Room-Temperature Operation of Buffer-Free GaSb–AlGaSb Quantum-Well Diode Lasers Grown on a GaAs Platform Emitting at 1.65 μm

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***Abstract*—Buffer-free growth of GaSb on GaAs using interfacial misfit (IMF) layers may significantly improve the performance of antimonide-based emitters operating between 1.6 and 3 μm by integrating III–As and III–Sb materials. Using the IMF, we are able to demonstrate a GaSb–AlGaSb quantum-well laser grown on a GaAs substrate and emitting at 1.65 μm, the longest known operating wavelength for this type of device. The device operates in the pulsed mode at room temperature and shows 15-mW peak power at $-10\ ^\circ$C and shows high characteristic temperature (T_0) for an Sb-based active region. Further improvements to IMF formation can lead to high-performance lasers operating up to 3 μm.**

***Index Terms*—GaAs, GaSb, interfacial misfits (IMFs), semiconductor lasers.**

I. Introduction

ANTIMONIDE (Sb)-based semiconductor lasers are an attractive solution for several applications that require emitters operating beyond standard fiber-based communication wavelengths (1.55 μm) such as carbon dioxide and phosphine detection, excitation of biological molecules for medical sensing, free-space optical communication, and military scene projection. In the last several decades, many researchers have reported Sb-based lasers operating at the near-infrared (NIR) (<2 μm) or midwavelength IR (MWIR) range (between 2 and 5 μm) [1]–[11]. Furthermore, high-performance lasers exhibiting very low threshold current density, high modal gain, high characteristics temperature (T_0), and high output power have been recently demonstrated [7]–[11]. These characteristics of GaSb-based lasers emitting in the NIR range have made their performance comparable to those of conventional InP-based lasers. Commercialization of these Sb-based devices would be enhanced by developing the devices on an established material platform such as GaAs (or InP) substrates.

Interfacial misfit (IMF) arrays offer a method to grow Sb-based layers on a GaAs platform without having to use metamorphic buffer layers to relieve the 8% lattice mismatch between GaAs and GaSb. Since IMF-based growth was first reported, the technology has led to the demonstration of optically pumped GaSb–AlGaSb edge emitters and VCSELs grown on Si substrates and an electrically injected GaSb–AlGaSb vertical-cavity light-emitting diode monolithically embedded between GaAs–AlGaAs distributed Bragg reflectors [12]–[14]. Work has also been conducted on the atomic modeling and the material characterization of the IMF interface [15]. In this letter, we report the demonstration of room-temperature operation of an electrically injected GaSb–AlGaSb quantum-well (QW) laser grown on a GaAs substrate using IMF arrays at the GaAs–GaSb interface. By monolithically integrating a thermally conductive GaAs substrate with an Sb-based active region, we demonstrate, to the best of our knowledge, the longest wavelength QW laser grown on a GaAs substrate. This report presents the foundation for a hybrid As–Sb approach to devices operating between 1.6 and 3 μm that might vastly improve heat spreading and contact resistance in Sb-based lasers. Improvements in each of these areas will also enable future development of hybrid As-Sb VCSELs, avalanche photodiodes, and photonic integrated circuits.

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II. Device Design, Growth, and Fabrication

The growth of the laser structure is performed on a V80-H solid-state molecular beam epitaxy reactor. The reactor houses valved Sb and As crackers for precise control of Group V incorporation during growth. The reactor is also equipped with a RHEED gun, critical to the confirmation of IMF formation during growth. The growth is initiated with a 100-nm GaAs smoothing layer followed by the IMF formation and 5 nm of undoped GaSb growth. After deposition of the undoped GaSb layer, growth proceeds directly to the doped AlGaSb n-type cladding layer. The remainder of the growth is carried out using conventional growth techniques for Sb-based devices.

The IMF is formed at the GaAs–GaSb interface through two-dimensional packing of Sb atoms on the GaAs surface. Misfit dislocations that form perpendicular to the plane of growth relieve completely the strain due to the lattice mismatch of the two materials. Moreover, we have confirmed that these misfit dislocations arise in a periodic fashion at a spacing corresponding directly with the lattice mismatch based on high-resolution transmission electron micrograph (TEM) analysis [16]. Previous modeling of the possible strain energies confirms that the formation of an IMF is an energetically favorable scenario during lattice mismatch growth [15].

A schematic of the complete device structure is illustrated in Fig. 1. The p-type and n-type cladding layers are both

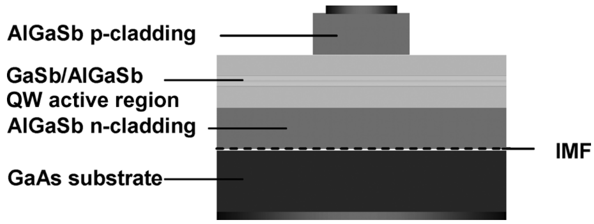

Fig. 1. Device structure for buffer-free GaSb–AlGaSb QW laser grown on a GaAs substrate using an IMF array.

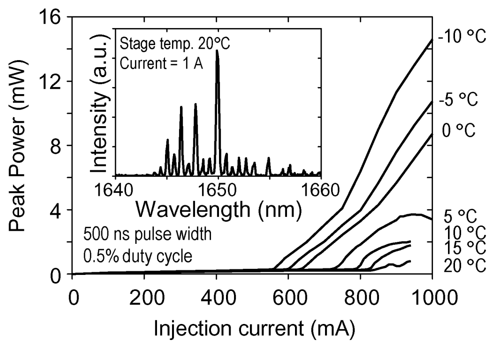

Fig. 2. L–I characteristics and lasing spectrum for hybrid laser over temperature (-10 °C to 20 °C) for a device 50 μm in width and 580 μm in length.

