Growth and characterization of AlInSb metamorphic buffers on GaAs substrates for the growth of MWIR lasers.

**REU Student:** Stephen Clark  
**Graduate Mentor:** Pankaj Ahirwar  
**Faculty Mentor:** Ganesh Balakrishnan

**Abstract**

The applications of MWIR lasers include remote sensing, LADAR, trace gas sensing, intelligence, surveillance and reconnaissance (ISR) and infrared countermeasures (IRCM). With the use AlInSb metamorphic buffers grown on GaSb, room temperature (RT) and near-room temperature operation of laser diodes has been achieved at wavelengths > 3.0 μm. The use of these antimonide metamorphic buffers has shown promise in extending the wavelength range of antimonide type-I lasers. The most successful instance of such a laser was by Pease et al. where AlInSb metamorphic buffers were used to achieve greater than 3.3μm room temperature lasing under pulsed conditions.

The growth and characterization of AlInSb metamorphic buffers grown on GaAs substrates to establish a 6.26 Å lattice constant that can then be used for the growth of >3.5 μm type-I active regions. These buffers will be characterized using a variety of techniques including X-ray diffraction, atomic force microscopy (AFM) and photoluminescence with the use of InGaSb quantum well structures to analyze the suitability MWIR lasers on AlInSb metamorphic buffers grown of GaAs substrates.

**Introduction**

A high power room temperature operation of semiconductor lasers, in the mid-wave infrared (MWIR) wavelength, has a variety of applications in remote sensing, LADAR, trace gas sensing for scientific and military applications and infrared countermeasures (IRCM). MWIR laser technology is currently being developed using different types of active regions and laser designs as well as varied materials such as lead (Pb) salts, II-VI, and III-V compound semiconductors[1-4]. Previous work done on III-V compound semiconductors with Type-I active regions specifically Al$_x$In$_{1-x}$Sb metamorphic and AlGaInAsSb quaternary buffers on GaSb substrates has shown near-room and room temperature operation of MWIR lasers at wavelengths above 2.5 μm[5-9]. Previous work on specific compositions of Al$_x$In$_{1-x}$Sb metamorphic buffers grown on GaSb substrates demonstrate promise for room temperature operation in the 3-4μm wavelengths specifically with optically pumped lasers designs[10]. Currently, under investigation is the feasibility of growing Al$_x$In$_{1-x}$Sb metamorphic buffers on GaAs substrates, because of mature substrate removal technology and a monetary incentive of growing on the cheaper growth template[11].

Due to the vast parameter space of compositions and techniques available just for metamorphic buffer growth[12], a single step growth mode and a composition of Al$_{0.64}$In$_{0.36}$Sb were chosen to create a 6.26 Å lattice constant. This buffer composition is based on desirable results from previous work done on GaSb substrates[10]. Previous
work done with engineered interfaces on GaAs such as, the interfacial misfit (IMF) interface has shown success with GaSb based 2μm VECSELs[13, 14]. Since the metamorphic buffer is AlSb instead of GaSb based, two different methods with and without the IMF interfaces will be explored to achieve an antimonide based metamorphic buffer on a GaAs substrate. The first growth method requires an initial 1000Å GaSb buffer before the Al$_{0.64}$In$_{0.36}$Sb layer and the second growth method will have no GaSb buffer, and the Al$_{0.64}$In$_{0.36}$Sb layer will be grown directly on the GaAs. The IMF GaSb buffer technique (IB) and the IMF direct buffer technique (ID) will both use the IMF engineered interface. The non-IMF GaSb buffer technique (NIB) and the non-IMF direct buffer technique (NID) will have an unadulterated interface between the GaAs and their respective antimonide layers. The different growth techniques of these Al$_{0.64}$In$_{0.36}$Sb metamorphic buffers on GaAs substrates will be characterized using X-Ray Diffraction (XRD), Atomic Force Microscopy (AFM) and Photoluminescence (PL). A major consideration when moving antimonide-based laser structures to GaAs substrates is optical properties. PL structures, consisting of a pair of Ga$_{0.5}$In$_{0.5}$Sb Quantum Well (QW) grown on the Al$_{0.64}$In$_{0.36}$Sb layer between an AlAs and AlSb confining layer, will show the viability of the different techniques for growing Al$_{0.64}$In$_{0.36}$Sb layers on GaAs.

