MBE-Grown Devices
Room Swan BC - Session GD-MoM2

Devices

Moderator: Jason Kawasaki, University of Wisconsin - Madison

10:30am **GD-MoM2-12 High Equivalent Quantum Efficiency InAs Avalanche Photodiode with Lattice Matched AlAsSb Layer**, ***Nathan Gajowski***, *M. Muduli, S. Lee, H. Jung,* The Ohio State University*; T. Basko, E. Cho,* SK Infrared*; D. Hollingshead,* The Ohio State University*; E. Fuller,* SK Infrared*; S. Krishna,* The Ohio State University

There is a growing interest in developing avalanche photodiodes (APDs) in the short-wave infrared region (SWIR, 1-3 μm). One of the primary applications for SWIR APD receivers is for eye-safe Light Detection and Ranging (LiDAR) with increased range due to the low absorption. In this work, we are developing high Equivalent Quantum Efficiency (EQE), low dark current InAs APDs for this wavelength range. InAs has a favorable bandstructure for single carrier impact ionization that leads to low excess noise. We have grown InAs APDs on InAs substrate using solid source molecular beam epitaxy. The design included a 6 μm undoped multiplication layer, a 700 *nm* *p*–type absorber with a $1x10^{17}\ cm^{-3}$ doping concentration, and a 3 μm graded absorber. The growth temperature, V/III ratio and growth rate were optimized to get low background doping. We report background doping below $1x10^{15}\ cm^{-3}$ for InAs layer as measured by capacitance voltage (CV) measurements. We have included a lattice matched AlAsSb electron blocking layer to reduce the dark current. We have fabricated single element and 4x4 arrays using standard lithography techniques. At the 2 μm operating wavelength, the devices exhibited a high equivalent quantum efficiency of 581% at the maximum voltage of 36 *V*. We are undertaking further work to understand the role of the AlAsSb layer in the impact ionization process.

10:45am **GD-MoM2-13 A High-Performance Epitaxial Transparent Oxide Thin-Film Transistor Fabricated at Back-End-of-Line Temperature (< 450 °C) by Suboxide Molecular-Beam Epitaxy**, ***Felix V.E. Hensling***, *J. Park, P. Vogt,* Cornell University*; D. Schlom,* Cornell University / Kavli Institute at Cornell for Nanoscale Science / Leibniz-Institut für Kristallzüchtung

Utilizing a recently developed variant of molecular-beam epitaxy (MBE) called suboxide MBE (S-MBE),[1] In_2O_3 films of unmatched crystalline quality are achieved as is evident from reflective high energy electron diffraction (RHEED) Fig. 1(a), root mean square roughness of the surface measured by atomic force microscopy (AFM) Fig. 1(b) and the rocking curve shown in Fig. 1(c), even at temperatures below the threshold for back-end-of-line (BEOL) fabrication, T_{sub} < 450 °C. This is based on the remarkable advantages of S-MBE for the deposition of epitaxial In_2O_3 films in comparison to conventional MBE. For conventional MBE the growth of In_2O_3 can be described by the two-step reaction: 2 In +3 O → In_2O + 2 O → In_2O_3, where the first reaction is the rate limiting step.[2] Heating a source of a carefully chosen mixture of In + In_2O_3 results in the generation of a molecular beam containing >90% In_2O molecules, thus bypassing the first step in the aforementioned two-step formation reaction of In_2O_3. In addition to eliminating this first step, supplying a molecular beam of In_2O has a second major advantage that it is a volatile species, ushering the possibility for adsorption-controlled growth. From In_2O_3 films grown by S-MBE at BEOL temperatures, transparent oxide thin film transistors (TFTs) were fabricated. It is well-established that epitaxial active layers result in TFTs with superior properties,[4] however, the epitaxial deposition of high-mobility channel layers usually requires high substrate temperatures that greatly exceed the BEOL limit. A comparison of our initial results on In_2O_3-based transparent transistors with those of the best transparent transistors in the literature (many of which are prepared at temperature above the BEOL temperature limit or are not fully transparent) is impressive as seen in Fig. 1(d). Further fine-tuning of the device architecture and film growth are expected to improve the TFT further and will be presented.

