MBE
Room Silver Creek - Session MBE-2TuM
MBE Devices

Moderator: Songrui Zhao, McGill University

10:30am **MBE-2TuM10 Development of AlAsSb Digital Alloys on GaSb and InP Substrates for Photo-Detector Applications***, **Baolai Liang**, B.C. Juang, M. Debnath, D. Huffaker,* University of California, Los Angeles

The III-(As, Sb) ternary or quaternary materials are commonly limited by spontaneous formation of clusters and phase separations during alloying. In particular, due to the wide miscibility band gap, growth of thick high-quality and lattice-matched AlAsSb alloy on GaSb or InP substrates is extremely challenging because of the non-unity sticking coefficient of group-V species. In this research, digital alloy growth by molecular beam epitaxy (MBE) has been adopted in preference to conventional random alloy growth because of the extra degree of control.

The AlAsSb structures are grown on epi-ready InP (001) and GaSb (001) substrates, respectively, via digital alloy growth technology by a Veeco GEN930 MBE reactor, in which both As_2 and Sb_2 fluxes are supplied using valved cracker cells. In order to get the precise lattice-matched AlAsSb alloy with high crystalline quality, digitally grown AlAsSb is realized by periodically alternating the As and Sb shutter to obtain the desired alloy composition. The AlAsSb epi-layers grown by digital alloy technique showed stronger photoluminescence intensity, narrower peak linewidth, and larger carrier activation energy than that grown via the random alloy technique, indicating an improved optical quality with lower density of non-radiative recombination centers for the AlAsSb digital alloy samples. In addition, a relatively long carrier lifetime was observed from the digital alloy samples, consistent with the results obtained from the photoluminescence study.

Finally, the AlAsSb epi-layers have been applied to constructed PIN and Separate Absorption and Multiplication Avalanche Photodiodes (SAM-APD) structures. The devices show optimized detection performance.

Figure (a) High-resolution cross-sectional TEM of the AlAsSb/GaSb interface and corresponding diffraction pattern of the AlAsSb digital-alloy epi-layer. (b) Low-temperature (7 K) PL emission from AlAsSb/GaSb digital-alloy epi-layer.

[1] E. Hall, H. Kroemer, L.A. Coldren, *J. Cryst. Growth* 203, 447 (1999).

[2] M. C. Debnath, B.L. Liang, R. B. Laghumavarapu, G.D. Wang, A. Das, B.C. Juang, D. L. Huffaker, *J. Appl. Phys.* 121, 214304 (2017).

[3] B.C. Juang, B.L. Liang, D.K. Ren, D.L. Prout, A.F. Chatziioannou, D. L. Huffaker, *Crystal* 7, 313 (2017).

[4] B.C. Juang, A. Chen, D.K. Ren, B.L. Liang, D.L. Prout, A.F. Chatziioannou, D. L. Huffaker, *Adv. Optical Mater.* 2019, 1900107

10:45am **MBE-2TuM11 Structural and Optical Properties of Bulk nBn InAsSb Metamorphic Detector***, **Vinita Dahiya**, Z. Taghipour, A. Blumer,* The Ohio State University*; D. Lubyshev, J. Fastenau, A. Liu,* IQE Inc.*; T. Grassman, S. Krishna,* The Ohio State University

With the availability of GaSb substrates, 6.1Å family based III-antimonide material system has shown enormous potential in the infrared detectors due to high design flexibility of various heterostructures. However, to compete with the incumbent HgCdTe technology, fabrication of large format focal plane arrays (FPAs) is required for higher throughput and yield. One promising path to larger FPAs and higher volumes includes the epitaxial growth on mismatch large area substrates, which includes the drawback of the generation of deleterious threading dislocations (TDs). The TDs impedes the minority carrier lifetime which in turn increases the dark current, hence noisy photodetector. Thus, it is important to minimize the TD density (TDD) and study its effect on the minority carrier lifetime.

For this purpose, InAsSb nBn photodetectors with a room temperature 50% cut-off wavelength of 4.2 µm are grown on three substrates, including GaSb itself, semi-insulating GaAs, and Ge/Si substrates using appropriate metamorphic buffer layers. To study the correlation between TDD and the minority carrier lifetime,*t* techniques including electron channel contrast imaging (for TDD measurement) and time resolved microwave reflectance (for minority carrier lifetime measurement) are employed.

The preliminary results indicated that the sample with lowest TDD (grown on GaSb substrate) has the highest minority carrier lifetime and the magnitude of minority carrier lifetime is reduced to half when grown on Ge/Si. Although, the nBn detector on Ge/Si has higher lifetime compared to the GaAs substrate. Interestingly, the difference in lifetime does not have a direct correlation with the diode performance measured on large-area devices, as the quantum efficiency measured ~60% on all three samples. Thus, Ge/Si can be used as an alternative approach to grow virtual substrates, enabling large format FPA processing with direct integration of the III-V devices with Si microelectronics read-out and processing architectures.

