MBE

Room Max Bell Auditorium - Session MBE-WeM

II-VI Materials and Heterovalent Growth/Topological Insulators and Quantum Computing

Moderators: Philip Poole, NRC, Michael Santos, University of Oklahoma

8:30am **MBE-WeM-1 High-Reflectivity Heterovalent Distributed Bragg Reflectors for Infrared Resonant Cavity Applications***, **Maxwell Lassise**, B Tracy, D Smith, Y Zhang,* Arizona State University

Monolithically integrated midwave infrared optoelectronic devices such as VCSELs, resonant-cavity LEDs and photodetectors are highly desirable for chemical sensing and environmental monitoring applications. One of the key components of these devices is the highly-reflective distributed Bragg reflector (DBR), which is comprised of a stack of alternating layers with different refractive indices designed to reflect a particular range of wavelengths. In this study, we first focus on ZnTe/GaSb DBRs, which have a high refractive index contrast (Δn≈1 for infrared wavelengths), similar lattice constants (lattice mismatch < 0.1%), and are epitaxially integrable with infrared absorber materials like InAs/InAsSb, GaSb/InGaSb, InAsSbBi, and PbSe. Several DBR samples were grown using a single-chamber MBE system equipped with both II-VI and III-V source materials. The grown structures demonstrate sharp interfaces and minimal interdiffusion between the heterovalent layers, as evidenced by TEM and XRD.

The measured and simulated reflectance for the ZnTe/GaSb DBRs have a peak reflection value of approximately 98 % and a stopband width of about 70 meV centered on a wavelength of 4.5 µm for a 6 pair structure. Fabry-Pérot cavities based on the DBRs are investigated to determine the viability of these structures for resonant-cavity devices. The reflectance spectra and minimum absorption levels of the DBR structures have been modeled using the transfer matrix formalism for a variety of material combinations lattice-matched to III-V substrates. Below-band gap losses such as free carrier absorption are calculated for short, mid, and longwave IR heterovalent DBR structures and compared with corresponding III-V DBRs. Additionally, the optical properties of resonant-cavity structures based on the heterovalent DBRs are simulated and the potential device characteristics, such as the cavity Q-factor, are compared for a range of cavity materials and operational wavelengths. Other lattice-matched heterovalent material combinations, such as ZnSe/GaAs and CdTe/InSb, are also under exploration for shortwave to longwave IR DBRs.

8:45am **MBE-WeM-2 Photoluminescence Characterization of a 1 ML CdSe Fully-Strained Ultra-Thin Quantum Well with very Thin ZnSe Barriers***, A Alfaro-Martínez,* DNyN, CINVESTAV, Mexico*; F Sutara, **Isaac Hernández-Calderón**,* CINVESTAV, Mexico

In fully strained CdSe/ZnSe ultra-thin quantum wells (UTQWs) grown on GaAs (001) substrates, both ZnSe and CdSe are under biaxial compressive stress. The critical thickness under these strains is around 90 nm for ZnSe and around 3.5 monolayers (1.2 nm) for CdSe. The physical properties of the 1 ML CdSe UTQW still deserve a detailed explanation and interpretation regarding its high excitonic emission intensity, full width at half maximum (FWHM) and peak energy [1]. Here, we present a study of a nominal 1 ML CdSe UTQW grown by atomic layer epitaxy at 275 °C within a ZnSe barriers of 20 nm and 25 nm (cap layer). The thickness of each layer and the total thickness of the heterostructure are chosen in such a way that each material is below its critical thickness. The 19 K photoluminescence spectrum presents an intense excitonic peak at 2.685 eV with a FWHM of 12.3 meV, which is lower than previous results of CdSe UTQWs grown on relaxed ZnSe barriers [2]. The evolution of the excitonic peak as a function of temperature suggests the absence of QW potential fluctuations, which in this case would correspond to composition fluctuations or to the formation of quantum islands. Since the actual CdSe coverage depends on growth temperature, the coverage of the studied structure is expected to be slightly lower than 1 ML. The results will be discussed and explained in terms of two different descriptions: a 1 ML $Zn_{1-x}Cd_xSe$ UTQW with very low Zn content, and large area 1 ML thick CdSe islands.

