NAMBE
Room Tamaya ABC - Session NAMBE2-TuA

Low Dimensional Nanostructures
Moderator: Kunal Mukherjee, Stanford University

3:30pm **NAMBE2-TuA-9 Optical and Structural Investigations of Antimonide-Exposed InAs/GaAs Quantum Dots in an InGaAs Quantum Well Matrix for 1380 nm Photoluminescent Emission**, ***Bhavya Kondapavuluri***, *Kai-Yang Hsu, Pin-Chih Liu,* Yuan Ze University, Taiwan*; Wei-Sheng Liu,* Yuan Ye University, Taiwan*; Ba Laji,* Yuan Ze University, Taiwan*; Jen-Inn Chyi,* National Central University, Taiwan

The increasing demand for high-speed optical communication has driven research beyond the conventional C (1530–1565 nm) and L (1565–1625 nm) bands, focusing on photon sources that emit in the O (1260–1360 nm), E (1360–1460 nm), and S (1460–1530 nm) bands, which remain compatible with existing optical infrastructure. Concurrently, advancements in facial recognition technology necessitate cost-effective and efficient photon sources operating at wavelengths of 1380 nm and beyond, ensuring enhanced safety for human-eye interactions. To address these technological needs, we investigate the extension of quantum dot (QD) emission wavelengths on GaAs substrates, which offer superior structural robustness and a more cost-effective alternative to InP-based vertical cavity surface-emitting lasers (VCSELs). In this study, high-quality InAs/InGaAs quantum dot-in-a-well (DWELL) heterostructures were fabricated using molecular beam epitaxy (MBE), achieving room-temperature photoluminescence (PL) emission at 1380 nm. The incorporation of an $\mathbf{In_xGa_{1-x}As}$ matrix (x = 14%) facilitated strain relaxation, enhancing In adatom surface diffusion and leading to the formation of QDs with an average diameter of 50 nm and a height of 7.6 nm. These uniform QDs exhibited a strong PL emission at 1310 nm with a narrow full width at half maximum (FWHM) of 29 meV.

To further redshift the emission wavelength, a 15-second antimony (Sb) exposure was applied immediately after QD deposition, leveraging its surfactant effect. This treatment promoted QD ripening, increasing the average QD diameter to 70 nm and the height to 8.2 nm, while reducing dot density. The structural enlargement is attributed to the alleviation of elastic strain, supported by the InGaAs strain-balancing layer, which facilitated Sb incorporation into the QD top layer. As a result, the emission wavelength was successfully extended to 1380 nm. However, the Sb surfactant effect also introduced inhomogeneous broadening, increasing the FWHM to 33 meV.

Temperature-dependent PL analysis revealed that Sb exposure induced bandgap shrinkage and enhanced hole confinement, as evidenced by an increase in activation energy from 254 meV (untreated QDs) to 294 meV. Power-dependent PL measurements further confirmed the retention of type-I band alignment following Sb exposure. However, excessive Sb soaking (25 seconds) led to degraded optical properties and reduced QD uniformity.

These findings provide crucial insights into optimizing Sb exposure for InAs DWELL heterostructures grown on GaAs, advancing the development of long-wavelength photon sources for next-generation optoelectronic applications.

3:45pm **NAMBE2-TuA-10 Low Temperature Growth of Ultra-Thin CdSe/ZnSe Quantum Wells**, *Yang A. Vázquez-Soto, Jorge Pérez-Saavedra, Frantisek Sutara,* ***Isaac Hernández-Calderón***, CINVESTAV, Mexico

