MBE
Room Silver Creek - Session MBE-2TuA
Quantum Dots

Moderator: Paul Simmonds, Boise State University

3:30pm **MBE-2TuA9 InAs Chirped Quantum Dot Growth on Si for Broadband Spectral Gain Mode--locked Laser**, ***Daehwan Jung***, Korea Institute of Science and Technology, Republic of Korea*; J. Norman, C. Shang, S. Tao, Y. Wan, A. Gossard, J. Bowers,* University of California, Santa Barbara

Monolithic integration of an efficient and reliable III-V light source onto Si has been heavily studied for the past decades. Recently, quantum dot (QD) lasers directly grown on Si have shown tremendous improvements in performance and device reliability, primarily due to the effective carrier localization of QDs. [1] Furthermore, QD lasers are promising for generation of ultra-short pulses by operating them in the passively mode-locking regime. We have shown that QD lasers epitaxially grown on Si could be used as a source for a dense wavelength-division multiplexing (DWDM) system. [2] The monolithically integrated mode-locked QD laser consisted of five layers of InAs/$In_{0.15}Ga_{0.85}As$ dot-in-a-well (DWELL) structure and showed an optical gain spectrum full-width at half-maximum (FWHM) of 3.56 nm. The relatively small optical spectrum width can be further increased by considerately designing the QD active region on Si.

For conventional low threshold current QD lasers, growing the multiple QD layers in an identical growth condition (i.e. temperature) is crucial. Doing so, a full epitaxial laser structure will have narrow photoluminescence (PL) linewidth. However, for broadband gain mode-locked lasers, growing the QD layers at slightly different QD structures is important so that the ensemble of individual PL spectra possesses broad PL spectrum while maintaining a high intensity.

Here, we report growth of chirped InAs/GaAs QDs by solid state molecular beam epitaxy. The InAs/InGaAs DWELL structures vary as shown in the Table I. Five samples were grown on native GaAs substrates to investigate their PL properties. The DWELL active region was grown at 495 °C by an optical pyrometer. The InAs QD deposition rate was 0.1132 monolayer (ML) per second. Figure 1 shows PL spectra of the five different samples. The PL peaks are well spaced to have a broadened optical gain. Full laser structures were grown on Si to compare the FWHMs of a broadband gain laser with chirped QD growth and a conventional laser. Figure 2 shows the two different lasers grown on Si have similar PL intensities. However, the broadband gain laser possesses a much wider PL linewidth (FWHM= 43 meV) than the reference laser in which the linewidth is 28.6 meV). More optimizations on the chirped QD growth could lead to further broadened PL widths. We believe that the chirped InAs DWELL structure is a promising method to realize passively mode-locked QD lasers with broadband optical gain spectrum.

[1] Daehwan Jung *et al.* Appl. Phys. Lett. 111 (12), 122107

[2] Song Tao *et al.* Appl. Phys. Lett. 113 (4), 041108

3:45pm **MBE-2TuA10 InP Quantum Dots for Dislocation-tolerant, Visible Light Emitters on Si**, ***Pankul Dhingra,*** University of Illinois Urbana-Champaign*; Y. Sun,* Yale University*; S. Fan, R. Hool, M.L. Lee,* University of Illinois Urbana-Champaign

We present the first demonstration of InP quantum dots (QDs) on Si showing room-temperature, visible photoluminescence (PL) intensity nearly identical to samples grown on GaAs. The past few years have seen tremendous progress in the development of 1.3 µm InAs quantum dot (QD) lasers on Si with low threshold current density and high reliability despite threading dislocation densities (TDD) of 10^7 cm^{-2} [1]. The high luminescence efficiency of InAs QDs on Si can be attributed to lateral carrier confinement of the QDs and high QD density, 3 orders of magnitude higher than the TDD. Epitaxial InP QDs embedded in $(Al_xGa_{1-x})_{0.52}In_{0.48}P$ can also be grown on GaAs and have recently been used to demonstrate red and near-infrared lasers with low threshold current density [2]. Here, we show that the apparent dislocation-tolerance of InAs QDs on Si also extends to InP QDs on Si, making them an ideal candidate for low-cost visible and near-infrared lasers and light emitting diodes (LEDs).

