Saturday Morning, July 20, 2024

Workshop on Epitaxial Growth of Infrared Materials
Room Cummings Ballroom - Session WEG-SaM

Workshop on Epitaxial Growth of Infrared Materials: Industry Perspectives

Moderator: Chadwick Canedy, Naval Research Laboratory

9:45am **WEG-SaM-1 Welcome & Sponsor Thank Yous***,*

10:00am **WEG-SaM-2 Antimonide-based Infrared Materials: Needs, Challenges and Recent Progress***, **Minh Nguyen**,* HRL Laboratories **INVITED**

Antimonide-based III-V semiconductors form an unique group of narrow bandgap materials as they are relatively mature to yield high-quality devices and are fab-compatible at industry foundries, yet still have many unanswered fundamental and scientific questions to investigate. Their small energy gap (<0.3 eV) corresponds to optical transitions in the infrared and terahertz regime which have tremendous potential in applications such as detectors, lasers, photovoltaic cells, spectroscopy, etc. In parallel, these narrow-gap compound semiconductors, comprised of large constituent atoms with intrinsically large spin orbit coupling, offer a great deal of advantages in semiconductor-based qubit technologies and spintronics.

In the field of infrared detection and imaging, antimonide-based materials have emerged as a serious alternative to the incumbent state-of-the-art Mercury Cadmium Telluride due to its superior "–ility" advantages: uniformity, stability, scalability, manufacturability, affordability. Another key advantage of this technology is the ability to leverage III-V foundries for material growth and device fabrication, which allow for rapid development of this small but diverse ecosystem. In this talk, we will provide an overview of recent progress, needs and challenges of infrared detector technology, from an industrial point of view.

10:30am **WEG-SaM-4 MBE Growth of GaSb- and InP-based Infrared Epitaxial Structures at IQE***, **Amy Liu**, J. Fastenau, D. Lubyshev, S. Nelson, M. Fetters, S. Cramb, W. Black,* IQE Inc. **INVITED**

The GaSb-based family of materials and heterostructures provides rich bandgap engineering possibilities for myriad infrared (IR) applications, and molecular beam epitaxy (MBE) is the primary growth technology for this material system.[1-4]There has been tremendous progress in GaSb-based IR photodetector (Sb-IRPD) technology in the last 10 years, and the transition from research and development to volume manufacturing is well underway with adoption of this technology by several US DoD programs of record and for many other commercial and defense applications.[4,5]

The MBE process for Sb-IRPD structures we originally developed on 2" diameter substrates using a research tool has been transferred to large-volume, multi–wafer production platforms, with 4" and 5" wafers now the industry standard for IR focal-plane array (FPA) applications.[6-9] The increase in production volume has also enabled us to apply statistical process control techniques to improve command over critical parameters, and thereby improve the yield and throughput of our MBE process. The robustness of our epitaxial process is further proven by the ability to not only readily reproduce Sb-IRPD material characteristics across multiple tools at the same production site, but across multiple tools at different production sites.[7]

There is also growing interest recently in exploring the metamorphic growth of Sb–IRPD structures on non-native, large-diameter substrates for large–format FPA and radiation-hard applications. We have demonstrated the feasibility of growing mid–wave Sb-IRPD structures on ≥6" GaAs, Ge and Si substrates.[8]

In this work, we will provide an update on the status of our Sb-IRPD epiwafer production with different absorber designs and on different substrates. Representative material characterization and large-area diode test data will be discussed.

In additional to IR detector structures, we also support development and production of IR emitter structures.[9] We will briefly discuss our MBE efforts for growing GaSb-based interband cascade laser and InP-based quantum cascade laser structures.

1. D. L. Smith and C. Mailhiot, J. Appl. Phys. **62**, 2545–2548 (1987).
2. S. Maimon and G. W. Wicks, Appl. Phys. Lett. **89**, 151109 (2006).
3. A. Soibel *et al*., App. Phys. Letts. **105**, 023512 (2014).
4. P. C. Klipstein *et al*., Proc. SPIE **12107**, 121070Q (2022).
5. D. A. Reago, SPIE DCS Conf., Orlando, FL, 2021, 11741-403.
6. D. Lubyshev *et al*., Proc. SPIE **7660**, 76601J (2010).
7. J. M. Fastenau *et al*., Proc. SPIE **12107**, 121070Z (2022).
8. J. M. Fastenau *et al*., J. Vac. Sci. Technol. B, **37**, 031216 (2019).
9. A. W. K. Liu *et al*., Proc. SPIE **PC12009**, PC120091 (2022).

