Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-MoM1

Frequency Combs

Moderator: David Burghoff, University of Notre Dame

8:20am **MIOMD-MoM1-1 Welcome and Opening Remarks***,*

8:30am **MIOMD-MoM1-2 Mid-Infrared Semiconductor Laser Frequency Combs: From FM-Combs to Nozaki-Bekki Solitons***, N. Opacak,* TU Wien, Austria*; D. Kazakov,* Harvard University*; L. Columbo,* Politecnico di Torino, Italy*; S. Dal Cin, M. Beiser, F. Pilat,* TU Wien, Austria*; T. Letsou,* Harvard University*; M. Brambilla,* Universit`a e Politecnico di Bari, Italy*; F. Prati,* Universit`a dell'Insubria, Italy*; M. Piccardo,* Universidade de Lisboa, Portugal*; F. Capasso,* Harvard University*; **Benedikt Schwarz**,* TU Wien, Austria **INVITED**

Optical frequency combs (OFCs) stand as the cornerstone of modern optics, with applications ranging from fundamental science to sensing and spectroscopy. Generation of short optical soliton pulses in passive media such as optical fibers and microresonators has been an established technique for stable OFC formation with a broad optical spectrum – however these platforms are driven by an external optical signal and often rely on additional bulky elements that increase the complexity of the system.

Here, we aim to overcome these difficulties by direct OFC generation in mid-infrared semiconductor lasers, such as quantum and interband cascade lasers. After a general introduction to such combs and their nonlinear dynamics, the soliton concept from microresonator Kerr combs will be generalized to active media that are electrically-driven and a new type of solitons in free-running semiconductor laser integrated on a chip will be demonstrated.

9:00am **MIOMD-MoM1-5 Temporal Solitons in Coherently-Driven Ring Lasers***, **Theodore Letsou**, D. Kazakov,* Harvard University*; M. Piccardo,* Universidade de Lisboa, Portugal*; L. Columbo,* Politecnico di Torino, Italy*; M. Brambilla,* Politecnico di Bari, Italy*; F. Prati,* Università dell'Insubria, Italy*; S. Dal Cin, M. Beiser, N. Opačak,* TU Wien, Austria*; M. Pushkarsky, D. Caffey, T. Day,* DRS Daylight Solutions*; L. Lugiato,* Università dell'Insubria, Italy*; B. Schwarz,* TU Wien, Austria*; F. Capasso,* Harvard University

Pulsed lasers have been the workhorse of ultrafast optics since their advent and rapid development throughout the 20th century, revolutionizing a wide variety of fields from spectroscopy to tattoo removal. Over the past twenty years, pulsed laser sources have shrunk from tabletop laboratory setups down to micron-sized chips, making them ideal components for integrated photonic devices. Despite this miniaturization, chip-scale pulsed laser sources have eluded the mid infrared (IR) spectral region. Active mode-locking of mid IR semiconductor lasers—such as quantum cascade lasers (QCLs)—has produced pulse widths on the order of 6 picoseconds [1]. Pulse compression techniques can be utilized to shrink these pulses to hundreds of femtoseconds [2], but rely on large optical setups that cannot be scaled down. Here, we present a fundamentally new way to produce bright pulses of mid IR light by optically pumping ring QCLs. This technique unifies the physics of passive, Kerr microresonator combs and ring QCLs [3]. Using a modified racetrack QCL with an integrated directional coupler, we injection-lock the unidirectional laser field circulating in the racetrack to a commercial external cavity QCL. Much like in Kerr microresonator combs, when the injection-locked field is detuned from its natural cavity resonance, the resonance becomes bistable, with its unstable branch supporting bright solitons with pulse widths of ~1 picosecond at a center wavelength of 8 µm. This method of pulse formation is well-suited for lasers with fast gain dynamics, which encompasses the entire family of QCLs, spanning from 3 µm to 300 µm. Furthermore, the optical drive can, in principle, be integrated with the racetrack, providing a route for on-chip, ultrashort pulse formation throughout the entire mid-IR.

[1] J. Hillbrand, *et. al.*, Nat. Commun. **11**, 5788(2020).

[2] P. Täschler, *et. al.*, Nat. Photon. **15**, 919-924(2021).

[3] L. Columbo, M. Piccardo, *et. al.*, Phys. Rev. Lett. **126**, 173903(2021).

9:20am **MIOMD-MoM1-7 Full-Band Modeling of AM and FM Interband Cascade Laser Frequency Combs***, **Michael Povolotskyi**,* Jacobs*; I. Vurgaftman,* Naval Research Laboratory, USA

Compact and efficient mid-infrared (MIR) frequency combs are expected to find widespread use in chemical sensing applications, such as on-chip spectroscopy of toxic substances. While most of the experimental MIR laser comb work has involved quantum cascade lasers (QCLs), interband cascade lasers (ICLs) operate cw at room temperature in the 3-4 mm spectral range, which remains difficult for QCLs, and also promise significant reductions in the operating power throughout the MIR spectral range. Furthermore, owing to the long carrier lifetime in an ICL, both passive mode-locking with short pulses (AM) and quasi-cw (FM) comb generation should be possible.

In spite of these promising characteristics, only FM combs based on ICLs have been demonstrated to date. In order to clarify the physical requirements for both AM and FM operation, we have developed a multiscale numerical model that efficiently solves the Maxwell-Bloch equations for the full subband dispersion in the ICL's active type-II wells over a time period of µs. We compare the results of this model to those derived from the two-level approximation relevant to QCLs, and evaluate the importance of such parameters as the second-order and higher-order group velocity dispersions, saturable absorber length and recovery time, ambipolar diffusion coefficient, and polarization relaxation time (homogeneous gain broadening linewidth). We determine the optimal design parameters for experimentally demonstrating both passively mode-locked and FM ICL combs, and outline how they can be realized in practice.

Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-MoM2

Interband Cascade and Diode Lasers

Moderator: Benedikt Schwarz, TU Wien, Austria

10:30am **MIOMD-MoM2-14 Recent Advances in Interband Cascade Lasers for Mid-Wave Infrared Free-Space Optical Communications***, **Frederic Grillot**,* Telecom Paris, France **INVITED**

Free-space laser communications constitute a promising alternative for transmitting high bandwidth data when fiber optic cable is neither practical nor feasible. This technology has emerged as a strong candidate with a large potential of applications from daily-basis broadband internet to satellite links. Although the availability of high-quality transmitters and detectors operating in the near-infrared window makes the 1.55 microns optical wavelength a natural choice for free-space optical systems, two other wavelength ranges can also be considered. First, the mid-wave infrared (MWIR) window between 3 and 5 microns, and second, the long-wave infrared (LWIR) window between 8 and 12 microns. Both are well known for their superior transmission performance through adverse atmospheric phenomena, such as fog, clouds, and dust. In order to develop free-space laser communications in the MWIR, interband cascade lasers (ICL) are currently emerging as very serious candidates. In this presentation, we will review our recent progress in the physics and applications of interband cascaded devices. We will discuss their intensity noise and modulation properties and reveal the existence of the oscillation relaxation frequency that is of paramount importance to achieve very fast modulation rates. In summary, these novel findings in interband cascade devices provide clear scientific guidelines that will be very useful to researchers and engineers in the design and deployment of future free-space MWIR laser communication systems.

11:00am **MIOMD-MoM2-17 Continuous Wave Room Temperature Operation of the Epitaxially Regrown GaSb-Based Diode PCSELs***, **Leon Shterengas**,* Stony Brook University **INVITED**

Photonic crystal surface emitting laser (PCSEL) device architecture can dramatically improve brightness of semiconductor laser sources. The development of the PCSELs within nitride [1], arsenide [2], phosphide [3], and antimonide [4] material systems is subject of active research to enable high power high brightness surface emitting diode laser operation from UV to mid-infrared. One of the key technological challenges associated with PCSEL development is integration of the high-index-contrast photonic crystal layer into laser heterostructure. The air-pocket-retaining epitaxial regrowth [5] was shown to be effective technique which yielded high-power diode PCSELs. The air-pocket-retaining regrowth within antimonide material system was explored by our research group.

We report on the continuous wave (CW) room temperature operation of epitaxially regrown monolithic GaSb-based ~2 µm diode PCSELs. The devices are based on laser heterostructure containing carrier stopper layer designed to inhibit electron carrier leakage into buried photonic-crystal section. Atomic hydrogen cleaning of the nanopatterned surface followed by optimized epitaxial step resulted in highly uniform air-pocket-retaining regrowth. The laser heterostructure with buried high-index-contrast photonic crystal layer generated about 10 mW of power near 2 µm in CW regime and tens of mW in 5% duty cycle at 20 oC.

[1] K. Emoto, et al, Commun Mater 3, 72 (2022).

[2] K. Hirose, et al, Nat. Phot. 8, 406 (2014).

[3] Y. Itoh, et al, Opt. Exp. 30, 29539 (2022).

[4] L. Shterengas, et al, Phys. Status Solidi RRL 16, 2100425 (2022).

[5] M. Nishimoto, et al, Appl. Phys. Exp. 6, 042002 (2013).

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11:30am **MIOMD-MoM2-20 Single-Mode Tunable Interband Cascade Lasers with a Wide Tuning Range***, J. Gong, Z. Wang, J. He,* Zhejiang University, China*; **Rui Yang**,* University of Oklahoma

Type-II interband cascade lasers (ICLs) [1,2] are efficient and compact mid-infrared light sources with many applications such as gas sensing and environmental monitoring. Here, we report the demonstration of single-mode tunable ICLs with a wide tuning range based on V-coupled cavity [3,4]. By optimizing the coupling coefficient and the cavity structure design, the tuning range of V-coupled cavity single-mode ICLs is significantly extended with a side mode suppression ratio (SMSR) exceeding 37 dB in continuous wave operation near 3.4 µm. At a fixed temperature, a tuning range of up to 97 nm has been demonstrated. By combining two temperatures at 82K and 100K, a total tuning range of about 150 nm has been achieved, as shown in Fig. 1. The total tuning range exceeded 150 nm when operation temperature extended to 110K. More details and updated results will be presented at the conference.

11:50am **MIOMD-MoM2-22 Expanding the Frontiers of Long Wavelength Interband Cascade Lasers using Innovative Quantum Well Active Regions***, **Yixuan Shen**, J. Massengale, R. Yang,* University of Oklahoma*; S. Hawkins, A. Muhowski,* Sandia National Laboratories, USA

Interband cascade lasers (ICLs) [1-2] based on type-II quantum wells (QWs) are an efficient mid-infrared light source for many practical applications due in large part to their low power consumption. High performance operation of ICLs has been demonstrated at room temperature across a wavelength range from 2.7 µm to about 6 µm [2-4]. However, extending the operation of ICLs to longer wavelengths with similar performance as their short wavelength counterparts is challenging due to factors such as the reduced wavefunction overlap in the type-II QW and the increased free-carrier absorption loss. In this work, we report significant progress in long wavelength ICLs from newly designed and grown ICL wafers by employing an innovative QW active region containing strained InAsP layers [5]. These ICLs were able to operate at wavelengths near 14.3 µm, the longest ever demonstrated for III-V interband lasers, suggesting great potential of ICLs to cover an even wider wavelength range. Devices from another wafer were able to lase at a low threshold current density (*e.g.*, 15 A/cm^2 at 80 K) and at temperatures up to 210 K near 12.3 µm. Detailed results will be presented at the conference.

Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-MoA1

THz Sources and Detectors

Moderator: Daniel Wasserman, University of Texas at Austin

1:30pm **MIOMD-MoA1-1 Stabilization of Terahertz Quantum-Cascade VECSELs***, C. Curwen, J. Kawamura, D. Hayton,* Jet Propulsion Laboratory, California Institute of Technology*; S. Addamane, J. Reno,* Center for Integrated Nanotechnologies at Sandia National Laboratories*; B. Karasik,* Jet Propulsion Laboratory, California Institute of Technology*;* ***Benjamin S. Williams,*** University of California Los Angeles

Terahertz metasurface quantum-cascade (QC) vertical external cavity surface emitting lasers (VECSELs) are excellent candidates for frequency agile local oscillators and spectroscopic sources, that emit milliwatts to tens-of-milliwatts continuous-wave power with excellent beam power. We present the first high resolution studies of the free-running laser behavior of QC-VECSELs at 2.5 THz and 3.4 THz, and demonstrate phase-locking to a microwave reference, by using subharmonic Schottky-diode mixer instrumentation to downconvert the THz signal to a GHz intermediate frequency (IF). Feedback from reflections at the mixer are observed to have a strong influence on the free-running QC-VECSEL frequency stability as a result of efficient coupling to free-space compared to more typical ridge waveguide lasers. Instabilities in feedback result in free-running linewidths of tens of MHz. The QC-VECSEL IF signal is phase locked to a 100 MHz reference using the bias on the device as a means of error correction. Between 90-95% of the QC-VECSEL signal is locked within 2 Hz of the multiplied RF reference, and amplitude fluctuations on the order of 1-10% are observed, depending on the bias point of the QC-VECSEL. The bandwidth of the locking loop is ~1 MHz. Many noise peaks in the IF signal corresponding to mechanical resonances in the 10 Hz-10 kHz range are observed. These peaks are generally -30 to -60 dB below the main tone, and are below the phase noise level of the multiplied RF reference which ultimately limits the phase noise of the locked QC-VECSEL.

2:10pm **MIOMD-MoA1-5 RF Injection Locking of THz Metasurface Quantum-Cascade-VECSEL: Effect of Cavity Length Variation***,* ***Yu Wu,*** University of California, Los Angeles*; C. Curwen,* Jet Propulsion Laboratory*; J. Reno,* Sandia National Laboratories*; B. Williams,* University of California, Los Angeles

Quantum-cascade (QC) lasers are ideally suited for high-resolution, high speed spectroscopy techniques in terahertz (THz) spectral region. Their inherently high optical nonlinearity promotes the generation of spontaneous frequency combs via four-wave mixing in Fabry-Pérot or ring QC-lasers, based on which THz dual-comb spectroscopy has been demonstrated. Besides that, THz QC-laser has recently been implemented in the vertical-external-cavity surface-emitting laser (VECSEL) architecture, which is considered as a great candidate for THz frequency comb or mode-locking operations.

