Novel Materials
Room Swan A & Sandpiper - Session NM-MoP
Novel Materials Poster Session

NM-MoP-1 Slow Photoluminescence Lifetime of Heavily Be-doped GaAsN,
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The GaAsN alloy has been receiving increasing attention owing to its drastic band gap reduction property in a dilute nitrogen composition ([N]) [1]. Therefore, a heavily doped p-type GaAsN system alloy such as (In)GaAsN is expected to be applicable for a tunnel diode inserted to a multi-junction solar cell with GaAs system alloys [2]. In this multi-junction solar cell, the recombination mechanism is needed to be revealed for increasing its efficiency. For undoped GaAsN and lightly Si-doped n-type GaAsN, the recombination mechanisms were systematically discussed using both continuous and time-resolved photoluminescence (PL) measurements [3, 4]. However, it was only partially discussed for heavily doped p-type GaAsN using the continuous PL measurement [5]. Therefore, in this study, temperature dependence of PL lifetime is evaluated using the time-resolved PL measurement to reveal the recombination mechanism for heavily Be-doped p-type GaAsN.

Be-doped GaAsN layers were grown by radio-frequency plasma-assisted molecular beam epitaxy on semi-insulating GaAs (001) substrates using nitrogen RF plasma. The Be impurity concentrations ([Be]) were designed at 1×10^{19}, 6×10^{19}, and 3×10^{20} cm^{-3}, and [N] was fixed at about 0.8 %. The time-resolved PL measurement unit consisted of a picosecond Ti-sapphire laser with a photon energy of 1.80 eV and time-correlated photon counting module using superconducting single photon detector.

PL decay curves are well fitted by the bi-exponential decay function for Be-doped GaAsN independent of [Be] and temperature, meaning that two distinct PL lifetimes coexist as well as undoped GaAsN and lightly Si-doped GaAsN [3, 4]. Especially, the slow PL lifetimes are slightly less than 1 ns for Be-doped GaAsN independent of [Be] and temperature, which correspond to the optical transition from inherent localized levels in dilute GaAsN [3, 4, 6]. This result also shows that these localized levels are formed for ultra-heavily Be-doped GaAsN with extremely high [Be] of 3×10^{20} cm^{-3}. In contrast, the fast PL lifetimes tend to decrease with increasing [Be] for Be-doped GaAsN. This is due to increasing density of nonradiative recombination centers with increasing [Be] for Be-doped GaAsN. On the basis of these discussions of two distinct PL lifetimes, the recombination mechanism is revealed for heavily Be-doped GaAsN.

References

[1] J.A.H. Coaquira *et al*., JAP, 102 (2007) 073716.

[2] D.E. Mars *et al*., APL, 84 (2004) 2560.

[3] C. Chen *et al*., JAC, 699 (2017) 297.

[4] Z. Zaaboub *et al*., SSC, 314 (2020) 113913.

[5] K. Umeno *et al*., JCG, 312 (2010) 231.

[6] T. Tsukasaki *et al*., Physica B, 625 (2022) 413482.

NM-MoP-2 A Route Towards Actinide Heterostructure Synthesis and Science,
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Actinide-based materials possess unique physics due to the presence of 5*f* electrons, yet their study has been primarily focused on nuclear fuel applications, leaving aspects of their fundamental physics largely open for investigation. Effective examination of the unique quantum phenomena in these materials requires high purity monocrystalline samples. However, thin film synthesis of actinide compounds is particularly underexplored relative to other material systems because of limited source availability and safety regulations due to radioactivity. We will discuss the promises, challenges, and synthesis routes for these actinide-bearing heterostructures. Molecular beam epitaxy (MBE) presents an attractive avenue for the study of actinide heterostructures because of the high degree of control over dimensionality, strain, and interfaces. Idaho National Laboratory has recently installed an MBE chamber with the specific goal of studying uranium, cesium, and thorium containing compounds. To facilitate deposition of these low vapor-pressure elements, the chamber is outfitted with a quad-pocket electron beam source, several high temperature cells, and a nitrogen plasma source. Introductory studies on transition metals with complex oxidation states (Zr, Nb, Mn, Ni, and Cr) will function as early-stage surrogates for actinide-based nitride compounds. These new capabilities will create unrivaled opportunities for the exploration of functional and energy materials with complex electron correlations and provide important experimental validation for computational models of these systems.

