

## PCSI

### Room Ballroom South - Session PCSI-WeA2

#### Semiconductor Heterostructures (Growth Nanostructures & Interfaces) II

Moderator: Jason Kawasaki, University of Wisconsin - Madison

##### 4:30pm PCSI-WeA2-31 Heteroepitaxy of PbSe-SnSe Semiconductors on GaAs for Infrared Optoelectronics, *Kunal Mukherjee*, Stanford University INVITED

The IV-VI semiconductor alloy of PbSe-SnSe has rich materials physics and several device applications[1]. This narrow band gap semiconductor system spans a 3D-bonded rocksalt structure on the PbSe-rich side and a closely related Van der Waals bonded 2D/layered-orthorhombic structure on the SnSe-side, and has long been studied for its rare electronic, photonic, and thermal properties. We present results from epitaxial integration of IV-VI semiconductor films with III-V templates using molecular beam epitaxy to understand how we may harness their properties for emerging applications infrared optoelectronics.

With attractively low temperatures for epitaxy below 300 °C, we describe the nucleation and growth of IV-VI materials on III-V substrates and the formation of extended crystal defects that arise due to integration[2]. We find bright band-edge photoluminescence in the mid-infrared (3–4 μm) from PbSe and PbSnSe epitaxial films on ~8% mismatched GaAs at room temperature, despite a threading dislocation density exceeding 10<sup>9</sup>/cm<sup>2</sup>. We present measurements of carrier recombination in PbSe and show preliminary results from junction devices of mid-infrared light emitting diodes and photodetectors that highlight the promise of this materials platform.

The IV-VI on III-V template also enables us to probe deeper into the structural phase boundaries and miscibility gaps in PbSnSe, with an aim to harness the high contrast in optical properties across the transition between 3D/rocksalt to 2D/layered bonding. We show that MBE synthesis can stabilize the layered phase deep in the bulk miscibility gap. Close to a composition of Pb<sub>0.5</sub>Sn<sub>0.5</sub>Se, we find evidence for a displacive or martensitic transformation (without composition change) between the rocksalt and layered phases in our thin films. These results, in agreement with recent reports in high temperature quenched samples[3], point the way to phase change devices.

[1] G. Springholz and G. Bauer, *physica status solidi (b)*, 244, 8, 2752–2767, 2007

[2] B. B. Haidet, E. T. Hughes, and K. Mukherjee, *Phys. Rev. Materials*, 4, 3, 033402, 2020

[3] T. Katase et al. *Science Advances*, 7, 12, eabf2725, 2021

##### 5:10pm PCSI-WeA2-39 Investigation of Localized Electric Fields of InAs/GaAs Quantum Dot Interfaces, *T. Kang, Jong Su Kim*, Department of Physics, Yeungnam University; *S. Lee*, Division of Convergence Technology, Korea Research Institute of Standards and Science

In InAs/GaAs QDs, the strain-induced lattice deformation and strain induced dislocation could generate localized electric fields (LEF) due to the piezo-electric fields [1]. Therefore the electric field distribution could be more complex at the interface of QDs than for the 2D superlattice (SL). The strain-induced complex electric fields can significantly modify the quantum confinement states. Direct observation of strain-related effect, such as the LEFs caused by strain-induced polarizations and defects, is therefore very important. Photoreflectance spectroscopy (PR) is useful for investigating LEFs of semiconductors [2]. In the case of GaAs, the Franz-Keldysh oscillations (FKOs) that appear above the band gap of GaAs and contain information about the LEFs in GaAs. To investigate InAs/GaAs quantum confinement states PR experimental results were reported [3]. However, experimental observation of LEFs attributed to strain between InAs QD and GaAs has not been the focus of many studies.

