MBE-Grown Devices
Room Ballroom A - Session GD-MoA1

Photonic Devices

Moderator: Prof. Dr. Minjoo Larry Lee, University of Illinois Urbana-Champaign

1:30pm **GD-MoA1-1 Separate Absorption, Charge, and Multiplication Avalanche Photodiodes With InGaAs/GaAsSb Type-II Superlattices Grown by Molecular Beam Epitaxy***, **Hyemin Jung**, S. Lee,* The Ohio State University*; X. Jin, Y. Liu,* University of Sheffield, UK*; T. Ronningen,* The ohio state university*; C. Grein,* University of Illinois at Chicago*; J. David,* University of Sheffield, UK*; S. Krishna,* The Ohio State University

Avalanche photodiodes (APDs) can be used in remote sensing applications, such as atmospheric greenhouse gas monitoring, free-space optical communications, and medical diagnostics, including the extended short-wavelength infrared (eSWIR) range between 1.3 µm and 2.5 µm. APDs have internal multiplication characteristics that allow them to detect weak signals. However, traditional p-i-n structure APDs, commonly used for longer infrared wavelengths (1.55 – 3.4 µm), can be performance-limited by the high dark currents due to band-to-band tunneling when subject to high electric fields. A separate absorption, charge, and multiplication (SACM) structure can be employed to improve their performance. The SACM structure decouples the absorption region from the multiplication regions, maintaining the absorber region below the tunneling threshold while keeping a high electric field only in the multiplier. In this work, we designed, grew, and fabricated an eSWIR SACM APD. The epitaxial layers grown by molecular beam epitaxy consist of a 5 nm-In0.53Ga0.47As/5 nm-GaAs0.51Sb0.49(InGaAs/GaAsSb) type-II superlattice (SL) absorber and 1000 nm-thick Al0.85Ga0.15AsSb (AlGaAsSb) multiplier on a InP substrate. The development of the SL involved the growth of InGaAs with a growth rate of 1 µm/hr and a V/III beam equivalent pressure (BEP) ratio of ~10, along with GaAsSb grown at a rate of 0.47 µm/hr and a V/III BEP ratio of ~20. Both were grown at a temperature of 470 °C, as measured by the Bandit system. Meanwhile, AlGaAsSb was grown at a rate of 0.6 µm/hr and a temperature of 500 °C. The X-ray diffraction (XRD) result of our devices is presented in Figure 1, which reveals a mismatch of -440 arcsec and -260 arcsec for AlGaAsSb and SL, respectively. The period of the SL was calculated from a distance between the satellite peaks, determined to be 9.75 nm. These devices have a cut-off wavelength of 2.4 µm, a gain of up to 60 at room temperature, and a resulting quantum efficiency of 600% at 2 µm. as shown in Figure 3. Furthermore, the excess noise factor of our AlGaAsSb-based SACM APD stays below 2.2, up to a gain of 30. This value is considerably lower than competing technologies, with 2 times lower than InAlAs-based SACM APD and 1.2 times lower than InAlAsSb SACM APD on GaSb at the gain of 10. These results demonstrate the potential of AlGaAsSb-based SACM APDs with InGaAs/GaAsSb SLs for various eSWIR detection applications and provide insight into the design and fabrication of SACM APDs with good noise and sensitivity characteristics, making them suitable for a range of remote sensing applications in the eSWIR range.

1:45pm **GD-MoA1-2 Growth of MWIR ICLEDs on Silicon using Molecular Beam Epitaxy***, **Mega Frost**, T. Rotter, F. Ince, G. Balakrishnan,* University of New Mexico*; M. McCartney, D. Smith,* Arizona State University*; C. Canedy, W. Bewley, S. Tomasulo, C. Kim,* U.S. Naval Research Laboratory*; M. Kim,* Jacobs Corporation*; I. Vurgaftman, J. Meyer,* U.S. Naval Research Laboratory

Previously, interband cascade light-emitting diodes (ICLEDs) grown on GaSb substrates have been demonstrated as useful emitters in the mid-wave infrared (MWIR) region of 3 – 5 µm for room-temperature (RT) continuous wave (CW) operation [1,2]. Transferring this technology to growth on Silicon substrates would be advantageous for applications in chemical sensing and IR scene projectors (IRSPs), providing improved manufacturability through direct integration onto these circuits. This presentation will discuss the comparison of high-performance ICLEDs grown at NRL on GaSb/Si buffers that were grown at UNM and on lattice-matched GaSb substrates, including L-I characteristics, cross-section transmission electron microscopy (XTEM) and x-ray reciprocal space mapping (RSM).

