NAMBE

Room Cummings Lobby - Session NAMBE-MoP

NAMBE Poster Session

NAMBE-MoP-1 Synthesis and Characterization of Molybdate Pyrochlore Thin Films, ***Kyeong-Yoon Baek***, *M. Anderson, C. Brooks, J. Mundy,* Harvard University

The molybdate pyrochlore oxides, $R_2Mo_2O_7$ (R = rare earth), form a series of compounds where there is a transition from a ferromagnetic metal to a spin glass insulator as a function of the R^{3+} radius [1]. To date, most of the work on this family of materials has been on bulk polycrystalline samples [2]. In this work, we synthesized pyrochlore $Gd_2Mo_2O_7$ and $Tb_2Mo_2O_7$ in thin-film form using reactive oxide molecular-beam epitaxy; in the bulk samples, $Gd_2Mo_2O_7$ and $Tb_2Mo_2O_7$ are a metallic ferromagnet and an insulating spin glass, respectively, both sitting adjacent to the phase boundary. The crystal structure of our films is confirmed through X-ray diffraction and scanning transmission electron microscopy. Electric transport measurements exhibit the insulating behavior of both films and magnetic ground states are confirmed through SQUID measurements. Our work continues to explore phase boundary of molybdate pyrochlore oxides by thin-film deposition.

References

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NAMBE-MoP-2 Growth of InGaBiAs for Extended Short Wave Infrared Photodetectors, ***Mrudul Parasnis***, *J. Bork, M. Islam, A. Razi, N. Babikir, J. Phillips, J. Zide,* University of Delaware

Dilute bismuthides are a class of highly mismatched alloys consisting of small amounts of bismuth incorporation in III-V semiconductors.[1]This incorporation of bismuth, due to its larger size compared to other elements within the host matrix, induces valence band anticrossing, thereby reducing the bandgap.[2] For this reason, dilute bismuthides are explored as a class of materials in optoelectronic devices such as infrared photodetectors.[2,3,4]

Previous studies have shown that InGaAs based photodetectors have a wavelength of 1.7µm. Bi incorporation in InGaAs reduces bandgap by 56meV/%Bi.[3] In our work, we aim at optimizing InGaBiAs to establish it as a promising material in the intrinsic region of shortwave infrared photodetectors and extend the wavelength beyond 1.7µm. Growth of dilute bismuthides is a challenging process. Hence, we are using molecular beam epitaxy to grow InGaBiAs at low temperatures of 265°C (as measured by band-edge thermometry) and near-stoichiometric conditions. Be:InGaAs as a capping p-type layer and Si:InGaAs as a n-type layer are grown at 490°C for infrared photodetectors. In our work, we show that 1.5%Bi incorporation in InGaBiAs extends the wavelength up to 1.8µm. We are also studying the recombination lifetime of the carriers in InGaBiAs using optical pump terahertz probe spectroscopy. The optimization of Bi in InGaBiAs to give longer wavelengths and higher recombination lifetimes is currently ongoing research.

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NAMBE-MoP-3 Investigating the Influence of Bismuth Surfactant on InSb Thin Films for Mid-Infrared Devices Applications, ***Pan Menasuta***, *J. McElearney,* Tufts University*; K. Grossklaus,* Lincoln Lab*; T. Vandervelde,* Tufts University

Indium antimonide (InSb) possesses a narrow direct bandgap, 0.17eV at 300K, facilitating efficient absorption and conversion of infrared photons in the mid-wave infrared (MWIR) spectrum. Consequently, InSb detectors demonstrate high sensitivity in thermal imaging, spectroscopy, and astronomical observation. Recently, there has been notable interest in employing bismuth as a surfactant during the epitaxial growth of many III-V material systems. A very low bismuth flux can modify the ad-layer surface and eventually desorb, leading to improved surface morphologies across multiple materials. However, no studies on Bi surfactancy have been conducted on MBE-grown InSb thin films. This work aims to document the effects of Bi surfactancy on InSb growth across a range of temperatures. We have recently shown that the Bi surfactant can substantially modify the morphology of GaSb thin films over a broad spectrum of growth temperatures. Given the significance of surface morphology control in multilayer epitaxial growth, especially those that require high-quality InSb layers, understanding its influence is crucial. Additionally, the systematic characterization of homoepitaxial InSb surfaces holds value for the MBE community.

Two series of homoepitaxial InSb(100) thin films are grown via molecular beam epitaxy (MBE) on an InSb(100) substrate over a range of growth temperatures. All other growth parameters remain identical. The first set serves as a control, while the second are grown under Bi surfactancy. Surface characterization is conducted using atomic force microscopy (AFM), and scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) to analyze large features and elemental distribution. Raman spectroscopy and variable-angle spectroscopic ellipsometry (VASE) are employed to detect alterations in lattice and optical properties induced by the surfactant. Finally, high-resolution X-ray diffraction (HRXRD) is performed to detect any potential Bi incorporation. This study seeks to assess the effects of Bi surfactancy on the surface morphology and material properties of InSb thin films, potentially contributing to the advancement of next-generation MWIR detectors with improved performance for diverse applications.

NAMBE-MoP-4 Surface Stability of Thin Film Tin Selenide, ***Jonathan Chin***, *B. Gardner, M. Frye, J. Wahl, D. Liu,* Georgia Institute of Technology*; S. Marini,* Cornell University*; J. Shallenberger,* The Pennsylvania State University*; M. Hilse,* Pennsylvania State University*; S. Law,* The Pennsylvania State University*; L. Garten,* Georgia Institute of Technology

Tin selenide (SnSe) is a two-dimensional (2D) material that exhibits a piezoelectric response when reduced to an odd number of layers near the monolayer limit. As 2D materials are scaled down, surface interactions, particularly oxidative degradation, will play an increasing role in performance. Oxides are known to form on not only on the surface but also between layers in transition metal dichalcogenides (TMDs). In bulk SnSe at high temperature (and in isostructural SnS at room temperature) oxide layers have been shown to form at the surface, but the impact of oxygen between layers has yet to be fully explored. Therefore, it is critical to understand the stability of the surface and interlayer structure in SnSe under standard operating condition.

This poster describes the chemical stability of thin film SnSe grown by molecular beam epitaxy (MBE) after a two-year exposure to ambient atmospheric conditions. X-ray diffraction (XRD) before and after the exposure show no measurable change in the crystallographic phase or orientation. Raman spectra similarly show the known SnSe vibrational modes, but there is no sign of the mode corresponding to $SnSe_2$, SnO or SnO_2. These measurements show that the bulk of the SnSe thin film is not degrading over time as the incorporation of oxygen between layers would have impacted the XRD and Raman response. The chemical stability of the bulk phase is further supported by x-ray photoelectron spectroscopy (XPS) measurements that Show that the preponderance of the film maintains a 1:1 stoichiometry. The XPS also shows signs of a layer of SnO_2 but only at the surface of the SnSe film. An argon ion etch was performed to create a depth profile of the elemental composition from the surface down to the substrate of the thin film to measure the extent of the oxidation. The oxide layer was limited to the surface within the accuracy of the depth profiling, which is approximately 5 nm. This XPS depth profile in conjunction with the lack of oxide peaks in XRD and Raman spectrometry suggests that exposure to atmosphere creates a passivated layer of SnO_2 on the surface of SnSe but does not impact the bulk. Thus, from the results of this work, we have determined that SnSe is chemically stable in atmospheric conditions over extended durations and is suitable for device applications that take advantage of the natural metal oxide layer protecting the inner layers of SnSe.

NAMBE-MoP-5 Si / TiN Backside Thermal Absorbers for MBEGrowth on Transparent Substrates, ***D. Scott Katzer***, *M. Hardy, N. Nepal, E. Jin, D. Meyer, V. Wheeler,* US Naval Research Laboratory

Efficient, controlled absorption of thermal radiation from the MBE system substrate heater into the growth substrate continues to be a technological challenge [1]. This problem is especially difficult for the case of wide- and ultra-wide bandgap (WBG and UWBG) semiconductors where near IR absorption is low and growth temperatures exceeding 1000°C may be required for high quality epitaxy. UWBG semiconductors are attracting increased attention for high power density RF electronics and other applications, so addressing the practical MBE growth temperature issues is important. In addition, a commonly-used method to increase IR absorption by using thick, opaque, specular backside metal layers can be detrimental to substrate temperature monitoring with diffuse reflectance [1,2], so a

different approach is needed.

Woltersdorff [3] showed that in the far IR where the optical constants *n* and *k* are both large for metals, the maximum absorption is 50% for a thin metal film that has a sheet resistance of half that of the characteristic impedance of free space, namely 377/2 = 188.5 ohms/sq.Thus, one would expect that the ideal thickness of a thermal absorbing layer to depend on the wavelength range and the absorbing layer properties, and that thick layers may be counter-productive for efficient heating.

Here we report our recent work in modeling and experiments using thin stacks of silicon (Si) on titanium nitride (TiN) to greatly increase the thermal absorption of WBG SiC substrates during MBE growth.Modeling with the Python software package WPTherml [4] indicates that a 100 nm thick Si layer on a 9 nm thick TiN layer increases the peak absorbance of IR from a 1000ºC blackbody substrate heater to over 58%.We used a similar thin layer stack on a 4H-SiC substrate and a substrate heater temperature of 1100ºC to efficiently heat the substrate to a real temperature of ~ 1000 ºC (hundreds of degrees hotter than bare SiC [1]) as revealed by a bright Ö3 x Ö3 R30º RHEED pattern [5], showing the value of this approach.