References

[1] P. Vogt, *et al.*, *APL Materials* **9**(2021) 031101

[2] P. Vogt, O. Bierwagen, *Phys. Rev. Mat.***2** (2018) 120401

[3] K.M. Adkison, *et al.*, *APL Materials***8** (2020) 081110

[4] J. Park, *et al.*, *APL Materials***8** (2020) 011110

11:00am **GD-MoM2-14 Low Temperature Crack Formation in III-V Quantum Dot Lasers Epitaxially Grown on Silicon**, ***Rosalyn Koscica***, *C. Shang, K. Parto, G. Moody, J. Bowers,* University of California, Santa Barbara

Monolithic integration of III-V films on silicon presents a scalable approach to combining high performance III-V lasers with existing silicon photonics platforms. When III-V films are epitaxially grown on Si substrate, the mismatch between coefficients of thermal expansion (CTE) causes formation of misfit dislocations (MD) and threading dislocations (TD), limiting device performance. Recent efforts in reducing TD density (TDD) for GaAs on (001) Si have resulted in levels as low as 1.5×10^6 cm^{-2}. In such low-TDD films, stress from the CTE mismatch is not relieved through dislocation formation or glide. This results in wafer bowing or film cracking, which hinder device fabrication and reduce performance. Here, we examine bowing and cracking of monolithic III-V quantum dot laser films on Si over a temperature range of 4 K to 294 K.

The structure consists of GaAs/AlGaAs grown on a GaP/(001) Si template by molecular beam epitaxy (MBE). The active region contains five InGaAs quantum wells with InAs quantum dots. Samples of varied TDD between 1×10^6 cm^{-2} and 4×10^8 cm^{-2} are investigated with different post-growth cooling rates, either slow or rapid. Additionally, different thickness stacks, thicker with lower (40%) Al content or thinner with higher (70%) Al content in AlGaAs layers, are considered. The deformation of these epitaxial structures was recently examined at temperatures between MBE growth at 540 °C and room temperature, where cracks were only found in a rapidly cooled sample with TDD 1×10^6 cm^{-2}. Here, films are further inspected from 294 K to 4 K, in the regime where samples are expected to experience no stress relief from plastic deformation through dislocation glide. At low temperature, additional cracking occurs in quenched samples of all TDD levels. The low-TDD slow-cooled sample also shows cracking at lower temperatures. However, slow-cooled samples with higher TDD remain crack-free. This identifies structural stress cases that border the critical cracking stress at room temperature, but are pushed beyond that threshold by additional CTE mismatch when cooled. Wafer curvature measurements taken at 294 K before and after cooling to 4 K indicate elastic deformation outside of cracking: macroscopic sample bowing is unchanged by local crack effects. Identifying the stress threshold that results in sample cracking is critical for the development of monolithic III-V on Si structures that capitalize on the performance advantages of low TDD without trading off structural integrity of the epitaxial film.

11:15am **GD-MoM2-15 Thin Film Engineering in Er-Doped CeO_2 for Quantum Memory**, *K. Sautter,* ***Gregory Grant***, Argonne National Laboratory; Pritzker School of Molecular Engineering, University of Chicago*; S. Sullivan,* Argonne National Laboratory*; P. Nittala, C. Ji, M. Singh, F. Heremans, S. Guha,* Argonne National Laboratory; Pritzker School of Molecular Engineering, University of Chicago

Developing a commercially available quantum memory device is essential for building wide-area ground-based quantum networks, which will yield applications like guaranteed cryptographic security that uses existing telecommunication infrastructure.However, a functional quantum memory requires the discovery of the optimal materials for these devices, and the optimization of their processing parameters. Researchers have investigated a multitude of materials that could be useful, especially diamond nitrogen-vacancy centers, silicon carbide, and rare-earth doped oxides. A particularly promising candidate for quantum memory is erbium-doped ceria (Er:CeO_2), which theoretically could yield long quantum coherence times of up to 47 ms [1]. Er:CeO_2 is also favorable due to erbium's $^4I_{15/2}$ to $^4I_{13/2}$ optical transition in the telecom-C band (~1.5 µm), which would allow for direct incorporation of Er:CeO_2 quantum memory into already-existing telecom optical fiber infrastructure with minimal signal attenuation. Recent research on MBE-grown Er:CeO_2 on Si(111) suggests that the emission lifetime of Er:CeO_2 can be further improved through thin film engineering and the reduction of Er^{3+} concentration below 1% [2].