NM-MoP-3 Epitaxial Growth of Antimony Selenide on Bismuth Selenide,
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In addition to being a traditional thermoelectric material, Sb_2Se_3 has recently been investigated as a candidate for next generation photovoltaic devices, such as solar cells. Under ambient conditions, Sb_2Se_3 has orthorhombic crystal structure. It has recently been shown that rhombohedral Sb_2Se_3 can be stable up to five quintuple layers (5QL≈5nm) when grown on top of Bi_2Se_3, a topological insulator. In rhombohedral Sb_2Se_3, a quintuple layer refers to vertical stacking of atomic layers of 'Se-Sb-Se-Sb-Se' which make up one monolayer. Angle-resolved photoemission spectroscopy measurements on the Sb_2Se_3-Bi_2Se_3 heterostructure indicate that the rhombohedral Sb_2Se_3 is a topologically trivial material at ambient pressure. Beyond 5QL thickness, Sb_2Se_3 films tend to form in the thermodynamically stable orthorhombic phase.

To grow heterostructures of Sb_2Se_3 and Bi_2Se_3 that take advantage of the Sb_2Se_3 photovoltaic properties and the topological properties of Bi_2Se_3, we have investigated growth of 50nm Sb_2Se_3 on a 10nm Bi_2Se_3 seed layer on sapphire via direct co-deposition in a Veeco GENxplor R&D molecular beam epitaxy system. Instead of the 'worm-like' structure that is normally obtained when Sb_2Se_3 is directly grown on sapphire, we see a hexagonal mesh of orthorhombic Sb_2Se_3 nanoneedle structure. The surface roughness of the Sb_2Se_3 film decreases as the substrate temperature decreases from 300°C to 150°C. From the x-ray diffraction (XRD) pattern, we conclude that the Sb_2Se_3 growth plane is (021), and its crystallinity is enhanced by adding a Bi_2Se_3 seed layer instead of growing directly on sapphire. A high index plane of Bi_2Se_3 is obtained when we grow it on the mesh of Sb_2Se_3 nanoneedles rather than the standard (001) orientation. This research has paved the way for investigations of Sb_2Se_3 heterostructures with novel quantum materials like Dirac/Weyl semimetals and topological insulators.

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NM-MoP-4 Defect Free Ingaas/Inalas Superlattice on a Inp(111)B Substrate,
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Epitaxial growth on (111) substrates, using molecular beam epitaxy (MBE), was mainly studied in the 1970s, 1980s and 1990s with the focus on GaAs [1-3]. However, since most of the growth conditions resulted in a defective and rough surface, McFee et al. [4] concluded that growth on (111) substrates is too difficult; therefore, efforts should focus on (001) surfaces for reproducible device quality epitaxial layers. In recent years, growth on the polar (111) surfaces has generated renewed interest due to the emergence of new applications. Prime examples are devices based on spin transport [5] and novel tensely strained quantum dots for quantum computing applications [6].

InGaAs/InAlAs grown on (001) InP substrates has application in optoelectronics. Also, MBE-grown InGaAs/InAlAs superlattices (SLs) on (001) InP have been successfully used for terahertz (THz) transmitters (Tx) and receivers (Rx) in photoconductive antennas for THz time-domain spectroscopy systems [7]. Unlike the more established MBE-grown low-temperature GaAs (LT-GaAs), InGaAs can be excited over fiberoptics at a wavelength of 1.55 µm using compact and relatively inexpensive telecom lasers. However, MBE growth conditions must be separately optimized for Tx and Rx structures, adding to cost and complexity. Recently, InGaAs/InAlAs SLs grown on InP(111) substrates were proposed as a next-generation material system, combining advantages of LT-GaAs and non-polar InGaAs/AlGaAs material systems. However, attempts resulted in defective growth [8]. Additional tailoring of strain in (111) InGaAs and InAlAs SL layers can embed strong piezoelectric fields in the material, bringing further enhancement of the Tx and Rx antennas performance without the need for individual MBE growth optimization.

