PCSI
Room Ballroom South - Session PCSI-WeM2
Crystal Growth

Moderator: Christopher Palmstrøm, University of California, Santa Barbara

11:00am **PCSI-WeM2-31 Droplet Epitaxy of Quantum Nanostructures**, ***Stefano Sanguinetti***, University of Milano-Bicocca, Italy **INVITED**

Quantum materials represent the novel frontier of physics, chemistry, and engineering, aiming to tailor the electronic and optical properties of materials via the artificial nano-synthesis of quantum nanostructures (QNs). QNs have been systematically explored to improve “classical” optoelectronic devices like low-threshold and thermally stable semiconductor lasers, amplifiers, detectors, solar cells, etc. Even more relevant is their application as solid-state building blocks for emerging quantum technologies, allowing the fabrication of deterministic sources of single photons and quantum entangled photon pairs for quantum communication, quantum simulation, and computing.Among the more successful growth processes to self-assemble three-dimensional quantum nanostructures, Droplet Epitaxy has demonstrated a high flexibility, from non-classical photon sources to quantum infrared photodetectors, thus becoming a fundamental growth procedure for the fabrication of advanced quantum devices. The Droplet Epitaxy growth protocol [1] exploits the controlled crystallization of metal nano-droplets into compound semiconductor QNs of high crystalline and optical quality. This makes it possible, by controlling the process kinetics, to obtain QNs with an extended chart of materials, and to tailor shape and topology, thus making it possible to engineer electronic, spin, and optical properties for targeted applications [2,3].We report on the recent advances in the understanding of droplet epitaxy self-assembly fundamental processes and in the fabrication of non-classical photon emitters (optimizing entangled photon cascade devices, tuning the emission in the telecom range, etc.) and of advanced optoelectronic devices.[1] K. Watanabe, N. Koguchi, and Y. Gotoh, Jpn. J. Appl. Phys. 39, L79 (2000)[2] S. Sanguinetti, S. Bietti, N. Koguchi, Chapter 13 - Droplet Epitaxy of Nanostructures, Editor(s): Mohamed Henini, Molecular Beam Epitaxy (Second Edition), Elsevier, 293 (2018)[3] M. Gurioli, Z. Wang, A. Rastelli, T. Kuroda, and Stefano Sanguinetti, Nature Materials, 18, 799 (2019)

11:40am **PCSI-WeM2-39 Realization of Quantum Size Effects in Rocksalt-Structured MgZnO/MgO Multiple Quantum Wells Grown by Mist CVD**, ***Hiroyuki Aichi***, *Kotaro Ogawa,* Kogakuin University, Japan*; Yukino Abe,* kogakuin University, Japan*; Kyosuke Tanaka, Tomohiro Yamaguchi, Tohru Honda, Takeyoshi Onuma,* Kogakuin University, Japan

Rocksalt (RS)-structured MgZnO alloys have ultrawide bandgap energies up to 7.7 eV. Our group has grown RS-MgZnO epitaxial films by the mist chemical vapor deposition (mist CVD) method. Observation of near-band-edge cathodoluminescence (CL) peak at 187 nm at 300 K paves a way for vacuum ultraviolet light source application. We have developed an alternating precursor supply system to fabricate RS-MgZnO/MgO multiple quantum well (MQW) structures. The MQWs showed smooth surfaces comparable to single layers, and excellent interface flatness and periodicity were confirmed. Present study reports on well thickness dependence to discuss quantum size effects. Magnesium acetate tetrahydrate and zinc acetate dihydrate were used as metal-organic precursors. The Mg molar fraction in source solution was fixed at 0.86. A mixed solvent of deionized water and acetic acid with a volume ratio of 4:1 was used. All layers were grown at 720°C with O_2 carrier and dilution gas flow rates of 4.0 slm and 0.5 slm, respectively. 20-period MQW structures were grown by fixingthe barrier thickness of 10 nm, and by varying the nominal well thicknesses as 0.5, 1, and 3 nm. MQWs show atomically-flat surface morphology with root mean square (RMS) roughness of less than 1 nm. The CL peak energy at 300 K exhibited a distinct blueshift by thinning the well layer thickness. The blueshift is well reproduced by 1D Poisson–Schrödinger calculation. The results indicate the presence of the quantum size effects.

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11:45am **PCSI-WeM2-40 Selective Area Growth of PbSe Nanostructures by Molecular Beam Epitaxy**, ***Ashlee Garcia***, *Jarod Meyer, Kira Martin,* Stanford University*; Maksim Gomanko, Sergey Frolov,* University of Pittsburgh*; Kunal Mukherjee,* Stanford University

Selective area growth (SAG) by molecular beam epitaxy of PbSe offers exciting opportunities for integrated photonics and quantum technologies. By using an amorphous mask to define crystal growth, geometric control and deterministic placement of epitaxially smooth nanostructures can be achieved without etching, which can degrade quantum efficiency.[1] Integrating SAG with the advantageous properties of PbSe, including a narrow bandgap, high spin-orbit coupling, low Auger recombination rate, and a desirable defect tolerance,[3-4] could be instrumental for applications such as site-selective quantum dots, nanowire networks, and micro-light-emitting diodes in the mid-infrared. In this work, we explore PbSe SAG and characterize the promising growth morphology and optical quality.