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NAMBE-MoP-6 Verification of Epitaxially Grown InAs/GaInSb Topological Insulators using Spectroscopic Ellipsometry, ***Lawrence Qiu****, P. Simmonds, J. Rushing, X. Xie,* Tufts University

The theoretical and practical implications of topological materials have captured intense research interest. Topologically nontrivial phases emerge from the crossing of electron and hole band energies, resulting in novel phenomena like topologically protected surface states. Established topological insulators like Bi_2Se_3 rely on spin-orbit-coupling to induce band crossing, limiting configurability and requiring exotic materials. Topological insulators based on widely used III-V materials would simplify the creation of hybrid topological/semiconductor devices. Topologically nontrivial phases have already been demonstrated in the broken gap InAs/GaSb material system. We hope to achieve a tunable topological phase change in III-V quantum wells by carefully adjusting their widths to tailor the confined electron and hole states and inducing band inversion.

Quantum well behavior is sensitive to aspects of the epitaxial growth process, such as growth rate variations, composition inaccuracy, impurity contamination, and poor interface quality. Topological insulators based on quantum wells are especially sensitive to thickness imperfections because they emerge from the configuration of relative and absolute electron and hole energies. Single digit variations of the monolayer count can induce topological phase change, so confirming that the intended structure was grown is an essential step in understanding the behavior of novel quantum well-based topological insulators.

Spectroscopic ellipsometry is an established method of confirming sample structure and composition through the nondestructive survey of device optical properties. We report the use of spectroscopic ellipsometry in characterizing InAs/GaInSb quantum well structures. These structures consist of a GaSb buffer that includes a superlattice for improved active region quality, an AlSb bottom barrier, a GaInSb quantum well, an InAs quantum well, an AlSb top barrier and a GaSb cap. Such a complex structure increases the degrees of freedom for an ellipsometer thickness measurement, and makes single layer changes subtle and unpredictable. Additional difficulties for these measurements include the use of a previously uncharacterized GaInSb ternary compound and variations between samples grown on (001) and (111) substrates. We will show how the careful use of ellipsometry can give us useful information about these growths without the need for costly and time consuming tunneling electron microscopy.

NAMBE-MoP-7 Investigation of Tunable Parameters Influence in InAs/GaInSb Quantum Wells Heterostructure, ***Xikai Xie****, P. Simmonds,* Tufts University

Quantum spin Hall insulators (QSHIs) are advanced materials with topologically protected surface states that allow electronic transport without scattering from defects. QSHIs with a large energy gap in the topological phase are of great interest for development of both quantum and electronic devices. The ability to control the topological phase transition in a QSHI would represent a functional improvement for applications that require in-situ tunability of the material's topological properties such as spintronics and fault-tolerant quantum computing.[1]

It is possible to induce topological states in III-V semiconductor quantum wells with a brokengap band alignment and use quantum well width to adjust the size of the hybridization energy gap. We are therefore interested in investigating the topological phase transition in InAs/GaInSb quantum well heterostructures varying different structural parameters. By simulating band topology and topological invariants we can observe changes in wavefunction in k-space and control the quantized responses of the material.[2] Two key parameters that shape a material's band structure are symmetry and strain. We compare (001)- and (111)-oriented III-V semiconductor quantum well heterostructures under both compressive and tensile strain to explore their effects on the emergent topological states.

QSHIs consisting of InAs/GaInSb quantum well heterostructures are considered since by changing the well widths and gate voltage we can control the degree of band inversion and corresponding topological properties.[3] The ability to tune the strain in these structures by varying the composition of the ternary GaInSb quantum well can enhance the size of the hybridization gap energy between the topological states compared to QSHIs based on binary InAs/GaSb QWs.[3]

We have therefore carried out computational simulation to investigate InAs/GaInSb double quantum well heterostructures with both (001) and (111) crystalline orientations.[4] We will present our results that show the influence of tunable parameters such as quantum well width and strain on topological band structure.

Furthermore, given the result of our computational work, we can create these structures with molecular beam epitaxy (MBE) down to monolayer precision. This precise control enables us to adjust the quantum well widths and strain levels, to influence topological properties of the InAs/GaInSb quantum wells. We anticipate that MBE's high degree of control over the deposition of our simulation parameters will lead to the realization of QSHIs with optimized performance for applications in spintronics and quantum computing.

NAMBE-MoP-8 Exploring In situ Aluminum Deposition Kinetics on InSb Substrates for Hybrid Superconductor/Semiconductor Materials Systems, ***Ahmed Elbaroudy****,* University of Waterloo, Canada

Hybrid Superconductor/Semiconductor (SP/SE) structures play an important role in condensed matter and mesoscopic physics, particularly in topological quantum computing aimed at realizing Majorana Zero Modes. Aluminum growth on InAs or InSb quantum wells using Molecular Beam Epitaxy emerges as the most promising direction due to the high electron mobility and strong spin-orbit interactions within these wells. Nevertheless, achieving a thin, continuous Al layer (~10 nm) poses challenges in standard MBE systems due to Al's high surface mobility in ultra-high vacuum environments and its tendency for 3D nucleation.

We have demonstrated that a thin, continuous Al layer can be successfully grown on an InGaAs surface at temperatures above room temperature using a high Al-growth rate of 3 Å/s [1]. In the current study, we compare this process with the growth of Al on a homomorphic epitaxial InSb surface. In-situ RHEED studies reveal similar Al behaviors on both surfaces. Regardless of the semiconductor surface used, 3D nucleation occurs after the initial Al monolayers for both growth rates tested (0.1 and 3 Å/s). With a growth rate of 0.1 Å/s, the 3D growth mode dominates throughout the deposition of the nominal 10 nm of Al. In contrast, at the Al growth rate of 3 Å/s, the initial 3D nucleation RHEED pattern quickly transitions to a streaky pattern, indicating the coalescence of Al islands and a shift to 2D growth for both InSb and InGaAs surfaces.

Surface morphology inspections with SEM and AFM of the samples grown at 0.1 Å/s reveal a similar discontinuous layer of Al islands, regardless of the semiconductor surface type. For InGaAs surface, faster deposition rates consistently result in a 2D Al layer. However, for the InSb surface, 2D morphology is preserved only for Al deposition on InSb with Sb-rich surface reconstruction, while growth on Sb-depleted reconstruction, despite

showing 2D growth mode during deposition, was found to have a distinct 3D morphology when inspected with SEM. Most likely, the dewetting process took place at some point after finishing Al deposition, before moving the wafer out of the MBE system.

For both InSb and InGaAs surfaces, the 3D to 2D growth mode transition is abrupt and is governed by the interplay between the wafer's thermal trajectory and the Al deposition rate.We will discuss the temperature evolution during and after Al deposition, as monitored with band-edge thermometry. Detailed surface morphology and interface characterization using SEM, AFM, and STEM will also be addressed during the presentation.

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NAMBE-MoP-9 Phases Control of Epitaxial MnTe through Buffer Layers, ***Yuxing Ren**, H. Huang, L. Tai, Q. Tao, K. Wang,* University of California at Los Angeles

MnTe is one of the 3D semiconductors that can exhibit anomalous Hall effect. The potential edge states correlated with the alter-magnet properties in the α-phase MnTe is also under study these days. The epitaxial growth becomes one method to tune the electronic structure. In this work we have grown both α-phase and β-phase MnTe by Molecular Beam Epitaxy on GaAs (111) and sapphire (0001) substrates with different buffer layers.

While in bulk crystal MnTe α-phase is the most stable state at room temperature, in the epitaxial structure β-phase MnTe can also be achieved in the as-grown thin films without post-growth annealing. On GaAs (111) substrates α-phase MnTe are naturally favored without any buffer layer. When using Bi_2Te_3 series TI (topological insulators) the buffer layers on sapphire (0001) substrates, we found out that β-phase MnTe are favored over pure Bi_2Se_3 due to the smaller lattice mismatch. However, when we add some alloy effect to the buffer layer, though the lattice mismatch is still smaller in β-phase, α-phase is actually grown. This unveil the role of the entropy effect and the changed in the surface potential. The nanorods structure in MnTe α-phase can also be controlled by buffer layer control and a $CrSe_x$ layer under it.

NAMBE-MoP-10 Self-Bias Bi-Directional Photocurrent Switching Effect in Epitaxial GaN-NWn, ***PARGAM VASHISHTHA**,* RMIT University, Australia*; G. Gupta,* CSIR-National Physical Laboratory, India*; S. Walia,* RMIT University, Australia

Conventional optoelectronic devices face limitations when serving as a single detector for broadband and narrow-band applications due to their one-way photocurrent, restricting their potential uses in photodetection. However, a promising solution is emerging: bi-directional photocurrent switching. This advancement opens doors to unique functions like optical logic operations. We design an epitaxial GaN nanowall network-based ultraviolet bidirectional photocurrent photodetector. By introducing the different surface potential-induced photocurrent switching effects, the photocurrent direction can be switched in response to the wavelength of incident light at 0V bias. In particular, the photocurrent direction exhibits negative when the irradiation wavelength is less than 285 nm, but positive when the wavelength is longer than 285 nm. Special logic gates in response to different dual UV light inputs are proposed via a single bipolar PD, which may be beneficial for future multifunctional UV photonic integrated devices and systems.