With the use of density functional theory calculations and extensive scanning transmission electron microscopy (STEM) analysis along with the STEM Moiré Geometrical Phase analysis, we showed the first defect-free epitaxial growth of InGaAs/InAlAs heterostructures on InP (111)B

substrates. Our work sets the stage for developing InGaAs/InAlAs/InP(111) photoconductive antennas for THz-TDS system with properties tuned by the embedded piezoelectric fields.

[1] K.C. Rajkumar et al., J. Appl. Phys. 69, 2219 (1991).
[2] H.Q. Hou et al., Appl. Phys. Let. 62, 281 (1993).
[3] M.R. Fahy et al., Appl. Phys. Let. 64, 190 (1994).
[4] J.H. McFee et al., J. Electrochem. Soc. 124, 259 (1977).
[5] M. Yamada et al., NPJ Asia Mat. 12, 47 (2020).
[6] C.F. Schuck et al., Scientific Report 9, 18179 (2019).
[7] R.J. Dietz et al., Optics Express 19, 25911 (2011).
[8] G.B. Galiev et al., Crystallography Reports 65, 496 (2020).

NM-MoP-5 Site-Controlled InAs Quantum Dot Columns for Templating Self-Assembled Quantum Dots*, L. McCabe, **Nazifa T. Arony**, J. Zide,* University of Delaware

We present on the growth of low-density, site-controlled InAs quantum dot columns (QDCs) for templating high optical quality, self-assembled InAs quantum dots (QDs) and quantum dot molecules (QDM). The epitaxial formation of InAs QDs has been extensively studied[1] and have largely been considered as possible qubits[2]. However, a scalable platform to produce large arrays of identical QDs for integration into semiconductor devices is still being refined[3]. It is a challenge to produce high-optical quality site-templated QDs due to the presence of defects at the regrowth interface. We have previously shown a molecular beam epitaxy (MBE) grown low-density site-templated InAs QD platform[4]. Using this initial site-controlled growth, we are exploring the growth and morphology of InAs QDCs to serve as templated buffer layers for self-assembled QDs. This method maintains the spatial location of our patterns while obtaining QDs with optical qualities of self-assembled structures.

[1] Prog. Mater. Sci. 64, 121-199 (2014) [2] Adv. Quantum Technol. 3, 1900034 (2020) [3] J. Vac. Sci. Technol. A 39, 010802 (2021) [4] J. Vac. Sci. Technol. B 38, 022803 (2020)

NM-MoP-6 Characterizing SiGeSn Stability by Temperature Varying Spectroscopic Ellipsometry*, **Amanda Lemire**, K. Grossklaus, T. Vandervelde,* Tufts University

Tin-containing group IV alloys are being developed for infrared photonic devices. $Si_{1-x-y}Ge_xSn_y$ alloys grown by molecular beam epitaxy, particularly high tin content films with direct bandgaps, require low substrate temperatures during growth. The resulting layers are metastable, so additional heat exposure for subsequent layer growth or device processing may induce strain relaxation and tin segregation within or to the surface of the film. A complex set of material and temperature factors contribute to the relative degrees of defect formation and tin segregation. Each mechanism has different implications for device design, processing methods, and working lifetime at elevated temperatures such as those experienced by thermophotovoltaic cells.

In this work, we show studies of the thermal stability and annealing behaviors of $Si_{1-x-y}Ge_xSn_y$ films performed by temperature varying spectroscopic ellipsometry (SE). Heating was carried out on a Linkam heating stage mounted to a JA Woollam VASE instrument under a nitrogen atmosphere. Changes in strain state and material uniformity present as changes in the location and shape of the bandgap absorption edge and critical points in the dielectric function, and overall shifts in optical properties of the films. Findings and additional evidence of film changes are confirmed by Nomarski optical microscopy, high-resolution x-ray diffraction, and atomic force microscopy. We collect data at room temperature after in-situ rapid thermal anneals to approximate thermal effects from device processing, and take continuous SE measurements at elevated temperatures for lifetime assessment. Tin content, film thickness, and strain state are varied to examine the effects of these properties on breakdown behaviors and to demonstrate the flexibility of the SE technique.