We grew InP/AlGaInP QD PL structures on bulk GaAs and GaAs/Si virtual substrates using MBE. GaAs/Si virtual substrates were grown on commercially available GaP/Si (001) templates using a 3.6 µm thick $GaAs_xP_{1-x}$step-graded buffer. Cross-sectional transmission electron microscope (XTEM) images of samples grown on both GaAs and GaAs/Si were nearly identical, showing coherently strained InP QDs capped by a smooth InGaP QW. Planar-view cathodoluminescence (CL) maps showed essentially no dislocations for the sample grown on GaAs, as expected. In contrast, a TDD of 3.3×10^7 cm^{-2} was observed for the sample grown on GaAs/Si. Atomic force microscopy (AFM) showed a high QD density of 1.3×10^{11} cm^{-2} on both substrates, which is several orders of magnitude greater than the TDD in the active region. We performed room-temperature PL measurements to characterize the emission wavelength and intensity of InGaP QWs and InP QDs grown on both GaAs and GaAs/Si virtual substrates. The integrated intensity of the InGaP QW sample grown on GaAs/Si is ~9× lower than the QW on GaAs due to the high TDD. In contrast, the integrated intensity of InP QDs on Si is ~16× higher than the InGaP QW on Si and within 15% of InP QDs grown on GaAs, showing the high dislocation tolerance of InP QDs. In conclusion, we show that high density InP/AlGaInP QDs can be grown on Si with similar structural and optical properties as growth on bulk GaAs, paving a pathway towards low-cost, integrated light emitters with potential applications ranging from micro-LEDs to optogenetics.

[1] Jung, ACS Photonics, **5**, 1094 (2018)

[2] Lutti, Electron Lett., **5**, 247 (2005)

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4:00pm **MBE-2TuA11 Gallium-assisted Deoxidation for Spatially and Spectrally Controlled InAs Quantum Dot Molecules**, ***Lauren McCabe****, J. Zide,* University of Delaware

InAs quantum dots (QDs) have long been considered as possible qubits and numerous proof-of-concept quantum operations have been performed [1, 2]. However the random nucleation for these self-assembled QDs and the spectral inhomogeneity that arises from variations in size, composition, and shape have made it impossible to produce arrays of identical QDs that are desired for scalable production of devices. Other material platforms for quantum device technologies face similar problems with inhomogeneity [3, 4]. To overcome these challenges we are engineering a new, molecular beam epitaxy (MBE) grown III-V QD material platform with built-in spectral tunability and site control. We present on using improved gallium-assisted deoxidation [5, 6] of patterned GaAs substrates for InAs QD growth used in photonic crystal cavities.

Typical patterned growth of QDs produces low optical quality structures [7]. To address this we are implementing a column of QDs in between the patterned GaAs surface and the optically active QD. This maintains the spatial location but creates a buffer layer away from defects at the growth interface. However in the fabrication of the patterned substrates surface oxide forms. Conventional thermal deoxidation leaves the surface pitted due to the stable surface oxide Ga_2O_3 reacting to form a volatile oxide Ga_2O. These surface pits compete with the fabricated nano-holes of the pattern for QD nucleation. A previous study by Atkinson et. al. successfully investigated gallium-deoxidation for patterned nano-holes [5, 6]. The nano-holes were spaced 500 nm apart and used a gallium deposition rate of 1 ML per minute to deposit 6 to 8 ML in 30-second intervals with 30-second growth interrupts. This study achieved 60% doubly and 40% singly occupied QDs in nano-holes. For implementation into our photonic crystal cavities we require a 10-µm spacing of nano-holes for the devices, single QD occupancy in nano-holes, and higher gallium flux for continued growth of the QD column in a GaAs matrix. We have shown 89% single QD occupancy in our pattern using a 12 ML per minute gallium deposition rate to deposit 4 to 6 ML in 1-second intervals with 30-second growth interrupts. The growth parameters and oxide removal for this system will be discussed.

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[2] J. L. O'Brien, et. al., Nat. Photon, **3**, 687–695 (2009)

[3] M. Grydlik et. al., Appl. Phys. Lett. **106**, 251904 (2015)

[4] M. Ikezawa, et. al., Phys. Rev. B, **72**, 153302 (2005)

[5] P. Atkinson, O.G. Schmidt, J. Cryst. Growth. **311**, 1815 (2009)

[6] P. Atkinson, et. al., Appl. Phys. Lett. **93**, 101908 (2008)

[7] S. Kiravittaya, et. al., Rep. Prog. Phys. **72**, 046502 (2009)

4:15pm **MBE-2TuA12 Influence of the Growth Conditions on the Performance of InAs Sub-Monolayer Quantum Dot Infrared Photodetectors**, ***Kevin Vallejo,*** Boise State University; *A. Zeidan, T. Cantalice, A. Quivy,* University of Sao Paulo, Brazil; *P. Simmonds,* Boise State University

