MBE-Grown Devices
Room Hall of Ideas E-J - Session GD-MoP
MBE-Grown Devices Poster Session

GD-MoP-2 Parity-Time Symmetry Single-Mode Double-Microdisk InGaAs Quantum Dot Lasers*, K. Lin, C. Xu,* ***Tsong-Sheng Lay,*** National Chung Hsing University, Taiwan

We successfully demonstrate the parity-time symmetry (PT-symmetry) single-mode lasing operationof laterally coupled double-microdisk lasers. The microdisk lasers of disk diameter = 2.85 µm are fabricated by usingMBE-grown InGaAs quantum dots as the gain medium. The gain materials of dots-in-a-well (DWELL) structures are grown on (001) n^+-GaAs substrate by molecular beam epitaxy. The wafer structure consists of a 1 µm-thick $Al_{0.5}Ga_{0.5}As$ sacrifice layer, and an active layercomprised of a stack of six InGaAs DWELLs.In spite of the lasing output of multiple whispering-gallery modes (WGMs) from the single microdisk lasers, the laterally coupled double-microdisk lasers achieve single WGM lasing under gain-loss contrast pumping condition, literally pumping only one disk for the double-microdisk. We change the air gap distance (*d*) for the coupled double-microdisk structures to change the coupling strength (*k*) between the microdisks. Under single selective pumping (gain-loss contrast) at room temperature, the laterally coupled double microdisk lasers of *d* = 150nm, and 200nm show single lasing mode at WGM m = 1,21 (λ= 1199nm). We also fabricate the double-microdisk lasers by coating the microdisks with HfO_2 to change the coupling strength *k*. Under single selective pumping, the HfO_2–coated double microdisk lasers show a single lasing mode at WGM m = 1,20 (λ= 1277nm).

GD-MoP-3 Impact Ionization Coefficients of AlxGa1-xAsSb (*x*=0 – 1) Lattice Matched to InP Substrates*,* ***Seunghyun Lee,*** The Ohio State University*; X. Jin,* University of Sheffield, UK*; H. Jung,* The Ohio State University*; J. David,* University of Sheffield, UK*; S. Krishna,* The Ohio State University

Impact ionization is a crucial process in the physics of semiconductors that influences the operation and performance of various semiconductor devices. It is utilized in avalanche photodiodes (APDs) to increase the signal-to-noise ratio, but it can also lead to avalanche breakdown in electronic devices. To ensure reliable device operation, it is vital to determine the impact ionization coefficients of electrons and holes (α and β), respectively. In this study, we present the α and β for a range of $Al_xGa_{1-x}AsSb$ compositions, covering x from 0 to 1, as determined through measurements of avalanche multiplication. Additionally, we explore the relationship between the impact ionization coefficients and the bandgap (E_g) change (Γ and X points) along with the indirect-to-direct transition. This is because the impact ionization process is influenced by the material's band structure and the E_g.

Four PIN $Al_xGa_{1-x}AsSb$ APDs with x of 0, 0.5, 0.65 and 0.85 were grown on InP using the RIBER Compact 21DZ molecular beam epitaxy, and were fabricated for electrical characterizations. The measured photocurrent spectra of the four APDs are presented in Fig. 1 (a), which illustrates that the cut-off tail moves toward lower energy as the x gradually decreases. To investigate the behavior of the E_g with various Al compositions, the $E_{g,\Gamma}$, and $E_{g,X}$ were extracted, as shown in Fig. 1 (b), and compared with the theoretical change in Eg proposed by Adachi. The discrepancy of Eg between the theory and experiment may come from the alloy disorder that can induce lower E_g than expected in the theoretical calculation. The result suggests that the cross-over should happen around x=0.5 which is similar value predicted by Adachi.