11:00am **WEG-SaM-6 MBE HgCdTe: The Material Leading to High Performance Infrared Imaging Sensors***, **Aristo Yulius**,* Teledyne Imaging Sensors **INVITED**

Teledyne Imaging Sensors (TIS) is the leading supplier of Infrared Imaging Sensors for high performance applications, producing arrays with the lowest reported dark currents and near unity quantum efficiency over a broad range of cutoff wavelengths and operating temperatures. TIS infrared focal plane arrays are used for both ground- and space-based astronomy applications, including high profile missions like the Hubble Space Telescope (HST), the James Webb Space Telescope (JWST), and the Euclid Space Telescope to investigate the Dark Matter and Dark Energy. TIS HgCdTe device architecture is based on Molecular Beam Epitaxy (MBE)-grown HgCdTe grown on near lattice-matched bulk CdZnTe substrates.

TIS presents an overview of the HgCdTe detector technology by MBE. MBE is the ideal epitaxial growth method to achieve high performance HgCdTe epi-layers. MBE HgCdTe is grown on (211)B-oriented bulk CdZnTe substrates. The primary surface defects that are observed during MBE growth of HgCdTe are addressed. The limitations of CdZnTe substrate are examined. The quality of MBE-grown HgCdTe ultimately depends on the quality of the starting CdZnTe substrate. The properties of CdZnTe substrate such as Te precipitate size and density, Etch Pit Density (EPD), p-type impurity such as copper, and the Zn concentration and its uniformity across the substrate play significant roles in determining the characteristics of HgCdTe. The purity along with the quality of the starting substrate is also critical for "ultra-low" doping control during MBE growth of HgCdTe. The composition and "bandgap engineering" controls of MBE-grown HgCdTe are discussed. TIS backside-illuminated p-on-n device architecture is described, including discussion of the TIS activation and vacancy filling anneal of implanted HgCdTe devices. Similarly, TIS' CdZnTe substrate removal process to extend the wavelength range of the spectral response from the infrared to the ultraviolet (UV) is shown. TIS infrared detector performance is reviewed, including discussion of the widely recognized "Rule 07" dark current Figure of Merit (FOM) and update to "Rule 07" ("Rule 22"). Examples of TIS infrared detector imagery are presented.

11:30am **WEG-SaM-8 Status of Production MBE Capabilities for Infrared Applications at IntelliEPI***, **Paul Pinsukanjana**, J. Li, E. Fraser, J. Shao, S. Hill, M. Debnath, J. Middlebrooks, C. Chen, W. Li, K. Vargason, P. Chin, Y. Kao,* Intelligent Epitaxy Technology, Inc. **INVITED**

To support the growing needs for high-performance infrared (IR) epitaxy materials, IntelliEPI has established production MBE capabilities to produce advanced III-V epi wafers based on GaAs, InP and GaSb material systems. Some of the optoelectronic applications include Focal Plane Array (FPA) for IR imaging; APD for telecom/datacom & automotive LIDAR; Laser & LED for gas sensing; and components for SOA, EAM and detector for high-speed optical fiber network. Strategy/philosophy of how IntelliEPI approaches setting up production MBE for commercial manufacturing will be discussed.

Workshop on Epitaxial Growth of Infrared Materials
Room Cummings Ballroom - Session WEG-SaA

Workshop on Epitaxial Growth of Infrared Materials: IR Devices and Applications

Moderator: Minh Nguyen, HRL Laboratories

1:30pm **WEG-SaA-1 The Quantum Cascade Laser Pumped Molecular Laser: A Widely Tunable THz Source**, ***Federico Capasso***, Harvard University **INVITED**

Generation of radiation in the terahertz frequency range (100 GHz to 10 THz) is a challenging problem. The lack of powerful and tunable sources in that frequency region can also limit the accuracy and resolution of spectroscopy techniques. In addition, the relevant part of molecules' rotational spectrum lies within that frequency region. While the ground state rotational spectrum of molecules is easily measured thanks to the large thermal population of lower rotational levels at room temperature, measuring the rotational spectrum of a molecule in the excited state can be much harder. Here we introduce the quantum cascade laser pumped molecular laser (QPML): a widely tunable source that can emit light between 100 GHz up to 10 THz and uses a widely tunable quantum cascade laser to pump ro-vibrational transitions. We first demonstrated the QPML concept using the nitrous oxide molecule [1], where more than 30 lines were measured between 300 GHz and 772 GHz. We subsequently utilized the methyl fluoride and the ammonia molecule to demonstrate the universality of the concept [2], [3].

