canada*; E Scholl, K Jons, V Zwiller,* KTH Royal Institute of Technology, Sweden*; R Williams,* NRC, Canada

Optics based quantum information technologies require high brightness quantum light sources, and single semiconductor quantum dots show great promise for this application. Using site selected InP nanowires containing single InAsP quantum dots we have demonstrated both highly efficient single photon emission and bright entangled photon pairs in the 900 to 1000 nm wavelength range. There is great interest in extending the emission of these sources to longer wavelength to make use of telecommunication based fibre to transmit these photons over large distances. In this contribution we show how you can modify our present nanowire growth to produce high brightness nanowire structures emitting in the telecom 1310 nm and 1555 nm wavelength ranges.

The nanowires used in this study were grown using the selective area VLS growth technique by chemical beam epitaxy (CBE). They consist of a wurtzite InP nanowire core containing an InAsP quantum dot, where the diameter of the core is determined by the Au seed particle. The growth mode is then switched from axial to radial to increase the nanowire diameter and control the tapering of the nanowire tip to provide efficient coupling of the dot emission to the collection optics. To extend the dot emission to longer wavelength we use a combination of higher As flux and longer growth time for the dot.

We demonstrate a dramatic dependence of the emission rate on both the emission wavelength and the nanowire diameter. With an appropriately designed waveguide, tailored to the emission wavelength of the dot, an increase in the count rate by nearly 2 orders of magnitude (0.4 to 35 kcps) is obtained for quantum dots emitting in the telecom O-band, showing high single-photon purity with multiphoton emission probabilities down to 2%.

10:30am **MBE-SuM-8 Continuously-Graded Parabolic Quantum Wells in AlGaAs***, **Chris Deimert**, Z Wasilewski,* University of Waterloo, Canada

Parabolic quantum wells have unique properties that make them crucial for certain applications. However, they are much more challenging to grow with molecular beam epitaxy than standard rectangular quantum wells, as they require a smooth, precise variation in the composition during growth. Typically, such composition variations have been produced using the digital alloy technique. However, digital alloys are limited by things such as the speed at which cell shutters can be actuated. Further, the high density of interfaces can be problematic, especially in material systems like AlInAsSb.

In our approach, we instead create a smooth parabolic potential in $Al_xGa_{1-x}As$ by varying the Al cell flux as a function of time. This is not trivial, as there are complicated thermal dynamics which cause the flux to lag behind changes in the input temperature. The input must be carefully selected to counteract these dynamics and achieve the correct flux profile.

To accomplish this, we approximate the effusion cell as a linear system and experimentally measure its impulse response. Once the impulse response is known, it is possible to determine the appropriate temperature input sequence for any desired composition profile. We have applied this to the case of a sequence of parabolic quantum wells in $Al_xGa_{1-x}As$. Despite the somewhat crude assumption of linearity, the approach already performs remarkably well. The target composition profile is achieved to within $\Delta x < 0.005$, without any further refinement of the method.

We anticipate that this method will allow for the growth of $Al_xGa_{1-x}As$ parabolic quantum wells which are of higher quality than those achievable with digital alloying. Importantly, though, this method can be applied much more generally. Once the impulse response is known, essentially arbitrary composition profiles can be grown without any recalibration. Further, this method could be straight-forwardly extended to more challenging material systems like AlGaInAs, or even mixed group V systems such as AlInAsSb, where digital grading is not possible due to high interfacial strain.

10:45am **MBE-SuM-9 Growth and Characterization of $Al_{0.48}In_{0.52}As$ on InP (100) by Hybrid MBE-CBE for Optoelectronics Applications***, **Thierno Mamoudou Diallo**, A Poungoue Mbeunmi, M El-Gahouchi, M Jellite, S Fafard, R Arès, A Boucherif,* Université de Sherbrooke, Canada

$Al_{0.48}In_{0.52}As$ ternary alloy lattice matched to InP is of great interest for optoelectronics devices [1]. In fact, AlInAs alloys are very desired for new generation avalanche photodiode (APD) due to their large band gap, high ionization ratio and low excess noise [1]. However, high quality growth of these alloys either by MBE, MOCVD or CBE is quite difficult due to clustering, lattice matching control and impurities (O and C) contamination [2], [3].

In this work, we demonstrate the epitaxial growth of high quality, low strain and low background doping of $Al_{0.48}In_{0.52}As$ at 500°C on Fe-doped semi-insulating InP(100) substrate by using hybrid MBE-CBE technique. The precursors that were used are: solid aluminum, solid indium, TriMethylIndium (TMIn) and thermally cracked arsine. Using Nomarski, we observed smooth surfaces for the as grown layers. High-Resolution X-ray Diffraction (HR-XRD) in the vicinity of the (004) reflexion shows a lattice mismatch in the range -137 to 127ppm. The carrier density of undoped layers, obtained by Hall measurement at room temperature, is as low as 3E+15 cm^{-3} which is three orders of magnitude lower than the identical layers grown by organometallics sources. Photoluminescence (PL) for $Al_{0.48}In_{0.52}As$ at low temperature (LT) shows a good optical quality. The quality and purity of the alloys grown here are compatible with high performance APD for optical communication.

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11:00am **MBE-SuM-10 InAlAs/InGaAs Growth on InP(111)A and InP(111)B Substrates with Varying Substrate Offcut Angle***, **Ida Sadeghi**, M Tam, Z Wasilewski,* University of Waterloo, Canada

InAlAs/InGaAs growth on polar InP(111) wafers offers physical properties of interest for optoelectronic and spintronic applications . However, growth on the (111) wafers is much less understood than that on conventional (001) substrates. Strong surface roughening with high density of hillocks and pits is the primary challenge for the growth on (111) substrates. Growth on offcut substrates may promote step-flow growth mode and avoid hillock formation [1]. Although growth on such substrates have been reported, the systematic study on the optimization of such offcut angle is lacking.

In this work the influence of substrate misorientation on the surface morphology of InGaAs/InAlAs on InP(111) was studied. We grew on wafers with rounded by chemo-mechanical polishing edges. Such surface bowing at the wafer edge exposes vicinal surfaces with monotonically varying effective offcut angle and the entire range of atomic step crystallographic orientations. The epitaxial structures consisted of InAlAs buffer layer followed by InGaAs layer. Grown wafers were analyzed using Nomarski DIC microscopy, atomic force microscopy and surface profilometry. The optimum As overpressure for the growth on (111)B and (111)A was found to be $6\times P_{min}$ and $12\times P_{min}$, respectively. Here P_{min} stands for minimum As overpressure ensuring As stable surface reconstruction during GaAs growth on (001)GaAs substrate at 580°C, using equivalent group III flux. It was also found that for growth on (111)B the optimum growth rate can be higher than that for the growth on (111)A; 1 Å/s compared to 0.5 Å/s. There is a range of surface orientations, particularly well-defined for (111)B (Fig. 1), which promotes smooth surface morphology. The width of such smooth region depends on the azimuth around the wafer. At its widest, this smooth region corresponds to a range of surface offcuts of 4.5°-12.5°. A much smoother surface was obtained on (111)B substrate.

11:15am **MBE-SuM-11 Growth and Characterization of Undoped InGaAs by Hybrid MBE-CBE for Optoelectronic Applications***, **Alex Brice Poungoue Mbeunmi**, T Diallo, M El-Gahouchi, M Jellite, G Gomme, A Boucherif, S Fafard, R Ares,* Université de Sherbrooke, Canada

InGaAs is one of the most commonly used active layer in III-V based optoelectronic devices [1], thanks to its distinctive properties such as high electron mobility, peak velocity and direct band gap [2], [3]. So far, this alloy is grown by standard technics such as MBE, MOCVD or CBE. However, there are several challenges to overcome in order to obtain pure and cost effective InGaAs epitaxial layers.

In this work, we will discuss the use of a custom MBE-CBE reactor which combines solid and vapour sources to grow high quality InGaAs layers. This alloy has been grown on semi insulating InP substrate (001) using an indium K-cell, triethilgallium (TEGa) as group III precursors and arsine (AsH3) as group V at 500°C. An in-situ reflection high energy diffraction (RHEED) pattern of InGaAs shows streaky lines which are observed, demonstrating a layer-by-layer growth mode. The high resolution X-ray diffraction (HR-XRD) measurements along the (004) direction was carried out on $In_{0.53}Ga_{0.47}As$ epilayers and gives a lattice mismatch of 9E-03. Furthermore, Hall effect measurements performed on undoped InGaAs layers show carrier densities around 1E+15 cm^{-3}, which are roughly two orders of magnitude lower than samples grown by standard CBE. These preliminary results are promising toward achieving the growth of photodetector heterostructures, such as avalanche photodiode, which requires pure active layers.

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11:30am **MBE-SuM-12 Epitaxial Growth and Properties of II_3V_2 Semiconductors: Mg_3N_2 and Zn_3N_2**, ***Peng Wu**, T Tiedje,* University of Victoria, Canada

The II_3V_2 semiconductors are a little-explored class of semiconductor materials which can be composed of environmentally-benign, earth-abundant elements, and have bandgaps in the visible and near infrared part of the spectrum. The crystal structure of these materials is relatively complex consisting of three interpenetrating fcc lattices, with one of the lattices half occupied. Epitaxial zinc nitride [1] and magnesium nitride [2] thin films were grown on (110) sapphire and (200) MgO substrates by plasma-assisted molecular beam epitaxy with nitrogen gas. The Mg_3N_2 and Zn_3N_2 films were grown at temperatures of 300-350°C and 140-180°C respectively. The RHEED pattern during growth and the x-ray q /2q scans suggest that the films are epitaxial single crystals. In situ optical reflectivity during growth was used to determine the growth rate as a function of the metal flux and the growth temperature. The in-situ reflectivity was simulated by an optical model from which we derived the growth rate (up to 0.05 nm/s) and the indices of refraction of the deposited Mg_3N_2 and Zn_3N_2 films at 488 nm (2.4 and 2.65 respectively). X-ray diffraction shows that the thin films were (400) oriented on both the (110) sapphire (Zn_3N_2 only) and (200) MgO substrates. The optical absorption coefficient was calculated from the transmittance spectrum; the optical band gap of the Mg_3N_2 and Zn_3N_2 thin films were found to be 1.3 eV and 2.5 eV, respectively. Ellipsometry measurements show that the refractive index of zinc nitride is 2.3-2.7, and extinction coefficient is ~0.5-0.7 in the energy range of 1.5-3.0 eV. The index of refraction of Zn_3N_2 has the unusual characteristic of decreasing with photon energy in the 1.7-3.0 eV range, whereas the index of Mg_3N_2 shows a normal dispersion with photon energy. The electron transport measurement shows that the single crystal zinc nitride has an electron mobility as high as 395 cm^2 /Vs. Both materials are air sensitive and uncapped films oxidize in room air, especially Mg_3N_2 films which oxidize fully in minutes.

11:45am **MBE-SuM-13 Examining the Effects of Strain and Tl Content on the Properties and Structure of TlGaAs Films**, ***Kevin Grossklaus**, J Ganguly, M Stevens, J McElearney, T Vandervelde,* Tufts University

Tl containing III-V semiconductor compounds have been put forth as a promising material set for small band-gap optoelectronic devices active in the mid to far-IR. However, it has been found that only low concentrations of Tl may be incorporated into III-V alloys. In the $Tl_xGa_{1-x}As$ system, using solid-source MBE only up to x=7% Tl has been successfully incorporated into a single crystal TlGaAs film without Tl droplets appearing, and this required growth at low temperatures (200°C) and in a narrow growth window in order to prevent defects from forming in the films[1]. Difficulty in incorporating Tl into the III-V films of sufficient quality for device use has limited the practical application of Tl containing alloys.

In this work, we have examined the impact of film strain and Tl content on the properties and structure of $Tl_xGa_{1-x}As$ films, with the goals of improving film quality and examining the effect of strain on the amount of Tl that can be incorporated into TlGaAs. TlGaAs films were grown at low temperature in a Veeco GENxplor MBE system using a valved As-cracker and solid source effusion cells for group-III elements. TlGaAs growth was monitored by RHEED. Films were grown on GaAs, InGaAs, and AlGaAs underlayers of varying lattice parameter in order to examine the effect of compressive and tensile strain on the films. After growth HRXRD 004 2theta-omega scans and 224 RSMs were used to characterize film strain and to estimate Tl content. Spectroscopic ellipsometry was used to measure film optical properties and estimate band gap. TEM was used to examine defect formation in film stacks and to examine alloy segregation in the TlGaAs. We propose that strain engineering through underlayer substrate choice may be used to improve TlGaAs film quality.

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MBE
Room Max Bell Auditorium - Session MBE-MoM
Novel III-N Growth and Applications/III-Nitrides for Electronics

Moderators: Thomas Tiedje, University of Victoria, Isaac Hernandez-Calderon, CINVESTAV, Maria Tamargo, City College of New York, City University of New York

8:30am **MBE-MoM-1 MBE Innovator Award Talk: Evolution, Development and Commercialization of the Quantum Dot Laser: Brief History and Recent Progress***, **Pallab Bhattacharya**,* University of Michigan **INVITED**

The advantages of using quantum dots in the active (gain) region of semiconductor lasers were obvious. However, a technique to incorporate these nanostructures in the laser heterostructure was not available. The breakthrough occurred with the invention of selfassembled quantum dots during the growth of strained (mismatched) InGaAs/GaAs heterostructures. This was followed by quantitative characterization of the epitaxial process and optimization of the optical and structural properties of the quantum dots. It was evident that multiple quantum dot layers could be inserted *in-situ* in laser heterostructures. Subsequently 980nm, 1.3µm and 1.55µm lasers with unprecedented characteristics such as $T_o \rightarrow \infty$, low chirp, small α-factor and high differential gain were developed and also quantum dot lasers on silicon substrates. More recently, the author's group demonstrated the first III-nitride visible quantum dot lasers, with the emission wavelength extending to 630nm (red). Use of quantum dots provides more advantages in the III-nitride system than the conventional III-V system. The ability to epitaxially grow blue-, green- and red- emitting quantum dots enables the realization of all-semiconductor white LEDs. Finally, the characteristics of 1.3µm III-nitride dot-in-nanowire optical interconnects on (001)Si substrate, consisting of a diode laser, waveguide and photodetector, will be briefly described. Quantum dot light sources are now used in a number of applications and these will be highlighted.

9:15am **MBE-MoM-4 High Growth Rate Plasma Considerations for Indium-rich III-nitrides***, **Evan Clinton**, E Vadiee, W Doolittle,* Georgia Institute of Technology

A high nitrogen flow rate Veeco plasma source has been employed to achieve GaN growth rates above 10 µm/hr utilizing the metal modulated epitaxy (MME) growth technique in a plasma-assisted molecular beam epitaxy (PAMBE) reactor. High growth rates enable thick buffer layers which can lower threading dislocation densities, essential for III-nitride optoelectronic devices such as solar cells and green light emitting diodes (LEDs). Additionally, PAMBE is capable of growing single phase $In_xGa_{1-x}N$ films for all indium compositions ($0 \le x \le 1$). It is shown that as the indium content increases and the bandgap of the material decreases, the surface becomes more sensitive to plasma-induced damage, as observed via atomic force microscopy (AFM) and reflection high energy electron diffraction (RHEED). Thus, in order to grow thick $In_xGa_{1-x}N$ films with fast growth rates, the plasma induced crystal damage must be minimized by optimizing the nitrogen plasma discharge. *In-situ* plasma discharge monitoring and optimization can be accomplished with a combination of optical emission spectroscopy (OES) as well as utilizing a flux gauge collector pin as a Langmuir probe. OES determines a plasma's molecular and atomic content, while the Langmuir probe current-voltage characteristics can determine the plasma discharge floating acceleration voltage and ion densities. In this work, correlations between plasma conditions and crystal quality are established. It is shown that by increasing the nitrogen flow the positive ion content increases, however, the acceleration voltage reduces. Additionally, a higher applied plasma power results in a negligible increase in positive ion content. In particular, AFM results demonstrate that the surface pit density of MME grown InN films dramatically reduces with reduced ion content. Finally, a roadmap will be presented to minimize damage in high indium content III-nitride devices.

9:30am **MBE-MoM-5 Molecular Beam Epitaxy of III-Nitride Nanowires on Amorphous and Nanocrystalline Metals***, **Brelon May**, E Hettiaratchy, R Myers,* The Ohio State University

The high surface area to volume ratio of nanowires allows them to have a larger degree of strain relaxation relative to their thin film counterparts. This enables high quality material to be grown on a variety of materials, including polycrystalline metal foils [1]. However, inhomogeneity associated with self-assembled growth reduces device efficiency. The polycrystalline nature of typical metal foils adds additional nonuniformities related to the metallic microstructure, e.g. grain boundaries and orientations (Fig. 1(a)). One possible solution is to tailor the substrate microstructure to have grain sizes of the same order as the nanowires, such that flux shadowing would limit the impact of microstructure variation. A more ideal option is to eliminate the microstructure altogether through the use of a metallic glass substrate i.e. amorphous metal. Here we demonstrate the growth of III-Nitride nanowires on Pt thin films as well as on amorphous metal foils. SEM measurements show that growth on amorphous foils enhances not only the uniformity of the density but also results in a higher degree of vertical nanowire alignment (Fig. 1(b)). The variations in optical and structural properties of the nanowire ensembles will be discussed in relation to the substrate microstructure.