NAMBE-MoP-11 Systematic Study on Synthesis of High Quality SnTe Layers by Molecular Beam Epitaxy, ***Qihua Zhang**, M. Hilse, J. Gray, M. Stanley, N. Samarth, S. Law,* Pennsylvania State University

Tin telluride (SnTe) is a narrow bandgap semiconductor which has many attractive properties, such as in-plane ferroelectricity, good thermoelectric performance, and a topological crystalline insulator (TCI) band structure.[1] In addition to these properties, SnTe also serves as an important buffer layer for developing Te-based heterostructures for magneto-transport devices.[2] Despite such promises, there have been few investigations focused on understanding the optimal epitaxial growth conditions for SnTe layers, which has led to poor surface morphologies and/or low crystallinity in synthesized films.[3] A major challenge in the growth of thin film SnTe is the lack of suitable substrates, owing to the rock-salt crystal structure of SnTe and the large lattice mismatch with common substrates.

In this study, we report on the molecular beam epitaxy (MBE) growths of SnTe(111) layers on InP(111)A substrates. We have conducted a detailed investigation of the surface morphology and film crystal quality based on growth parameters including substrate temperature, Te/Sn flux ratio, and film growth rate. Despite the 7.4% lattice mismatch between the film and substrate, we found that a narrow substrate temperature range from 300 °C to 340 °C, a Te/Sn flux ratio of ~3, and a growth rate of 0.48 Å/s yield both smooth and single-crystalline SnTe(111) layers with thicknesses ranging from 10 nm up to 800 nm. Using these conditions, fully coalesced and smooth SnTe layers with root-mean-square (rms) roughness as low as 0.3 nm (Fig. 1a) can be obtained. The as-grown SnTe layer is free of rotational twin domains (Fig. 1b) and has exceptional crystal quality, including a full-width-at-half-maximum (FWHM) value as narrow as 0.06° from x-ray diffraction (XRD) rocking curves (Fig. 1c). Reciprocal space mapping confirms that thin (15 nm) SnTe layers are fully relaxed. Detailed transmission electron microscopy (TEM) imaging suggests that formations of In-Sn-Te nanoclusters during substrate annealing in a Te environment prior to growth aids strain relaxation as well as improves crystalline quality (Fig. 1d). Finally, preliminary angle-resolved photoelectron spectroscopy further indicates the three-fold symmetry of SnTe (111) layer at the Γ point, as well as Fermi level located 0.19 eV below the Dirac point. These promising results lay the foundation for employing SnTe on InP as a platform for developing all-telluride heterostructures integrated with III-V semiconductor devices.

[1]DOI:10.1063/5.0012300.

[2]DOI:10.1038/ncomms11623.

[3]DOI:10.1002/pssa.202200555.

NAMBE-MoP-12 Single-Mode Interband Cascade Lasers for Environmental Gas Sensors, ***Stefania Isceri**, G. Marschick, M. Giparakis, W. Schrenk,* Technische Universität Wien, Austria*; S. Höfling,* Universität Würzburg, Germany*; J. Koeth, R. Weih,* nanoplus Advanced Photonics Gerbrunn GmbH, Germany*; E. Kolibalova, J. Michalicka,* CEITEC, Czechia*; B. Schwarz, G. Strasser, A. Andrews,* Technische Universität Wien, Austria

Interband cascade lasers (ICLs) [1] are MIR devices exploiting interband transitions in type-II band alignment heterostructures. This enables spectroscopy applications combined with low power consumption [2]. Efficient single-mode vertical emission has remained challenging for ICLs. We present GaSb-based ICLs, grown by MBE, with a center wavelength 4.22-4.38 µm for CO_2 detection, processed for single-mode facet- and surface-emission ring-cavities.

To improve the epitaxy, the substrate temperature and Sb flux are tuned to remove the native oxide and grow a smooth GaSb buffer layer with an RMS roughness equal to 0.27 nm measured by atomic force microscopy. The growth temperature, As flux, shutter sequences, and opening times are adjusted to obtain high-quality strain-compensated InAs/AlSb and InAs/GaSb superlattices (SLs). This is complicated by the As-for-Sb exchange [3]. The high-quality SLs are evident by streaky reflection-high energy electron diffraction patterns and high-resolution x-ray diffraction scans, where the peaks corresponding to the cladding, the active region, and the thin InAs capping layer are distinguishable. Scanning transmission electron microscopy images reveal sharp interfaces, confirming that there is no intermixing between adjacent layers. To improve the waveguides, ellipsometry measurements of the InAs/AlSb cladding are performed to analyze the refractive index, important for light confinement. Its real part is 3.78 for the substrate and 3.30 for the cladding, similar to values calculated using the Lorentz-Drude model. The losses of the SL are negligible in the wavelength range of interest.

For single-mode emission, distributed-feedback gratings for low dissipation and focused far field emission are designed. We compare 1st- and 2nd-order gratings of ridge- and ring-ICLs. The coupling strength of surface gratings on ridge cavities improves by reducing the cladding thickness from 2 µm to 800 nm. The ring-cavities are vertically-emitting devices [4], with the advantage that they can be integrated in arrays [5]. When the central waveguide radius increases between 40 and 120 µm, the effective mode refractive index decreases from 3.51 to 3.44, consistent with results of fabricated devices operating in continuous wave at RT. The loss of the symmetric mode is minimum for a radius equal to 100 µm, while the asymmetric mode has a weak radial dependence.

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NAMBE-MoP-13 Self-Limiting Stoichiometry of SnSe Thin Films, ***Jonathan Chin**, M. Frye, J. Wahl,* Georgia Institute of Technology*; D. Liu, M. Hilse,* The Pennsylvania State University*; I. Graham,* Georgia Institute of Technology*; J. Shallenberger, K. Wang,* The Pennsylvania State University*; R. Engel-Herbert,* Paul-Drude-Institut für Festkörperelektronik Leibniz-Institut im Forschungsverbund Berlin, Germany*; M. Wang,* The Pennsylvania State University*; Y. Shin,* Pennsylvania State University*; N. Nayir,* Istanbul Technical University, Turkey*; S. Law, A. van Duin,* The Pennsylvania State University*; L. Garten,* Georgia Institute of Technology

Tin selenide (SnSe) is a 2D material that will exhibit piezoelectricity when scaled down to the monolayer limit, due to the transition from the centrosymmetric *Pnma* space group to the non-centrosymmetric $Pmn2_1$ space group.[1,2] However, the strong van der Waals forces between SnSe layers limits the ability to mechanically exfoliate individual layers. Consequently, direct growth by molecular beam epitaxy (MBE) is an ideal approach, because it grants a great degree of layer and compositional control during thin film growth. SnSe thin films were grown by MBE on (100) magnesium oxide (MgO) in ultrahigh vacuum from 240 to 300 °C across a range of Sn:Se flux ratios from 0.34 to 1.72. Increasing the selenium content surprisingly did not impact the stoichiometry – a 1:1 Sn:Se stoichiometry was maintained for all flux ratios – but instead reduced the surface roughness and encouraged in-plane growth. ReaxFF molecular dynamics (MD) simulations help explain why SnSe experiences a self-limiting stoichiometric process in the presence of excess selenium by showing how the excess selenium atoms form clusters that only weakly interact with the SnSe grains. The proposed formation of selenium clusters restricts the formation of $SnSe_2$. Conversely, when depositing with a deficit of selenium, the deposited tin atoms clump together and form metallic tin droplets that exclude the incorporation of further incoming selenium atoms. Thus by growing under increased selenium in addition to increasing the substrate temperature to 280 ± 5 °C lead to increased planar growth. Atomic force microscopy (AFM) scans show that at higher temperatures, SnSe continuously covers the substrate surface and forms layered islands. These observations enable the growth of monolayer-thin grains of SnSe with in-plane dimensions large enough for device testing.

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NAMBE-MoP-14 In Situ Curvature Measurement: A Great Breakthrough for MBE Growth Monitoring, ***Romain Bruder**, Y. Rousseau,* RIBER, France

As a long-known high performance epitaxial technique, Molecular Beam Epitaxy has experienced several major innovation across the past 50 years. Epitaxy recipes complexity has gradually increased to obtain advanced structures and devices thanks to the unique MBE capabilities. To cover this complexity, numerous monitoring probes and communicating devices (pumps, valves, gauges, thermocouples,...) have gradually been used on the reactors.

Nowadays, the MBE process is integrating additional class of optical in situ real time measurement techniques, including curvature / bowing monitoring.

Based on Magnification Inferred Curvature principle, Riber developed a dedicated curvature instrument on the basis of a CNRS-LAAS Toulouse patent. Named EZ-CURVE®, this instrument aims at giving insight in real-time about the growth process: it enables investigations at the growth mechanisms level for fundamental and applied research purposes, or alternatively, it can help evaluating process repeatability and stability without requiring detailed knowledge of all growth parameters.

This talk will give recent examples of EZ-CURVE uses' cases for different class of materials (arsenides, antimonides, phosphides, others,...), and highlight the capability of such an approach to quickly converge on process optimization and monitoring.