CdSe has demonstrated great capabilities for the elaboration of light emitting nanostructures such as quantum dots and ultra-thin quantum wells (UTQWs). In fully strained CdSe/ZnSe ultra-thin quantum wells grown on GaAs (001) substrates CdSe is under large biaxial compressive stress resulting in a critical thickness of around 3.5 monolayers (MLs). We grow the CdSe by means of atomic layer epitaxy (ALE). During each Cd-Se ALE cycle a nominal coverage of 0.5 ML is obtained due to the surface reconstruction properties of Cd. We have observed that in the 260 – 290 °C range higher substrate temperatures (T_s) produce a lower Cd content of the UTQWs, as indicated by the blue-shifted UTQW excitonic emission [1]. This is attributed to the thermally activated substitution of Cd atoms by Zn during the first stages of ZnSe growth on top of the CdSe layer due to the chemical interaction of Zn atoms with underlaying Cd atoms which are removed from the UTQW layer and reevaporated or mixed with the Zn atoms of the growing ZnSe barrier. Then, the resulting Cd content of the UTQW is slightly lower than 100%. One could expect that lowering T_s below 260 °C will allow us to reach 100% Cd content quantum well layers, which would be evident by the red shift of the excitonic emission as the Cd content increases. With the purpose of investigating the structural and excitonic properties of CdSe UTQWs grown at lower temperatures we elaborated heterostructures containing nominally 1 and 3 ML CdSe UTQWs at T_s = 230 and 250 °C. Deoxidized GaAs(001) semi-insulating substrates covered by a 500 nm thick buffer layer of ZnSe grown by molecular beam epitaxy at 275 °C were employed for the growth. After the ZnSe buffer layer was finished, a careful procedure was used to set the desired T_s. We obtained photoluminescence spectra using a typical setup with an HeCd laser as excitation. The low and room temperature excitonic spectra of the heterostructures showed larger than expected red shifts and broadening of the peaks and reduced excitonic emissions. These results strongly suggest that, besides the Cd content increase, the low T_s produce significant roughness of the CdSe layers due to reduced surface diffusion and the characteristics of the growth mode. The observed exciton emission energies are compared with theoretical calculations considering several configurations of the QW roughness.

1. I. Hernández-Calderón, J.C. Salcedo Reyes, A. Alfaro-Martínez, M. García Rocha, Microelectronics J. 36, 985 (2005).

4:00pm **NAMBE2-TuA-11 Spatial and Spectral Control Over MBE Grown InAs/GaAs Quantum Dots for Device Platforms**, ***Nazifa Tasnim Arony***, University of Delaware*; Lauren N. McCabe,* University of Delaware (Now working at Yale University)*; Joshya Rajagopal, Lan Mai, Lottie Murray, Prashant Ramesh, Matthew Doty, Joshua Zide,* University of Delaware

Over the past few decades, InAs quantum dots (QDs) grown epitaxially on GaAs substrates have attracted significant attention due to their promising applications as single-photon emitters and as potential qubits. Additionally, the compatibility of GaAs platform with existing semiconductor manufacturing techniques offers a path toward building practical, large-scale quantum devices with applications in quantum sensing, computing and information processing. To create fully functional epitaxial quantum devices, it is essential to achieve uniformity in spatial, spectral, and structural properties, along with ensuring scalability. Recent work from our group has shown a method for site-controlled QD growth, where InAs/GaAs QDs are grown on nanofabricated substrates containing site-templated arrays of nano-pits. [1] Despite these advancements, one of the major challenges is maintaining high-quality optical emission from these QDs, as impurities introduced during the fabrication processes can affect their performance. In this work, we investigate the use of quantum dot columns (QDCs) as a buffer layer for the topmost QD arrays. This approach helps "bury" defects beneath the QDCs, effectively improving the optical quality of the QDs. Additionally, we present initial photoluminescence (PL) data demonstrating the spectral control of InAs/GaAs QDs using the 'cap and flush' technique, which further explores the possibility of tuning the emission properties of these quantum dots.

[1] J. Vac. Sci. Technol. B 38, 022803 (2020)

4:15pm **NAMBE2-TuA-12 2D-Assisted Nanoscale Nucleation for Selective III-V on Silicon Heteroepitaxy**, ***Corey White***, University of Illinois Urbana-Champaign*; Yiteng Wang,* University of Illinois at Urbana-Champaign*; Archishman Saha, Soo Ho Choi,* University of Illinois Urbana-Champaign*; Kuangye Lu, Ne Myo Han,* Massachusetts Institute of Technology*; Ze-Wei Chen,* University of Illinois Urbana-Champaign*; Doa Kwon, Jeehwan Kim,* Massachusetts Institute of Technology*; Hyunseok Kim,* University of Illinois at Urbana-Champaign*; Minjoo Larry Lee,* University of Illinois Urbana-Champaign

Selective area growth (SAG) presents an opportunity to monolithically integrate dissimilar materials during growth. Historically, SAG has relied only on conventional dielectric mask materials,[1,2] ultimately limiting the potential of the technique. Recently, two-dimensional (2D) masks, which are ultra-thin, flexible, and possess "slippery" sp^2 bonds, have been employed in SAG by both MOCVD[3] and MBE.[4] Such masks have the potential to enable long adatom diffusion lengths and reduced dislocations in lattice mismatched III-V heteroepitaxy. By applying this growth technique to III-V on Si heteroepitaxy, we predict the formation of dislocations and anti-phase boundaries can be mitigated due to the strain-accommodating nature of graphene. Here, we present the first selective MBE-nucleation of templated GaAs and GaP grown in nanoscale openings in an amorphous graphene (a-Gr) mask on Si.