9:45am **MBE-MoM-6 RF-Plasma MBE Growth of Epitaxial Metallic TaN_x Transition Metal Nitride Films on SiC***, **D. Scott Katzer**, N Nepal, M Hardy, B Downey, D Storm, D Meyer,* U.S. Naval Research Laboratory

Integration of epitaxial metal layers within semiconductor devices will enable substantial performance benefits, design flexibility, and novel device structures such as metal-base transistors [1] and integrated epitaxial superconductor / semiconductor heterostructures [2]. We have previously reported on the use of RF-plasma MBE to epitaxially grow metallic niobium nitride (NbN_x) thin films and III-N/NbN_x heterostructures on hexagonal SiC substrates [3-5]. More recently, we have reported on novel device lift-off processing enabled by the selective etching of NbN_x under III-N HEMTs [6]. In this presentation, we will discuss our recent work on the epitaxy of a similar transition metal nitride (TMN) material: TaN_x . As with NbN_x , the equilibrium phase diagram for TaN_x is complex, so demonstrating control of the TaN_x phase is important for practical applications. We have successfully grown single-phase thin films of single-crystal TaN_x on 3"-diameter SiC substrates using a customized Scienta-Omicron PRO-75 MBE system equipped with a six-pocket electron-beam evaporator to generate the Ta flux. We will discuss the MBE growth conditions for TaN_x and demonstrate the epitaxy of AlN/TaN_x heterostructures on SiC. The films were characterized in-situ using RHEED, and ex-situ using optical and atomic-force microscopy, contactless sheet resistance, x-ray diffraction, and transmission electron diffraction.

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10:30am **MBE-MoM-9 Magneto-Photoluminescence Properties of an AlGaN/GaN 2DEG Grown on Bulk GaN***, **Stefan Schmult**,* TU Dresden, Germany*; V Solovyev,* Institute of Solid State Physics RAS, Russia*; S Wirth,* Max-Planck-Institute for Chemical Physics of Solids, Germany*; A Grosser,* NaMLab gGmbH, Germany*; T Mikolajick,* TU Dresden & NaMLab gGmbH, Germany*; I Kukushkin,* Institute of Solid State Physics RAS, Russia

Landau level (LL) splitting of the density of states at moderate magnetic fields (~1T) is characteristic for high-quality 2-dimensional electron gases (2DEGs) confined in semiconductor heterostructures. In magneto-transport measurements this LL splitting leads to pronounced Shubnikov-de Haas oscillations in the longitudinal resistance and emergence of the quantum Hall effect. Reports on the optical detection of LLs in magneto-photoluminescence (PL) spectra are so far speculative for 2DEGs formed in AlGaN/GaN heterostructures.

Here, the LL splitting in a 2DEG confined at an $Al_{0.06}Ga_{0.94}N$/GaN interface is spectroscopically confirmed. The ultra-pure GaN/AlGaN/GaN (1µm/16nm/3nm) layer stack was grown by MBE on 650µm thick semi-insulating GaN with a vendor-specified density of threading dislocations (n_{TDD}) < 1e6cm^{-2}. Atomic force microscopy reveals 5x5µm^2 surface sections without a single defect, verifying the defect level to < 4e6cm^{-2}. An active area is laterally defined in Hall bar geometry, allowing for simultaneous measurements of magneto-transport and –PL under steady illumination at low-temperatures and magnetic fields up to 15 Tesla. The B-field induced oscillations commence in both cases at ~2T. Identical frequencies governing both oscillation types confirm the inherent 2D nature of the discussed PL features. The energy splitting between the PL LLs allows for extraction of an effective electron mass of ~0.24 m_e. Optical detection of the 2DEG represents a contactless method - even on wafer level - independent of e.g. lateral device definition, electrical contact issues or parasitic conduction paths.

10:45am **MBE-MoM-10 Kinetically Limited Growth of High Scandium Fraction Scandium Aluminum Nitride***, **Matthew Hardy**, B Downey, N Nepal, D Storm, D Katzer, D Meyer,* U.S. Naval Research Laboratory

Thin film AlN-based resonators are the industry standard for microwave-frequency filters used in 4G cell phone technology, and a variety of other RF applications [1]. $Sc_xAl_{1-x}N$ has the potential to replace AlN in next generation devices due a factor of five improvement in piezoelectric response for x = 0.43 [2]. ScAlN is previously been grown by reactive sputtering, which often has relatively high impurity incorporation and high densities of structural defects. Growth of electronic-device-quality ScAlN by molecular beam epitaxy (MBE) has been demonstrated in high-electron-mobility transistor (HEMT) structures using lattice-matched $Sc_{0.18}Al_{0.82}N$barriers [3]. MBE-growth of high ScN mole fraction ScAlN will enable novel acoustoelectric devices, such as resonant body HEMTs, which take advantage of both the piezoelectric and electronic properties of ScAlN.

200-nm $Sc_xAl_{1-x}N$ samples were grown on 10-nm AlN nucleation layers on 4H-SiC substrates using an RF-plasma MBE equipped with a high temperature effusion cell to supply Sc flux and a dual-filament effusion cell to supply Al flux. Samples with ScN molar fraction varying between 0.10–0.38 were grown at substrate thermocouple temperatures ranging from 400 °C to 920 °C. At moderate ScN fractions of 0.10–0.25, the substrate temperature had minimal impact on ScAlN quality, with films grown at lower temperature having rougher surfaces, but all samples were single-phase wurtzite ScAlN. Reflection high-energy electron diffraction (RHEED) patterns of samples with x = 0.38 grown at 800 °C and 400 °C are shown in Fig. 1, and cross-sectional transmission electron micrographs (TEM) of the same two samples are shown in Fig. 2. The RHEED pattern for the 800 °C-grown sample in Fig. 1(a) shows an extra set of first order spots, consistent with rotated cubic domains, while the TEM image in Fig. 2(a) shows evidence of rock-salt cubic inclusions. However, when grown at 400 °C, both RHEED in Fig. 1(b) and TEM in Fig. 2(b) show single-phase wurtzite ScAlN.

This work was funded by the Office of Naval Research.

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11:00am **MBE-MoM-11 Low Resistivity Al-rich AlGaN Grown by Plasma-assisted Molecular Beam Epitaxy***, **Ayush Pandey**,* University of Michigan*; X Liu,* McGill University, Canada*; D Laleyan, K Mashooq, E Reid, W Shin, P Bhattacharya, Z Mi,* University of Michigan

A highly conductive p-type AlGaN layer is crucial for obtaining high efficiency deep ultraviolet (UV) light emitting diodes (LEDs) and semiconductor laser diodes. Mg, which is a common p-type dopant for III-nitrides has a very large activation energy (up to 500-600 meV) in Al-rich AlGaN [1-3], and its solubility decreases significantly with increasing Al composition [4, 5]. Resistivity values ~10^2 to 10^4 Ω·cm have been commonly reported for p-type AlGaN epilayers with Al compositions ~80%, compared to <1 Ω·cm for p-type GaN.

We report on the achievement of low resistivity (~1-10 Ω·cm) p-type AlGaN epilayers with Al compositions in the range of 75-95% by using plasma-assisted molecular beam epitaxy. The growth was carried out under slightly metal rich conditions to ensure a smooth surface and good crystalline quality. Detailed characterization of the samples was carried out using X-ray diffraction (XRD), atomic force microscopy, and Hall effect measurements. We measured a hole concentration of ~1×10^{18} cm^{-3} and mobility ~6 cm^2/V·sec for AlGaN with Al composition ~75% at room temperature, which are significantly higher than previously reported values for AlGaN grown by MOCVD. Moreover, a relatively high hole concentration ~4×10^{17} cm^{-3} was achieved for AlGaN with Al composition >90%. The resistivity varies from ~1 to 4 Ω·cm with increasing Al composition from 75% to 92%. Detailed temperature dependent Hall measurements showed a small activation energy (~15 meV) for hole concentration near room temperature, suggesting the important role of hole hopping conduction in the Mg impurity band. The realization of high efficiency AlGaN deep UV LEDs is in progress and will be reported.

11:15am **MBE-MoM-12 RF-MBE Growth of AlN/GaN/AlN Resonant Tunneling Diodes on Freestanding GaN and GaN Templates***, **David Storm**,* U.S. Naval Research Laboratory*; T Growden,* The Ohio State University*; W Zhang,* Wright State University*; S Katzer, M Hardy, D Meyer,* U.S. Naval Research Laboratory*; E Brown,* Wright State University*; P Berger,* The Ohio State University

AlN/GaN/AlN resonant tunneling diodes (RTD) grown by RF plasma-assisted MBE on low dislocation-density, freestanding (FS) GaN substrates exhibit repeatable, stable, and hysteresis-free negative differential resistance at room temperature [1], extremely high current density [2], and near-UV cross-gap light emission [3]. In order to investigate the effects of growth conditions and dislocation density on the materials and electronic properties, we have grown AlN/GaN/AlN RTD structures by RF-MBE on hydride vapor-phase epitaxy (HVPE) grown FS GaN substrates and on metal organic chemical-vapor deposition (MOCVD)-grown GaN templates on sapphire. Nominally identical sets of structures were grown in the Ga-rich and Ga-stable growth regimes on each substrate type. The as-grown samples were characterized by optical microscopy, atomic force microscopy (AFM), and high-resolution x-ray diffractometry (HRXRD). Ga droplets were observed on the as-grown surfaces of the samples grown below 800 °C, and no droplets were observed on samples grown at or above 800 °C. AFM reveals surface morphologies of samples grown Ga-rich to be smoother, as expected; however, previous investigations indicate that smoother surface morphology does not correlate with improved device properties [4]. Dynamical simulations of the HRXRD data suggest trends toward thinner AlN barriers and thicker GaN wells in samples grown on freestanding GaN, potentially indicative of greater interfacial roughness, as growth temperature increases and the growth mode transitions from Ga-rich to Ga-stable. RTDs have been fabricated on all samples and devices tested. Electronic device results will be presented.

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11:30am **MBE-MoM-13 Low-resistance GaN Homojunction Tunnel Diodes and Low Voltage Drop Tunnel Contacts***, E Vadiee, **Evan Clinton**, W Doolittle,* Georgia Institute of Technology

The III-nitride material system is promising for optoelectronic and electronic applications. There have been continuing efforts in the development of GaN-based tunnel junctions (TJs) as one of the main remaining challenges in III-nitride materials, which can enable the next generation of III-nitride devices. The TJ can significantly improve the efficiency of visible and ultraviolet emitters as well as solar cells. However, achieving GaN-based TJs are extremely challenging due to the large band gap and the low hole concentration typical in GaN.

In this work, for the first time, we present a high-conductance GaN homojunction tunnel diode with a distinctive negative differential resistance (NDR) at a forward bias of 1.35 V and an intrinsic reverse Zener characteristic grown via metal modulated epitaxy (MME). The most recent achievements in the growth of extremely high doped GaN materials are also presented. In addition, the effect of the Mg doping concentration on the carrier transport of the TJs is studied, showing an increase in the forward and reverse tunneling current densities, the peak-to-valley ratio (PVR), and the NDR peak voltage by increasing the Mg doping concentration. In particular, the TJ using Mg and Si doping concentrations of 5×1020 and 7×1020 cm^{-3} shows a current density of 400 A/cm^2 at -1.2 V and PVR of ~1.1.

Furthermore, the temperature dependent current-voltage (I-V) characteristics of the TJ are discussed to provide insight into the nature of the tunneling behavior in the wide bandgap GaN. We present defect-assisted tunneling as the main carrier transport mechanism rather than interband tunneling. The low-temperature I-V characteristics of the best-performing TJ revealed repeatable NDR features with no hysteresis and PVR of ~1.3, which indicates a minimal carrier freeze-out in the GaN: Mg (see Fig 1). The highest silicon-doped n++/p++/i/n tunnel-contacted diode demonstrates a turn-on voltage of 3.12 V, only 0.14 V higher than that of the p/i/n control diode, and an improved specific on-resistance of 3.24 x10^{-4} Ωcm^2, which is 13% lower than that of the control diode.

Finally, recent results on low-resistance TJ contacts to LEDs with minimal voltage drop and the first demonstration of InGaN solar cells with p-n GaN homojunction tunnel contacts with an open-circuit voltage of ~2.2 V are presented.

11:45am **MBE-MoM-14 On the Efficiency and Long-term Stability of MBE-grown III-Nitride Nanostructures for Unassisted Overall Water Splitting***,*

Faqrul A. Chowdhury*, H Tran, H Guo,* McGill University, Canada*; Z Mi,* University of Michigan

The direct conversion of sunlight to hydrogen via water splitting has emerged as one of the key technologies to achieve energy sustainability. Progress in this field, however, has been limited by the low photocatalytic efficiency of conventional metal-oxide materials. We have recently demonstrated that nearly defect-free GaN-based nanostructures can meet the thermodynamics for overall water splitting (OWS) [1]; and by tuning the surface Fermi-level through controlled Mg-dopant incorporation, the apparent quantum efficiency for solar-to-hydrogen conversion can be enhanced by nearly two orders of magnitude under UV [2] and visible light illumination [3-4]. In this work, we demonstrate multi-band InGaN nanosheet photochemical diode (PCD) structures, which can spontaneously induce charge carrier separation and steer charge carriers toward the distinct redox sites for water oxidation and proton reduction. During the synthesis of InGaN photochemical diode nanosheet structure, p-type dopant (Mg) concentrations are rationally tailored, which induces a large built-in electric field between the two parallel surfaces. Due to the presence of a net built-in potential ~300 meV (ΔE) along the lateral dimension, the two surfaces are enriched with photo-generated holes and electrons to perform water oxidation and proton reduction reactions, respectively [5]. With spatially separated catalytic sites and reduced carrier recombination, the nanoscale PCDs exhibit stoichiometric H_2 and O_2 evolution, with a production rate of ~1.62 mmol $h^{-1}cm^{-2}$ and ~0.784 mmol $h^{-1}cm^{-2}$, respectively, which is equivalent to a solar-to-hydrogen efficiency over ~3%. We are currently developing novel III-Nitride nanostructured device on Si, which can demonstrate unprecedented performance-stability for more than ~580 hours in unassisted photochemical water splitting reaction when the surface is modified with suitable co-catalyst nanoparticles. With structural engineering, we aim to further enhance the solar-to-hydrogen efficiency in the range of 5-10%.

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MBE
Room Max Bell Auditorium - Session MBE-MoA
Novel Materials and Oxides/2D Materials and Characterization

Moderators: Joshua Zide, University of Delaware, Geoffrey Gardner, Microsoft Research

1:30pm **MBE-MoA-1 Epitaxial Stabilization of Monoclinic Fe_2O_3 on β-Ga_2O_3**, ***John Jamison**, B May, R Myers,* The Ohio State University

There is a surge in interest in β-Ga_2O_3 because of its thermodynamic stability, wide bandgap, and excellent figures of merit for high power devices. Additionally, β-Ga_2O_3 is quite similar to structures found in magnetic 3d transition metal oxides, which also consist of networks of tetrahedra and octahedra. Specifically, there are several naturally occurring Fe_2O_3 phases, and Fe^{3+} and Ga^{3+} cations exhibit similar ionic radii. However, there are no Fe_2O_3 phases the same monoclinic structure as β-Ga_2O_3. Here, we investigate the possibility of using epitaxial strain to stabilize a new form of monoclinic Fe_2O_3 (m-Fe_2O_3) on β-Ga_2O_3. Molecular beam epitaxy was used to grow a sample on a (010) β-Ga_2O_3 substrate, consisting of multiple Fe depositions of increasing amounts separated by 10 nm β-Ga_2O_3 spacers (Fig. 1(a)). Reflection high energy electron diffraction (RHEED) shows the preservation of the β-Ga_2O_3 overgrowth quality even for quite high m-Fe_2O_3 thicknesses. High resolution X-ray diffraction of the structure shows distinct thickness fringes and superlattice peaks. High resolution scanning transmission electron microscopy confirms that the overgrown β-Ga_2O_3 remains high quality after multiple Fe containing layers. The high Fe regions also show the same crystal structure as β-Ga_2O_3, i.e. m-Fe_2O_3. The optical and magnetic properties of this new form of Fe_2O_3 will also be discussed.

1:45pm **MBE-MoA-2 Homo- and Hetero-epitaxial Growth of β -Ga_2O_3 Thin Films by Molecular Beam Epitaxy**, ***Neeraj Nepal**, D Katzer, B Downey, V Wheeler, M Hardy, D Storm, D Meyer,* U.S. Naval Research Laboratory

β-Ga_2O_3 is emerging as a next generation ultra-wide bandgap semiconductor (UWBGS) material with a bandgap of 4.5-4.9 eV with applications in high-power/temperature electronics devices [1-3]. A distinct advantage of β-Ga_2O_3 over other UWBGS materials is availability of inexpensive large area bulk substrates synthesized by melt growth techniques at atmospheric pressure [2]. Homoepitaxial growth on bulk substrates offers the potential of low defect density films for vertical power devices. Despite the crystalline quality advantages of homoepitaxy, future device performance is anticipated to be limited by the low thermal conductivity of β-Ga_2O_3, so one approach to improve thermal performance is through hetero-epitaxy of β-Ga_2O_3 on a high thermal conductivity substrate such as SiC. For these reasons, both homo- and hetero-epitaxial growth of Ga_2O_3 films are of general interest to be investigated.

Figure 1. X-ray diffraction measurements of epitaxial β-Ga_2O_3 on on-axis 4H-SiC (blue, 86 nm thick), c-sapphire (black, 126 nm) and (010) β-Ga_2O_3 (purple, ~200 nm).

In this paper, we report homo- and hetero-epitaxial growth 100-200 nm thick β-Ga_2O_3 thin films on sapphire, (010) β-Ga_2O_3 and 4H-SiC substrates by molecular beam epitaxy (MBE) at 650 °C and compare the impact of substrate. The growth parameter space including thermocouple-measured growth temperature, relative Ga flux, and oxygen plasma flow were varied to grow β-Ga_2O_3 films on c-plane sapphire substrates. Figure 1 shows about 86-130nm thick single phase MBE-grownβ-Ga_2O_3 films that are insulating with relatively low surface roughness. The heteroepitaxial films have rocking curve full-width-at-half-maximum of 256 and 720 arc-sec on sapphire and SiC, respectively. In this paper we will discuss MBE growth parameter space optimization of β-Ga_2O_3 on sapphire and the structural, morphological, and electrical properties of MBE grown β-Ga_2O_3 thin films on (010) Ga_2O_3 and SiC.

