Science and Technology of MBE
Room Swan BC - Session ST-MoA1

MBE Technology

Moderator: Paul Simmonds, Boise State University

1:30pm **ST-MoA1-1 NAMBE Innovator Awardee Talk: Physics and Technology of Antimonide Based Short Wave Infrared Avalanche Photodiodes on InP Substrates***, **Sanjay Krishna***[1]*,* Ohio State University
INVITED

There are a variety of applications ranging from greenhouse gas detection, 3D topographic mapping and light detection and ranging (lidar) are limited by the sensitivity of the receiver system. In particular, there is a needed for high sensitivity photonic detectors in the short wave infrared (1.5-3 microns) A low noise linear mode avalanche photodiodes (LmAPDs) is a critically enabling component for eye-safe long range LiDAR and remote sensing applications. Unlike PIN diodes, APDs provide internal gain that can lead to increased signal to noise ratio and suppress downstream circuit noise. The highest performing infrared APDs are based on interband transitions in mercury cadmium telluride (MCT, HgCdTe). State of the art (SoA) MCT diodes have large multiplication gains and low excess noise factors due to the favorable bandstructure that promotes single carrier impact ionization. However, their dark currents are high (3-5e-4A/cm2 at a gain of 10 at 125K) that requires cryogenic cooling. Commercial APDs use an InGaAs absorber with an InAlAs or InP multipliers. We are investigating two antimonide based multipliers, AlGaAsSb and AlInAsSb, on InP substrates. We have recently demonstrate GaAsSb/AlGaAsSb separate absorber charge and multiplier (SACM) heterostructures[i] [file:///C:/Users/Yvonne/AppData/Local/Microsoft/Windows/INetCache/Content.Outlook/C2N18W2U/Krishna%20OSU%20NAMBE%20Invited%20Talk%20Sept%202022.doc#_edn1] . We will discuss the technical challenges associated with the design, growth, fabrication and test of these LmAPDs and the potential for the development of these critical APD arrays for active 3D sensing and imaging systems.

[i] S. Lee et al " High Gain, Low Noise, Room Temperature 1550 nm GaAsSb/AlGaAsSb Avalanche Photodiodes", Manuscript under preparation (2022).

2:00pm **ST-MoA1-3 Overview of Virtual Substrate Technologies for 6.3 Angstrom Lattice Constant***, S. Svensson,* Army Research Laboratory*; N. Mahadik,* Naval Research Laboratory*; G. Kipshidze, **Dmitri Donetski**, G. Belenky,* SUNY at Stony Brook

Over the years the approaches to lattice mismatch have ranged from ignoring the problem, to brute force growth of very thick layers, to application of various schemes to engineer a strategy for gradually changing the lattice constant to ideally form a dislocation free virtual substrate (VS) with the desired properties.

A specific lattice constant range of interest is that between GaSb and InSb, in which no other substrate exists, which imposes limitations on our ability to exploit the (Al,Ga,In)(As,Sb) alloy system. This is of great interest primarily because of InAsSb, the III-V alloy with the smallest bandgap among compounds that can be grown with sufficient quality. The minimum energy gap occurs around 6.3 Å, which is why we focus specifically on this value.

InAsSb was set aside in the early 1990's since measurements seemed to indicate that its bandgap was not small enough to reach the long-wavelength infrared wavelength band. The decision was mainly based on investigations of defect-dominated materials. By using a VS approach based on the theoretical work by Tersoff we have been able to improve the quality of InAsSb so that its intrinsic properties could be investigated and the results show a material that closely resembles HgCdTe, the current LWIR performance standard. Even though our VS approach allows determination of basic materials and device properties, it remains to be determined if it, or indeed any VS, is good enough for large array development. IR detector arrays are some of the largest devices made from semiconductors and are usually sensitive to crystalline defects. The first question that needs to be addressed then is what the density of threading dislocations needs to be. Even for the well-studied case of HgCdTe, there is no publically available information on what density allows what technical application to be addressed, although a general consensus seems to be that a density of 1E5 cm-2 or better is a minimum.

A significant related problem is to find a suitable tool for determining crystalline defect densities at this order of magnitude. However, recent progress in X-ray topology (XRT) is now enabling such investigations. We have been able to apply XRT on thick InAsSb-layers and determine promising defect densities that are close to the target value.

We will further discuss the strategies for designing grades, ongoing programs for modeling VS, summarize the materials properties of InAsSb, compare it with competing materials and discuss other hetero-structures enabled by the VS technique.

