MBE-Grown Devices
Room Ballroom A - Session GD-TuA1
Solar Cell and Quantum Computing

Moderator: Prof. Dr. Minjoo Larry Lee, University of Illinois Urbana-Champaign

1:30pm **GD-TuA1-1 InSb-Based Dilute-Bismide Alloys Towards Long-Wave Infrared Sensing**, ***Corey White***, *M. Bergthold, T. Leonard, A. Ricks, D. Wasserman, S. Bank,* The University of Texas at Austin

It is well-established that bismuth incorporation into III-V alloys produces a significant reduction in bandgap energy[1, 2] that can be advantageously leveraged for optoelectronic devices operating at extended wavelengths. For accessing the long-wave infrared, InSb is a particularly promising candidate host alloy due to both its narrow bandgap energy and the relatively similar ideal growth conditions for InSb and III-Bi materials. Here we report progress towards achieving wavelength extension from InSbBi with photoluminescence (PL) from InSbBi with the highest substitutional bismuth concentrations yet reported as well as methods for post-growth bismuth droplet removal.

Epitaxial InSbBi films were grown by solid-source MBE on InSb substrates. Low substrate temperatures, Sb/In flux ratios near stoichiometry, and fast growth rates were employed to encourage significant bismuth incorporation. From these films, X-ray diffraction and Rutherford backscattering spectrometry measurements were used to confirm the bismuth concentration in the films and extrapolate the InBi lattice parameter, which was found to be ~6.63 Å. This is in line with previous reports of the InBi lattice parameter[3-5] confirming that the incorporation of bismuth into InSb causes the lattice to expand. PL measurements from the InSbBi films demonstrated significant wavelength extension beyond that of InSb with emission out to ~6.5 µm at 83 K. Atomic force microscopy surface morphology measurements revealed that the samples exhibited droplet formation.

As is typically observed for dilute-bismide alloys,[3, 6] it is increasingly challenging to achieve droplet-free InSbBi surfaces at elevated bismuth concentrations. We investigated post-processing techniques for droplet removal as an alternative to attempting to completely mitigating droplet formation during growth. HCl/H_2O_2 digital wet etching, physical polishing, and ion milling were performed on a film with large bismuth droplets resulting in improvements in roughness of 2.2×, 3.7×, and 4.0×, respectively. Studies on the effects of these techniques on InSbBi optical quality are underway and will be reported at the conference.

[1]S. Francoeur et al., *APL* **82** (2003).

[2]S. Tixier et al., *APL* **82** (2003).

[3]M. Rajpalke et al., *APL* **105** (2014).

[4]A. Shalindar et al., *JAP* **120** (2016).

[5]B. Joukoff and A. Jean-Louis, *JCG&D* **12** (1972).

[6]A. Ptak et al., *JCG&D* **338** (2012).

This work was performed at the UT Austin MRC, a member of the NNCI (NSF No. ECCS-1542159) and supported by Lockheed Martin, NSF (ECCS-1933836), and an NSF GRF (RCW). RBS measurements were performed at Rutgers LSM.

1:45pm **GD-TuA1-2 Abrupt Te Doping of MBE-Grown GaInP for Solar Cell Applications**, ***Brian Li***, *Y. Sun, R. Hool, M. Lee,* University of Illinois, Urbana-Champaign

For III-V multi-junction solar cells (MJSC), 1.9 eV $Ga_{0.51}In_{0.49}P$ (hereafter GaInP) is a primary material for the high-bandgap top cell [1]. In recent years, GaInP solar cells grown by molecular beam epitaxy (MBE) have achieved high efficiencies after post-growth rapid thermal annealing (RTA) [2] similar to cells grown by metalorganic chemical vapor deposition (MOCVD). Another avenue to improve MBE-grown GaInP cells is the use of group VI dopants (Se, Te) instead of group IV dopants such as Si. For example, MOCVD-grown AlGaAs and AlGaInP cells reported superior internal quantum efficiency (IQE) by changing the dopant from Si to Se [3], [4], an improvement that correlates with the shallower defect energy levels of Se [5], [6]. MBE-grown phosphide cells may also be improved by the use of a group VI dopant, but such studies have not been reported. In this work, we show improved IQE of GaInP solar cells with Te doping of the n-type emitter over Si, which was modeled to show improved carrier lifetime in n-GaInP:Te.