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2:00pm **MBE-MoA-3 Epitaxial Growth and Electronic Structure of Semiconducting Half-Heusler FeVSb**, ***Estiaque Haidar Shourov**, P Strohbeen, D Du,* University of Wisconsin Madison*; J McChesney,* Argonne National Laboratory*; A Janotti,* University of Delaware*; J Kawasaki,* University of Wisconsin Madison

Although FeVSb is experimentally known as a high figure of merit thermoelectric material [1], challenges associated with fabricating high quality single crystalline samples have hampered a fundamental understanding of its electronic structure [2]. For example, while recent first-principles calculations show that the DFT band gap is highly sensitive to the choice of exchange and correlation functional (LDA predicts 0.36 eV and HSE predicts 1.45 eV [3,4]), its experimental bandgap is not known. Here, we demonstrate the epitaxial growth of FeVSb on MgO (001) by solid source molecular beam epitaxy. The single crystalline phase and epitaxial alignment were confirmed by reflection high-energy electron diffraction (RHEED) and X-ray diffraction (Fig. 1). By tuning the growth temperature and relative Sb flux, we find that FeVSb can be grown in a self-limiting, Sb adsorption-controlled window. Further tuning of the Fe:V flux ratio (by QCM and RBS measurements) then allows us to grow stoichiometric FeVSb. Our angle-resolved photoemission spectroscopy (ARPES) reveals that the band gap of FeVSb is at least 0.6 eV (Fig. 2), much larger than the 0.36 eV band gap predicted by LDA calculations, and the measured valence band width is smaller than the LDA width by nearly a factor of two. We present further calculations and experimental results to decipher this discrepancy.

2:15pm **MBE-MoA-4 Growth of Candidate Polar Metal Hexagonal Half Heuslers**, ***Dongxue Du**, J Kawasaki,* University of Wisconsin Madison

Hexagonal half Heuslers (space group P63mc, LiGaGe-type structure) have recently been proposed as a new hyper-ferroelectric materials system. In these ABC intermetallic compounds, layers of B and C atoms form a buckled honeycomb lattice, resulting in a net polarization along the c axis that is robust against the depolarizing field [1]. Moreover, many of these compounds exhibit large Rashba coefficients and magnetic order, making them a promising system for finding multiferroics [2]. However, demonstration of these properties and understanding the mechanism for hyper-ferroelectricity require high quality epitaxial films, which haven't yet been demonstrated.

Here we demonstrate the first epitaxial growth of LaPtSb and LaAuGe. These compounds are grown on *c*-plane Al2O3 by solid source MBE, using an Sb adsorption controlled window for LaPtSb, and by flux matching for LaAuGe. Symmetric 2theta-omega (Fig. 1) and in-plane rotation (phi scans Fig. S1) x-ray diffraction measurements confirm that the films are epitaxial and single crystalline, with the desired LiGaGe-type buckled hexagonal structure. RHEED patterns confirm well-ordered surfaces with surface reconstructions. Through a combined analysis of cross sectional TEM, second harmonic generation (SHG), and angle-resolved photoemission spectroscopy (ARPES) measurements, we are exploring the coupling of polar distortions to electronic structure and magnetism in these materials.

We gratefully acknowledge support from the ARO YIP (W911NF-17-1-0254, Dr. Chakrapani Varanasi)

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2:30pm **MBE-MoA-5 Optimizing Cesium Antimonide Photocathode Performance Using Real-time *In-situ* Monitoring of Photoemissive Properties**, ***Mark Hoffbauer**,* Los Alamos National Laboratory*; S Celestin,* Northeastern University*; V Pavlenko, F Liu, N Moody,* Los Alamos National Laboratory

Alkali antimonide semiconductor photocathodes like Cs_3Sb or K_2CsSb are promising electron sources for use in next-generation light sources such as advance Free Electron Lasers (FEL) due to their high quantum efficiency in the visible spectrum, short response time, good lifetime, and the ability to produce high-brightness beams with a relatively low emittance. Traditional methods of alkali antimonide photocathode growth, sequential deposition, dates back to 1960s when quantum efficiency (QE, number of electrons emitted per incident photon) was prioritized over other parameters. Sequential deposition allows fabrication of acceptable photocathodes, but the crystalline quality is always low and surface roughness is high. Photocathodes for next-generation light sources must be smooth and have high crystalline quality in order to generate "colder" electron beams (low emittance). Recently, a co-deposition alkali antimonide growth technique was introduced that mimics MBE but, lacking meaningful feedback, fails to achieve acceptable control over the growth parameters. Understanding the correlation between growth conditions (substrate temperature, fluxes of alkali metals and Sb), film characteristics (stoichiometry, crystal structure, roughness), and cathode metrics (QE, emittance, and response time) is necessary for developing reliable growth procedures for alkali antimonide photocathodes.

We have performed detailed studies on the growth of Cs_3Sb photocathodes using a new MBE growth capability at LANL with better control of the growth kinetics for optimizing photoemissive properties. The growth capability utilizes a Sb effusion cell and a custom-built Cs evaporator assembly for precise control of their fluxes. A multiple wavelength laser assembly is used to illuminate the surface of the growing cathode and measure the spectral response (QE vs. wavelength) in real-time. These *in situ* measurements were used to tune the growth parameters (fluxes, temperature, etc.) and attain the spectral response indicative of a stoichiometric Cs_3Sb film. Our results demonstrate the ability to fine tune the Sb and Cs fluxes in a co-deposition film growth mode and improve the overall spectral response. Improved photoemissive properties can be correlated with initiating the film growth under conditions for forming Cs_3Sb at the earliest stages and maintaining the film stoichiometry throughout the growth. These films can be grown over a range of substrate temperatures and show excellent long term photoemission stability. The relationship between the optimized growth conditions and the photocathode emittance properties will also be discussed.

2:45pm **MBE-MoA-6 Optically Triggered Semiconductor Hyperbolic Metamaterial for Controlled Single Photon Emission***, **Kurt Eyink**, H Haugan, V Pustovit, A Urbas,* Air Force Research Laboratory

Quantum photonics opens doors for applications in sensing, data transfer, quantum computing. A key technological hurdle is a system for controlled single photon emission. Hyperbolic metamaterials, composed of metallic building blocks embedded in dielectric media control emission lifetime by modifying the photon density of states. However, limited previous efforts have explored the transient modification of metamaterials to control emission. Antimony-based semiconductor hyperbolic metamaterials (SHMMs) offer a route to modulation of these resonances at the mid-infrared (IR) wavelength range, which would modulate emission. In this work we propose to demonstrate SHMMs such as InAsSb alloys, and InAs/InAsSb stacks embedded with dielectric GaSb media in which a transient carrier concentration will be generated through optical pumping. Modelling of these films show that optical concentration of 10^{19}-10^{20} e-h/cm^3 would generate responses in the IR range. This transient excitation of the SHMM would enable triggered single photon emission as well as optical gating and modulation. Calculations show 2-3 orders of magnitude change in the photon density of states predicting dramatic changes in the emission rate. If successful, this study would establish a new platform for deterministic single photon emission that would be integrable into opto-electronic platforms and dramatically advance optical quantum technologies. This initial study will serve as an ideal test bed for next-generation plasmonic architectures, where optically engineered metals can be integrated with a loss-less dielectrics to explore the ultimate limits of plasmonic devices.

3:30pm **MBE-MoA-9 Epitaxy of *M*/graphene/Ge (*M* = Fe, Sb) Heterostructures: Testing the Limits of Remote Heteroepitaxy***, **Patrick J. Strohbeen**, E Shourov, V Saraswat, D Du, M Arnold, J Kawasaki,* University of Wisconsin Madison

It was recently demonstrated through the creation of GaAs/graphene/GaAs (001) heterostructures that monolayer graphene may act as a general platform for epitaxy through an atomic barrier[1]. However, the underlying mechanisms of "remote epitaxy" and its generalization to other material systems, e.g. transition metal compounds or oxides, remains unclear. Here, using *M*/graphene/Ge (*M* = transition metal or Sb) as a model system we (1) explore the limits of the remote epitaxy mechanism and (2) demonstrate that single layer graphene is also an excellent solid state diffusion barrier.

In systems containing more volatile species (*M* = Sb) we have found that carefully controlling growth kinetics both via substrate temperature and the cracked Sb species enables growth of nearly single oriented Sb/graphene/Ge (111) heterostructures. The resultant films are readily exfoliated using scotch tape (Fig. 1). In contrast, we find that when *M* = Fe, the films grown on graphene are polycrystalline regardless of substrate temperature and Ge orientation. Though we still show that the polycrystalline films are easily exfoliated. These results suggest that volatile adatom species may be a required ingredient for "remote epitaxy". With *M* = Fe we also show that graphene behaves as an excellent solid state diffusion barrier as supported by our in-situ x-ray photoemission spectroscopy (XPS) measurements as a function of annealing temperature. Our work suggests highly flux dependent growth mechanisms due to both the difficulty in wetting the graphene monolayer as well as the high in-plane diffusivity on graphene. The effects of growth conditions as well as the effectiveness of graphene as a solid state diffusion barrier will be discussed.

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3:45pm **MBE-MoA-10 Molecular Beam Epitaxy of $MoSe_2$ Directly on Si***, **Elline Hettiaratchy**, B May, R Myers,* The Ohio State University

Van der Waals bonding relaxes the constraints of lattice matching, making two-dimensional (2D) transition metal dichalcogenides attractive in the field of epitaxy. Recently, molecular beam epitaxy (MBE) of $MoSe_2$ has been demonstrated on AlN and GaAs [1,2] but, to our knowledge, the direct growth of $MoSe_2$ on Si by MBE has not yet been reported. Here we investigate the early stages of 2D nucleation of $MoSe_2$ grown on Si by MBE in order to pursue tunable grain size. In principle, large area $MoSe_2$ (0001) will grow on Si (111) with two domain orientations. After removing the oxide by a Piranha etch, Mo and Se are codeposited on Si (111). At constant flux ratios the 2D nucleation rate is controllable with substrate temperature, as confirmed using x-ray diffraction and atomic resolution force microscopy (AFM). Film morphology and structural quality in the high temperature, Mo-limited, regime of $MoSe\text{-}_2$ growth using high Se vapor overpressures will be discussed.

4:00pm **MBE-MoA-11 Atomic Scale Characterization Showing Kinetic Compositional Instability and Phase Separation in MBE-grown InGaAs***, **Michael Yakes**, M Twigg, N Kotulak, N Mahadik, S Tomasulo,* U.S. Naval Research Laboratory

Phase separation in III-V semiconductor alloys remains a problem that limits the performance and quality of electronic materials. As the first stage in a comprehensive program addressing this issue, we have begun investigating an alloy system in which only the group III elements differ: InGaAs. Lattice-matched InGaAs alloy films were deposited at three temperatures (400, 450, and 500 ºC) by MBE on a (001) InP substrate. Using TEM, APT and XRD, we have found phase separation in all three growths to varying degrees.

According to the kinetic compositional instability (KCI) model developed by Glas [1], the critical temperature for kinetic spinodal phase separation in InGaAs is 814 ºC, a temperature well above the growth temperatures commonly used in InGaAs growths. Our XTEM measurements found that the amplitude of composition modulations averaged over the thickness of the XTEM sample are 0.7, 0.5, and 0.4 atomic percent for the growth temperatures 400, 450, and 500 ºC, respectively. APT indicates that the amplitude of composition modulation for the 400 ºC growth is approximately 1 atomic percent, a value that compares favorably with the 0.7 atomic percent measured by XTEM.

We have used KCI theory to evaluate the average amplitude of composition modulation for a given growth temperature by integrating the KCI vertical composition profile over thickness. The KCI model explicitly addresses the kinetics of the volatile near-surface region of the film, where surface undulations driven by surface diffusion introduce the kinetic component that undermines compositional stability beyond the point dictated by thermodynamics alone. This analysis finds that the kinetically unstable layer is approximately 2 nm thick when the lateral composition modulation wavelength is 3 nm. The thickness of this kinetically unstable layer corresponds to features marking both lateral and vertical composition, providing good evidence for the kinetic origins of the observed phase separation in the material.

4:15pm **MBE-MoA-12 Investigation of Gallium-related Defects in III/V Epitaxial Layers***, **Yossi Cohen**, O Klin, I Grimberg, N Yaron, E Weiss,* SemiConductor Devices Company, Israel

III/V materials are among the most common materials for the production of IR detectors. Gallium and indium droplets in MBE grown material are long-time known to be a major cause for decrease in detector operability (percentage of good pixels). In this work we present the investigation of gallium-related defects formed in an InAs/GaSb strained layer superlattice (SLS) structure. The SLS structure allows us to understand, in details, the mechanism in which the defect is formed and evolves.

Based on TEM analysis shown in figure 1 and other results (AFM, SEM, cross-section EDS mapping), we conclude that after a gallium droplet reaches the epilayer, it etches and dissolves several hundreds of nanometers below its landing point. Gallium from the droplet migrates sideways on the surface (at different rates along the [01-1] and [011] directions) for few microns, increasing temporarily the growth rate of the epilayer around the droplet and changing its composition (figure 1c). The incoming fluxes together with the dissolved material enrich the Ga droplet with Sb, As and In. In our growth conditions, the Ga droplet top surface solidifies, forming a GaAs shell [1]. High threading dislocation density is formed in the InAs-GaSb SLS grown on such surface due to the large mismatch between the SLS and the GaAs shell. The InGaAsSb solution inside the droplet separates, at some point, to the thermodynamically stable InSb and GaAs phases. In some parts of the core we see pure gallium that probably solidifies only when the sample is cooled down.

4:30pm **MBE-MoA-13 Acoustic Nanostructures for Charge Carrier Confinement in GaAs/Al$_x$Ga$_{1-x}$As Multiple Quantum Wells**, ***Kevin Vallejo***, *C Schuck, T Garrett,* Boise State University*; Z Hua, D Hurley,* Idaho National Laboratory*; P Simmonds,* Boise State University

Quantum confinement of charge carriers in semiconductors is at the heart of next generation energy conversion technologies, as well as new encryption and computation paradigms. We propose a novel approach that uses picosecond-duration surface acoustic phonon pulses to produce lateral carrier confinement (2D and 3D confinement) in III-V (i.e. polar) semiconductor quantum wells. Strain generated by the phonon pulses varies with depth below the sample surface (Fig. 1), locally deforming the valence and conduction bands to produce lateral confinement in the plane of a quantum well. This approach offers the prospect of continually modifying confinement in a manner that can be externally controlled. Using molecular beam epitaxy, we grew the GaAs/AlGaAs structure consisting of three quantum wells of width 5, 7, and 10 nm, buried beneath the sample surface at depths of 14, 49, and 112 nm respectively. These wells are positioned so as to coincide with different conditions of shear strain and dilatation, and hence piezoelectric field strength. We will present results from preliminary studies showing carrier transport at the speed of sound in the sample with extended lifetimes due to acoustic confinement. This approach could find useful applications in nanocircuitry.

MBE
Room Elder Tom Crane Bear - Session MBE-MoP
MBE-Poster Session

MBE-MoP-1 Hydrogen Permeation Behavior of BN film, ***Motonori Tamura,*** The University of Electro-Communications, Japan

The hydrogen permeation behavior of BN-coated Type 316L stainless steel was investigated. In comparison with TiN and SiC films, the BN (boron nitride) film, deposited by molecular beam epitaxy (MBE), was effective to reduce the rate of hydrogen permeation through stainless steel (Fig. 1).

Hydrogen-permeation tests were performed on the coated stainless steel samples. These tests were based on the differential-pressure methods in ISO15105-1.

The permeation of hydrogen through solid materials involves a series of steps including adsorption, dissociation, diffusion, and recombination coupled with desorption.

The permeability, Q, is generally defined by the expression

$Q = J d / A (dP)^n$

where J is the permeation flux of hydrogen through a sample of area A and thickness d, under a partial pressure gradient (dP) across the sample called the driving pressure. The exponent n represents different permeation regime s : diffusion- limited and surface- limited when n = 0.5 and 1, respectively.

The double- logarithmic plots show ed that the two sets of data of BN- and TiN-coated samples were linearly related. The exponent n showed a value of 0.48 – 0.53 at 573 – 773 K, which indicated that hydrogen passed through the samples in the diffusion- limited permeation mode.

MBE-MoP-3 Growth of Pure Wurtzite InGaAs Nanowires for Photovoltaic and Energy Harvesting Applications, ***Hangkyu Kang,*** *M Baik,* Yonsei University, Republic of Korea*; B Yoo,* Hanyang University, Republic of Korea*; J Song,* Korea Institute of Science and Technology, Republic of Korea*; M Cho,* Yonsei University, Republic of Korea

Vertically aligned and highly densified InGaAs nanowires were grown on Si (111) substrates by Au-assisted molecular beam epitaxy, and antireflection characteristics of the InGaAs nanowires were characterized. The bandgap of InGaAs NWs was tuned by varying the In to Ga ratio; the compositions of Ga and In were controlled to adjust a bandgap to ~1.0 eV. The obtained nanowires were vertically aligned with a diameter of ~20 nm near the top and ~44 nm at the bottom, a slightly tapered morphology. This morphological shape can be formed because of the different surface diffusivities and affinities of In and Ga to the Au catalyst. By controlling the deposition conditions, InGaAs nanowires with no significant stacking defects, kinking, and bending were grown successfully on Si (111) substrates. High-resolution transmission electron microscopy studies showed that the InGaAs nanowires were grown with a pure wurtzite single crystalline structure with a maximum length of ~18 µm. Photo-reflectometry and spectroscopic ellipsometry measurements showed a significant reduction in the reflectance, less than ~5% for normal incidence in the wavelength range of 200-1700 nm and considerable reduction at incident angles of 30-70°, demonstrating the antireflection properties of the InGaAs nanowires. Furthermore, piezoelectric properties were observed in all the areas where InGaAs nanowires were grown for a contact area of 2 µm × 2 µm, as the growth direction was along the polar *c*-axis (<111> direction) of the hexagonal structure.