2:15pm **ST-MoA1-4 Measurement of Low Semiconductor Substrate Temperatures Using Reflectance Tracking of High Energy Critical Points***, **Kevin Grossklaus**, J. McElearney, A. Lemire, T. Vandervelde,* Tufts University

Small bandgap semiconductor alloys, including the $Si_{1-x-y}Ge_ySn_x$ and III-V-Bi alloy families, are in development for a range of infrared photonic applications.When produced by molecular beam epitaxy (MBE) these alloys are, out of necessity, grown at low temperatures to ensure Sn or Bi solute incorporation and produce films of good epitaxial quality.Those growth temperatures can be less than 200°C in some cases, far below the optimal epitaxial growth temperatures used for their base materials.Accurate measurement of substrate and buffer temperature before alloy film growth is critical for ensuring film quality and process repeatability.However, measurement is difficult using common non-contact techniques such as optical pyrometry at very low growth temperatures, and difficult for band-edge thermometry in the case of indirect or small bandgap substrates.

In this work we examine in-MBE temperature measurement of some common semiconductor substrates using a reflectance thermometry technique to track above bandgap, higher energy critical points in the dielectric function of those materials.This approach uses a broad spectrum, unpolarized UV-NIR light reflected specularly off the target substrate.The spectrum of reflected light is measured, processed, and then the locations of peaks corresponding to above band-gap critical points are identified in the reflectance data.The locations of those peaks can then be compared to reference reflectance data generated ex-situ at known temperatures, here collected by temperature varying spectroscopic ellipsometry, to determine in-situ process temperature.Temperature measurement by this method is relatively insensitive to background and stray light sources in the MBE system, and by optical system adjustment can be made insensitive to substrate rotation.Data will be presented showing successful temperature measurement of Ge, InAs, and GaSb from approximately room temperature up to or near the higher growth temperatures commonly used for these materials.The sensitivity and accuracy of the technique as shown by this data will be examined.The applicability of this temperature measurement technique to alloy buffer layers, heavily doped substrates, and MBE at cryogenic temperatures will also be discussed.Finally, the shortcomings of the present technique and optical system as employed will be reviewed, with discussion of how those issues may be overcome to enable temperature measurement of other materials, including InSb, InP, GaAs, and Si.

2:30pm **ST-MoA1-5 Perovskite Hetero-Chalco-Epitaxy Enabled by Self-Assembled Surface Passivation and Gas-Source MBE***, **Ida Sadeghi**, R. Jaramillo,* MIT

Chemical intuition, first-principle calculations, and recent experimental results suggest that chalcogenide perovskites feature the large dielectric response familiar in oxide perovskites, but also have band gap in the VIS-IR and strong light absorption [1]. Preliminary results suggest that chalcogenide perovskites feature excellent excited-state charge transport properties familiar in halide perovskites, while also being thermally-stable and comprised of abundant and non-toxic elements. Nearly all experimental results on chalcogenide perovskites to-date were obtained on powders and microscopic single-crystals. Advances in fundamental

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[1] **NAMBE Innovator Award**

understanding and development for applications hinges on the availability of high-quality thin films.

We recently reported the first epitaxial synthesis of chalcogenide perovskite thin films by MBE: $BaZrS_3$ films on (001)-oriented $LaAlO_3$ substrates [2]. The films are atomically-smooth, and scanning transmission electron microscopy (STEM) data show an atomically-abrupt substrate/film interface. The sulfide perovskite film has a pseudo-cubic lattice constant more than 30% larger than the oxide perovskite substrate. This strain is fully accommodated by a remarkable, self-assembled interface buffer layer that enables epitaxial growth of strain-free films, and that the propensity for buffered epitaxy can be controlled by the H_2S gas flow during growth.

We further demonstrate control of the band gap by making layered (Ruddleden-Popper) phases, and by alloying $BaZrS_3$ with Se. We have made the first epitaxial $BaZrS_{(3-y)}Se_y$ films with varying Se composition, up to and including a pure selenide perovskite $BaZrSe_3$. $BaZrSe_3$ is theoretically predicted to be stable in a non-perovskite, needle-like phase with very low band gap. We instead find two distinct phases, which we can control by choice of growth conditions. On non-lattice-matched substrates, $BaZrSe_3$ forms textured films in a hexagonal phase with surprisingly high band gap above 2 eV. On a perovskite $BaZrS_3$ buffer layer, we achieve pseudomorphic epitaxy of $BaZrSe_3$ in the perovskite phase with band gap in the near-infrared. We support these findings with experiments including high-resolution STEM, high-resolution X-ray diffraction, and photocurrent spectroscopy.