A selective growth regime was identified on a-Gr at a slow growth rate of 0.15 Å/s, a relatively high V/III flux ratio, and a substrate temperature of 605˚C. Under these conditions, growth of GaAs and GaP was performed in nanoholes (diameters ≤ 100 nm) etched in an a-Gr mask on Si. Structural

characterization was performed by atomic force microscopy, scanning electron microscopy (SEM), and high-resolution transmission electron microscopy (HR-TEM).

GaAs nanoseeds grown in ~100 nm diameter holes were ~30 nm tall and ~100 nm in diameter with most of the nuclei showing clear faceting in planview SEM. Unsurprisingly, HR-TEM revealed that the majority of the nuclei were relaxed and single-crystalline with misfit dislocations visible along the GaAs/Si interface. Furthermore, energy dispersive X-ray spectroscopy showed no signs of oxide present at the interface indicating successful deoxidation. Recently, fabrication optimization has enabled nanoholes as small as 20 nm in diameter with templated growth of both GaAs and GaP resulting in nanoseeds as small as ~25 nm in diameter or less and ~10 nm tall, on the order of a conventional self-assembled quantum dot. HR-TEM investigations of these smaller nuclei are underway and the effects of nuclei size and lattice mismatch on dislocation formation and strain accumulation will be presented at the conference.

Here, we have demonstrated the first 2D-assisted SAG of GaAs and GaP on Si via a nanopatterned a-Gr mask. Such templated growth has the potential to unlock new III-V on silicon templates for (opto)electronics applications.

[1]S. Lee et. al., *J. Appl. Phys.* **92** (2002).

[2]D. Ironside et. al., *Prog. Quantum Electron.* **77** (2021).

[3]H. Kim et. al., *Nature Nanotechnology*, **17** (2022).

[4]S. Manzo et. al., *ACS Appl. Mater. Interfaces*, **15** (2023).

4:30pm **NAMBE2-TuA-13 Production Processing of 300mm BTO Films on Silicon, for Photonic Applications***, **Sabina Hatch,*** DCA Instruments, Finland

Molecular Beam Epitaxy (MBE) growth on 300 mm/12" silicon wafers has, until now, been hindered by plastic deformation during thermal processing. This is primarily due to the thermal and gravitational stresses that generate slip lines and can severely degrade the electrical properties.[1] Here, DCA Instruments presents the first instance of slip-free high-temperature MBE processing of 300 mm silicon wafers through the development of novel MBE technology.

The 300mm/12" production MBE system capability was thoroughly tested by growing a Barium Titanate (BTO) film on 12" Si wafers and examining the material properties (i.e. film thickness, lattice parameter, refractive index, and rocking curve). The low 3-sigma variation (for > 100 wafers) over the 12” wafer demonstrates the system's suitability for production processing. Further verification is provided by the excellent device performance (and sigma) across the 12” wafer, i.e. optical losses < 5 $dB.cm^{-1}$, leakage current < 10 µA, and V.π < 2.5 V.

More importantly, for MBE to be a viable technology for SEMI-FAB production environments, it requires an ultra-low particle count and cross-compatibility with the SEMI-FAB infrastructure.

To achieve these exceptional results and achieve SEMI-FAB compatibility, fundamental changes were made to MBE production system. These include (but are not limited to):

1. The integration of a Brooks© equipment front entry module (EFEM) with FOUP cassettes for wafer loading and unloading was required for ultra-low particle generation.
2. Modification of the automated wafer transfer system to handle bare Si wafers.
3. Upgrading the control software to allow automated processing using feedback control from analytical tools (e.g. RHEED, flux monitoring) to improve throughput and reliability.

The ongoing limitations for BTO growth on 300 mm wafers and expected advancements to address these issues for MBE production technology will also be discussed.