We build on this research by doping CeO_2(111) with low Er^{3+} concentrations (<1%). We use Raman spectroscopy, atomic force microscopy (AFM), and photoluminescence excitation (PLE) spectroscopy to investigate the effects of MBE growth parameters, grown host material quality, and low Er^{3+} concentrations on Er:CeO_2 optical linewidths and emission lifetime. We expand this investigation from Si(111) to two additional substrates, GaAs(111)A and yttria-stabilized zirconia(111) (YSZ), to identify the effects of different substrates and compressive/tensile strain on PLE spectra.

[1] Kanai *et al*., arXiv:2102.02986 [quant-ph], (2021).

[2] Inaba et al., Opt. Mater. Express, **8**(9), (2018).

+Authors for correspondence: ksautter@anl.gov [mailto:ksautter@anl.gov], grantg@anl.gov [mailto:grantg@anl.gov], sguha@anl.gov [mailto:sguha@anl.gov]

11:30am **GD-MoM2-16 Hybrid MBE Growth of Metastable $SrNbO_3$ for High Mobility 2DEGs**, *S. Thapa,* Auburn University, Department of Physics*; S. Mahatara,* Department of Physics, New Mexico State University*; P. Gemperline,* Department of Physics, Auburn University*; B. Kiefer,* Department of Physics, New Mexico State University*; **Ryan Comes**,* Auburn University, Department of Physics

Two-dimensional electron gases (2DEGs) in complex oxide interfaces offer great promise for high-speed electronics. $BaSnO_3$ (BSO) is well known for its high mobility due to an availability of unoccupied 5s bands in Sn. $SrNbO_3$ (SNO) is a 4d transition metal oxide serving as a good donor material in interfacial oxide systems. Synthesis is challenging, however, due to the metastable nature of the d^1 Nb^{4+} cation and the challenges of delivery of refractory Nb. To that end, SNO thin films were grown using hybrid MBE (hMBE) for the first time using a tris(diethalamido)(tert-butylimido) niobium (TDTBN) precursor for Nb and an elemental Sr source on $GdScO_3$ substrates. Varying thicknesses of $SrHfO_3$ (SHO) capping layers were deposited using a precursor for Hf on top of SNO films to preserve the metastable surface. Grown films were transferred *in vacuo* for X-ray photoelectron spectroscopy studies to quantify elemental composition and Nb oxidation state. *Ex situ* studies by XANES illustrates the SHO capping plays vital role in preserving the Nb $4d^1$ metastable charge state in atmospheric conditions.

Heterostructures of SNO were also prepared on high mobility semiconductor $BaSnO_3$ (BSO) thin film surfaces to examine charge transfer between SNO and BSO across the interface. Using a combination of density functional theory (DFT) modeling of the BSO/SNO interface and *in vacuo* XPS, we find sheet carrier densities ~10^{14} e-/cm^2, which are the largest observed for SNO heterostructures. Angle-resolved XPS measurements are in agreement with the DFT model and show that the interfacial BSO layer receives ~0.3 e- per Sn ion and that there is significant electron diffusion farther into the BSO layer due to the low effective mass and highly dispersive bands of BSO. These results demonstrate that SNO can serve as a strong donor material for future 2DEG structures.

11:45am **GD-MoM2-17 Vertical AlGaN Deep-UV LEDs Grown on Si Using Nanowire-Assisted AlN Template by Molecular Beam Epitaxy**, ***Qihua Zhang**, H. Parimoo, S. Zhao,* McGill University, Canada

Aluminum gallium nitride (AlGaN) deep ultraviolet (UV) light emitting diodes (LEDs) are the ideal candidates to replace the conventional bulky, poisonous mercury lamps for deep UV light emitting in various applications. In addition, given the advantages of uniform current injection, reduced joule heating, and easy chip packaging process, fabricating vertically injected AlGaN deep UV LEDs have been an interest of research. Hitherto, existing AlGaN deep UV LEDs rely mainly on lateral injection, hindered by the insulating substrates and the difficulty of substrate removal. In this context, silicon (Si) is a promising substrate choice, given its excellent conductivity and easy removal by wet etching. Nonetheless, owing to the large lattice and thermal mismatches between AlGaN and Si, thick AlN buffer layers and costly substrate patterning processes are required in order to realize high quality AlGaN thin films on Si.

