MBE
Room Silver Creek - Session MBE-1TuM
Technology of MBE

Moderator: Sanjay Krishna, The Ohio State University

8:15am **MBE-1TuM1 Epitaxy: State of the Art & and Future Trends**, ***Manijeh Razeghi,*** Northwestern University **INVITED**

Nature offers us the periodic table—a full assortment of atoms. Through science and engineering we can put them together in elegant ways to realize functional structures. One of the most transformative structures we have discovered is the semiconductor. It has become one the most pervasive and powerful inventions in human history, ranked fourth in the list of top innovations since the wheel, behind the printing press, electricity, and penicillin, but ahead of eyeglasses, paper, and the steam engine.

As our growth tools have improved we have gained the ability to manipulate atoms on ever-smaller lengths scales. With an understanding of quantum mechanics these growth techniques allow us to harness the power of the semiconductor to create new structures never before found in nature. This has been an enabling technology and through our manipulation of these structures we have developed a whole host of new applications that are shrinking the World and fostering the rapid advancement of human society.

We are able to create quantum devices that allow us to see invisible light from deep UV to THZ. We can probe the human body to find cures and treat diseases. We can communicate with each other faster over ever-larger distances, sharing even more information, thanks to quantum technologies. A particularly rich playground for quantum technology is the so-called III-V semiconductors made of atoms from columns III and V of the periodic table, and constitution compounds with many useful optical and electronics in their own right.(having direct band gap, Strong Covalent bonding with Zinc blend symmetry) Guided by highly accurate simulations of the electronics structure, modern semiconductor optoelectronic devices are literally made atom by atom using advance growth technology such as MBE and MOCVD in ways to give them new properties that neither material has on its own.

In this talk I will review the growth of state of the art semiconductor materials for high performance and quantum devices ranging from the deep UV (200 nm) all the way up to THZ (300 micron) based on MBE MOMBE, Gas-MBE,LPE, VPE , and MOCVD. I will cover the advantages and disadvantages of each technique and discuss the need for future epitaxial techniques to allow us to continue expanding our atomic control of quantum materials.

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8:45am **MBE-1TuM3 Growth-Induced Temperature Changes During Transition Metal Nitride Epitaxy on Transparent SiC Substrates**, ***D. Scott Katzer****, M. Hardy, N. Nepal, D. Storm, B. Downey, E. Jin, D. Meyer,* U.S. Naval Research Laboratory

Accurate non-contact substrate temperature monitoring and control during MBE growth has been a topic of continued interest for more than 25 years [1-3]. While accurate temperature control is well understood for homoepitaxial growth, large substrate temperature changes that are not accurately sensed by the substrate heater thermocouple can be induced by high carrier densities [4-5], reduction of the effective bandgap of the substrate/epitaxial layer stack [1-2], and changes in the surface reflectivity (e.g. induced by the accumulation of gallium droplets in GaN MBE) [6] during growth. In general, any change of the thermal cavity that partially encloses the substrate can also be expected to lead to a change in substrate temperature.

An experimental case that exemplifies the one of most extreme examples of growth-induced temperature changes is the MBE growth of metallic films on transparent semi-insulating SiC. Integration of epitaxial metal layers are technologically important as they will enable substantial performance benefits, design flexibility, and novel device structures such as metal-base transistors [7] and integrated epitaxial superconductor/semiconductor heterostructures [8]. Metals are highly reflective, have very high carrier densities, and have very small or zero band gaps compared to the ~ 3 eV gap of SiC. All of these factors mean that even very thin epitaxial metal layers can be expected to lead to large substrate temperature changes during growth.

In this presentation, we will discuss the use of in-situ SiC band-edge thermometry and pyrometry to quantify and control the substrate temperature excursion during the MBE growth of transition metals and transition metal nitrides on transparent 3” diameter 4H- and 6H-SiC substrates.

This work was funded by the Office of Naval Research.

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9:00am **MBE-1TuM4 Using the Desorption Mass Spectrometry Technique to Optimize Sb Flux in GaSbBi Growth**, ***Jedidiah McCoy****, C. Lu, R. Kaspi,* Air Force Research Laboratory

Bismuth incorporation into GaSbxBi1-xis of interest because the bandgap is substantially reduced within manageable levels of strain. However, MBE growth of this alloy has yet to mature. This is because achieving substantial (>10%) Bi incorporation while maintaining good crystal quality is challenging. To assist Bi competition over Sb in group V incorporation, growths must be conducted at relatively low substrate temperatures (<300 ℃) with near-stoichiometric V/III flux ratios [1]. Because these conditions are outside of the typical GaSb growth window, it becomes imperative to precisely establish the Sb/Ga flux ratio as it is observed to have a large effect on Bi incorporation.

In this study, we utilized the desorption mass spectrometry (DMS) technique to establish a near-stoichiometric Sb/Ga flux ratio at the growth temperature of interest. The DMS technique allows for in-situ monitoring of desorbed Sb so that fine-tuning of the Sb/Ga flux ratio can be accomplished. Using this methodology, GaSb1-xBix layers were deposited at temperatures ranging from as low as 125 ℃ to 300 ℃. Bismuth incorporation exceeding 15% was achieved as well as room temperature luminescence approaching 4 µm, as shown in figure 1.

The DMS technique was also used to explore the GaSb1-xBixgrowth surface. This was done by interrupting the growthsequence and raising the substrate temperature thereby releasing any unincorporated Bi at the surface, which could then be quantified using the desorption spectra, see figure 2. A correlation between this steady-state concentration of unincorporated Bi with growth conditions such as substrate temperature and Bi flux will be discussed.