The α and β for $Al_xGa_{1-x}AsSb$ with x=0, 0.85, and 1 were plotted as a function of inverse electric field as shown in Fig. 2 (a). Fig. 2 (b) illustrates the α and β for $Al_xGa_{1-x}AsSb$ with x=0, 0.85, and 1 as a function of x at 290 kV/cm. The α remains fairly constant until x=0.85, where it jumps up at x=0, while the β gradually increases as the x decreases from 1 to 0. This suggests that the α can change abruptly at a critical x point, and a similar point may exist for the rate of change in the β, as seen in other material systems such as AlGaInP and AlGaAs on GaAs. To gain more insight, we will explore the behavior of Eg and α and β for additional x=0, 0.2, 0.4, 0.45, 0.50, 0.55, 0.65, 0.75, 0.85, and 1 in $Al_xGa_{1-x}AsSb$. Knowing these coefficients and Eg parameters will allow engineers and scientists to design and optimize the performance of optoelectronic and electronic devices.

GD-MoP-4 Superconducting Germanium for Scalable Qubit Architectures*,* ***Patrick Strohbeen****, A. Brook, J. Shabani,* Center for Quantum Information Physics, New York University

As superconducting qubit platforms mature and algorithms demand ever-increasing qubit numbers, it is becoming increasingly clear that platform scalability is an issue that must be addressed[1]. Current state-of-the-art transmon qubits simply take up too large of a footprint to reach the number of qubits required for the exciting proposed applications[1]. One proposed solution is to merge the large shunting capacitance with the non-linear Josephson inductance into a singular circuit element[2]. This "mergemon" design is similar in concept to the original superconducting qubits in this design philosophy, however the junction area is significantly larger to accommodate the large shunt capacitance desired[2]. By increasing the area of the junction however, the contribution of the superconductor-insulator interface to the overall loss of the qubit becomes much more impactful. Thus, highlighting the need for new materials discovery and development to tackle these scalability challenges in new qubit designs.

In this talk, I will discuss our work in the Shabani lab on the development of one such superconducting material system: superconducting germanium thin films. We have previously shown attainable superconductivity via MBE growth[3] and will now discuss our work in the context of developing new qubits. The growth of these covalent superconductors by MBE is highly enticing for applications in such mergemon architectures due to the natural homoepitaxial growth relationship with lower microwave loss substrates. Growth of these superconducting films and characterization of the superconducting phase in context of qubit applications will be discussed.

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[2] R. Zhao *et. al*, Phys. Rev. Applied **14,** 064006 (2020).

[3] P. J. Strohbeen *et. al*, In Preparation (2023).

GD-MoP-5 Epitaxial Growth of High-Quality Aluminum Thin Films via Mbe for the Experimental Realization of Majorana Bound States*, A. Elbaroudy, B. Khromets, E. Bergeron, T. Blaikie, Y. Shi, A. Tam, S. Sadeghi, F. Sfigakis,* ***Zbig Wasilewski****, J. Baugh,* University of Waterloo, Canada

In-situ epitaxial Al on InAs\InGaAs shallow quantum well (QW) has become a promising material platform for condensed matter systems hosting Majorana Zero Modes (MZMs) and, ultimately, topological quantum computing. This is due to the high mobility, large Landé g-factor, and strong spin-orbit interactions (SOI) of the two-dimensional electron gas (2DEG) in InAs quantum wells as well as the relatively high critical value of the in-plane magnetic field for very thin films of aluminum. It has been shown that with a sufficiently transparent Al/InGaAs interface, a proximity-induced superconducting gap in InAs approaches that of aluminum. Other benefits of Al are its large coherence length at low temperatures and its presence in III-V MBE systems; growing Al in situ produces an ultra-clean aluminum layer and a low-defect metal-semiconductor interface. However, growing a thin (~10 nm) continuous Al layer in standard MBE systems is challenging due to the high surface mobility of aluminum in a UHV environment, even at room temperature, and its tendency for 3D nucleation. In this work, we report a study of epitaxial Al thin film growth on InGaAs surface inside a standard Veeco GEN10 MBE reactor. We investigated the effect of Al deposition rate and substrate temperature on the quality of Al layers grown. Reflection High-Energy Electron Diffraction (RHEED) was performed simultaneously at four azimuths, and Band Edge Thermometry (BET) was used to monitor the substrate heating by the radiation from the Al source. Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) were used to analyze the morphology of the Al films. X-Ray Reflectivity (XRR) and critical magnetic field measurements were performed to verify the thickness and superconductivity of the continuous smooth Al layers, respectively. The results give new insights into the kinetics of Al deposition and show that with sufficiently high Al flux, at close to room substrate temperatures, 2D growth can be achieved within the first few monolayers of Al deposition. This eliminates the need for complex LN2 cooling of the substrate and paves the way for the development of high-quality superconductor-semiconductor interfaces in standard MBE systems.