Semiconductor devices that can efficiently emit or detect infrared radiation (IR) are in ever increasing demand for applications in fields as diverse as medicine, agriculture, astronomy and national security. A common type of IR detector is the quantum well infrared photodetector (QWIP), which relies on intraband carrier transitions between the confined states of the quantum wells. Although QWIPs perform well under certain conditions, these devices are not sensitive to normal incident radiation, have high values of dark current and require cryogenic temperature to operate, making them bulky and expensive. In contrast, quantum dot infrared photodetectors (QDIPs) offer higher sensitivity to normal incidence light, longer photoexcited carrier lifetime, and lower dark current values. Quantum dots for QDIP devices are often grown via the Stranski-Krastanov growth mode, but this self-assembly process places limits on how closely we can control QD size and composition. However, sub-monolayer quantum dots (SML-QDs) offer enhanced height and composition uniformity, higher surface density of nanostructures, the absence of a wetting layer and improved 3-dimensional confinement [2].

The nucleation of InAs islands on GaAs(001) is influenced by our choice of MBE growth parameters, leading to SML-QDs with different shapes, sizes and compositions that can impact QDIP performance. In the present work, we have explored the effects of growth rate and arsenic flux on the growth and performance of InAs/GaAs SML-QD structures for QDIPs. We consider the influence of these variables on the formation and stacking of the small 2D InAs islands, verifying their structure with x-ray diffraction (Fig. 1). We tested the QDIP devices optically and electrically at 10 K (Fig. 2), measuring specific detectivities in the 10^{11} cm $Hz^{1/2}$ W^{-1} range. We will discuss differences in QDIP performance as a function of the MBE conditions used.

[1] Liu, Opto-Electronics Rev. **11**, 1 (2003). [2] Sengupta *et al.* Appl. Phys. Lett. **100**, 191111 (2012)

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4:30pm **MBE-2TuA13 Effect of Annealing on Structure and Luminescence of InP/AlGaInP Quantum Dots**, ***Pankul Dhingra,*** University of Illinois Urbana-Champaign; *Y. Sun,* Yale University; *E. Moog, M.L. Lee,* University of Illinois Urbana-Champaign

Lasers based on self-assembled quantum dots (QDs) have attracted widespread interest due to their unique characteristics that include low threshold current density and resistance to threading dislocations. While most work to date has focused on 1.3µm InAs/GaAs QDs, InP QDs have also aroused interest for low threshold lasers in the visible and near-infrared regime. For example, electrically injected room-temperature InP QD lasers showed a J_{th} of 190 A/cm^2 with emission at 740 nm [1]. Growth of phosphides by MBE typically requires a relatively low substrate temperature (500ºC) compared to MOVPE (≈700ºC), which leads to degraded optical properties and makes post-growth annealing a crucial step to improve the material quality [2]. For InAs/GaAs QDs grown using MBE, thermal annealing leads to a significant blueshift of emission wavelength due to the interdiffusion of In between the QDs and the surrounding matrix [3]. In contrast, little is known about the effects of annealing on InP/AlGaInP QDs. Here we report the exceptional thermal stability of InP/AlGaInP QDs, showing ≈50X improvement in room temperature photoluminescence intensity without signs of structural degradation or blueshifting for annealing temperatures T < 875ºC.

We found that annealing improves the optical properties of InP QDs, InGaP QWs and AlGaInP DHs, with QDs showing the greatest benefit and up to 50X enhancement in the integrated PL intensity. While high-T rapid thermal annealing (RTA) of InP QDs led to > 50X intensity increase, the emission spectra showed an abrupt blueshift of ≈20 nm for T > 875ºC. Cross-sectional transmission electron microscopy (XTEM) of such QD samples showed a reduction in strain contrast, indicating strong interdiffusion between the matrix and the QDs. Given the lack of blueshift for T < 875ºC, we next investigated the effect of furnace annealing for longer times (≈10-100 minutes) at lower T and found that similar PL intensity improvements of ≈50X could be attained while avoiding any blueshift. XTEM and HAADF-STEM of furnace-annealed samples showed clear strain and composition contrast from individual QDs, similar to the as-grown structure. The remarkable improvement in emission intensity without significant structural changes at T < 875ºC proves thermal annealing to be a crucial step towards the development of visible InP QD LEDs and low-threshold lasers using MBE.