[1]Thin Solid Films. Volume 315, Issues 1–2, 2 March 1998, Pages 286-293

4:45pm **NAMBE2-TuA-14 MBE of Epitaxial Al/Ge Quantum Wells for Quantum Computing***, **Jason Dong**, Joshua Thompson, Bernardo Langa Jr., Chomani Gaspe, Riis Card,* Laboratory for Physical Sciences*; Brycelynn Bailey, Shiva Davari Dolatabadi, Hugh Churchill,* University of Arkansas*; Thomas Hazard, Kyle Serniak,* MIT Lincoln Laboratory*; Kasra Sardashti, Christopher Richardson,* Laboratory for Physical Sciences

High mobility strained Ge quantum wells (QWs) have been of interest as a material host for hole spin qubits [1] and superconducting-semiconducting Josephson junctions (JJs) [2]. To date, these Ge QWs have been grown using Chemical Vapor Deposition (CVD) grown material with JJs created with *ex-situ* superconducting contacts. Epitaxial superconducting contacts are often desired in superconductor/semiconductor JJs due to their high transparency. The difficulty of integrating epitaxial superconductor deposition on Ge QWs grown by CVD motivates the investigation of the growth of Ge QWs with MBE.

In this work, we investigate the growth of Ge QWs on float zone silicon substrates with epitaxial Al by MBE. Using two electron guns, the unintentionally doped Ge QWs are grown strained on $Si_{0.2}Ge_{0.8}$ virtual substrates, which are grown with a reverse graded buffer layer (RGBL) sitting on an abrupt metamorphic Ge buffer. The effect of different growth conditions and different layer thickness of the Ge QWs are investigated with XRD, AFM, defect selective etching, and low temperature magnetotransport measurements. An optimal RGBL thickness that maximizes relaxation of the metamorphic buffer and minimizes the defect density is identified. Low temperature mobilities of shallow QWs exceeding 44,000 cm^2/Vs are obtained. The mobility of the shallow MBE-grown Ge QWs is comparable to those grown using CVD. Modeling the mobility of samples with varying depths from the surface indicate that bulk 3D impurities do not limit that low-temperature transport in these samples.Rather, surface scattering is the limiting scattering mechanism in shallow QWs, while interface roughness scattering is identified to be the limiting mechanism in deeper quantum wells. The spatial length scale of the interface roughness strongly influences the interface roughness scattering, and evidence of this length scale is observed with AFM. The impact of different growth conditions on the interface roughness and how the mobility can be further improved will be discussed. Finally, we have recently demonstrated gate tunable superconductivity with JJs fabricated from our material [3]. These findings demonstrate Ge QWs grown by MBE as an emerging platform for quantum computing.

[1] Watzinger et al. “A germanium hole spin qubit” *Nat. Commun.* 9, 3902 (2018).

[2] Vigneau et al. “Germanium Quantum-Well Josephson Field-Effect Transistors and Interferometers” *Nano Letters* 19(2), 1023–1027 (2019).

[3] Thompson et al. “Characterization of MBE-grown Ge/SiGe Josephson junctions for voltage tunable qubits” in APS March Meeting 2025

5:00pm **NAMBE2-TuA-15 Reducing Contact Resistance of Ultra-thin High Al-content AlGaN PolFETs Grown by NH_3-MBE***, **Ashley Wissel-Garcia,*** University of California at Santa Barbara*; Yinxuan Zhu, Siddharth Rajan,* The Ohio State University*; James Speck,* University of California at Santa Barbara