A well reported issue for MOCVD GaInP:Te is undesirable Te surface segregation [7], so we first optimized MBE growth conditions to minimize segregation. GaInP samples were grown at different target concentrations of [Te] = $5.7*10^{17}$ to $1.7*10^{18}$ cm^{-3}, and doping profiles from secondary ion mass spectrometry (SIMS) indeed showed high Te surface segregation at the nominal substrate growth temperature T_{sub} = 460 °C. For example, the doping profile for target [Te] = $1.7*10^{18}$ cm^{-3}ranged by orders of magnitude ($5*10^{16}$ cm^{-3} at the start of growth to $7*10^{19}$ cm^{-3} at the surface). Next, reducing T_{sub} from 460 °C to 420 °C greatly suppressed surface segregation for all samples. Abrupt doping profiles were obtained for target [Te] = $5.7*10^{17}$ cm^{-3} solely by this reduced $T_{sub,}$ while [Te] = $1.7*10^{18}$ cm^{-3} also required a Te "pre-dose" or deposition prior to GaInP growth to achieve an abrupt doping profile. The cause of this difference in pre-dose requirement as a function of doping will be the subject of future work.

Lastly, n-on-p front junction GaInP cells were grown with both GaInP:Te and GaInP:Si n-type emitters (n > $1*10^{18}$ cm^{-3}). For as-grown cells, the IQE of the GaInP:Te cell was significantly higher than that of GaInP:Si, with the short-circuit current density derived from IQE increasing from 13.2 mA/cm^2 to 14.1 mA/cm^2. Modeling of the IQE indicates a ~4x higher carrier lifetime of GaInP:Te than GaInP:Si. This work shows the promise of GaInP:Te for improved optical material quality, and future work will explore GaInP:Te for rear-junction cells with n = 1–$5*10^{17}$ cm^{-3}, as well as the effect of RTA on GaInP:Te.

2:00pm **GD-TuA1-3 MBE Growth of Metamorphic 1 eV InGaAs Solar Cells with Low Threading Dislocation Density**, ***Adrian Birge***, *M. Kim, B. Kim, D. Montealegre, M. Lee,* University of Illinois at Urbana-Champaign, USA

Growth of metamorphic (MM) $In_xGa_{1-x}As$ enables optoelectronic devices, such as near-infrared photovoltaics, detectors, and lasers with bandgap energies (E_g) ranging from 0.8-1.3 eV, to be integrated on GaAs substrates. Most previously reported MM $In_xGa_{1-x}As$ structures with x=0.3 (E_g=1.0 eV) have used metal-organic chemical vapor deposition (MOCVD) at substrate temperatures (T_{sub}) over 700°C to facilitate high dislocation glide velocity and thus low threading dislocation density (TDD)[1], while thermodynamically suppressing phase separation. MBE growth of MM $In_xGa_{1-x}As$ cannot be done at such high T_{sub} due to excessive In desorption. Thus, the MBE growth window must be chosen carefully to balance the need for adequate dislocation glide velocity while kinetically suppressing phase separation. In this work, we describe a two-step method for fully relaxed $In_{0.3}Ga_{0.7}As$ with a TDD = ~$7x10^5$ cm^{-2}, comparable to the lowest reported values for this material. On this platform we fabricated the first MM 1.0 eV $In_{0.3}Ga_{0.7}As$ solar cells grown via MBE to our knowledge.

$In_xGa_{1-x}As$ (x=0-0.3) buffers showed strong phase separation in electron channeling contrast imaging (ECCI) when all growth was carried out at T_{sub}=500°C. Therefore, we adopted a two-step approach where $In_xGa_{1-x}As$ (x=0-0.18) was grown at T_{sub}=500°C to facilitate dislocation glide[2], followed by 460°C for x=0.18-0.3 to prevent PS[3]; an $In_{0.35}Ga_{0.65}As$ overshoot layer was also included to facilitate strain relaxation. ECCI yielded a TDD < $1x10^6$ cm^{-3} without PS, while reciprocal space mapping showed 97.9% relaxation in the $In_{0.3}Ga_{0.7}As$ cap.

