Abstract—A new approach in the design of (Al)InGaAsSb–GaSb quantum-well separate confinement heterostructure (QW-SCH) diode lasers has led to continuous-wave (CW) room-temperature lasing up to 2.7 μm. This has been achieved by using quaternary heavily strained InGaSb(As) QW’s inside a broad-waveguide SCH laser structure. The QW compositions are chosen in the region outside the miscibility gap and, as a consequence, do not suffer from clustering and composition inhomogeneity normally found with quaternary InGaAsSb compounds of 2.3–2.7-μm spectral range. Very low threshold current density (~300 A/cm²) and high CW output powers (>100 mW) were obtained from devices operating in the 2.3–2.6-μm wavelength range.

Index Terms—Broad-waveguide separate confinement quantum-well laser structure, continuous-wave operation, heavily strained quantum well, mid-infrared AlGaAsSb–InGaAsSb diode lasers.

I. INTRODUCTION

ALTHOUGH considerable progress has been made in the development of 2-μm wavelength diode lasers, both in the InGaAs(P)–InP [1] and (Al)InGaAsSb–GaSb [2] material systems, numerous attempts to expand upon these results to the longer emission wavelengths has proven unsuccessful. Only recently we reported considerable progress in achievement of longer wavelength operation for GaSb-based diode lasers [3].

In previous publications, we demonstrated that, despite low-confinement barrier for holes in the InGaAsSb quantum wells (QW’s), the separate confinement structure including a broad Al0.25Ga0.75As0.02Sb0.98 waveguide layer can provide very low thresholds for MQW and single QW (SQW) 2-μm wavelength laser diodes [4]–[6]. The condition of electroneutrality prevents current leakage from the QW in the structures with low confinement barriers for one of the types of carriers [7], [8]. In the case of (Al)InGaAsSb–GaSb separate confinement heterostructure (SCH) QW structures, the electrons strongly confined in the QW’s create an electrostatic potential providing effective confinement for holes [4]. Using broad waveguide (BW)-(Al)InGaAsSb–GaSb SCH-SQW structures, very efficient 2-μm wavelength wide-contact (100–200 μm) lasers [6] and recently tapered diode lasers [9] have been fabricated.

In all the above versions of 2-μm lasers, 1% compressively strained In0.47Ga0.53As0.02Sb0.98 material was used for the QW’s in the SCH structure.

During our first attempts to achieve the longer wavelength operation we maintained 1% strain in the QW’s by increasing compositional values for both In and As simultaneously. Photoluminescence (PL) studies of the QW revealed considerable changes in the behavior of peak position and spectral width for structures with In and As contents in QW’s exceeding 20% and 4%, respectively. Instead of a continuous PL-peak shift to longer wavelength, we observed a very fast increase of the PL peak half-width. At temperatures below 150 K, the QW peak position depended strongly on the excitation level. The QW peak wavelength shift rate with temperature in the range of 77 K–300 K was considerably less than that for structures with less In and As content in the QW’s. The PL behavior described above is typical for material with spatial fluctuations in the bandgap [10]. The bandgap fluctuations in the QW plane lead to the band-tailing effect, valence subband mixing, and deterioration of the advantages of strained QW structures. We believe that these phenomena are the reasons for the degradation of AlInGaAsSb–GaSb laser parameters at wavelengths exceeding 2.1 μm.

In this letter, we attempted to eliminate degradation of the QW-material by increasing only the In composition while holding the As composition constant at about 2%. This is the same As value which we used previously for 2-μm lasers [4]–[6]. We call these QW’s “quasi-ternary,” [InGaSb(As)], since the As level is maintained at a very low value and is not intentionally varied during molecular beam epitaxy (MBE) growth. The composition and strain of the QW’s are designed to operate with InGaSb(As) compounds in a region outside the miscibility gap.

The diode structures, grown by MBE on n-GaSb substrates, consist of two In0.3Ga0.7–xAs0.9Sb0.1–y QW’s located in the central part of an undoped 0.8 μm thick Al0.3Ga0.7Sb0.07 waveguide layer (Fig. 1). A double QW (DQW) structure was chosen to avoid fast gain saturation previously observed for 2-μm lasers with SQW active region [6]. For most of the structures the distance between the QW’s was approximately ten times greater than the QW thickness. At the present time we do not have experimental data indicating the significance of this distance on laser performance.

The cladding layers of Al0.3Ga0.7As0.07Sb0.93 were 2 μm thick. The n-cladding layer was doped using Te to n = 2 x 10^17 cm⁻³. The p-cladding layer and p-GaSb cap layer

Manuscript received November 4, 1998; revised February 11, 1999. This work was supported in part by the Air Force Office of Scientific Research under Grant F-49620-98-10133.

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Publisher Item Identifier S 1041-1135(99)05122-8.
had the same Be step-doping profile as in [5], with \( p = 4 \times 10^{19} \text{ cm}^{-3} \) in the cap layer. X-ray measurements were subsequently performed on all structures, which exhibited a lattice matched condition with the GaSb substrate for all layers except the strained QW’s.

About ten laser structures were grown where only the In composition was intentionally varied (0.25 to 0.4) in the DQW active region. The QW thicknesses were in the range of 10–20 nm. The compressive strain in the QW’s increased from 1.5% to 2.3% with increasing In content.

