NAMBE
Room Cummings Ballroom - Session NAMBE2-MoM
III-Vs

Moderator: Eric Jin, Naval Research Laboratory

10:30am **NAMBE2-MoM-11 Exploring MBE Growth Parameters and Material Quality of III-V Topological Insulators Grown on GaSb(111)A Substrates***, **James R Rushing**, L. Qui,* Tufts University*; X. Xie,* tufts University*; T. Menasuta, J. Mcelearney, P. Simmonds,* Tufts University

Since the discovery of the Quantum Spin Hall effect (QSHE), topological insulators have received significant attention for their novel uses in electronic devices. Spin-momentum locking in the surface states of a Quantum Spin Hall Insulator (QSHI) offers electron transport without scattering. These topological surface states arise due to strong spin-orbit coupling and band inversion. The QSHE was proposed for HgTe/CdTe heterostructures in 2006 and was experimentally realized in 2007[Bernevig 2006] [König 2007]. In our work, we focus on QSHI's based on InAs/GaInSb-based quantum well heterostructures. Creating robust QSHI's out of extensively studied III-V materials is highly desirable. Doing so would allow for an ease of integration with existing III-V devices such as 2DEG's. Quantum size effects should enable one to tune the device in and out of the topological insulating phase by adjusting the quantum well widths. Furthermore, we can tune the strain and confined hole state energy by altering the indium percentage in the ternary GaInSb layer [Irie 2020]. The other nice feature of these structures is that the electrons and holes are strongly localized in the InAs and GaInSb wells, respectively. This spatial separation allows for additional tunability of the topological phase using top- and bottom-gates.

Accessing the rich topological phases of these materials requires precise control of quantum well thickness [Schmid 2022]. This is best achieved with molecular beam epitaxy (MBE). To our knowledge, research into these structures has been limited to III-V quantum wells grown on (001) surfaces. Our calculations show that quantum wells with a (111) orientation are likely to exhibit distinct electronic behavior, for example a larger hybridization energy gap than on (001). However, growth on (111) surfaces is typically more difficult and the literature available for optimal growth parameters is sparse. Furthermore, the growth of even relatively simple structures is complicated by the mismatched lattice constants and the need to switch group V species between the quantum wells.

We will present our results exploring the growth and subsequent material quality of InAs/GaInSb double quantum wells grown on GaSb(111)A substrates as a function of growth parameters that include: group V flux, substrate temperature, and growth rate. We mirror these results with control quantum well structures grown on on the (001). From the result of AFM, XRD, and SEM characterization, we will describe how the variation in the above growth methods effect material quality, with an eye to exploring emergent topological states in these quantum wells.

10:45am **NAMBE2-MoM-12 Molecular Beam Epitaxy Growth and Regrowth of InAs/Al Heterostructures***, **Ido Levy**,* New York University*; J. Issokson,* New york University*; A. Danilenko, P. Strohbeen, T. Cowan,* new york University*; W. Strickland,* New York University*; L. Baker, M. Mikalsen, J. Shabani,* new york University

Heterostructures of a 2-dimensional electron gas (2DEG) semiconductor and a superconductor are prime candidates for various applications including quantum computing and topological superconducting circuits [1,2]. It is required that the 2DEG layer will be in close proximity to the superconductor and the layers will have an Ohmic contact. A high 2DEG mobility as well as high quality interface are often needed for device applications. The system of near-surface InAs (InGaAs/InAs/InGaAs) quantum well (QW) is a prime candidate. It has a narrow bandgap with the Fermi level close to the conduction band and a thin epitaxial Al layer grown above it. The high mobility of the 2DEG embedded in the InAs QW and the compatibility between the QW and epitaxial Al makes this heterostructure a promising candidate. However, the close proximity of the QW to the surface hinders the mobility and limits it to low values of 100,000 cm^2/(V s). While QWs that are not close to the surface (buried) show greater mobility, there is no way to couple them with a superconductor due to the distance between them.