Using our two-step $In_xGa_{1-x}As$ graded buffer as a virtual substrate, a 1 eV InGaAs solar cell was grown and devices were fabricated both as-grown (AG) and with rapid thermal annealing (RTA)[4]. Internal quantum efficiency (IQE) measurements showed improved minority electron diffusion length in the base of the RTA cell, resulting in a 1.15x increase in short-circuit current density (J_{SC}). Lighted current-voltage (LIV) curves showed a strong improvement in the open-circuit voltage (V_{OC}) after RTA, with a bandgap-V_{OC} offset (W_{OC}) of 0.46 V, ~0.1 V higher than the best cells in the literature grown by MOCVD at NREL[5]. The fill factor (FF) and cell efficiency (η) of our RTA'd cells were hampered by high contact resistance, which will be addressed in future runs. Nonetheless, the J_{SC} (29.96 mA/cm^2) and V_{OC} (0.538 V) values of our RTA'd cells compare favorably with the best lattice-matched 1.0 eV solar cells (e.g. InGaAsN on GaAs, InGaAsP on InP) grown by MBE[6], presenting a promising path for MBE-grown MM 1.0 eV $In_{0.3}Ga_{0.7}As$ solar cells.

2:15pm **GD-TuA1-4 Strained Superlattice InAlGaAs/AlGaAs Spin-Polarized Photocathodes Implemented with Random and Digital Alloying**, ***Aaron Engel***, University of California, Santa Barbara*; M. Stutzman,* Thomas Jefferson National Accelerator Facility*; J. Dong,* University of California, Santa Barbara*; C. Palmstrøm,* University of California, Santa Barabara

Spin-polarized electron beams are a crucial tool in particle physics experiments and specialized characterization techniques. Their production involves exciting a III-V semiconductor (the photocathode) with near-bandgap circularly polarized light. Spin-polarized photoelectrons are produced through optical selection rules. These photoelectrons are then extracted after functionalizing the surface to create a negative electron affinity condition. Increasing the electron spin polarization (ESP) and the quantum efficiency (QE) of the photocathodes enhances overall experimental efficiency, extends the photocathode lifetime, and enables the production of high bunch charge beams. The current state-of-the-art spin-polarized photocathodes consist of $GaAs/GaAs_{0.67}P_{0.33}$ strained superlattice quantum wells grown on metamorphic $GaAs_{0.67}P_{0.33}$ virtual substrates on GaAs(001), which consistently produce QE over 1% and ESP around 85%.

While the GaAs/GaAsP system is mature, it still faces many limitations. Growth of the relaxed virtual substrate results in a higher density of threading dislocations than there would be in a fully pseudomorphic system, thereby limiting QE, ESP, and photocathode lifetime. In addition, since the As/P ratio in the virtual substrate controls the lattice constants, band offsets, and band gaps, it is difficult--if not impossible--to design a stack that optimizes each of these parameters simultaneously.

Here we demonstrate fully pseudomorphic spin-polarized photocathodes based on the InAlGaAs/AlGaAs system grown by molecular beam epitaxy. By switching to this quaternary well/ternary barrier system, we may more independently optimize the strain, superlattice bandgap, and band offsets. Furthermore, control of Group III alloy composition should be more precise, reproducible, and uniform than control of Group V alloy composition. The fully pseudomorphic stack simplifies growth and reduces the dislocation density in the active region. Unfortunately, the transition from a binary/ternary system to a quaternary/ternary system will increase the random alloy disorder in the photocathode. This random alloy disorder can then cause significant reductions in ESP. To solve this, we investigate using a digital alloy for the well and/or barrier in the superlattice. Our first test structure using a random alloy photocathode design yielded polarization over 80%, but a QE of only about 0.3%. We will report on further optimization of the growth conditions of both random and digital alloy photocathodes. In addition, we will discuss the changes to the QE and ESP of the photocathodes between the two alloy schemes.