[1] See, for example, T. V. Shubina, G. Pozina, A. A. Toropov, Phys. Status Solidi B254, 1600414 (2017).

[2] I. Hernández-Calderón, AIP Conf. Proc. 809, 343 (2006).

9:00am **MBE-WeM-3 Hybrid II-VI/III-V Infrared Photodetectors***, **Marcel Claro**,* City College of New York, City University of New York*; Y Kaya,* Princeton University*; T Garcia, C Forrester, V Deligiannakis,* City College of New York, City University of New York*; C Gmachl,* Princeton University*; M Tamargo,* City College of New York, City University of New York

Despite the huge success of intersubband infrared devices based on III-V semiconductors in the past few decades, namely quantum cascade lasers (QCLs) and detectors (QCDs), and the quantum well infrared photodetectors (QWIPs), the fabrication of multi-band device is still a challenge. In the GaAs/AlAs and InGaAs/AlInAs/InP material systems, the material properties are not the optimum to cover the entire infrared (IR) range. Recently, QWIPs and QCDs working from 4 to 10µm were shown using ZnCdSe/ZnCdMgSe II-VI materials, and they have particularly high-detectivity in the short wavelength IR range, wherein the intersubband III-V devices lack in performance.

Aiming for a high-detectivity multi-band photodetector, we grew several structures consisting of a ZnCdSe/ZnCdMgSe QCD, designed to have peak responsivity at 5µm, stacked on top of an InGaAs/AlInAs QCD, designed to have peak responsivity at 8µm. They were grown lattice matched to InP (100) substrates. The practical integration of two devices made from these two materials in a single chip has not been yet demonstrated, and would increase the materials landscape for the design of novel advanced devices.

High-Resolution X-Ray Diffraction (HR-XRD) and Photoluminescence (PL) measurements of the hybrid structures confirm the high quality of the two materials components. Full device characterization was made on the device stack using top and bottom contacts, which means the II-VI and III-V components are connected in series, as well as using the middle contact to measure each device separately. The same characterization was performed on individual III-V and II-VI QCD devices with the same design as the hybrid. The results show that II-VI QCD devices have a much higher resistance, R_0, and higher responsivity than III-V QCD devices, and typically dominate in the hybrid responsivity spectrum. The comparison between the III-V in the hybrid stack and the pure III-V device indicates that the presence of an InGaAs/ZnCdSe interface may affect negatively the III-V device performance. Additionally, etching away of the II-VI layers in a hybrid device has also shown greatly improved performance of the underlying III-V device. Several causes are being investigated, such as built-in electric field and deep defects due to elements inter diffusion at the II-VI/III-V interface, or optical interference of the two different device structures.

The effects of modifying the interfacial layer on the hybrid devices are explored. Different device geometries are also explored to identify electrical and optical characteristics of the materials that may affect device performance.

9:15am **MBE-WeM-4 Cd_3As_2/II-VI Heterostructures on (111) GaAs***, **Anthony Rice**, K Park, K Alberi,* National Renewable Energy Laboratory

Cd_3As_2 is an exciting material system. As a Dirac semimetal, it is a 3-D analogue of graphene [1] and provides access to a variety of interesting physics, ranging from massless Dirac fermions to topological superconductivity. It also exhibits very high electron mobility and large phonon-phonon scattering, which are ideal for a number of energy-related applications. While interest in Cd_3As_2 has recently risen, most work to date has been confined to bulk single crystals rather than thin films. Epitaxial growth on foreign substrates would allow strain and heterostructure engineering as well as permit careful studies of doping and confinement. Molecular beam epitaxy of Cd_3As_2 has been carried out primarily on GaSb (111) layers grown on GaAs (111) substrates (-3.5% mismatch) [2] and directly on CdTe(111)B substrates (2.3% mismatch) [3]. Both take advantage of the preferred (112) growth surface of Cd_3As_2. However, no efforts to further improve lattice matching have been reported to date.

