MBE
Room Max Bell Auditorium - Session MBE-WeA
Quantum Dots/Growth and Heterogeneous Integration on Si, Ge

Moderators: Shanthi Iyer, North Carolina A&T State University, Preston T. Webster, Air Force Research Laboratory

1:30pm **MBE-WeA-1 96 GHz Colliding Pulse Mode-locked Quantum Dot Lasers Grown on Silicon**, ***Justin Norman***, *S Liu, D Jung, M Kennedy, A Gossard, J Bowers,* University of California, Santa Barbara

Needed increases in internet bandwidth require developing chip-scale photonic interconnects to displace electronics. The silicon photonics platform is favorable for photonic integration due to silicon's mature manufacturing techniques and large substrates. In recent years, quantum dot (QD) lasers have proven themselves as ideal candidates for epitaxial integration with the silicon photonics platform due to their defect tolerance which results in low threshold currents and long device lifetime [1,2]. Here, we report the first QD colliding pulse mode-locked lasers (MLLs) grown on Si. The tunable gain bandwidth and ultrafast recovery of QDs makes them ideal for MLLs with narrow, high repetition rate pulses and wide bandwidth frequency combs for dense wavelength division multiplexed data transmission.

Samples were grown on a defect free, pseudomorphic 45 nm GaP on Si template from $NAsP_{III/V}$, GmbH. An optimized buffer (Fig. 1(a)) consisting of a low temperature GaAs nucleation layer, thermal cycling, and InGaAs filter layers was utilized to achieve a dislocation density of 6×10^{7} cm^{-2} (Fig. 1(b)). Quantum dot lasers were then grown with AlGaAs cladding and five periods of p-modulation doped InAs QDs in InGaAs quantum wells. The QDs were grown at 485°C and V/III ratio of 35 with nominal InAs deposition of 2.55 ML. These conditions yield dot densities ~6×10^{10} cm^{-2} and photoluminescence full-width at half-maximum of 30 meV. Standard dry etching and metal deposition techniques were used to fabricate the lasers. Mode-locking was observed with 96 GHz repetition frequency and 2 ps pulsewidth. The continuous wave light output curve, mode-locked optical spectrum, and corresponding autocorrelation trace are shown in Fig. 2.

1:45pm **MBE-WeA-2 InAs/GaAs Submonolayer (SML) Quantum Dot-based Semiconductor Saturable Absorber Mirrors (SESAMs)**, ***Sadhvikas Addamane***, University of New Mexico*; A Laurain, J Moloney,* University of Arizona*; G Balakrishnan,* University of New Mexico

Semiconductor saturable absorber mirrors (SESAMs) have been used in recent years, with considerable success, for passively modelocking both semiconductor and solid-state lasers. Most state-of-the-art SESAMs around the 1µm wavelength range employ a quantum well (QW)-based absorber which has enabled stable modelocking in the picosecond and femtosecond regime. Recently, there has been substantial interest in studying SESAMs using quantum dot (QD) absorbers in order to exploit their advantages over QWs: atom-like density of states, variation in dot sizes and control over areal density. Around the 1µm wavelength range, using traditional Stranski-Krastonov QDs would require using an AlGaAs matrix which reduces the optical confinement factor. An alternative active component is submonolayer (SML) QDs that combine high excitonic gain and fast gain recovery (characteristic features of QDs) with the high modal gain of QWs. This work focuses on exploring the use of InAs/GaAs submonolayer (SML) QDots as absorbers in SESAMs.

The samples analyzed in this study are grown using molecular beam epitaxy (MBE) on epi-ready GaAs (100) substrates. The 1030nm SESAM structure consists of a 29 quarter-wave GaAs/AlAs pairs distributed bragg reflector (DBR) and an absorber region (QW or QD) sandwiched between GaAs spacer and cap layers. The SML QD absorber is formed by stacking 0.5ML/2.3ML of InAs/GaAs. The DBRs and absorber regions are calibrated to ensure that the reflectivity stopband and photoluminescence spectra are respectively centered at 1030nm at operating temperature and incidence angle. As part of this work, both QW and SML QD-based SESAMs are grown, comprehensively characterized and their device performances are compared. These SESAMs are characterized for reflectivity, temperature-dependence, dispersion control and lifetimes (both carrier and device) and are tested in a Vertical Cavity Surface Emitting Laser for modelocking. Through this process, we were able to achieve pulse durations as short as 128fs with InGaAs QW-based SESAMs and ~185fs with InAs/GaAs SML QD-based SESAMs. Along with higher output power, it is found that SML QD-based SESAMs have substantially longer device lifetimes compared to QW-based SESAMs.