Compared to many existing THz sources, the QPML operates at room temperature is widely tunable and can be made compact. The first demonstration of the QPML was performed using the nitrous oxide (N_2O) molecule [1]. This molecule has a simple rotational spectrum due to its linear geometry, and a typical energy diagram for the considered vibrational transitions of N2O is shown in Fig. 1(a) of supplemental document. By placing the molecule into a tubular copper cavity and pumping vibrational transitions with a mid-infrared (MIR) QCL, laser emission at THz frequency was obtained (see Fig. 1(b)).

References

[1] P. Chevalier, A. Amirzhan, F. Wang M. Piccardo, A. Amirzhan, S. G. Johnson, F. Capasso and H. O. Everitt, "Widely tunable compact terahertz gas lasers.", Science 366, 856-860 (2019).

[2] A. Amirzhan, P. Chevalier, J. Rowlette, H. T. Stinson, M. Pushkarsky, T. Day, H. O. Everitt and F. Capasso,"A quantum cascade laser-pumped molecular laser tunable over 1 THz.", APL Photonics 7, 016107 (2022).

[3] P. Chevalier, A. Amirzhan, J. Rowlette, H. T. Stinson, M. Pushkarsky, T. Day, F. Capasso and H. O. Everitt, "Multi-line lasing in the broadly tunable ammonia quantum cascade laser pumped molecular laser", Appl. Phys. Lett. 120, 081108 (2022).

2:00pm **WEG-SaA-3 MBE Growth of Midwave and Longwave Infrared Materials**, ***Chadwick Canedy***, *S. Tomasulo, C. Kim,* Naval Research Laboratory, USA; *M. Kim,* Jacobs Technologies Inc; *J. Massengale, A. Grede,* NRC Postdoctorate Residing at NRL; *W. Bewley, I. Vurgaftman, J. Meyer,* Naval Research Laboratory, USA **INVITED**

For over 3 decades, our group's research has focused almost exclusively on understanding and developing novel emitters and detectors operating in the midwave and longwave infrared (MWIR and LWIR) portions of the electromagnetic spectrum (3µm – 14 µm). Despite early theoretical achievements in this area, progress was limited until we obtained the capability for in-house molecular beam epitaxial (MBE) growth of III-V compounds, and in particular Sb-based materials. We will discuss important considerations and developments in the growth methodology of these materials as they relate to our IR device development. Much was developed from the ground-up synergistically with on-going theoretical and processing advances.

Most of the IR laser and detector structures grown epitaxially by MBE in our on-site reactors employ type-II InAs/Ga(In)Sb/AlSb or InAsSb/InAs/AlSb quantum well and superlattice layers. One prime example is the interband cascade laser (ICL), for which iterative optimization of the design, growth, and device processing ultimately culminated in our demonstration of the first ICL operating at room-temperature in continuous wave (CW) mode. This led within a few years to the commercialization of MWIR ICL products marketed by three distinct companies (Nanoplus, Alpes and Thorlabs). More recently, we have investigated expanded designs, architectures and functionalities including interband cascade light emitting devices (ICLEDs), ICLEDs grown on lattice mismatched substrates (Si), ICLs integrated on Si by heterogeneous bonding and optical frequency combs. JPL and NRL recently demonstrated the first ICL optical frequency combs, which display stable operation, low electrical power consumption (< 1 W) at RT, and sub-MHz free-running optical linewidth. New designs that suppress substrate modes and provide substantial reduction of the group velocity dispersion have been proposed and are now being implemented. The ICLEDs grown at NRL display higher radiance and efficiency than any previous MWIR LEDs. Procedures were developed for growing ICLEDs on offcut silicon substrates (12% lattice mismatch). Processed devices were found to operate with high yield and uniform performance on a given wafer. We have also dedicated significant resources to developing optimized procedures for growing type-II InAs/GaInSb and InAsSb/InAs MWIR and LWIR detectors. This work has more recently culminated in demonstrations of resonant cavity infrared detectors (RCIDs). Recent MWIR RCIDs displayed 59% external quantum efficiency, < 30 nm linewidth, and 3× higher specific detectivity (D*) than state-of-the-art broadband HgCdTe if operated in a dewar with f/4 optic at 125 K.