Building off of previous work of improved GaAs(001)/ZnSe(001) interfaces [4], growth of II-VI compounds on (111) GaAs is explored both as a route toward improved growth surfaces as well as integration into heterostructures. $Cd\text{-}_3As_2$ epilayers were first grown on CdTe/ZnTe buffers on GaAs (111) substrates. The resulting Cd_3As_2 layers grown on these structures showed comparable carrier/mobility relationships and improved RMS roughness to materials in previous reports, as shown in fig. 1. Alloyed $Cd_xZn_{1-x}Te$ (111) layers were then developed to explore lattice-matched growth as well as systematic strain effects (fig. 2). Effects of light stimulation during growth will also be discussed.

[1] Z.K. Liu, *et al., Nature Materials*, **13**, 677 (2014)

[2] T. Schumann *et al.,* APL Mater. **4**, 126110 (2016)

[3] M. Goyal *et al.* APL Mater. **6**, 026105 (2018)

[4] K. Park, K.A. Alberi. *Scientific Reports.* **7**, 8516 (2017)

9:30am **MBE-WeM-5 Demonstration of the Growth of ZnCdTe/ZnTe Quantum Wells with Variable Composition by Submonolayer Pulsed Beam Epitaxy (SPBE)***, F Sutara,* ***Isaac Hernández-Calderón,*** CINVESTAV, Mexico

The growth of specifically designed semiconductor heterostructures very often requires the growth of several quantum wells (QWs) with different alloy compositions. In the case of molecular beam epitaxy (MBE) and related techniques, the modification of the alloy composition is obtained by the change of the cell temperatures. Then, the growth process is interrupted to allow the modification of the growth parameters for each QW and the deposition process is restarted when the growth conditions reach stability. If many layers with different composition are required, the complexity and duration of the growth process becomes impractical. Submonolayer pulsed beam epitaxy (SPBE) has been employed to overcome those difficulties for the growth of ZnCdSe QWs [1]. SPBE allows the modification of the ternary alloy composition in real-time, without interruption of the growth process and without modification of the cell fluxes. SPBE is based on the pulsed supply of the reactant species and on the self-regulated process of the surface saturation, leading to a layer-by-layer growth mode with precise thickness control. Here, we demonstrate the successful application of SPBE to the growth of a single heterostructure containing three $Zn_{1-x}Cd_xTe$/ZnTe QWs with different composition, each 8 monolayers (MLs) thick; the QWs were grown on a GaAs (001) substrate at ~ 275 °C. All ZnTe layers were grown by MBE. The photoluminescence (PL) spectrum of the heterostructure acquired at 20 K exhibits three well defined emissions confirming the different composition of each ZnCdTe QW. A detailed explanation of the growth process and its advantages will be explained.

[1] I. Hernández-Calderón, “Epitaxial growth of thin films and quantum structures of II-VI visible-bandgap semiconductors,” in Molecular Beam Epitaxy: From Research to Mass Production, edited by M. Henini (Elsevier, Oxford, 2013), pp. 310–346.

9:45am **MBE-WeM-6 Interface Modification in Type-II ZnCdSe/Zn(Cd)Te QDs***,* ***Vasilios Deligiannakis****, S Dhomkar, M Claro,* City College of New York, City University of New York*; I Kuskovsky,* Queens College*; M Tamargo,* City College of New York, City University of New York

Intermediate band solar cells (IBSCs) have been proposed as a possible solution to overcoming the Shockley-Queisser limit [1] for solar cell quantum efficiencies. In these, a mid-gap energy band is formed, for instance, by quantum dots within a large bandgap semiconductor matrix. Type-II ZnCdSe/Zn(Cd)Te submonolayer (QDs) have been explored by our group for their promising properties as IBSCs [2, 3]. The ZnCdSe host material when latticed matched to InP has an energy bandgap of ~ 2.1 eV in which the Zn(Cd)Te QDs can form an intermediate band with an energy between 0.5 - 0.7 eV [3]. The similarity of these parameters with those required for an optimal IBSC makes this material system an outstanding candidate. However, challenges arise during the growth of these materials due to the lack of a common anion, resulting in formation of an unintentional ZnSe interfacial layer (IL) between the ZnCdSe spacer and the QDs, causing high tensile strain in the structure. Here we report the results of several modified growth sequences that modify and suppress the IL, allowing for the host material and QDs to be both simultaneously lattice matched.