9:15am **MBE-1TuM5 BBr_3 as a B Source in Plasma Assisted MBE**, ***Richard Cramer****, B. Bonef, J. Speck,* University of California, Santa Barbara

Boron is a difficult material to use in MBE due to its high melting point. Traditionally group III molecular beams are generated by vaporizing samples of pure metal at temperatures well above their melting points. For B which has a melting point of 2076° C this is not currently feasible as even high temperature effusion cells max out around 2000° C. Due to this limitation there is interest in exploring other B sources for MBE such as ion-beam, electron-beam, and gas sources including BBr_3. In this talk we will present BGaN growth experiments which serve as a proof of concept for BBr_3 as a B source for plasma assisted MBE.

We will present data from our experiments in which we grow fully coherent, random alloy, $B_xGa_{1-x}N$ thin films with x up to 3% and thickness up to 280 nm.[1] High resolution XRD was used to characterize the film quality and determine the strain state of the films. On axis ω-2θ scans were used to determine the c parameter of the films and the presence of thickness fringes in these scans is indicative of high crystal quality and was used to measure thickness. Reciprocal space maps around off axis peaks were used to determine that the films were fully coherent to the GaN on sapphire substrates. Using the elastic coefficients of GaN and standard stress-strain relations we calculated the relaxed c parameter and from that the B composition using Vegard's law and theoretical values for wurtzite phase BN lattice constants.

Atom probe tomography (APT) was performed on samples to demonstrate that they had a random, binomial, distribution of B and Ga atoms and are therefore true random alloys.[2] APT and secondary ion mas spectroscopy (SIMS) results were also used to characterize the impurity levels in the films and it was found that our initial growth conditions lead to high levels of O, C, and Br impurities.

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9:30am **MBE-1TuM6 Assessing MBE Regrowth Quality on Transfer Printed Virtual Substrates***, **Michael Yakes**,* Naval Research Laboratory*; M. Lumb, M. Bennett,* George Washington University*; J. Nolde, S. Tomasulo,* Naval Research Laboratory*; C. Haughn,* Army Research Laboratory*; S. Mack, S. Maximenko, K. Schmieder,* Naval Research Laboratory

III-V semiconductor devices provide the highest performance in many optoelectronic applications, including solar cells. However, the large cost to produce these devices can make them very expensive compared to lower quality counterparts. One key factor driving the cost of III-V devices is the high cost of high quality, single crystalline substrates. To address this issue, we have been developing a new technique which we call transfer printed virtual substrates (TPVS). In this technique, shown in Figure 1, a large number of virtual substrate layers, separated by epitaxial release layers, are grown on a source substrate. From this source substrate, virtual substrate layers are moved to separate low cost handles using micro-transfer printing. By iterating through many layers of the source substrate stack, one source substrate can be used to produce a large number of low-cost, epi-ready virtual substrates, which can in turn be used to produce a variety of microscale devices.

In this presentation, we will illustrate the quality of epilayers grown on TPVS by MBE [1,2]. To evaluate surface morphology and optical quality we grew a GaAs/AlGaAs MQW structure on a GaAs TPVS and control wafer. We observed similar surface roughness, XRD peak width and PL linewidths on both the TPVS and the control samples. We've also produced a device demonstration using identical GaAs solar cell structures grown on a native substrate and a TPVS. The efficiency of devices grown on a TPVS is degraded by less than 2% absolute efficiency from the control structures (Figure 2), both under one-sun conditions and under concentration. The experiments suggest that with further process enhancement, TPVS should be able to produce identical performance devices with much lower cost.

9:45am **MBE-1TuM7 LATE NEWS: Mechanism of Si Doping in O_2 Plasma-Assisted MBE Growth of β-Ga_2O_3***, **Nidhin Kurian Kalarickal**, Z. Xia, J. McGlone, S. Krishnamoorthy, W. Moore, M. Brenner, A.R. Arehart, S.A. Ringel, S. Rajan,* The Ohio State University

Si has been shown to be a shallow donor in β-Ga_2O_3 and the MBE growth of Si-doped β-Ga_2O_3 thin films is of extensive importance for realization of electronic and optoelectronic devices based on this promising ultra-wide bandgap material. The dependence of Si flux on effusion cell temperatures have been found to be significantly higher in oxygen environments when compared to non-oxide growth chambers, suggesting that the mechanism of Si flux generation is different from sublimation [1]. *In this work, we report on understanding the mechanism of Si doping during oxygen plasma-assisted MBE (PAMBE) growth of β-Ga_2O_3.*

We studied the dependence of Si deposition as a function of oxygen chamber pressure, Si cell temperature, plasma power and shutter time using Secondary Ion Mass Spectroscopy analysis.Our studies show that (a) Si flux is not limited by Si vapor pressure but by the formation of SiO species on the Si surface, (b) the low sublimation energy of SiO leads to weak dependence of the SiO flux on Si cell temperature and strong dependence on the background oxygen pressure and (c) extended exposure to activated oxygen can lead to passive oxidation of Si surface to SiO_2 leading to reduction in SiO flux.

The work reported provides key understanding for incorporating Si into future oxide-based semiconductor heterostructure and device MBE growth. This work was funded by AFOSR GAME MURI (Grant FA9550-18-1-0479, Program Manager Dr. Ali Sayir).

[1] Xia, Zhanbo, et al." *IEEE Electron Device Letters* 39.4 (2018): 568-571 .

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