NAMBE
Room Cummings Ballroom - Session NAMBE2-WeM
IR Materials and Devices (and SiGeSn)

Moderator: Carolina Adamo, Northrop Grumman

10:45am **NAMBE2-WeM-11 Characterization of Random Alloy $Al_{0.85}Ga_{0.15}As_{0.07}Sb_{0.93}$ for Mid-Wave Infrared Avalanche Photodiodes**, ***Nathan Gajowski***, *M. Muduli, T. Ronningen, S. Krishna,* Ohio State University

The success of Short-Wave Infrared (SWIR) linear mode Avalanche Photodiodes (APDs) has created a growing interest in creating Mid-Wave Infrared (MWIR) photodetectors with gain.Creating effective MWIR linear mode APDs has the potential to increase the signal to noise ratio of an infrared receiver system by reducing the effect of the read-out circuit noise.To reduce the Size, Weight, Power, and Cost (SWaP-C) of these systems, III-V solutions are being researched as an alternative to the industry standard Mercury Cadmium Telluride (MCT) devices which must operate at low temperatures that require bulky and costly cryogenic cooling.These III-V APDs implement a Separate Absorption Charge and Multiplication (SACM) design to achieve these higher operating temperatures.III-V material systems also offer the advantage of higher yield and therefore lower production cost than MCT devices.AlInAsSb on GaSb has shown promise as an electron multiplier but has a high conduction band offset electrons must overcome when transiting from the MWIR absorber to the multiplier region.This band offset requires complicated grading to enable the carrier transport.AlGaAsSb on GaSb is alternative multiplier in which hole impact ionization dominates, and there is very little valence band offset between the required absorbers.The impact ionization coefficients of high band gap AlGaAsSb on GaSb have been reported, but only for thin multiplication regions [1].In this study, we grew 600 nm thick $Al_{0.85}Ga_{0.15}As_{0.07}Sb_{0.93}$NIP and PIN devices to study the gain properties in thick layers of this material. One of the key parameters that we want to optimize is the background concentration. A low background concentration is required to maintain a flat electric field profile in the multiplier. We chose to study a thicker multiplier as thicker layers of AlAsSb on InP have shown reduced excess noise over thin layers despite the dead space effect [2].

The $Al_{0.85}Ga_{0.15}As_{0.07}Sb_{0.93}$material was grown using MBE as a random alloy for simplicity with a growth rate of 1 µm/hr at 500 °C.Using ex-situ material characterization feedback, the optimal total V/III and As/Sb BEP flux ratios were determined to be 4.8 and 16.8, respectively.We achieved a background doping of $<1x10^{16}$ cm^{-3}as extracted from capacitance measurements.Sub 2 Å RMS surface roughness's were achieved for device growths with 20 nm GaSb caps over a 5x5 µm area as measured by atomic force microscopy.Devices were fabricated and tested using dark and illuminated current-voltage (IV) measurements to extract the gain mechanics of the material.

11:00am **NAMBE2-WeM-12 Comparison Study of InAs/InAsSb and InAs/GaSb Type-II Superlattices**, ***Allison McMinn***, *Z. Ju, X. Liu, Y. Zhang,* Arizona State University

Type-II superlattices (T2SLs) have been extensively studied for their IR applications in sensing and imaging. An early T2SL of interest was InAs/GaSb, which is predicted theoretically to have superior performance to leading HgCdTe technology [1]. Utilizing conventional InAs/GaSb T2SLs in photodetector applications has become challenging due to the short carrier lifetime of ~ 90 ns [2]. An alternative, Ga-free InAs/InAsSb T2SL was discovered experimentally to have improved performance over conventional InAs/GaSb T2SLs due to its much-improved carrier lifetime [3]. To our knowledge, a direct experimental comparison of these two T2SL materials has not been reported in the literature. This abstract reports a side-by-side comparison of these two types of T2SLs to evaluate the differences in their fundamental material properties.

A Ga-free and a conventional T2SL structure were grown consecutively via MBE. Samples were designed with similar electron-hole wavefunction overlaps and bandgaps. A 1-µm thick absorber consisting of a Ga-free or a conventional T2SL with a 10 nm GaSb cap was grown on GaSb substrates with a GaSb buffer. HR-XRD patterns for the T2SLs show sharp satellite peaks, indicating uniform layer thicknesses of the SL periods and close strain balance between constituent layers. The Ga-free T2SL also showed a nearly perfect overlap between the substrate peak and the T2SL 0^{th} order peak.