MBE-MoP-4 Effect of ex-situ Passivation of the GaAsSb Nanowires, *M Sharma, J Li, S Iyer,* ***Rabin Pokharel,*** North Carolina A&T State University

Semiconductor nanowires (NWs) due to their one-dimensional architecture result in unique electronic properties with a wide range of applications towards optoelectronic devices. The high aspect ratio enables a broader choice of the substrates attributed to better stress-strain management, enhanced optical light trapping due to multiple scattering at NW surface, and the possibility of implementing numerous heterostructures (axial, core-shell). Further, the large surface/volume ratio plays a pivotal role at the nanoscale in controlling optoelectronic properties of devices. A large density of surface state (D_{it}) results in pinning of the Fermi level and surface band bending leading to the formation of the non-radiative levels.[1] The surface effects can be minimized using in-situ or ex-situ passivation of the surface enabling enhanced device performance.

In this presentation, we report on ex-situ chemical passivation of GaAs, GaAsSb axial NWs grown on Si (111) via Ga-assisted molecular beam epitaxy. GaAsSb is an important material system due to a broad tunability of its bandgap encompassing the 0.94-1.55 µm wavelength in the near-infrared region. Normally, the in-situ passivation of this material system is accomplished by the growth of AlGaAs/GaAs shells, which need to be etched in order to make a metal contact at the tip of the NWs. The advantage of ex-situ lies in eliminating this extra step as a couple of monolayers of the passivation layer is sufficient to minimize the surface effects. The ex-situ chemical passivation of the NWs was performed using hydrazine-sulfide solution, which first removes the pristine layer along with a formation of one or two monolayers of GaN shell. The I-V characteristics of the passivated single GaAs (GaAsSb) NW exhibit three-orders of magnitude increase in current, while the 4K micro-photoluminescence (µ-PL) peak at 1.25 eV revealed an increase in the intensity by four-fold in comparison to the unpassivated NWs. These improvements are attributed to increasing in the non-depleted region in the NW, resulting in a reduction in the D_{it} and surface recombination velocity [2] by one (two) order of magnitude for GaAs (GaAsSb) NWs. Thus, the outer shell of a higher bandgap material has been used to move the surface states away from and charge confinement in the core of the NWs.

Acknowledgment : This work is supported by the ARO (W911NF-15-1-0160), technical monitors- Michael Gerhold and Joe Qiu .

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MBE-MoP-5 Study of As-rich Interfaces with Exponentially Decaying As Content within InAs/AlSb Superlattices, ***Yunong Hu,*** *M Tam, Z Wasilewski,* University of Waterloo, Canada

Highly strained interfaces may exist between InAs and AlSb layers grown by MBE [1]. The composition and thickness of the interfacial layer influence strongly the electronic properties of InAs/AlSb based structures. However, they are hard to characterize and nominally identical growth run may give very different interfaces in different MBE systems.

In this work, we study the influence of As flux interruption procedure on the unintentional incorporation of As into AlSb layers. This effect can significantly alter the strain distribution in AlSb barrier by changing it into compositionally graded AlAsSb layer. In the first stage, the As flux temporal dependence was measured during mock growths, inside Veeco GEN10 MBE system using a beam flux monitor (BFM) at wafer position. A storage scope was used to record the BFM signal at 2ms intervals. When the As beam was interrupted, instead of abrupt flux drop, exponential decay was observed. An excellent fit was obtained using double exponent function (Fig. 1). As expected, very abrupt flux termination was observed with closing Sb shutter. Subsequently, three samples of 200Å/150Å InAs/AlSb superlattices with 5 repeats were grown on InAs(001) substrates at 420°C using As_2. Identical shutter/valve sequence was used as during the mock growths. When the deposition was switched from InAs to AlSb, at the shutter closure, the As cell valve setting was kept unchanged for sample A, decreased to achieve 80% flux reduction for sample B, and fully closed for sample C.

The dynamical simulations of the High- Resolution X-ray Diffraction (HRXRD) gave very good agreement with experiment assuming that the profile of arsenic content in the $AlAs_ySb_{1-y}$ barrier followed the experimentally measured As_2 flux during the mock growths (Fig.1). This included the $In_xAl_{1-x}As_ySb_{1-y}$ interfacial monolayer (ML) at the start of the barrier. No additional strain was introduced at the second interface. For the growth performed with As beam interrupted only by the shutter, we find that the barrier composition y is still at 6.8% at the ends of the 150Å barriers. A considerable amount of As is incorporated even when both valve and shutter were closed for As interruption during barrier growth. However, in this case, arsenic is mostly confined to the first 5MLs.

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MBE-MoP-7 The Characteristics of Phototransistor based on the Grown $MoSe_2$ by Molecular Beam Epitaxy, ***Yoon-Ho Choi,*** *J Jeong, G Kwon, H Kim,* Yonsei University, Republic of Korea*; H Kim,* Sungkyunkwan University, Republic of Korea*; M Cho,* Yonsei University, Republic of Korea

Transition metal dichalcogenides (TMDs) have been explored as the promising active layer for the optical and electronic devices because they have a bandgap corresponding to visible light range and the high mobility at the subnanometer thickness. We studied molecular beam epitaxy (MBE) method in order to grow uniform $MoSe_2$ on large area substrate. The high-purity Se and Mo were evaporated by e-beam evaporator and Knudsen cell, respectively. The quality of the film was confirmed by spectroscopic measurement. The chemical composition and elemental ratio were studied by high resolution X-ray photoelectron spectroscopy (HRXPS). Scanning transmission electron microscopy (STEM) was conducted to observe growth mechanism and Moirè pattern. The growth mechanism involves layer by layer growth, expanding the bilayer gradually on the covered monolayer with the deposition time in figure 1. We also observed that the localized strain is induced by grain boundary between rotational stacking layer and oriented stacking. The band alignment of the film was confirmed by ultraviolet photoelectron spectroscopy (UPS) and spectroscopic ellipsometry (SE): The grown $MoSe_2$ by MBE is n-type semiconductor, having the optical band gap as 1.39eV and the valance band as 1.10eV. In addition, we fabricated the phototransistor based on the grown $MoSe_2$. The device exhibited the fast rising and decay time, 6ms and 8ms, respectively, at wavelength of 532 nm in figure 2. The variable on/off current with gate bias and laser power was measured, indicating the excellent photoresponsivity. Finally, we have successfully grown the $MoSe_2$ film on amorphous SiO_2, demonstrating phototransistor device applications.

MBE-MoP-8 Experimental Determination of Band Overlap in Type II InAs/GaSb Superlattice based on Temperature Dependent Photoluminescence Signal*, J Huang, Y Zhang, Y Cao, K Liu, W Huang, S Luo, H Ji, T Yang,* ***Wenquan Ma****,* Institute of Semiconductors, Chinese Academy of Sciences, China

Type II InAs/GaSb superlattice (SL) material has been widely used to make infrared photodetectors. In addition, this material system may play a unique role for some fundamental studies like spin–orbit interaction, topological insulator, and novel exciton condensates. A fundamental parameter of the material [1,2], the band overlap at the interface between InAs and GaSb, should be known. We have determined the band overlap in type II InAs/GaSb SL structure based on the temperature dependent photoluminescence (PL) results of a short- wave SL sample. The band overlap value is treated as a temperature variable and is simulated by fitting the PL peak position using the 8KP method. It is found that the band overlap monotonically decreases from 0.325 to 0.225 eV when temperature is increased from 12 to 90 K [3]. The calculated e1-hh1 transition using the obtained band overlap data shows an agreement with the PL results of another SL sample.

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MBE-MoP-10 Significantly Enhanced Performances of 1.3 µm InAs/GaAs Quantum Dot Lasers by Direct Si-doping*, Z Lv, Z Zhang,* ***Tao Yang****,* Institute of Semiconductors, Chinese Academy of Sciences, China

Direct Si-doping into InAs/GaAs quantum dots (QDs) has shown dramatically enhanced photoluminescence of the QDs [1]. This Si-doping technology has been used to fabricate intermediate band QD solar cells and led to a markedly increased conversion efficiency of the cells from 11.3% to 17% [2]. In this work, we demonstrate significantly improved performances of 1.3 µm InAs/GaAs QD lasers using the direct Si-doing technology.

Two QD laser structures with the doping concentration of 1×10^{18} cm^{-3} and without any doing were grown by MBE. The active region of the two lasers consists of five stacked layers of InAs/GaAs QDs. Ridge waveguide lasers with a ridge width of 30 µm for the two laser structures were fabricated using standard wet etching and metallization techniques.

Figure 1 shows single-side CW power-current (P–I) curves of the two lasers with a cavity length of 2.5 mm, obtained at 20 °C. It can be clearly seen from the figure that the threshold current of the doped QD laser is as low as 53.7 mA, which is much smaller than for the undoped one (125.5 mA). The corresponding threshold current density for the doped laser is only 71.6 A/cm (14.3 A/cm^2 per QD layer), whereas it is 167.3 A/cm^2 (33.5 A/cm^2 per QD layer) for the undoped QD laser. In addition, the single-side slope efficiency is improved from 0.28 W/A for the undoped QD laser to 0.42 W/A for the doped QD laser.

This work was supported by the National Natural Science Foundation of China (No. 91433206).

Figure 1 S ingle-side CW P–I curves of the two QD lasers

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MBE-MoP-11 Effect of in-situ Annealing on the GaAsSb Nanowire-based Photodetector*, M Sharma, E Ahmad, M Parakh,* ***Rabin Pokharel****, S Iyer,* North Carolina A&T State University

Amongst the III-V nanowires (NWs) of different material systems, interest in GaAsSb NWs stems from the tunability of its bandgap encompassing the telecommunication wavelength in the near-infrared region. One-dimensional (NWs) architectures have attracted considerable attention due to its better stress-strain management, high aspect ratio enhancing optical trapping, ability to implement different heterostructures (axial, core-shell),and quantum confinements leading to devices with advanced functionalities. NWs exhibit large surface/volume ratio adversely impacting the device performance, which is attributed to surface related and other defect states. In this report, reduction of surface states effects by in-situ annealing along with in-situ surface passivation has been presented, and NW photodetector has been demonstrated.

GaAsSb axial (core) NWs have been grown on Si (111) via Ga-assisted molecular beam epitaxy. To minimize the effect of surface states, in-situ vacuum annealing (10^{-10} Torr) at 465º C followed by in-situ growth of AlGaAs/GaAs shell around the core have been carried out. These NWs exhibit a significant improvement in µ-photoluminescence (PL) peak intensity and electrical characteristics as compared to bare GaAsSb axial NWs, attributed to suppression of band tail states. The analysis of temperature-dependent µ-PL peak intensity for unannealed NWs revealed the presence of two non-radiative thermal energy levels, which reduced to a single level in annealed nanowires. This further attests to the suppression of band tail states on annealing.

Hence the device was fabricated using the in-situ annealed nanowires. The performance of the p-i GaAsSb/AlGaAs NW ensemble based photodetector (PD) device was assessed under an illumination of 540 nm with an intensity of 173 $\mu W/cm^2$. The I-V characteristics were found to be well explained considering Schottky contact (SC) at both ends of the NWs. The PD device exhibited a responsivity of 540 A/W with an external quantum efficiency of 1.25×10^5 %. The best fit of the COMSOL fitting to the experimental I-V graphs indicated that the high spectral responsivity could be attributed to two orders of magnitude increase in carrier concentration under illumination.

Acknowledgment: This work is supported by the Army Research Office (W911NF-15-1-0160).

MBE-MoP-12 Reduced Heating Effects in MBE Grown Nanowire Array LEDs*, S Yang,* McGill University, Canada*; A Tian,* St. Maximillian Kolbe CHS, Canada*;* ***Yongyuan Zang****,* McGill University, Canada

It has been theoretically demonstrated that junction temperature in nanowires can be significantly lower than that in bulk devices [1]. However, very little research has been reported on the thermal properties of nanowire LED devices. In this regards we have investigated the impact of the Joule heating of axial InGaN/GaN nanowire light-emitting diodes (LEDs) grown by molecular beam epitaxy (MBE) on Si (111) for the first time. In this study, four nanowire LEDs are spontaneous formatted under nitrogen rich conditions and nanowire with different geometries were obtained through different growth conditions.

Figure 1 shows the measured peak wavelength of the samples at the same injection level. It can been seen that the peak wavelength shows a red shift of ~ 40 nm for sample with high filling factor while only shows a red shift of ~ 20 nm for samples with low filling factor. Since the red shift is commonly considered as the evidence of the LED self-heating effect [2], therefore the Joule heating effect of nanowires is significantly reduced for less dense geometry. Also observed is the large inhomogeneous broadening of the active region interplay with the higher filling factor which can be attributed to rising temperature (Shown in the inset). A significant reduced EQE also can be observed in sample with high filling factor, as shown in Figure 2. These results indicated that the nanowire have a better thermal dissipation and conversion efficiency than conventional planar structures.

Based on the results in this work, a systematic simulation and theoretical model was presented for the first time to interpret all the thermal transport process of the nanowire LEDs.

Figure 2 Measured EQE for samples with different filling factor.

Figure 1 Peak wavelength of nanowire LEDs samples with different filling factor under different duty cycle at same injection level. The inset is the EL spectrum of nanowire led samples under cw injection with filling factor of 10% and 70% respectively.

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MBE-MoP-13 Effect of Column Diameter and Height on Optical Properties of Regularly Arranged GaN Nanocolumn Grown by rf-MBE, ***Hiroto Sekiguchi***, *Y Higashi, K Yamane, H Okada, A Wakahara,* Toyohashi University of Technology, Japan; *K Kishino,* Sophia University, Japan

GaN nanocolumns have a great potential in improving emission efficiency in the longer-wavelength due to dislocation filtering and strain relaxation [1]. The regularly arranged (RA) nanocolumns have been demonstrated on GaN layer, however, the selective area growth of nanocrystals on Si is required in terms of low-cost and large-area substrate. In this study, the effects of diameter and height on optical properties were investigated because it is important to know key points to obtain high crystalline nanocolumns.

The RA-GaN nanocolumns were fabricated on AlN/Si substrate by Ti-mask selective-area growth technique [2]. GaN nanocolumns with different height (350 and 700 nm) were prepared. Figure 1 shows the peak intensity of near-band edge (NBE) emission at RT as a function of diameter. While peak intensity at NBE drastically decreased with increasing the diameter for low height nanocolumns, high PL intensity kept at almost constant value up to 200 nm and dramatically decreased at 230 nm for high height nanocolumns. To understand this reason, CL measurement were performed (Fig. 2). While the ratio of strongly emitting nanocolumns decreased with increasing dimeter for 350 nm-height nanocolumns, it hardly decreased with increasing diameter for 700 nm-height nanocolumns. It would result from that threading dislocation did not propagate to the upper part in the 700 nm-height nanocolumn [1]. Next, the effect of diameter and height on yellow luminescence was investigated. While the ratio of yellow luminescence intensity to total PL intensity monotonically increased with increasing diameter for low height columns, it was constant at small value of less than 0.1 up to thick diameter of 360 nm. Finally, PL spectra at 15 K were evaluated. NBE emission and oxygen-related luminescence (3.41 eV) were observed for high height columns [3]. I_{OX} intensity monotonically decreased with decreasing diameter from 260 to 160 nm. Based on these result, the height and the diameter are important parameters to obtain high crystalline GaN nanocolumns.

Acknowledge This work was partly supported by #18K04233 from the Ministry of Education, Culture, Sports, Science and Technology and The Toyota Riken Scholar.

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MBE

Room Max Bell Auditorium - Session MBE-TuM

Bismuth Alloys/Antimonides

Moderators: Richard Mirin, National Institute of Standards and Technology, James Gupta, NRC

8:30am **MBE-TuM-1 MBE Young Investigator Award Talk: Tensile-strained Self-assembly of Quantum Dots for Entangled Photon Sources and Band Structure Engineering***, **Paul Simmonds**,* Boise State University **INVITED**

Since the 1990s, self-assembled quantum dots (QDs) have been the subject of intensive research for technologies ranging from high-stability lasers, to intermediate band solar cells. Driven by compressive strain, semiconductor QDs form spontaneously on the (001) surfaces of III-V and group IV materials. There are however certain applications for which QDs on *non*-(001) surfaces, or QDs under *tensile* rather than compressive strain, are highly desirable. For example, theory predicts that the low fine-structure splitting of (111) QDs should make them ideal entangled photon sources; tensile strain would induce a dramatic reduction in QD band gap, with implications for infrared optoelectronics and nanoscale band structure engineering. However, until recently it has been extremely challenging to synthesize non-(001) or tensile-strained QDs that are free from crystallographic defects.

Since 2010, I have been working on a robust new MBE-based approach to QD self-assembly that overcomes these difficulties, and enables the controllable growth of defect-free, tensile-strained QDs on (111) and (110) surfaces. By engineering a situation where the kinetic barrier to dislocation nucleation and glide is large, we open a window within which tensile strain is instead relieved elastically by 3D self-assembly. Our model predicts this approach will work for any material with a zinc-blende or diamond-cubic crystal structure.

I will describe some different material systems for which we have explored the use of tensile-strained self-assembly to create nanomaterials with novel functionalities. For example, I will discuss the promising properties of tensile-strained (111) QDs for entangled photon emission. I will also present some early results from our quest to transform Ge from an indirect to a direct band gap semiconductor by producing tensile-strained Ge QDs. The effects of tensile strain on QD band structure could impact a wide range of technologies, from highly tunable infrared devices, to quantum media conversion based on light-hole excitons. I am confident that tensile-strained self-assembly represents a powerful, versatile new tool for heterogeneous materials integration, and nanomaterial development.