Here, we demonstrate RF injection locking in THz metasurface QC-VECSEL for the first time. An intra-cryostat focusing VECSEL cavity design is applied to reduce the intra-cavity diffraction loss and enable continuous wave lasing at 3.4 THz in an external cavity length over 30 mm (Fig. 1(a)). RF current modulation is applied to the QC-metasurface at a frequency close to the cavity round-trip frequency. Under weak RF power, pulling and locking of the round-trip frequency to the injected RF signal has been observed with locking bandwidth characterized using Adler's equation; Under strong RF power, broadening of the lasing spectrum with a maximum observable bandwidth around 110 GHz has been demonstrated under an injected RF power of 20 dBm (Fig. 1(b)). Injection locking phenomenon using metasurfaces with different gain/dispersion and tunable external cavity lengths has also been explored, taking the advantage of design flexibility of the VECSEL configuration. This experimental setup is suitable for further exploration of active mode-locking in THz QC-VECSELs.

2:30pm **MIOMD-MoA1-7 THz Quantum Photodetector Based on LO-Phonon Scattering-Assisted Extraction***,* ***Joel Pérez Urquizo,*** Laboratoire de Physique de l'École Normale Supérieure, France

The use of the LO-phonon scattering mechanism has proven effective to enhance electron transfer between quantum wells in diverse intersubband devices, such as Mid IR QCDs [1] and THz QCLs [2,3]. In this work we present a THz quantum detector based on GaAs/$Al_{0.25}Ga_{0.75}As$ heterostructure which is designed to exploit LO phonon scattering as an extraction mechanism for photoexcited electrons. The absorbing quantum well has an intersubband transition of 15.5 meV. When an electric field is applied a miniband is formed in the subsequent quantum wells, the edge of which is aligned resonantly with the first subband of the next period's absorbing quantum well, exhibiting a transition at roughly the LO phonon energy in GaAs E_{LO}= 37 meV. Spectral-resolved measurements were performed on samples processed into arrays of patch microcavities [4]. Measurements show detection in the THz with a peak responsivity of 80 mA/W at 3.5 THz at 20 K. This type of quantum detectors allows exploiting the degrees of freedom of quantum confinement for a constant Al content.

[1] F. R. Giorgetta, et al. IEEE Journal of Quantum Electronics, vol. 45, no. 8, pp. 1039-1052. 2009.

[2] B.S. Williams, et al. Appl. Phys. Lett. 82, 1015-1017 (2003).

[3] G. Scalari, et al. Appl. Phys. Lett. 86, 181101 (2005).

[4] Y. Todorov et al. Opt. Express 18, 13886-13907 (2010).

2:50pm **MIOMD-MoA1-9 Multi-Octave THz Wave Generation in PNPA crystal at MHz Repetition Rates***,* ***Lukasz Sterczewski,*** *J. Mnich, J. Sotor,* Wroclaw University of Science and Technology, Poland

Terahertz (THz) wave generation using organic nonlinear optical (NLO) crystals has received considerable attention in the past decades as a viable method to convert broadband near-infrared radiation to the far-infrared region. Nowadays, the rapid development of fiber laser oscillators at telecom wavelengths creates a demand for novel NLO crystals optimized for longer-wavelength excitation and lower pulse energy compared to conventional solutions optimized for millijoule-level pulses with kHz repetition rates at near-visible wavelengths. This requirement is partially addressed by well-established NLO materials like DAST, DSTMS, or OH-1. However, further improvements in terms of conversion efficiency are still desired. Very recently, PNPA ((E)-4-((4-nitrobenzylidene)amino)-*N*-phenylaniline) has been identified as a potential candidate to address this need. Spectra in the 0.2–5 THz range have been obtained using mJ-level 100 fs long pump pulses with kHz repetition rates, yet lower-energy MHz-rate excitation has not been tested to date. In this work, we demonstrate multi-octave THz generation from PNPA pumped by a simple all-fiber femtosecond laser providing 17 fs pulses at a 1550 nm wavelength with 50 MHz repetition rate (4 nJ pulse energy). Increasing the repetition rate 5×10^4 times accompanied by a 5-fold decrease in the pulse duration grants us access to the longwave infrared and THz region from 10 µm of wavelength (30 THz) to 300 µm (1 THz). Using the THz-induced lensing technique we optically sample the emitted field as shown in Fig. 1a. Without purging the measurement chamber, persistent oscillations of water molecules persist over tens of picoseconds, which appear as sharp absorption dips in the spectrum (Fig. 1b). We will discuss the time-frequency characteristics of the waveform and compare them with other well-established THz emitters like DSTMS.

Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-MoA2

Quantum and Interband Cascade Lasers

Moderator: Benjamin S. Williams, University of California Los Angeles

3:40pm **MIOMD-MoA2-14 Low Threshold Long Wavelength Interband Cascade Lasers***,* ***Jeremy Massengale,*** *Y. Shen, R. Yang,* University of Oklahoma*; S. Hawkins, A. Muhowski,* Sandia National Laboratories, USA

Interband cascade lasers (ICLs) [1-2] employ type-II quantum wells (QWs) as the active region and can cover a wide range of mid-IR spectrum with high performance especially in wavelength range from 3 µm to about 6 µm [2-4]. In this work, we report significantimprovements in long wavelength ICLs in terms of reduced threshold current density J_{th} and voltage V_{th} compared to previous ICLs [5]. For example, in cw operation, the J_{th} at 80 K is below 9 A/cm^2 with output power exceeding 100 mW/facet and with a lasing wavelength near 10.7 µm close to 140 K. Such a low J_{th} indicates a weak SRH recombination, suggesting a good material quality. The threshold voltage V_{th} at 80K is 3.61 V with a voltage efficiency of 73%, which is quite high considering that the photon energy (126meV) is low at such a long wavelength (9.83 µm at 80 K). ICLs from another wafer EB7910 lased at a longer wavelength in cw mode near 11.4 µm at 80 K with a J_{th} of 24.9 A/cm^2 and V_{th} of 3.95 V, corresponding a voltage efficiency of about 55%. These ICLs were able to operate at wavelengths exceeding 12 µm in pulsed mode at 135 K, the longest ever reported for ICLs with standard W-shape QW active regions. Detailed results will be presented at the conference.

4:00pm **MIOMD-MoA2-16 Progress in Terahertz Quantum Cascade Lasers Supporting Clean N-Level Systems*, Asaf Albo,*** Bar-Ilan University, Israel

Although Terahertz Quantum Cascade Lasers (THz-QCLs) have a lot of potential, since they were first demonstrated in 2002, their use has been restricted due to lack of portability due to the requirements of cooling machinery. Therefore, raising the T_{max} is the main goal in the field. In 2021, a new T_{max} of ~250 K was achieved and demonstrated [1], enabling the launch of the first high-power portable THz-QCL. Although portable, this device, still required thermoelectric cooling, and the T_{max} was reached in pulsed operation. Moreover, up to date, other groups did not report similar T_{max} values, indicating how big of a challenge this represents.

The design that reached the T_{max} of ~250 K [1] is a two-well (TW) design supporting a clean three-level system (meaning the electron transport occurs only within the laser´s active subbands and all thermally activated leakage paths for electrons were suppressed). This design is like the design demonstrated beforehand with small variations (Design HB2 in Ref. [2]), and it is not the only design with a clean n-level system. Other designs that showed to have successfully suppressed thermally activated leakage channels are a resonant-phonon design presented in 2016 [3], and a split-well direct-phonon (SWDP) proposed in 2019 [4]. However, it is not clear why designs with very similar characteristics show very different T_{max} values, hence, the investigation is still ongoing.

Within our study, we suggest two other novel designs with clean n-level system. The first one is a highly diagonal split-well resonant-phonon (SWRP) scheme [5] and the second is a two-well injector direct-phonon (TWI-DP) scheme. Just as the structures mentioned earlier, both these new designs support clean 4-level systems.

The focus of the research we are presenting is on investigating these designs and comparing their device performance with other designs supporting clean n-level systems. Considering that THz-QCL designs supporting clean n-level systems are not limited by thermal leakage, a detailed comparison of their temperature performance should be the key for improvements beyond the state-of-the-art.

4:20pm **MIOMD-MoA2-18 Improving Transverse Mode Quality of QCLs with Novel Waveguides*, Matthew Suttinger,*** *R. Go, A. Lu,* Air Force Research Laboratory

Quantum Cascade Lasers (QCLs) are reaching a level of commercial maturity. With multiple watts of CW power available from a single QCL source with near transform limited (“fundamental mode-like”) beam quality. This beam quality is achievable due to the standard configuration of the QCL waveguide, with an laser core having transverse dimensions of 1-2 µm X 8-12 µm relative to the 4-5 µm wavelengths produced by higher power Midwave infrared (MWIR) devices. However, remaining with this form factor will limit the amount of available power produced by the laser, as the longitudinal extent of the waveguide cannot be indefinitely extended without issue. Multiple geometries have been explored to expand the total achievable power of single emitter beyond that of the narrow Fabry-Perot cavity, most immediately available being the broad area QCL. In this presentation, results of novel QCL waveguides fabricated at Air Force Research Laboratory are discussed.

In the “ultrawide” Fabry-Perot waveguide, extremely wide laser cores exceeding the standard configuration width by an order of magnitude allow for the scaling of average power, but with severely reduced and divergent beam quality. Through a modification of waveguide to bring the waveguide mode closer to the electrical contact, and splitting said contact into a Dual Contact Strip, the mode quality can be rectified to fundamental-like behavior.

Another approach to improving mode quality relative to the Fabry-Perot geometry is through an angled cavity waveguide. On its own, an angled cavity with a severe enough tilt may induce improved transverse mode quality, but at the expense of overall power potential through losses induced by sidewall interaction. A similar effect may be achieved by using a less pronounced angle and interrupting the waveguide with “notches” etched out of areas far from the internal beam path of the fundamental mode. This allows losses to preferentially disrupt higher order modes. Power can then be scaled by overlapping multiple angled cavities to produce a coherent array with an output beam envelope reflected by that of the output of its components in isolation.

4:40pm **MIOMD-MoA2-20 Broadly Tunable Single Spatial Mode Quantum Cascade Lasers in an External Cavity*, B. Knipfer,*** *D. Ruiz, S. Ruder, K. Oresick, M. Klaus, M. Dwyer, C. Galstad, T. Earles,* DRS Daylight Solutions

Broadly tunable laser sources spanning mid- to long-wave IR are highly sought after for their ability to characterize materials with non-destructive spectroscopy techniques. The wavelengths of interest typically span 3-13 µm, or approximately 2500 cm^{-1}. Given such a large spectrum window finding materials adequately suited can be a challenge, however, given the scalability of MOCVD growth, and the wavelength agility of quantum cascade lasers, MOCVD-grown QCLs fill this niche perfectly.

Previous work has shown heterogeneous quantum cascade lasers emitting in the LWIR that span, up to 760 cm^{-1}, however, at relatively low pulsed powers and in a double-channel ridge configuration [1]. We have previously reported on tuning capabilities within an external cavity in the 4.0-4.8 µm regime [2] and here we push wavelengths across the MW- to LWIR while optimizing CW and pulsed powers with superb beam pointing stability.

This work shows advances in the tuning capabilities of single-core and heterogeneous quantum cascade structures within an external cavity. Previous state-of-the-art products would use four QCL chips to cover 1000 cm^{-1}, but here we are able to further expand the tuning range of individual chips such that the same range can be covered by only three QCLs, shown in Figure 1. Typically, the expansion of tuning range is achieved by broadening the spectral gain through either broadening of a single core, the introduction of additional cores supporting different wavelengths, or both. These different methods typically correspond to a decrease in output power; however, we show this expansion is achieved while maintaining high single mode powers. Through optimization of the active region, a relatively flat modal gain can be achieved across the desired emission range.

These devices exemplify the ability of QCLs to span significant wavenumbers, at high pulsed and CW power levels while maintaining strong single spatial mode operation which has been verified through pointing stability measurements. Beam measurements show deviations of less than 100 µrad over the range of tuning under CW and pulsed operation.

Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-TuM1
Plenary Lecture & Integrated Photonics

Moderator: Fisher Yu, University of Arkansas

8:30am **MIOMD-TuM1-2 Plenary Lecture: Hybrid Passive Photonics in the Longwave-Infrared***, **David Burghoff**,* University of Texas at Austin **INVITED**

The development of passive low-loss material platforms is vital for advancing quantum and nonlinear photonics. Recently, mature nanophotonic platforms like Si3N4 and Si-on-insulator have emerged in the near- and midwave-infrared. These platforms have enabled the creation of a wide range of devices that exploit nonlinear effects, including frequency comb generation, supercontinuum generation, quantum frequency conversion, and generation of entangled biphotons. However, none of these platforms are suitable for the longwave-infrared (6 to 14 µm), as most optical materials become too lossy.

Recent advances in low-loss longwave-infrared photonic platforms, such as diamond, chalcogenide glasses, and germanium, have now made it possible to explore novel applications of nonlinear photonics. In this talk, we will discuss our recent work on the development of low-loss platforms based on hybrid photonic integration and will outline a roadmap for novel nonlinear photonic devices using similar schemes. Hybrid approaches could enable novel sensing modalities using supercontinuum and frequency comb technology, with significant implications for chemical and biological sensing, healthcare, and environmental monitoring.

In particular, we will highlight our work demonstrating ultra-high-quality factor microresonators based on Ge-on-glass. By coupling the output of a quantum cascade laser (QCL) into a partially suspended Ge-on-glass waveguide and coupling it into a waveguide, we demonstrate resonators with an intrinsic quality factor of 2.5×105, approximately two orders of magnitude better than the prior state-of-the-art. In addition, we will discuss our more recent results demonstrating that the same approach can be used to create fully-integrated Ge-on-ZnSe waveguides with losses nearly as low. Our results demonstrate the importance and potential of using high-quality native materials for passive photonics in the longwave infrared range and will allow for a number of new device topologies.

9:10am **MIOMD-TuM1-6 Modeling of GaSb-Based Monolithically Integrated Passive Photonic Devices at λ > 2 µm***, **Md Saiful Islam Sumon**,* The Ohio State University*; S. Sankar, S. Nikor,* Ohio State University*; I. Faruque,* university of Bristol, UK*; S. Dwivedi,* Rockley Photonics*; S. Arafin,* Ohio State University

Photonic integrated circuits for the extended short and mid-wave infrared (eS-MWIR) wavelength regime are crucial for potential applications including on-chip chemical and biological sensing and non-invasive medical diagnosis. The lack of high-performance lasers on an SOI wafer and material limitations in InP necessitate an alternative material system. A monolithic platform based on GaSb addresses these concerns through the tight integration of both passive and active components since it is an optimal material system for realizing long-wavelength lasers and photodetectors. In this work, we modeled and optimized various fabrication-compatible passive components including 1×2 power splitters/combiners based on directional coupler (DC), multimode interferometer (MMI), and Y-branch as well as a grating coupler on GaSb substrates at 2.56 µm.