NM-MoP-7 Band Structure and Strain Distribution of InAs Quantum Dots Encapsulated in (Al)GaAs Asymmetric Matrixes*, **Pablo Olvera Enríquez**, C. Mercado Ornelas,* Center for the Innovation and Application of Science and technology, UASLP, Mexico*; L. Espínoza Vega,* Facultad de Ciencias, Universidad Autónoma de San Luis Potosí (UASLP). Center for the Innovation and Application of Science and technology, UASLP, Mexico*; I. Cortes Mestizo,* CONACYT-Center for the Innovation and Application of Science and technology, UASLP, Mexico*; F. Perea Parrales, A. Belio Manzano,* Center for the Innovation and Application of Science and technology, UASLP, Mexico*; C. Yee Rendón ,* Facultad de Ciencias Físico-Matemáticas, Universidad Autónoma de Sinaloa, Mexico*; V. Méndez García ,* Center for the Innovation and Application of Science and technology, UASLP. Facultad de Ciencias, Universidad Autónoma de San Luis Potosí (UASLP), Mexico

Quantum dots (QDs) based devices often requires for their functionality to successfully stack several layers barrier/QD/barrier structures. Nevertheless, the growth gets more challenging as each layer of QDs is added, since diffusion, segregation, alloy intermixing, and strain effects intrinsically appear along the process. In this work, the strain distribution, and the electronic band structure of InAs QDs embedded in (Al)GaAs matrixes are investigated by numerical analysis based on finite element method.As input data, experimental parameters from MBE grown samples such as the QDs morphology, wetting layer (WL) thickness and the composition of the materials were employed. The biaxial (ε_{xx}) and hydrostatic (ε_{hydro}) strain tensors were calculated for pyramidal and truncated pyramidal QDs shapes, considering that capping usually flattens the apex of the islands [1]. The results revealed that ε_{xx} resulted more affected with the variations of InAs QDs geometry, which is correlated with changes in the heavy hole (HH) and light hole (LH) band structure behavior of the simulated heterostructures. Differences of the maximum and minimum values of ε_{xx} and ε_{hydro} tensors above islands, which carry information about the vertical pairing probability, for each type of heterostructure geometry were observed. The electronic confinement states and eigenfunctions probability distributions were calculated for the QD well. Higher energy states and lower number of eigenfunctions can be confined in truncated pyramids, as compared with non-modified shape QDs. This work shows a clear picture of the strain fields and their consequences on the band structure of InAs/(Al)GaAs multi-stacked heterojunctions found in actual QDs devices.

[1] C.A.Mercado-Ornelas, et.al., Physica E: Low-dimensional Systems and Nanostructures. 2020. Vol. 124.

NM-MoP-8 High Temperature Growth of Thick AlN on Si*, **Rohith Allaparthi**, M. Ware,* University of Arkansas*; C. Taylor, H. Edwards,* Texas Instruments*; Y. Mazur, F. Maia de Oliveira, M. Refaei,* University of Arkansas

Direct wide bandgap (WBG) III-Nitride (III-N) semiconductor material is promising alternative to silicon (Si) technology for high-power density, high-frequency, and high-voltage applications. However, native substrate material for most WBG semiconductors is not yet commercially available at low cost.One inexpensive alternative is to use standard Si wafers as substrates due to their extremely mature development.This has been relatively well developed for GaN on Si, with several commercial examples of well-developed devices. Here, we investigate the growth of the ultra-WBG semiconductor, AlN, on Si(111) in a high-temperature regime by plasma-enhanced MBE. For thick films, the low surface roughness and monocrystalline quality is characterized by the AFM and XRD respectively. Additionally, metal Al (111) signal is seen in the XRD, which corresponds to Al droplets resulting from the metal rich growth. Optical microscopy, however, reveals the presence of two distinct regions on the surface. Further investigation using micro-Raman spectroscopy identifies one region as high-quality, relaxed, crystalline Si and the other region as relaxed AlN.Analysis of the Raman spectra reveals week AlN peaks alongside the Si peaks, indicating that the Si exists as a film on the surface. AFM on the AlN regions is extremely smooth with surface roughness of less than 0.4 nm, while the Si regions are slightly rougher. In addition, it is found that small, three-dimensional crystals of Si have started to nucleate out of the Al droplets.All elemental conclusions are confirmed by electron dispersive x-ray (EDX) spectroscopy performed in a scanning electron microscope. Piezoresponse force microscopy has been performed on the free AlN regions and demonstrates that the AlN is single domain and metal polar. Thinner films, in stark contrast to the thick films, reveal only AlN domains with no areas of Si apparent.These results along with the findings from cross-sectional material analysis demonstrate a complicated diffusion

effect between Al, Si, and AlN, occurring during the material growth, which will be discussed.

