

## NAMBE

### Room Cummings Ballroom - Session NAMBE1-MoM

#### Low Dimensional Materials

Moderator: **Badih A. Assaf**, University of Notre Dame

8:00am **NAMBE1-MoM-1 Welcome & Sponsor Thank You**,

8:15am **NAMBE1-MoM-2 Art Gossard MBE Innovator Awardee Talk: How MBE Enabled Polarization Doping in Ultrawide Bandgap Semiconductor Heterostructures for Photonics and Electronics**, *Debdeep Jena*, Cornell University **INVITED**

The story of each semiconductor is intertwined with the story of its doping, so much so that a modern definition of an insulator may well be: "An insulator is a semiconductor that has not been successfully doped yet". In this presentation, I shall discuss the early discovery of chemical doping of semiconductors of Ge and Si at Bell Labs, the dramatic impact of MBE in modulation doping in GaAs, followed by the discovery of new forms of doping in polar nitride semiconductors enabled and perfected by MBE. I will discuss how the new method of *abrupt* polarization doping produces dopant-free 2D electron and hole gases in semiconductor quantum heterostructures. Then I will discuss how the new method of *distributed* polarization doping creates dopant-free mobile 3D electron and hole gases which enable new forms of vertical photonic and electronic devices with ultrawide bandgap semiconductors. In this light, I will discuss how polarization-induced doping has only recently enabled the first p-channel HFET RF power amplifiers, and the first electrically injected deep-UV lasers, and the exciting new frontiers coming up in the future.

8:45am **NAMBE1-MoM-4 Site-Templated MBE Grown InAs/GaAs Quantum Dot Platforms with Spectral Homogeneity and Tunability**, *Nazifa Tasnim Arony*, University of Delaware; *L. McCabe*, University of Delaware (Now working at Yale University); *J. Rajagopal*, *L. Murray*, *L. Mai*, *P. Ramesh*, *T. Long*, *M. Doty*, *J. Zide*, University of Delaware

Epitaxially grown semiconductor quantum dots (QDs) have been well studied in the past few decades and have shown great promise as single photon emitters, and as a basis for potential qubits. These features of quantum dots grown on a semiconductor matrix make it a desirable platform/building block for quantum devices which has a wide-range of applications in quantum information, quantum sensing and quantum computing. For a complete epitaxially grown quantum device, spatial, spectral, and structural homogeneity, and scalability are the key requirements. Recent work from our group has shown a method for site controlled QD growth where InAs/GaAs quantum dots are grown on nanofabricated substrates with site-templated arrays of nano-pits.[1] However, achieving good quality of optical emission from these QDs is still a big challenge due to the impurities introduced in the regrowth surface from the nanofabrication process. These aforementioned challenges are addressed in this work and three different objectives are being explored, first one being the domain of quantum dot columns (QDCs) as a buffer layer for the topmost QD-arrays of interest while burying defects underneath the QDCs. Additionally, initial experiments on spectral control of InAs/GaAs QDs by 'cap and flush' are discussed and the concept of quantum dot molecules is introduced for optical tunability.

[1] *J. Vac. Sci. Technol. B* 38, 022803 (2020)

9:00am **NAMBE1-MoM-5 Site Controlled InAs/GaAs Quantum Dots for Photonic Integration**, *Ian Farrer*, *C. Chan*, *A. Verma*, *A. Trapalis*, *C. Ovenden*, *D. Hallett*, *E. Clarke*, *M. Skolnick*, *J. Heffernan*, University of Sheffield, UK

Controlling the position of quantum dots (QDs) is desirable for nanophotonic devices due to their potential as single photon emitters for quantum technology applications.[1] Challenges that are associated with forming site-controlled (SC) QDs include single QD occupation, planarisation, narrow linewidths and controllable wavelength. For Stranski-Krastonov growth, QDs nucleate preferentially in local minima in the surface chemical potential.[2] In this study, we use ex-situ fabrication of arrays of nanoholes to form preferential nucleation sites, investigating the effects of nanohole size, nanohole density and other parameters on the emission wavelength of single QDs for undoped and doped structures.

Initial development focused on good site-selectivity of QD arrays, which allowed for optimisation of growth parameters to control emission wavelength and QD linewidth. Planarisation on the patterned surface was also crucial: during the GaAs buffer layer, preservation of the nanoholes is important to allow them to function as preferential nucleation sites, but

after QD formation, planarisation of the capping layer is important for good optical properties, for example in waveguides. This is a crucial step for doped structures, as insufficient planarisation can result in optically inactive QDs due to close proximity to the doped layer. Each sample contains different arrays with variations in nanohole size and spacing, allowing for direct investigation of the effects of these parameters on the emission wavelength and linewidth of nucleated quantum dots using site-specific photoluminescence (PL) measurements.

