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].

[1] R. M. Sheetz *et al.*, *Phys. Rev. B* **84** (7), 075304 (2011). [2] P. G. Moses *et al.*, *Appl. Phys. Lett.* **96** (2), 021908 (2010). [3] F. A. Chowdhury *et al.*, *Appl. Phys. Lett.* **111**, 061101 (2017). [4] Q. Shi *et al.*, *Phys. Rev. Mater.* **1**, 034602 (2017). [5] A. Martinez-Garcia *et al.*, *Adv. Energy Mater.* 1703247(2018).

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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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.

[1] J. P. R. David and C. H. Tan, "Material considerations for avalanche photodiodes," IEEE J. Sel. Top. Quantum Electron, vol. 14, no. 4, pp. 998–1009, 2008.

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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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[2] Z. Tabatabaie, "Chemical beam epitaxial growth of extremely high quality InGaAs on InP," vol. 170, pp. 1–4, 1986.

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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 300-350ºC and 140-180ºC 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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