In this work, we aim to bridge the gap between buried and surface InAs QWs and grow buried, fabricated, semiconductor/superconductor heterostructures by molecular beam epitaxy. We present a newly developed 2-stage growth procedure which aims to enhance 2DEG mobilities while keeping the proximity to the Al. The first step includes growth of surface InAs and an epitaxial Al layer. After growth, we remove the sample and fabricate our structure as usual, and then reintroduce the sample back to the chamber and regrow a thick (~100nm) layer of In0.81Al0.19As in order to bury the structure. By burying the structure we aim to improve transport by reducing the effects of surface scattering, which normally limits mobilities in these near-surface QWs. We compare surface morphology and magnetotransport characterization data for buried and unburied structures, as well as for varying growth conditions. The growth process and characterization of the samples will be presented.

[1] H. Kroemer, Physica E 20, 196 (2004)

[2] J. A. del Alamo, Nature 479, 317 (2011)

11:00am **NAMBE2-MoM-13 Engineering MBE Structures for Ultraclean 2D Hole Systems with Mobilities Exceeding 10^7 cm^2/Vs***, **Adbhut Gupta**, C. Wang, S. Singh, K. Baldwin,* Princeton University*; R. Winkler,* Northern Illinois University*; M. Shayegan, L. Pfeiffer,* Princeton University

Two-dimensional (2D) carrier systems confined to modulation-doped semiconductor structures provide a nearly ideal testing ground for exploring new physical phenomena. The advances in molecular beam epitaxy (MBE) has substantially elevated the quality of these systems, notably reflected in the emergence of plethora of many-body states stemming from electron-electron interactions, for instance, the fractional quantum Hall (FQH) liquid, the Wigner solid, and the newly discovered striped and bubble phases in the higher Landau levels. Following innovations in MBE growth chamber design, and purification of source materials, we achieved a recent breakthrough in mobility of 2D electrons in GaAs quantum wells with the peak mobility ~ 60 x 10^6 cm^2/Vs at a 2D density ~ 1.55 x 10^{11} /cm^2. This implies an incredibly low number <10^{13}/cm^3 of background charged impurities. Building up on the already extreme levels of vacuum and source material purity in our MBE growth chamber, we present an alternative way our achieving new world-record mobilities for 2D hole systems (2DHSs) by optimizing the sample structure design. 2DHSs in GaAs quantum wells host many unique properties as compared to their electron counterparts – large effective mass, strong and tunable spin-orbit coupling, heavy-hole and light-hole coupling in the valence band, and a complex energy-band and Landau level fan diagram. We systematically grew 60 GaAs 2DHS samples, optimizing two structural parameters, the alloy fraction x of the $Al_xGa_{1-x}As$ barriers near the GaAs quantum well, and the quantum well width. For the first time, in a 2DHS in any material, we obtain peak mobility $\simeq$10 x 10^6 cm^2/Vs at density of only $\simeq$3.8 x 10^{10} /cm^2, at 300 mK which rises to $\simeq$18 x 10^6 cm^2/Vs (a mean-free-path $\simeq$57 μm) when measured at 30 mK. Low-temperature magnetotransport data exhibit a numerous delicate FQH states, the collection of which has never been seen before in any 2D system. The achievement of mobilities up to 18 x 10^6 cm^2/Vs in 2D hole systems represents a giant, 10-fold, leap, considering that the highest recorded mobilities, until two years ago, were only $\simeq$2 x 10^6 cm^2/Vs. The quality improvement and concomitant new FQH states evince a bright future for exploring interaction driven physics in GaAs based 2D systems.

11:15am **NAMBE2-MoM-14 Selective Area Regrowth of High Aspect Ratio Microstructures for Mid-Infrared Optoelectronics***, **Ashlee Garcia**, B. Aguilar, W. Doyle,* University of Texas at Austin*; Y. Wang,* University of Illinois at Urbana-Champaign*; D. Ironside, A. Skipper, M. Bergthold,* University of Texas at Austin*; M. Lee,* University of Illinois at Urbana-Champaign*; D. Wasserman, S. Bank,* University of Texas at Austin

A molecular beam epitaxy (MBE) approach to selective area epitaxy (SAE) of III-V semiconductors enables the seamless integration of metals, dielectrics, and high-quality crystalline semiconductors. While SAE by metal organic chemical vapor deposition has been widely successful due to its high material deposition selectivity, an all-MBE method could enable further advances through its high layer precision and access to non-equilibrium growth conditions[1,2].

