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.

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