In this work, we present a new path to realize vertical AlGaN deep UV LEDs on Si by plasma-assisted molecular beam epitaxy, which exploits a nanowire-assisted AlN buffer layer [1]. By using such a technique AlGaN epilayers over a wide Al content range have been obtained. Moreover, such as-grown AlGaN epilayers can possess a surface roughness as low as 0.4 nm (rms value). Further studies suggest that such AlGaN epilayers are metal-polar. As initial device demonstration, AlGaN double-heterojunctions (DH), schematically shown in Figure 1, are used. Such devices are able to emit light from 298 nm to down to 247 nm (Figure 2). Moreover, I-V characteristics as a function of device size indicate uniform current injection, due to the use of vertical injection scheme. Current progress on optimizing the growth of AlGaN epilayers as well as the device performance will be presented as well.

12:00pm **GD-MoM2-18 Long Lifetime Mid-Wave InGaAs/InAsSb Superlattice Photodetectors with a 2× Reduction in Proton Radiation Induced Quantum Efficiency Degradation**, *A. Newell, G. Balakrishnan,* Center for High Technology Materials, University of New Mexico*; R. Carrasco,* Air Force Research Laboratory, Space Vehicles Directorate*; Z. Alsaad,* A-Tech, LLC, a BlueHalo company (ATA BlueHalo)*; J. Logan, C. Morath,* Air Force Research Laboratory, Space Vehicles Directorate*; C. Hains, M. Milosavljevic,* A-Tech, LLC, a BlueHalo company (ATA BlueHalo)*; S. Johnson,* Center for Photonics Innovation & Electrical, Computer, and Energy Engineering, Arizona State University*; J. Duran, G. Ariyawansa,* Air Force Research Laboratory, Sensors Directorate*; D. Maestas, **Preston T. Webster**,* Air Force Research Laboratory, Space Vehicles Directorate

In the years to come, manufacturable sensors tolerant of the space radiation environment will be critically important to outfit increasingly larger networks of satellites that our society has come to depend on. III-V materials have long been the workhorse of the telecom industry due to their high yield of manufacturing and performance in the short-wave infrared, thus there could be great value in leveraging the manufacturing capability built up in this industry if one could extend their operability to longer wavelengths. In one III-V solution discussed here, InAs/InAsSb superlattices already in use today can be significantly improved by the inclusion of Ga in an InGaAs/InAsSb superlattice. Work in 2021 demonstrated that these materials can be produced with minority carrier lifetimes exceeding 1 µs, and since then lifetimes in the range of 0.8-2.5 µs have been demonstrated, depending on the active region doping.

In this work, the lifetime, quantum efficiency (QE), and dark current of 5.3 µm wavelength cutoff InGaAs/InAsSb *n*B*n* photodetectors are examined as a function of *n*-type doping and proton radiation. Undoped InGaAs/InAsSb *n*B*n*'s exhibit the longest lifetime of 2.5 µs, maximizing QE but at the expense of higher diffusion dark current enhanced by its smaller lifetime×doping product. Doping degrades the *n*B*n*'s lifetime with a slight negative impact on QE, but yields an overall higher signal-to-noise ratio. A doping grade offers the best performance, as it offers the lower dark current of doped material while imparting an electric field across the detector's active region that enhances carrier collection. This graded *n*B*n* exhibits the same signal-to-noise as its constant-doped counterpart, but its QE degrades at half the rate when subjected to proton irradiation, resulting in a more radiation-tolerant detector.

The minority carrier lifetime, QE, and dark current are examined as a function of temperature and voltage before and after 64 MeV proton irradiation, and as a function of proton fluence up to 7.5×10^{11} cm^{-2}. The lifetime and device samples are held at operating temperature and evaluated as a function of step-wise proton dose throughout radiation experiments to eliminate thermal annealing effects that would not occur in space, which would compromise the proton damage analyses. Characterizing all of these metrics on the same materials provides insight into the fundamental physics governing these detector's operation in the space environment. The performance of these detectors are compared to the aggregate of over 30 III-V *n*B*n*'s that have been evaluated in our lab.

Author Index

Bold page numbers indicate presenter