Ultrawide bandgap (UWBG) AlGaN is a promising material for future RF devices due to its predicted high critical electric field; however, the difficulty in making low resistance contact to high Al-content AlGaN field effect transistors degrades on-resistance and high-frequency performance. In this work, we show how careful optimization of growth and device design leads to successful operation of UWBG AlGaN polarization-doped field effect transistor (PolFET) channels and reverse-graded AlGaN contacts. The total thickness of the AlGaN devices was limited to avoid relaxation due to the large in-plane lattice mismatches between AlN and AlGaN. Devices were epitaxially grown by NH_3-MBE using a Veeco Gen930 system. Before growth, the AlN template substrate surface was cleaned in-situ with Ga polishing. A 300 nm homoepitaxial AlN buffer layer followed by Si δ-doping and 4 nm $Al_{0.5}Ga_{0.5}N$ spacer served as the back barrier. The 40 nm thick $Al_xGa_{1-x}N$ channels were grown by linearly grading from x = 0.5 to 0.75 while maintaining a constant V/III ratio and doping with 2×10^{18} cm^{-3} Si donors. For the channel-only device, ohmic source and drain contacts were made to $Al_{0.75}Ga_{0.25}N$ with annealed Vanadium-based contact stacks with a contact resistance of 5 Ω-mm. The highly scaled channel-only device had μ_n = 80 $cm^2/V\cdot s$, achieved a maximum I_{ds} of 850 mA/mm, and f_T/f_{max} of 26/27.8 GHz. Reverse graded $Al_xGa_{1-x}N$ contacts were grown on the same channel structure by linearly grading the composition from x = 0.75 to 0.15. Si dopant concentrations in the reverse graded contacts were varied to determine the most effective concentration to counteract the 3D hole gas formed from the compositional grade. The highest Si dopant concentration, 5×10^{19} cm^{-3}, created an insulating layer and depleted the channel charge. Contacts doped with 2×10^{19} cm^{-3} and 1×10^{19} cm^{-3} Si donors remained conductive, but μ_n and n_s were degraded by a factor of 2 in the higher doped layers, possibly due to DX center formation. Ohmic source and drain contacts were made to the device doped with 1×10^{19} cm^{-3} Si with Ti-based contacts to $Al_{0.15}Ga_{0.85}N$, and the gate recess etch did not degrade the channel mobility. The contact resistance of the graded contact device was 0.6 Ω-mm – an order of magnitude better than the channel-only device. The unscaled graded contact device achieved a maximum I_{ds} of 800 mA/mm, which is double that of the unscaled channel-only PolFET. This work shows that state of the art UWBG AlGaN RF devices can be grown by NH_3-MBE and that careful understanding of material properties is needed

to produce high quality devices. This work was funded by the Army Research Office (Award # W911NF2220163).

5:15pm **NAMBE2-TuA-16 Molecular Beam Epitaxy Growth and X-Ray Analysis of α and γ MnTe***, **Candice R. Forrester**, Sina Mohammadi, Aran Barton, Jisoo Moon,* The City University of New York*; Rei Miyazawa, Masakazu Kobayashi,* Waseda University, Japan*; Maria C. Tamargo,* The City University of New York

MnTe is the subject of renewed attention due to its promising magnetic properties. MnTe has two prominent phases: α-MnTe and γ-MnTe, each having distinct crystalline and magnetic properties. In particular, α-MnTe has recently been shown to exhibit a novel class of magnetism known as altermagnetism, which may significantly broaden the frontiers for unconventional d-wave superconductivity and for new and better spintronic devices[1,2] However, the growth of pure single phase MnTe could be challenging. In this study we report the growth of MnTe using molecular beam epitaxy (MBE). Several growth parameters were varied to optimize the MnTe properties including Te:Mn ratio and growth temperature (T_g), as well as different substrates and buffer layers. High resolution X-ray diffraction 2θ-ω scans and pole figure analysis were done to characterize the layers.

MnTe layers grown on InP(111)B, in which the Te:Mn beam equivalent pressure (BEP) ratio was varied between 180:1to 5:1 resulted in predominantly γ-MnTe phase. While the higher Te:Mn BEP ratios exhibited only γ-MnTe phase, the very low ratios exhibited mixed α-MnTe and γ-MnTe phases. Variation of the T_g also had an important effect on the crystalline phase. For example, with Te:Mn BEP ratio of 1:5, higher growth temperatures (350 – 400°C) yielded a significant increase in the presence of the α-MnTe phase. Growth of the MnTe on InP(111)A substrates using optimized flux ratios and T_g resulted in predominantly α-MnTe, although some evidence of the γ-phase was seen in 2θ-ω scans. Furthermore, the intensity of the γ-MnTe peaks in the 2θ-ω scans remains the same while intensity of the α-MnTe signal increases as a function of thickness, suggesting that the mixed phases are formed near the interface, and that use of the appropriate substrate-layer interface or buffer layers may lead to fully single phase materials.

Evidence of the mixed phases, even for residual quantities, was particularly clear in the pole figure analysis. For example, pole figures indicated that for high BEP ratio samples grown on InP(111)B, two cubic phases could be distinguished; one cubic phase is aligned to the substrate and another one is rotated by 60°. A hexagonal phase, which may originate from the buffer layer, was also observed. A single hexagonal phase was identified when the layer was grown on InP(111)A. In both cases, the relationship between the substrate symmetry and that of the layer provides key evidence to understand the details of the epitaxial relationship of the structure.

1. *Phys. Rev. X **12**, 031042 (2022)*
2. *Phys. Rev. X* 12, 040501 (2022)

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