Surface ridge waveguides designed on GaSb-based epitaxial layers are schematically shown in Figure 1(a). Figure 1(b) shows the effective refractive indices n_{eff}, of a few lowest-order guided modes as a function of the ridge width W, and the inset shows the mode profile of TE_0 at $W = 4$ µm. Figure 1(c) shows the transmission through the two output ports of DC-, MMI-, and Y-branch- splitters with 1-dB bandwidth, Δλ ~ 1 µm at a center wavelength of 2.56 µm. For all the splitters, we achieve 50:50 power splitting with an excess loss lower than 0.12 dB. For the grating coupler, a coupling efficiency of -5.4 dB and a 3-dB bandwidth of 80 nm are achieved at 2.56 µm. Details of the design and simulation results of all these passive photonic devices will be presented at the conference.

Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-TuM2
Silicon Photonics

Moderator: Daniel Wasserman, University of Texas at Austin

10:30am **MIOMD-TuM2-14 GaSb-Based ICLs Grown on GaSb, GaAs and Si Substrates***, M. Fagot, D. Díaz-Thomaz, A. Gilbert, G. Kombila N'Dmengoye, Y. Rouillard, A. Baranov, J. Rodriguez, E. Tournié, **Laurent Cerutti**,* IES - University Montpellier, France **INVITED**

GaSb-based Interband Cascade lasers (ICLs) have emerged as the leading optoelectronic source in the 3-6µm wavelength range. Although ICLs are very attractive for various applications such as laser spectroscopy or free-space communication, the cost and size of substrates pose a significant limitation to their widespread commercialization. However, recent studies have shown that the unique band diagram of the ICLs active zone, is tolerant to mid-gap defect states induced by dislocations. Thus, the growth of ICLs on large, inexpensive, and mismatched substrates presents a viable solution for the low-cost production of high-performance mid-infrared (MIR) lasers and MIR photonic sensors on GaAs or Si-photonic integrated circuits (PIC).

In this study, we have examined the performance of ICLs designed to emit at 3.3 µm , which were grown simultaneously on GaSb, GaAs, and on-axis Si (001) substrates. The ICL structures consisted of two n-type AlSb/InAs superlattice claddings and a 5-stage interband cascade active region sandwiched between two n-type GaSb separate confinement layers. After the growth, the structures were processed into 8 µm x 2 mm laser devices and bonded epi-side up, with the bottom contact taken into the bottom cladding.

All the lasers operated in the continuous wave (CW) regime at RT and emitted around 3.3 µm. The threshold current is approximately 40 mA whereas the maximum output power decreased from 42 mW for the lasers on GaSb to 37 and 32 mW for the devices on GaAs and Si substrates, respectively. We attribute the observed decrease in the optical power to a higher voltage drop which results in overheating of the active region. The higher series resistance in these devices can be explained by poorer lateral electrical conductivity of the cladding in presence of threading misfit dislocations in the mismatched structures. These encouraging results open the way to the development of low cost ICLs and integrated photonic sensors for PIC.

11:00am **MIOMD-TuM2-17 Electrically Injected GeSn Laser on Si Substrate Operating Up to 130 K***, **Sudip Acharya**, S. Yu,* University of Arkansas

Germanium-tin (GeSn) semiconductors have gained significant attention over the last years as a group IV material for the development of novel Si-based optoelectronic devices. Specifically, direct band gap GeSn alloys with Sn fractions above 8% are of interest as light emitting sources in the near- and mid-infrared spectral range. In addition, GeSn epitaxy is monolithic on Si and also fully compatible with the complementary metal-oxide semiconductor (CMOS) technology, making it a promising candidate for the integrated light source on the Si platform, with advantages such as cost-effectiveness, reliability, and compactness [2]. Recently, GeSn lasers on Si substrate were demonstrated both under optical pumping and electrical injection. In this work, we report an electrically injected GeSn/SiGeSn are grown on Si substrate operating up to 130 K. Our study is mainly focused on the cap layer effect on the optical loss for lasing devices. The GeSn/SiGeSn heterostructure was grown using chemical vapor deposition (CVD) technique. The GeSn lasers devices were fabricated in ridge waveguide structures with 80 µm, 100 µm and 120 µm wide ridges. The lasing performance was investigated under pulsed conditions. The electroluminescence signal was collected through a monochromator and liquid-nitrogen-cooled InSb detector (response range 1–5.5 µm). The L-I characteristics of devices with different cavity length was studied at different temperatures. Our results suggest a promising way for enhancing the lasing performance of electrically injected GeSn laser diodes.

11:20am **MIOMD-TuM2-19 Temperature and Band Structure Dependent Properties of GeSn Double Heterostructure Lasers***, **Aneirin Ellis**,* University of Glasgow, UK

The development of monolithically integrated group-IV lasers remains a key challenge in realising Si-based integrated optoelectronic circuits [1]. With its direct bandgap and the possibility for wavelength tuning through strain and composition engineering, GeSn has emerged as an interesting approach. However, GeSn lasers have been primarily limited to low temperature operation. Understanding the carrier recombination behavior is therefore vital to develop improved devices with higher operating temperatures. Here, we investigate bulk $Ge_{0.89}Sn_{0.11}$ lasers grown using chemical vapor deposition [2]. In this study, high pressure, low temperature measurements are used to vary the electronic band structure for a fixed thermal carrier distribution, enabling purely band structure dependent mechanisms to be probed. Analysis of the threshold current density with pressure indicates an L-valley occupation of ~1% at 85K, determined from the fit in Fig. 1 a). Above this temperature, the fractional L-valley occupation increases strongly, indicated by a sharp rise in the threshold carrier density (assuming only mirror losses), illustrated by the red line in Fig. 1 b). This increases the pump threshold leading to device heating, increasing the L-valley occupation further and heightening free carrier absorption losses. The implications for this in terms of optimising the laser design for ambient temperature operation will be discussed.

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[2] Zhou, Y. *et al.* Optica **7**, 924-928 (2020).

11:40am **MIOMD-TuM2-21 Integrating GaSb-Based Infrared Detectors with Si Substrates via Interfacial Misfit Arrays*, Trent Garrett,* ***J. Tenorio, M. Drake,* Boise State University*; P. Reddy, K. Mukherjee,* Stanford University*; K. Grossklaus,* Tufts University*; S. Miamon,* NetzVision LLC*; P. Simmonds,* Boise State University

With applications from night vision and aerial target acquisition, to space telescope operation, infrared (IR) detectors are of great interest to the defense and scientific communities alike. The functionality of these detectors hinges on achieving a high signal-to-noise ratio so that weak signals can still be resolved. Of the many IR detector designs, the nBn device has emerged as a leading choice. As the name suggests, nBn detectors comprise an electron-blocking barrier between *n*-type absorber and contact layers [1]. nBn-based IR detectors are typically grown on GaSb substrates, which are expensive and only widely available up to 4–6” diameter. In addition, integrating a detector grown on a GaSb substrate with the Si-based ROIC via direct bonding interconnect processing is difficult. nBn detectors produced directly on Si substrates would overcome these problems. However, this approach comes with its own set of challenges, primarily due to the large lattice mismatch between GaSb and Si. We therefore adopt the use of interfacial misfit (IMF) arrays grown by molecular beam epitaxy (MBE) to manage strain at the III-Sb/Si heterointerface. IMFs consist of the spontaneous formation of a 2D array of 90º dislocations that lie in the plane of the heterointerface. Previous studies show that thin initiation AlSb layers between the GaSb and Si are critical. GaSb deposited onto an AlSb/Si IMF heterostructure has dramatically improved material quality and lower threading dislocation density (TDD) [2]. We will discuss how choices regarding AlSb growth initiation, substrate temperature, annealing, AlSb thickness, and AlSb growth rate affect the quality of GaSb overlayers. By optimizing these MBE growth parameters, initial results suggest that we can grow GaSb layers with quality comparable to the current state-of-the-art, giving us a benchmark against which to measure further improvements. We will discuss the performance of nBn devices integrated with our optimized GaSb-on-Si buffers. Promising initial results include background limited infrared photodetection (BLIP) at 150 K, and the ability to carry out thermal imaging with a 300 K blackbody background. This work is supported by the Office of Naval Research through grant #N00014-21-1-2445 and by the National Science Foundation grant GRFP #1946726

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[2] K. Akahane, N. Yamamoto, S.-I. Gozu, and N. Ohtani, Journal of Crystal Growth **264**, 21 (2004).

Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-TuA1

ICLs and LEDs

Moderator: Jerry Meyer, Naval Research Laboratory

1:30pm **MIOMD-TuA1-1 Interband Cascade Technology for Long Wavelength GaSb based Lasers and LEDs***, **Robert Weih**, J. Nauschütz,* nanoplus Advanced Photonics Gerbrunn GmbH, Germany*; H. Knötig,* TU Wien, Austria*; N. Schäfer,* nanoplus Advanced Photonics Gerbrunn GmbH, Germany*; B. Schwarz,* TU Wien, Austria*; J. Koeth,* nanoplus Advanced Photonics Gerbrunn GmbH, Germany **INVITED**

Since the first demonstration of continuous wave operation [1] Interband Cascade Lasers (ICLs) have shown tremendous improvement in their performance. Not only cw operation up to a temperature of more than 100°C has been shown [2] but also the capability of the interband cascade concept to operate to wavelengths beyond 13µm [3]. Recently we demonstrated another design improvement which focusses on the mitigation of intervalence band absorption [4]. This in turn led to a significant improvement of laser performance in the wavelength region around 6 µm [5]. A spectrum and LIV characteristics of an epi down mounted laser are shown in Figure 1. Furthermore, the latest results on resonant cavity ICLEDs and long wavelength ICLEDs with emission um to 10.2µm will be shown.

2:00pm **MIOMD-TuA1-4 Metamorphic Growth of MWIR ICLED on Silicon***, **Fatih Furkan Ince**, T. Rotter, M. Frost, G. Balakrishnan,* University of New Mexico*; M. McCartney, D. Smith,* Arizona State University*; C. Canedy, W. Bewley, S. Tomasulo, C. Kim,* U.S. Naval Research Laboratory*; M. Kim,* Jacobs Corporation*; I. Vurgaftman, J. Meyer,* U.S. Naval Research Laboratory

Interband cascade light emitting diodes (ICLEDs) grown on GaSb substrates have emerged as an effective continuous wave (CW) room temperature emitter technology in the 3 – 5 µm wavelength range [1,2]. The integration of ICLEDs directly on a silicon substrate can lead to significant benefits in manufacturability for applications including chemical sensing and IR scene projectors (IRSPs).

This presentation will discuss the growth at NRL of high performance ICLEDs on GaSb/Si buffers that were grown at UNM. The growths on GaSb *vs*. GaSb/Si are compared for crystallographic quality using cross section transmission electron microscopy (XTEM) and X-Ray reciprocal space maps (RSM). XTEM images show the presence of threading dislocations in the GaSb buffer grown on Si, with a higher density near the silicon substrate and reduced closer to the ICLED. We measure a range from 5 x 10^7 to 2 x 10^8 cm^2 in different samples. Individual threading dislocations in the GaSb buffer can reach the ICLED and multiply once they reach the active stages (figure 1). Another artifact of growth on silicon is an undulation in the ICLED layers. Our presentation will provide a detailed mechanism for both of these observations, and we will compare the results to those for an ICLED grown lattice-matched to a GaSb substrate (figure 2). We will also discuss possible strategies for improving the epitaxial quality and device performance.

2:20pm **MIOMD-TuA1-6 Production MBE Growth of QuiC SLED with Emission in the Longwave Infrared for Custom Gas Sensing Solutions***, **Everett Fraser**, J. Shao, B. Barnes, P. Frensley, P. Pinsukanjana, Y. Kao,* Intelligent Epitaxy Technology, Inc.*; M. Miller,* Terahertz Device Corporation

We have demonstrated quantum interband cascaded superlattice light emitting diodes (QuiC SLED) operating in the longwave infrared for gas sensing applications. Production scale growth of strained layer superlattice (SLS) based materials presents challenges associated with volume material manufacturing and requires solutions for both uniformity and consistency of material output. We have developed a MBE growth methodology for routine production of SLS materials for focal plane array applications and applied these capabilities to growth of QuiC SLED materials for the gas sensing market. The QuiC SLED materials were developed based on Terahertz Device's Version 1.5 technology node architecture and produced by IntelliEPI on an Sb-equipped Riber MBE6000 multi-wafer production MBE system. The multi-wafer growth run was characterized for defect levels, uniformity of deposition and wafer warpage. The QuiC SLED materials were processed into surface emitting diodes based on standard photolithography and wet chemical etching. Electroluminescence emission was measured by FTIR spectrometer at various operating temperatures and show emission within the LWIR spectral band. The emission peak wavelength decreased with drive current from 10.6 µm to 10.2 µm.

2:40pm **MIOMD-TuA1-8 Interband Cascade Laser on Silicon for High-Speed Applications in the Mid-Infrared Domain***, **Sara Zaminga**,* Mines-ParisTech, France

Quantum cascade structures are nowadays becoming mature solutions enabling mid-infrared (MIR) light-generation for diverse applications, such as free-space communications [1] and precision spectroscopy [2].

In the 3-6-µm transmission window, the interband cascade laser (ICL) is an excellent candidate over the quantum cascade laser (QCL) due to its low-threshold drive power [3]. Such reduced energy consumption meets the requirement for ultracompact devices and photonic integration: the utilization of epitaxial growth of III-V materials on silicon (Si) presents a compelling cost advantage compared to other material platforms [4]. The laser under study is a type-II Fabry-Perot (FP) ICL grown on Si, operating continuous-wave (CW) at room temperature (RT). Despite the high dislocations density and high non-radiative carrier recombination rates [5], the ICL still exhibits performances very similar to those grown on the native GaSb substrate. As shown in the light-intensity-voltage (LIV) characteristics in Figure 1a, the threshold current is 59 mA at 293 K; the maximum output power is around 11 mW per facet, the slope efficiency (per facet) is 0.12 W/A, and the external differential quantum efficiency (related to the two facets) is about 70\%. The frequency response in Figure 1b shows a sharp cut-off around 1 GHz, which is promising for multi-Gbit/s wireless transmissions. Ulterior results in this direction will be presented during the conference.

[1] Didier, P. et al.,Photonics Research11, 582-590 (2023).
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[4] Liu, A. Y., et al.,IEEE Journal of Selected Topics in Quantum Electronics24, 6, 6000412 (2018).
[5] Cerutti, L., et al.,Optica8, 1397-1402 (2021).

Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-TuA2

Mid-IR Plasmonics

Moderator: Qijie Wang, Nanyang Technology University, Singapore

3:30pm **MIOMD-TuA2-13 All-Epitaxial Nanophotonic Architectures for Mid-Infrared Optoelectronics***, L. Nordin,* University of Texas at Austin*; A. Kamboj,* University of Delaware*; P. Petluru, M. Bergthold, Y. Wang, A. Muhowski, **Daniel Wasserman**,* University of Texas at Austin **INVITED**

The mid-infrared (mid-IR) provides a design space where a wide range of engineered and intrinsic light matter interactions can be harnessed to develop a new generation of optical materials and devices. In particular, the highly-doped semiconductor class of materials offers an intriguing opportunity to control the permittivity of epitaxially-grown semiconductors, and can serve as low-index dielectrics, epsilon-near-zero materials, or even as plasmonic materials. Because these materials can be directly integrated with epitaxially-grown optoelectronic device active regions, there exists an opportunity to develop new mid-IR device architectures leveraging co-design of optical and electronic properties, all in a monolithic material system.

In this presentation I will discuss recent results showing strongly enhanced performance of mid-IR structures and devices leveraging all-epitaxial photonic enhancement of response, including distributed Bragg reflectors, leaky cavity LEDs and detectors, guided mode LEDs and detectors, and plasmonic infrared detectors, operating across the mid-infrared. I will present the opportunities and challenges for these new device architectures, and discuss potential future approaches for further enhancement and systems integration.

4:00pm **MIOMD-TuA2-16 Strategies for Electrical Tuning of Thermal Emissivity in Metamaterials***, B. Shrewsbury, A. Ghanekar, R. Audhkhasi, M. Sakib, **Michelle Lynn Povinelli**,* University of Southern California **INVITED**

Achieving tunable control over the thermal emission spectrum of materials is expected to enable new possibilities in applications including thermophotovoltaics, waste heat recycling, and infrared communication and sensing. In recent work, we have introduced several strategies for achieving electrical control over thermal emission based on resonant coupling and symmetry breaking in infrared metamaterials.

In one thrust of our work, we consider control over emissivity amplitude. We employ metamaterials comprised of several, coupled resonators in each unit cell. By tuning the dimensions of each resonator, we can arrange for either a bright mode (one that couples to normally incident light) or a dark mode (one that does not) to fall within a specified region of the spectrum. This leads to several possibilities for spectral control. In an exemplar strategy, we consider two, initially bright modes that couple to form a dark mode. At zero applied voltage, the system is mirror symmetric, and the dark mode does not produce any observable feature in the emission spectrum. When a voltage is applied to tune the refractive index in a portion of the unit cell, mirror symmetry is broken. The formerly dark mode becomes bright, switching on an emissive peak. We present design strategies for implementing this concept within both graphene and III-V semiconductor platforms.

In a second thrust, we consider control over directionality of thermal emission. In this case, we consider a metamaterial based on weakly coupled resonators, which give rise to a nearly flat photonic band. We then consider the effect of a small index perturbation of the refractive index of the structure. We show that for fixed wavelength, the flatness of the photonic band magnifies the change in angle for emitted radiation. We present several practical designs for realizing this effect in a III-V semiconductor platform.

4:30pm **MIOMD-TuA2-19 Nonlocal Effects in Heavily Doped Semiconductor***, P. Loren,* University of Montpellier, France*; E. Sakat,* Université Paris-Saclay, CNRS, C2N, 91120 Palaiseau, France*; J. Hugonin,* Université Paris-Saclay, CNRS, Laboratoire Charles Fabry, 91127 Palaiseau, France*; L. Cerutti, F. Gonzalez-Posada,* IES, Univ Montpellier, UMR CNRS 5214, Montpellier, France*; A. Moreau,* Université Clermont Auvergne, CNRS, SIGMA Clermont, Institut Pascal, F-63000 Clermont-Ferrand, France*;* ***Thierry Taliercio****,* IES, Univ Montpellier, UMR CNRS 5214, Montpellier, France

The Drude model is the most adapted model to describe the optical properties of metal and nano-antennas. Unfortunately, it starts to fail when the size of the nanostructures becomes small enough, that is a few nanometers for noble metals or a few tens of nanometers in the case of heavily doped semiconductors. It is then necessary to consider a nonlocal susceptibility tensor to describe accurately the optical properties of these metallic nanostructures. The best-suited approaches are the semi-classical quantum model [1] or the hydrodynamic Drude model (HDM). HDM can describe accurately the ultra-confined light of the plasmonic mode by the introduction of an electron quantum pressure in the equation of motion of the free electron gas.[2] It is particularly well adapted to be implemented in electromagnetic modeling. In this work, we compared experimental measurements of the volume plasmon modes with HDM.

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[2] E. Sakat, A. Moreau and J.-P. Hugonin, Phys. Rev. B 103, 235422 (2021).

4:50pm **MIOMD-TuA2-21 Low Doping Level and Carrier Lifetime Measurements in InAs with a Novel THz Characterization Technique***,* ***Julien Guise****, S. Blin, T. Taliercio,* Univ. of Montpellier, Montpellier, France

In this abstract, we present a novel, contactless opto-THz technique for measuring low doping levels and carrier lifetime in InAs. Preliminary studies proved that THz waves can be modulated using an optically-pumped InAs slab [1]. This optically-driven modulation is efficient in the 0.75–1.1-THz frequency band because of its vicinity with the plasma frequency of electrons, that leads to a strong dependence of the real and imaginary parts of the dielectric permittivity of InAs on free carrier density, the latter being strongly increased using optical pumping. Additionally, without any optical pumping, we show that n-type doping levels around 1016 cm-3 could be measured thanks to THz transmission measurements analyzed using a single-variable Drude-Lorentz model, as shown in Fig. 1(a), thus offering an original and accurate technique to measure very low doping levels. Using an amplitude- modulated optical pump, we could also easily retrieve the effective carrier lifetime by measuring the transmission of a THz probe signal, as shown in Fig. 1(b).

Mid-IR Optoelectronics: Materials and Devices
Room Great Hall, Sam Noble Museum - Session MIOMD-TuP

Mid-IR Optoelectronics: Materials and Devices Poster Session

MIOMD-TuP-1 Temperature Dependence of the Infrared Dielectric Function and the Direct Band Gap of InSb from 25 to 800 K*, **Sonam Yadav**,* New Mexico State University

In experiment, the infrared dielectric function of InSb in the region of the direct band gap at temperatures from 77 to 725 K using Fourier-transform infrared spectroscopic ellipsometry is determined. At the highest temperatures, the free carrier concentration due to thermally excited electron-hole pairs becomes very large and the Fermi level is above the conduction band minimum. The observed band gap increases again at 600 K (Burstein-Moss shift).

Theoretically, the temperature dependence of the chemical potential μ for an ideal intrinsic semiconductor (InSb) at fixed temperatures is calculated by using Polylogarithm forms of FD integrals from 25 K to 800 K. It is known that at absolute zero, the chemical potential (μ) is equal to the Fermi energy (ε_f). μ versus T is plotted for Degenerate and Non-Degenerate case (this calculation assumes parabolic bands, a constant band gap, and constant effective masses). On comparing both graphs we can see at higher temperature degenerate graph goes up (deviate up) but for non-degenerate case, it remains linear. Due to the small electron to hole mass ratio, the optical activation energy (OAE, i.e., the experimental band gap measured with transmission or ellipsometry measurements) is almost the same as the chemical potential, once μ is larger than the band gap (above about 400 K). It is apparent that there is a thermal Burstein-Moss shift for temperatures above 400 K, because the chemical potential and the OAE are larger than the intrinsic band gap.

MIOMD-TuP-3 Sb-based Mid-Wave Infrared Laser Arrays*, **Rowel Go**, A. Lu, M. Suttinger,* Air Force Research Laboratory

Mid-wave infrared lasers have advanced in both spectral coverage and power level in the past decade. Particularly, Sb-based semiconductor laser structures are of interests for many applications such as remote sensing, direct diode pump sources, and defense countermeasures. Here we report high power diode laser arrays using these laser structures. The laser structures as shown in Fig 1. were grown using molecular beam epitaxy on GaSb substrates with designed emission wavelengths of 2.0µm, 2.4µm, and 2.7µm. All structures share the same lattice-matched AlGaAsSb quaternary cladding doped with Te for n-type and Be for p-type clad layers. The waveguide consists of lattice-matched quaternary or quinary alloy and compressively strained InGaAsSb quantum wells laced at the center with inter-well spacings. Changing in wavelength is controlled by adjusting In content in the waveguide. Single and four-bar stack arrays were processed, fabricated, and packaged with water-cooled microchannel coolers. Some of the laser performance results tested in various conditions are shown in Fig 2.

MIOMD-TuP-5 Carrier Concentration-Dependent Optical Properties of Narrow Gap Semiconductors*, **Yixuan Shen**, R. Yang, M. Santos,* University of Oklahoma

This work provides a comprehensive assessment of the optical properties of narrow bandgap semiconductors based on the k.p method [1] across a wide range of carrier concentrations and wavelengths. Based on a commonly used two-band model [2] and a less explored three-band model that include the spin-orbit split-off band, the refractive index and absorption coefficient due to free-carrier absorption are evaluated and compared with experimental data to assess their suitability for different scenarios. It is found that the values of electron energy based on the two models can substantially differ as the carrier concentration is increased. Fig. 1 shows the energy calculations for InAs, with the resulting effective masses shown in Fig. 2. The refractive index and absorption coefficient calculated from the two models will have some differences that depend on the carrier concentration. The results provide a guideline for selecting the appropriate model in different wavelength and carrier concentration ranges for various applications. The attained results may help with the optimization of interband cascade laser performance and other applications, and lead to improved device performance and more accurate measurements.

This work was partially supported by NSF (No. ECCS-1931193) and OCAST (AR21-024).

[1] E. O. Kane, "Physics of III-V compounds," Chapter 3 in Semiconductors and Semimetals, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1966), Vol.1

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MIOMD-TuP-7 Tuning the Plasmonic Response of Heavily-Doped Semiconductors in Epsilon-Near-Zero Regime*, P. Fehlen,* French-german research institute of Saint-Louis, France*; J. Guise,* University of Montpellier, France*; G. Thomas,* French-german research institute of Saint-Louis, France*; F. Gonzalez-Posada, J. Rodriguez, L. Cerutti,* University of Montpellier, France*; D. Spitzer,* French-german research institute of Saint-Louis, France*;* ***Thierry Taliercio**,* University of Montpellier, France

Epsilon-near-zero (ENZ) materials display vanishing permittivity at precise frequencies, e.g., plasma frequency ωp. They exhibit several peculiar properties such as a unique field enhancement or ultrafast nonlinear efficiencies, and will be useful in the field of integrated Photonics. Heavily doped semiconductors have a tunable ENZ regime over the infrared spectral range by adjusting their doping level and thus their plasma frequency ωp. In this work, we investigate the correlation between the localized surface plasmon-polariton resonance and the nano-antenna size within a metal-insulator-metal structure composed of heavily-doped semiconductor InAsSb:Si. In this study, while the metals have a high plasma frequency ωp1, the insulator is also doped InAsSb:Si at lower plasma frequency ωp2. In doing so, we uncover the origin of the resonance pinning, which has been previously mentioned in the literature, as the spacer permittivity approaches zero [1]. Plus, we demonstrate that doping is an excellent additional degree of freedom to engineer the optical response of plasmonic structures, especially in the ENZ regime where the response becomes nearly geometry-independent, and is rather dispersive dependent.

MIOMD-TuP-9 Interfacial Misfit Dislocation Array Assisted MBE Growth of InSb Quantum well on InAs using AlInSb Buffer Layer*, **Fatih Furkan Ince**, A. Newell, T. Rotter, G. Balakrishnan,* University of New Mexico*; M. McCartney, D. Smith,* Arizona State University

Mid-wave infrared (MWIR) detectors are commonly used in medical devices, remote sensing, and spectroscopy. InSb-based infrared focal plane arrays (FPAs) offer spatial uniformity, temporal stability, scalability, and affordability. Type-II superlattices and metamorphic buffers are used to cover the MWIR spectrum and reach the long-wave infrared (LWIR) region. We propose using interfacial misfit dislocations to grow fully relaxed InSb on InAs substrate, and direct growth of AlxIn1-xSb buffer layers on InAs, for developing tunable InAsSb absorbers for MWIR and LWIR applications [1], [2].

In this presentation will discuss the interfacial misfit dislocation growth mode to form instantly relaxed buffer layer on top of InAs substrates. We analyze both directly grown AlInSb and InSb epilayers on InAs substrates using HR-XRD ω-2θ scans as well as reciprocal space mapping. HR-XRD results indicate a relaxation of 99.4% for InSb directly grown on InAs, and a slightly reduced value for the Al0.1In0.9Sb and Al0.2In0.8Sb epilayers. Reciprocal space mapping allows us to estimate the screw and mixed dislocation density for the layers. Additionally, TEM analysis shows the formation of misfit dislocation arrays at the AlInSb/InAs interface. We investigate InSb quantum wells grown with different AlxIn1-xSb barrier layers using photoluminescence (PL). We will present a comprehensive analysis of the buffer layers with respect to threading dislocation density using XRD scans and TEM images. Furthermore, we will provide a detailed analysis of the InSb QWs based on PL and TRPL results.

MIOMD-TuP-11 High Efficiency Room Temperature HgTe Colloidal Quantum Dot Photodiodes*, **John Peterson**, P. Guyot-Sionnest,* The University of Chicago

Colloidal quantum dots offer an inexpensive, solution-processed alternative to conventional, crystalline material devices for mid-infrared photodetection. Photodiodes of size 1 mm by 1 mm made using HgTe quantum dots previously reached the background limit at cryogenic temperatures but suffered from a 30-fold decrease in signal near room temperature. This was attributed to a decreased carrier diffusion length at higher temperatures, where the thermal carrier concentration is high. An alternative explanation based on a simple circuit model suggests that it is instead due to the effects of a finite series resistance, coming mainly from the semitransparent indium tin oxide electrode.

Using microfabrication, devices were prepared which use an insulating polymer to restrict the active device area to 50 by 50 microns. This decrease in size increases the shunt resistance to be greater than the series resistance even at room temperature. It was also found to be important to employ a guard ring in the final design to only collect carriers within this restricted area, which limits crosstalk between nearby devices and allows one to measure the true resistance of the devices. As a result of these alterations, greater signal is collected, leading to 15% EQE and a four-fold improvement in the detectivity in excess of 10^9 Jones near room temperature for photodiodes with a cutoff at 4 microns.