NAMBE-MoP-15 Synthesis and Transport Properties of Doped Samarium Nitride Thin Films, ***Kevin Vallejo**, Z. Cresswell, B. May, V. Buturlim, S. Regmi, K. Gofryk,* Idaho National Laboratory

Lanthanide-based nitride compounds are an understudied group of materials compared to lanthanide oxides. Their 4*f* electron shell gives rise to a variety of interesting physics such as unconventional superconductivity. Samarium nitride (SmN) has been recently identified as a material where ferromagnetic order and p-type superconductivity coexist. Our team will present results on the growth conditions of pure and doped SmN using molecular beam epitaxy, and its electronic transport properties as a function of temperature and magnetic field. The team used an yttria-stabilized zirconia (YSZ) substrate in the (001) crystallographic direction. After outgassing and removal of the native oxide, substrates were heated to 600°C and Sm and N were deposited for 60 minutes. Sm films deposited under similar conditions oxidized immediately upon contact with the air, while optimized SmN films avoided these samarium oxide peaks. Substrate temperature during growth of SmN films heavily influences the level of oxidation upon removal from the vacuum environment. The films have so far not been confirmed to be single crystalline due to the presence of SmN(111) peaks. AC magnetic susceptibility studies have shown the oxidized sample to be mostly paramagnetic, with a potential superconductive transition around ~10 K. Doping effects on crystal structure and electronic properties are characterized.

NAMBE-MoP-16 Tunable Ordering of 2D Tin on Silicon, ***Caitlin McCowan**, S. Misra,* Sandia National Laboratories

The atomic site-to-site correlations of a binary alloy can determine its optical and electronic properties. A direct bandgap is theoretically expected to occur in group IV alloys composed of silicon, germanium, and tin. However, an indirect bandgap is observed experimentally, which is thought to be caused by short range order (SRO). The atomic organization of thin films is determined by a combination of deposition rates, temperature, and templating effects of the substrate. The characterization needed for visual representation is made further arduous due to the atomic-scale nature of these factors. Here, using scanning tunneling microscopy (STM), we visualize step-by-step growth of Sn on Si *in situ* by separately controlling sub-monolayer growth and sample heating.

This work aims to understand the impact that SRO has on a material's electronic proprieties through systematic characterization. While long-range ordering of monolayers of Sn has been observed on Si and Ge substrates in both 100 and 111 orientations, the impact of temperature and film thickness on SRO remain unknown. Additionally, surface segregation of Sn depends strongly on annealing, which is expected to influence SRO. We use *in situ* STM to analyze growth in a series of steps that include Sn deposition, Si deposition, and various annealing stages to probe the dynamics of thin film growth at the substrate interface. By discretizing the growth process, we create regions of metastable ordering that can be dynamically tuned throughout investigations, improving our ability to relate growth conditions to SRO and, correspondingly, to a material's optical and electronic properties.

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NAMBE-MoP-17 Continuous Wave Lasing from Individual InAs Nanowires, ***Steffen Meder**,* Technical University Munich, Germany

Extending the emission wavelengths of monolithically integrated nanowire (NW) lasers to longer wavelengths and even the mid-infrared (MIR) spectral range, shows great promise for optical on-chip communication and sensing applications using the mature silicon photonic circuit platform. Strong absorption within the visible range in silicon waveguides necessitates the integration of lasers with wavelengths in the near- or mid-IR for low-loss optical transmission. While examples of NW lasers have been shown with emission in the near [1] to mid-infrared [2], few operate under continuous wave operation necessary for on-chip processors.

In this work, we report on the mid-infrared continuous wave lasing of individual InAs nanowires at cryogenic temperatures. Figure 1a shows finite difference time domain simulations of the diameter dependent threshold gain, that allow us to determine the optimal nanowire geometry. Catalyst-free InAs NWs are grown site-selectively and with high homogeneity on SiO_2-templated Si(111) substrates via molecular beam epitaxy, whereby the diameter and length is tuned from 160-745nm and 6-28µm by varying the pitch and growth durations (Fig 1c). Under optical pumping with a 976nm continuous wave laser, stimulated emission is demonstrated for individual NWs transferred on a sapphire substrate with diameters of 745±55 nm and nanowire resonator lengths between 10-30 µm (Fig 1b). Typical lasing thresholds are found to range from 2-30 kW/cm^2 with emission wavelengths of 2.4-2.7µm (0.455-0.515eV).

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NAMBE-MoP-18 Impact of Growth Temperature on the Formation of AlGaN During the MME Growth of AlN/AlGaN Short Period Superlattice Structures, ***Alexander Chaney***, *S. Mou, K. Averett, T. Asel,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA

We have previously shown that AlN/$Al_xGa_{1-x}N$ short period superlattices (SPSL's) can be formed through the introduction of a constant Ga overpressure during the metal modulated epitaxy (MME) growth of AlN. It was found that when a growth temperature of 830 °C was used, the incorporation of Ga into the layer structure was limited due to the final stages of Al consumption due to Ga adatom desorption. As a result, the lowest Al composition in the $Al_xGa_{1-x}N$ layers obtained was 72% for a Ga BEP of $1x10^{-6}$ Torr. For this work, the impact of Ga adatom desorption on the formation of the AlGaN layer was investigated in order to realize the growth of AlN/GaN SPSL's. In this study, a series of 3 growths was done where substrate temperatures of 800 °C, 760 °C or 730 °C were used. Outside of the variations in substrate temperature, Al, Ga and N fluxes were kept constant for each sample. Shutter conditions were chosen such that the Ga shutter opened only after complete consumption of Al on the surface had occurred. This removes any potential influence that Al adatoms have on Ga. Comparing XRD coupled scans of each sample showed that the 0^{th} order peak shifted to lower ω-2Θ angle as the growth temperature was lowered. However, the position of the higher order peaks remained mostly unchanged. Therefore, while there was a reduction in the Al composition of the $Al_xGa_{1-x}N$ layers, the overall SPSL period remained mostly unchanged. This was confirmed by STEM imaging, which found that for all 3 samples, the AlN had a thickness of ~ 5 nm while the $Al_xGa_{1-x}N$ had a thickness of ~3 ML. By inserting the thickness values determined by STEM into XRD simulations it is possible to determine the Al content in the $Al_xGa_{1-x}N$ layers. For the growth temperatures of 800 °C, 760 °C, and 730 °C, the resulting Al composition was calculated to be 84.3%, 66% and 52.5% respectively. These results represent the lowest Al content we have achieved using MME to date. However, the fact that no GaN formed serves to highlight that the current model explaining the formation of $Al_xGa_{1-x}N$ is incomplete. Fully fleshing out this model will be the focus for continuation of this work.

NAMBE-MoP-19 Buffer Layer Approach for Smooth GaSe Epitaxial Films on GaAs (111) B, ***Joshua Eickhoff***, University of Wisconsin; *M. Yu, M. Hilse, S. Law,* Penn State University; *D. Rhodes, J. Kawasaki,* University of Wisconsin - Madison

GaSe is a layered semiconductor with potential applications for single photon emission and for ultrathin field effect transistors. The quality of epitaxially grown GaSe critically depends on the roughness and chemical termination of the starting surface. Previous work reports improved GaSe film morphology on GaAs (111)B using a pre-growth surface selenization treatment of the de-oxidized GaAs (111)B (1). Here I will show that an epitaxially grown buffer layer of GaAs (111) B in conjunction with the surface selenium treatment results improved GaSe film quality, as determined by X-ray diffraction, Raman spectroscopy, and cross sectional TEM.

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NAMBE-MoP-20 Incorporating ErAs Into InGaAlBiAs Material by Interrupted Growth: Effects on Optical and Electronic Properties Targeting Terahertz Pulse Emitters and Detectors for Telecom Wavelength Excitation, ***Wilder Acuna***, *W. Wu, J. Bork, M. Doty, M. Jungfleisch, L. Gundlach, J. Zide,* University of Delaware

Our study focuses on the growth of ErAs:InGaAlBiAs thin films using a digital alloy approach to achieve a bandgap of 0.8 eV suitable for telecom wavelength excitation (1550 nm). This semiconductor thin film is the active layer within a photoconductive switch (PCS) designed for terahertz (THz) pulse generation and detection. Key to the performance of such PCSs are several intrinsic semiconductor properties, such as dark resistivity, carrier lifetime, and carrier mobility. The incorporation of ErAs nanoparticles within the InGaAlBiAs matrix significantly influences these properties. Beyond the solubility limit, erbium incorporation leads to the formation of ErAs nanoparticles, resulting in a decrease in the material's carrier lifetime. Additionally, ErAs nanoparticles exert a pronounced pinning effect on the effective Fermi level of the material, thereby impacting carrier concentration and, consequently, dark resistivity. The size of these nanoparticles impacts the position of the Fermi level, a parameter controlled through interrupted growth and migration-enhanced epitaxy due to constraints posed by the bismuthide matrix, necessitating lower growth temperatures. Despite the requirement for relatively low growth temperatures (~280°C) for the bismuthide matrix, this system offers enhanced flexibility in tuning bandgap and band alignment while ensuring the growth of high-quality lattice-matched films on an InP substrate. The ability to manipulate band alignment facilitates positioning the Fermi level deep in the bandgap, thereby reducing carrier concentration and elevating dark resistivity. Moreover, the positioning of the Fermi level with respect to the band edges plays a pivotal role in carrier lifetime, affecting the efficacy of nanoparticles in trapping free carriers.