The growth of GaSb/Si involves GaSb buffer layers which were grown on Silicon (001) with a 4° offcut towards (111). The native oxide was removed using a dilute HF solution to obtain a hydrogen-passivated surface. To achieve III-V nucleation on Silicon, a ~10 nm thick AlSb layer was grown at a substrate temperature of 500°C followed by a 1 µm buffer layer and an antimony cap to prevent oxidation. The GaSb/Si wafers were then transferred to NRL where an additional 2-3 µm GaSb buffer and the ungrouped active ICLED stages were grown. This same 22-stage structure was grown on a GaSb substrate as a control sample. Accounting for differences in architecture, the ICLED structures grown on Silicon show efficiencies that are 75% of those measured in ICLEDs grown on GaSb. At 100 mA, 200-µm-diameter mesas produce 184 µW CW at 25°C and 140 µW at 85°C.

Threading dislocations were observed in GaSb buffer grown on Si from the XTEM images, showing a higher density near the Silicon substrate but reduced near the ICLED. Individual dislocations which reached the active ICLED layers exhibited a multiplying effect throughout the structure. Another growth artifact seen in these images was a slow-varying oscillation in the ICLED layers. Our presentation will provide a detailed explanation for both mechanisms and a comparison of the ICLEDs grown on Silicon to those grown on GaSb. Possible strategies for improving the epitaxial quality and device performance will also be discussed.

[1] C. S. Kim et al., Opt. Engr. 57, 011002 (2018).

[2] N. Schäfer et al., Opt. Engr. 58, 117106 (2019).

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2:00pm **GD-MoA1-3 Monlithic Integration of InAs Quantum Dot Lasers with Silicon Photonic Waveguides***, **Alec Skipper**, K. Feng,* University of California Santa Barbara*; G. Leake, J. Herman,* SUNY POLY, Albany*; C. Shang, R. Koscica,* University of California Santa Barbara*; D. Harame,* SUNY POLY, Albany*; J. Bowers,* University of California Santa Barbara

Modern silicon photonic platforms promise to drastically improve bandwidth, data rate, and power consumption in data centers while data usage is rising rapidly every year. Silicon's indirect band gap makes it impractical for use in the lasers necessary for transmitting data, requiring integration with other materials such as III-V semiconductors. Monolithic integration by growth of III-V semiconductors on silicon is a promising pathway for cost-efficient production due to the large wafer sizes and ease of packaging and testing compared to hybrid approaches utilizing separate chips [1]. However, on-chip coupling between silicon photonic waveguides and directly grown III-V lasers shows extremely high insertion losses of 7.35 dB [2], significantly reducing the chip's overall performance.

After etching a window in a patterned silicon photonics wafer, a laser stack can be grown in the opening by molecular beam epitaxy to create a chip where silicon nitride-based waveguides are aligned with InAs quantum dot active regions. Careful calibration of etch and growth rates allows good control of the vertical alignment of the active region and waveguides, but typical MBE growth conditions result in a large horizontal gap between them. While high-performance lasers have been demonstrated on 300mm silicon photonics wafers [3], this gap makes coupling challenging and needs to be addressed for monolithic integration to be competitive with hybrid and heterogeneous silicon photonic implementations.

To improve the coupling between III-V lasers and silicon photonic waveguides, growth conditions must be tailored to minimize the gap between the laser's active region and the waveguide. Polycrystalline III-V material formed on the silicon dioxide sidewall during the growth of the GaAs buffer causes the crystalline laser stack material to facet and grow away from the sidewall. By increasing the growth temperature, decreasing the growth rate, and decreasing the arsenic overpressure during the growth of the GaAs buffer, the formation of polycrystalline material is suppressed and the horizontal gap between the active region and the waveguide can be reduced from ~5 µm to ~1 µm. Active-passive coupling tests are in-progress and will be reported at the conference.

[1] Z. Zhou et al., "Prospects and applications of on-chip lasers," eLight 2023.