PL spectra, measured with a FTIR spectrometer, showed a peak wavelength of 4.74 µm and 4.40 µm for the Ga-free and conventional T2SL at 12 K, respectively. The slopes of the integrated-PL-intensity vs. excitation-density plots show that radiative recombination dominates under excitation over 1 W/cm^2 at 12 K for the conventional T2SL. Over 77 K, the PL from the conventional T2SL is weak under excitations between 0.1 ~ 1 W/cm^2 and SRH recombination dominates. Above 1 excitation a mixture of SRH and radiative recombination is observed. In contrast, the Ga-free T2SL shows radiative recombination dominates under excitation between 0.1 ~ 1 W/cm^2 and Auger recombination dominates under 1 ~ 10 W/cm^2 excitation, below 77K. Additionally, SRH recombination begins to dominate at 150 K below 1 W/cm^2 in the Ga-free T2SL and radiative recombination still dominates above 1 W/cm^2. These findings are consistent with previously reported results where carrier lifetime in Ga-free T2SLs was found to be longer [3] due to low non-radiative defect density [4], so the photogenerated carrier concentration is higher than conventional T2SLs, offering an advantage in device applications. A comparison of the absorption coefficients and carrier lifetimes will be reported at the conference.

11:15am **NAMBE2-WeM-13 Use of Hydrogen Plasma to Increase Minority Carrier Lifetime in $InAs_xSb_yBi_{1-x-y}$**, *F. Estevez Hilario, M. Bergthold,* University of Texas at Austin; ***Oleg Maksimov***, *H. Bhandari,* Radiation Monitoring Devices; *C. Morath, A. Duchane, P. Webster,* Air Force Research Laboratory; *D. Wasserman,* University of Texas at Austin

$InAs_xSb_yBi_{1-x-y}$ is of interest for the fabrication of mid-wavelength and long-wavelength infrared (MWIR and LWIR) detectors. It can be grown lattice-matched to commercially available large area GaSb substrates while its bandgap energy can be tuned from 0.32 eV to 0.10 eV (4 µm to 12 µm).

$InAs_xSb_yBi_{1-x-y}$ is grown by Molecular Beam Epitaxy (MBE). However, the desired Bi incorporation into the $InAs_xSb_y$ lattice can be accomplished only at low growth temperatures of < 400 °C, below the optimal growth temperature for III-V semiconductors [1]. The low growth temperature results in the formation of point defects in the $InAs_xSb_yBi_{1-x-y}$ lattice degrading its optical quality and reducing the minority carrier lifetime. Hence, to realize $InAs_xSb_yBi_{1-x-y}$ for the fabrication of MWIR and LWIR detectors, it is essential to develop strategies for improving the minority carrier lifetimes in the low temperature grown material.

Hydrogen and its radicals (plasma) are known to react in semiconductors with broken or weak covalent bonds associated with extended and localized defect centers. These interactions can shift the energy levels of the defects out of the gap resulting in electrical passivation of defects. Hydrogen passivation was shown to be effective in increasing carrier lifetime in InAs/InAsSb superlattices [2] and improving performance of HgCdTe LWIR detectors [3].

Here, we present the use of post-growth remote hydrogen plasma treatment to improve minority carrier lifetimes of MBE-grown $InAs_xSb_yBi_{1-x-y}$ films. The process produces hydrogen concentration of 1.0 x 10^{16} atoms/cm^{3}at depth exceeding 2.5 µm. When followed by the low temperature annealing at 160 °C, it results in the 2 – 3.5 extension of the minority carrier lifetime, from ~70 ns to 170 – 220 ns, as estimated using the time resolved photoluminescence measurements. This effect remains stable over a period of months after the treatment [4].

References:

[1] Schaefer, S. T., Kosireddy, R. R., Webster, P. T., & Johnson, S. R. (2019). *J. Appl. Phys.*, *126*(8), 083101.

[2] Hossain, K., Höglund, ... & Gunapala, S. D. (2016). *J. Electron. Mater.*, *45*(11), 5626-5629.

[3] Boieriu, P., Velicu, S., ... & Hagler, P. (2013, February). *Quantum Sensing Nanophotonic Devices X* (8631, 284-303). SPIE.

[4] Estévez H, F. A., Bergthold, M., ... & Wasserman, D. (2024). Appl. Phys. Lett., 124(2).