[1] A.-R. Bellancourt, et al., Optics Express 17, no.12 (2009)

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2:00pm **MBE-WeA-3 Strain-Compensated Quantum Dot Cascade Lasers**, ***Feng-Qi Liu,*** Institute of Semiconductors, Chinese Academy of Sciences, China

Over the past two decades, quantum cascade lasers (QCLs) have been constantly improved in their performance and at this point have matured into the preferred choice of coherent sources in the mid-infrared (mid-IR) spectral region for a wide range of applications. More and more companies have attempted the usages of QCL on air-pollution, water-contamination, industrial-discharge, breath-medicine, and toxicant detection. Due to the essence of the extremely short non-radiative lifetimes commonly associated with the intersubband transitions in the quantum wells, the room temperature wall plug efficiency of QCL is no more than 30%.

At present, how to increase the efficiency of QCL further on is still a challenge. Quantum dot cascade laser (QDCL), in which quantum well active region is replaced by quantum-dot active region, is predicted as high-efficiency. However, the design and growth of QDCLs is extremely difficult. In this talk we demonstrate the development of QDCLs by two-step strain-compensation active region design and material growth technique. The QDCLs based on three-layer QDs active region, two-layer QDs active region, and single-layer QD active region have been exploited, paving a route for developing QDCLs.

2:15pm **MBE-WeA-4 (111)-oriented Stranski-Krastanov Quantum Dots Optimized for Entangled Photon Emission**, ***Christopher Schuck***, *K Vallejo, S Roy, T Garrett, K Sautter,* Boise State University*; B Liang, D Huffaker,* University of California, Los Angeles*; C Palmstøm,* University of California, Santa Barbara*; P Simmonds,* Boise State University

(111)-oriented quantum dots (QDs) are a promising source for entangled photons due to their high symmetry and the low fine-structure splitting (FSS) between their bright exciton states.[1,2] Therefore, they are of great interest for developing compact, scalable quantum information devices for quantum computing and quantum encryption applications.[1]

We have previously presented results showing the Stranski-Krastanov (SK) growth of (111)-oriented tensile-strained GaAs/InAlAs QDs (TSQDs).[3-5] These TSQDs form as highly-symmetric tetrahedra (Fig. 1(a)) with very low FSS.[4] The use of tensile strain allows for their dislocation-free formation, and reduces their bandgap toward the infrared.[3] Further, TSQDs exhibit clear processing-property correlations, whereby adjusting deposition amount, growth temperature, growth rate, and V/III flux ratio allows us to control QD size, shape, and spectral emission. The resulting roadmap now allows us to optimize TSQDs for specific applications.[5]

Building on that work, here we describe the growth conditions and resultant structural and optical properties of TSQDs optimized specifically for entangled photon emission. We will present a detailed analysis of the structure of individual GaAs TSQDs; power-dependent, temperature-dependent, and time-resolved photoluminescence; and island scaling statistics. We also present experimental results of the reconstruction of the InAlAs(111)A buffer surface. Finally, we will show that we can transform the in-plane shape of the GaAs TSQDs from equilateral triangles to regular hexagons, simply by switching from As_2 to As_4. The hexagonal TSQDs exhibit improved optical quality and higher symmetry, properties that we expect to be critical for robust quantum entanglement.

[1] Shields, Nat. Phot. 1, 215 (2007). [2] Schliwa et al., PRB 80, 161307(R) (2009). [3] Simmonds et al., APL 99, 12 (2011). [4] Yerino et al., APL 105, 251901 (2014). [5] Schuck et al., JVSTB 36(3), 031803 (2018).