[2] W.-Q. Wei et al., "Monolithic integration of embedded III-V lasers on Soi," Light: Science & Applications 2023.

[3] C. Shang et al., "Electrically pumped quantum-dot lasers grown on 300 mm patterned si photonic wafers," Light: Science & Applications 2022.

2:15pm **GD-MoA1-4 Reducing Threading Dislocation Density of Pocket-Grown InAs Quantum Dot Lasers on Patterned SiO_2/Si*, Rosalyn Koscica*,** *C. Shang, K. Feng, J. Bowers,* University of California Santa Barbara

The push for scalable silicon photonics drives interest in monolithic integration of InAs quantum dot lasers on the same chip as passive waveguides. One integration method embeds silicon nitride waveguides in SiO_2 across a Si (001) wafer. The SiO_2 is patterned to form rectangular "pockets" where the III-V laser stack is grown. Pocket lasers were recently developed on 300 mm Si (001) wafers, but they have limited optical performance and thermal tolerance compared to devices grown on unpatterned "blanket" Si (001) substrate [1]. Identifying the source of this discrepancy is essential to produce blanket-level device performance within the monolithically integrated platform. One fundamental aspect is the material quality of the pocket-grown III-V epi.

Threading dislocations (TD) generated from the mismatch in III-V/Si lattice and coefficient of thermal expansion diminish laser performance and reliability. In blanket III-V on Si growth, thermal cyclic annealing (TCA) and insertion of dislocation filter layers (DFL) lowers TD density (TDD) by over two orders of magnitude compared to untreated growths [2]. In fully pocket-grown III-V epi on Si, it is impractical to apply TCA due to temperature control and uniformity challenges across a wafer surface containing mixed SiO_2, polycrystalline III-V, and epitaxial III-V regions. Pocket-grown lasers lacking TCA have TDD on the order of 10^7 cm^{-2}, suggesting TDD as a major contribution to limited performance compared to blanket-grown lasers.

Here, an annealed GaAs interlayer is inserted between the Si substrate and the patterned SiO_2 to reduce the TDD of in-pocket devices. A planar GaAs buffer is grown on a blanket GaP/Si (001) wafer and exposed to TCA before SiO_2 deposition. After SiO_2 and waveguide patterning, DFLs and the QD laser are grown inside the pockets. The modified structure retains a patterned SiO_2 device configuration while successfully reducing TD presence in pocket-grown material to mid-10^6 cm^{-2}. Lasers with continuous-wave (CW) power of 15 mW and CW lasing up to 55 °C are demonstrated and compared to equivalent lasers grown on native GaAs substrates, showing the effect of TDs. The reduced TDD platform helps separate the known performance impact of TDD presence from subtler pocket-specific thermal or geometric effects that may also differentiate the characteristics of pocket and blanket lasers. Thus, these reduced TDD pocket-grown devices lead one step closer to realizing blanket-quality lasers for monolithic integration.

[1] C. Shang, K. Feng, E. T. Hughes, et al. Light Sci Appl 11, 299 (2022).

[2] C. Shang, Y. Wan, J. Selvidge, et al. ACS Photonics 8, 2555−2566 (2021).

2:30pm **GD-MoA1-5 MBE Growth of Near-Infrared Heterojunction Phototransistors and Visible LEDs for Night Vision Applications*, David Montealegre,*** University of Illinois at Urbana Champaign*; Y. Song,* Yale University*; S. Lee,* University of Washington*; B. Kim, M. Kim,* University of Illinois at Urbana Champaign*; F. Xia,* Yale University*; M. Li, A. Majumdar,* University of Washington*; M. Lee,* University of Illinois at Urbana Champaign

Night-vision goggles (NVGs) based on GaAs photocathodes and vacuum-based charge multipliers are highly sensitive with a long battery life exceeding 20 hours [1]. However, the weight and length of the bulk lenses, high-voltage transformer, and fiber bundle inverter lead to neck strain and fatigue for users. Furthermore, the response of the GaAs photocathodes cuts off at 870 nm and cannot fully use the night glow spectrum extending to 1.7 µm. The DARPA ENVISION program aims to create night vision systems that combine thin and lightweight meta-lenses with a solid-state NIR upconverter to reduce the neck torque from current NVGs. In this work, we describe MBE growth of InP/InGaAs npn heterojunction phototransistors (HPTs) and AlInGaP/GaAs visible LEDs, enabling us to demonstrate upconversion of 1.55 µm light to 625 nm visible light. Rapid thermal annealing (RTA) of the LED greatly reduced the forward current needed for visible electroluminescence and promises to increase the upconversion sensitivity by ~6x. The high sensitivity and low power consumption of the devices demonstrated here are promising for next-generation night vision systems.