Selective PbSe growth studies were performed over SiO_2 films patterned by e-beam lithography on Si-doped (001) GaAs with a flux supplied by a compound PbSe source equivalent to a growth rate of 0.42 Å/s. Preferred growth of PbSe in the mask openings was observed for substrate temperatures from 345-375°C with no polycrystalline growth on the mask at 375°C. Growth in 100×100nm^2 squares was observed to be largely dominated by one nuclei orientation, producing arrays of well-faceted and ordered squares with low-energy {001} sidewalls at ~365°C, even despite the large lattice mismatch. Atomic force microscopy confirmed smooth surfaces with an average 0.4 nm root-mean-square roughness within individual and 1.3 nm over all grains in Figure 1c. PbSe arrays showed room temperature photoluminescence in the mid-infrared, matching the planar emission wavelength. We aim to understand the structure of the nucleated islands with electron microscopy. This work was supported by the US Department of Energy (DE-SC0019274) and NSF (DMR-1906325).

[1] P. Aseev et al. Nano Lett. 2019, 19, 9102−9111 [2] J. Meyer et al. APL Mater. 9, 111112 (2021), [3] G. Springholz. Molecular Beam Epitaxy (Second Edition), Chapter 11, Elsevier, 2018. [4] P. Kumar, 8 - Efficient PbSe colloidal QDs for optoelectronics devices, Woodhead Publishing, 2022.

11:50am **PCSI-WeM2-41 Ge Quantum Well Structure on Si with Reduced Thickness Using Growth and High-Temperature Diffusion**, ***Riis Card***, *Jason Dong, Joshua Thompson, Christopher Richardson,* Laboratory for Physical Sciences

The growth of strained Ge quantum wells is of great interest in the fabrication of gate-tunable Josephson junctions. For instance, microwave-frequency superconducting circuits have recently utilized Ge-based Josephson junctions to demonstrate gate-tunable transmon qubits. Historically, the epitaxial growth of high-quality strained Ge on relaxed SiGe buffers has demanded metamorphic growth. To grow a metamorphic buffer with a desired lattice constant at low defect density, microns of material are generally required. Conversely, shrinking total growth thickness is necessary to streamline device fabrication; mesa-etch designs reduce loss from epilayer thickness, but, in its immediate vicinity, a tall mesa structure poses the additional issues of low lithography resolution and irregular deposition thicknesses. In this work, molecular beam epitaxy is leveraged to grow an undoped strained Ge quantum well structure with an over 90% reduction in thickness compared to previous undoped designs.

An alternative heterostructure is presented where 100 nm of Ge has been diffused into an undoped Si (001) substrate wafer to generate a $Si_{0.2}Ge_{0.8}$ virtual substrate. After cooling, growth nominally proceeds with a 100 nm $Si_{0.2}Ge_{0.8}$ buffer, 16 nm strained Ge quantum well, and 22 nm relaxed $Si_{0.2}Ge_{0.8}$ spacer. In a Hall bar, the hole mobility associated with the quantum well exceeds $4.4 \cdot 10^4$ cm^2/V·s with a sheet carrier density of $5.7 \cdot 10^{11}$ cm^{-2} at a temperature of 2 K.

The composition of the $Si_{0.2}Ge_{0.8}$ virtual substrate is verified via an asymmetric reciprocal space map, capturing a distinct SiGe peak and indicating a strained quantum well. Atomic force microscopy reveals that the surface of the sample possesses a leaf-like morphology, closely adhering to the qualities of other anneal-based designs. In this thin heterostructure, a root-mean-square surface roughness of nearly 4 nm suggests that mobility is limited by the roughness of the quantum well interfaces. Further optimization in growth and anneal temperature shall be pursued in order to reduce interface roughness.

11:55am **PCSI-WeM2-42 Investigating the Mechanisms of Remote Epitaxy: Interfaces, Interactions, Nucleation, and Defects***, **Scott Schmucker**, Manny De Jesus Lopez, Sadhvikas Addamane, Quinn Campbell, Ping Lu, Anthony Rice,* Sandia National Labs*; Kevin Jones,* University of Florida*; Justine Koepke,* Sandia National Labs

Remote Epitaxy refers to epitaxial growth on a crystalline substrate coated with a two-dimensional (2D) material. In this process, the epi-layer is oriented to, but not covalently bonded with, the substrate, which facilitates detachment and hetero-integration. This configuration also allows for dynamic rearrangement or “sliding” relaxation at the 2D interface, thereby reducing defects in the epi-layer.

Our results indicate that for the growth of AlN films on SiC substrates, a greater fraction of relaxed AlN is achieved when grown on graphene/SiC compared to AlN grown directly on SiC (Figure 1). However, the success of this epitaxial growth is strongly dependent on the uniformity of a high-quality graphene monolayer on the SiC substrate.

Remote Epitaxy of GaAs and other III-V materials presents different challenges. While SiC has a well-developed graphitization process, high-quality graphene growth on GaAs remains elusive. In the literature, CVD growth of amorphous carbon has been explored as a 2D substitute for graphene. An equivalent fully MBE process has not yet been demonstrated and would enable in situ MBE Remote Epitaxy. We demonstrate epitaxy through amorphous carbon films; however, growth is dominated by pinholes due to film morphology (Figure 2).

To corroborate our experimental results, we employ DFT modeling to elucidate Remote Epitaxy in the context of island sliding energy barriers during the early stages of growth. Additionally, Kinetic Monte Carlo simulations are utilized to assess pinhole defects in 2D materials and evaluate relative contributions of lateral overgrowth versus Remote Epitaxy.

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