2:30pm **MBE-WeA-5 Optimization of InAs Quantum Dots for Scintillation Applications**, ***Michael Yakimov***, *V Tokranov, K Dropiewski, A Minns,* SUNY Polytechnic Institute*; P Murat,* Fermi National Accelerator Laboratory*; S Oktyabrsky,* SUNY Polytechnic Institute

Use of semiconductors as scintillators for particle detection is limited by self-absorption in material bulk. Introducing below-bandgap transitions – e.g by doping (ZnS:Cu) is a way to address absorption. Use of heterostructures was proposed [1] and a scintillating medium of GaAs with artificial luminescent centers, InAs quantum dots (QD) was demonstrated [2].

A prototype scintillation device is grown by MBE and consists of 20 um thick GaAs layer with 50 sheets of embedded self-assembled InAs QDs. A m etamorphic p-i-n detector with InGaAs absorber is grown on top of the structure for high-speed integrated photo-detection. Overall structure and measurement diagram is shown in fig 1. After detector fabrication, the epi layer is separated from GaAs by epitaxial lift-off to form a scintillation waveguide and bonded to glass for testing, cross-sectional TEM of top layers is shown in fig 2.

We use elevated QD growth temperature of 520 ºC to reduce native defect density and associated recombination. Indium surface evaporation is addressed with high indium flux. Modulation p-doping and potential profile engineering was employed to achieve 60% luminescent efficiency at room temperature with low excitation level. This enables observations of single-particle events in QD medium, reduced self-absorption and scattering on structural defects. Shape engineering of QDs and barrier shape using thermal cycling, AlAs capping layers on QD for preserving shape and InGaAs barrier engineering to reduce carrier thermal escape rate from QDs were further optimized. We demonstrate a prototype scintillator in the form of a free-standing 20 um GaAs waveguide impregnated with InAs QD with self-absorption in the range of 3-5 cm^{-1}, and scintillator operation by detection of alpha particles using integrated InGaAs photodetector with time resolution of 60ps.

[1] Kastalsky, A., Luryi, S. and Spivak, B., *Nucl. Inst. Methods Phys. Res. Sect. A*, **565**(2), pp.650-656. (2006)

[2] Oktyabrsky, et al, *IEEE Trans. On Nuclear Sci.*, **63**(2), pp.656-663, (2016)

2:45pm **MBE-WeA-6 Tensile-Strained Ge Quantum Dots on (111)A Surfaces***, **Kathryn Sautter**, C Schuck, T Garrett, A Weltner, K Vallejo, P Simmonds,* Boise State University

Si and Ge are ubiquitous in electronics, but their indirect bandgaps make them unsuitable for optoelectronic devices. Theory shows that placing Ge under tensile strain reduces its semiconductor bandgap by reducing the Γ-valley in Ge's conduction band faster than the L-valley. Once at ~2% tensile strain, Ge should acquire a direct bandgap. Researchers have therefore tried various ingenious methods to create tensile strain in Ge, but these attempts typically generate strain-induced defects and do not result in viable optoelectronic materials. Our approach to this problem is to synthesize Ge quantum dots (QDs) that self-assemble as a result of biaxial tensile strains on (111) surfaces. We have previously developed a method to grow defect-free GaAs(111) QDs at ~4% tensile strain with molecular beam epitaxy (MBE). Since GaAs and Ge have similar lattice constants, we simply replace GaAs with Ge in these structures. Initial data suggest spontaneous formation of Ge QDs under 3.7% tensile strain, which we anticipate should lead to optically active Ge with a reduced bandgap. We will present results demonstrating control of the structural and optoelectronic properties of tensile-strained Ge QDs with MBE parameters. Specifically, we will report on the effects of growth parameters via atomic force microscopy (AFM), transmission electron microscopy (TEM), scanning tunneling microscopy (STM), and preliminary measurements of their optoelectronic properties.

This work is supported by the Air Force Office of Scientific Research under award #FA9550-16-1-0278.