GD-MoP-6 Submicron-Scale Light Emitting Diode with Efficient and Robust Red Emission*,* ***Yixin Xiao****, R. Maddakka,* University of Michigan, Ann Arbor

Light emitting diodes (LEDs) with characteristic length scales on the order of microns or less, also known as µLEDs, have been under intense investigations for their immense promise in various display and communications scenarios. Among the many material systems investigated for µLEDs, the III-nitride family possesses many desirable material properties such as comparatively low surface recombination velocities and excellent wavelength tunability. To date, however, it has remained a challenge to achieve efficient red III-nitride µLED that is robust under different operational conditions, largely due to the material synthesis difficulties in the high levels of indium incorporation in the indium gallium nitride (InGaN) active region that are required for red emission. Here, we demonstrate, for the first time, a device synthesis strategy that enables robust and efficient red-emitting µLED with device dimensions near the submicron scale. We employ selective area plasma-assisted molecular beam epitaxy as the material synthesis platform and a combination of short-period superlattice, thick n-type GaN interlayer, and a relatively thick single-segment InGaN active region as the device structure to achieve near-submicron-scale µLEDs that emits at red wavelengths (>625 nm) over two orders of magnitude of current injection levels with 3% external quantum efficiency.

GD-MoP-7 Impact of Built-in Electric Field Direction on Performance of GaN-Based Laser Diodes*, **Henryk Turski**,* Institute of High Pressure Physics PAS, Poland*; L. van Deurzen,* Cornell University*; M. Hajdel, M. Chlipala, M. Zak, G. Muziol, C. Skierbiszewski,* Institute of High Pressure Physics PAS, Poland

Nitride devices are mainly obtained along [0001] direction. That is why the internal polarization-induced electric fields in violet to green nitride light emitting diode (LED) and laser diode (LD) structures point in a direction opposite to what is desired for efficient flow of electrons and holes. This arrangement persists because of the need to have p-type layers on top of the structure to activate it and the lack of efficient structures grown along [000-1] direction.

To go around these problems one can use plasma-assisted molecular beam epitaxy (PAMBE), instead of metalorganic vapor phase epitaxy, to grow buried p-type layers and bottom tunnel junction (TJ) to invert current flow direction, with respect to the built-in polarization [1]. We also shown that p-type-down construction can be used to realize true-blue laser diodes, but obtained devices suffered from relatively high operating voltage [2].

In the present work, we report on optimization of the Ge-doping in PAMBE [3] for the growth of low resistance and high crystal quality TJs. The use of InGaN instead of GaN led to significant enhancement of Ge incorporation enabling the improvement in the operating voltage, bringing it to the similar level as for standard laser diodes without tunnel junction. This recent improvement in electrical performance of bottom TJ laser diodes opens the possibility to present the advantages of this constructions. Thanks to suppressed current overflow past the active region and the placement of p-type layers in close contact with the substrate bottom TJ laser diodes are expected to profit from lower optical losses and more efficient heat dissipation, respectively. Continues-wave operation of the cyan bottom TJ laser diodes will be presented. Comparison between p-up and bottom TJ devices will be discussed. Other device constructions built based on bottom TJ design will be shown.

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Reference

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[3] H. Turski *et al.*, Materials **15** (2022).

GD-MoP-8 Demonstration of a 4.32 µm Cutoff InAsSbBi nBn Photodetector, a Lattice-matched Random Alloy III-V Solution for Mid-wave Infrared Sensing*, P. Webster, J. Logan, L. Helms, P. Grant, C. Hains, R. Carrasco, A. Newell,* Air Force Research Laboratory, Space Vehicles Directorate*; **Marko S. Milosavljevic**, S. Johnson,* Arizona State University*; G. Balakrishnan,* University of New Mexico*; D. Maestas, C. Morath,* Air Force Research Laboratory, Space Vehicles Directorate