Different characterization techniques are employed to assess these pertinent properties comprehensively. Dark resistance is determined through the Hall effect and Van der Pauw measurements, while carrier lifetime is evaluated via optical pump THz probe spectroscopy. Optical bandgap measurements are conducted using spectrophotometry, and material quality is scrutinized through high-resolution X-ray diffraction analysis.

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NAMBE-MoP-21 Ferromagnetic Nanostructures Formation by Metal Modulated Epitaxy of AlN:Mn, ***Jesús Fernando Fabian Jocobi***, *S. Gallardo Hernández, A. Conde Gallardo,* CINVESTAV, Mexico; *D. Olguin Melo,* CINVESTAV-Queretaro, Mexico; *Y. Casallas Moreno,* UPIITA - Unidad Profesional Interdisciplinaria en Ingeniería y Tecnologías Avanzadas IPN, Mexico; *M. Zambrano Serrano, M. López López,* CINVESTAV, Mexico

Diluted magnetic III-N semiconductors (DMSs) are promising for spintronic devices. Incorporating Mn atoms induces ferromagnetic behavior in III-nitride materials, notably AlN. Doping atoms during molecular beam epitaxy (MBE) growth process can significantly impact film properties. This study delves into the growth technique of AlN:Mn films using alternating Al and Mn atom fluxes, a technique known as metal modulated epitaxy (MME).

Samples were grown on Si (111) substrates utilizing a 200 nm thick AlN buffer layer grown at 850°C (Figure 1(a)) by MBE. Al and Mn atom fluxes were supplied from Knudsen-type effusion cells. Active Nitrogen (N) flux was provided by a rf-plasma source operating at 150 W with a N_2 flow of 0.25 sccm. The first set of samples employed a continuous growth method, simultaneously supplying fluxes of Al and Mn atoms along with Nitrogen. The second set of samples was grown using an alternating method, with the Al shutter opened for 5 s followed by Mn shutter for 1 s, with a 3 s pause in between, while the Nitrogen flux was constant. The alternated shutters sequence during the growth process are depicted in Figure 1(b). The continuous growth utilized a growth temperature of 750°C, while the alternating method employed 720°C. In both samples, the Al flux was set at $BEP_{Al}=2\times10^{-7}$ Torr and the Mn flux at $BEP_{Mn}=5\times10^{-9}$ Torr.

Reflection High-Energy Electron Diffraction (RHEED) patterns revealed that continuous growth process yielded a surface with flat regions with some 3D features, evident from the combination of linear and spotty patterns (Fig. 2(a)). In contrast, the alternating growth process resulted in a completely spotty RHEED pattern, indicating nanostructure formation, as depicted in Fig 2(b). This observation was corroborated by AFM micrographs (Fig. 3), showcasing flat regions in the continuous growth method, and nanostructures formation for the alternating growth process. From AFM measurements we estimated the size of the AlN:Mn nanostructures of 30 nm in height with a base of 80 nm. Moreover, we confirmed that Mn atoms induced ferromagnetic behavior in the material. As illustrated in Fig. 4, magnetization curves exhibited clear hysteresis at 300K, with no diamagnetic signal in either case, and stronger magnetic moments observed in nanostructured samples.

In conclusion, supplying alternating fluxes of Al and Mn atoms facilitates the formation of AlN:Mn nanostructures exhibiting ferromagnetic behavior at room temperature, with higher magnetic moment intensity compared to samples prepared by the continuous growth process. Thus, an alternative approach for forming ferromagnetic nanostructures is presented.

NAMBE-MoP-22 Ultralow Threshold Surface Emitting Ultraviolet Lasing by Low-Temperature Selective Area Epitaxy of GaN Nanowires, ***Mohammad Fazel Vafadar***, *S. Zhao,* McGill University, Canada

Surface emitting lasers have become indispensable in our everyday life, with applications in a wide range of fields from optical communications and data transmission to medical diagnostics and therapeutics. While surface emitting lasers in the near-infrared (NIR) range are relatively mature,

progress in the development of GaN based surface emitting lasers operating in the ultraviolet (UV) range has been sluggish. To mitigate various issues related to conventional vertical cavity surface emitting lasers (VCSELs) such as material quality, mirror reflectivity, and so on, nanowire photonic crystals (NPCs) have received increasing attention over the past few years for surface emitting lasers. NPCs offer a promising approach by simplifying the design of the lasing cavity in which utilizing the photonic band edge mode at the *Γ* point in a photonic crystal structure can produce optical gain through the formation of slow light and further achieve light emission form top surface when proper diffraction condition is satisfied. However, for these lasers, the formation of NPCs often requires selective area epitaxy (SAE) at high substrate temperatures on patterned substrates. Such a high substrate temperature could affect the NPC formation and lasing performance.

Herein, we demonstrate ultralow threshold surface emitting lasing in the UV range by exploiting molecular beam epitaxy (MBE) grown GaN NPCs using low-temperature SAE regime, which offers an unprecedented controllability of nanowire formation on patterned substrates (Figure S1a). Utilizing GaN NPC arranging in a square lattice with a center-to-center spacing (*a*) of 200 nm and a nanowire diameter (d_{NW}) of 173 nm, UV SE lasing at ~367 nm is measured with a threshold of merely 7 kW/cm^2 (Figure S1b), a 100× reduction compared to the conventional AlGaN UV VCSELs at a similar wavelength (Figure S1c). Further developments on such GaN based surface emitting UV lasers will also be reported in the conference.

NAMBE-MoP-23 Trade-Off between Hall Sensitivity and Frequency Limit of Two-Dimensional Electron Gas Iii-Nitride Hall Effect Sensor*, **Satish Shetty**,* Institute for Nanoscience and Engineering, University of Arkansas, Fayetteville, AR, 72701, USA*; A. Hassan,* Department of Electrical Engineering, University of Arkansas, Fayetteville, AR, 72701, USA*; Y. Mazur,* Institute for Nanoscience and Engineering, University of Arkansas, Fayetteville, AR, 72701, USA*; H. Mantooth,* Department of Electrical Engineering, University of Arkansas, Fayetteville, AR, 72701, USA*; G. Salamo,* Institute for Nanoscience and Engineering, University of Arkansas, Fayetteville, AR, 72701, USA

We investigated the tradeoff between Hall sensitivity and frequency limit of an AlGaN/GaN two-dimensional electron gas Hall effect sensor. For this study, we utilized three different heterostructure designs that had variations in sheet carrier density, carrier mobility, sheet resistance, and capacitance. The heterostructure designs used for fabricating Hall sensors are capable of operating at high temperatures. The efficiency of Hall sensor quantified in terms of supply voltage-related sensitivity (SVRS) is 0.024, 0.044, and 0.051 T^{-1}, while the supply current-related sensitivity (SCRS) is 101, 48, and 67 VA^{-1} T^{-1}, similarly supply power related sensitivity (SPRS) is measured to be 57, 92, and 103 VW^{-1}T^{-1}, at room temperature respectively. By varying the Hall device carrier velocity, carrier density, and inbuilt capacitance, we investigate in detail the tradeoff between Hall sensitivity and frequency limit in terms of Hall signal rise time and phase shift.In addition, we have proposed a method to address the frequency limitation that arises from the current spinning technique. This method involves measuring the induced voltage at the Hall measurement terminal, which results from the time-variable magnetic field, without applying any external bias to the Hall sensor.

NAMBE-MoP-24 Photonic Crystal Surface Emitting Lasers (PCSELs) based on InAs Quantum Dots-in-a-Well*, **Thomas J Rotter**, S. Seth, K. Reilly, F. Ince,* Center for High Technology Materials, The University of New Mexico, Albuquerque, NM*; A. Kalapala, C. Gautam, Z. Liu,* Department of Electrical Engineering, The University of Texas at Arlington, Arlington, TX*; S. Addamane,* Center for Integrated Nanotechnologies, Sandia National Laboratories, Albuquerque, NM*; W. Zhou,* Department of Electrical Engineering, The University of Texas at Arlington, Arlington, TX*; G. Balakrishnan,* Center for High Technology Materials, The University of New Mexico, Albuquerque, NM

Lasers based on self-assembled quantum dot (QD) gain media have attracted considerable attention due to their low sensitivity to operating temperature and record-low threshold current densities. InAs QD based edge emitting lasers (EELs), vertical cavity surface emitting lasers (VCSELs) or vertical external cavity surface emitting lasers (VECSELs) have been demonstrated with excellent performance. In this study, we demonstrate a QD based optically-pumped photonic crystal surface emitting laser (QD-PCSEL). The PCSEL fabrication process includes epitaxial regrowth, which enables the photonic crystal (PC) to be buried in the laser's waveguide near the upper clad layers. The structure is grown using elemental source molecular beam epitaxy (MBE). In the first epitaxial step the bottom AlGaAs cladding layer and the GaAs waveguide including the QD active region are grown. In the next step, the wafer is removed from the MBE reactor and the PC layer is fabricated by electron beam lithography (EBL) patterning and etching into the GaAs waveguide using inductively coupled plasma (ICP) dry etching. Subsequently the top AlGaAs cladding layer and a top contact layer are grown on the sample. One of the most crucial steps is the removal of the native oxide before growing the top clad layer. This is accomplished by an acid etch prior to loading the sample into the vacuum chamber and a thermal surface treatment with arsenic supply prior to growth. The thermal step at >600°C can alter the QD gain medium, i.e. cause a blue shift and narrowing of the emission spectrum of self-assembled QDs [1-3]. This study employs a dot-in-a-well (DWELL) design as the active region, where the InAs QDs are embedded in a InGaAs quantum well (QW). Our experiments indicate that the DWELL active region is stable during the regrowth process, i.e. there is no significant change to the emission wavelength. This is key to the realization of this laser. The PCSEL is tested by optical pumping and we present measurements of both light-input light-output (LL) and optical spectrum.