MIOMD-TuP-13 Experimental Study of Band Offsets at the GeSn/SiGeSn Interface by Internal Photon Emission*, **Justin Rudie**, H. Tran, S. Amoah, S. Ojo,* University of Arkansas*; M. Shah,* University of Arkansas at Pine Bluff*; S. Yu,* University of Arkansas

In heterojunction semiconductor devices the band structure of the interfacing materials plays a pivotal role in the resulting device's performance and characteristics. Therefore, measuring and understanding the band offsets of emerging materials is crucial since the type of band alignment (Type I, Type II, Type III) and the magnitude of energy offsets determine the magnitude of the potential barriers, and thus, the possible carrier confinement in any resulting device. [1]

The band offsets between GeSn and SiGeSn in a quantum well photoconductor device were measured using internal photon emission (IPE). This technique was used as it is precise with values reported with sub millielectronvolt resolution and is not limited by surface depth penetration like many electron spectroscopy techniques.[1],[2] IPE is characterized by the product of a device's responsivity and energy of incident exciting photons. This product is known as quantum yield (Y) and is proportional to photon energy exceeding the energy threshold required for photocurrent generation from an emitter material to a collector material.[2] In the measurement of the GeSn/SiGeSn device it was determined that the band alignment was Type-1 with a VBO of 0.06 eV and a conduction band offset (CBO) of 0.02 eV.

MIOMD-TuP-15 A Comparative Study of Ion-Implantation of As and B in GeSn Epilayers Grown on Si (001) by Chemical Vapor Deposition*, **Amoah Sylvester**, H. Stanchu, F. Yu,* University of Arkansas

Recently, direct band gap GeSn alloy semiconductors with Sn concentration above 6-8% have attracted considerable attention as a tunable mid- and near-infrared materials of group IV for light emitting and detection applications with the advantage of monolithic integration on Si substrate and CMOS compatibility [1]. Due to the low miscibility of Sn and Ge, Sn-rich metastable GeSn alloys are typically grown under non-equilibrium conditions, such as by chemical vapor deposition (CVD) and molecular beam epitaxy (MBE). With these techniques, *in-situ* doping is somehow limited, in particular for the fabrication of devices with laterally selected doping regions. Alternatively, *ex-situ* ion implantation is a commonly used process for engineering the structure and precise control of different dopant species in materials.

The poor thermal stability of Sn-rich GeSn materials imposes a low thermal budget for dopant activation. At elevated annealing temperatures, phase separation into thermodynamically favored elemental Ge and β-Sn is ubiquitous. Recently, an annealing study of ion-implantation of As in Ge have shown a 60% substitutional occupation of As atoms in the Ge lattice for annealing temperatures below 200 °C and almost 100% substitutional occupation at higher temperatures [2]. In this work, the implantation of As and B in GeSn epilayers is investigated under different conditions.

MIOMD-TuP-17 Snowflakes Patterns Formation Enhances Performance of Nanostructure-based MWIR PbSe Photoconductive Detector*, **Richard Kim**, R. Dahl, J. Park,* OPTODIDOE/ITW Research and Development

We present a novel approach to fabricate a PbSe thin film photoconductive detector using the chemical bath deposition technique, resulting in the formation of various snowflakes-like patterns on the active area of the detector. Our findings reveal the presence of clusters of nanostructures, primarily nanoprisms, beneath the snowflakes patterns, which enhance the performance of the PbSe photoconductive detector. This is a new observation that has not been previously reported. Our investigations have shown that when snowflakes-like patterns appear on the surface of the detector's active region, a large number of PbSe nanostructures are formed within the PbSe thin film. We have also found a strong correlation between the size and compactness of the snowflakes patterns, and thus the nanostructures, and the performance of the PbSe photoconductive detector. As the snowflakes patterns get larger, the detection signal becomes stronger. We have examined changes in the microstructure and carrier concentrations resulting from sensitizing treatments such as oxygen and iodine. Our findings suggest that the snowflakes patterns are a direct evidence of the crystallization process. Finally, we have thoroughly examined the FTIR spectral response of the nanostructure-embedded PbSe photoconductive detector at various temperatures ranging from 77K to 340K.

MIOMD-TuP-19 GaSb-based Interband Cascade Lasers with Hybrid Cladding Layers Operating in the 3-4 µm Wavelength Region*, Y. Shen, **Jeremy Massengale**, R. Yang, T. Mishima, M. Santos,* University of Oklahoma

We report the demonstration of interband cascade lasers (ICLs) [1] with hybrid cladding layers [2-4] in the 3-4 µm wavelength region. These ICLs were grown on GaSb substrates and employed n^+-doped $InAs_{0.91}Sb_{0.09}$ cladding layers and n-doped InAs/AlSb superlattice (SL) intermediate cladding layers. In contrast to a regular ICL with only SL cladding layers, an ICL with the hybrid cladding layers can have an enhanced optical confinement and improved thermal dissipation. A room temperature (RT) threshold current density (J_{th}) as low as 177 A/cm^2 was measured for a broad area device emitting at 3.28 µm (Fig. 1) with pulsed operation extending up to 390 K. The characteristic temperature (T_0) was nearly 60 K, which is the highest value among RT ICLs with similar lasing wavelengths. ICLs from two wafers grown later exhibited a RT pulsed J_{th} as low as 151 A/cm^2 for emission near 3.82 µm (Fig. 2), which is comparable to the best ICLs with only SL cladding layers [5]. Considering the substantial deviations (>10%) in the grown layer thicknesses from the design values, it is expected that ICLs with hybrid cladding layers will have significantly better performance once the growth process is improved. Updated results will be reported at the conference.

MIOMD-TuP-21 Halide Perovskite Material Development, Growth, and Characterization for Infrared Optoelectronics*, **Yash Mirchandani**,* Syrnatec

Syrnatec has developed innovative technology for the growth, characterization, and development of halide perovskites. The technology is based on a two-step solution process, which involves the deposition of a precursor film followed by annealing to form the perovskite.The precursor film was deposited using a novel spin-coating method that utilizes a mixture of $PbBr_2$ and CsBr in dimethyl sulfoxide (DMSO). The deposition was followed by annealing at a temperature of 150°C for 15 minutes to convert the precursor film to the perovskite.The synthesized $CsPbBr_3$ perovskite was characterized using various techniques such as X-ray diffraction, scanning electron microscopy, and photoluminescence spectroscopy. The X-ray diffraction patterns of the perovskite showed sharp diffraction peaks, indicating excellent crystallinity. The scanning electron microscopy images revealed that the perovskite had a well-defined morphology with a cubic shape. The photoluminescence spectra of the perovskite showed a narrow emission peak at around 510 nm, indicating a narrow bandgap of 2.25 eV and indicative of high quantum efficiency.The unique technology also enables the control of the crystal structure and morphology of the synthesized $CsPbBr_3$ perovskite. By adjusting the annealing temperature and time, we were able to obtain different crystal structures of the perovskite, including tetragonal and orthorhombic structures. We were also able to control the morphology of the perovskite by varying the concentration of the precursor solution.Our experiments demonstrated that the synthesized $CsPbBr_3$ perovskite has potential applications in United States optoelectronics. The photodetector showed excellent photoresponse with 23.4% external quantum efficiency and a fast response time of 40ms.Finally, this proposed technology will be having a potential for the large-scale production of $CsPbBr_3$perovskite for US infrared optoelectronic applications like solar cells, photodetectors, and light-emitting diodes. The technology will provide a simple and low-cost solution-based approach for the synthesis and growth of high-quality $CsPbBr_3$ perovskite with controlled crystal structure and morphology and will makes it a promising candidate for the commercialization of infrared optoelectronics applications in US.

MIOMD-TuP-23 Infrared Endovascular Navigation for Enhanced Sensing and Treatment*, D. DeVries, M. Salter, S. Balzora,* ***Linda Olafsen****, J. Olafsen, K. Schubert,* Baylor University*; S. Dayawansa, J. Huang,* Baylor Scott & White Health System

We present recent results toward development of an endovascular navigation system comprised of a programmable surgical wire with infrared (IR) emitters and detectors on the tip. This system is intended for enhanced sensing and medical treatment, particularly for remote treatment sites, including telemedicine. Successful demonstration of this system has the potential to enhance urgent care provided by field surgeons and medics, as well as to open opportunities for remote practitioners minimally to observe and provide expertise and maximally to operate or assist in the field by expertly guiding the wire. The proposed device has great potential (1) to enable imaging and sensing deeper in the head and body, (2) to increase the sensitivity of infrared measurements of biomarkers, (3) to result in more efficient and safer navigation of catheters and surgical instruments for treatment of aneurysms and other endovascular procedures, especially in remote settings, and (4) to reduce exposure of patient and surgeon to harmful radiation by employing ultrasound or infrared imaging techniques. This endovascular device uses wire made of a shape-memory alloy, such as Nitinol, to navigate arteries for treatment.Nitinol has prior FDA approval and a long record of biocompatibility, especially when an oxide and/or another passivating layer is applied. The wire is programmed to bend at temperatures above core body temperature and navigate arterial branches using current control.Blind navigation of wires by physical pushing can result in rupture of vessel walls with lethal consequences.Stents have been used to deploy deep brain stimulation devices, but no deep system for *in vivo* near-infrared spectroscopy exists.The ability to effectively insert and guide an infrared emitter to the brain for neurological monitoring and treatment would be of significant benefit in the operating room, particularly during cardiothoracic surgery or neurosurgery.

MIOMD-TuP-25 Residual Gas Analysis of Reactions between Germane and Tin Tetrachloride for the Optimization (Si)GeSn CVD Growth*,* ***Joshua M. Grant****, E. Yang, A. Golden, W. Du,* University of Arkansas*; B. Li,* Arktonics LLC*; S. Yu,* University of Arkansas

Since the introduction of (Si)GeSn alloys to the world of semiconductors for silicon based photonic applications, the material has become highly desired for both detectors and sources [1]. By capitalizing on the ability to tailor the band gap of the material by varying the Sn content, transforming an indirect bandgap material to a direct, holds great potential for Near to Mid-IR wavelength photonics. The growth of GeSn for devices and material study has been performed by Molecular Beam Epitaxy (MBE) and Chemical Vapor Deposition (CVD), with Plasma-enhanced Chemical Vapor Deposition (PECVD) and its low thermal requirements [2, 3] gaining popularity. The CVD growth of GeSn has been performed using the commercially available precursors Tin tetrachloride (SnCl4) and Germane (GeH4) [4]. To better understand the growth mechanisms of GeSn on a Si (100) substrates using $SnCl_4$ and GeH_4 during the CVD process, reactions between the two precursors was studied utilizing a differential pumping system for a 300 amu Residual Gas Analyzer (RGA) that was isolated from the CVD reactor. The focus of this talk will be to present the most recent findings from the mass spectra of the interactions between the two precursors.

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MIOMD-TuP-27 Low Temperature Plasma Enhanced Growth of $Si_{1-x}Sn_x$ by Chemical Vapor Deposition*,* ***Alexander Golden****, J. Grant, E. Yang, S. Acharya, S. Yu,* University of Arkansas

Thin films of Silicon-tin alloys ($Si_{1-x}Sn_x$) were grown on Si (001) substrate using low temperature plasma-enhanced chemical vapor deposition. These alloys have potential in the application of optoelectronic devices however their growth conditions have not been studied as thoroughly as similar GeSn materials [1]. Precursors like silane have a high breakdown temperature compared to the CMOS process and the solid solubility of Sn in Si is very low and is further complicated by segregation at higher temperatures. Therefore, the growth mechanism of $Si_{1-x}Sn_x$ needs to be better understood [2]. The thin film growth of $Si_{1-x}Sn_x$ in this work was accomplished by adjusting plasma intensity and controlling the precursor flow fractions. The film thickness was measured by Spectroscopic Ellipsometry, and the Sn incorporation and crystallinity were estimated using X-ray Diffraction measurements. In particular, an increase of Sn composition in the Si1-xSnx epilayers was concluded by observing the migration of the (004) peak towards the lower angles on the X-ray diffraction 2θ/ω scans, Figure 1, which corresponded to an overall improvement of Sn incorporation of more than 10% relative to the previous work. Moreover, a significant enhancement in material quality was concluded by comparing the line widths (FWHM) of the SiSn peak to those reported previously [3].

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MIOMD-TuP-29 Long Wavelength Distributed Feedback Tapered Quantum Cascade Lasers*, D. Pinto, B. Lendl,* TU Wien, Austria*; A. Baranov,* ***Kinjalk Kumar****,* Université de Montpellier, France

We present an investigation of tapered QCLs with taper angles between 0° and 3°. Tapered cavities benefit from bigger active zone volume, preserving the beam quality of the fundamental transverse mode [1]. The QCL was based on the InAs/AlSb material system emitting around 14-15 µm [2], where BTEX compounds exhibit strong absorption, making such laser source interesting for sensing applications. The active zone is composed of an InAs/AlSb superlattice sandwiched between undoped InAs spacers and highly-doped InAs cladding layers. The wafer grown by MBE on an InAs substrate was processed into deep mesa ridge lasers using optical photolithography and wet chemical etching. E-beam lithography and dry etching were employed to pattern Bragg gratings on top of the ridge waveguide, for single longitudinal mode operation. A gold layer was deposited to provide electrical contact.

In Fig. 1(a) a scanning-electron microscope image of the tapered devices is shown. The devices were tested and compared in terms of electrical and optical properties, and in terms of spectral purity. Single-longitudinal mode operation was obtained, with a side-mode suppression ratio (SMSR) greater than 15 dB. In Fig. 1(b), emission spectra of a straight QCL, measured at different temperatures in CW operation, are portrayed. In Fig. 1(c) voltage-light-current characteristics of the tapered devices are shown. Tapers with wider angles provide a greater power output. The different improvement of the slope efficiency is observed, which can be justified by the higher collection efficiency of the system towards higher taper angle devices. The larger front facet of tapered lasers reduces the divergence angle along the slow axis, allowing to collect more light. The far-field intensity profiles were measured in order to determine the beam divergence and estimate the devices brightness.