This work sets the stage for developing chalcogenide perovskites as a family of semiconductor alloys with properties that can be tuned with strain and composition in high-quality epitaxial thin films, as has been long-established for other semiconductor materials.

[1] R. Jaramillo, J. Ravichandran, APL Materials 7(10) (2019) 100902.

[2] I. Sadeghi et al., Adv. Func. Mater., (2021) 2105563.

2:45pm **ST-MoA1-6 Molecular Beam Epitaxy of Monocrystalline GaAs on Water Soluble NaCl Thin Films***, **Brelon May**,* National Renewable Energy Laboratory*; J. Kim,* Shell International Exploration and Production*; H. Moutinho, P. Walker, W. McMahon, A. Ptak, D. Young,* National Renewable Energy Laboratory

The high cost of III-V substrates for growth can be cost-limiting for technologies that require large area semiconductors. Thus, being able to separate device layers and reuse the original substrate is highly desirable, but many existing techniques to lift off a film from a substrate have substantial drawbacks. This work discusses some of the complexities with the growth of water-soluble NaCl as sacrificial layers for removal of GaAs thin films from GaAs (100) substrates. Much of the difficulty stems from the growth of the GaAs overlayer on the actively decomposing NaCl surface at elevated temperatures. We investigate a wide range of growth temperatures and the timing of the impinging flux of both elemental sources and high energy electrons at different points during the growth. We show that an assortment of morphologies (discrete islands, porous material, and fully dense layers with sharp interfaces) and crystallinity (amorphous, crystalline, and highly textured) occur depending on the specific growth conditions, driven largely by changes in GaAs nucleation. Interestingly, the presence of the reflection high energy electron diffraction (RHEED) beam incident on the NaCl surface, prior to and during GaAs deposition, affects the nucleation of GaAs islands, as well as the resultant crystallinity, and morphology of the III-V overlayer. By utilizing careful exposure of the NaCl to the RHEED beam and a low temperature GaAs nucleation layer, single-crystalline and epitaxial GaAs templates on continuous NaCl layers are realized. The low temperature GaAs layer functions as a template for subsequent single crystalline GaAs homojunction cell deposition by MBE or hydride vapor phase epitaxy. The GaAs cells are removed nearly immediately from the substrate via dissolution of the NaCl layer. However, fusion of as little as a few nanometers of the overlayer to the substrate results in holes that prove detrimental to fabrication of working devices. The frequency of fused locations can be reduced by engineering the early nucleation stages of GaAs on NaCl. Atomic force microscopy between these defects reveals that this process results in an increase in a rms surface roughness of the original wafer of only 0.2 nm. Therefore, combination of these systems could be well-suited for heteroepitaxial liftoff with further reduction of the density of fused locations.

3:00pm **ST-MoA1-7 Thermal Laser Epitaxy of Refractory Metals***, **Lena Nadine Majer**, H. Wang, W. Braun, P. van Aken, J. Mannhart, S. Smink,* Max Planck Institute for Solid State Research, Germany

Thermal laser epitaxy is a promising method for the production of epitaxially grown, refractory-metal layers, which may open up exciting perspectives, e.g., for solid state quantum computing devices. In thermal laser epitaxy, high-power continuous-wave lasers heat both the substrate and the individual evaporation sources, very similar to a MBE process. This method combines the advantages of MBE and PLD, allowing the efficient thermal evaporation and epitaxial deposition of practically any combination of elements from the periodic table, because there are practically no limits on substrate and source temperatures. Our setup has a liquid-nitrogen-cooled shroud, which allows us to grow layers with background pressures below 10^{-10} mbar. Moreover, in many cases crucibles can be replaced by free-standing cylinders of source material, which possibly contain a melt within the solid. Both of these factors allow producing very clean layers with low impurity levels.

We demonstrate and discuss the epitaxial growth of refractory metals on c-plane sapphire. As examples we present and discuss Ru and Ta films. We have optimized the growth parameters to obtain epitaxial films of superior quality, which are apparently devoid of defects over large areas. These films grow in a single phase, with a low surface roughness and an atomically sharp interface between the layer and the substrate.

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