NM-MoP-9 Correlating Charge Carrier Profiles and Elemental Compositions in MBE-grown GaN/AlGaN Stacks*, **Stefan Schmult,*** TU Dresden, Germany*; P. Appelt, C. Silva, A. Großer, A. Wachowiak,* NaMLab gGmbH, Germany*; T. Mikolajick,* TU Dresden, Germany

Capacitance vs. voltage (C(V)) measurements represent a common way to trace levels of free charge carriers in semiconductors and semiconductor heterostructures. Concentration profiles of free charges obtained from C(V) measurements are widely accepted to reflect residual impurity background levels in GaN/AlGaN layer stacks. Particularly when the material is grown by MBE on highly compensated (insulating) GaN substrates, free carrier concentrations reaching levels below 10^{15} cm^{-3} are often reported for GaN buffer layers [1]. The growth of GaN/AlGaN stacks, hosting a 2-dimensional electron gas (2DEG), on insulating substrates is essential to probe the intrinsic 2DEG transport properties and to enable lateral HEMT functionality.

We realized a strong discrepancy in such GaN/AlGaN layer stacks - grown by MBE on highly compensated GaN substrates - between the concentrations of free charges extracted from C(V) data and the elemental donor background observed in secondary ion mass spectroscopy (SIMS) runs [2]. The conversion of the C(V) data into depth profiles relies on a model assuming a parallel plate capacitor geometry with defined top and bottom electrodes. The low level of free charges $<10^{15}$ cm^{-3} compared to the unintentional oxygen donor background of $>2{\cdot}10^{16}$ cm^{-3} is attributed to the experimental details of the measurement. A gate metal layer serves as the top electrode, while a defined bottom electrode is missing once the 2DEG is completely depleted and the C(V) data become unreliable for charge profiling.

Such a defined bottom electrode can be introduced by either growing GaN/AlGaN stacks on conductive substrates or – as implemented here - by making use of atmospheric silicon adhesion at the surface of unintentionally-doped (uid) substrates, which leads to parasitic conductivity at the substrate/MBE regrowth interface [3]. This parasitic channel is detrimental for investigating the intrinsic 2DEG transport properties and for HEMT functionality. On the other hand, the free charge carrier and donor background concentrations both agree well at a level of $4{\cdot}10^{16}$ cm^{-3}. Here, the bottom electrode is preserved after the 2DEG is depleted.

In summary, a parasitic channel in GaN/AlGaN heterostructures is a building block for a parallel plate capacitor, as it represents a defined bottom electrode for C(V) measurements. Consequently, free charge carrier concentrations extracted from C(V) data agree well with the elemental donor concentrations determined by SIMS.

[1] M.J. Manfra et al., J. Appl. Phys. **92**, 338 (2002)

[2] S. Schmult et al., J. Vac. Sci. Technol. B **35** (2), 02B104 (2017)

[3] S. Schmult et al., accepted, J. Crys. Growth (2022)

NM-MoP-10 Thin-film Growth of ζ- Mn_2N on MgO (001) Using Molecular Beam Epitaxy*, **Ashok Shrestha,** A. Smith,* Ohio University

The growth and structure of the cubic manganese nitride, namely θ - MnN, η- Mn_3N_2(010), η- Mn_3N_2(001), and ε- Mn_4N have already been investigated intensively on MgO (001) substrate [1,2]. However, the hexagonal ζ- Mn_2N has remained unexplored. The thin films of hexagonalζphase Mn_2N were grown successfully on MgO (001) using molecular beam epitaxy (MBE) under manganese-rich conditions. Multiple samples were grown by varying the Mn: N flux ratio from 0.6:1 to 0.9:1, and the ζphase is observed at the flux ratio of 0.9:1 at 455 ± 30 °C growth temperature. The sample growth process was monitored by *in-situ* reflection high energy electron diffraction (RHEED). During the sample growth, the streaky RHEED pattern with reduced streak spacing compared to MgO substrate was observed. The chemical composition of the samples was determined by *in-situ* Auger electron spectroscopy (AES) at different locations of the sample. The stoichiometric ratio of Mn: N on the film is nearly 2:1 which is consistent with the ζ- phase Mn_2N. The experimentally measured *in-plane* lattice constant, based on the RHEED, is 2.86 ± 0.02 Å, and the *out-of-plane* lattice constant, measured using X-ray diffraction (XRD), is 4.56 ± 0.02 Å, which agrees with the *a* (2.82 Å)and *c* (4.54 Å) value of Mn_2N reported by Aoki *et al.* (2004) [3]. Furthermore, the room temperature scanning tunneling microscopy (STM) studies show some steps with a step height of 4.50 Å and atomic resolution of hexagonal arrays. This research was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under Award No. DE-FG02-06ER46317.