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9:00am **MBE-TuM-3 Mechanisms of Compositional Inhomogeneities in Bismide Films***, C Tait, B Carter, V Caro, **Joanna Millunchick**,* University of Michigan

III-V semiconductor alloys containing Bi have attracted attention due to their novel properties, including a large reduction of bandgap [1], reduced temperature dependence of the bandgap [2], and an increase in spin orbit-coupling [3] with increasing Bi concentration. It has proven difficult to grow high Bi content films, as droplet formation and compositional inhomogeneities arise during growth. These phenomena are crucial to understand, because such fluctuations can cause carrier localization and degradation of device performance. Kinetic Monte Carlo growth simulations (Fig. 1a.) predict that the highest Bi incorporation rates occur when Ga droplets form on the surface [4]. This is because Bi incorporation requires a high availability of Ga [5]. However, growths exhibiting Ga droplets on the surface result in compositional fluctuations (Fig. 1b). We postulate this effect is caused by local variations in Bi incorporation rates due to the nonuniform Ga availability near the droplet. Indeed, high contrast related to high scattering from Bi on the surface near the droplet is seen in Fig. 1b. It was also observed that droplets led to degradation of film crystallinity, verified with X-Ray diffraction [6]. Growing under a higher As/Ga ratio eliminates Ga droplets, but not necessarily compositional inhomogeneities. Figure 1c. shows the formation of a lateral composition modulation. Nanometer-sized clusters of Bi-enriched GaAsBi also form [7]. Raising the growth temperature can mitigate lateral composition modulation and clustering, but results in lower Bi incorporation. In this talk we will also map out the droplet free-growth conditions to maximize the Bi incorporation and mitigate droplet-induced inhomogeneities.

9:15am **MBE-TuM-4 In-situ UV Irradiation on the Uniformity and Optical Properties of GaAsBi Epi-layers Grown by MBE***, **Daniel Beaton**,* ScientaOmicron

The remarkable tunability of the band gap and spin orbit splitting in III-V alloys with only a small amount of bismuth makes the alloy potentially useful material for many applications. However, it is difficult to synthesize GaAsBi epi-layers with sufficiently high optical quality hampering the technological impact of the material. Spectral linewidths are typically exceedingly broad and band edge emission often suppressed at low temperatures by recombination at low energy states . In-situ UV irradiation of semiconductor alloys has been shown to lead to material quality improvements in the past and we apply it here to the growth of GaAsBi. Samples were irradiated by a pulsed 248nm laser focused to a 7x7mm spot, where rotation during growth results in a uniformly illuminated central region and a periphery that is radiated by a fluctuating fluence. With irradiation GaAsBi was shown to be much improved, where luminescence linewidths as low as 14meV were demonstrated and band edge emission observed to low temperatures.

Using the inherent variation of the fluence across the sample we explore the role of the irradiation. In the central uniformly lit region, steady state growth processes are achieved more quickly, yielding more abrupt interfaces, as well as uniform GaAsBi epi-layers. Comparing photoluminescence spectra at low (6K) temperature shows an increasing density of cluster related emission with decreasing fluence. This is observed in the shift in the peak emission energy away from the band edge, where the peak is shifted most dramatically far from the illuminated region. These results indicate a reduction in clustering of incorporated bismuth atoms with the use of the incident UV irradiation, and additionally the density of clusters may be controlled by the degree of irradiation

9:30am **MBE-TuM-5 Manipulating Film and Underlayer Strain to Understand Composition Modulation in GaAsBi***, **Margaret Stevens**, K Grossklaus, J McElearney, T Vandervelde,* Tufts University

$GaAs_{1-x}Bi_x$ is an interesting optoelectronic material that opens up new band gap and lattice constant possibilities for near-, mid-, and far-IR applications. Although thin films of high Bi content $GaAs_{1-x}Bi_x$ (up to x=0.22 at <50nm [1]) have been grown on GaAs in the literature, it is still difficult to grow high Bi content materials that are thick enough to act as active layers in devices. Additionally, we find that materials grown >30nm phase separate into vertically segregated bands and have periodic Bi content. By lowering the compressive strain or adding tensile strain into our 250nm thick GaAsBi layers, we achieve increased Bi incorporation as well as reduced compositional variations, as demonstrated by TEM and atom probe tomography (APT). In this work, we expand our underlayer study, incorporating underlayers of AlGaAs and lower bismuth composition GaAsBi to decouple strain effects from changes in surface reconstruction and surface composition. We hypothesize that moving from high compressive strain to tensile strain in the epilayer provides a more favorable starting surface for both incorporation of Bi as well as for growing homogenous films.

We grew our layers with a Veeco GENxplor MBE using a valved As_4 cracker and a solid source effusion cell for group III elements and Bi. We measured lattice constants and estimated average bismuth content using 004 and 224 HRXRD scans, alongside spectroscopic ellipsometry to measure the room temperature band gap. We characterized the degree of strain relaxation by examining reciprocal space maps around the 224 asymmetric reflection. We additionally used TEM to identify defect centers and APT to measure bismuth variation along the growth direction. We examined structures of GaAsBi/(underlayer)/GaAs with underlayers of InGaAs, GaAsBi, and AlGaAs. We propose that strain engineering may be applied to increase Bi content in GaAsBi films, allowing for the growth of small band gap optoelectronic devices on GaAs substrates.

[1] R.B. Lewis, M. Masnadi-Shirazi, and T. Tiedje Appl. Phys. Lett.101 082112 (2012)

9:45am **MBE-TuM-6 Long-Wavelength InAs-based Interband Cascade Lasers Grown by MBE***, **James Gupta**, X Wu, G Aers,* National Research Council of Canada, Canada*; Y Li, L Li, W Huang, R Yang,* University of Oklahoma

Interband cascade lasers (ICLs) are becoming a leading semiconductor laser technology for the mid-infrared because of their high efficiency and low power consumption, especially as compared with conventional diode lasers and intersubband quantum cascade lasers (QCLs) in the wavelength range from 3-5 µm. Although a greater effort has been directed towards GaSb-based ICLs in the ~3-5µm range, recent work has highlighted the exciting potential for InAs-based ICLs for reaching longer emission wavelengths.

In this work we report the development of low-threshold InAs-based ICLs with a room-temperature emission wavelength of 6.3µm. The devices were grown on n+-InAs (100) substrates by solid-source molecular beam epitaxy in a custom V90 system using valved crackers for Sb2 and As2. The ICL structures employ an improved waveguide design using intermediate AlAs/AlSb/InAs strain-balanced superlattice cladding layers surrounded by heavily-doped n+-InAs plasmonic claddings. The active region includes 15-stages with AlSb/InAs/In(0.35)Ga(0.65)Sb/InAs/AlSb type-II "W" quantum wells and optimized electron injector doping.

In pulsed mode, broad-area devices lased at 300 K at a lasing wavelength of 6.26 µm and a threshold current density of 395Acm-2 which is the lowest ever reported among semiconductor lasers at similar wavelengths. The broad-area devices lased up to 335K in pulsed mode at a wavelength of 6.45 µm. These results provide strong evidence of the potential for InAs-based ICLs as efficient sources in the mid-IR.

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10:30am **MBE-TuM-9 Atomically Smooth InSb Quantum Wells on GaAs Substrates**, ***Yinqiu Shi***, *E Bergeron, F Sfigakis, J Baugh, Z Wasilewski,* University of Waterloo, Canada

High-quality InSb quantum wells (QW) are one of the most desirable material systems for the top-down approach in realizing Majorana bound states for topological quantum computing. Such QWs are typically grown with AlInSb metamorphic buffers on GaAs substrates. However, as predicted by the BCF theory [1], high-density pyramid-shaped hillocks form on the surface, which may cause spatial modulation in AlInSb barrier composition as well as variations in InSb QW thickness. Suppression of hillocks is thus essential. Here we report a comparative study on the surface morphology with and without InSb QWs on top of AlInSb metamorphic buffers, as a function of substrate offcut angle.

Modulation-doped InSb/AlInSb QWs were grown on edge-exposed 2" GaAs (001) substrates, using a Veeco Gen10 molecular beam epitaxy (MBE) system (Fig.1(a)). At the wafer centre, a large density of hillocks are formed on the surfaces of both the AlInSb metamorphic buffer and the complete InSb QW structure (Fig.1(b),(d)). Their surface morphologies then transition into smooth regions and eventually become rough again, as the polishing-induced effective offcut increases towards the wafer edge (Fig.1(c),(e)). Formation of hillocks is suppressed for effective substrate offcuts at around 0.4~0.5° towards [1̄10] direction on the AlInSb buffer surface, which coincide with the facet angles of the hillock sidewall at the wafer centre, as derived from AFM scans revealing surface atomic steps. With InSb QW overgrown on the buffer, the large hillocks originated from the AlInSb surface are preserved while small hillocks, due to the very thin InSb QW layer, emerge on the large hillock sidewalls at the wafer centre (Fig.1(d)). The steeper sidewalls of these InSb hillocks indicate a larger substrate offcut needed for their complete suppression, as we predicted recently [2]. Indeed, as shown in Fig.1(e), a new morphological transition region is seen, where large AlInSb hillocks are already suppressed while small InSb hillocks persist. With the growth conditions used, an atomically smooth InSb QW surface is found at substrate offcut angles of around 0.5~0.6°. We propose a model to explain the observed morphological transitions.

10:45am **MBE-TuM-10 Narrow Bandgap InAsSb Detector on Digital Alloy AlInSb Metamorphic Buffer**, ***Vinita Dahiya***, *A Kazemi,* The Ohio State University*; E Fraser,* Intelligent Epitaxy Technology, Inc.*; J Deitz, J Boyer, S Lee,* The Ohio State University*; P Pinsukanjana,* Intelligent Epitaxy Technology, Inc.*; T Grassman, S Krishna,* The Ohio State University

Recently, the $InAs_{1-y}Sb_y$ alloy system has emerged as a promising material in the long wave infrared (LWIR, 8-14 µm). However, to target LWIR wavelengths, Sb composition of more than 40% is required, which is relatively difficult to grow due to the non-availability of lattice-matched commercial substrates. This requires the growth of virtual substrates to target the desired lattice constant using, for example, step- or linear-graded metamorphic buffers. However, these structures typically suffer from various complexities, such as long growth interruptions and intricate cell temperature ramp profiles. In our previous work, we demonstrated the application of digital alloy (DA) defined compositions to produce step-graded $Al_{1-x}In_{-x}Sb$ metamorphic buffers, which helps eliminate the issues mentioned above. The buffer layers grown via the DA technique exhibited relaxation behavior similar to conventional bulk, random alloy compositions. In the present work, this effort was further extended to grow subsequent lattice-matched InAsSb absorber layers and nBn detectors.

To enable probing of the material and optical properties, 1.5 µm thick $InAs_{0.55}Sb_{0.45}$ absorber material was grown lattice-matched to an $Al_{0.68}In_{-0.32}Sb$ terminal composition $Al_{1-x}In_{-x}Sb$ DA (1.85 nm period thickness) metamorphic buffer, as described previously [2]. Based on high resolution X-ray diffraction reciprocal space mapping measurements, the absorber layer $InAs_{0.55}Sb_{0.45}$ was found have residual strain of ~0.1%. Electron channeling contrast imaging characterization indicated a low threading dislocation density on the order of 5×10^6 cm^{-2} in the target $InAs_{0.55}Sb_{0.45}$ layer. A photoluminescence peak was observed at ~9 µm at 77K, close to the expected value based on the XRD-derived composition [1].

nBn detector structures were then grown with an undoped 1.5 µm thick $InAs_{0.55}Sb_{0.45}$ absorber and 100 nm thick $Al_{0.68}In_{0.32}Sb$ barrier (Be doped; $1x10^{16}$ cm^{-3}). Single pixel detectors of different sizes were fabricated via standard lithographic techniques. Preliminary spectral response of front side illuminated pixels revealed a 50% cutoff wavelength of 9 µm at 150K. Radiometric characterization of the devices including dark current and quantum efficiency are being undertaken and results will be presented later.

[1] W. L. Sarney et al. , J. Appl. Phys. **122**, 025705, (2017).

[2] V. Dahiya et al., J. Vac. Sci. Technol., B**36**, 02D111(2018).

11:00am **MBE-TuM-11 Molecular Beam Epitaxy of Wide-Bandgap InAlAsSb**, ***Stephanie Tomasulo,*** U.S. Naval Research Laboratory*; M Gonzalez,* Sotera Defense Solutions*; M Lumb,* The George Washington University*; M Twigg, I Vurgaftman, J Meyer, R Walters, M Yakes,* U.S. Naval Research Laboratory

Triple-junction solar cells, lattice-matched to InP, have recently gained interest as an alternative to traditional GaAs-based devices. To maximize efficiency, this design requires a top subcell with bandgap (E_g) of 1.74 eV, thus motivating the development of the widest direct-gap material lattice-matched to InP, $In_xAl_{1-x}As_ySb_{1-y}$. Both the immaturity and mixed group-V nature of this alloy pose significant challenges, requiring in depth investigation. Initial attempts at molecular beam epitaxy (MBE) of $In_xAl_{1-x}As_ySb_{1-y}$ resulted in anomalously low photoluminescence (PL) emission energies, compared with energies extracted from variable angle spectroscopic ellipsometry (referred to as ellipsometry herein). To further investigate the cause of this discrepancy, in this work we have performed a systematic study of the substrate temperature (T_{sub}) and V/III of $In_{0.26}Al_{0.24}As_{0.28}Sb_{0.22}$ (expected E_g=1.64 eV).

We grew seven samples of $In_xAl_{1-x}As_ySb_{1-y}$ (x≈0.26, y≈0.28) on InP by solid source MBE with valved crackers supplying cracked As and Sb. We investigated T_{sub} (measured via bandedge thermometry) ranging from 325 to 455 °C and V/III ratios (beam equivalent pressure) of 16 and 30. Given that the alloy composition varies with T_{sub}, we re-calibrated the group-V fluxes for each growth, using energy extracted from ellipsometry (E=1.69 ± 0.05 eV) and lattice matching (to within 0.1% mismatch) via x-ray diffractometry as our compositional guide. Room temperature PL yielded emission from only four of the seven samples and we again found that it underestimates the energies extracted from ellipsometry. Low-temperature PL will be performed to inform the remaining three samples. Furthermore, we hypothesize that phase separation and clustering is responsible for this behavior and will probe this via power- and temperature-dependent PL measurements and transmission electron microscopy. By quantifying phase separation in this way, we can relate degree of phase separation to growth conditions, guiding us toward the appropriate conditions for $In_xAl_{1-x}As_ySb_{1-y}$ yielding the least phase separation and widest E_g.

11:15am **MBE-TuM-12 Minority Carrier Lifetime and Recombination Dynamics in Strain-Balanced GaInAs/InAsSb Superlattices**, ***Preston T. Webster***, *E Steenbergen, G Ariyawansa, C Reyner,* Air Force Research Laboratory*; J Kim,* Sandia National Laboratories

Strain-balanced InAs/InAsSb superlattices are rapidly emerging as a contending mid-infrared sensing technology as decreasing dark currents lead to ever more sensitive detectors. Dark current can be minimized by increasing the absorption coefficient and utilizing a thinner absorber region, thereby reducing the volume over which dark current is generated. While the InAs/InAsSb superlattice design may be optimized for maximum absorption, there remains great room for improvement by establishing a more favorable strain-balance condition. Specifically, replacing the lightly-tensile InAs layers with more-tensile GaInAs leads to a more symmetric wavefunction overlap profile and correspondingly stronger absorption for the same energy cutoff. The absorption coefficient in GaInAs/InAsSb superlattices improves substantially with Ga content up to 20%.

In this work, two strain-balanced GaInAs/InAsSb superlattices (0% and 20% Ga) designed for maximum absorption at 5 µm wavelength are examined using temperature- and excitation-dependent photoluminescence spectroscopy and time-resolved microwave reflectance. The superlattices are 1 µm thick and doped 4×10^{15} cm^{-3} *n*-type in order to examine the optimal doping density × lifetime product in a potential diffusion-limited detector. The 77 K time-resolved microwave reflectance decays of the 0% and 20% Ga designs are 1.2 µs and 2.1 µs respectively. The photoluminescence is evaluated using a recombination rate model to extract the Shockley-Read-Hall, radiative, and Auger rate constants as a function of temperature, to compare to the temperature-dependent minority carrier lifetimes determined by the time-resolved photoconductivity decay.

11:30am **MBE-TuM-13 Inhibited Hot-Carrier Cooling in InAs/$AlAs_{1-x}Sb_x$ Quantum Wells**, *H Esmaielpour, V Whiteside,* University of Oklahoma*; H Piyathilaka,* West Virginia University*; S Vijeyaragunathan, B Wang,* University of Oklahoma*; E Adcock-Smith, K Roberts,* University of Tulsa*; T Mishima, **Michael Santos**,* University of Oklahoma*; A Bristow,* West Virginia University*; I Sellers,* University of Oklahoma

Semiconductor quantum wells (QWs) have been shown to exhibit decreased hot-carrier thermalization relative to bulk systems. Recently, we proposed that type-II QWs have the potential to further inhibit hot-carrier relaxation via the decoupling of the phonon channels through the spatial separation of photogenerated carriers. The spatial separation increases the radiative lifetime for the hot electrons, and leads to the formation of a robust phonon bottleneck at elevated temperatures. A decoupling of the thermalization coefficient was observed when the system transitioned from efficient type-I radiative recombination at low temperature to less efficient type-II recombination at elevated temperatures.

The multiple-QW structure consists of a 10 nm $AlAs_{0.14}Sb_{0.86}$ barrier followed by 30 repetitions of a 2.4 nm InAs QW and a 10 nm $AlAs_{0.14}Sb_{0.86}$ barrier grown by molecular beam epitaxy on a GaAs (001) substrate. Photoluminescence (PL) measurements at several lattice temperatures were modeled via a generalized Planck radiation law using the carrier temperature as a fitting parameter. The effective temperature of the carriers above the lattice temperature is weakly dependent on the excitation power, but becomes significantly hotter with increasing lattice temperature. When the lattice is at room temperature, the carrier temperature is 490K. Carrier lifetimes were determined by THz time-domain spectroscopy, which measures the AC photocurrent as a function of delay time between a near-infrared pump pulse and a THz probe pulse. Inspection of the three decay contributions reveals that the mechanism for the fast component (~0.01 ns) is different than for the intermediate and slow components. The fast decay is attributed to direct recombination within the QW, due to transitions from the electron ground state to localized hole states arising from alloy fluctuations. The intermediate (~0.3 ns) and slow (~2 ns) decay times, which dominate at high temperatures, are due to a two-step decay process between the same sets of initial and final states. These competing faster and slower components are attributed to the redistribution of photogenerated holes and the degeneracy of the valence band at elevated temperatures. This leads to competition and the convolution of the PL from multiple confined hole states and the ground state electrons. Confirmation of the long-lived nature of the photogenerated electrons in the InAs QWs supports the notion that the carriers in the QW facilitate a phonon bottleneck.