Samples were grown by a combination of MBE and migration enhanced epitaxy (MEE) in which sub-monolayer dot formation was achieved by exposure of the sample surface to alternating Zn, Cd and Te fluxes. By incorporating a modified shutter sequence (Fig 1b inset) with a Cd-only exposure between the growth of the spacer layer and the MEE cycles, significant suppression of the ZnSe tensile layer was achieved. The HR-XRD (Fig 1a) of two samples with different shutter sequences shows that the sample with the modified shutter sequence (sample A) has nearly lattice matched ZnCdSe spacers, as well as the zero-order peak of the QD superlattice [SL(0)], while the previously adopted shutter sequence required a strain compensated ZnCdSe spacer (sample B). The type II nature of the band structure for sample A is confirmed by the intensity dependent blue shift of the PL peak (Fig 1b). Further adjustments to the band structure were obtained by modifying the QD composition.

[1]A. Luque and A. Marti, Phys. *Rev. Lett.,***78,** 5014 - 5017 (1997).

[2]S.Dhomkar, et al. *Solar Energy Materials and Solar Cells,* 117, 604 (2013)

[3] M. Imperato, e al. *Journal of Electronic Materials* (2018). 10.1007/s11664-018-6241-6

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10:30am **MBE-WeM-9 Molecular Beam Epitaxy Growth of Near Surface InAs Two-dimensional Electron Gas for Topological Quantum Computation***,* ***Candice Thomas****, A Hatke, M Capano, T Wang, R Diaz, S Gronin, G Gardner, M MANFRA,* Purdue University

Hybrid superconductor-semiconductor heterostructures subjected to an in-plane magnetic field have experimentally demonstrated their potential to host non-abelian Majorana Zero Modes (MZMs) in both bottom-up nanowires [1] and recently with two-dimensional electron gas (2DEG) [2], the latter allowing scalable top-down fabrication of more and more complex devices. Specifically, MZMs have been observed with InAs 2DEG grown on InP (100) substrates. However, the large lattice mismatch (3.3%) between these two materials result in threading dislocations and surface roughness that play a prominent role in electronic transport by introducing disorder.

To address this issue, we consider the molecular beam epitaxy (MBE) growth of InAs 2DEG on quasi-lattice matched GaSb (100) substrates (lattice mismatch of -0.6%). As GaSb is not perfectly insulating, the growth of a high bandgap and lattice matched buffer of AlGaSbAs is utilized and allows an isolation between device mesas of the order of the GΩ, as required for density of state measurements in the tunneling regime. The As/Sb incorporation ratio and thus the lattice matching of this quaternary compound are mostly tuned by the substrate temperature. By growing 20 nm deep InAs quantum well on top of 800 nm-thick AlGaSbAs buffer, 2DEG with carrier mobility larger than $2x10^6$ cm^2/Vs for a density of about $6x10^{11}$ cm^{-2} is achieved.

The MBE growth development of these heterostructures will be reported relying on structural and electrical characterizations. Moreover, we will present our efforts to transform these semiconductor structures into a topological quantum computing platform. This will include optimization of the heterostructure design through the implementation of an in-situ back gate.

[1] V. Mourik *et al*., Science, 336, 1003-1007, (2012)

[2] F. Nichele *et al*., Physical Review Letters, 119 (13), 136803, (2017)

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10:45am **MBE-WeM-10 InAs Surface 2DEG and Interface Characterization of InAs/Al Structures Using Josephson Junctions***,* ***Kaushini Wickramasinghe****, W Mayer, J Yuan, K Sardashti, J Shabani,* New York University

Surface InAs quantum wells have become the focus of renewed theoretical and experimental attention partly because of their potential applications in topological[1] and superconducting quantum computation [2,3]. These applications require epitaxial contacts to superconductors with high transparency, tunable proximity effect, and coupling of the two-dimensional electron gas (2DEG) and superconductor. Thus it is really important to study the properties of 2DEGs at the surface and details of structural properties of interface between the Al and InAs.