3:30pm **MBE-WeA-9 Relaxed GaP on Si with Low Threading Dislocation Density***, **Ryan Hool**, Y Chai, P Dhingra, B Eng,* University of Illinois Urbana-Champaign*; Y Sun,* Yale University*; S Fan,* University of Illinois Urbana-Champaign*; K Yaung,* Yale University*; M Lee,* University of Illinois Urbana-Champaign

Epitaxial growth of 1.7 eV $GaAs_{0.75}P_{0.25}$ on GaP/Si templates offers a promising path to low-cost, high-efficiency tandem solar cells. While nucleation of thin, strained GaP on Si without anti-phase domains and stacking faults is now well established, the relaxation process of GaP on Si remains poorly understood. Threading dislocation densities (TDD) > 10^7 cm^{-2} in relaxed GaP on Si have been observed, despite the small lattice mismatch of ~0.45%. Our prior work revealed that the TDD of relaxed GaP on Si is dominated by dislocation glide at low temperatures (e.g. < 505°C) and by dislocation nucleation at high temperatures (e.g. > 575°C), with lowest TDD of 1.7×10^6 cm^{-2} [1]. We also showed that the TDD of the relaxed GaP layer strongly influences the TDD and efficiency of the $GaAs_{0.75}P_{0.25}$ active region, which emphasizes the importance of controlling the initial relaxation.

Here, we describe a two-step MBE growth process to suppress heterogeneous dislocation nucleation and improve dislocation glide during relaxation of GaP on Si. Initiating growth with a thin, low-T layer and subsequently growing a high-T layer for a combined thickness of ~0.5 µm enabled TDD reduction to 1.0×10^6 cm^{-2} in relaxed GaP on Si, which is the lowest value to date. We will show that the low-T step strongly suppresses dislocation nucleation, while the high-T step improves dislocation glide and surface morphology. This reduction in GaP TDD is expected to enable TDD values of 2-3×10^6 cm^{-2} for $GaAs_{0.75}P_{0.25}$ solar cells on GaP/Si along with substantial efficiency improvements over current state-of-the-art.

[1] K. N. Yaung et al., Appl. Phys. Lett. **109**, 032107 (2016).

3:45pm **MBE-WeA-10 Development of Hybrid Gas-source MBE to make Thin Films of Sulfide Perovskites and Related Complex Chalcogenides***, S Filippone, Y Li, **Rafael Jaramillo**,* Massachusetts Institute of Technology

Ternary sulfides and selenides in the distorted-perovskite and related structures ("complex chalcogenides") are predicted by theory to be semiconductors with band gap in the visible-to-infrared and may be useful for optical, electronic, and energy conversion technologies [1-4]. We will present progress towards growing films of complex chalcogenides by hybrid gas-source MBE, including thermodynamic modeling and gas-source optimization.

We use computational thermodynamics to predict the pressure-temperature phase diagrams for select chalcogenide perovskites [5-6]. We highlight the windows of thermodynamic equilibrium between solid chalcogenide perovskites and the vapor phase. For $ABCh_3$ (Ch = S, Se) materials with B = transition metal, the growth windows lie at very high temperature and low pressure (*e.g.* $T > 1000$ °C and $P < 10^{-9}$ torr) that are challenging for most MBE chambers. The growth window becomes much more accessible for materials for which the quasi-binary phase diagram includes a compound (*e.g.* SnS) with high vapor pressure.

We then report on the effect of hydride gas source placement in our growth chamber on the growth of chalcogenide films using hydrogen sulfide (H_2S) and hydrogen selenide (H_2Se) gas sources. Taking a cue from the history of complex oxides, we hypothesize that the location of the gas injectors is quite important for optimizing film growth, more so than the chamber growth pressure read by a remote pressure gauge. We test this hypothesis by measuring gas cracking by a heated substrate and the growth of binary sulfides MoS_2 for two different gas injector positions. We support our experimental measurements by Monte Carlo simulations of gas flow in our chamber. The results highlight the importance of gas source location for optimized hybrid MBE.

[1] Brehm, J. A., Bennett, J. W., Schoenberg, M. R., Grinberg, I. & Rappe, A. M. *J. Chem. Phys.***140,** 224703 (2014).

[2] Sun, Y.-Y., Agiorgousis, M. L., Zhang, P. & Zhang, S. *Nano Lett.***15,** 581–585 (2015).