2:30pm **WEG-SaA-5 MBE Digital Alloying for IR Avalanche Photodiodes**, ***Seth Bank***, University of Texas at Austin **INVITED**

Digital alloying has a rich history in the MBE community as a technique for improving key properties including lattice-matching, optical absorption/emission efficiency, phonon transport, compositional grading, and phase stability to name but a few. More recently, it has been found to improve high-field transport leading to the emergence of AlInAsSb on GaSb as the first low-noise III-V alloy family for conventional avalanche photodiodes (APD).The seamless band engineering afforded by digital alloying has also enabled ultra-low-noise staircase APDs, which are the solid-state analog of photomultiplier tubes.

Here, we will discuss our work on the digital alloy growth of AlInAsSb alloys and its impact on key APD performance criteria (noise, gain, dark current, breakdown, etc.), enabling single photon detection up to room temperature and out to record long wavelengths for III-Vs with conventional APDs, as well as near-ideal noise and gain scaling with staircase APDs.In the spirit of a workshop, we will also discuss our ongoing work (1) covering broader swaths of the IR with low-noise APDs by taking advantage of the large digital alloy design space, (2) translating AlInAsSb to InP and silicon substrates, and (3) combining with MBE selective-area regrowth for dense focal plane arrays. This work is in close collaboration with Prof. Joe Campbell's group at UVA and we acknowledge support from ARO, DARPA, NASA, AFRL, Northrop Grumman, and Lockheed Martin.

3:00pm **WEG-SaA-7 Epitaxial Quantum Dots for Infrared Emitters**, ***Sadhvikas Addamane***, *P. Iyer,* Sandia National Laboratories, USA; *S. Seth,* University of New Mexico; *O. Mitrofanov,* University College London, UK; *D. Shima,* University of New Mexico; *I. Brener,* Sandia National Laboratories; *G. Balakrishnan,* University of New Mexico **INVITED**

Semiconductor quantum dots (QDs), also referred to as artificial atoms, offer unique properties such as discrete and size-controlled energy levels. They have recently emerged as a pivotal platform for various optoelectronic applications including emitters and detectors. Specifically, epitaxial III-V QDs serve as the active component of choice in solid-state infrared emitters such as lasers and single/entangled photon sources. QD-based emitters in the near IR regime have demonstrated exceptional performance with state-of-the-art device parameters. A critical step towards realizing these QD-based IR emitters is high-quality epitaxial growth, with separate optimization strategies required for different device classes. This presentation will focus on our recent work in developing epitaxial strategies for realizing QD-based IR emitters, specifically lasers and single/entangled photon sources (SPS).

Different methods for realizing III-V epitaxial QDs - Stranski-Krastanov, droplet epitaxy, in-situ etching and patterned growth - will be reviewed. The QDs are grown using molecular beam epitaxy (MBE) on various III-V substrates including GaAs, GaSb and InP. Structural optimization studies to tune areal density, shape, size and position will be presented and are based on atomic force microscopy and transmission electron microscopy results. It is to be noted that the objectives for structural optimization are slightly different between laser- and SPS-based applications. Preliminary work on deterministic placement of QDs will be discussed. From the optical perspective, all emitter applications demand wavelength control and higher photon counts (on different scales) and these findings will be presented based on photoluminescence (PL) measurements. Optimized QD recipes are used to grow both laser and SPS structures and device fabrication is carried out. Device-specific characterization results will be shared: for lasers

- LIV (light-current-voltage) characteristics, light traces and spectrum measurements; for SPS - low-temperature imaging/spectrum and g2 measurements.