11:00am **MBE-2TuM12 All-Epitaxial Mid-Wavelength Infrared Resonant Cavity-Enhanced Photodiodes***, **Gregory Savich**, G. Wicks, J. Shao, K. Jamison, L. Fredin, T. Golding,* Amethyst Research Inc.*; M. Carmichael,* Amethyst Research Ltd., UK*; A. Craig, F. Al-Saymari, A. Marshall,* Lancaster University, UK

III-V semiconductor-based mid-wavelength infrared (MWIR) detectors have reached a point of diminishing returns in the drive towards reduced dark current. To realize a significant improvement in dark current magnitude, new concepts and approaches must be explored. One approach is to reduce the thickness of the optical absorber of the detector. Typical MWIR detectors require several micron thick absorbers in order to absorb most of the light and obtain high quantum efficiency. This results in elevated dark current as dark current is directly proportional to optical absorber thickness [1]. One approach to reducing optical absorber thickness is to place a thin optical absorber within a resonant cavity between high reflectivity mirrors, similar to vertical-cavity surface emitting laser (VCSEL) structures. This resonant cavity-enhanced photodiode (RCE-PD) architecture creates many optical passes through the absorber, allowing an absorber which is 50-100x thinner than conventional MWIR detectors while offering other unique features including: narrow spectral linewidth, reduced dark and background current, and enhanced detection at cavity resonance.

We report on all-epitaxial MWIR RCE-PDs via MBE. Distributed Bragg reflector upper and lower mirrors are deposited on either side of an optical cavity containing a thin MWIR optical absorber via a single growth. Results show dark current magnitudes near or below Rule07 [2] at the cut-off wavelength of the absorber, spectral linewidths <40 nm, and a 300K D* > $1x10^{10}$ cm $Hz^{1/2}$ W^{-1}. Creating an all-epitaxial RCE-PD requires careful epitaxial design and exact control of MBE growth parameters which will be discussed.

[1] G. R. Savich, *et al,* Applied Physics Letters 106(17), 173505 (2015).

[2] W. E. Tennant, Journal of Electronic Materials 39(7), 1030-1035 (2010).

11:15am **MBE-2TuM13 Molecular Beam Epitaxy of Coalesced AlGaN Nanowires: Ultraviolet Transparent Electrodes for Large-Area LEDs***, **Brelon May**,* National Renewable Energy Laboratory*; E. Hettiaratchy, B. Wang, C. Selcu, B. Esser, D. McComb, R. Myers,* The Ohio State University

Nanowire based AlGaN optoelectronics have the advantage of providing high crystalline quality material on a variety of different substrates. However, the efficiency of nanowire-based LEDs is not on par with similar thin film devices. This is in part because each individual nanowire must be wired in parallel. Typical heterostructures have a p-type up design, requiring a conformal metal top contact which is highly opaque in the ultraviolet (UV) wavelengths. This work uses plasma assisted molecular beam epitaxy (PAMBE) to demonstrate coalesced n-AlGaN nanowires as a transparent semiconductor electrode top contact to improve the light extraction efficiency of UV nanowire LEDs on Si. Electron microscopy reveals coalescence of nanowire tops into a continuous top electrode. Conductive atomic force microscopy (cAFM) is used to measure the uniformity of the resistance of the coalesced nanowire LEDs. Direct imaging of operational devices is used to investigate the homogeneity of the current spreading in the coalesced nanowire LEDs at the sub-micron scale. Compared with conformal semi-transparent metallic contacts, the UV transparent n-AlGaN coalesced layer results in efficiency improvement of about 37×. Additionally, the coalesced contact avoids the direct wiring of electrical shorts resulting in a greatly increased yield of working large-area (>1 mm^2) nanowire UV LEDs.