In this work, we investigated LEFs between InAs QD and GaAs by PR. FIG. 1 shows the InAs/GaAs QDs sample used in this work. FIG. 2 shows the PR spectra of the InAs/GaAs QD samples obtained at low temperature. The low-temperature PR spectrum of the InAs/GaAs QD shows clear FKO transitions above the GaAs band gap energy. This work suggests that the interface electric fields attributed to strain originate from the strain-induced polarization near the InAs QD interface in GaAs metric. We suggested that the FKOs originated from the LEFs predominately caused by the strain-induced polarization at GaAs interface near the InAs QDs. The

InAs/GaAs QDs have a broad range of interface electric fields from ~10<sup>4</sup> V/cm to ~2x10<sup>5</sup> V/cm.

[1] C. Pryor, *Phys. Rev. B* 60, 2869(1999).

[2] C.W. Sohn, I.S. Han, R.P. Smith, J.S. Kim, et al, *Korean Phys. Soc.* 64, 1031 (2014).

[3] R. Nedzinskas, B. Cechavicius, A. Rimkus, et al, *J. Appl. Phys.* 117, 144304 (2015).

5:15pm PCSI-WeA2-40 X-STM Study of Interlayer Effects on InAs Quantum Dots in InP, *Edoardo Guido Banfi*, Eindhoven University of Technology, Netherlands; *E. Sala*, Sheffield University, UK; *R. Gajjala*, Eindhoven University of Technology, Netherlands; *J. Heffernan*, Sheffield University, UK; *P. Koenraad*, Eindhoven University of Technology, Netherlands  
Quantum dots (QDs) have been studied in the past two decades in order to optimize their performances in a wide range of applications, from QD lasers, photovoltaics, single photon emitter, memories, and last but not least, quantum communication and information technologies [1-6]. In order to further follow this line of optimization it is relevant to achieve more size and shape uniform QDs. This work targets the optimization process of droplet epitaxy (DE) InAs QDs in InP by the use of interlayers.

In this work we performed, with atomic scale resolution, cross-sectional scanning tunneling microscopy (X-STM) on InAs DE QDs in InP, we also characterized the QDs with atomic force microscopy (AFM) and performed finite element simulations (FES). We measured two samples with different compositions in the interlayer (IL), the region below the QDs. The first sample has an In<sub>0.53</sub>Ga<sub>0.47</sub>As IL and consists of two separate QDs layer with different amount of In (referred to as QDL1 and QDL2). The two regions are separated by 100nm of InP in order to reduce the chances of seeding of the QDs formation. The second sample has an IL composed by In<sub>0.719</sub>Ga<sub>0.281</sub>As<sub>0.608</sub>P<sub>0.392</sub> (Fig. 1) lattice matched to the InP of the host. Our study performed on these samples, highlighted how some previously identified effects (trenches and etch-pit formation [7]) were successfully avoided in these samples. We studied size, shape and composition of all the QDs measured. AFM and X-STM proved that these dots have a rhombic base elongated preferentially along the {110}. We performed FES and we can conclude that in the second sample the QDs purity is 95±5% InAs, while in the other sample the purity is around 90±5%. Results confirmed are not only by the relaxation and lattice constant but also from our X-STM measurements. These results prove that introducing P in the IL region can enhance the purity of the QDs and allow for a stress-free structure.

##### 5:20pm PCSI-WeA2-41 UPGRADED: Atomic Scale Analysis of N Dopants in InAs, *T. Verstijnen, D. Tjeertes, E. Banfi*, Eindhoven University of Technology, Netherlands; *Q. Zhuang*, Lancaster University, UK; *Paul Koenraad*, Eindhoven University of Technology, Netherlands

The band gap of most III-V semiconductors is strongly reduced with the introduction of only a few percent of N, even if the III-N alloy has a much bigger band gap. N impurities in InAs introduce an impurity state around 1 eV above the conduction band minimum, much deeper in the band than in other III-V materials. Topographic scanning tunneling spectroscopy measurements (STS) and areal spectroscopy measurements performed on N atoms up to two layers below the (110) surface of InAs show a reduction of the resonance energy of the N atom with increasing depth. This is attributed to tip induced band bending, pulling the N states up at positive bias and acting most strongly on surface N atoms. An example of STM images on InAs:N is shown in figure 1. STS measurements obtained on undoped InAs and N-doped InAs show a band gap reduction of <0.1 eV. Spatial imaging of features corresponding to N dopants up to two layers below the surface are also compared to density functional theory simulations and show excellent correspondence. Spectroscopy maps of N atoms up to two layers below the surface provide a high resolution spatial and spectroscopic view of the N atoms. Here the characteristic shape of the N atoms in different layers below the surface is observed as an enhancement of the dI/dV signal compared to the InAs background. At energies above the enhancement a reduction of the dI/dV is observed, which has the same shape and size as the enhancement. This shows that the redistribution of density of states caused by the N impurities is mainly energetic in nature.