11:45am **MBE-TuM-14 Observation of Interface Electronic States from InAs/GaSb Multi Quantum Wells Grown by Molecular Beam Epitaxy**, *S Alyamani, **Jong Su Kim**, J Shin,* Yeungnam University, Korea*; S Lee, J Kim,* Korea Research Institute of Standards and Science, Korea*; S Lee, V Dahiya, S Krishna,* The Ohio State University

We have investigated optical transitions in the InAs/GaSb multiple quantum wells (MQWs) by photoreflectance (PR) and photoluminescence (PL) spectroscopy with various temperatures and excitation intensities. PR measurements were performed using a 405 nm laser diode as an excitation source. The probe beam obtained from a tungsten-halogen lamp dispersed through a monochromator. The reflected beam was collected by using a Si (400 ~ 1100 nm: high energy region) and InGaAs (1200 ~ 2400 nm: low energy region) photodiodes. The PR was employed to investigate the inter-band transitions such band-to-band (E_{GaSb}), spin-orbit split off (Δ_0), E_1 and Δ_1 of GaSb [1] as well as their interface quantum states (IQS).

Fig. 1(a) and (b) show the room temperature PR spectra at near band transition and above band transition for InAs/GaSb (5 ML/50 nm) MQW, respectively. PR spectra of the InAs/GaSb MQWs showed the E_{GaSb}, the Franz-Keldysh oscillation (FKO) and IQS. We confirmed the transition energies from 0.72 eV, 1.52 eV, 2.07 eV and 2.53 eV corresponding to the E_{GaSb}, $E_{GaSb}+\Delta_0$, E_1 and $E_1+\Delta_1$, respectively. Moreover, at room temperature PR spectrum, we observed sharp transition features due to the IQSs from the interface of InAs/GaSb. At near 1.2 eV region, we found unidentified transitions (UIS) and which were investigated by excitation intensity and temperature dependent PR. At low temperature PR and PL results, we found the QS transition between confined electrons states in InAs QW and GaSb valence band at energy of 0.506 eV as shown in Fig. 2

MBE
Room Max Bell Auditorium - Session MBE-TuA
Solar Cells

Moderator: Paul Simmonds, Boise State University

1:30pm **MBE-TuA-1 Smart Stacked InGaP/GaAs/GaAs//Si Quadruple-Junction Solar Cells Grown using Molecular Beam Epitaxy*, Takeyoshi Sugaya,*** National Institute of Advanced Industrial Science and Technology (AIST), Japan

InGaP(1.9 eV)/GaAs(1.42 eV) on Si(1.1 eV) multijunction solar cells have been studied to realize low-cost and high-efficiency solar cells [1]. However, the current matching is not appropriate in this material system because the current generated in a Si subcell is smaller than that generated in InGaP and GaAs subcells. Therefore, a triple-junction top cell on a Si bottom cell configuration is suitable for obtaining the current matching among connected subcells. Although we demonstrated InGaAsP and AlGaAs second (1.7 eV) cells in the triple-junction top cells, InGaAsP cells were difficult to grow and AlGaAs cells exhibited poor performance when they were grown using molecular beam epitaxy (MBE) [2]. In this paper, we demonstrated an InGaP/GaAs/GaAs triple-junction solar cell grown using MBE to use as a top cell in a Si-based quadruple-junction solar cell.

The sample structure is shown in Fig. 1. A MBE-grown InGaP/GaAs/GaAs top cell was stacked to a Si bottom cell by smart stack technology which is a new semiconductor bonding technique using conductive nanoparticle alignments [3]. Figure 2 shows a *J-V* curve of a quadruple-junction solar cell. An efficiency of 18.5% with a high V_{oc} of 3.3V was obtained in InGaP/GaAs/GaAs//Si multijunction solar cells. External quantum efficiency (EQE) spectra of the solar cell are shown in Fig. 3. The highest and lowest current densities were generated by the first InGaP and second GaAs cells, respectively. The $J_{sc}$of 7.4 mA/cm^2 shown in Fig. 2 was in good agreement with the value estimated from the EQE measurements, which was limited by the second GaAs cell. This can be improved by reducing the absorption layer thickness of the first InGaP cell. In the presentation, we will discuss the role of substrate miscut on the properties of InGaP top cells.

[1] R. Cariou *et al*., IEEE J. Photovoltaics 7, 367 (2017).

[2] T. Sugaya *et al*., J. Vac. Sci. Technol. B 35, 02B103 (2017).

[3] H. Mizuno *et al*., Appl. Phys. Lett. 101, 191111(2012).

1:45pm **MBE-TuA-2 2.0 – 2.2 eV AlGaInP Solar Cells Grown by MBE*, Yukun Sun,*** Yale University*; S Fan,* University of Illinois Urbana-Champaign*; J Faucher,* Yale University*; B Li, M Lee,* University of Illinois Urbana-Champaign

$(Al_xGa_{1-x})_{0.51}In_{0.49}P$ (AlGaInP), with a tunable bandgap energy (E_g) of 1.9 – 2.2 eV, is an ideal top cell material for high-efficiency multi-junction (MJ) solar cells with 5 – 6 junctions. However, AlGaInP growth is challenging by both molecular beam epitaxy (MBE) and metalorganic vapor phase epitaxy (MOVPE) due to O-related defects. Recent work has shown that the performance of MOVPE-grown AlGaInP solar cells can be greatly improved by growth at very high temperatures of ~740 – 780 °C [1]. However, the MBE growth temperature of AlGaInP is typically restricted to < 500 °C, making post-growth annealing a crucial step to improve material quality [2]. In this work, we report on MBE-grown 2.0 – 2.2 eV AlGaInP solar cells, as well as effects of rapid thermal annealing (RTA). All aspects of cell performance were improved by RTA, though the enhancement diminished at the highest E_g and Al content. A 14.3% efficiency (η) was achieved in an anti-reflection-coated (ARC) 2.0 eV AlGaInP solar cell, closely matching record cells grown by MOVPE.

Cells with E_g = 2.02, 2.09, and 2.19 eV were grown by solid-source MBE at substrate temperatures of ~480 °C and V/III ratios of 10 – 15, while RTA was conducted at ~700 – 800 °C prior to device fabrication.

RTA led to improvements in internal quantum efficiency (IQE) for all cells, though the gain was most pronounced in the 2.02 eV AlGaInP. Short-circuit current density (J_{SC}) was accordingly boosted. V_{OC} also increased, together with a dark current reduction of 3 – 4 x. The boosts in J_{SC}, V_{OC}, and efficiency show that RTA substantially improves the minority carrier lifetime and diffusion length in AlGaInP. An efficiency of 14.3% was achieved in the 2.02 eV AlGaInP cell after RTA with ARC, closely matching the record set by MOVPE.

[1] Perl, E. E., et al. *J. Photovolt.* 6.3 (2016): 770-776.

[2] Faucher, J., et al. *Appl. Phys. Lett.* 109.17 (2016): 172105.

2:00pm **MBE-TuA-3 Optoelectronic Analysis of MBE Grown Symmetric and Asymmetric 1 eV Dilute Nitride Quantum Well Solar Cells*, Khim Kharel,*** *M Fitchette,* University of Houston*; K Shervin,* Alta Device*; W Wang,* First Solar Cell*; A Freundlich,* University of Houston

In order to minimize the effects of the degraded minority carrier transport properties of bulk dilute nitride GaAs, we have demonstrated that by incorporating MBE grown symmetric or asymmetric (i.e. resonantly coupled) dilute-nitride-GaAsN/GaAs multiple quantum wells (MQW's) into the intrinsic region of a p-i-n GaAs photovoltaic device (see figure 1) enables a significant sub-GaAs-bandgap photocurrent generation while maintaining a high open-circuit voltage (V_{oc}) [1]. In fact, for the case of a 1 eV resonantly coupled MQW cell, the V_{oc} (the figure of merit for the performance of a solar cell) showed a record-setting performance approaching the near ideal radiative limit (i.e. W_{oc}=Eg-V_{oc} ~ 0.4 V) [2].

To gain a better understanding of the photo-generated carrier escape and recombination mechanisms for these MQW devices, we examine their optical and electrical properties using the following characterization techniques: temperature dependent photoluminescence spectroscopy (PL), modulated photo-reflectance spectroscopy (PR), photo-current spectroscopy (i.e. the spectral response-SR or External Quantum Efficiency-EQE) under different applied bias and temperatures), and the temperature dependence current-voltage (IV) while the cell is under either dark or illuminated conditions.

The bias-dependent EQE analysis, performed at room temperature, shows 30X faster carrier escape times for the RTT devices than those of the conventional MQWs cell (0.2 ns and 6.38 ns, respectively). Similarly, the activation energies (which correspond to the effective barrier to electron extraction from the QW's) were determined from temperature dependence PL measurements are significantly lower (35meV and 75meV) than those of the conventional periodic MQWs cell (269meV); this contributes to the improvement in the carrier extraction for the RTT structure. The temperature dependent analysis enabled us to modulate and even freeze out the carrier thermalization phenomena. While the simultaneous measurement of the photogenerated current (SR) and radiative recombination (PL), as a function of the applied load (bias), enabled us to probe the correlation between the evolution of I-V characteristics and the physics at play. Finally, the electronic temperature of the photo-generated minority carriers' was extracted from the measured PL intensities which show a significantly high and unusual carrier temperature for a given lattice temperature; and this suggests the presence of a significant hot carrier effect.

1) D. Dang, G. Vijaya, A. Mehrotra, A. Freundlich, & D. J. Smith, JVST B. 34 (2016)

2) S. Shervin, W. Wang, K. Kharel, M. Fitchette & A. Freundlich, 33rd NAMBE, 2017, Galveston, TX

2:15pm **MBE-TuA-4 Reflections on NAMBE and MBE*, Charles Tu,*** University of California - San Diego **INVITED**

MBE

Room Max Bell Auditorium - Session MBE-WeM

II-VI Materials and Heterovalent Growth/Topological Insulators and Quantum Computing

Moderators: Philip Poole, NRC, Michael Santos, University of Oklahoma

8:30am **MBE-WeM-1 High-Reflectivity Heterovalent Distributed Bragg Reflectors for Infrared Resonant Cavity Applications***, **Maxwell Lassise**, B Tracy, D Smith, Y Zhang,* Arizona State University

Monolithically integrated midwave infrared optoelectronic devices such as VCSELs, resonant-cavity LEDs and photodetectors are highly desirable for chemical sensing and environmental monitoring applications. One of the key components of these devices is the highly-reflective distributed Bragg reflector (DBR), which is comprised of a stack of alternating layers with different refractive indices designed to reflect a particular range of wavelengths. In this study, we first focus on ZnTe/GaSb DBRs, which have a high refractive index contrast ($\Delta n \approx 1$ for infrared wavelengths), similar lattice constants (lattice mismatch < 0.1%), and are epitaxially integrable with infrared absorber materials like InAs/InAsSb, GaSb/InGaSb, InAsSbBi, and PbSe. Several DBR samples were grown using a single-chamber MBE system equipped with both II-VI and III-V source materials. The grown structures demonstrate sharp interfaces and minimal interdiffusion between the heterovalent layers, as evidenced by TEM and XRD.

The measured and simulated reflectance for the ZnTe/GaSb DBRs have a peak reflection value of approximately 98 % and a stopband width of about 70 meV centered on a wavelength of 4.5 µm for a 6 pair structure. Fabry-Pérot cavities based on the DBRs are investigated to determine the viability of these structures for resonant-cavity devices. The reflectance spectra and minimum absorption levels of the DBR structures have been modeled using the transfer matrix formalism for a variety of material combinations lattice-matched to III-V substrates. Below-band gap losses such as free carrier absorption are calculated for short, mid, and longwave IR heterovalent DBR structures and compared with corresponding III-V DBRs. Additionally, the optical properties of resonant-cavity structures based on the heterovalent DBRs are simulated and the potential device characteristics, such as the cavity Q-factor, are compared for a range of cavity materials and operational wavelengths. Other lattice-matched heterovalent material combinations, such as ZnSe/GaAs and CdTe/InSb, are also under exploration for shortwave to longwave IR DBRs.

8:45am **MBE-WeM-2 Photoluminescence Characterization of a 1 ML CdSe Fully-Strained Ultra-Thin Quantum Well with very Thin ZnSe Barriers***, A Alfaro-Martínez,* DNyN, CINVESTAV, Mexico*; F Sutara, **Isaac Hernández-Calderón**,* CINVESTAV, Mexico

In fully strained CdSe/ZnSe ultra-thin quantum wells (UTQWs) grown on GaAs (001) substrates, both ZnSe and CdSe are under biaxial compressive stress. The critical thickness under these strains is around 90 nm for ZnSe and around 3.5 monolayers (1.2 nm) for CdSe. The physical properties of the 1 ML CdSe UTQW still deserve a detailed explanation and interpretation regarding its high excitonic emission intensity, full width at half maximum (FWHM) and peak energy [1]. Here, we present a study of a nominal 1 ML CdSe UTQW grown by atomic layer epitaxy at 275 °C within a ZnSe barriers of 20 nm and 25 nm (cap layer). The thickness of each layer and the total thickness of the heterostructure are chosen in such a way that each material is below its critical thickness. The 19 K photoluminescence spectrum presents an intense excitonic peak at 2.685 eV with a FWHM of 12.3 meV, which is lower than previous results of CdSe UTQWs grown on relaxed ZnSe barriers [2]. The evolution of the excitonic peak as a function of temperature suggests the absence of QW potential fluctuations, which in this case would correspond to composition fluctuations or to the formation of quantum islands. Since the actual CdSe coverage depends on growth temperature, the coverage of the studied structure is expected to be slightly lower than 1 ML. The results will be discussed and explained in terms of two different descriptions: a 1 ML $Zn_{1-x}Cd_xSe$ UTQW with very low Zn content, and large area 1 ML thick CdSe islands.

[1] See, for example, T. V. Shubina, G. Pozina, A. A. Toropov, Phys. Status Solidi B254, 1600414 (2017).

[2] I. Hernández-Calderón, AIP Conf. Proc. 809, 343 (2006).

9:00am **MBE-WeM-3 Hybrid II-VI/III-V Infrared Photodetectors***, **Marcel Claro**,* City College of New York, City University of New York*; Y Kaya,* Princeton University*; T Garcia, C Forrester, V Deligiannakis,* City College of New York, City University of New York*; C Gmachl,* Princeton University*; M Tamargo,* City College of New York, City University of New York

Despite the huge success of intersubband infrared devices based on III-V semiconductors in the past few decades, namely quantum cascade lasers (QCLs) and detectors (QCDs), and the quantum well infrared photodetectors (QWIPs), the fabrication of multi-band device is still a challenge. In the GaAs/AlAs and InGaAs/AlInAs/InP material systems, the material properties are not the optimum to cover the entire infrared (IR) range. Recently, QWIPs and QCDs working from 4 to 10µm were shown using ZnCdSe/ZnCdMgSe II-VI materials, and they have particularly high-detectivity in the short wavelength IR range, wherein the intersubband III-V devices lack in performance.

Aiming for a high-detectivity multi-band photodetector, we grew several structures consisting of a ZnCdSe/ZnCdMgSe QCD, designed to have peak responsivity at 5µm, stacked on top of an InGaAs/AlInAs QCD, designed to have peak responsivity at 8µm. They were grown lattice matched to InP (100) substrates. The practical integration of two devices made from these two materials in a single chip has not been yet demonstrated, and would increase the materials landscape for the design of novel advanced devices.

High-Resolution X-Ray Diffraction (HR-XRD) and Photoluminescence (PL) measurements of the hybrid structures confirm the high quality of the two materials components. Full device characterization was made on the device stack using top and bottom contacts, which means the II-VI and III-V components are connected in series, as well as using the middle contact to measure each device separately. The same characterization was performed on individual III-V and II-VI QCD devices with the same design as the hybrid. The results show that II-VI QCD devices have a much higher resistance, R_0, and higher responsivity than III-V QCD devices, and typically dominate in the hybrid responsivity spectrum. The comparison between the III-V in the hybrid stack and the pure III-V device indicates that the presence of an InGaAs/ZnCdSe interface may affect negatively the III-V device performance. Additionally, etching away of the II-VI layers in a hybrid device has also shown greatly improved performance of the underlying III-V device. Several causes are being investigated, such as built-in electric field and deep defects due to elements inter diffusion at the II-VI/III-V interface, or optical interference of the two different device structures.

The effects of modifying the interfacial layer on the hybrid devices are explored. Different device geometries are also explored to identify electrical and optical characteristics of the materials that may affect device performance.

9:15am **MBE-WeM-4 Cd_3As_2/II-VI Heterostructures on (111) GaAs***, **Anthony Rice**, K Park, K Alberi,* National Renewable Energy Laboratory

Cd_3As_2 is an exciting material system. As a Dirac semimetal, it is a 3-D analogue of graphene [1] and provides access to a variety of interesting physics, ranging from massless Dirac fermions to topological superconductivity. It also exhibits very high electron mobility and large phonon-phonon scattering, which are ideal for a number of energy-related applications. While interest in Cd_3As_2 has recently risen, most work to date has been confined to bulk single crystals rather than thin films. Epitaxial growth on foreign substrates would allow strain and heterostructure engineering as well as permit careful studies of doping and confinement. Molecular beam epitaxy of Cd_3As_2 has been carried out primarily on GaSb (111) layers grown on GaAs (111) substrates (-3.5% mismatch) [2] and directly on CdTe(111)B substrates (2.3% mismatch) [3]. Both take advantage of the preferred (112) growth surface of Cd_3As_2. However, no efforts to further improve lattice matching have been reported to date.

