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

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

Moderator: Minh Nguyen, HRL Laboratories

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

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

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

References

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

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

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

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

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

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

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

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

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

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

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

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

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

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