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NAMBE-MoP-25 Determination of Optical Properties and Band Structure Parameters of MBE-grown InAs and InAsSb Bulk and InAs/InAsSb and InGaAs/InAsSb Superlattices from Photoluminescence Lineshape*, **Marko Milosavljevic**,* Arizona State University*; P. Webster,* Air Force Research Lab*; S. Johnson,* Arizona State University

The development of sensors that operate in the mid (3-5 µm) and long (8-14 µm) wavelengths are essential for space-based sensing applications. Many Sb-based, III-V material solutions exist ranging from random alloys to superlattices. Furthermore, the growth of high-quality coherently-strained materials is required to achieve the desired long (1-10 µs) lifetimes for sensor applications. Yet, performance is limited by alloy and interface disorder and also band structure. The impact of disorder on the performance and band structure of MBE-grown InAs, InAsSb, InAs/InAsSb, and InGaAs/InAsSb is examined using the temperature and excitation dependent photoluminescence lineshape.

The excitation and temperature-dependent measurements are analyzed using a lineshape model that is sensitive to the band structure parameters, including bandgap energy, characteristic energy of Urbach tail states, and the electron-hole effective mass ratio and Coulomb interaction. The model also captures the quasi-Fermi level separation, which is the chemical potential of the photoexcited electron-hole population. As a result, the model predicts an excitation induced blue-shift in the lineshape peak position as the chemical potential approaches the bandgap energy. Furthermore, the lineshape model predicts the so-called S-shape behavior of the peak position as a function of temperature and excitation for materials with large Urbach tails. The S-shape behavior typically occurs at low temperatures, where in disordered materials, the width of the electronic Urbach tail states exceeds the width of the thermal Fermi occupation tail. This causes the lineshape to red shift as the electron-hole chemical potential is reduced and the occupied tail states dominate emission. As the temperature is reduced further, the chemical potential for a given excitation density increases, thereby blue-shifting the lineshape peak back towards the bandgap, thus completing the S-shape.

In the experiment, the various materials listed above are grown by MBE and examined using excitation and temperature dependent photoluminescence spectroscopy. The measurement temperatures range from 12 to 295 K and the pump powers range from 0.4 to 200 mW. The lineshape model is fit to the resulting families of spectra from each material. From the results, i) the lineshape peak position and the chemical potential of the photoexcited electron-hole population is determined as a function of both pump power and temperature, ii) the bandgap and Urbach tail width are determined as a function of temperature, and iii) the effective mass ratio is determined as a single global parameter for all temperatures and excitations measured.

NAMBE-MoP-26 Comparative Study of the Temperature Quenching of the Excitonic Emission of CdSe and ZnCdSe Quantum Wells*, J. Pérez-Saavedra, Y. Vázquez-Soto, F. Sutara, **Isaac Hernández-Calderón**,* CINVESTAV, Mexico

The tuning of the excitonic emission of $Zn_{1-x}Cd_xSe$ quantum wells (QWs) within ZnSe barriers to a specific photon energy can be made by choosing diverse combinations of quantum well thickness and alloy composition (*x*). However, the photoluminescence (PL) properties will not be the same because the electronic structure of each QW will present differences. With

the purpose of optimizing the luminescence emission, it is particularly interesting to compare the PL properties of $Zn_{1-x}Cd_xSe$ alloy QWs versus the binary CdSe QW. Here, we present a study of the quenching of the PL with temperature in the range of 20 to 300 K of an 8 monolayers (MLs) thick $Zn_{1-x}Cd_xSe$ (x ~ 0. 38) QW and a 2 ML thick CdSe QW, both embedded in the same heterostructure. The CdSe QW was grown closer to the heterostructure surface. The $Zn_{1-x}Cd_xSe$ QW was grown on a 0.5 µm ZnSe buffer layer grown on top of a deoxidized GaAs (001) substrate. The QWs were separated by a 100 nm ZnSe barrier and on top of the 2 ML CdSe QW a 60 nm ZnSe cap layer was deposited. The PL excitation was provided by the 442 nm line of a HeCd laser. The QWs presented a very bright blue-green low temperature (LT) excitonic emission which was still intense at room temperature (RT). The behavior of the band gap of the QWs with increasing temperature indicates the presence of small potential fluctuations, which are lower for the CdSe QW. At 20 K, the CdSe QW doubles the intensity of the $Zn_{1-x}Cd_xSe$, and both QWs show an apparently anomalous increase in emission from 20 K up to ~ 80 K, then, the emission diminishes, as expected. After ~ 80 K the CdSe QW presents a slightly faster PL quenching up to RT. The quenching of the emission with increasing temperature is explained in terms of the heterostructure geometry and the specific electronic structure of each QW.

NAMBE-MoP-27 Mbe Epitaxy Solution of the Quantum Well Heterostructure: Atomistic Tnl-Epigrow Simulator, ***Praveen Kumar Saxena,*** Tech Next Lab, Lucknow, India*; P. Srivastava, A. Srivastava,* Tech Next Lab, India

The use of standard manufacturing techniques based on highly uniform and well controlled MBE growth on GaAs wafers paves the way for the development of quantum well heterostructure-based semiconductor device technologies, e.g., infrared sources and detectors, memories, lasers, solar cells, HEMT, etc. In order to create a high-quality quantum well, the layers of semiconductor material must be grown with extremely high precision, with thicknesses that are accurate down to the atomic scale. This requires sophisticated equipment and expertise. Even a small variation in the growth process can lead to defects in the material that can significantly impact its electronic properties. The substrate temperature and flux are important factors that affect the growth. A small fluctuation in the substrate temperature, or flux, during the growth process generates several defects. The intensity of the atomic/molecular beam current depends not only on the temperature of the beam source furnace, but also on other influencing factors, such as the shape of the crucible opening and the surface area of the source material. So, it is difficult to extract the right values of flux. The calibration of the flux requires a hit-and-trial. It results in the waste of various costly raw materials, manpower consumption, time, etc., with no guarantee of reproducibility of similar results due to the occurrence of various unpredicted events during growth [1 -2].

In the present paper, the authors have attempted to provide a solution through atomistic simulation to reduce the experimentation cost and the technology development time cycle. To demonstrate the capabilities of the TNL-EpiGrow™ simulator, the MBE growth simulation example used GaSb substrate to simulate the three periods of InAs and AlSb epitaxy, respectively, at atomistic scale. The input conditions used in the simulation are given in Table I. The capabilities to extract the position of each atom on the lattice provide direct access to the various details of the growth morphology, along with defects generated in each monolayer. [2 - 5].

The optimization of the flux is carried out by variations in the effusion cell temperature under the MBE reactor environment. The GaSb/InAs/AlSb quantum well structure is depicted in Fig.1, and the other data are tabulated in Table II. The results are matched with the experimental results [6].

TNL-EpiGrow™simulator shows great promise for epitaxial growth of II-VI and III-V materials based on various reactor geometries, with potential capabilities to understand the underlying atomistic process inside the reactor [2-5].

NAMBE-MoP-28 Room Temperature Extended Shortwave Infrared Light Emitting Diode, *M. Benker,* Applied NanoFemto Technologies LLC*; G. Gu,* Stonehill College*;* ***Xuejun Lu,*** University of Massachusetts - Lowell

High efficiency infrared light emitting diode (LED) are needed in numerous sensing and imaging applications. In this paper, we report an exteneded shortwave infrared (e-SWIR) LED cacapble of working at room temperature (RT). To extend the detection wavelength, the e-SWIR is based on a higher indium (In) composition, i.e. $In_{0.3}Ga0.7As0.25Sb0.75$/GaSb/AlGaSb multiple quantum well (MQW) heterostructures. The strong carrier confinement allows the e-SWIR LED to work at RT. Detailed analysis and experimental results will be presented.

NAMBE-MoP-29 Infrared Plasmon-Polariton Modes in Hyperbolic Metamaterials Made from Patterned Doped/Undoped InAs Multilayers, *E. Caudill,* University of Oklahoma*; M. Lloyd,* US Naval Research Laboratory*; K. Arledge, T. Mishima, C. Cailide,* University of Oklahoma*; J. Nolde, C. Ellis,* US Naval Research Laboratory*; P. Weerasinghe, T. Golding,* Amethyst Research Inc*; J. Murphy,* US Naval Research Laboratory*;* ***Michael Santos****, J. Tischler,* University of Oklahoma

In *k*-space, the iso-frequency surface of an electromagnetic wave in a hyperbolic material is a hyperboloid, in contrast to the spherical or elliptical surface for an ordinary dielectric material. This unusual property arises when one principal component of the dielectric tensor has the opposite sign to the other two principal components. Hyperbolic materials are expected to exhibit a range of distinctive behaviors, including negative refraction and enhanced superlensing effects [1]. Ionic crystals with anisotropic optical-phonon frequencies provide natural low-loss infrared hyperbolic resonances through the excitation of phonon polaritons. However, the operational bandwidth of these materials is limited to a few hundred wavenumbers (cm^{-1}) or tens of millielectronvolts. A promising route to a wider infrared bandwidth is the excitation of plasmon polaritons in homoepitaxial material engineered to have alternating layers of high- and low-carrier concentration [2,3].