11:30am **MBE-2TuM14 High Peak-current Density AlN/GaN Resonant Tunnel Diodes Grown by rf-MBE on GaN Templates*, David Storm,*** U.S. Naval Research Laboratory*; T. Growden,* Naval Research Laboratory*; E. Cornuelle, L. Whitaker,* The Ohio State University*; P. Peri,* Arizona State University*; W. Zhang,* Wright State University*; J. Daulton,* Massachusetts Institute of Technology*; D.S. Katzer, M. Hardy, N. Nepal,* U.S. Naval Research Laboratory*; R. Molnar,* Massachusetts Institute of Technology*; E. Brown,* Wright State University*; P. Berger,* The Ohio State University*; D. Meyer,* U.S. Naval Research Laboratory*; D. Smith,* Arizona State University

AlN/GaN resonant tunnel diodes (RTD) exhibiting peak current density (J_P) as high as 930 kA/cm^2 and peak-to-valley current ratios (PVCR) of 1.1 have been grown by rf plasma-assisted MBE on MOCVD-grown GaN templates on sapphire. The threading dislocation density of the GaN templates was estimated to be 3×10^8 cm^{-2} by atomic force microscopy (AFM). Nominally identical structures were grown at temperatures between 760 °C and 860 °C under growth conditions identical to those used to demonstrate repeatable, stable, room-temperature negative differential resistance (NDR) and high J_P in AlN/GaN RTDs grown on freestanding GaN substrates [1, 2]. The device structures were characterized by AFM, high-resolution x-ray diffractometry (HR-XRD), and transmission electron microscopy (TEM). AFM revealed increasing surface roughness with increasing temperature. HR-XRD of similarly-grown samples indicated a constant, N-limited growth rate of 3.21 nm/min. TEM revealed sub-surface pits below the active region and corroborated the previous estimate of the dislocation density. Stable, repeatable, room-temperature NDR was observed from all samples. In general, higher growth temperatures resulted in higher J_P but with fewer devices exhibiting proper NDR. In particular, the sample grown at the highest temperature, 860 °C, yielded the highest J_P (930 kA/cm^2), but only the smallest-area devices exhibited NDR. Conversely, samples grown at lower temperature yielded a higher fraction of devices exhibiting NDR, including larger area devices, but the J_P and PVCR were much reduced. Thermal modeling indicates these devices exhibit NDR despite active region temperatures in excess of 400 °C, and that for a given J_P this temperature increases markedly with increasing device area, suggesting device performance is thermally limited.

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[1] T.A. Growden *et al.*, Appl. Phys. Lett. **109**, 083504 (2016)

[2] T.A. Growden *et al.*, Appl. Phys. Lett. **112**, 033508 (2018)

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11:45am **MBE-2TuM15 Optimized Material for Intermediate Band Solar Cells: Type-II CdTe Quantum Dots in a ZnCdSe Matrix*, Vasilios Deligiannakis,*** The City College of New York/Graduate Center of CUNY*; M. Begliarbekov,* CUNY Advanced Science Research Center*; S. Alsheimer,* City College of New York, City University of New York*; I. Kuskovsky,* Queens College*; M. Tamargo,* City College of New York, City University of New York

Intermediate band solar cells (IBSCs) based on quantum dots (QDs) have the potential to overcome the Schockly-Quisser limit for single junction soar cells. By forming an intermediate band (IB) within a host material with a larger band gap, QDs can ultimately increase light absorption of the solar spectrum without compromising the open circuit voltage of the device. This is achieved by a two-step photon process that occurs from the valence band (VB) to the IB and from IB to the conduction band (CB), while the conventional band to band transitions from the VB to CB of the host material is still allowed.

Type-II ZnCdSe/Zn(Cd)Te sub-monolayer QDs have been explored by our group for their promising properties as IBSCs. However, it was recently shown that at the interface between the ZnCdSe host material and the QDs an unintentional highly strained interfacial layer (IF) is formed comprised of ZnSe[1]. The presence of this layer can affect the band structure of the device and result in an accumulation of strain, which can lead to the formation of defects, reducing the device performance. Here we pursue a new material system: sub-monolayer CdTe QDs embedded in the ZnCdSe host material. Besides providing a platform in which the ZnSe IF layer is highly suppressed, this system has several advantages over the ZnCdTe QD system previously studied. Two main advantages are: 1) the binary composition of the QDs which makes them more easily controlled and more uniform, and 2) its larger valence band offset with the matrix material (ZnCdSe) which allows for better device bandstructure engineering.

The ZnCdSe/CdTe QD superlattice (SL) is grown by a combination of conventional molecular beam epitaxy (MBE) and migration enhanced epitaxy (MEE). A spacer region of ~3nm was grown made of ZnCdSe nearly lattice matched to InP. The formation of CdTe QDs was achieved by using a shutter sequence of alternating Cd and Te fluxes with short wait times between them. A triple cycle of this alternating shutter sequence was used, and the spacer and QD layers were repeated 100 times. High resolution XRD data illustrates the high quality of the IB absorption material and shows that the superlattice (SL) structure is under high compressive strain due to the CdTe QDs and indicates no evidence of a ZnSe IF layer. Calculations indicate that only sub-monolayer quantities of CdTe are required for the observed SL mismatch. Both IB absorption layers and full solar cell device structures will be discussed.

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