Building off of previous work of improved GaAs(001)/ZnSe(001) interfaces [4], growth of II-VI compounds on (111) GaAs is explored both as a route toward improved growth surfaces as well as integration into heterostructures. $Cd{-_3}As_2$ epilayers were first grown on CdTe/ZnTe buffers on GaAs (111) substrates. The resulting Cd_3As_2 layers grown on these structures showed comparable carrier/mobility relationships and improved RMS roughness to materials in previous reports, as shown in fig. 1. Alloyed $Cd_xZn_{1-x}Te$ (111) layers were then developed to explore lattice-matched growth as well as systematic strain effects (fig. 2). Effects of light stimulation during growth will also be discussed.

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[2] T. Schumann *et al.,* APL Mater. **4**, 126110 (2016)

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9:30am **MBE-WeM-5 Demonstration of the Growth of ZnCdTe/ZnTe Quantum Wells with Variable Composition by Submonolayer Pulsed Beam Epitaxy (SPBE)**, *F Sutara, **Isaac Hernández-Calderón,*** CINVESTAV, Mexico

The growth of specifically designed semiconductor heterostructures very often requires the growth of several quantum wells (QWs) with different alloy compositions. In the case of molecular beam epitaxy (MBE) and related techniques, the modification of the alloy composition is obtained by the change of the cell temperatures. Then, the growth process is interrupted to allow the modification of the growth parameters for each QW and the deposition process is restarted when the growth conditions reach stability. If many layers with different composition are required, the complexity and duration of the growth process becomes impractical. Submonolayer pulsed beam epitaxy (SPBE) has been employed to overcome those difficulties for the growth of ZnCdSe QWs [1]. SPBE allows the modification of the ternary alloy composition in real-time, without interruption of the growth process and without modification of the cell fluxes. SPBE is based on the pulsed supply of the reactant species and on the self-regulated process of the surface saturation, leading to a layer-by-layer growth mode with precise thickness control. Here, we demonstrate the successful application of SPBE to the growth of a single heterostructure containing three $Zn_{1-x}Cd_xTe$/ZnTe QWs with different composition, each 8 monolayers (MLs) thick; the QWs were grown on a GaAs (001) substrate at ~ 275 °C. All ZnTe layers were grown by MBE. The photoluminescence (PL) spectrum of the heterostructure acquired at 20 K exhibits three well defined emissions confirming the different composition of each ZnCdTe QW. A detailed explanation of the growth process and its advantages will be explained.

[1] I. Hernández-Calderón, “Epitaxial growth of thin films and quantum structures of II-VI visible-bandgap semiconductors,” in Molecular Beam Epitaxy: From Research to Mass Production, edited by M. Henini (Elsevier, Oxford, 2013), pp. 310–346.

9:45am **MBE-WeM-6 Interface Modification in Type-II ZnCdSe/Zn(Cd)Te QDs**, ***Vasilios Deligiannakis**, S Dhomkar, M Claro,* 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) have been proposed as a possible solution to overcoming the Shockley-Queisser limit [1] for solar cell quantum efficiencies. In these, a mid-gap energy band is formed, for instance, by quantum dots within a large bandgap semiconductor matrix. Type-II ZnCdSe/Zn(Cd)Te submonolayer (QDs) have been explored by our group for their promising properties as IBSCs [2, 3]. The ZnCdSe host material when latticed matched to InP has an energy bandgap of ~ 2.1 eV in which the Zn(Cd)Te QDs can form an intermediate band with an energy between 0.5 - 0.7 eV [3]. The similarity of these parameters with those required for an optimal IBSC makes this material system an outstanding candidate. However, challenges arise during the growth of these materials due to the lack of a common anion, resulting in formation of an unintentional ZnSe interfacial layer (IL) between the ZnCdSe spacer and the QDs, causing high tensile strain in the structure. Here we report the results of several modified growth sequences that modify and suppress the IL, allowing for the host material and QDs to be both simultaneously lattice matched.

Samples were grown by a combination of MBE and migration enhanced epitaxy (MEE) in which sub-monolayer dot formation was achieved by exposure of the sample surface to alternating Zn, Cd and Te fluxes. By incorporating a modified shutter sequence (Fig 1b inset) with a Cd-only exposure between the growth of the spacer layer and the MEE cycles, significant suppression of the ZnSe tensile layer was achieved. The HR-XRD (Fig 1a) of two samples with different shutter sequences shows that the sample with the modified shutter sequence (sample A) has nearly lattice matched ZnCdSe spacers, as well as the zero-order peak of the QD superlattice [SL(0)], while the previously adopted shutter sequence required a strain compensated ZnCdSe spacer (sample B). The type II nature of the band structure for sample A is confirmed by the intensity dependent blue shift of the PL peak (Fig 1b). Further adjustments to the band structure were obtained by modifying the QD composition.

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[3] M. Imperato, e al. *Journal of Electronic Materials* (2018). 10.1007/s11664-018-6241-6

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10:30am **MBE-WeM-9 Molecular Beam Epitaxy Growth of Near Surface InAs Two-dimensional Electron Gas for Topological Quantum Computation**, ***Candice Thomas**, A Hatke, M Capano, T Wang, R Diaz, S Gronin, G Gardner, M MANFRA,* Purdue University

Hybrid superconductor-semiconductor heterostructures subjected to an in-plane magnetic field have experimentally demonstrated their potential to host non-abelian Majorana Zero Modes (MZMs) in both bottom-up nanowires [1] and recently with two-dimensional electron gas (2DEG) [2], the latter allowing scalable top-down fabrication of more and more complex devices. Specifically, MZMs have been observed with InAs 2DEG grown on InP (100) substrates. However, the large lattice mismatch (3.3%) between these two materials result in threading dislocations and surface roughness that play a prominent role in electronic transport by introducing disorder.

To address this issue, we consider the molecular beam epitaxy (MBE) growth of InAs 2DEG on quasi-lattice matched GaSb (100) substrates (lattice mismatch of -0.6%). As GaSb is not perfectly insulating, the growth of a high bandgap and lattice matched buffer of AlGaSbAs is utilized and allows an isolation between device mesas of the order of the GΩ, as required for density of state measurements in the tunneling regime. The As/Sb incorporation ratio and thus the lattice matching of this quaternary compound are mostly tuned by the substrate temperature. By growing 20 nm deep InAs quantum well on top of 800 nm-thick AlGaSbAs buffer, 2DEG with carrier mobility larger than $2x10^6$ cm^2/Vs for a density of about $6x10^{11}$ cm^{-2} is achieved.

The MBE growth development of these heterostructures will be reported relying on structural and electrical characterizations. Moreover, we will present our efforts to transform these semiconductor structures into a topological quantum computing platform. This will include optimization of the heterostructure design through the implementation of an in-situ back gate.

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10:45am **MBE-WeM-10 InAs Surface 2DEG and Interface Characterization of InAs/Al Structures Using Josephson Junctions**, ***Kaushini Wickramasinghe**, W Mayer, J Yuan, K Sardashti, J Shabani,* New York University

Surface InAs quantum wells have become the focus of renewed theoretical and experimental attention partly because of their potential applications in topological[1] and superconducting quantum computation [2,3]. These applications require epitaxial contacts to superconductors with high transparency, tunable proximity effect, and coupling of the two-dimensional electron gas (2DEG) and superconductor. Thus it is really important to study the properties of 2DEGs at the surface and details of structural properties of interface between the Al and InAs.

In our work we study the quality of the InAs/Al interface using transport measurements. Quality of transparency is reflected in the supercurrent and induced gap through the Josephson junction. The product of the critical current (I_C) and the normal state resistance (R_n) is used to characterize Josephson junction properties. We compare the product of IcRn for variety of MBE grown InAs/Al wafers with different mobility, mean free path, interface barriers, and density. Currently we have reached IcRn = 374 µV approaching ideal case for ballistic short junctions. We discuss our data within known theoretical models and identify crucial material properties that influence the proximity effect and transparency between superconductors and semiconductors.

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11:00am **MBE-WeM-11 Epitaxial Growth of Superconducting Thin Aluminum Films on InAs for Topological Quantum Computing**, ***Geoffrey Gardner,*** Microsoft Research; *C Thomas, T Wang,* Purdue University; *S Gronin,* Microsoft Research; *M Capano, M MANFRA,* Purdue University

MBE grown material based upon hybrid semiconductor-superconductor has generated a lot of interest recently due to the possibility that it allows for the emergence of Majorana Zero Modes (MZM) which may offer topological protection for quantum computing. [1]

Relevant material platforms for MZM based devices include semiconductors with high spin-orbit coupling such as InAs on GaSb, and InAs on InP which are coupled to a s-wave superconductor that shows 2e periodicity in a closed system. Thin aluminum films, ~7nm, meet these requirements and have been shown to have a high critical in-plane magnetic field. Additionally, the aluminum has remarkable epitaxial relationship with InAs allowing for atomic ordering of Al (111) parallel to InAs (100). [2]

The growth of thin epitaxial aluminum is extremely sensitive to temperature. Deposition at T>0°C causes many grains to form or the film to ball up. Depositing thin Al films at T~77°K shows good morphology but not the requisite crystallinity. Thin films, <10nm, deposited within the good temperature window show structure which matches the semiconductor and has two distinct in-plane orientations, both (111) in plane (Fig. 1). This Al-InAs hybrid system shows an induced gap >200μeV. Here we present optimization and characterization of superconducting Al layers on MZM devices.

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11:15am **MBE-WeM-12 Morphological Control Over $(Bi_xIn_{1-x})_2Se_3$ Grown on GaAs**, ***Theresa Ginley**, S Law,* University of Delaware

Bismuth chalcogenides, such as Bi_2Se_3 , have become increasingly popular materials to study as prototypical topological insulators (Tis). TI materials have a bulk band gap crossed by linear surface states that form a graphene-like Dirac cone. Plasmons excited in the TI surfaces states have been demonstrated to have exceptionally large mode indices and relatively long plasmon lifetimes[1], making them ideal candidates for sensing and waveguiding applications in the difficult-to-access THz regime. Bi_2Se_3 can be grown by van der Waals (vdW) epitaxy on a variety of substrates, yet previous studies have shown that film quality is limited by a disordered layer between the substrate and the film, leading to large trivial carrier densities and low mobility[2]. $(Bi_{1-x}In_x)_2Se_3$ (BIS) is an ideal material to use as a buffer layer as it shares the crystal structure, lattice constant, and vdW bonding of Bi_2Se_3 but is a trivial band insulator for x>0.3. Major improvements in sheet density and mobility have already been reported for films grown using BIS buffer layers as compared to growths directly on sapphire[3], indicating that the Fermi energy is within the bulk band gap.

We are interested in growing Bi_2Se_3 films with BIS buffers on GaAs substrates to integrate TI materials with semiconductor optoelectronic structures. We find that the morphology for BIS grown on GaAs(001) is strongly dependent on selenium overpressure. At lower selenium fluxes rectangular needles form (Sample A), while at high selenium fluxes terraced hexagonal features are present (Sample C), as shown in the scanning electron microscopy images in Figure 1. All features are aligned along the (011) plane of the GaAs. At intermediate selenium fluxes (Sample B), the film is ultra-smooth. This is significant, because growth of Tis and related materials on sapphire usually exhibit spiral growth with either triangular or hexagonal domains, especially at these relatively large thicknesses (50nm). An ultra-smooth BIS buffer layer improves the quality of overgrown Bi_2Se_3. From x-ray diffraction measurements, we suspect that the hexagonal features seen at high selenium fluxes are self-assembled Bi_2Se_3 nanostructures. By tuning the BIS growth conditions, we can exercise substantial control over the film morphology, despite the use of vdW epitaxy. Control over the buffer morphology will ultimately pave the way for unique TI devices.

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11:30am **MBE-WeM-13 Dielectric Functions of MBE-grown $Bi_2(Te_{1-x}Se_x)_3$ Thin Films**, *E Holmgren, J Lyons,* ***Frank Peiris,*** Kenyon College*; X Li, X Liu, M Dobrowolska, J Furdyna,* University of Notre Dame

Using spectroscopic ellipsometry, the dielectric functions of a series of topological insulators, including Bi_2Te_3, Bi_2Se_3 and their ternary alloys, were determined. The topological insulator-thin films were grown on GaAs substrates using a dual-chamber Riber 32 solid-source MBE system. The ellipsometry measurements were obtained using an IR-spectroscopic ellipsom eter, spanning a spectral range between 2000 nm to 35,000 nm. A standard inversion technique was used to model the ellipsometry spectra, which produced the dielectric functions of each of the topological insulator-films. These dielectric functions were analyzed further to obtain characteristics such as their bad gap and carrier concentration. Specifically, Kramers-Kronig-consistent oscillators were used to represent the Drude contribution as well as the energy gap. We found that the band gap blue shifts as the concentration of *Se* increases in the ternary compound. More importantly, best fits for experimental spectra were obtained when an anisotropy was introduced in the dielectric functions of the topological insulators. Furthermore, the model allowed us to calculate the anisotropy of the effective mass, suggesting that there is roughly a factor of four difference between the *xy* and *z*-axis effective masses.

11:45am **MBE-WeM-14 MBE Growth and Properties of Bi_2Se_3/Sb_2Te_3 p-n-p-n Short-period Superlattices**, ***Ido Levy**, T Garcia, H Deng, S Alsheimer, L Krusin-Elbaum, M Tamargo,* City College of New York, City University of New York

We present the growth and properties of Bi_2Se_3/Sb_2Te_3 short-period superlattices and investigate the transport of carriers of the bulk and surfaces of this material. Surface roughness between 1 and 3nm was measured. For each sample we extract the average composition from the HR-XRD zero order superlattice peak and the period from the superlattice fringes. The field dependent hall resistance changes from n-type to p-type with the transition occurring at an effective composition ~42% Bi_2Se_3. A weak anti-localization cusp in the magnetoresistance suggests the preservation of topological surface states. These results indicate this is an excellent system for further study.

MBE

Room Max Bell Auditorium - Session MBE-WeA

Quantum Dots/Growth and Heterogeneous Integration on Si, Ge

Moderators: Shanthi Iyer, North Carolina A&T State University, Preston T. Webster, Air Force Research Laboratory

1:30pm **MBE-WeA-1 96 GHz Colliding Pulse Mode-locked Quantum Dot Lasers Grown on Silicon**, ***Justin Norman***, *S Liu, D Jung, M Kennedy, A Gossard, J Bowers,* University of California, Santa Barbara

Needed increases in internet bandwidth require developing chip-scale photonic interconnects to displace electronics. The silicon photonics platform is favorable for photonic integration due to silicon's mature manufacturing techniques and large substrates. In recent years, quantum dot (QD) lasers have proven themselves as ideal candidates for epitaxial integration with the silicon photonics platform due to their defect tolerance which results in low threshold currents and long device lifetime [1,2]. Here, we report the first QD colliding pulse mode-locked lasers (MLLs) grown on Si. The tunable gain bandwidth and ultrafast recovery of QDs makes them ideal for MLLs with narrow, high repetition rate pulses and wide bandwidth frequency combs for dense wavelength division multiplexed data transmission.

Samples were grown on a defect free, pseudomorphic 45 nm GaP on Si template from $NAsP_{III/V}$, GmbH. An optimized buffer (Fig. 1(a)) consisting of a low temperature GaAs nucleation layer, thermal cycling, and InGaAs filter layers was utilized to achieve a dislocation density of 6×10^7 cm^{-2} (Fig. 1(b)). Quantum dot lasers were then grown with AlGaAs cladding and five periods of p-modulation doped InAs QDs in InGaAs quantum wells. The QDs were grown at 485°C and V/III ratio of 35 with nominal InAs deposition of 2.55 ML. These conditions yield dot densities ~6×10^{10} cm^{-2} and photoluminescence full-width at half-maximum of 30 meV. Standard dry etching and metal deposition techniques were used to fabricate the lasers. Mode-locking was observed with 96 GHz repetition frequency and 2 ps pulsewidth. The continuous wave light output curve, mode-locked optical spectrum, and corresponding autocorrelation trace are shown in Fig. 2.

1:45pm **MBE-WeA-2 InAs/GaAs Submonolayer (SML) Quantum Dot-based Semiconductor Saturable Absorber Mirrors (SESAMs)**, ***Sadhvikas Addamane***, University of New Mexico; *A Laurain, J Moloney,* University of Arizona; *G Balakrishnan,* University of New Mexico

Semiconductor saturable absorber mirrors (SESAMs) have been used in recent years, with considerable success, for passively modelocking both semiconductor and solid-state lasers. Most state-of-the-art SESAMs around the 1µm wavelength range employ a quantum well (QW)-based absorber which has enabled stable modelocking in the picosecond and femtosecond regime. Recently, there has been substantial interest in studying SESAMs using quantum dot (QD) absorbers in order to exploit their advantages over QWs: atom-like density of states, variation in dot sizes and control over areal density. Around the 1µm wavelength range, using traditional Stranski-Krastonov QDs would require using an AlGaAs matrix which reduces the optical confinement factor. An alternative active component is submonolayer (SML) QDs that combine high excitonic gain and fast gain recovery (characteristic features of QDs) with the high modal gain of QWs. This work focuses on exploring the use of InAs/GaAs submonolayer (SML) QDots as absorbers in SESAMs.