In this work, we implement a low-loss Type-II hyperbolic metamaterial covering a wide spectral bandwidth of 2000 cm^{-1} for wavelengths above 5.3 µm. We produced the hyperbolic metamaterial with a stack of intercalated heavily-doped InAs and undoped InAs epilayers grown by molecular beam epitaxy. Electron concentrations of 7×10^{19} cm^{-3} were obtained by Tellurium doping of InAs epilayers and the optical properties of this stack were measured by infrared ellipsometry. These materials were then dry etched to form one-dimensional square gratings (with periods from 2 to 10 µm) and modeled by finite-element electromagnetic calculations (COMSOL). The models agree with measurements, showing the formation of hyperbolic plasmon polaritons at the same frequencies where experimental features were observed. Additionally, we have identified an Epsilon Near Zero mode associated with long-range surface plasmon polaritons contained in the dielectric layers. This work demonstrates that highly subdiffractional light confinement can be achieved with a III-V metamaterial that can be integrated with III-V semiconductor infrared devices such as photodetectors and emitters at a large scale.

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NAMBE-MoP-30 Impact Ionization Coefficients in $Al_{0.9}Ga_{0.1}as_{0.08}Sb_{0.92}$ Lattice Matched to GaSb, ***Jingze Zhao,*** *E. Portyankin, L. Sheterengas, D. Donetski, G. Kipshidze, G. Belenky,* Stony Brook University/Brookhaven National Laboratory

There is a demand for mid-wave infrared (MWIR) photodetectors capable of detecting single photons for advanced industrial, military, and biomedical applications. This goal can be realized with cooled avalanche photodiodes (APD) operating in Geiger-mode for single photon counting. The development of the APDs with InAsSb absorption and AlGaAsSb multiplication regions grown lattice matched to GaSb was pursued. $Al_{0.9}Ga_{0.1}As_{0.08}Sb_{0.92}$ alloys are reported to have high hole impact ionization coefficients compared to electrons in these materials as well as greater than the corresponding coefficients in other semiconductors[1]. Following the procedure in Ref. 1 we determined the hole and electron multiplication coefficients in $Al_{0.9}Ga_{0.1}As_{0.08}Sb_{0.92}$separately using p-i-n and n-i-p diodes within the field range of 140 to 600 $kVcm^{-1}$. The structures were grown in Veeco GEN-930 solid-source MBE system. The p-i-n diode structures for measurements of the hole impact ionization coefficient were grown on p-type GaSb substrates consisting of a 500-nm-thick $Al_{0.9}Ga_{0.1}As_{0.08}Sb_{0.92,}$ Be-doped contact layer, a 300-nm-thick nominally undoped $Al_{0.9}Ga_{0.1}As_{0.08}Sb_{0.92}$hole multiplication region, and a 1.2-mm thick $Al_{0.9}Ga_{0.1}As_{0.08}Sb_{0.92}$Te-doped top contact layer capped with a 50-nm-thick Te-doped GaSb. The n-i-p diode structures for electron impact ionization measurements were grown on n-type GaSb with Te-doped, undoped and

Be-doped $Al_{0.9}Ga_{0.1}As_{0.08}Sb_{0.92}$ layers of similar thicknesses. The wafers were processed into diodes with mesa diameters in the range from 80 mm to 320 mm. CV measurements confirmed that the 300-nm-undoped multiplication regions were fully depleted. Temperature dependences of I-V characteristics showed that above 140 K the dark current was limited by thermal generation of excess carriers in the depletion region with the activation energy of 0.3 eV. The carrier multiplication coefficients were determined by measuring photocurrent versus bias voltage. For a nearly complete absorption of photons in the top layer and multiplication dominated by one type of carriers the excess carriers were generated at 532 nm. Preliminary experimental data show that the hole ionization coefficients are up to 100 times greater than the electron ionization coefficients.

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NAMBE-MoP-31 High-Mobility III-V Core-Shell Nanowire Heterostructures for Thermoelectric Energy Conversion, ***Genet Bacha Hirpessa,*** Technical University of Munich, Germany*; S. Fust, R. Maier,* Technical University Munich, Germany*; F. Del Guidice, J. Finley,* Technical University of Munich, Germany*; G. Koblmüller,* Technical University Munich, Germany

Thermoelectric energy conversion offers widespread applications in waste heat recovery for power generation but requires suitable materials with large thermoelectric conversion efficiency. To aim at high efficiency with large figure-of-merit $ZT=\sigma S^2T/\kappa$, relevant parameters such as electrical conductivity (σ), thermoelectric power factor (σS^2), and thermal conductivity (κ) need to be optimized for any given Seebeck coefficient S and operating temperature T. Due to the interdependence between thermal and electrical properties, modification of parameters for high ZT is limited in bulk materials, but in nanostructures, the properties can be decoupled[1].

The aim of our research is to demonstrate independent control of these parameters by exploiting the 1D density of states in very high mobility III-V nanowires (NWs). First proof-of-principle studies were performed on modulation-doped GaAs-AlGaAs core-shell NWs grown by MBE, where we found enhanced thermopower in 1D-subbands at substantially lowered κ[2]. While these initial studies were limited to cryogenic temperatures, studying more suitable low-bandgap III-V materials with lower electron effective mass are more appealing for enhanced 1D-thermoelectric transport at higher temperatures. Here, we show our recent progress towards InAs/AlAsSb core-shell NW heterostructures[3], where both contact formation establishment and electrical characterization were performed up to elevated temperatures. Using NW-field effect transistor (NW-FET) test structures, the DC output characteristics were confirmed and transfer characteristics up to temperatures >100 K demonstrated clear 1D sub-band quantization, with transmission probabilities of ~0.4 for 700-nm long channel devices.

To further introduce n-type modulation-doping (Si-δ doping) into the InAs/AlAsSb core-shell NW-system, two strategies are illustrated: first, δ-doping of a very thin (<2nm-thin) InAs quantum well (QW) embedded in the AlAsSb shell to overcome the otherwise p-type nature of amphoteric Si-dopants in Al(As)Sb[4]. Secondly, we also developed quaternary InAlAsSb shell layers to enable direct Si-δ doping without the need of InAs QWs. By guiding the design via band-profile calculations (nextnano-3), first results of the MBE growth and structural characterization of the desired InAs-InAlAsSb core-shell NW heterostructures are demonstrated[5].

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NAMBE-MoP-32 Wafer Scale GaAs/AlGaAs Core-Shell Nanowires on 2-inch Si Substrate Showing Efficient Light Emission/Absorption with High Thermal Stability, ***Keisuke Minehisa,*** *H. Hashimoto, K. Nakama,* Research Center for Integrated Quantum Electronics, Hokkaido University, Japan*; H. Kise, S. Sato, J. Takayama, S. Hiura, A. Murayama, F. Ishikawa,* Faculty of Information Science and Technology, Hokkaido University, Japan

Semiconductor nanowires (NWs) are promising materials for nanoscale devices with diameters of less than several hundred nanometers. GaAs has a high electron mobility and direct bandgap, and is used in lasers, solar cells, and transistors through heterojunctions with related compounds. In addition, the integration of III-V semiconductor NWs on Si can integrate superior electrical and optical properties to mature Si technology, which is expected to be applied to the next generation optical and electronic devices. However, the surface recombination velocity of GaAs is several orders of magnitude higher than that of other III-V semiconductors, and the effect is further exacerbated by the large surface-to-volume ratio in NWs. To suppress the effect of non-radiative recombination, surface passivation on the GaAs core with an AlGaAs shell is known to be effective.[1] Besides, preserved material properties at temperatures higher than room temperature is desirable for the practical device applications.

We here report wafer scale growth of GaAs/$Al_{0.8}Ga_{0.2}As$ core–shell NWs on the 2-inch Si(111) wafer by constituent Ga-induced vapor–liquid–solid growth using molecular beam epitaxy (MBE).[2]The sample is investigated by the optical reflectance, photoluminescence (PL) and time-resolved PL measurements from 300 to 400 K. The nature of the light scattering induced by the complex NWs structure on the Si substrate enables the measurement of diffuse reflectance, making the Kubelka-Munk (K-M) transformation[3] to be applicable, obtaining the absorption characteristics of the sample. The sample shows a low optical reflectance less than 2% at energies higher than GaAs absorption edge in the visible to near-infrared region at 300 K, resulting in the dark observation of the sample wafer. That band gap of the sample is estimated to be 1.41 eV from the K-M plot, and it's deviation between the PL peak energy suggests that the Stokes shift is close to be negligible. The carrier lifetime obtained from the time-resolved PL measurement is longer than 1 ns between 300 and 400 K. That indicates the effective passivation of the GaAs core by the AlGaAs shell, suppressing the surface non-radiative recombination. From these results, we obtain wafer scale GaAs/AlGaAs core-shell nanowires on 2-inch Si(111) substrate showing efficient light emission/absorption with high thermal stability.