In our work we study the quality of the InAs/Al interface using transport measurements. Quality of transparency is reflected in the supercurrent and induced gap through the Josephson junction. The product of the critical current (I_C) and the normal state resistance (R_n) is used to characterize Josephson junction properties. We compare the product of IcRn for variety of MBE grown InAs/Al wafers with different mobility, mean free path, interface barriers, and density. Currently we have reached IcRn = 374 μV approaching ideal case for ballistic short junctions. We discuss our data within known theoretical models and identify crucial material properties that influence the proximity effect and transparency between superconductors and semiconductors.

[1] Jason Alicea. Rep. Prog. Phys. **75**, 076501 (2012)

[2] Z. Qi, H. Xie, J. Shabani, V. E. Manucharyan, A. Levchenko, and M. G. Vavilov. Phys. Rev. B **97**, 134518 (2018)

[3] T. W. Larsen, K. D. Petersson, F. Kuemmeth, T. S. Jespersen, P. Krogstrup, J. Nygård, and C. M. Marcus. Phys. Rev. Lett. **115**, 127001 (2015)

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11:00am **MBE-WeM-11 Epitaxial Growth of Superconducting Thin Aluminum Films on InAs for Topological Quantum Computing***,* ***Geoffrey Gardner,*** Microsoft Research*; C Thomas, T Wang,* Purdue University*; S Gronin,* Microsoft Research*; M Capano, M MANFRA,* Purdue University

MBE grown material based upon hybrid semiconductor-superconductor has generated a lot of interest recently due to the possibility that it allows for the emergence of Majorana Zero Modes (MZM) which may offer topological protection for quantum computing. [1]

Relevant material platforms for MZM based devices include semiconductors with high spin-orbit coupling such as InAs on GaSb, and InAs on InP which are coupled to a s-wave superconductor that shows 2e periodicity in a closed system. Thin aluminum films, ~7nm, meet these requirements and have been shown to have a high critical in-plane magnetic field. Additionally, the aluminum has remarkable epitaxial relationship with InAs allowing for atomic ordering of Al (111) parallel to InAs (100). [2]

The growth of thin epitaxial aluminum is extremely sensitive to temperature. Deposition at T>0°C causes many grains to form or the film to ball up. Depositing thin Al films at T~77°K shows good morphology but not the requisite crystallinity. Thin films, <10nm, deposited within the good temperature window show structure which matches the semiconductor and has two distinct in-plane orientations, both (111) in plane (Fig. 1). This Al-InAs hybrid system shows an induced gap >200μeV. Here we present optimization and characterization of superconducting Al layers on MZM devices.

[1] S. Das Sarma, et al., npj Quantum Information (2015). doi:10.1038/npjqi.2015.1

[2] P. Krogstrup, et al., Nature Materials (2015). doi:10.1038/nmat4176

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11:15am **MBE-WeM-12 Morphological Control Over $(Bi_xIn_{1-x})_2Se_3$ Grown on GaAs***, **Theresa Ginley**, S Law,* University of Delaware

Bismuth chalcogenides, such as Bi_2Se_3 , have become increasingly popular materials to study as prototypical topological insulators (Tis). TI materials have a bulk band gap crossed by linear surface states that form a graphene-like Dirac cone. Plasmons excited in the TI surfaces states have been demonstrated to have exceptionally large mode indices and relatively long plasmon lifetimes[1], making them ideal candidates for sensing and waveguiding applications in the difficult-to-access THz regime. Bi_2Se_3 can be grown by van der Waals (vdW) epitaxy on a variety of substrates, yet previous studies have shown that film quality is limited by a disordered layer between the substrate and the film, leading to large trivial carrier densities and low mobility[2]. $(Bi_{1-x}In_x)_2Se_3$ (BIS) is an ideal material to use as a buffer layer as it shares the crystal structure, lattice constant, and vdW bonding of Bi_2Se_3 but is a trivial band insulator for x>0.3. Major improvements in sheet density and mobility have already been reported for films grown using BIS buffer layers as compared to growths directly on sapphire[3], indicating that the Fermi energy is within the bulk band gap.