$Al_{0.45}Ga_{0.55}Sb$-doped 1×10^{18} cm^{-3}. The active region consists of six layers of 17-nm GaSb QWs surrounded by 20-nm $Al_{0.35}Ga_{0.65}Sb$ barriers. The QW/barrier region is enclosed in a 300-nm $Al_{0.35}Ga_{0.65}Sb$ undoped waveguide layers on both sides.

The samples are processed such that they form gain-guided stripe lasers with widths varying from 25 to 100 μm. The process involves a Ti–Pt–Au p-metal evaporation to the top p-type GaSb contact layer, a boron tetra-chloride (BCl_3) inductively coupled reactive-ion etch of the p-type cladding layer to just above the waveguide layer, followed by thinning of the substrate to 150 μm, and then a Ge–Au–Ni–Au evaporation to the backside of the GaAs n-type substrate. We then cleave the initial 9 mm × 9 mm chip into laser bars of various lengths.

III. Device Results and Discussion

Fig. 2 shows the output power–current (L–I) characteristics for a device 560 μm in length and 50 μm in width. The L–I characteristics vary between (-10) °C and 20 °C. Fig. 2 shows spectral data at $1.16 \times I_{th}$ and a stage temperature of 20 °C. Optical characteristics are measured under pulsed conditions with a 500-ns current pulse operating at 0.5% duty cycle.

The L–I shows a maximum peak power of 15 mW at 1-A drive current and an ambient temperature of -10 °C. The maximum peak power drops to 1 mW at an ambient temperature of 20 °C. While several growth and device parameters are not yet optimized, the power levels show great promise for future IMF-based devices on a GaAs substrate. The spectral data in the inset of Fig. 2 shows lasing emission at 1650 nm. This is the longest reported lasing wavelength for any QW laser grown on a GaAs substrate, surpassing the previous results using novel GaInNAsSb growth methodologies [17]. Furthermore, this wavelength can be extended out to $\cong$3 μm through indium

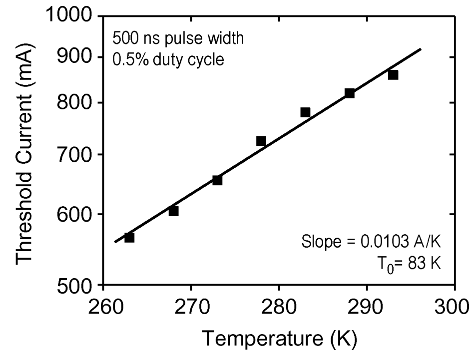

Fig. 3. Threshold current versus stage temperature characteristics of laser. The slope of the curve yields a room-temperature T_0 value of 83 K.

and arsenic incorporation into the QWs, making the platform a candidate in the development of extended NIR and MWIR emitters [9]–[11]. Current–voltage (I–V) characteristics (not shown) indicate a diode turn-on voltage of $\sim$2.5 V. The device also shows a differential resistance (R_d) of 9 Ω at 100-mA drive current, indicating a nominal operating voltage of $>$5 V. Fig. 3 shows the threshold current versus stage temperature characteristics for the laser. The threshold current density rises from 2 to 3 kA/cm^2 between -10 °C and 20 °C, where the characteristics temperature of $T_0 = 83$ K is obtained.

Several changes can be made in the future to improve device performance. First, the 2.5-V turn-on voltage of the diode must be reduced. We expect this value to be $\sim$1 V based on the built-in potential of the laser diode. A key source of this added potential arises from current conduction across the IMF interface which is limited by a 0.7-V potential barrier to electrons. We expect to improve this barrier using delta doping at the interface to compensate the acceptor like dangling bonds at the IMF [14]. We have also modeled and demonstrated that the potential barrier to holes is negligible, and thus placing the interface in p-material can also improve the voltage characteristics.

Additionally, no contact anneal is performed on these devices since the annealing process for n- or p-metal contact causes the increase in the current leakage under reverse bias (not shown). This is likely caused by the enhancement of the threading dislocation density originating from the IMF regions during the anneal process. While the IMF process reduces the threading dislocation density by several orders of magnitude compared with conventional lattice mismatch growth mechanisms, it must be reduced further to ensure that metal does not spike through the active region during an anneal process.

Finally, the threshold current is quite high on these devices compared to those reported elsewhere. A likely reason is the energy difference between split-off and top valence band of GaSb that exactly matches the direct bandgap photon energy. This might result in a Auger recombination process involving the CHHS process which becomes dominant at wavelengths near 3 μm. The gain might improve by using more highly strained GaInAs(Sb) QWs instead of GaSb QWs to bring the bandgap to 1.7–5 μm. In addition, nonradiative recombination due to threading dislocations generated during the IMF growth process might also increase the threshold current. The threading dislocation density still approaches a density of 10^5 cm^{-2} and should continue to decrease as we further optimize the IMF growth process.

IV. Conclusion

The growth and fabrication of a GaSb–AlGaSb laser grown on a GaAs platform using a buffer-free IMF layer at the interface has allowed us to demonstrate the longest wavelength QW laser ever developed on a GaAs substrate (1650 nm). The laser operates room temperature in the pulsed regime and shows 15-mW peak power at -10 °C in the pulsed regime using a 500-ns current pulse at 0.5% duty cycle. While there is further work to be done in optimizing the IMF growth and minimizing the voltage drop of carriers across the IMF layer, this result indicates great promise for using GaAs templates to develop hybrid As–Sb-based emitters operating between 1.6 and 3 μm.

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