##### 5:40pm PCSI-WeA2-45 Direct Wafer Bonding of GaN on AlN Through the Optimization of Chemical Mechanical Polishing, *Kaicheng Pan, K. Huynh, M. Li, Y. Ge, T. Fisher, Y. Hu, M. Goorsky*, UCLA

Optimization of surface preparation and interfacial characterization of direct wafer bonded GaN to AlN are presented in this study. In particular, the Ga face of the GaN wafer was bonded to the N face of the AlN wafer.

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The as received Ga-face of GaN substrates showed <1 nm roughness while the N-face AlN had a starting roughness of ~3 nm RMS. The N-face of the AlN was successfully polished to <1 nm RMS roughness suitable for direct wafer bonding using chemistry based on our previous work with GaN CMP [1]. For bonding, 2" GaN (Unipress) and 2" AlN (Hexatech) were bonded using standard cleaning and immersion in a (NH<sub>4</sub>)<sub>2</sub>S solution. The samples were rinsed, dried and pressed Ga- to N-face (AlN) under moderate pressure (~50 kPa) and room temperature bonding was initiated. A significant fraction of the surfaces bonded, except for a couple of triangular regions associated with growth sector boundaries in the GaN. Subsequent annealing up to 800 °C was performed to strengthen the bond and to test the structure for high temperature stability. Similar coefficient of thermal expansion between GaN and AlN at high temperatures allows for high temperature annealing without debonding or cracking. The GaN substrate was then grinded and also subject to CMP to < 1µm for transmission electron microscopy and time-domain thermal reflectance measurements of the bonded interface.

High resolution transmission electron microscopy shown in Figure 1 reveals complete crystallinity across the interface. However, only a ~1.5 nm interfacial region is observed, which is suspected to be caused by reconfiguration of the interface after a total anneal of 350 °C 22 hours, 600 °C 1 hour, and 800 °C 1 hour. No thicker amorphous or oxide interfacial layer commonly found in other bonding methods (surface activated bonding, plasma treatment, or other interfacial layers) [2-5] are observed in this study. Preliminary thermal boundary conductance measurements via time domain thermal reflectance have been measured and will be reported.

- [1] S. Hayashi, et al., *J. Electrochem. Soc.*, 155(2), p.H113 (2007)
- [2] M.E. Liao, et al., *ECS Trans.*, 86(5), 55 (2018)
- [3] V. Dragoi, et al., *ECS Trans.*, 86(5), 23 (2018)
- [4] Y. Xu, et al., *Ceram. Int.*, 45, 6552 (2019).
- [5] F. Mu, et al., *Appl. Surf. Sci.*, 416, 1007 (2017)

5:45pm **PCSI-WeA2-46 Strategies for Analyzing Non-Common-Atom Heterovalent Interfaces: The Case of CdTe-on-InSb**, *Esperanza Luna, A. Trampert*, Paul-Drude-Institut für Festkörperelektronik Leibniz-Institut im Forschungsverbund Berlin, Germany; *J. Lu, T. Aoki, Y. Zhang, M. McCartney, D. Smith*, Arizona State University

Semiconductor heterostructures are intrinsic to a wide range of modern-day electronic devices. Knowledge of chemical interfacial profiles in these complex structures is critical to the task of optimizing the device performance. Here, we report on an innovative methodology that enables reliable interface structure analysis of non-common-atom heterovalent interfaces on all relevant length scales from hundred-nm to atomic resolution.