**Experimental**

The structures were grown using a VG-80H elemental source molecular beam epitaxy (MBE) reactor. GaAs substrates were used with residual surface contaminants being removed thermally, by heating the substrates at 400°C for ~30 minutes in the preparation chamber of the MBE reactor. The substrates are then transferred into the growth chamber of the MBE reactor were the native oxide is removed at 650°C, and measured via pyrometer for ~30 minutes, until an un-obscured rough reflective high energy electron diffraction (RHEED) pattern is observed. After the oxide desorption the substrate temperature is brought down to 580°C and a GaAs smoothing layer of 1000Å is grown. For the NIB and IB the substrate temperature is reduced to 490°C after the smoothing layer, but before GaSb buffer layer. The NIB is kept in an As overpressure while the substrate temperature stabilizes. The IB requires a high temperature Sb soak before the substrate temperature is reduced to formulate the IMF interface[15-17]. After the 1000Å of GaSb is deposited the substrate temperature is brought down further to ~375°C under Sb overpressure for the Al$_{0.64}$In$_{0.36}$Sb layer. For the NID and ID the substrate temperature is reduced to the Al$_{0.64}$In$_{0.36}$Sb growth temperature of ~375°C after the GaAs smoothing layer. The NID is held in an As overpressure while the substrate temperature stabilizes. The ID requires a high temperature Sb soak before the substrate temperature is reduced to formulate the IMF interface[15-17]. Once at ~375°C, 5000Å of Al$_{0.64}$In$_{0.36}$Sb is deposited and then capped with 50Å of GaSb to prevent the oxidation of the Aluminum in ambient atmosphere. All of the different techniques had the same growth rate for the Al$_{0.64}$In$_{0.36}$Sb layer of 0.5μm/hr, and a III/V beam equivalent pressure ratio of 1:8. Since our pyrometry setup has no accurate calibration below 440°C the substrate temperature is controlled by the substrate heater thermocouple and kept constant at 450°C for all of the Al$_{0.64}$In$_{0.36}$Sb layers, with an extrapolation approximating a 350-400°C equivalence.
Results and Discussion

Using XRD scans as an indication of overall crystal quality with higher intensities corresponding to more crystalline material[18]. The four different techniques were analyzed using a $\omega$-2\(\theta\) scan in the symmetric <0 0 4> crystal lattice orientation with the scans being normalized to the GaAs substrate and converted to arcsecs for a direct comparison of peak separations for the use in simulations of the epilayer’s relaxation[18]. The 0.5 \(\mu\)m thickness of the \(\text{Al}_{0.64}\text{In}_{0.36}\text{Sb}\) layer is simulated and experimentally verified to be thick enough to achieve 100% relaxation on GaAs and still permit a GaSb peak to be visible, with the use of the GaSb buffer techniques. The relative thinness of the \(\text{Al}_{0.64}\text{In}_{0.36}\text{Sb}\) buffer generate broad scans due to how close the top layer is to the mismatched interface[19]. Figure 1(a) is an XRD comparison of the interface using the GaSb buffer technique. With the NIB’s most intense XRD peak corresponds to the \(\text{Al}_{0.64}\text{In}_{0.36}\text{Sb}\) layer with the GaSb peak clearly being less intense. The IB has a weaker

Figure 1(a) – Shows a symmetric [0 0 4] $\theta$-2\(\theta\) x-ray diffraction scan normalized to the GaAs substrate peak of the two different two step buffer techniques. With NIB technique having the stronger overall signal compared to the IB technique. The IB technique has a stronger relative peak that corresponds to GaSb.