MBE SAE has been historically difficult to achieve under conventional growth conditions due to its poor III-V deposition selectivity. This leads to an aggregation of adatoms on the amorphous mask which results in the formation of polycrystalline material on the mask surface.[2-5] Despite many efforts to improve selectivity[2-5], the accessible growth window remains narrow necessitating high temperatures and low growth rates. Mask surface roughness further restricts the selective growth regime by lowering the barrier for nucleation.[6] This limits applications requiring microns-tall high aspect ratio dielectric structures, such as mid-wave infrared highcontrast photonics[7-8] and aspect ratio trapping for metamorphic growth[9], due to the innately rough surfaces produced by plasma-enhanced chemical vapor deposition of thick films.

Here we demonstrate hydrogen silsesquioxane (HSQ) planarization[10,11] as an effective solution to aid MBE regrowth selectivity for the design of novel device and optical structures by mitigating the surface roughness of micron-scale dielectric features. By restoring the surface of 2 µm tall SiO_2 features with 100 nm HSQ, a 4x decrease in RMS roughness was demonstrated. GaAs selective regrowth of the 2 µm tall SiO_2 features saw significant improvement in selectivity as compared to the un-planarized features with no polycrystalline formation on SiO_2 bars <10 µm wide alongside a 30x increase in achievable feature aspect ratio. Experiments are underway to extend this approach to InAs regrowth for accessing applications in the mid-wave infrared regime. This work was supported by NASA (Award 80NSSC22K0287), NSF (ECCS-1926187), and Lockheed Martin.

[1] D.J. Ironside et al., *J. Cryst. Growth,* 2019. [2] F.E. Allegretti et al., *J. Cryst. Growth,* 1995. [3] S.C. Lee et al. *J. of Appl. Phys*., 2002. [4] S. Yokoyama et al. *J. Cryst. Growth*, 1989. [5] Aseev et al. *Nano Lett.*2019. [6] M. Ohring, The Material Science of Thin Films, *Academic Press*, 1992. [7] J. Wang et al. *Laser Phys. Lett.*, 2017. [8] C.J. Chang-Hasnain et al. *Adv. Opt. Photon.*, Sep 2012. [9] J.Z. Li et al. Appl. Phys. Lett., 2007. [10] F. Salmassi et al, *Appl. Opt.*, 2006. [11] C.-C. Yang et al., J. *Mater. Chem*., 2002.

11:30am **NAMBE2-MoM-15 Shadow Mask Molecular Beam Epitaxy***, S. Mukherjee, R. Sitaram, X. Wang,* University of Delaware*;* ***Stephanie Law,*** Penn State University

Shadow mask molecular beam epitaxy (SMMBE) is a form of selective area epitaxy (SAE)which uses a mask either directly fabricated on or placed in contact with the substrate. During film deposition, epitaxial layers are grown on the substrate through apertures in the mask. In addition to selective area growth, SMMBE also produces a shadowing effect near the mask edges in which elemental fluxes vary as a function of position. This results in a gradient of film thickness and/or composition near the mask edges. The steepness of the gradient can be controlled by varying the mask thickness and/or the angle of the mask edges. In this paper, we demonstrate the potential of the SMMBE technique to create in-plane gradient permittivity materials (GPMs) by taking advantage of the shadowing effect. A GPM is a material in which the permittivity varies as a function of location. Our aim is to synthesize in-plane GPMs, in which the permittivity varies in the lateral in-plane direction rather than in the vertical growth direction. In an in-plane GPM, different wavelengths of light can be confined at different in-plane locations on the chip. We are interested in creating an infrared GPM, so we chose Si:InAs as our material. To create our GPMs, we use the SMMBE approach: by creating flux gradients of both indium and silicon near the edges of the mask, we can control the doping density and thus the permittivity of Si:InAs in the lateral in-plane direction. We started with reusable Si masks that are 200 mm thick and 1 cm ´ 1 cm in dimension. Each mask has an aperture at its center which has a dimension of 0.5 cm ´ 0.5 cm at the top and ~0.528 cm ´ 0.528 cm at the bottom. Nano-FTIR spectra obtained via s-SNOM using a mid-IR nano-FTIR module demonstrates that we successfully synthesized infrared GPMs. The GPM grown using a 200 mm mask can confine light with wavenumbers ~650 cm^{-1} to 900 cm^{-1} over an in-plane distance of ~13 mm. In this talk, I will discuss the influence of several growth parameters in controlling the in-plane permittivity of the GPMs, including the growth temperature, mask thickness, and As:In ratio. In particular, the 500 mm mask provides a larger shadowing effect in comparison to 200 mm mask. This leads to a larger gradient in permittivity over a longer in-plane distance in the GPM: light with wavenumbers ~650 cm^{-1} to 1400 cm^{-1} can be confined over an in-plane distance of ~30 mm. This provides a larger surface area for the construction of an ultracompactspectrometer. Tailored mask designs can be employed to synthesize in-plane GPMs with tailored permittivity gradients in the future.