Workshop on Epitaxial Growth of Infrared Materials
Room Cummings Lobby - Session WEG-SaP

Workshop on Epitaxial Growth of Infrared Materials Poster Session

WEG-SaP-1 Thermoradiative Diodes: A Novel Application of Mid-Infrared Materials*, **Stephen Bremner**, M. Zlatinov, M. Nielsen, M. Sazzad, P. Reece, N. Ekin-Daukes,* UNSW Sydney, Australia

Photovoltaic (PV) power generation is a familiar and important process that exploits a large temperature difference between a source (the sun) and a converter (a solar cell) in order to produce electrical power [1]. There is, however, a not so well-known symmetric counterpart to the photovoltaic process, in which a warm converter radiates light to a cold environment, enabling the generation of electrical power [2,3]. Thermodynamic analysis in the radiative limit (only radiative recombination present) reveals that power densities of 54.8 W/m^2 and more [4], offering applications in waste heat recovery [5] and terrestrial night sky power generation [6]. Whilst the concept of thermoradiative power generation has been proven [7] in HgCdTe photodiodes, the generated power is orders lower than theoretical limits. This is due to non-radiative recombination processes like Auger and SRH recombination/generation. So high radiative efficiencies is a critical requirement to unlock the potential of thermoradiative power generation. The first goal aligns well with research in mid-infrared photodetectors and light emitting diodes, where such non-radiative processes are also detrimental to performance, leading to materials development and numerous design approaches to mitigate their impact [8].

Related to the ability to generate thermoradiative power is the presence of so-called negative luminescence [9], a process in which the application of a reverse bias sees net radiative emission drop below that for thermal equilibrium. Negative luminescence is an indicator of being able to generate thermoradiative power, so the search for TRD materials can build on previous work on negative luminescence in III-V materials systems such as InAs/GaSb [10]. The final presentation will discuss thermoradiative power generation and the requirements of materials for thermoradiatvie diodes (TRDs), building on previous work on mid-infrared materials. This search will be focused on III-V materials, but the requirements would drive a search in any materials system.

[1] De Vos et al., J. Appl. Phys., 74(6), 3631-3637, 1993.

[2] S. J. Byrnes et al., Proc. Natl. Acad. Sci. USA,

vol. 111, 3927, 2014.

[3] R. Strandberg, J. Appl. Phys., 118, 215102, 2015.

[4] S. Buddhiraju et al., Proc. Natl. Acad. Sci. USA, vol. 115, E3609, 2018.

[5] J. Wang et al., AIAA Propuls. Energy Forum Expo., 3977, 2019.

[6] E. J. Tervo et al., Cell Reports Phys. Sci., 1, 100258, 2020.

[7] A. Rogalski, Sensors, 20,7047, 2020. [8] M. P. Nielsen et al., ACS Photonics, 9(5), 1535-1540, 2022.

[9] T. Ashley et al., Infrared Phys. Technol., 38, 145-151,1997.

[10] L. J. Olafsen et al., Appl. Phys. Lett., 74, 2681-2683, 1999.

WEG-SaP-2 Low-temperature Epitaxial Growth of ZnTe and CdTe for Passivation of MWIR and LWIR Detectors*, **Oleg Maksimov**, H. Bhandari,* Radiation Monitoring Devices

Surface leakage current is one of the main factors limiting the performance of mid-wave infrared and long-wave infrared (MWIR and LWIR) $Hg_xCd_{1-x}Te$ and InAs/GaSb focal plane arrays (FPAs). A stable surface passivation layer is needed to overcome this problem. II-VI semiconductors, such as CdTe and ZnTe, are particularly promising due to the wide bandgap and close lattice match to the underlying structure. These are usually epitaxially grown by Molecular Beam Epitaxy (MBE) at 250 °C or higher e [1, 2, 3]. Unfortunately, high growth temperature can cause Hg diffusion in $Hg_xCd_{1-x}Te$ and Zn diffusion into InAs/GaSb degrading device performance.

Here, we report on the use of Atomic Layer Deposition (ALD) to grow ZnTe and CdTe at temperatures as low as 85 ˚C. Epitaxial growth is achieved at closely lattice-matched substrates, such as GaSb and InAs. In addition, unlike MBE, ALD allows to grow CdTe and ZnTe conformally, as was established at Si wafers with the trenches with aspect ratio as high as 10:1. This should significantly improve passivation and encapsulation of pixelated surfaces of FPAs.

[1] Zhang, J., Westerhout, R. J., Tsen, G. K. O., Antoszewski, J., Yang, Y., Dell, J. M., & Faraone, L. (2008, July). Sidewall effects of MBE grown CdTe for MWIR HgCdTe photoconductors. In *2008 COMMAD* (pp. 82-85). IEEE.