[3] Wang, H., Gou, G. & Li, J. *Nano Energy***22,** 507–513 (2016).

[4] Ju, M.-G., Dai, J., Ma, L. & Zeng, X. C. *Adv. Energy Mater.***7,** 1700216 (2017).

[5] Filippone, S. A., Sun, Y.-Y. & Jaramillo, R. *MRS Commun.***8,** 145–151 (2018).

[6] Filippone, S. A., Sun, Y.-Y. & Jaramillo, R. *MRS Adv.* 1–6 (2018).

4:00pm **MBE-WeA-11 Epitaxial III-V Growths on 0.1-mm Grain-size Polycrystalline Germanium Thin-films***, **Abhinav Chikhalkar**, C Zhang, N Faleev,* Arizona State University*; E McClure, S Hubbard,* Rochester Institute of Technology*; C Honsberg, R King,* Arizona State University

III-V solar cells have demonstrated the highest efficiencies, for both single-junction and multijunction cells. Low defect tolerance and Fermi-level pinning at grain boundaries of these compounds has focused III-V growth on single-crystal thin-films, on single-crystal gallium arsenide, indium phosphide and germanium wafers that are both heavy and costly.

Polycrystalline thin-films of these materials are attractive candidates to reduce high substrate costs, but to maintain high efficiencies we require (a) large grain size, and (b) effective grain boundary passivation. R. Venkatasubramanian et al. [1] have demonstrated 18.2% (AM1.5) efficiencies on polycrystalline GaAs solar cells with 1-2 millimeters grain size, grown on polycrystalline germanium wafers cut from ingots with the same size of grains. Use of aluminum-induced crystallization for growth of polycrystalline germanium (AIC germanium) opens a new parameter space for growth of III-V tandem architectures on germanium-templated low-cost substrates such as glass and Mo foil. In addition to the light weight of the substrate, relatively large grain size of ~100 µm with high <111> orientation preference can be achieved, reducing the effect of grain boundary recombination. These characteristics along with the theoretical studies by S. Kurtz et. al. [2] which project >20% GaAs efficiency with grain size of 50-70 µm makes III-V growth on AIC germanium a promising avenue.

In this talk, we demonstrate the epitaxial growth of GaInP and Ga(In)As on AIC germanium. The growth mechanism was studied in situ using reflection high-energy electron diffraction. The presence of streaks indicates a layer-by-layer growth. Morphology and surface roughness of the grown film are studied using scanning electron microscopy and atomic force microscopy, respectively, while grain orientation is characterized using X-ray diffraction. A high crystal orientation preference and reduction in surface roughness were observed on the grown III-V films compared to the initial Ge template, both encouraging signs for the grown film quality. Recombination kinetics are characterized through room-temperature photoluminescence (PL) intensity and measurements of minority charge carrier lifetime in GaInP/GaAs/GaInP double heterostructures. The influence of substrate grain size and pre- and post-deposition treatments on minority charge carrier lifetime will be presented.

[1] R. Venkatasubramanian, et. al., IEEE Photovoltaic Specialists Conference Proceeding, 31(1996).

[2] S. R. Kurtz, et. al., AIP Conference Proceedings 404, 191(1997).

4:15pm **MBE-WeA-12 Grating Coupled Quantum Well Infrared Photodetector on a Si Substrate***, **HoSung Kim**,* University of Waterloo, Canada*; G Ryu, S Ahn,* Korea Institute of Science and Technology, Korea*; Z Wasilewski,* University of Waterloo, Canada*; W Choi,* Korea Institute of Science and Technology, Korea

Integration of III-V on Si has been widely studied due to the possibility of low-cost fabrication using Si substrate and excellent opto-electronic conversion efficiency of III-V material. The wafer bonding and epitaxial lift-off (ELO) techniques can transfer III-V layers on any substrates whose surface is clean and atomically smooth without changing material characteristics.

Quantum well infrared photodetectors (QWIPs) are currently used for two-dimensional long-wavelength infrared light detection due to the good uniformity produced by well-established MBE techniques. However, selection rules prevent quantum wells from absorbing normal-incidence light directly, so most usable QWIPs must incorporate grating couplers to convert TE light into TM light for absorption.