InAsSbBi *n*B*n* photodetectors are demonstrated that are lattice-matched to the underlying GaSb substrate with a 4.32 µm wavelength cutoff at 150 K; that is 0.3 µm longer than that of lattice-matched InAsSb at this temperature reflecting a 0.5% Bi mole fraction in the InAsSbBi active region. A low growth temperature was utilized to facilitate the incorporation of Bi, resulting in a minority carrier lifetime on the order of 24 ns in the InAsSbBi active region. Nevertheless, the detectors exhibits a quantum efficiency of 17% at 3.3 µm wavelength with a dark current density of 50 µA/cm^2 at 150 K and -0.4 V bias, and the strong photoresponse turn-on characteristic of a random alloy at 4.32 µm wavelength and 150 K. A shot noise-equivalent irradiance analysis indicates that these detectors' dark-current-limited noise-equivalent irradiance of 10^{12} cm^{-2}s^{-1} is 2 orders of magnitude greater than the Rule 07 expectation for this cutoff, and dark-current-limited shot noise-equivalent irradiance performance transitions to photon-limited at 1.7×10^{15} photons/cm^{2}s. [1]

[1] P.T. Webster, J.V. Logan, L. Helms, P.C. Grant, C. Hains, R. A. Carrasco, A. T. Newell, M.S. Milosavljevic, S.R. Johnson, G. Balakrishnan, D. Maestas, C. P. Morath, Appl. Phys. Lett. 123, TBD (2023). DOI: https://doi.org/10.1063/5.0161051

GD-MoP-11 Zeeman Field-Induced Two-Dimensional Weyl Semimetal Phase in Cadmium Arsenide Thin Films*, **Binghao Guo**, W. Miao, V. Huang, A. Lygo,* University of California, Santa Barbara*; X. Dai,* University of Science and Technology, Hong Kong, China*; S. Stemmer,* University of California, Santa Barbara

We report a topological phase transition in MBE-grown, quantum-confined cadmium arsenide (Cd_3As_2) thin films under an in-plane Zeeman field when the Fermi level is tuned into the topological gap via an electric field. Symmetry considerations in this case predict the appearance of a two-dimensional Weyl semimetal (2D WSM), with a pair of Weyl nodes of opposite chirality at charge neutrality that are protected by space-time inversion (C_2T) symmetry. We show that the 2D WSM phase displays unique transport signatures, including saturated resistivities on the order of h/e^2 that persist over a range of in-plane magnetic fields. Moreover, applying a small out-of-plane magnetic field, while keeping the in-plane field within the stability range of the 2D WSM phase, gives rise to a well-developed odd integer quantum Hall effect, characteristic of degenerate, massive Weyl fermions. A minimal four-band $k\cdot p$ model of Cd_3As_2, which incorporates first-principles effective g factors, qualitatively explains our findings.

Reference: B. Guo … S. Stemmer, *Phys. Rev. Lett.* 131, 046601 (2023)

GD-MoP-12 MBE Grown InAs/GaAs Quantum Dot Columns as a Buffer Layer for Spatial and Spectral Homogeneity*, **Nazifa Tasnim Arony**, L. McCabe, J. Zide,* University of Delaware

MBE grown InAs quantum dots (QDs) on GaAs substrates have been widely studied[1] because of their wide range of applications in complex quantum devices including quantum sensors and quantum computers, since the QDs can serve as a basis for potential qubits[2]. Advanced quantum devices require spatial, spectral, compositional and structural homogeneity and scalability in the grown quantum dots that must have definitive locations in an array on the substrate. Non-templated self-assembled MBE grown QDs are not a feasible option in this regard due to their spatial and spectral randomness. There is ongoing research being conducted on effective methods to overcome the current challenges of producing defect-free, homogeneous and scalable QD platforms[3]. Recent work[4] has been done by our group on low-density site-controlled MBE grown InAs QDs on GaAs platform using nano-fabricated arrays of nano pits. However, achieving spectral homogeneity and thus, scalability is still a challenge because of the impurities introduced in the regrowth surface from the nanofabrication steps. Hence, we are exploring the domain of quantum dot columns (QDCs) as a buffer layer for the top QD-arrays of interest. In this process, the spatial homogeneity can be maintained by the templated QDs in the bottom layers while burying defects underneath the QDCs and potentially, scalable platforms for devices can be achieved.

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