MIOMD-TuP-31 Low-Loss Plasmonic Resonances in Heavily Doped InAs for Infrared Optoelectronic Integration*,* ***Ethan Caudill****, C. Cailide,* University of Oklahoma*; M. Lloyd, J. Murphy,* Naval Research Laboratory*; K. Arledge, T. Mishima,* University of Oklahoma*; J. Nolde, J. Frantz, C. Ellis,* Naval Research Laboratory*; P. Weerasinghe, T. Golding,* Amethyst Research Inc.*; M. Santos, J. Tischler,* University of Oklahoma

Plasmonic resonances supported by traditional metals (e.g., gold, silver, and aluminum) have been used to enhance optoelectronic devices such as emitters and detectors. However, these materials are very lossy in the infrared region, hindering their use in actual devices that operate in the infrared. To overcome this issue, we use doped III-V semiconductors as a low-loss plasmonic material that can be easily integrated with traditional III-V infrared optoelectronic devices. Here we show that an InAs epilayer, when highly-doped with Tellurium (up to 10^{20} cm^{-3}), exhibits a plasma frequency corresponding to light at a free-space wavelength of 4.5 µm.

When a 1D grating with a period shorter than 5 µm is formed in the epilayer via dry etching, resonances at longer wavelengths (5.5 to 14 µm) are observed with quality factors around 7 and absorption as high as 95%. Finite element electromagnetic models of the resonances show good agreement with our experimental results. This material is based upon work supported by the Office of the Undersecretary of Defense for Research and Engineering Basic Research Office STTR under Contract No. W911NF-21-P-0024. Disclaimer: The content of the information does not necessarily reflect the position or the policy of the Government, and no official endorsement should be inferred.

MIOMD-TuP-33 Advancing Precise Control of Electromagnetic Radiation: An Innovative Nanophotonic Multilayer Structure for Mid-Infrared Applications*, **Masoumeh Nazari**, M. Banad, S. Sharif,* University of Oklahoma

The precise control of electromagnetic radiation within atmospheric windows holds significant importance in diverse applications, including solar energy harvesting [1] thermal regulation, and optical communication systems. In this study, we propose an innovative nanophotonic multilayer structure designed with a combination of graphene, polymer, and PbSe (lead selenide) materials to achieve accurate control over electromagnetic wave absorption in the mid-infrared (mid-IR) range.

Our research demonstrates that the carefully chosen materials, layer composition, number of layers, and optimized thickness yield a highly efficient structure with narrow band absorption capabilities across the entire mid-IR wavelength range. Moreover, we showcase the ability to manipulate the absorption range at each wavelength by applying a DC bias electric field to the graphene surfaces.

The proposed nanophotonic multilayer structure is composed of alternating layers of graphene, polymer, and PbSe, strategically leveraging the unique properties of each material as shown in figure 1. Graphene and polymer layers contribute exceptional electrical and optical characteristics, including high conductivity and broad spectral absorption. Meanwhile, PbSe exhibits remarkable properties in the mid-IR region, such as strong absorption and efficient thermal management. To enhance the absorption rate in the graphene layers, we incorporate a semi-infinite layer of gold as the substrate, effectively reflecting light in the mid-IR range.

This well-designed nanophotonic multilayer structure promises enhanced control over absorption rates and presents a promising avenue for advancing various applications reliant on precise electromagnetic radiation control in the mid-IR spectrum.

To design and evaluate the performance of the proposed structure, we employ rigorous electromagnetic simulations based on the finite-difference time-domain (FDTD) method in COMSOL and we combine it with the Micro-genetic algorithm to define the minimum thickness of each layer to find the optimized unique thickness for each wavelength. Next we modeled the conductivity of graphene using Kubo formula leading to electrical control of graphene’s refractive index.

Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-WeM1

Plenary Lecture & Applications of Mid-Infrared

Moderator: Rui Yang, University of Oklahoma

8:30am **MIOMD-WeM1-2 Plenary Lecture: Coherent Control of Quantum Cascade Laser Frequency Combs via Optical- and RF-Injection*, Gerard Wysocki,*** Princeton University **INVITED**

Quantum cascade laser (QCL) frequency combs are compact, all-electrically driven, broadband semiconductor laser sources operating in the mid-infrared spectral region that give access to fundamental vibrational bands of many molecular species of environmental and industrial importance. These lasers are being extensively used to perform dual-comb spectroscopy (DCS) and sensitive molecular sensing with high temporal resolution. However, unlike the metrological-grade frequency combs based on mode-locked lasers, freerunning QCL-combs are susceptible to intrinsic phase and intensity noise, which makes applications to high-resolution spectroscopy relatively difficult. In this talk I will discuss techniques utilizing external cavity optical feedback injection as well radio-frequency (RF) electrical signal injection to achieve improved comb coherence for dual-com spectroscopy, as well as generate higher-order harmonic QCL comb-states with improved coherence and broader optical bandwidth. Experimental results demonstrating independent control of primary comb parameters (offset frequency , f0, and repetition rate frequency, frep) via opticaland RF-injection, resulting in MHz-level frequency control and gapless DCS tuning, will be discussed in details.

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9:10am **MIOMD-WeM1-6 Compact QCL-Based Coherent Lidar in the Mid-Infrared*, Bruno Martin,*** Thales / Laboratoire de physique de l'Ecole normale supérieure, France*; P. Feneyrou,* Thales research and technology, France*; N. Berthou,* Thales SIX, France*; D. Gacemi,* Laboratoire de physique de l'Ecole normale supérieure, France*; A. Martin,* Thales Research and Technology, France*; C. Sirtori,* Laboratoire de physique de l'Ecole normale supérieure, France **INVITED**

Frequency-modulated continuous-wave light detection and ranging (FMCW LiDAR) is a technique for fast and precise measurements of distances and speeds of hard and diffuse targets. Moreover, the effects of feedback reinjection on the laser parameters, such as the optical power, wavelength or voltage can be utilized for numerous sensing applications. We show the first experimental demonstration of a FMCW LiDAR in the mid-infrared, based on a novel self-mixing interferometry technique and compare it with a conventional mid-infrared FMCW system. Thanks to an injection current predistortion technique, high-speed and precise linear optical frequency modulation (LFM) up to 8 GHz in 1µs with less than 1% error to linearity is achieved, allowing a greater FMCW signal-to-noise ratio.

One part of the beam (> 90%) is sent to a target in order to perform distance & speed measurement. In the absence of optical isolation, a part of the reflected light will come back inside the laser cavity, interfering with the intracavity field. The changes induced simultaneously on the optical power and frequency are monitored on a photodiode at the output of the interferometer. More specifically, the measurement of the periodic perturbation on the LFM allows for speed and distance measurement, without adding any new components to the LFM system. Taking advantages of intrinsic high-speed dynamics of mid-infrared unipolar sources and detectors, we achieved kHz-rate sub-cm precision measurement of low-reflective targets at distances up to 25 m. Such results pave the way to systems more robust against meteorological perturbations and with an improved discreetness. Moreover, the overall compactness and robustness of the optical setup constitute a leap toward the development of mid-infrared quantum optoelectronic devices and their integration into components.

9:40am **MIOMD-WeM1-9 A Markov Chain Approach for Modeling Polarized Infrared Radiative Transfer in Optically Anisotropic Media*, Feng Xu,*** University of Oklahoma*; W. Espinosa,* NASA Goddard Space Flight Center*; O. Kalashnikova, A. Davis, D. Diner, M. Garay,* Jet Propulsion Laboratory (NASA/JPL)*; J. Gong,* NASA Goddard Space Flight Center*; B. Chen, L. Gao, J. Redemann,* University of Oklahoma*; Z. Zeng,* California Institute of Technology, China

The polarization state of atmospheric radiation contains abundant information about aerosol and cloud particle properties. To assist in the combined use of reflected and emitted radiation for dust and cloud remote sensing, we developed a Markov chain approach to model polarized infrared radiative transfer in an optically isotropic or anisotropic medium (e.g. Earth atmosphere). A multi-steam scheme is adopted to resolve the angular dependence of total radiance and polarized radiance. Our model accounts for atmospheric emission, scattering, and absorption, as well as directional surface emission and reflection. Non-spherical particles with random and preferred orientations are considered. Simulation is performed for three reference Earth atmospheres (mid-latitude summer, sub-arctic winter, and tropical) which contains dust particles, water droplets, and ice particles of preferred or random orientations. These reference atmospheres overly an ocean or a land surface which contributes both surface emission and reflection. The numerical simulation shows a) remarkable impact of particle orientations, non-sphericities, and the linear and circular polarization components of infrared extinction matrix on the infrared polarimetric signals. By contrast, the infrared radiances are much less impacted.

Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-WeM2

Sensing

Moderator: Gerard Wysocki, Princeton University

10:30am **MIOMD-WeM2-14 Mid-Infrared Trace Gas Detection Enhanced by Tuning Fork, Optical Cavity and Hollow-Core Fiber*, Wei Ren,*** The Chinese University of Hong Kong **INVITED**

Mid-infrared trace gas detection plays a significant role in many sectors such as energy systems, transportation, environmental monitoring, agriculture, safety, and security. With quantum cascade laser (QCL) and interband cascade laser (ICL) used as the light source, it is promising to develop high-resolution mid-infrared laser-based spectrometers with a portable size and low power consumption. Photoacoustic spectroscopy (PAS) and photothermal spectroscopy (PTS) are two highly sensitive methods for chemical analysis by detecting the absorption-induced acoustic wave and refractive index change, respectively. However, there is still room for improvement compared to the most sensitive spectroscopic techniques such as cavity ring-down spectroscopy (CRDS) or noise-immune cavity-enhanced optical-heterodyne molecular spectroscopy (NICE-OHMS).

In this talk I will discuss recent advances in the development of ultra-sensitive PAS enhanced by tuning fork and optical cavity, as well as PTS enhanced by hollow-core fiber and phase-sensitive interferometry. PAS signal is proportional to the overall incident laser power (W). The most recent innovation of PAS with a double opto-acoustic resonance enables ultra-sensitive and wide-dynamic-range gas detection [1]. The merging of a high-Q-factor acoustic resonator (i.e., quartz tuning fork) with a high-finesse optical resonator leverages on a double standing wave effect. By using a mW-level QCL, the doubly resonant QEPAS sensor demonstrates ppt-level CO detection in the mid-infrared. In comparison, PTS signal is proportional to the light power density (W/m^2), which can be readily achieved in a hollow-core fiber [2]. By taking advantage of mid-infrared fiber technology, I will present our recent innovation of mid-infrared-pump near-infrared-probe PTS for trace gas sensing [3-5]. The variation of refractive index caused by the pump-laser can be sensitively detected by agile interferometric methods such as the Mach-Zehnder interferometer, heterodyne interferometer, Fabry-Pérot interferometer, and fiber mode interferometer.

11:00am **MIOMD-WeM2-17 Highly Selective Toluene Detection using Quartz Enhanced Photoacoustic Spectroscopy at λ = 13.71 µm**, ***Kumar Kinjalk***, IES, University of Montpellier, CNRS, France; *G. Menduni, A. Zifarelli, M. Giglio,* PolySense Lab, Dipartimento Interateneo di Fisica, University and Politecnico of Bari, Italy; *R. Teissier,* MirSense, France; *A. N. Baranov,* IES, University of Montpellier, CNRS, France; *A. Sampaolo,* PolySense Lab, Dipartimento Interateneo di Fisica, University and Politecnico of Bari, Italy

Among anthropogenic and natural volatile organic compounds (VOCs), benzene, toluene, ethylbenzene, and xylene isomers (commonly called BTEX) are the main sources of air pollution. The World Health Organization has classified BTEX compounds as highly aggressive cancer-causing agents, and therefore there is a high interest in developing efficient techniques for their detection.

Although optical sensors proved high performances in terms of sensitivity and selectivity, there is a lack of suitable sources emitting in the 13-15 µm wavelength range, where BTEX exhibits strong absorption features. This work demonstrates a custom-built InAs-based QCL operating at 13.71 µm and its employment in a quartz enhanced photoacoustic spectroscopy (QEPAS) sensor for detecting toluene. The fabricated QCL allowed the excitation of the absorption lines of toluene at 729.39 cm^{-1}. The QEPAS sensor employs a quartz tuning fork (QTF) excited by sound waves generated via a photoacoustic effect to detect gas traces. The QTF has a fundamental resonance frequency of f_0=12.457 kHz and a quality factor Q=22,197 at 200 Torr. A 2f-wavelength modulation detection scheme is implemented by modulating the QCL current with a frequency of $f_0/2$ and acquiring the f_0 component of the QTF using a lock-in amplifier. Starting from the obtained calibration curve and the measured noise level, a minimum detection limit of 592 ppb at 0.1s of integration time is achieved. Using the Allan deviation analysis, a detection limit of 150 ppb can be obtained at 10 s of integration time. Furthermore, the study of gas mixtures revealed no spectral interference from benzene or ethylbenzene.

11:20am **MIOMD-WeM2-19 Quartz Enhanced Photoacoustic Spectroscopy Exploiting Beat Frequency Approach for Environmental Monitoring of Pollutants**, ***Giansergio Menduni,*** PolySense Lab - Dipartimento Interateneo di Fisica, University and Politecnico of Bari, Italy

Fast and accurate monitoring of pollutant gases in the environment is critical to safeguard public health. Among different sensing solutions, quartz enhanced photoacoustic spectroscopy (QEPAS) is a highly sensitive optical technique, implementing quartz tuning forks (QTFs) to convert sound waves, produced by gas molecules when modulated light is absorbed, into an electric signal. The slow signal acquisition speed depends on the long scan time of the gas absorption feature, requiring few minutes. Furthermore, the real-time monitoring of the QTF resonance frequency (f_0) and quality factor (Q) cannot be carried out during the laser tuning range scan. In this work, the beat frequency-QEPAS (BF-QEPAS) approach was employed to both overcome these limitations and detect NO, using an interband cascaded laser emitting at a central wavelength of 5.263 µm and a 12.4 kHz custom QTF. In BF-QEPAS, a staircase ramp with a rising time of ~1s and a sinewave detuned with respect to f_0 allow exciting the QTF with an acoustic pulse. Considering the typical BF-QEPAS signal, i) the gas concentration is retrieved from the value of the first peak, ii) f_0 is measured from the time difference between the detectable peaks, and iii) Q is determined by the decay time, evaluated with an exponential fit of the detectable peaks. We achieved a minimum detection limit and a normalized noise equivalent absorption of 180 ppb at 5 ms of the lock-in time constant and $2.5 \cdot 10^{-9}$ cm^{-1}WHz$^{-1/2}$, respectively. Furthermore, the BF-QEPAS signal allows determining the f_0 with an accuracy of 0.1 Hz and the Q with a relative error of ~1%.

Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-ThM1

Detectors I

Moderator: Robert Weih, nanoplus Advanced Photonics Gerbrunn GmbH, Germany

8:20am **MIOMD-ThM1-1 Progress in Antimonide Unipolar Barrier Infrared Detectors***, **David Ting**, S. Rafol, C. Hill, A. Khoshakhlagh, B. Pepper, A. Soibel, A. Fisher, S. Keo, Y. Maruyama, t. wenger, S. Gunapala,* NASA Jet Propulsion Laboratory **INVITED**

The unipolar barrier device architecture introduced by the nBn [1] and XBn [2] has led to significantly improved performance in III-V semiconductor infrared detectors. In particular,the combination of the unipolar barrier device architecture and antimonide absorbers, including the InAsSb and the GaInAsSb bulk alloys, the InAs/GaSb type-II superlattice (T2SL), and the InAs/InAsSbtype-II strained-layer superlattice (T2SLS), has enabled a new generation of high-performance infrared detectors that can provide continuous cutoff wavelengths coverage in the short-, mid-, and long-wavelength range. Notably, focal plane arrays (FPAs) based on the mid-wavelength Ga-free InAs/InAsSb T2SLS unipolar barrier infrared detector have demonstrated a 40 – 50 K higher operating temperature than the InSb FPA, while retaining the same III-V semiconductor manufacturability and affordability benefits [3]. We will provide an overview of the progress and challenges [4] in the development of antimonide unipolar barrier infrared detectors, as well as some of their applications for NASA infrared spectral imaging needs.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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8:50am **MIOMD-ThM1-4 MWIR Resonant Cavity Infrared Detectors (RCIDs) with High Quantum Efficiency and High Frequency Response***, C. Canedy, E. Jackson, R. Espinola, C. Kim, E. Aifer, I. Vurgaftman,* Naval Research Laboratory*; V. Jayaraman, B. Kolasa,* Praevium Research*; R. Marsland, B. Knipfer,* Intraband, LLC*; M. Turville-Heitz, J. Ryu, L. Mawst, D. Botez,* University of Wisconsin*; **Jerry Meyer**,* Naval Research Laboratory

NRL recently demonstrated the first MWIR resonant cavity IR detectors (RCIDs) to exhibit high performance [1]. At resonance wavelength λ_{res} = 4.0 µm, devices with a grown GaSb/AlAsSb bottom mirror, dielectric top mirror, and absorber thickness of only 50 nm attained external quantum efficiency EQE = 34%, with linewidth 46 nm. U. Lancaster subsequently reported RCIDs with InAs absorber displaying λ_{res}» 3.3 mm and 52% EQE [2].

Here we report devices for which an *nBn* detector chip with 20 InAs/InAsSb active quantum wells and total absorber thickness 103 nm was bonded to a GaAs/AlGaAs mirror with reflectivity > 99%. The GaSb substrate was then removed, and mesas processed from the backside of the as-grown detector epitaxy. The RCID's very thin absorber allows rapid extraction of the photoexcited carriers for high frequency response. For a device with small diameter (*d* = 21 µm) for reduced capacitance, the optical heterodyne data illustrated in Fig. 1 (taken before the top dielectric mirror was deposited) confirm a 3dB response of 5.9 GHz. The EQE spectrum for a larger RCID (*d* =105 µm) was measured with an FTIR by fitting the ratio of photocurrent to measured blackbody flux through a calibrated narrowband filter (blue curve in Fig. 2). This yielded peak EQE =57% at λ_{res}= 4.618 µm,with FWHM = 31 nm. EQEs for the same device were also characterized from the photocurrent induced by excitation from a quantum cascade laser (QCL) with calibrated incident power, in independent measurements at NRL (blue points) and Intraband, LLC (red points).

9:10am **MIOMD-ThM1-6 Growth and Development of Antimony-Based III-V Detector Materials for the Regime from eSWIR to LWIR***, **Volker Daumer**, L. Kirste, R. Müller, J. Niemasz, M. Wobrock, A. Wörl, Q. Yang, R. Rehm,* Fraunhofer Institute for Applied Solid State Physics IAF, Germany

The family of the 6.1 Å-materials (InAs, GaSb, AlSb), their ternary and quaternary alloys, and the corresponding type-II superlattices (T2SLs) permit wavelength tuning over a wide spectral range in the infrared (IR). The flexibility in detector design that these materials provide, allows for sophisticated device concepts and high-performance bandgap engineered IR technology for various applications. Grown lattice matched on GaSb substrate by molecular beam epitaxy (MBE), these materials can be combined to address the requested requirements. At Fraunhofer IAF, we utilize these materials to develop IR detectors and arrays for the extended shortwave infrared (eSWIR), the mid-wavelength infrared (MWIR), the long-wavelength infrared (LWIR) and combinations thereof. For the eSWIR region from 1.7 up to 3.0 µm, where InGaAs on InP substrates suffers from a high dislocation density resulting in limited performance, InGaAsSb on GaSb is currently

under investigation for room temperature operation employing a heterojunction approach. This talk will report on fundamental material study as well as electro-optical characterization results of heterojunction diodes. For the thermal infrared in the range from 3 up to 12 µm covering MWIR to LWIR, T2SLs based on InAs/GaSb and InAs/InAsSb are developed. The activities range from basic studies up to pilot line production with detectors at TRL9. Recent advances aiming at high operating temperatures (HOT) for MWIR, enhanced quantum efficiency for LWIR and extended sensitivity combining MWIR and LWIR diodes will be presented.

9:30am **MIOMD-ThM1-8 Optically-Addressed Monolithically-Integrated Triple-Band Photodetectors Using Type-II Superlattice Materials***, Z. Ju, **Allison McMinn**, X. Qi,* Arizona State University*; S. Schaefer,* National Renewable Energy Laboratory*; T. McCarthy, Y. Zhang,* Arizona State University

Multiband photodetectors are desired in various applications, including thermal imaging, environmental resources surveying, and chemical sensing. When implementing multiband photodetectors into an FPA, reducing the number of terminals on the photodetector is necessary since an increase in terminal count reduces the detector's active area and complicates ROIC and FPA layout and device processing [1]. This talk reports the demonstration of two-terminal multiband monolithically integrated optically addressed photodetectors using InAs/InAsSb type-II superlattice (T2SL) to cover SWIR, MWIR, and LWIR, as shown by the device structure in Figure 1.

The operating principle of the optical-addressing design is to use multiple optical biases on a stack of photodiodes (PDs) connected in series to switch detection bands, as shown in Figure 1 schematically. The detecting PD becomes the current-limiting device and determines the spectral response. Our preliminary results show that the MBE-grown InAs/InAsSb T2SLs as MWIR and LWIR photodetectors are nearly perfectly strain-balanced onto GaSb, showing distinct satellite peaks and a perfect overlap of the 0 order SL peak with the substrate peak, as plotted in Figure 2. Additionally, an analytical model has been established to analyze the noise characteristics and cross-talk between bands of the optically-addressed multiband detectors.

[1] E. H. Steenbergen, Appl. Phys. Lett. **97**, 161111-161114 (2010).

9:50am **MIOMD-ThM1-10 Optimizing the Design of Type-II InAs/InAsSb Superlattices for the Incorporation of Unintentional Sb in the Tensile Electron Well***, **Marko Milosavljevic**,* Arizona State University*; P. Webster,* Air Force Research Laboratory, USA*; S. Johnson,* Arizona State University

Several strain-balanced 5.3 µm midwave and 12.0 µm longwave InAs/InAsSb superlattices are grown on (100) GaSb substrates by molecular beam epitaxy and examined using X-ray diffraction and temperature-dependent photoluminescence. A significant amount of surface Sb incorporates into the tensile InAs layer that subsequently affects the design and performance. For a given wavelength design the presence of unintentional Sb in the InAs layer i) increases the tensile electron well thickness, thereby increasing electron confinement and decreasing electron wavefunction intensity, ii) decreases hole well depth, thereby decreasing hole well width and hole confinement, and as a result iii) decreases the absorption coefficient by 8% for midwave and 11% for longwave. This is presented in Figure 1 in terms of total wavefunction overlap and that within the tensile and compressive layers for structures with and without unintentional Sb as a function of the compressive layer Sb mole fraction. The solid curves show the case with unintentional Sb and the dashed curves show the case without unintentional Sb, with the compressive layer in red, the tensile layer in black, and the total (sum of red and black) in blue. The values for the grown superlattices are shown as open circles. The measurements and calculations are for an operating temperature of 77 K.

The grown superlattice tetragonal distortion ranges from -0.019% to 0.020% with a -0.001% average for midwave and from 0.021% to 0.039% with a 0.027% average for longwave. A combination of X-ray diffraction and photoluminescence is utilized to determine that the unintentional Sb mole fraction in the tensile layer is 1.9% for midwave and 1.2% for longwave.

Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-ThM2

Detectors II

Moderator: David Ting, NASA Jet Propulsion Laboratory

10:30am **MIOMD-ThM2-14 Top-Illuminated Mid-IR HgTe Colloidal Quantum Dot Photodiodes***, **John Peterson**, P. Guyot-Sionnest,* The University of Chicago

Colloidal quantum dots offer an inexpensive, solution-processed alternative to conventional, crystalline material devices for mid-infrared photodetection. pn-junction devices using HgTe quantum dots previously reached the background limit at cryogenic temperatures. These devices have since shown increased effective operating temperatures. [1] [2] For use in thermal imaging arrays, devices must be developed which are illuminated from the top.

The focus of this work is to understand and improve the performance of top-illuminated HgTe quantum dot photodiodes. Signal collection is a function of series resistance, diffusion length, and thin film absorption, and all can be improved separately for higher operating temperatures. We show results with a bottom n-type reflector contact, varying thicknesses of HgTe films of different mobility and doping profile and a semi-transparent metallic top electrode, made in a process compatible with integration into silicon readout chips. We also show an analysis of the temperature and photon flux dependence of the diode current, to gain insight into the dominant recombination mechanisms present in the device and the nature of the shunt resistance.

10:50am **MIOMD-ThM2-16 Synthesis of HgTe Colloidal Quantum Dots and Processing of Films to Maximize Photodetector Performance***, **Philippe Guyot-Sionnest**,* University of Chicago

Since 2011, HgTe colloidal quantum dots have been researched for infrared photodetection in the MWIR,[1] but also in the SWIR and LWIR. They are readily tunable in the MWIR by controlling the size around 12 nm as shown in Fig. (a). The detector performances are still below those of single crystal and epitaxial materials, but the solution processing promises high throughput and low-cost fabrication of simple detectors and imagers. Our goal is to raise the performance of 4.5 microns HgTe quantum dot at 300K to match polycrystalline PbSe ($D^*=10^{10}$Jones), for fair and fast thermal imaging at room temperature, and another related goal is to raise the BLIP temperature to thermolelectric temperatures.

This presentation focuses on the measurements of optical absorption, carrier mobility, and carrier lifetime of MWIR HgTe colloidal quantum dots, and how these properties inform the best possible performance achievable. Simple experimental methods based on photoconductors, as shown in Fig. (b), allow to obtain these properties.[2] Then we distinguish film preparations that use non-polar inks or polar inks of quantum dots.While both can give similar carrier mobility after mild annealing, the carrier lifetime is retained in one instance, while the carrier lifetime is shortened by trapping in the other. Such a study indicates clearly which is the better process, and leads to improved device performances as shown in Fig (c).

11:10am **MIOMD-ThM2-18 Exploring Quantum Dots/Graphene van der Waals Heterostructures for Uncooled SWIR-MWIR Detection***, **Judy Wu**,* University of Kansas

Semiconductor quantum dots/graphene (QD/Gr) heterostructures provide a quantum sensor scheme for photodetection and have witnessed remarkable progress in broadband photodetection. The QD/Gr photodetectors take advantages of the quantum confinement in QDs for spectral tunability and that in graphene for superior charge mobility to enable a high photoconductive gains or high photoresponsivity. A key question on whether high detectivity (D*) may be achieved in uncooled QD/Gr photodetectors in infrared (IR) spectrum is whether thermal noise in narrow bandgap semiconductor QDs in the QD/Gr photodetectors would degrade the detector performance in a similar way to conventional IR detectors based on semiconductor films and therefore demand cryogenic cooling to reduce the thermal noise. In order to answer this question, this talk presents our recent investigation on the noise origin of the QD/Gr heterostructures in the short-wave to middle-wave (SWIR-MWIR) spectra.Interestingly, it is found to be dominated by the noise in graphene either in dark or illuminated by SWIR-MWIR illumination. Furthermore, it has been found that the narrow-bandgap semiconductor QDs may be designed to reduce the noise towards the intrinsic limit in graphene by shifting its Fermi energy towards the Dirac point. Through development of atomic-scale surface and interface engineering approaches for optimize QD/Gr interface, uncooled $D^* > 10^{11}$ Jones at wavelengths of 2.25-3.25 mm has been achieved. This result reveals a different noise origin in the QD/Gr heterostructures, which is not directly affected by the thermal noise in narrow-bandgap semiconductor QDs. Therefore, QD/Grheterostructures may provide a promising low-cost, scalable scheme for uncooled SWIR-MWIR detection.

11:30am **MIOMD-ThM2-20 Core-Shell Pbse/CdSe Quantum Dot Mid-Infrared Photoconductor***, **Milad Rastkar Mirzaei**, Z. Shi,* University of Oklahoma

Reducing Size, Weight, Power consumption, and Cost (SWaP+C) while maintaining good range and resolution has been the key goal for focal plane array (FPA) imagers. In mid-wave infrared (MWIR), a low SWaP+C imager with fast response time is highly desirable for many applications such as small unmanned aerial vehicles, smart munitions, and missile defense. Elimination of bulky and expensive cryogenic cooling systems and monolithic integration on Si readout integrated circuitry (ROIC) to reduce fabrication cost and to increase yield become two essential requirements for low SWaP+C MWIR imagers. Polycrystalline IV-VI semiconductor PbSe photoconductor (PC) meets both requirements and thus has been used by for years. However, one key challenge for the current PbSe PC FPA is the inhomogeneity of polycrystalline film which requires ROIC to perform non-uniformity correction on pixels and thus increases the power consumption and cost.

In this study, we report a novel threading core-shell PbSe/CdSe quantum dots (QDs) (QD Shish Kebab) room-temperature MWIR detector with much-improved homogeneity. The detector is grown on a SiO_2/Si substrate which enables monolithic integration of FPA on Si ROIC. We have optimized the QDPC's layer thickness, Core to shell ratio, and the total number of layers to improve its performance. The cutoff wavelengths can be tuned with different QD sizes.

To evaluate the performance of the QDPC, we have performed various characterization measurements, including current-voltage (IV) measurements, and blackbody radiometric measurements. The charge separation model is used to explain the QD 3-dimensional (3D) Shish Kebab detector structure.

The successful demonstration of our 3D network Core-Shell PbSe/CdSe nano-structured Photoconductor with improved homogeneity will have significant implications for many applications including large-format FPA monolithically integrated on Si ROIC with small pixel size.