We observe a shift in emission in the range of 900 to 1000nm, which is compatible with high-efficiency Si detectors. Clusters of uniform single-line emissions are obtained from micro-PL measurements. These conditions resulted in nucleated QDs with a minimum linewidth of 22 $\mu$ eV (resolution limited) and an average linewidth of  $\sim$ 87 $\mu$ eV measured using non-resonant excitation. In addition, we demonstrate the emission and tuning of groups of QDs for doped diode structures with good site selectivity.

#### References

[1] Carter, S., Sweeney, T., Kim, M. et al. *Quantum control of a spin qubit coupled to a photonic crystal cavity*. *Nature Photon* 7, 329–334 (2013)

[2] Srolovitz, D.J. *On the stability of surface of stressed solids*, *Acta Metallurgica*, 37, 621-625, (1989)

9:15am **NAMBE1-MoM-6 Commercializing Nanowire LEDs**, *David Laleyan*, *B. Le*, *G. Frolov*, NS Nanotech Canada; *M. Stevenson*, *S. Coe-Sullivan*, NS Nanotech

MicroLED display technology consists of many carefully arranged microscopic light-emitting diodes (LEDs) to directly create color pixels. MicroLED displays thus have the potential brightness, efficiency, and response time of inorganic LEDs, but suffer from the high cost of epitaxy, as well as the challenges of creating red, green, and blue materials on a single material and substrate. Furthermore, conventional approaches of growing planar LEDs and then etching them into micron scale devices causes a fundamental loss of efficiency, especially for the smallest devices. In this regard, nanowire-based LEDs for microLED applications have been of great interest and a topic of extensive research for over a decade. This is due to their unique ability to maintain high efficiencies even as the LED size becomes quite small, even into the sub-micron regime, contrary to conventional thin-film LEDs. Another valuable benefit is the ability to form photonic crystal arrangements, such that the formation of a photonic bandgap leads to highly directional and narrow bandwidth emission. More recently, reports have shown nanowire LEDs in the green with >25% external quantum efficiency (EQE) and red with >8% EQE, competitive with the best direct green and InGaN red LEDs ever fabricated – despite being sub-micron in size. These structures were obtained by molecular beam epitaxy (MBE) using a selective area epitaxy (SAE) technique, where nanostructures can be controllably grown on a thin-film template. Novel development and engineering efforts are required for such nanowire LEDs to become commercially viable. This work presents a pathway towards the wafer-scale production of nanowire LEDs for displays. This talk will explain how breakthrough academic research can be made manufacturable by studying run-to-run variability, understanding the process windows, targeting yield-limiting steps, and ensuring process scalability. Focusing on the reproducibility and uniformity of nanowire growth by SAE is the first critical step toward the large-scale deployment of these highly efficient LED that are perfectly suited for the next generation of microLED displays.

9:30am **NAMBE1-MoM-7 Epitaxial Ge Membranes Detachment via Porous Ge Layer and Adhesion Force Engineering**, *Ahmed Ayari*, *T. Hanuš*, *N. Paupy*, *F. Zouaghi*, 1-Institut Interdisciplinaire d'Innovation Technologique (3IT), Université de Sherbrooke, 2-Laboratoire Nanotechnologies Nanosystèmes (LN2)-IRL3463, CNRS, Université de Sherbrooke., Canada; *B. Illahi*, 1-Institut Interdisciplinaire d'Innovation Technologique (3IT), Université de Sherbrooke, 2-Laboratoire Nanotechnologies Nanosystèmes (LN2)-IRL3463, CNRS, Université de Sherbrooke., Canada 3-DistriQ - Zone d'Innovation Quantique, Canada; *J. Cho*, *K. Dessein*, Umicore Electro-Optic Materials, Belgium; *D. Machon*, 1-Institut Interdisciplinaire d'Innovation Technologique (3IT), Université de Sherbrooke, 2-Laboratoire Nanotechnologies Nanosystèmes (LN2)-IRL3463, CNRS, Université de Sherbrooke., Canada

Recently, there has been an increasing interest in single-crystal germanium (Ge) membranes for lightweight, low-cost solar cells and flexible optoelectronic devices. A viable solution for the large-scale fabrication of

such Ge membranes, appears to be the direct growth of Ge on porous Ge (PGe) template [1-3], allowing the detachment and substrate reuse [4].