References:

[1] H. Yang, H. Al-Brithen, E. Trifan, D. C. Ingram, and A. R. Smith, J. Appl. Phys. **91**, 3 (2002).

[2] A. Foley, J. Corbett, A. L. Richard, K. Alam, D. C. Ingram, and A. R. Smith, J. Crystal growth **446**, 60 (2016).

[3] M. Aoki, H. Yamane, M. Shimada, and T. Kajiwara, Material Research Bulletin **39**, 827 (2004).

NM-MoP-11 Impurity Doping of β-Ga_2O_3 Thin Films*, **Neeraj Nepal,** . Downey, V. Wheeler, D. Katzer, E. Jin, . Hardy, V. Gokhale, T. Growden,* US Naval Research Laboratory*; K. Chabak,* Air Force Research Laboratory*; D. Meyer,* US Naval Research Laboratory

Ultra-wide bandgap (UWBG) semiconductors with a bandgap greater than 3.4 eV, such as c-BN, AlN, high Al content AlGaN, β-Ga_2O_3, anddiamond, have higher figures of merit values than GaN and SiC for power and rf devices making them candidates for next generation high-power/high-temperature electronic materials [1-4]. Higher operating frequency and power density enable smaller transformers and better power quality filter components, which mitigate Navy architecture space/weight/power (SWaP) issues, and also allow smaller size, higher-speed for future ship payloads and electric propulsion systems [1].

The availability of inexpensive large-area bulk substrates synthesized by melt growth techniques at atmospheric pressure provides a scaling advantage for β-Ga_2O_3 over other UWBG semiconductors [2]. In addition, homoepitaxial growth on bulk substrates offers the potential for low defect density films for vertical power devices. Further, controlled n-type doping with a shallow donor level (15-50meV [5]) is another advantage of β-Ga_2O_3 compared to AlN and high Al-content AlGaN. For these reasons, homoepitaxial growth of unintentionally- and impurity-doped Ga_2O_3 films and their electrical and structural properties is of great interest.

In this talk, we will present advances in MBE growth homoepitaxial of β-Ga_2O_3 thin films. First, the growth rate was increased approximately from 1 to 3 nm/min by optimizing the growth conditions such as Ga flux, plasma conditions and growth temperature (T_g). At optimal conditions with a T_g of 725 °C, surface roughness and X-ray rocking curve full-width at half maximum were 0.36 nm and 20 arc-sec, respectively, for 390 nm thick films. Optimal growth conditions that resulted in high structural and surface quality were used to explore doping parameter space using Sn and Si impurity. Hall effect measurements were carried out doped layers. For Sn-doped layers, the free carrier density can be controlled in the range $1x10^{16}$ to $3x10^{19}$ cm^{-3}. A mobility of 49 cm^2/V-s with free carrier density of $3x10^{19}$ cm^{-3} was measured which is comparable to the previously reported values for Sn-doped β-Ga_2O_3 [6]. We will also present the data on Si doped homoepitaxial β-Ga_2O_3 thin films.

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References

[1]Naval Power Systems Technology Development Roadmap PMS 320

[2]H.H. Tippins, Physical Review **140**, A316 (1965).

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

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

[5]Neal et al., Appl. Phys. Lett. **113**, 062101 (2018).

[6]A.J. Green et al., APL Materials **10**, 029201 (2022).