Figure 1(b) – Shows a symmetric [0 0 4] $\theta$-2\(\theta\) x-ray diffraction scan normalized to the GaAs substrate peak of the two different single step buffer techniques. With the ID technique having the stronger overall signal compared to the NIB technique.
overall XRD intensity, but the GaSb peak is stronger than the Al$_{0.64}$In$_{0.36}$Sb peak, suggesting that a well-formed GaSb buffer negatively affects the Al$_{0.64}$In$_{0.36}$Sb layer. Figure 1(b) is an XRD comparison of the interface using the direct buffer technique. With the NID demonstrating an especially broad peak and the lowest XRD intensity while the ID comparably has one of the strongest Al$_{0.64}$In$_{0.36}$Sb peaks of all the techniques. The discrepancy in the XRD results in the direct buffer technique is from the IMF interface’s capacity for strain relief in highly mismatched layers[16]. Figures 2(a) and (b) shows the surface topography, measured by AFM, of the GaSb buffer techniques.
with the surface morphology of these films being especially rough. Regardless of the interface, both GaSb buffer techniques have large RMS roughness between 20 and 25 nm. The large surface features of these GaSb buffer techniques are haphazardly arranged on the surface. Which is caused by compressive strain from the lattice mismatch between the GaSb and Al₃₄In₃₆Sb layers. **Figure 2(c)** shows the surface topography of the NID measured by AFM, with the surface morphology and features for this technique being starkly then GaSb buffer techniques with the size and distribution of the surface defects being even and ordered. The 18-22 nm RMS surface roughness of the NID technique is comparable to that of the GaSb buffer techniques. **Figure 2(d)** is the AFM surface morphologies of the direct buffer technique (NID and ID). **Figure 2(e)** shows a well ordered surface morphology for the NID technique with an RMS surface roughness of 18-22nm. **Figure 2(d)** shows the surface morphology of the ID technique which has a RMS surface roughness of 22-25nm due to the larger defects.
topography image of the ID technique with the density of the surface defects dramatically decreased. Though the 22-25 nm RMS surface roughness is indicative of much larger surface defects. This change in surface morphology in the NIB and IB due to similar effects, with the distribution and size of defects caused by the 10.8% mismatch between the GaAs and Al$_{0.64}$In$_{0.36}$Sb layers. The change in size and density in the ID is related to how the IMF interface relieves strain.

The different methods and interfaces are characterized using PL structures consisting of a pair of In$_{0.5}$Ga$_{0.5}$Sb QWs. The PL setup consisted of 514 nm Argon Gas Laser at 500 mW was used to pump the PL structures and a cryostat using a Helium compressor to reduce the sample’s temperature to cryogenic temperatures so that the carrier lifetime is increased and carrier loss minimized. Figure 3 shows a comparison of the PL for the different growth method. The peak emission being measured at 2650 nm at 50K from the NID QWs, with the wavelength being comparable to QWs grown on GaSb substrates. The surface morphology and PL intensity are directly correlated with the less dense surfaces measuring significantly more PL intensity[19]. Figure 4 show temperature dependent PL of the NID and ID, showing that the PL is temperature dependent a strong indication of an electron bandgap. An interesting note is that the crystal quality, as determined by XRD intensity, gave no indication of the PL intensity. The NID yielded the least intense XRD but gave orders of magnitude better PL than the NIB-Technique. This discrepancy in characterization methods is most likely due to deep seeded crystal defects that the XRD is incapable of registering, such as threading.
dislocations that bypass carrier confining layers and non-radiative impurities PL measurements near impossible.

**Summary and Conclusion**

In conclusion, Al$_{0.64}$In$_{0.36}$Sb metamorphic buffers are grown on GaAs substrates using MBE. XRD verified the composition and that crystalline Al$_{0.64}$In$_{0.36}$Sb buffers could be grown. The buffers surface morphology have been characterized using AFM and found to contain surface defects that varied in size and distribution with different growth methods. The techniques that used no GaSb buffer saw a minimal reduction in RMS surface roughness but had a significant increase in the uniformity of these features. Temperature dependent PL shows the viability of QW growth on Al$_x$In$_{1-x}$Sb metamorphic buffers grown on GaAs substrates. Further optimization of the direct buffer technique could yield higher intensity in the QW PL on GaAs, expectantly reaching intensity comparable to QWs grown on GaSb substrates.