2:30pm **GD-TuA1-5 Molecular Beam Epitaxy Growth and Characterization of InAs Quantum Wells Grown on Metamorphic III-V Buffer Layers***, I. Levy, **Patrick Strohbeen**, W. Strickland, M. Hatefipour, J. Issokson, L. Baker,* New York University*; M. Mikalsen,* new york University*; S. Farzaneh, J. Shabani,* New York University

Heterostructures of a 2-dimensional electron gas (2DEG) semiconductor and a superconductor are prime candidates for various applications including quantum computing and topological superconducting circuits [1,2]. The 2DEG layer needs to be in close proximity to the superconductor, within the structure, and to form an Ohmic contact. Heterostructure of containing a quantum well (QW) of InAs (InGaAs/InAs/InGaAs) that have a narrow bandgap with the Fermi level close to the conduction band as a 2DEG semiconductor and thin epitaxial Al layer grown on it as a superconductor. This heterostructure makes a prime candidate due to the high mobility in the 2DEG and the compatibility between the QW and the epitaxial Al.

In this work, we present our study of the growth of these heterostructures (InAs QW/Al) grown by molecular beam epitaxy [3]. We show the effect of modification of the growth conditions on the heterostructures and analyze the disorder in the samples using different techniques. Various impurities including background impurity, surface impurities, alloy scattering and surface roughness can be moderated as a function of the growth conditions. We find samples that have high indium content in their graded buffer layer show a decrease in surface roughness with growth temperature. In addition, anisotropy along rapid diffusion directions during the growth results in anisotropy in the resulting carrier mobilities parallel with these directions. We also analyze the typical cross hatch pattern of the surface on the InAs heterostructures as a function of growth parameters and relate the strain state anisotropy (or lack thereof) to the observed electrical characteristics. Lastly, we show that growth of a thin capping layer of 1 - 6 nm of $In_{0.81}Al_{0.19}As$ modifies the surface scattering on the quantum well, the implications of which will be discussed.

[1] H. Kroemer, Physica E 20, 196 (2004)

[2] J. A. del Alamo, Nature 479, 317 (2011)

[3] W.M. Strickland et al. Appl. Phys. Lett. 121, 092104 (2022)

2:45pm **GD-TuA1-6 Cryogenic Growth of Superconducting Thin Films on GaAs, Si, and Sapphire Substrates***, **Teun van Schijndel**, A. Engel,* University of California Santa Barbara*; J. Dong,* University of California at Santa Barbara*; A. McFadden,* NIST-Boulder*; C. Palmstrøm,* University of California Santa Barbara

Superconducting thin films are crucial in various fields of quantum information technology, including superconducting qubits and topological quantum computing. The vast majority of either of these qubit technologies use aluminum as the superconducting component. Al is generally grown at low temperatures to achieve smooth thin films. This allows for easy integration of Al-based devices with material systems such as sapphire, Si, Ge, or III-V materials due to minimal interfacial reactions.

While aluminum is the most common, other superconductors show promising results as well. In particular, Ta- and Nb-based superconducting qubits on sapphire show low loss and long coherence times.[1,2] Due to its resilience to high temperatures, low-loss sapphire can withstand the growth of Ta and Nb at elevated temperatures necessary for the realization of desirable superconducting properties. These superconductors could be interesting for topological qubits as well, but integration of these refractory metals on high-purity semiconducting substrates with high spin-orbit coupling remains a challenge due to interfacial compound formation at higher temperatures. In fact, this can lead to additional roughness and consequently degradation of superconducting properties such as T_c.

In this work, we explore the MBE growth of superconducting thin films at ultralow temperatures below 10K (LT). In particular, we focus on the growth of refractory metals such as Ta, Nb, and V. Through a comparative study of thin film growth at ultralow temperature and room temperature (RT), significant changes in the properties of the superconducting thin films are observed. Initial experiments on SiO2/Si surfaces indicate a notable improvement in film smoothness with lower temperature growth measured by Atomic Force Microscopy. Furthermore, four-probe resistance measurements demonstrate a significant increase in the superconducting Tc for all superconductors studied. Most dramatically, we found that 20 nm Ta grown at RT did not exhibit a superconducting transition above 2K, while LT growth of Ta resulted in a superconducting film with a Tc of 3.95K. We will further investigate this behavior on GaAs(001), Si(001), and Al_2O_3(0001) surfaces and extend our study to superconductors such as Pb, Sn, and Al. Our work demonstrates the growth of high-quality superconducting thin films with ultralow temperature growth, which enables the exploration of different substrate and superconductor combinations for use in quantum information technology.

References

1) Nat Commun 12, 1779 (2021).

2) npj Quantum Inf 8, 3 (2022).

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