[2] Plis, E., Kutty, M. N., Myers, S., Krishna, S., Chen, C., & Phillips, J. D. (2014, June). Passivation of long-wave infrared InAs/GaSb superlattice detectors with epitaxially grown ZnTe. In *Infrared Technol. Appl. XL* (Vol. 9070, pp. 289-296). SPIE.

[3] Haakenaasen, R., Selvig, E., Heier, A. C., Lorentzen, T., & Trosdahl-Iversen, L. (2019). Improved passivation effect due to controlled smoothing of the CdTe-HgCdTe interface gradient by thermal annealing. *J. Electron. Mater.*, *48*(10), 6099-6107.

WEG-SaP-3 CdTe/InSb(211) Virtual Substrates for IR Detector Application*, **Tyler McCarthy**, Z. Ju, A. McMinn,* Arizona State University*; R. Kodama, F. Aqariden, P. Liao, P. Mitra,* Leonardo DRS*; Y. zhang,* Arizona State University

CdTe as a virtual substrate for HgCdTe IR detectors are grown by MBE on InSb(211) substrates. The advantages of such a virtual substrate to those grown on Si(211) or bulk CdZnTe substrates are: i) large, low-cost (compared to CdZnTe) substrate up to 6” available for detector arrays; ii) improved crystal quality and low In out-diffusion in CdTe layers grown on lattice-matched InSb substrates; iii) expected improved crystal quality in HgCdTe (compared to HgCdTe/CdTe/Si) and thus low dark current in IR detectors. The MBE growth of CdTe traditionally is done under Te-rich condition by employing a compound CdTe effusion cell and a supplementary Te cell. This work uses separate Te and Cd cells to achieve high-quality CdTe films grown under Cd-rich conditions, and compares different conditions for growth of CdTe on (100) and (211)B InSb substrates. Further Cd-rich CdTe(211) results will be discussed at the workshop.

Our experimental study has revealed the following: i) a Te soak of the InSb surface results in poor CdTe epilayer crystalline quality, indicated by an XRD linewidth above 100 arcsec; ii) SIMS analysis showed there was a high amount of out-diffused In present throughout the CdTe epilayer grown on InSb under Te-rich conditions; iii) in contrast, the In out-diffusion is quickly suppressed to below SIMS detection limit within the first 100 nm CdTe grown on InSb substrate by utilizing a Cd soak of the InSb surface prior to the initiation of Cd-rich growth. Up to 3 µm thick CdTe layers were successfully grown on InSb(211)B with: twin-free, streaky RHEED pattern; low haze; surface defect densities below 0.3 and 5 cm^{-2} for macro defects larger than 100 and 50 µm, respectively; and an XRD rocking curve linewidth below 30 arcsec.

Workshop on Epitaxial Growth of Infrared Materials
Room Cummings Ballroom - Session WEG-SuM2

Workshop on Epitaxial Growth of Infrared Materials: IR Superlattices II

Moderator: Philip Klipstein, Semiconductor Devices, Israel

10:30am **WEG-SuM2-8 Antimonide Superlattices and Avalanche Photodiodes: Paving the Way for the 4th Gen of Infrared Detectors?**, ***Sanjay Krishna,*** Ohio State University **INVITED**

Photonic infrared detectors have witnessed three generations of development since their first reports in the 1950s-60s. The detectors have evolved from single element to linear to large format 2D arrays. In this talk we will discuss a vision for the fourth generation of infrared detectors that incorporate on demand functionality like gain, color, polarization at the pixel level. 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). Commercial ADPs use an InGaAs absorber with an InAlAs or lnP multipliers. We are investigating two antimonide based multipliers, AlGaAsSb and AlinAsSb, on inP substrates. We have recently demonstrated separate absorber charge and multiplier (SACM) ADPs using an InGaAs/GaAsSb Type-ll superlattice absorber and an AlGaAsSb multiplier[1]. 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 longer wavelengths.

Jung et al 'Low Excess Noise, High Quantum Efficiency Avalanche Photodiodes for Beyond 2 µm Wavelength Detection' (Nature Photonics in review, 2024).