NAMBE-MoP-33 Optimizing Growth on GaAs (111)B for Enhanced Parametric Downconversion Efficiency in Quantum Optical Metasurfaces, ***Trevor Blaikie,*** University of Waterloo, Canada*; S. Stich,* Walter Schottky Institut, Technische Universität München, Germany*; M. Tam,* University of Waterloo, Canada*; M. Belkin,* Walter Schottky Institut, Technische Universität München, Germany*; M. Chekhova,* Max-Planck-Institut für die Physik des Lichts, Germany*; Z. Wasilewski,* University of Waterloo, Canada

Quantum optical metasurfaces (QOMs) hold promise for generating entangled photons and engineering complex quantum states. To generate entangled photon pairs, QOMs leverage spontaneous parametric downconversion (SPDC). Despite SPDC being the leading method for generating entangled photon pairs in quantum optics, QOMs dependent on SPDC face limitations due to low conversion efficiency. This project aims to enhance SPDC efficiency in QOMs by utilizing GaAs (111)B substrates for the growth of the bulk GaAs material from which the QOMs are fabricated.

GaAs is appropriate for QOMs because of its very high second-order susceptibility. It is predicted that the nonlinear response of GaAs in the (111) orientation is even stronger than it is in the typically used (001) orientation. Calculations indicate a potential 1-3 orders of magnitude increase (pump frequency dependent) in QOM conversion efficiency for GaAs with (111) surface orientation as compared to (001).

Growth on (111) oriented GaAs substrates is challenging and requires a very different set of growth parameters for optimized deposition than growth on (001) surface; therefore, precise in-situ monitoring and control are necessary.

In the pursuit of optimized growth parameters, we have grown GaAs and AlGaAs on GaAs (111)B substrates with an intentional 2° surface misorientation towards [11-2]. In-situ reflection high-energy electron diffraction (RHEED) is monitored to observe changes in surface reconstruction. Desorption mass spectrometry is used to monitor the group V/III ratio. A laser light scattering system has been implemented to measure the diffuse scatter from the wafer during the epitaxial process. The latter is a sensitive probe of the onset of roughening of the growth front.

Ex-situ, the growth surface morphologies are studied with Nomarski interference contrast microscopy and atomic force microscopy. Surface morphologies resulting from different growth conditions will be compared, and their effect on QOM fabrication and operation will be discussed.

NAMBE-MoP-34 Magnetization Switching Behavior in Anisotropy Gradient GaMnAsP Film Grown by Molecular Beam Epitaxy, ***Kyung Jae Lee,*** Korea University, Canada*; S. Lee,* Korea University, Germany*; X. Liu,* University of Notre Dame, Canada*; M. Dobrowolska, J. Furdyna,* University of Notre Dame, Germany

Magnetization switching behavior of GaMnAsP ferromagnetic semiconductor (FMS) films with magnetic anisotropy gradient along the

growth direction has been investigated. To achieve such magnetic anisotropy gradient in the GaMnAsP film, the phosphorus concentration was gradually decreased from 24% to 3% with step of about 5 % during the growth of 62.5 nm film by molecular beam epitaxy. The continuous adjustment of phosphorus results in a change of strain from tensile to compressive in the film. Such strain gradation leads a progressive change of the magnetic anisotropy of the film from out-of-plane to an in-plane direction.In order to perform the spin-orbit torque (SOT) magnetization switching experiments, a Hall device was fabricated along the [110] crystal direction where the Rashba-type and Dresselhaus-type spin-orbit fields are antiparallel to each other. The SOT magnetization switching experiment was performed at a temperature of 2.5 K by applying a pulsed current of 10 ms duration in the presence of an in-plane bias field. The magnetization state was monitored by Hall resistance (HR) measurement, in which a small direct current of 10 uA was used for sensing magnetization. We observed that the chirality of magnetization switching changes depending on the strength of the external field. Specifically, the SOT switching chirality changes from clockwise at a small external field (e.g., 200 Oe) to counterclockwise as the field increases (e.g., 1000 Oe), and then back to clockwise again at a strong field (e.g., 2500 Oe). This unusual dependence of SOT switching chirality on the strength of an in-plane external field can be explained by the coexistence of the in-plane and out-of-plane magnetization components, which vary with strength of in-plane external fields.

NAMBE-MoP-35 Growth, Electrical and Optical Properties of $SrMoO_3$ Grown by Suboxide Molecular Beam Epitaxy, ***Roman Engel-Herbert,*** Paul - Drude-Institute for Solid State Electronics, Leibniz Institute within the Forschungsverbund Berlin, Germany*; T. Kuznetsova, J. Roth, J. Lapano, A. Pogrebnyakov,* Penn State University

Correlated metals with perovskite structure have generated much interest due to their intriguing combination of electrical and optical properties rendering them as alternative transparent conductor material to degenerately doped wide band gap oxide semiconductors, such as ITO. While $SrVO_3$ and $CaVO_3$ have been reported to outcompete ITO, $SrNbO_3$ has been shown unparalleled performance of electrical conductivity while maintaining a high optical transparency deep into the UV range to show unparalleled performance in the UV range. $SrMoO_3$ is yet another candidate material, which meets the requirement of the new transparent conductor design paradigm.

In this talk we will discuss the growth of SrMoO3 thin films by suboxide molecular beam epitaxy. We will show that optically transparent and electrically conductive $SrMoO_3$ films can be grown by supplying elemental strontium via a conventional effusion cell and thermally evaporating MoO_3 pellets as a molybdenum source. The direct supply of a molecular oxygen flux to the MoO_3 charge was found critical to prevent Mo reduction to lower oxidation states and to ensure congruent evaporation. Optimal growth conditions were found by varying the Sr to MoO_3 flux ratio resulting in $SrMoO_3$ films being optically transparent with transmission between 75 toand 91% throughout the visible spectral range, and electrically conducting with a room temperature resistivity of 5.0 × 10-5 Ω· cm.

NAMBE-MoP-36 Modeling and Characterization of GaAsSb/InGaAs 'W'-Quantum Wells with GaAsP Strain Compensated Layers, *Z. Li, T. Lo,* ***Charles W. Tu,*** National Chung Hsing University, Taiwan

Vertical-cavity surface-emitting lasers (VCSELs) have applications in facialrecognition in smart phones, 3D sensing for augmented reality/virtual reality, etc. The current VCSELs emitting at 940 nmfor cell phones are manufactured on GaAs substrates, utilizing the well-established GaAs/AlGaAs distributed Bragg reflectors (DBRs). However, long-wavelengths, 1300 nm to 1550nm,are desirablefor eye-safety and transparency to cell phone screens.

Here we explore strain-compensated GaAsP/InGaAs/GaAsSb W quantum wells (W QWs), grown by MBE, for long-wavelength emission on GaAs substrates. The tensile-strained GaAsP compensates for the compressive-strained InGaAs and GaAsSb layers. Three cycles (samples A-D) and one cycle (samples E and F) of $GaAs_{1-z}P_z/In_yGa_{1-y}As/GaAs_{1-x}Sb_x/In_yGa_{1-y}As/GaAs_{1-z}P_z$ 'W' QWs were grown with$y$ = 0.3 and z = 0.3. The Sb composition (x = 0.06-0.21) of $GaAs_{1-x}Sb_x$ QW in all samples was controlled by the QW growth temperature in the range of 410-520 ^{o}C. X-ray rocking curve (XRC) analysis and 20K photoluminescence (PL) measurement are performed.

The W QW with different Sb contents are modelled by the energy band-diagram simulations. The input parameters, QW thicknesses and material compositions, are extracted by the XRCanalysis. The one-cycle of 15 nm-$GaAs_{1-z}P_z$/3.5 nm-$In_yGa_{1-y}As$/16 nm-$GaAs_{1-x}Sb_x$/3.5nm-In$yGa_{1-y}As$/15nm-$GaAs_{1-z}P_z$WQWstructureis designed as shown in **Fig. 1**. The strained bandgap energies of QWs are obtained from the bulk bandgap using various bowing parameters as the fitting parameters and energy shifts due to strain using various deformation potentials.

where b_i is the bowing parameters, and i = g, c, $v_{hh,\ lh}$ for bandgap, conduction and heavy hole/light hole valence bands, respectively. The material parameters are taken from the literaturefor the end compounds of InAs, GaSb, GaP and GaAs. In our calculations, the bandgap bowing parameters b_g of $GaAs_{1-x}Sb_x$ and $InGa_{1-y}As_y$ are set as the fitting parameters to our experimental results. The experimental PL peak positions can be fit well by b_g of -1.58 and -1.1 for the strained $GaAs_{1-x}Sb_x$ and $In_yGa_{1-y}As$ QWs, respectively.The one-band time-independent Schrödinger equation with Hamiltonian in the effective mass approximation is solved by COMSOL Multiphysics, enabling us to obtain the electron and hole wavefunctions, the energy levels of electrons in conduction band and holes in valence band, and the estimated emission wavelengths.

In summary, in consideration of strain effect in band alignment simulation, the PL peak positions as a function of Sb composition (samples A-C) are well fitted by the simulated transition wavelength of strained WQWs at 20 K

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