NAMBE
Room Tamaya ABC - Session NAMBE2-MoA
Infrared Materials

Moderator: Aaron J. Muhowski, Sandia National Laboratories

3:30pm **NAMBE2-MoA-9 James S. Harris MBE Scientific Discovery Awardee Talk***,* **INVITED**

4:00pm **NAMBE2-MoA-11 Deep Level Transient Spectroscopy and Time-Resolved Photoluminescence as a Function of Room Temperature 63 MeV Proton Irradiation of Inas Nbn Detectors Grown by Molecular Beam Epitaxy***,* ***Rigo Carrasco,*** Air Force Research Laboratory, USA*; Christopher Hains, Alexander Newell, Christian Morath, Preston Webster,* Air Force Research Laboratory*; Evan Anderson,* Sandia National Laboratory

A semiconductor material's technology readiness for space-based sensing applications is largely dictated by its detection capability, where a holistic examination of the material's detector dark current and quantum efficiency determines its sensitivity. One of the most significant detriments to a detector's performance are crystalline defects that introduce deep levels within the band gap that act as recombination centers. These defects can naturally arise during semiconductor growth, and over the course of a detector's space-based mission life from exposure to cosmic rays, high energy ions in the Van Allen belts and magnetosphere, and solar events. These defects lead to a decrease in the minority carrier lifetime which yields a corresponding increase in dark current and decrease in quantum efficiency. As a result, there is motivation to investigate candidate materials' minority carrier lifetimes and corresponding defect character both before and after high energy proton irradiation to characterize the materials-level factor that inhibits detector performance throughout its mission life.

Here, we report the defect characteristics of an InAs *nBn* detector structure grown by molecular beam epitaxy. The detector structure's minority carrier lifetime is examined by time resolved photoluminescence and the defect character is assessed by deep level transient spectroscopy. Deep level transient spectroscopy is carried out using a medium-frequency impedance analyzer to collect the time-resolved capacitance transients over temperatures ranging from 10-300 K. Analysis of the transient data indicates the presence of one defect level with an activation energy greater than the InAs bandgap energy (~650 meV) which is shown to be due to a defect in the AlGaAsSb barrier, and another level with a ~30 meV activation energy in the InAs. The concentration of the latter defect is then shown to increase monotonically with each step dose of room temperature 63 MeV proton irradiation. The minority carrier lifetime is also measured as a function of step-wise proton fluence to evaluate the lifetime damage factor, to compare with the 30 meV irradiation-dependent defect level identified in the deep-level transient spectroscopy analysis. The results are analyzed alongside dark current and capacitance-voltage measurements of the InAs *nBn* to tie the results of both techniques to typical device benchmark measurements. A discussion on synthesizing the results from these two techniques will be provided, giving a characterization suite that can provide a materials-level connection to device performance. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

4:15pm **NAMBE2-MoA-12 Evaluation of the Optical Absorption Properties of MBE Grown InAs/InAsSb and InGaAs/InAsSb Superlattices for Infrared Photodetector Applications***,* ***Marko Milosavljevic,*** Arizona State University*; Rigo Carrasco, Alexander Newell,* Air Force Research Laboratory, USA*; Jaden Love, Stefan Zollner,* New Mexico State University*; Christian Morath, Diana Maestas, Preston Webster,* Air Force Research Laboratory, USA*; Shane Johnson,* Arizona State University

Several midwave (3 - 5 µm) and longwave (8 - 12 µm) type-II InAs/InAsSb and InGaAs/InAsSb superlattices are grown by molecular beam epitaxy and investigated using spectroscopic ellipsometry.The work evaluates the absorption edge and the refractive index of these superlattice materials for photodetector design and performance.In particular, the absorption edge position, width, and absorption intensity determine the photodetection wavelength range and the photodetector material thickness required to achieve optimal detectivity.

A Kramers-Kronig consistent model for the refractive index and absorption coefficient in the vicinity of the fundamental bandgap of the superlattice miniband structure is developed.A fit of this model to the raw ellipsometric data establishes the bandgap energy, the magnitude of the absorption coefficient at the bandgap, the characteristic energy width of Urbach tail below the bandgap, and the impact of the Coulomb interaction, all of which determine the shape of the absorption edge.The absorption coefficient is modeled using an Urbach-tail absorption edge coupled to the observed power law behavior of absorption above the bandgap.The refractive index is modeled using a long wavelength pole oscillator and a Cauchy integral over the absorption coefficient model, which as well mirrors the shape of the absorption edge and provides the energy position of the transverse optical phonon absorption peak that typically occurs at energies below the measurement range.Measuring the optical constants of superlattices is challenging since they contain a large number of interfaces and must be grown thick to ensure enough periods to determine the optical properties of the miniband structure.For the samples measured, this results in the presence of spurious periodic interference peaks in the optical constants extracted using a point-by-point fit.Multi-sample fits to the same midwave superlattice structures grown at various thicknesses significantly reduces the presence of the interference peaks and in general improves the fit to the model and the extraction of the key absorption edge parameters.

In comparing the superlattice results, the shorter period InGaAs/InAsSb superlattices exhibit stronger absorption with a broader absorption tail compared to the InAs/InAsSb superlattices.The shorter period superlattices have larger electron-hole wavefunction overlap, but with a greater number of frozen-in tail states that result from alloy and interface disorder at the superlattice interfaces.These results are compared and evaluated with additional measurements of thick bulk layers of the superlattice binary and ternary constituents.

