MBE
Room Silver Creek - Session MBE-1MoA
Novel Materials

Moderator: Kunal Mukherjee, University of California, Santa Barbara

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

2:00pm **MBE-1MoA3 The Growth and Optical Properties of High Concentration of ErAs Embedded within GaAs***, **Yuejing Wang**, D. Wei, C. Ni, S. Law, J. Zide,* University of Delaware

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

2:15pm **MBE-1MoA4 Varying MBE Growth Conditions to Limit Droplet Formation and Improve the Material Properties of TlGaAs Films***, **Kevin Grossklaus**, J. McElearney, M. Stevens, T. Vandervelde,* Tufts University

TlGaAs may serve as a promising material for optoelectronic devices for the near to mid-IR range. $Tl_xGa_{1-x}As$ films of approximatley x=0.07 Tl have been achieved using solid-source MBE [1,2]. However, production of films with greater Tl content, device relevant thickness, and high material quality is limited by group III droplet formation, incorporation of excess arsenic, defect formation, and epitaxial breakdown. These detrimental effects result from the very low temperatures and high As fluxes needed for TlGaAs growth. Moving towards device quality TlGaAs films will require a better understanding of the trade-offs between conditions that produce high Tl incorporation and those that result in improved film quality.

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

2:30pm **MBE-1MoA5 Adsorption-controlled Epitaxial Growth of the Hyperferroelectric Candidate LiZnSb on GaSb (111)***, D. Du, P. Strohbeen, C. Zhang,* University of Wisconsin Madison*; H. Paik,* Cornell University*; P. Voyles, **Jason Kawasaki**,* University of Wisconsin Madison

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

This work was supported by the Army Research office (W911NF-17-1-0254) and the National Science Foundation (DMR-1752797) .

[1] K. F. Garrity, K. M. Rabe, and D. Vanderbilt, Phys. Rev. Lett. **112**, 127601(2014).

2:45pm **MBE-1MoA6 Tuning the Electronic Structure of LuSb via Epitaxial Synthesis***, **Shouvik Chatterjee**,* University of California, Santa Barbara*; S. Khalid,* University of Delaware*; H. Inbar, A. Goswami,* University of California, Santa Barbara*; F. Crasto deLima, A. Sharan, F. Sabino,* University of Delaware*; T. Brown-Heft, Y-H. Chang,* University of California, Santa Barbara*; A. Fedorov,* Lawrence Berkeley National Laboratory*; D. Read,* Cardiff University, UK*; A. Janotti,* University of Delaware*; C. Palmstrøm,* University of California, Santa Barbara

Observation of extreme magnetoresistance (XMR) in rare-earth monopnictides has raised enormous interest in understanding the role of its electronic structure. I present first demonstration of epitaxial synthesis of LuSb thin films on GaSb (001) substrates. Combining the techniques of molecular-beam epitaxy, low-temperature transport, angle-resolved photoemission spectroscopy, and hybrid density functional theory, we have unveiled the bandstructure of LuSb, where electron-hole compensation is identified as a mechanism responsible for XMR. In contrast to bulk single crystal analogues, quasi-two-dimensional behavior is observed in our thin films for both electron and holelike carriers, indicative of dimensional confinement of the electronic states. Introduction of defects through growth parameter tuning results in the appearance of quantum interference effects at low temperatures, which has allowed us to identify the dominant inelastic scattering processes and elucidate the role of spin-orbit coupling [1]. Furthermore, by fabricating ultra-thin films I show that it is possible to controllably create an imbalance in the band fillings of electron and hole-like carriers in this otherwise compensated semimetal. Moreover, magnetoresistance behavior can also be tuned by application of bi-axial strain by synthesizing thin films of LuSb on lattice mis-matched substrates. Our work demonstrates the efficacy of epitaxial synthesis of rare-earth monopnictides to control its electronic structure and thereby, its physical properties.

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

3:00pm **MBE-1MoA7 Programmable Magnetic Anisotropy in Ferromagnetic Semiconductor Films with Graded Composition***, **Jacek Furdyna**, S.-K. Bac, S. Dong, X. Liu, S. Rouvimov,* University of Notre Dame*; Y. Wang,* Nanjing University, China*; S. Lee,* Korea University, Republic of Korea*; M. Dobrowolska,* University of Notre Dame

Developing strategies for manipulating magnetic properties of ferromagnetic semiconductors such as $Ga_{1-x}Mn_xAs$ is of interest both because of the basic science involved and of its potential for spintronic applications. In this presentation we explore the effects of compositional grading of such alloys on their ferromagnetic properties using MBE. For this purpose, we chose the quaternary alloy $Ga_{1-x}Mn_xAs_{1-y}P_y$ grown by molecular beam epitaxy on a GaAs substrate, with Mn concentration kept constant at $x \approx 0.06$, while the concentration of P is graded along the growth direction, increasing stepwise from $y \approx 0.0$ to $y \approx 0.28$.

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

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

[1] V. K. Vlasko-Vlasov, et al., Phys. Rev. B 98, 180411 (2018).

Author Index

Bold page numbers indicate presenter