11:30am **NAMBE2-WeM-14 Micro-Transfer Printing of Gasb-Based Infrared Devices Grown by Molecular Beam Epitaxy**, ***Margaret A. Stevens***, US Naval Research Laboratory; *A. Grede, J. Murphy,* NRC Postdoctoral Fellow at the US Naval Research Laboratory; *S. Mack,* US Naval Research Laboratory; *K. Schmieder,* Formerly US Naval Research Laboratory; *J. Nolde,* US Naval Research Laboratory

III-V-Antimonide (Sb) compounds are useful for many different infrared device applications, ranging from full spectrum photovoltaics, to eye-safe photonic power converters, to light-emitting diodes for biomedical applications. The ability to remove the III-V-Sb device from its native

substrate and heterogeneously integrate it with different materials would further support these technologies. For GaSb-based devices, heterogeneous integration is typically achieved by inverting the device, bonding the epitaxial surface to a new handle, and etching through the substrate. However, this method is not compatible with substrate reuse or additive manufacturing capabilities that could be provided with micro-transfer printing. Though complete substrate removal is undesirable in some aspects, it is typically the most successful method of separating a sample from its substrate due to the low etch selectivity between 6.1 Å semiconductors.

In this work, we demonstrate how solutions of citric-acid ($C_6H_8O_7$) and hydrogen peroxide (H_2O_2) can achieve high etch selectivities and enable micro-transfer printing of MBE-grown GaSb devices. We found mixtures of citric acid and hydrogen peroxide yield the highest etch selectivity ratio, >850, between $InAs_{0.91}Sb$ and $Al_{0.33}GaAs_{0.03}Sb$ epilayers lattice-matched to GaSb. To monitor the lateral undercut rate, 2 µm AlGaAsSb membranes were grown on top of InAsSb sacrificial and AlGaAsSb etch-stop layers and monitored by infrared microscopy. While vertical etch tests demonstrated etch rates of InAsSb at ~554 nm/min, lateral etch rates were found to be 45% slower. To decrease the overall time required to undercut the device, the temperature of the solution can be increased without negatively impacting the etch selectivity. Using these findings, photovoltaic cells and quantum-well LEDs were grown by molecular beam epitaxy on GaSb substrates. Devices were fabricated on-substrate and immersed in a solution of 1:5 $C_6H_8O_7$:H_2O_2 for selective release. The importance of the thickness of the sacrificial etch layer, the tethering scheme, and the composition of the dielectric protection layer were explored to improve the etch-release yield and device performance.

[1] M. A. Stevens, et al."Selective Etching of 6.1 Å Materials for Transfer-Printed Devices," in *IEEE 49th Photovoltaics Specialists Conference (PVSC)*(2022) 0240-0243

11:45am **NAMBE2-WeM-15 The InAsSb-based SACM APD with Hole-Initiated Multiplication***, **Egor Portiankin,** L. Shterengas, G. Kipshidze, J. Zhao, D. Donetski,* Stony Brook University/Brookhaven National Laboratory

We have designed and fabricated separate absorption, charge, multiplication (SACM) mid-infrared avalanche diodes (APD) relying on hole-initiated impact ionization. The device heterostructures were grown onto Te-doped GaSb substrates and contained 1-µm-thick nominally undoped InAs0.91Sb0.09 absorber, ~100-nm-thick Te-doped Al0.9Ga0.1As0.07Sb0.93 charge layer and 300-nm-thick nominally undoped Al0.9Ga0.1As0.07Sb0.93 multiplier terminated with ~300-nm-thick p-doped contact layers. The epitaxial wafers were processed into circular shallow etched mesa devices with windows in top contact metallization. The barrier photodetector inspired APD architecture did not require etching through absorber section. The devices were indium-soldered epi-side-up onto gold-plated submounts and characterized in temperature range from 77K to 300 K. The APDs demonstrated cutoff wavelength of 3.9 µm at liquid nitrogen temperature and showed current responsivities well above 10 A/W (Figure 1). The linear mode multiplication gains exceeding 100 were observed at voltages near 17.5 V. The dark current values of several nA have been recorded for all devices before the breakdown. The analysis of the temperature dependences of the dark current values below and above punch-through voltage confirms diffusion limited absorber operation at temperatures above 150 K (activation energy ~360 meV). Independently measured responsivities values above 10 A/W at bias voltages above 17 V.

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