Non-common-atom (NCA) heterovalent interfaces offer potential benefits arising from the valence mismatch but also contain challenges due to the large charge imbalances. Whether a sharp polar interface is formed or, on the contrary, there are mixtures of chemical bonds across the interface leading to a nonpolar graded interface is under intense discussion. Furthermore, very little has so far been done to exploit the opportunities offered by NCA heterovalent interfaces, in part due to challenges determining the structure and properties of these types of interfaces, for example, by using scanning transmission electron microscopy (STEM) techniques. This work presents a comprehensive analysis of the composition profile across the case study NCA heterovalent CdTe/InSb interface, carried out using a combination of (S)TEM imaging and spectroscopic techniques. Techniques such as high-angle annular-dark-field and large-angle bright-field STEM, as well as electron energy-loss spectroscopy, give results from the interface region on the atomic scale. These measurements, however, are inherently difficult to interpret because of the close atomic numbers of the constituent elements. In contrast, use of the 002 dark-field TEM imaging mode emphasizes the interface location by comparing differences in structure factors between the two materials. Based on the 002 dark-field TEM, a methodology was developed for reliable determination of the composition profile across the interface and systematic quantification of the interface width. Since the identities of both cations and anions change across the heterointerface, the respective contributions of different elements need to be inserted separately. The intermixing at each sub-lattice is thus independently and completely determined. Comparisons of experimental and simulated CdTe-on-InSb profiles reveal that the interface is structurally abrupt to within about 1.5 nm defined by the variation between 10 and 90%. The present investigation

opens new routes to the systematic investigation of heterovalent interfaces, formed by the combination of other valence-mismatched material system.

5:50pm **PCSI-WeA2-47 Multi-Material Deposition for Spatial Atomic Layer Deposition Process**, *A. Varga, M. Carnoy, M. Plakhotnyuk, I. Kundrata*, ATLANT 3D, Denmark; *J. Bachmann*, Friedrich-Alexander-University Erlangen-Nürnberg (FAU), Germany; *M. Baraket*, ATLANT 3D, Denmark; *Simone Santucci*, ATLANT 3D Nanosystems, Denmark

Spatial Atomic Layer Deposition (sALD) offers a unique opportunity for localized deposition due to its physical separation and isolation of precursor and co-reagent dosing.<sup>[1]</sup> While simple in theory, due to well-developed examples of sALD, in practice miniaturization of sALD requires substantial effort into the creation of suitable micro-nozzles.<sup>[1]</sup> Uniquely, ATLANT 3D has developed proprietary sALD micronozzles, called microreactor Direct Atomic Layer Processing - µDALP™.

The µDALP™ process undergoes the same cyclic ALD process but is only done in a spatially localized area.<sup>[2]</sup> The microreactor or micronozzle confines the flows of gases used for ALD within a defined µm-scale area on the substrate, to deposit the desired material.

Since sALD and the µDALP™ process are based on physical separation, it is theoretically compatible with any ALD material process however requires development as ALD processes are highly tool dependent.<sup>[3]</sup> As such, the material capabilities can match traditional ALD and exceed other patterning techniques, such as lithography, which can be costly and time-consuming, especially for rapid prototyping required for innovation.<sup>[4,5]</sup>

Using a small amount of precursor multiple film materials and thicknesses can be deposited onto a single wafer within only a few hours, compared to days for a traditional ALD process (Fig 1.). Films deposited with ATLANT 3D technology have been shown to produce high-quality, crystalline, atomically precise thin films used to fabricate temperature (Fig 2.) and capacitive sensors with sensitivities that meet or exceed those of devices made using conventional vapor phase deposition techniques. Low-cost rapid prototyping facilitated by ATLANT 3D technology of such devices enables design innovation and optimization not possible with other thin film deposition techniques.

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- [2] Kundrata I., et al., *Small Methods.*, 2022, 6 (5), 2101546
- [3] Barry, S. T. *Chemistry of Atomic Layer Deposition*; De Gruyter
- [4] Kundrata I., et al., *ALD/ALE 2022 [Int. Conf.]*, 2022
- [5] Plakhotnyuk M, et al., *ALD/ALE 2022 [Int. Conf.]*, 2022

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