The samples analyzed in this study are grown using molecular beam epitaxy (MBE) on epi-ready GaAs (100) substrates. The 1030nm SESAM structure consists of a 29 quarter-wave GaAs/AlAs pairs distributed bragg reflector (DBR) and an absorber region (QW or QD) sandwiched between GaAs spacer and cap layers. The SML QD absorber is formed by stacking 0.5ML/2.3ML of InAs/GaAs. The DBRs and absorber regions are calibrated to ensure that the reflectivity stopband and photoluminescence spectra are respectively centered at 1030nm at operating temperature and incidence angle. As part of this work, both QW and SML QD-based SESAMs are grown, comprehensively characterized and their device performances are compared. These SESAMs are characterized for reflectivity, temperature-dependence, dispersion control and lifetimes (both carrier and device) and are tested in a Vertical Cavity Surface Emitting Laser for modelocking. Through this process, we were able to achieve pulse durations as short as 128fs with InGaAs QW-based SESAMs and ~185fs with InAs/GaAs SML QD-based SESAMs. Along with higher output power, it is found that SML QD-based SESAMs have substantially longer device lifetimes compared to QW-based SESAMs.

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2:00pm **MBE-WeA-3 Strain-Compensated Quantum Dot Cascade Lasers**, ***Feng-Qi Liu,*** Institute of Semiconductors, Chinese Academy of Sciences, China

Over the past two decades, quantum cascade lasers (QCLs) have been constantly improved in their performance and at this point have matured into the preferred choice of coherent sources in the mid-infrared (mid-IR) spectral region for a wide range of applications. More and more companies have attempted the usages of QCL on air-pollution, water-contamination, industrial-discharge, breath-medicine, and toxicant detection. Due to the essence of the extremely short non-radiative lifetimes commonly associated with the intersubband transitions in the quantum wells, the room temperature wall plug efficiency of QCL is no more than 30%.

At present, how to increase the efficiency of QCL further on is still a challenge. Quantum dot cascade laser (QDCL), in which quantum well active region is replaced by quantum-dot active region, is predicted as high-efficiency. However, the design and growth of QDCLs is extremely difficult. In this talk we demonstrate the development of QDCLs by two-step strain-compensation active region design and material growth technique. The QDCLs based on three-layer QDs active region, two-layer QDs active region, and single-layer QD active region have been exploited, paving a route for developing QDCLs.

2:15pm **MBE-WeA-4 (111)-oriented Stranski-Krastanov Quantum Dots Optimized for Entangled Photon Emission**, ***Christopher Schuck***, *K Vallejo, S Roy, T Garrett, K Sautter,* Boise State University; *B Liang, D Huffaker,* University of California, Los Angeles; *C Palmstøm,* University of California, Santa Barbara; *P Simmonds,* Boise State University

(111)-oriented quantum dots (QDs) are a promising source for entangled photons due to their high symmetry and the low fine-structure splitting (FSS) between their bright exciton states.[1,2] Therefore, they are of great interest for developing compact, scalable quantum information devices for quantum computing and quantum encryption applications.[1]

We have previously presented results showing the Stranski-Krastanov (SK) growth of (111)-oriented tensile-strained GaAs/InAlAs QDs (TSQDs).[3-5] These TSQDs form as highly-symmetric tetrahedra (Fig. 1(a)) with very low FSS.[4] The use of tensile strain allows for their dislocation-free formation, and reduces their bandgap toward the infrared.[3] Further, TSQDs exhibit clear processing-property correlations, whereby adjusting deposition amount, growth temperature, growth rate, and V/III flux ratio allows us to control QD size, shape, and spectral emission. The resulting roadmap now allows us to optimize TSQDs for specific applications.[5]

Building on that work, here we describe the growth conditions and resultant structural and optical properties of TSQDs optimized specifically for entangled photon emission. We will present a detailed analysis of the structure of individual GaAs TSQDs; power-dependent, temperature-dependent, and time-resolved photoluminescence; and island scaling statistics. We also present experimental results of the reconstruction of the InAlAs(111)A buffer surface. Finally, we will show that we can transform the in-plane shape of the GaAs TSQDs from equilateral triangles to regular hexagons, simply by switching from As_2 to As_4. The hexagonal TSQDs exhibit improved optical quality and higher symmetry, properties that we expect to be critical for robust quantum entanglement.

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2:30pm **MBE-WeA-5 Optimization of InAs Quantum Dots for Scintillation Applications**, ***Michael Yakimov***, *V Tokranov, K Dropiewski, A Minns,* SUNY Polytechnic Institute; *P Murat,* Fermi National Accelerator Laboratory; *S Oktyabrsky,* SUNY Polytechnic Institute

Use of semiconductors as scintillators for particle detection is limited by self-absorption in material bulk. Introducing below-bandgap transitions – e.g by doping (ZnS:Cu) is a way to address absorption. Use of heterostructures was proposed [1] and a scintillating medium of GaAs with artificial luminescent centers, InAs quantum dots (QD) was demonstrated [2].

A prototype scintillation device is grown by MBE and consists of 20 um thick GaAs layer with 50 sheets of embedded self-assembled InAs QDs. A m etamorphic p-i-n detector with InGaAs absorber is grown on top of the structure for high-speed integrated photo-detection. Overall structure and measurement diagram is shown in fig 1. After detector fabrication, the epi layer is separated from GaAs by epitaxial lift-off to form a scintillation waveguide and bonded to glass for testing, cross-sectional TEM of top layers is shown in fig 2.

We use elevated QD growth temperature of 520 ºC to reduce native defect density and associated recombination. Indium surface evaporation is addressed with high indium flux. Modulation p-doping and potential profile engineering was employed to achieve 60% luminescent efficiency at room temperature with low excitation level. This enables observations of single-particle events in QD medium, reduced self-absorption and scattering on structural defects. Shape engineering of QDs and barrier shape using thermal cycling, AlAs capping layers on QD for preserving shape and InGaAs barrier engineering to reduce carrier thermal escape rate from QDs were further optimized. We demonstrate a prototype scintillator in the form of a free-standing 20 um GaAs waveguide impregnated with InAs QD with self-absorption in the range of 3-5 cm^{-1}, and scintillator operation by detection of alpha particles using integrated InGaAs photodetector with time resolution of 60ps.

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[2] Oktyabrsky, et al, *IEEE Trans. On Nuclear Sci.*, **63**(2), pp.656-663, (2016)

2:45pm **MBE-WeA-6 Tensile-Strained Ge Quantum Dots on (111)A Surfaces***, **Kathryn Sautter**, C Schuck, T Garrett, A Weltner, K Vallejo, P Simmonds,* Boise State University

Si and Ge are ubiquitous in electronics, but their indirect bandgaps make them unsuitable for optoelectronic devices. Theory shows that placing Ge under tensile strain reduces its semiconductor bandgap by reducing the Γ-valley in Ge's conduction band faster than the L-valley. Once at ~2% tensile strain, Ge should acquire a direct bandgap. Researchers have therefore tried various ingenious methods to create tensile strain in Ge, but these attempts typically generate strain-induced defects and do not result in viable optoelectronic materials. Our approach to this problem is to synthesize Ge quantum dots (QDs) that self-assemble as a result of biaxial tensile strains on (111) surfaces. We have previously developed a method to grow defect-free GaAs(111) QDs at ~4% tensile strain with molecular beam epitaxy (MBE). Since GaAs and Ge have similar lattice constants, we simply replace GaAs with Ge in these structures. Initial data suggest spontaneous formation of Ge QDs under 3.7% tensile strain, which we anticipate should lead to optically active Ge with a reduced bandgap. We will present results demonstrating control of the structural and optoelectronic properties of tensile-strained Ge QDs with MBE parameters. Specifically, we will report on the effects of growth parameters via atomic force microscopy (AFM), transmission electron microscopy (TEM), scanning tunneling microscopy (STM), and preliminary measurements of their optoelectronic properties.

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3:30pm **MBE-WeA-9 Relaxed GaP on Si with Low Threading Dislocation Density***, **Ryan Hool**, Y Chai, P Dhingra, B Eng,* University of Illinois Urbana-Champaign*; Y Sun,* Yale University*; S Fan,* University of Illinois Urbana-Champaign*; K Yaung,* Yale University*; M Lee,* University of Illinois Urbana-Champaign

Epitaxial growth of 1.7 eV $GaAs_{0.75}P_{0.25}$ on GaP/Si templates offers a promising path to low-cost, high-efficiency tandem solar cells. While nucleation of thin, strained GaP on Si without anti-phase domains and stacking faults is now well established, the relaxation process of GaP on Si remains poorly understood. Threading dislocation densities (TDD) > 10^7 cm^{-2} in relaxed GaP on Si have been observed, despite the small lattice mismatch of ~0.45%. Our prior work revealed that the TDD of relaxed GaP on Si is dominated by dislocation glide at low temperatures (e.g. < 505°C) and by dislocation nucleation at high temperatures (e.g. > 575°C), with lowest TDD of 1.7×10^6 cm^{-2} [1]. We also showed that the TDD of the relaxed GaP layer strongly influences the TDD and efficiency of the $GaAs_{0.75}P_{0.25}$ active region, which emphasizes the importance of controlling the initial relaxation.

Here, we describe a two-step MBE growth process to suppress heterogeneous dislocation nucleation and improve dislocation glide during relaxation of GaP on Si. Initiating growth with a thin, low-T layer and subsequently growing a high-T layer for a combined thickness of ~0.5 µm enabled TDD reduction to 1.0×10^6 cm^{-2} in relaxed GaP on Si, which is the lowest value to date. We will show that the low-T step strongly suppresses dislocation nucleation, while the high-T step improves dislocation glide and surface morphology. This reduction in GaP TDD is expected to enable TDD values of $2\text{-}3\times10^6$ cm^{-2} for $GaAs_{0.75}P_{0.25}$ solar cells on GaP/Si along with substantial efficiency improvements over current state-of-the-art.

[1] K. N. Yaung et al., Appl. Phys. Lett. **109**, 032107 (2016).

3:45pm **MBE-WeA-10 Development of Hybrid Gas-source MBE to make Thin Films of Sulfide Perovskites and Related Complex Chalcogenides***, S Filippone, Y Li, **Rafael Jaramillo**,* Massachusetts Institute of Technology

Ternary sulfides and selenides in the distorted-perovskite and related structures ("complex chalcogenides") are predicted by theory to be semiconductors with band gap in the visible-to-infrared and may be useful for optical, electronic, and energy conversion technologies [1-4]. We will present progress towards growing films of complex chalcogenides by hybrid gas-source MBE, including thermodynamic modeling and gas-source optimization.

We use computational thermodynamics to predict the pressure-temperature phase diagrams for select chalcogenide perovskites [5-6]. We highlight the windows of thermodynamic equilibrium between solid chalcogenide perovskites and the vapor phase. For $ABCh_3$ (Ch = S, Se) materials with B = transition metal, the growth windows lie at very high temperature and low pressure (*e.g.* T > 1000 °C and $P < 10^{-9}$ torr) that are challenging for most MBE chambers. The growth window becomes much more accessible for materials for which the quasi-binary phase diagram includes a compound (*e.g.* SnS) with high vapor pressure.

We then report on the effect of hydride gas source placement in our growth chamber on the growth of chalcogenide films using hydrogen sulfide (H_2S) and hydrogen selenide (H_2Se) gas sources. Taking a cue from the history of complex oxides, we hypothesize that the location of the gas injectors is quite important for optimizing film growth, more so than the chamber growth pressure read by a remote pressure gauge. We test this hypothesis by measuring gas cracking by a heated substrate and the growth of binary sulfides MoS_2 for two different gas injector positions. We support our experimental measurements by Monte Carlo simulations of gas flow in our chamber. The results highlight the importance of gas source location for optimized hybrid MBE.

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[5] Filippone, S. A., Sun, Y.-Y. & Jaramillo, R. *MRS Commun.***8,** 145–151 (2018).

[6] Filippone, S. A., Sun, Y.-Y. & Jaramillo, R. *MRS Adv.* 1–6 (2018).

4:00pm **MBE-WeA-11 Epitaxial III-V Growths on 0.1-mm Grain-size Polycrystalline Germanium Thin-films***, **Abhinav Chikhalkar**, C Zhang, N Faleev,* Arizona State University*; E McClure, S Hubbard,* Rochester Institute of Technology*; C Honsberg, R King,* Arizona State University

III-V solar cells have demonstrated the highest efficiencies, for both single-junction and multijunction cells. Low defect tolerance and Fermi-level pinning at grain boundaries of these compounds has focused III-V growth on single-crystal thin-films, on single-crystal gallium arsenide, indium phosphide and germanium wafers that are both heavy and costly.

Polycrystalline thin-films of these materials are attractive candidates to reduce high substrate costs, but to maintain high efficiencies we require (a) large grain size, and (b) effective grain boundary passivation. R. Venkatasubramanian et al. [1] have demonstrated 18.2% (AM1.5) efficiencies on polycrystalline GaAs solar cells with 1-2 millimeters grain size, grown on polycrystalline germanium wafers cut from ingots with the same size of grains. Use of aluminum-induced crystallization for growth of polycrystalline germanium (AIC germanium) opens a new parameter space for growth of III-V tandem architectures on germanium-templated low-cost substrates such as glass and Mo foil. In addition to the light weight of the substrate, relatively large grain size of ~100 µm with high <111> orientation preference can be achieved, reducing the effect of grain boundary recombination. These characteristics along with the theoretical studies by S. Kurtz et. al. [2] which project >20% GaAs efficiency with grain size of 50-70 µm makes III-V growth on AIC germanium a promising avenue.

In this talk, we demonstrate the epitaxial growth of GaInP and Ga(In)As on AIC germanium. The growth mechanism was studied in situ using reflection high-energy electron diffraction. The presence of streaks indicates a layer-by-layer growth. Morphology and surface roughness of the grown film are studied using scanning electron microscopy and atomic force microscopy, respectively, while grain orientation is characterized using X-ray diffraction. A high crystal orientation preference and reduction in surface roughness were observed on the grown III-V films compared to the initial Ge template, both encouraging signs for the grown film quality. Recombination kinetics are characterized through room-temperature photoluminescence (PL) intensity and measurements of minority charge carrier lifetime in GaInP/GaAs/GaInP double heterostructures. The influence of substrate grain size and pre- and post-deposition treatments on minority charge carrier lifetime will be presented.

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4:15pm **MBE-WeA-12 Grating Coupled Quantum Well Infrared Photodetector on a Si Substrate***, **HoSung Kim**,* University of Waterloo, Canada*; G Ryu, S Ahn,* Korea Institute of Science and Technology, Korea*; Z Wasilewski,* University of Waterloo, Canada*; W Choi,* Korea Institute of Science and Technology, Korea

Integration of III-V on Si has been widely studied due to the possibility of low-cost fabrication using Si substrate and excellent opto-electronic conversion efficiency of III-V material. The wafer bonding and epitaxial lift-off (ELO) techniques can transfer III-V layers on any substrates whose surface is clean and atomically smooth without changing material characteristics.

Quantum well infrared photodetectors (QWIPs) are currently used for two-dimensional long-wavelength infrared light detection due to the good uniformity produced by well-established MBE techniques. However, selection rules prevent quantum wells from absorbing normal-incidence light directly, so most usable QWIPs must incorporate grating couplers to convert TE light into TM light for absorption.

In this talk, grating coupled GaAs/AlGaAs QWIPs are fabricated on a Si substrate by means of metal wafer bonding (MWB) and ELO method for the first time. The GaAs/AlGaAs QWIPs which have 50 periods of quantum wells (QWs) are grown by MBE. The grating was designed with a hexagonal periodic hole array structure and fabricated by dry-etching. After fabricating the grating structure, thin Pt/Au materials were deposited on the both detector and Si substrate. Two substrates were pressed and then dipped into the HF solution for ELO process. The final device was completed after metallization on the transferred QWIP layer on a Si substrate.

Our results show remarkable improvement compared to previous attempts to fabricate grated QWIPs. Previously, grated QWIPs were integrated with Si using In-bumps saw only a relatively small increase in photocurrent compared to the un-grated structure. However, as seen in Fig. 1, our grated shows 17 times higher intensity compared to the QWIP on a Si substrate without grating structure. This significant increase may be attributed to both the optical resonance cavity effects and increased light absorption of TM component.

4:30pm **MBE-WeA-13 Direct MBE Growth of Metamorphic nBn Infrared Photodetectors on 150 mm Ge-Si Substrates for Heterogeneous Integration***, **Joel Fastenau**, D Lubyshev, S Nelson,* IQE Inc.*; A Morgan, S Edwards,* IQE Silicon, UK*; M Fetters, H Krysiak, J Zeng, M Kattner, P Frey, A Liu,* IQE Inc.

GaSb-based infrared (IR) photodetectors continue to progress and improve, and the transition from pure development to a manufacturing phase is underway. The rich bandgap engineering possibilities of the GaSb materials system, with typical type-II broken-gap alignments, result in myriad device architectures, frequently based on the unipolar barrier design concepts commonly noted as nBn or XBn [1, 2]. To compete with HgCdTe in both performance and cost requires manufacturing processes based on larger-format focal plane array (FPA) detectors, leading to a requirement for larger diameter wafers for improved throughput, volumes, and yield. IQE has demonstrated a nBn production molecular beam epitaxy (MBE) growth process in multi-wafer configurations on 4-inch and 5-inch diameter GaSb substrates as well as via a metamorphic process on 4-inch and 6-inch GaAs substrates [3-5].

A next step in the progression of this IR photodetector technology is its heterogeneous integration with silicon. Such integration can provide the combined advantages of high-level volume production of Si-based electronic circuitry with superior high speed and optical performance of III-V components. In this work, we report the growth of GaSb-based metamorphic nBn (M-nBn) photodetector structures on large diameter (150 mm) Si substrates. Multiple growth steps are required to transition from the Si to the GaSb lattice constant, beginning with a Ge layer deposited by CVD at IQE-Silicon. This provides a Ge–Si substrate for the growth of the remaining III-V layers, from GaAs and GaSb buffer layers up to the M-nBn device layers, via MBE at IQE Inc. Standard epiwafer characteristics, including morphology, x-ray, and optical properties, will be presented. Large–area mesa diode characteristics from these M-nBn epiwafers compare favorably to those grown on lattice–matched substrates. The results represent an important technological path toward next–generation large-format IR detector array applications.

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Author Index

Bold page numbers indicate presenter

Author Index