11:00am **WEG-SuM2-10 Molecular Beam Epitaxy of Antimonides for Mid-to-Long Wavelength Infrared Sensing**, ***Stephanie Tomasulo***, *M. Twigg, A. Grede, W. Bewley, J. Massengale, I. Vurgatman,* U.S. Naval Research Laboratory; *J. Nolde,* U.S. Naval Research Lab **INVITED**

This presentation will cover the growth of antimonides for mid-to-long wavelength infrared sensing applications. High quality III-V materials in this wavelength range are difficult to access due to the prevalence of Auger recombination at these low bandgap energies. Furthermore, the materials with the lowest bandgap energies (and thus longest wavelength response) are lattice-mismatched to the nearest conventional binary substrates GaSb, InAs, and InSb. Techniques such as strain-balanced superlattices and compositionally graded buffers have been used to overcome these challenges. We will go over the basics of these techniques as well as our recent results employing them.

11:30am **WEG-SuM2-12 Panel Discussion**,

12:15pm **WEG-SuM2-15 Closing Remarks & Sponsor Thank Yous**,

Workshop on Epitaxial Growth of Infrared Materials
Room Cummings Ballroom - Session WEG1-SuM

Workshop on Epitaxial Growth of Infrared Materials: IR Superlattices I

Moderator: Stephanie Tomasulo, U.S. Naval Research Laboratory

8:45am **WEG1-SuM-1 Welcome & Sponsor Thank Yous**,

9:00am **WEG1-SuM-2 A Brief Review of InAs/InAsSb Type-II Superlattice: Its Electronic Properties and Applications in IR Photodetectors**, ***Yong-Hang Zhang,*** Arizona State University **INVITED**

The study of InAs/InAsSb T2SL on GaSb and its application to IR lasers and photodetectors was started in the early 90's. The observation of a 412 ns long carrier lifetime in a long-wavelength infrared (LWIR) InAs/InAsSb T2SL in 2011 triggered extensive research on the fundamental materials properties and device applications worldwide. Pressure-dependent photoluminescence experiments revealed some underlying material physics of these long carrier lifetimes. Its applications in devices, such as nBn, C-BIRD, and PIN photodetectors, and their commercialization have also achieved impressive accomplishments. Many of these devices are currently used in real applications and available commercially.

9:30am **WEG1-SuM-4 MBE Based Superlattice Photodetectors**, ***Philip Klipstein,*** Semiconductor Devices, Israel **INVITED**

Type II superlattices (T2SLs) based on layers of InAs and GaSb are ideal for absorbing photons in the high transmission long-wave and mid-wave infrared (LWIR and MWIR) windows of the atmosphere. They provide a useful and easier alternative to the legacy HgCdTe infrared material.

Before 2000, all high end MWIR and LWIR photodetectors were based on a simple photodiode architecture. This began to change in 2003 with the invention by the author of XB*n* and XB*p* barrier detectors, based on *n*-type and *p*-type photon absorbing materials respectively. The nearly lattice matched family of InAs/GaSb/AlSb has a unique arrangement of band offsets which allows the engineering of a tall barrier for majority carriers while minority carriers remain unobstructed. The depletion layer is confined completely within the wide bandgap barrier material, leading to suppression of the Generation-Recombination contribution to the dark current. Hence MWIR focal plane array (FPA) detectors based on InSb and traditionally operating at around 80K started to be superseded by XB*n* FPAs which operate between 120-150K. In the LWIR, XB*p* FPAs exhibit excellent and stable image quality, providing a realistic alternative to HgCdTe. The FPA resolution has also increased, with pitches today down to 5µm and formats up to 5 Megapixel in the MWIR.

A major effort has gone into T2SL band-structure simulation, based on an extended version of the **k·p** model. The quantum efficiency and diffusion limited dark current of a detector can also be simulated, agreeing well with experiment. Significant differences with bulk materials have been found, such as an intrinsic carrier concentration for a given band gap that has a weak dependence on the T2SL period and a high sensitivity of the XB*p* dark current to the acceptor binding energy. Holes and electrons are on opposite sides of the metal/insulator transition, which has a strong influence on detector design.

Finally, an intriguing aspect of type II InAs/GaSb quantum wells is that they can exhibit the quantum spin Hall effect at low temperatures, where the current flows only along the sample edges and is both quantized and spin polarized. Topological properties tend to be associated with infrared materials because both involve atoms of high atomic number. In the first case a high atomic number imparts a large spin-orbit coupling which is necessary for robust topological properties, and in the second, it reduces the semiconductor band gap to a value that matches the infrared photon spectrum.

Author Index

Bold page numbers indicate presenter