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Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-ThA1

Materials for Mid-Infrared

Moderator: Benjamin S. Williams, University of California Los Angeles

1:30pm **MIOMD-ThA1-1 Tensile-Strained InGaAs Quantum Dots with Interband Emission in the Mid-Infrared***, K. Vallejo,* ***Trent Garrett****,* Boise State University*; C. Cabrera-Perdomo,* Universidad Autónoma de Zacatecas, Mexico*; M. Drake,* Boise State University*; B. Liang,* UCLA*; K. Grossklaus,* Tufts University*; P. Simmonds,* Boise State University

Novel routes by which to produce tunable light sources operating in the mid-infrared are desirable for a wide range of applications. Quantum cascade approaches produces devices with excellent device characteristics but these structures are complex and time consuming to create. An alternative could be to use tensile strain as a way to reduce the band gap energy of semiconductors such as InGaAs, and push their emission deeper into the IR. We will discuss our efforts to use tensile-strain to drive the self-assembly of $In_{1-x}Ga_xAs$ quantum dot (QD) nanostructures on GaSb(111)A surfaces. The highly localized tensile strain stored in these QDs modifies the InGaAs band structure to red-shift the photon emission wavelength by ~2000 nm. We have determined a robust set of growth conditions for the self-assembly of the tensile-strained InGaAs QDs. During molecular beam epitaxy (MBE), InGaAs QDs form spontaneously on GaSb(111)A, seemingly with less than 1 ML deposited, indicating a Volmer-Weber growth mode. We characterized these nanostructures using atomic force microscopy (AFM), transmission electron microscopy (TEM) and energy-dispersive X-ray spectroscopy (EDS) to understand InGaAs/GaSb(111)A QD structure as a function of the MBE growth conditions. A combination of photoluminescence (PL) spectroscopy and computational modeling shows that residual tensile strain in the QDs reduces the InGaAs band gap energy, to produce band-to-band light emission at 3.2–3.9 µm (Figure 1). When coupled with quantum size effects, the use of tensile strain to red-shift QD emission offers an attractive way to create highly tunable mid-IR light sources.

1:50pm **MIOMD-ThA1-3 Broadband Room-Temperature Mid-Infrared Detection with Nanoparticles***, C. Wang,* Nanyang Technology University, Singapore*; L. Liang,* Nanyang Technological University, Singapore*; J. Chen, X. Liu,* National University of Singapore*;* ***Qijie Wang****,* Nanyang Technology University, Singapore **INVITED**

By utilizing ratiometric luminescence, which can be modulated at MIR radiation under ambient conditions, a novel lanthanoid nanocrystal-based transducers for broadband mid-infrared (MIR) sensing is created. The high photostability and simplicity of processing provide opportunities for developing low-cost, scalable MIR imaging and spectroscopy techniques with unprecedented sensitivity.

2:20pm **MIOMD-ThA1-6 Bi-Layered Silicon with Strain-Induced Tunable Optical Properties for IR Applications***, K. Vishal,* ***Yan Zhuang****,* Wright State University

The compatibility with the main-stream silicon technology makes silicene and a few layers of silicon very promising for VLSI beyond 3nm technology node. Similar as its carbon counterpart graphene, energy bandgap (EB) opening presents the most critical demand for potential applications in digital electronics. Based on density function theory, EB opening in bi-layer silicon structures (BLSi) has been obtained under biaxial in-plane strain in our previous works [1, 2]. In this work, we performed a theoretical study of the optical properties of the strained BLSi in mid-IR. It turns out that by applying the in-plane tensile strain, the optical properties of the BLSi can be tuned in a wide range over the entire mid-IR bandwidth.

Our previous works show that buckle-free bilayer silicon structure (Fig.1) can be obtained once the biaxial in-plan tensile strain exceeds 11.2% [1, 2]. As the in-plane strain continuously increases to 16.4%, a direct EB (E_{g_D}) is formed at G point in addition to the in-direct EBs (E_{g_ID}) (Fig.2), which promotes direct band transition at IR. To verify it, various optical properties including permittivity, refraction index, and optical conductivity of the BLSi have been calculated versus photonic energy at different strain levels. Figure 3 plots the complex in-plane permittivity of the BLSi under an in-plane strain of 14.8%. The observed absorption (P1 marked in Fig. 3) evidences the direct-band transition. By varying the applied strain, such featured absorptions can be tuned in the range between 0.154-1.056 eV, which covers the entire mid-IR (See supplementary pages). In addition to the featured absorptions, its real part of the permittivity in Mid-IR (<0.2 eV) is of a factor 3 greater than the fully relaxed BLSi, leading to two times enhancement of reflectance. We believe that the buckle-free planar BLSI might open new opportunities of applications at IR.

2:40pm **MIOMD-ThA1-8 Growth and Optical Properties of InGaAs QW on c-plane Sapphire for Laser Development***,* ***Subhashis Das****, R. Kumar, F. Maia de Oliveira, Y. Mazur, W. Du, S. Yu, G. Salamo,* University of Arkansas

Epitaxial growth of III-V semiconductors on c-plane sapphire would potentially allow the integration of microwave photonics on a single sapphire chip. We will report on the growth of high-quality crystalline InGaAs quantum well on a trigonal c-plane sapphire substrate by molecular beam epitaxy (MBE). For fabrication on sapphire, an AlAs nucleation layer was followed by a two-step GaAs growth method including an early-stage low temperature (LT) GaAs layer and a high-temperature GaAs growth layer. The high temperature GaAs buffer growth incorporates two annealing steps during the growth. An InGaAs quantum well (QW) with GaAs cap layer was epitaxially grown on the 70 nm GaAs buffer. We will discuss the surface morphology, structure quality, and the optical properties of the MBE grown samples. Two structures with 20 nm wide quantum well (QW), S1 and S2, were grown with indium molar fraction of 0.15 and 0.10, respectively. The QW energy transitions were observed at 1.46 eV and 1.48 eV from low temperature (10 K) photoluminescence spectra. Excitingly, the optical results were comparable with the same structure grown on a GaAs substrate. Overall, these observations exhibit potential to achieve an integrated microwave photonic chip on a sapphire platform.

3:00pm **MIOMD-ThA1-10 Low-Loss Infrared Ultrawide Type II Hyperbolic Metamaterials based on III-V Semiconductors***,* ***Weerasinghe Priyantha****,* Amethyst Research Incorporated*; E. Caudill, C. Cailide,* University of Oklahoma*; M. Lloyd, J. Murphy,* NRL*; K. Arledge, T. Mishima,* University of Oklahoma*; J. Nolde, J. Frantz, C. Ellis,* NRL*; T. Golding,* Amethyst Research Incorporated*; M. Santos, J. Tischler,* University of Oklahoma

While polar dielectric materials provide natural low-loss infrared hyperbolic resonances through the excitation of phonon polaritons, the operational bandwidth of these materials is limited to a few hundred wavenumbers (cm-1) or tenths of electronvolts. Also, integrating these materials with large-scale infrared optoelectronic devices presents many challenges. In this work, we implemented an ultrawide low-loss Type I hyperbolic metamaterial covering a spectral bandwidth of 2000 cm-1 for wavelengths above 4.7 µm. We produced the hyperbolic metamaterial with a stack of intercalated heavily-doped InAs and undoped InAs epilayers grown by molecular beam epitaxy. The InAs epilayer was heavily doped with Tellurium to obtain electron concentrations of ~8×1019 cm-3. The Type II hyperbolicity of these stacks was determined through infrared ellipsometry obtaining effective optical constants for the stacks. These materials were then dry etched to form one-dimensional (1D) square gratings with periods and linewidths ranging from 1 to 5 µm. The measured effective optical constants measured through ellipsometry were used to model the grating's optical response by finite element electromagnetic calculations (COMSOL). The models agree with measurements, showing the formation of hyperbolic plasmon polaritons at the same frequencies where experimental features were observed. This work demonstrates that high subdiffractional light confinement can be achieved with a III-V metamaterial that can be integrated with III-V semiconductor infrared devices such as photodetectors and emitters at a large scale.

This material is based upon work supported by the Office of the Undersecretary of Defense for Research and Engineering Basic Research Office STTR under Contract No. W911NF-21-P-0024. Disclaimer: The content of the information does not necessarily reflect the position or the policy of the Government, and no official endorsement should be inferred.

Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-ThA2

Metamaterials and Polaritons

Moderator: Lukasz Sterczewski, Wroclaw University of Science and Technology, Poland

3:50pm **MIOMD-ThA2-15 A 231 GHz Generation in High-Power Long-Wavelength Quantum Cascade Laser Operating at Room Temperature***,* ***Shohei Hayashi****, A. Ito, T. Dougakiuchi, M. Hitaka, A. Nakanishi, K. Fujita,* Hamamatsu Photonics K.K., Japan

The extension of the operating range on the low-frequency side down to <300 GHz in a terahertz nonlinear quantum cascade laser source based on intracavity frequency mixing in a long-wavelength (~13.7 µm), high-performance mid-infrared active region was achieved. The device was fabricated two section distributed feedback gratings with slightly different periods in order to obtain quite close dual mid-infrared laser pumps (λ_1 ~13.53 µm and λ_2 ~13.39 µm), achieving an emission at a frequency of 231 GHz as the difference frequency at room temperature. This is the lowest operating frequency in electrically pumped monolithic semiconductor laser sources operatable at room temperature.

4:10pm **MIOMD-ThA2-17 Mapping Surface Phonon Polaritons with Near-IR Light**, ***Kiernan Arledge**,* The University of Oklahoma*; M. Meeker,* U.S. Naval Research Laboratory*; C. Ellis,* U.S. Naval Research Lab*; N. Sarabi, V. Whiteside,* The University of Oklahoma*; C. Kim, M. Kim, D. Ratchford, B. Weng,* U.S. Naval Research Laboratory*; J. Tischler,* The University of Oklahoma

Surface phonon polaritons (SPhPs) show great promise for tailoring light-matter interactions in systems below the diffraction limit. Investigating SPhP modes has mostly been pursued by measuring the energy resonances of these modes (i.e., eigenvalues). In other instances the study of SPhPs has been accomplished, by mapping electromagnetic fields (i.e., eigenstates) only at the material interface by atomic force assisted techniques, and in some limited cases measuring the three-dimensional fields using electron scattering. An accurate knowledge of SPhPs has been hindered by the lack of experimental techniques to map eigenstates in three dimensions, that are easy, cheap, and non-destructive. In this work we demonstrate the direct experimental measurement of infrared SPhPs eigenstates through three-dimensional Raman mapping. We apply this technique to map SPhPs in nanopillars of Indium Phosphide (InP). Furthermore, we demonstrate that SPhPs couple to bulk Raman modes through the material's polarizability and to a lesser extent via electron-phonon coupling. These observations provide a new method for measuring SPhP modes in nanostructured materials, as well as a novel way to investigate the physical phenomena involved in the coupling of bulk phonons to SPhPs.

4:30pm **MIOMD-ThA2-19 Surface Phonon Polariton Coupling to 4H SiC Triangular Gratings Produced by Two-Photon Polymerization**, ***Nazli Rasouli Sarabi**, V. Whiteside,* University of Oklahoma*; E. Cleveland, E. Seabron, C. Ellis,* Naval Research Laboratory*; J. Tischler,* University of Oklahoma

Surface phonon polaritons (SPhPs) are a promising alternative to plasmon polaritons for localizing mid-IR to terahertz light in the nanoscale with low optical loss and higher quality factor. However, to excite SPhPs modes on the crystal surface, additional in-plane momentum needs to be added with methods such as grating coupling or evanescent fields from prism internal reflections. Previous work on square gratings has been limited by unwanted spatial frequencies and difficulty adding desired spatial frequencies, limiting their functionality [1]. Here, we propose using sinusoidal gratings as a Fourier surface to couple input light to surface modes and design the diffractive properties of the surface accordingly. Two-photon polymerization enables the creation of 2.5D metasurfaces of arbitrary shape on various materials.

In this work, we demonstrate the ability to produce metallic-like triangular one-dimensional gratings using a Photonic Professional GT2 Nanoscribe. We produced 4H SiC triangular gratings that support surface phonon polariton resonances within the Reststrahlen band of SiC between 797 cm-1 and 972 cm-1. Gratings were produced by etching a grayscale mask into the SiC substrate, resulting in triangular gratings with periods varying from 1 to 6.2 µm and heights varying from 0.3 to 2 µm. The Q factors of the resonances within the Reststrahlen band were in the range of 50-110, as expected from a low-loss phonon polar dielectric. To understand the origin of these surface phonon polariton resonances, we performed finite element calculations using COMSOL showing good agreement between theory and experiment.

[1] Caglayan, Humeyra, et al. "Near-infrared metatronic nanocircuits by design." Physical review letters 111.7 (2013): 073904.

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4:50pm **MIOMD-ThA2-21 Dielectric Resonances in Hexagonal Boron Nitride Nanodisks**, ***Milad Nourbakhsh**,* University of Oklahoma*; H. Ling,* University of California at Los Angeles*; V. Whiteside,* University of Oklahoma*; A. Davoyan,* University of California at Los Angeles*; J. Tischler,* University of Oklahoma

High-index nanomaterials play a substantial role in the enhancement of optical effects based on electric and magnetic Mie resonances. While hexagonal boron nitride (hBN) has been heavily explored within the Reststrahlen bands (RB) as a natural hyperbolic phonon polariton material [1], close to the transversal optical modes outside the RB the dielectric constant has extremely high positive values. The latter provides the opportunity of producing dielectric resonators with very large dielectric constants. We report infrared Mie resonances of hBN nanodisks (NDs). Reflection and transmission spectra of hBN NDs of different sizes have been investigated to understand Mie resonances within the infrared range. We show the presence of a strong magnetic dipole resonance which energy and strength depends on the size and geometry of the hBN NDs as well as the substrate properties. Finite element modeling of the electromagnetic fields has been performed and is in excellent agreement with our experimental results. Numerical and experimental data have indicated that by selecting the proper substrate thickness and hBN NDs radius, much more prominent Mie resonances are achieved. Mie resonances provide an opportunity to easily manipulate light confinement for the design of optical devices such as nanoresonators, nanolasers, highly efficient metasurfaces and ultrafast metadevices.

[1] Caldwell, Joshua D., et al. "Sub-diffractional volume-confined polaritons in the natural hyperbolic material hexagonal boron nitride." *Nature communications* 5.1 (2014): 5221.

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5:10pm **MIOMD-ThA2-23 Closing Remarks**,

Author Index

Bold page numbers indicate presenter

Author Index