NM-MoP-12 MBE Synthesis of Single-Crystal $LiMn_2O_4$ Thin Films as Li-Ion Battery Cathode Model Systems*, B. KC,* University of Illinois - Chicago*; G. Evmenenko, B. Buchholz,* Northwestern University*; **Robert Klie,*** University of Illinois - Chicago

To address the increasing demand for energy storage technology, model thin films Li-ion battery cathode systems are highly desirable since they avoid the complexity associated with polycrystalline or nano-sized powders which make detailed study of surfaces and interfaces difficult. However, the electro-chemical behavior of thin films depends on defect concentration, grain boundaries, and surface terminations. An ideal way to study the material and interface properties is by isolating a particular crystallographic orientation and investigate the orientation dependent performance.

To study such behavior, we have developed novel thin film MBE synthesis of single-crystal Li transition metal oxide spinels, such as $LiMn_2O_4$, to serve as Li-ion battery cathode model systems, where the thin film orientation and surface termination can be carefully controlled.We will discuss the

modification necessary to synthesize fully stoichiometric, single crystal $LiMn_2O_4$ thin films that show Li de/intercalation properties similar to that seen in bulk Li-ion battery cathodes. These thin films are characterized using a suite of approaches, including XPS, XRD, and analytical electron microscopy. We will utilize these thin films to study the interfacial ion diffusion and structural evolution as the result of electro-chemical cycling against a graphite anode. These model thin film cathode frameworks will not only be used for monovalent Li^+ ions but also for divalent Mg^{2+} ion intercalation to quantify the the role of bulk orientation, surface termination and ion valence on the interfacial ion mobility.

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NM-MoP-13 Tunable Electronic States and Instabilities in PbSnTe Heterostructures*, A. Al-Tawhid, A. Gonzalez, S. Poage,* NCSU*; **Kaveh Ahadi,*** NC State University

Combination of broken inversion symmetry and spin-orbit coupling gives rise to a wide range of exotic superconducting states, such as mixed-parity superconductivity, superconducting Weyl state, and superconducting diode effect. Incipient ferroelectrics e.g., PbTe, are near a polar instability. The emergence of superconductivity has been reported in some of these incipient ferroelectrics upon doping. Many unconventional superconductors, such as the cuprates, pnictides, and heavy fermion systems, occur in close proximity to magnetic fluctuations or magnetic orders, suggesting that these are important ingredients in the superconductivity in these materials. Here, ferroelectricity and superconductivity could be connected or accidental neighbors. Furthermore, the intersection of superconductivity and topologically nontrivial states is a fertile landscape for exciting quantum phenomena, including non-abelian excitations.

IV-VI compounds show a wide range of electronic and polar instabilities. $Pb_{1-x}Sn_xTe$ demosntrates a highly tunable superconductivity and ferroelectricity which are dependent on carrier density and Sn(Pb) concentration. Furthermore, a topological phase transition is expected at x~0.4, which inverts the conduction and valence bands for Sn rich compounds. I will report on our recent growth efforts of high quality $Pb_{1-x}Sn_xTe$ heterostructures,using a chalcogenide molecular beam epitaxy (Veeco 930) near the topological phase transition (x~0.4). The cross-sectionhigh-angle annular dark-field (HAADF) imaging in scanning transmission electron microscopy (STEM) shows abrupt interfaces. X-ray diffraction demonstrates single oriented films. The sheet resistancev.s. temperature demosntrates a metallic-like behavior, dR/dT >0, in doped samples extending to 2 K. The Hall carrier density was measured at various temperatures, resolving the carrier mobility. The carrier mobility is inversely proportional to doping concentration. We report on superconductivity in electron and hole doped $Pb_{1-x}Sn_xTe$ heterostructures and its relation to neighboring ferroelectric and topological phase transitions.

NM-MoP-15 Controlling the Size and Density of InN QDs formed on Sapphire Substrate by Droplet Epitaxy*, **Malak Refaei**, A. Kuchukc, R. Allaparthid, M. Sarollahiad, M. Maruf , M. Ware,* University of Arkansas

The growth of InN quantum dots (QDs) on c-plane sapphire by droplet epitaxy (DE) using radiofrequency plasma-assisted molecular beam epitaxy (MBE) was reported. The QD growth process from liquid In droplets to the InN QDs was described with a focus on the effect of RF-plasma on the formation of In droplets size and density as a function of substrate temperatures. Two nitridation procedures were used to investigate the crystallization of In droplets in order to understand the process. The variation in the shape and size of InN QDs was explained in terms of the In atom migration of droplets and surface diffusion. The growth of InN QDs using the DE method has many advantages over the classical Stranski-Krastinow technique, including the ability to control a wide range of QD shapes, sizes, and densities.