After creating a PGe template, a low-temperature buffer layer is grown to maintain the voids in the sealed surface. Then, a high temperature Ge layer is grown, ensuring a good crystallinity for the membrane, and allowing to the porous structure to transform into a weak layer that facilitates later detachment as shown in Fig 1 a-b. However, there is a lack of studies focusing on the Ge membrane detachment, the adhesion of the membrane to the parent substrate, and how it can be modulated by morphological changes of the porous structure underneath.

In this work, we demonstrate the adhesion force engineering of the Ge membranes by controlling the morphological transformations of the PGe layer, from porous structure to well-defined pillars, through thermal budget adjustments and variations in PGe porosity and thickness. Scanning electron microscopy (SEM) analysis reveals the evolution of pillar diameter and density with post-growth thermal annealing at temperatures between 650°C and 850°C as shown in Fig. 2 a-e. The membrane's adhesion strength can be successfully tailored through the control of this pillar transformation (Fig. 2 f). Moreover, with increasing PGe layer thickness and/or porosity, the membrane adhesion force is found to significantly change from a highly adhesive to easily detachable.

The high-quality Ge membranes on PGe substrates offer the possibility of detachment from the substrate using the weak nanostructured interface. By controlling the weak interface nanostructure through the thermal annealing and PGe substrate physical properties, allowing the tailoring of the adhesion force of the membrane for specific applications. This includes a high-temperature growth of III-V heterostructures, paving the way for lightweight and flexible photovoltaic and optoelectronic applications.

[1] N. Paupy et al., *Nanoscale Adv.*, **2023**, vol. 5, no. 18, pp. 4696–4702.

[2] T. Hanuš et al., *Materials Today Advances*, **2023**, vol. 18, p. 100373.

[3] V. Daniel et al., *Solar RRL*, **2024**, vol. 8, no. 1, p. 2300643.

[4] A. Chapotot et al., *Materials Science in Semiconductor Processing*, **2023**, vol. 168, p. 107851.

9:45am **NAMBE1-MoM-8 Synthesis of InSe Thin Films on Sapphire using Molecular Beam Epitaxy**, *Emily Toph*, C. Voigt, Georgia Institute of Technology; B. Wagner, Georgia Tech Research Institute; E. Vogel, Georgia Institute of Technology

InSe is a monochalcogenide two-dimensional (2D) semiconducting material<sup>1</sup> with a high room-temperature electron mobility of approximately  $10^3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  for encapsulated devices.<sup>2</sup> InSe is a promising material for high-sensitivity Hall sensors<sup>3</sup>, ballistic transistors,<sup>4</sup> and non-volatile memory applications.<sup>5</sup> The In-Se system contains many different stable phases<sup>6</sup> including selenium rich  $\text{In}_2\text{Se}_3$  and the selenium deficient phase  $\text{In}_4\text{Se}_3$ . One challenge in synthesizing InSe is that the stoichiometry of this phase is stable only in a narrow range on the phase diagram. Therefore, synthesizing high-quality InSe requires a detailed understanding of how the synthesis parameters effect the structure and stoichiometry of In<sub>x</sub>Se<sub>y</sub> thin films near and within the narrow range of stability for InSe.

Recently, the effect of precursor fluxes and substrate temperature on the synthesis of InSe on Si(111) substrates was explored, with differences found in morphology and stoichiometry across a range of synthesis parameters.<sup>7</sup> However, using InSe for device applications often requires using an insulating substrate for electrical isolation of the devices. Sapphire is a widely used insulating substrate for epitaxial synthesis of transition metal dichalcogenides, another 2D material system. This work investigates the impact of substrate temperature and precursor flux on the structure and stoichiometry of InSe thin films on sapphire substrates. The chemical bonding, crystalline structure, and morphology of the thin films are characterized with X-ray Photoelectron Spectroscopy, Raman spectroscopy, and Atomic Force Microscopy, respectively.

## References

<sup>1</sup>Camara, M., et al., *Physical Review B* (2002) **65** (12), 125206

<sup>2</sup>Li, M., et al., *Advanced Materials* (2018) **30** (44), 1803690

<sup>3</sup>Bandurin, D. A., et al., *Nature Nanotechnology* (2017) **12** (3), 223

<sup>4</sup>Jiang, J., et al., *Nature* (2023) **616** (7957), 470

<sup>5</sup>Lu, Y.-Y., et al., *ACS Applied Materials & Interfaces* (2021) **13** (3), 4618

<sup>6</sup>Bergeron, H., et al., *Applied Physics Reviews* (2020) **7** (4)

<sup>7</sup>Liu, D. S. H., et al., *ACS Applied Nano Materials* (2023) **6** (16), 15029

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