We are interested in growing Bi_2Se_3 films with BIS buffers on GaAs substrates to integrate TI materials with semiconductor optoelectronic structures. We find that the morphology for BIS grown on GaAs(001) is strongly dependent on selenium overpressure. At lower selenium fluxes rectangular needles form (Sample A), while at high selenium fluxes terraced hexagonal features are present (Sample C), as shown in the scanning electron microscopy images in Figure 1. All features are aligned along the (011) plane of the GaAs. At intermediate selenium fluxes (Sample B), the film is ultra-smooth. This is significant, because growth of Tis and related materials on sapphire usually exhibit spiral growth with either triangular or hexagonal domains, especially at these relatively large thicknesses (50nm). An ultra-smooth BIS buffer layer improves the quality of overgrown Bi_2Se_3. From x-ray diffraction measurements, we suspect that the hexagonal features seen at high selenium fluxes are self-assembled Bi_2Se_3 nanostructures. By tuning the BIS growth conditions, we can exercise substantial control over the film morphology, despite the use of vdW epitaxy. Control over the buffer morphology will ultimately pave the way for unique TI devices.

[1] T. P. Ginley, S. Law, *Adv. Opt. Mater.***2018**, 1800113.

[2] Y. Wang, T. P. Ginley, C. Zhang, S. Law, *J. Vac. Sci. Technol. B***2017**, *35*.

[3] Y. Wang, T. P. Ginley, S. Law, *J. Vac. Sci. Technol. B***2018**, *36*.

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11:30am **MBE-WeM-13 Dielectric Functions of MBE-grown $Bi_2(Te_{1-x}Se_x)_3$ Thin Films***, E Holmgren, J Lyons,* ***Frank Peiris****,* Kenyon College*; X Li, X Liu, M Dobrowolska, J Furdyna,* University of Notre Dame

Using spectroscopic ellipsometry, the dielectric functions of a series of topological insulators, including Bi_2Te_3, Bi_2Se_3 and their ternary alloys, were determined. The topological insulator-thin films were grown on GaAs substrates using a dual-chamber Riber 32 solid-source MBE system. The ellipsometry measurements were obtained using an IR-spectroscopic ellipsom eter, spanning a spectral range between 2000 nm to 35,000 nm. A standard inversion technique was used to model the ellipsometry spectra, which produced the dielectric functions of each of the topological insulator-films. These dielectric functions were analyzed further to obtain characteristics such as their bad gap and carrier concentration. Specifically, Kramers-Kronig-consistent oscillators were used to represent the Drude contribution as well as the energy gap. We found that the band gap blue shifts as the concentration of *Se* increases in the ternary compound. More importantly, best fits for experimental spectra were obtained when an anisotropy was introduced in the dielectric functions of the topological insulators. Furthermore, the model allowed us to calculate the anisotropy of the effective mass, suggesting that there is roughly a factor of four difference between the *xy* and *z*-axis effective masses.

11:45am **MBE-WeM-14 MBE Growth and Properties of Bi_2Se_3/Sb_2Te_3 p-n-p-n Short-period Superlattices***, **Ido Levy**, T Garcia, H Deng, S Alsheimer, L Krusin-Elbaum, M Tamargo,* City College of New York, City University of New York

We present the growth and properties of Bi_2Se_3/Sb_2Te_3 short-period superlattices and investigate the transport of carriers of the bulk and surfaces of this material. Surface roughness between 1 and 3nm was measured. For each sample we extract the average composition from the HR-XRD zero order superlattice peak and the period from the superlattice fringes. The field dependent hall resistance changes from n-type to p-type with the transition occurring at an effective composition ~42% Bi_2Se_3. A weak anti-localization cusp in the magnetoresistance suggests the preservation of topological surface states. These results indicate this is an excellent system for further study.

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