The HPT was grown on n-InP (001) and consisted of an n-InP:Si emitter (1.5 µm, n = 1E18 cm^{-3}), p-InGaAs:Be base (1 µm, p=5E16 cm^{-3}) and n-InGaAs:Si collector (500 nm, n = 1E18 cm^{-3}). HPTs showed responsivity of ~700-1000 A/W over a wide wavelength range of 1.25-1.65 µm and were sensitive to incident power densities as low as 12.2 nW/cm^2; high responsivity is critical, as the HPT acts as a current source to drive the LED. The LED was grown on n-GaAs (001) and consisted of a single, lattice-matched 4 nm $In_{0.48}Ga_{0.52}P$ QW with 50 nm $Al_{0.53}In_{0.47}P$ barriers emitting at 625 nm. Rapid thermal annealing at 975°C greatly improved the external quantum efficiency of the LED, enabling a strong reduction in the forward current needed to see light with the unaided eye. An HPT and LED (each on their own separate wafers) were configured in series such that the n-type emitter of the HPT was shorted to the n-type cathode of the LED, leading to clear upconversion for incident 1.55 µm laser power density as low as ~288 µW/cm^2; in the near-term, we anticipate reducing the required incident power by ~6x. In addition to improving the efficiency of the discrete components, future work will aim to realize imagers where each pixel consists of a series-connected HPT and LED, integrated through metal-metal wafer bonding.

2:45pm **GD-MoA1-6 Optically-Addressed Monolithically-Integrated Multi-band Photodetectors Using Type-II Superlattice Materials*, Zheng Ju,*** *X. Qi, A. McMinn, Y. Zhang,* Arizona State University

Multiband photodetectors and FPAs have been developed for various commercial and defense applications such as resources survey, chemical sensing, target seeking, and eye-safe imaging for autonomous automobiles. When implementing multiband photodetectors into an FPA with more than two bands, additional terminals for each pixel greatly complicate the FPA layout and device processing, decrease the fill factor, and increase the ROIC complexity.[1] It is therefore highly desirable to minimize the number of terminals so that the FPA can be integrated with off-the-shelf single-band ROICs. This talk reports the demonstration of multiband monolithically integrated optically-addressed photodetectors using GaSb and InAs/InAsSb type-II superlattices (T2SLs) to cover SWIR, MWIR, and LWIR detection range. The operating principle of the optical-addressing design is to use multiple optical biases on a stack of photodiodes (PDs) connected in series to switch detection bands. The detecting PD is the current-limiting device and determines the spectral response.

Several test structures have been grown on GaSb substrates for this study. The epitaxial growth of these samples starts with a GaSb buffer grown at 500 ℃, followed by InAs/InAsSb superlattices overgrowth at 410℃. RHEED patterns for the buffer growths on GaSb(100) show steaky 3×1 surface reconstruction, while growing InAs/InAsSb superlattice show the alternative transitions between a streaky 2×4 and a streaky 3×1. XRD results show that the MBE-grown InAs/InAsSb T2SLs as MWIR and LWIR photodetectors are perfectly strain-balanced onto GaSb, and PL measurements show that the cutoff wavelengths are 6 and 10 µm for MWIR and LWIR photodetectors, respectively. The SIMS measurements confirm that the Be (p-type dopant) and Te (n- type dopant) doping levels reach 1019 atom/cm^(-3) in both GaSb and barrier layers. Device fabrications are processed by sequentially applying top contact deposition, mesa etching, bottom contact deposition and annealing. The metal combinations of Ti/Pt/Au and Ge/Ni/Au are used for p-contacts and n-contacts, respectively. A mixture of HF, H2O2 and DI water is used for wet etching. Additionally, device performance such as dark current and spectral responsivity have been characterized and compared with the-state-of-art multiband photodetectors. More details will be reported at the conference.

[1] E. H. Steenbergen, Appl. Phys. Lett. 97, 161111-161114 (2010).

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