[1] Lutti, Electron Lett., **5**, 247 (2005),

[2] Jalonen, Appl. Phys. Lett., **71**, 479 (1997),

[3] Xu, Appl. Phys. Lett., **72**, 3335 (1998)

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4:45pm **MBE-2TuA14 Structural and Optical Properties of GaAs(111)A Tensile-strained Quantum Dots using As_2 and As_4**, ***Christopher Schuck*,** University of Delaware; *K. Vallejo, T. Garrett,* Boise State University; *Q. Wang, Y. Wang, B. Liang,* Hebei University, China; *P. Simmonds,* Boise State University

GaAs(111)A tensile-strained quantum dots (TSQDs) are the first optically active materials system to combine the benefit of epitaxial self-assembly, (111)-orientation, and tensile strain[1]. They are structurally and optically tunable, dislocation-free, exhibit low fine structure splitting (FSS), and have a tunably reducible bandgap[2,3]. To outline the full capabilities of this promising new material system, we recently presented a comprehensive study on the customization and optimization of GaAs(111)A TSQD properties[2]. However, all (111) TSQDs were grown using tetrameric arsenic (As_4) for consistency with previous (111) growths[1–4], since much of the original growth optimization on (111) surfaces was done before the advent of valved crackers. However, research shows that dimeric arsenic (As_2) often provides better material properties. Here we present the impact of arsenic species choice on the growth and properties of GaAs/InAlAs(111)A TSQDs.

Using As_2 or As_4 in the growth of GaAs(111)A TSQDs results in different TSQD structure and photon emission behavior. Structural differences with different arsenic species provide a greater ability to tailor TSQDs and reveal different nucleation and growth kinetics. Depending on the substrate temperature and arsenic species, GaAs(111)A TSQDs have a triangular base, with two possible crystallographic orientations, or a hexagonal base (Fig. 1 (a,b)). We attribute these different morphologies to differences in step edge growth rates. For all morphologies, As -grown TSQDs exhibits improved photoluminescence (Fig. 1 (c)). Additionally, the higher symmetry of the hexagonal TSQDs may result in lower FSS, which may further improve entangled photon emission.

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2. Schuck, C. F. *et al.* J. Vac. Sci. Technol. B **36,** 031803 (2018).

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4. Cho, A. Y. Thin Solid Films **100,** 291–317 (1983).

5:00pm **MBE-2TuA15 Comparing the Self-assembly of Tensile-strained Ge and GaAs Quantum Dots on InAlAs(111)A**, ***Kathryn Sautter,*** *C. Schuck, T. Garrett, K. Vallejo, A. Weltner,* Boise State University; *J. Smith, C. Ratsch,* University of California, Los Angeles; *P. Simmonds,* Boise State University

Compressively strained quantum dots (QDs) grown on (001) surfaces have been explored widely for optoelectronic applications. A recently developed process, tensile-strained self-assembly enables the tunable synthesis of defect-free QDs on non-(001) surfaces, opening up many potentially novel applications. For example, theory predicts that Ge will become a direct band gap semiconductor when grown on (110) surfaces under ~3% biaxial tensile strain and a semimetal on (111) surfaces under ~4% tensile strain.[1–4] (111)-oriented GaAs QDs are a promising source for entangled photons due to their high symmetry and low fine-structure splitting.

The development of tensile-strained self-assembly has chiefly focused on the growth of Ge and GaAs QDs on the (110) and (111)A surfaces of $In_{0.52}Al_{0.48}As$. With almost identical lattice constants, these Ge and GaAs QD systems are very similar from the point of view of tensile strain, with ~3.7% lattice mismatch. However, while exploring the self-assembly of tensile-strained Ge and GaAs QDs, we discovered significant differences between these two systems. Although both show excellent tunability in terms of QD size and areal density with growth conditions, Ge and GaAs QDs exhibit different shapes and nucleation behaviors. To understand these differences, we used a combination of experimental characterization and computational modelling. We compare experimentally derived island scaling and radial distribution functions to predictions from density functional theory and kinetic Monte Carlo simulations of potential energy surfaces (PES). We use this data to explore the surface diffusion behavior of the Ge and Ga adatoms on InAs(111)A.

Under the same MBE growth conditions, Ge QDs have a higher critical cluster size than GaAs QDs, although in both cases these critical clusters seem to adopt a three-fold symmetry consistent with the (111)A surface. Our models indicate that the InAlAs surface has an As-trimer reconstruction, and preliminary results show marked differences in the migration behavior of Ge and Ga adatoms on this surface. The potential barriers to Ge adatom surface diffusion appear to be lower than for Ga adatoms, resulting in longer diffusion lengths. We will discuss our experimental and computational results from both a kinetic and thermodynamic perspective.

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