11:45am **NAMBE2-MoM-16 Electron Microscopy Characterization of GaSb islands on Silicon substrates grown via Molecular Beam Epitaxy***,* ***Mega Frost****, S. Seth, F. Ince,* University of New Mexico*; N. Arony, L. Mai,* University of Delaware*; D. Shima, T. Rotter,* University of New Mexico*; M. Doty, J. Zide,* University of Delaware*; G. Balakrishnan,* University of New Mexico

GaSb quantum dots (QDs) grown on III-V substrates provide a promising alternative to the typical InAs QDs for emission in the NIR. This material system has shown that QDs can be grown strained under the typical Stranski-Krastanov (SK) growth mode or fully relaxed under the Interfacial Misfit dislocation array (IMF) growth mode. GaSb QDs are implemented in a variety of devices, with publications demonstrating their use in lasers, photovoltaics, detectors, and memory devices. Growing these GaSb QDs on Silicon substrates instead would enhance the fields of Silicon photonics and quantum computing. In this study we investigate the growth of GaSb grown on Silicon (100) and conduct characterization through Transmission Electron Microscopy (XTEM), Scanning Electron Microscopy (SEM), and Energy-Dispersive X-Ray Spectroscopy (EDS) analysis.

GaSb is grown on Si (100) using solid-source molecular beam epitaxy (MBE). The native oxide is removed from the Silicon substrate with a 49% HF etch, producing a hydrogen-passivated surface. This is verified in the MBE by observation of its reflection high energy electron diffraction (RHEED) pattern. Four samples are grown with thicknesses of 3 MLs, 5 MLs, 10 MLs, and 50 MLs. Imaging and investigation of the surface is performed using SEM and analysis of the crystallographic structure is performed using XTEM. The growth of GaSb on Silicon is compared to AlSb on Silicon, which has been well understood and documented in the literature [1].

These samples demonstrate no coalescence of the GaSb islands into a planar layer, whereas AlSb has been shown to planarize when 50 MLs has been reached. Instead, the samples display two distinct distributions of island growths: smaller islands that are grown via the direct nucleation of Ga and Sb atoms on the Silicon surface and noticeably larger islands which appear to be catalyzed under the the Vapor-Liquid-Solid (VLS) growth mode. This occurs due to the presence of liquid Ga on the Silicon surface, which acts as a trap for Sb atoms to facilitate the GaSb growth, thereby allowing the islands to grow visibly larger than those that are directly nucleated. Electron microscopy images show the highly-faceted, equilibrium crystalline structure of the islands and fully relaxed crystals with no observable threading dislocations. Furthermore, we will present a peculiar observation of Silicon diffusion from the substrate into the metallic droplet during growth, verified through EDS. We will also describe a growth method we are developing to take advantage of the faceted islands and the VLS growth mode to control the size and distribution of the GaSb QDs.

[1] *Appl. Phys. Lett.* 86, 034105 (2005)

Author Index

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