In this talk, grating coupled GaAs/AlGaAs QWIPs are fabricated on a Si substrate by means of metal wafer bonding (MWB) and ELO method for the first time. The GaAs/AlGaAs QWIPs which have 50 periods of quantum wells (QWs) are grown by MBE. The grating was designed with a hexagonal periodic hole array structure and fabricated by dry-etching. After fabricating the grating structure, thin Pt/Au materials were deposited on the both detector and Si substrate. Two substrates were pressed and then dipped into the HF solution for ELO process. The final device was completed after metallization on the transferred QWIP layer on a Si substrate.

Our results show remarkable improvement compared to previous attempts to fabricate grated QWIPs. Previously, grated QWIPs were integrated with Si using In-bumps saw only a relatively small increase in photocurrent compared to the un-grated structure. However, as seen in Fig. 1, our grated shows 17 times higher intensity compared to the QWIP on a Si substrate without grating structure. This significant increase may be attributed to both the optical resonance cavity effects and increased light absorption of TM component.

4:30pm **MBE-WeA-13 Direct MBE Growth of Metamorphic nBn Infrared Photodetectors on 150 mm Ge-Si Substrates for Heterogeneous Integration***, **Joel Fastenau**, D Lubyshev, S Nelson,* IQE Inc.*; A Morgan, S Edwards,* IQE Silicon, UK*; M Fetters, H Krysiak, J Zeng, M Kattner, P Frey, A Liu,* IQE Inc.

GaSb-based infrared (IR) photodetectors continue to progress and improve, and the transition from pure development to a manufacturing phase is underway. The rich bandgap engineering possibilities of the GaSb materials system, with typical type-II broken-gap alignments, result in myriad device architectures, frequently based on the unipolar barrier design concepts commonly noted as nBn or XBn [1, 2]. To compete with HgCdTe in both performance and cost requires manufacturing processes based on larger-format focal plane array (FPA) detectors, leading to a requirement for larger diameter wafers for improved throughput, volumes, and yield. IQE has demonstrated a nBn production molecular beam epitaxy (MBE) growth process in multi-wafer configurations on 4-inch and 5-inch diameter GaSb substrates as well as via a metamorphic process on 4-inch and 6-inch GaAs substrates [3-5].

A next step in the progression of this IR photodetector technology is its heterogeneous integration with silicon. Such integration can provide the combined advantages of high-level volume production of Si-based electronic circuitry with superior high speed and optical performance of III-V components. In this work, we report the growth of GaSb-based metamorphic nBn (M-nBn) photodetector structures on large diameter (150 mm) Si substrates. Multiple growth steps are required to transition from the Si to the GaSb lattice constant, beginning with a Ge layer deposited by CVD at IQE-Silicon. This provides a Ge–Si substrate for the growth of the remaining III-V layers, from GaAs and GaSb buffer layers up to the M-nBn device layers, via MBE at IQE Inc. Standard epiwafer characteristics, including morphology, x-ray, and optical properties, will be presented. Large–area mesa diode characteristics from these M-nBn epiwafers compare favorably to those grown on lattice–matched substrates. The results represent an important technological path toward next–generation large-format IR detector array applications.

[1] D. L. Smith and C. Mailhiot, J. Appl. Phys. **62**, 2545–2548 (1987).

[2] S. Maimon and G. W. Wicks, Appl. Phys. Lett. **89**, 151109 (2006).

[3] J. M. Fastenau, D. Lubyshev, Y. Qiu, A. W. K. Liu, E. J. Koerperick, J. T. Olesberg, and D. Norton, Jr., Infrared Phys. Technol. **59**, 158–162 (2013).

[4] D. Lubyshev, J. M. Fastenau, M. Kattner, P. Frey, A. W. K. Liu, and M. J. Furlong, Proc. SPIE **10177**, 1017718 (2017).

[5] J. M. Fastenau, D. Lubyshev, Y. Qiu, A. W. K. Liu, E. J. Koerperick, J. T. Olesberg, and D. Norton, Jr., J. Vac. Sci. and Technol. B, **31**, 03C106 (2013).

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