4:30pm **NAMBE2-MoA-13 Tunable Low-Loss Plasmonic Resonances in Heavily-Doped InAs for Infrared Optoelectronic Devices***, Thomas Shearer, Ethan Caudill, Kiernan Arledge, Tetsuya Mishima,* University of Oklahoma*; Chadwick Canedy, John Murphy, Jill Nolde, Chase Ellis,* US Naval Research Laboratory*; Priyantha Weerasinghe,* Amethyst Research Inc.*; Michael Lloyd,* NIST-Gaithersburg*; Terry Golding,* Amethyst Research Inc.*; Igor Vurgaftman, Jerry Meyer,* US Naval Research Laboratory*;* ***Michael Santos****, Joseph Tischler,* University of Oklahoma

Metals like gold, silver, and aluminum, which have a plasma frequency in the ultraviolet, have traditionally been used for plasmonic enhancement of optoelectronic devices such as emitters and detectors of visible light. However, these metals are of limited use for infrared plasmonic enhancement due to losses that become increasingly high at frequencies far below the plasma frequency. We have explored the use of heavily-doped InAs as a low-loss conductor for plasmonic enhancement of infrared devices. The infrared plasma frequency of InAs can be tuned by *n*-type doping and this plasmonic material can be monolithically integrated with III-V infrared optoelectronic devices during growth by molecular beam epitaxy (MBE).

Heavily-doped InAs layers were grown in three separate MBE systems using either Te or Si as the *n*-type dopant. The surface morphology was assessed by optical microscopy and atomic force microscopy. The plasma frequency and optical scattering rate were determined by fitting ellipsometry measurements as a function of infrared wavelength. A plasma frequency corresponding to an infrared wavelength of 4.5 to 10.5 µm in air was obtained for an electron concentration between 6.0 and 0.9×10^{19} cm^{-3}. A trend of deceasing optical scattering rate (1500 to 500 cm^{-1}) was observed as the plasma frequency was increased, or equivalently as the plasma wavelength was decreased (10.5 to 4.5 µm).

The doped InAs materials were photolithographically patterned and dry etched to form one-dimensional gratings with several pitches and linewidths up to 5 µm. Reflectivity measurements were performed using a Fourier transform infrared spectrometer equipped with an infrared microscope. Several plasmonic resonances were observed with up to 95% absorption and quality factors around 7. Modeling by finite-element electromagnetic calculations (COMSOL) confirmed that the experimental results demonstrated tunable low-loss plasma resonances at infrared frequencies.

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4:45pm **NAMBE2-MoA-14 Impact of Uncracked Group V Species on Unintentional Doping in AlInAsSb**, ***Ellie Wang***, *J. Andrew McArthur,* University of Texas at Austin; *Hannaneh Karimi, Joe Campbell,* University of Virginia; *Seth Bank,* University of Texas at Austin

$Al_xIn_{1-x}As_ySb_{1-y}$ (referred to as AlInAsSb) grown as a digital alloy by molecular beam epitaxy (MBE) has been shown to have characteristics useful for avalanche photodetectors (APD) operating in the near- to mid-IR. In addition to a broadly tunable bandgap over a wide compositional range, the material system has favorable band offsets and exhibits low excess noise due to low impact ionization coefficient ratios [1]. However, another consideration is the unintentional doping (UID) concentration, which depends on factors in the system, such as the source material and growth temperature, and is susceptible in the digital alloy due to the complex layers and interfaces. This important factor influences characteristics such as the electric field profile, depletion, and mobility [2]. We have previously shown UID reduction in AlInAsSb by outgassing the MBE source material [3]. Another potential avenue is through the group-V sources, such as by using As_4 instead As_2. Not only does As_2 contain contaminants such as sulfur that can contribute to impurity concentrations, but lowering the cracker temperature in the cell could also reduce the outgassing of impurities during growth [4,5].

Here, we compare the effects of As_4 and As_2 on the UID concentration of InAlAs on InP. InAlAs PIN diodes containing each arsenic species were grown by MBE on semi-insulating InP substrates. The transition from As_2 to As_4 was achieved by reducing the cracker temperature in the two-zone effusion cell. High-resolution X-ray diffraction ω-2θ scans indicated nominal strain-balancing to the substrate. Devices were fabricated, and capacitance-voltage characteristics were measured at room temperature to calculate carrier concentration versus depletion depth. A ~2-fold reduction in UID was observed, with a carrier concentration of $\sim 1\times10^{17}$ cm^{-3} in the As_4 device versus $\sim 4\times10^{16}$ cm^{-3} in the As_2 device. Dark and light current-voltage characteristics were also collected. While both devices showed comparable photoresponse, the onset of tunneling in the As_4 device was increased by >20%; importantly, just prior to breakdown of the As_2 device (-16 V), the dark current was an order of magnitude lower for the As_4 device. These results suggest that using As_4 is a feasible path to enhance APD sensitivity by decreasing the UID. Further reduction is anticipated through the antimony species, and additional investigation of the effects on digital alloys are in progress. This work was supported by DARPA and ARO.

[1] S. R. Bank, et al. *JSTQE,* 2018. [2] D. Chen, et al. *APL,* 2021. [3] J. A. McArthur, et al. *ACS Crys. Gr. and Des.* (submitted).[4] B. J. Skromme, et al. *J. Appl. Phys.*, 1985. [5] R. Chow, et al. *JVSTB,* 1990.

Author Index

Bold page numbers indicate presenter