NM-MoP-16 Selective-area Growth of GaN and AlGaN Nanowires on N-polar GaN Template with 4° Miscut by Plasma-assisted Molecular Beam Epitaxy*, **Kamruzzaman Khan**, A. Jian,* University of Michigan, Ann Arbor*; J. Li,* University of California at Santa Barbara*; E. Ahmadi,* University of Michigan, Ann Arbor

In this study, selective area growths (SAGs) of AlGaN/GaN nanowires on miscut N-polar GaN templates were studied and was compared with that grown on Ga-polar templates. The SAG of N-polar AlGaN/GaN nanowires demonstrated higher growth rate and more selectivity than that of Ga-polar AlGaN/GaN nanowires. Additionally, Lateral growth rate of N-polar nanowires was shown to be significantly lower than Ga-polar nanowires. Moreover, as opposed to top surface of Ga-polar NWs which have pyramidal shape, the N-polar GaN NW have a flat head. The combination of higher growth selectivity, larger growth window, negligible lateral growth, and flat head, makes N-polar (Al,Ga)N nanowires attractive for a variety of applications including UV LEDs and detectors as well as quantum sensing applications.

NM-MoP-17 Molecular Beam Epitaxy Grown Group-IV Alloys: Ideal Candidate for Momentum(*k*)-Space Carrier Separation Photodetectors*, **Tyler McCarthy**, Z. Ju, S. Schaefer, X. Qi, A. McMinn,* Arizona State University*; S. Yu,* University of Arkansas*; Y. Zhang,* Arizona State University

Recently, we proposed the momentum(*k*)-space carrier separation (*k*-SCS) concept that combines the advantages of both direct and indirect bandgaps for light detection/conversion devices. The basic principle is to have a direct bandgap in a semiconductor that has a slightly larger bandgap than the indirect fundamental bandgap, giving a thermalization barrier, D_{G-L}, such as $3k_BT$, for electrons at the conduction band edge. In this example, the Γ-valley minimum is $3k_BT$ higher in energy than the *L*-valley minimum. The sharp absorption edge of the direct bandgap energy, $E_{g,\Gamma}$, appears at just slightly ($3k_BT$) higher in energy than the slow onset of the absorption edge at the indirect bandgap, $E_{g,L}$,. Under light illumination, electrons are excited to the direct *Γ*-valley in the conduction band while leaving holes in the valence band edge at the symmetry point of *Γ*. The large majority of photogenerated electrons in the direct *Γ*-valley will quickly thermalize at a sub-picosecond time scale to the lower energy indirect *L*-valley. These electrons in the *L*-valley will recombine with the holes in the valence band at a time scale of tens of microseconds to milliseconds. Both carriers, electrons and holes, are transported in real space but with different momentums, i.e. separately in *k*-space, to their corresponding contacts with negligible recombination. This clever design not only improves photogenerated carrier lifetime, similar to indirect bandgap semiconductors, but also offers a large absorption coefficient, similar to direct bandgap semiconductors.

Group-IV alloys such as GeSn are a model material system to demonstrate the novel idea as photodetectors with Sn compositions near the indirect-to-direct bandgap transition are predicted to have greater detectivity than conventional IV-VI and III-V compound photodetectors at room temperature, and comparable detectivity to InAs detectors operating at 77 K. GeSn samples with D_{G-L} between $0.4k_BT$ and $3k_BT$ were grown by MBE on Ge substrates for MWIR (2 to 5 µm). Substrate surfaces were first cleaned using HF and HCl solution prior to a UHV outgas at 550 ˚C. A Ge buffer was grown at a substrate temperature of 500 ˚C before cooling down to 200 ˚C for GeSn growth. Ge effusion cell was held constant while Sn effusion cell was varied between 825 to 900 ˚C to obtain designed composition. RHEED showed a streaky (2x1) surface reconstruction pattern that transitions to a (1x1) with increasing Sn. Introducing Si expands the wavelength coverage range to 2 ~ 22 µm, making it ideal for MWIR, LWIR and VLWIR applications. More details of the theory and experiments will be reported at the conference.

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