A PL study was also conducted on the identical, undoped isotropic structures except for a thin top cladding layer to provide effective QW photoexcitation with an Ar⁺ laser [4]. Normal shift of QW luminescence peak was observed in all spectral range from 2.3 to 2.7 \( \mu \text{m} \) with increasing In composition in the QW’s. The PL intensity decreased by a factor of 2 over the spectral range of 2.3–2.6 \( \mu \text{m} \), and a more significant decrease was observed for structures with \( \lambda > 2.6 \mu \text{m} \).

Gain-guided Fabry–Perot lasers with 100-\( \mu \text{m} \)-wide stripe contacts and 1 or 2 mm cavity length were characterized. The facets of 2.6- and 2.7-\( \mu \text{m} \) lasers were uncoated. The rear facets of 2.3, 2.4, and 2.5 \( \mu \text{m} \) lasers had high-low dielectric stack reflectors, and neutral (\( \sim 30\% \)) or low-reflecting (3%–5%) single layer \( \text{Al}_2\text{O}_3 \) coatings were deposited on the front facets. The lasers were mounted p-side down onto water cooled copper heatsinks and measured in CW and pulsed regimes with a pulse duration of 1 \( \mu \text{s} \) at 10 kHz repetition rate.

Fig. 2 shows differential efficiency (\( \eta_d \)) and threshold current density \( (J_{th}) \) for 2 mm-long-cavity diodes prepared from the five wafers with increasing In composition in the QW’s. For lasers with In compositions in the QW’s exceeding 35%, a sharp increase of \( J_{th} \) and fast decrease of \( \eta_d \) was observed. This is shown in Fig. 2 for 2.7-\( \mu \text{m} \) devices where the In composition is 38%. For the case of \( x = 0.4 \), we measured a \( J_{th} \) value of 12 kA/cm², which is not shown in Fig. 2. From these results and results of PL studies mentioned above, we believe that the strain relaxation and the generation of dislocations near the QW’s starts at In compositions \( \geq 35\% \).

For lasers with wavelengths shorter than 2.7-\( \mu \text{m} \) at \( T \leq 20 \degree \text{C} \), the laser parameters are weakly dependent on QW composition. The threshold current density in the pulsed regime increases from only 230 to 300 A/cm², while wavelength increases from 2.3 to 2.6 \( \mu \text{m} \). The corresponding increase of \( J_{th} \) in the CW regime is slightly higher, from 230 to 400 A/cm². Output power characteristics \( (P-I) \) measured in the pulsed regime are linear up ten times the threshold current. Corresponding values of \( \eta_d \) (dashed line in Fig. 2) are independent of wavelength in the wavelength range of 2.3–2.6 \( \mu \text{m} \) and close to 30% for all 2-mm-long cavity devices.

Fig. 3 shows CW output powers of 500, 250, and 160 mW that were obtained for 100-\( \mu \text{m} \)-stripe-width lasers emitting at wavelengths of 2.3, 2.5, and 2.6 \( \mu \text{m} \), respectively. In contrast to pulsed-current measurements, the CW output powers increase with current sublinearly and the maximum available power is limited by the power saturation. The longer the emission wavelength the lower the current density at which the deviation from linearity starts and the larger the output power difference between the pulsed and CW \( P-I \) characteristics. Overheating of the device active region causes the saturation of \( P-I \) characteristics.

From our direct experimental measurement, the rate of the active region temperature rise is about 3–5 \( \degree \text{C} \) per 1 W of dissipated power, and this value depends very weakly on device wavelength. Therefore, to explain the enhancement of thermal-rollover effects for longer wavelength lasers, one should assume that their \( J_{th} \) and \( \eta_d \) are more temperature-sensitive above room temperature than that for shorter wavelength devices. An example of such behavior is given in Fig. 4. In this graph temperature dependencies of \( J_{th} \) for 2.6- and 2.3-\( \mu \text{m} \)
lasers are compared. The threshold currents were measured in the pulse regime for diodes with 2-mm cavity length. Below 15 °C, the difference in J_{th} does not exceed 40%, while at 70 °C, J_{th} for the 2.6-μm laser is three times higher than that of the 2.3-μm laser.

These results imply that the temperature dependencies of J_{th} for these lasers arises from two different mechanisms, one of them operating at below room temperature, and the other becoming dominant at high temperatures. Below room temperature, the rate of J_{th} increase with temperature is low and independent of In composition in the QW’s. At high temperatures, the rate of the threshold increase is very sensitive to the In composition in the QW’s. The values of parameter T_0 characterizing the threshold current temperature dependency at high temperature, decrease with laser wavelength from 90 K–100 K for 2.3-μm lasers to 30 K–40 K for 2.7-μm lasers.

Along with increasing J_{th} with increasing temperature, we observed a decrease of differential efficiencies, and the rate of this decrease for 2.6-μm lasers was twice that for 2.3-μm lasers. Therefore, the second degradation mechanism arising at T > 15 °C affects both J_{th} and η_d. Carrier leakage from the QW’s could be one such mechanism. In order to confirm this mechanism, we conducted experiments with 2.3-μm p-GaSb-based laser-transistor devices, similar to InP-based devices used for direct measurement of leakage currents in 1.5- and 1.3-μm lasers [11], [12]. The hole leakage currents less than 1% measured were not high enough to explain the observed temperature dependencies of laser parameters. Our estimation of the valence band offsets at the QW/waveguide interface shows that for 2.3-μm lasers a positive, 100-meV-high hole barrier in the valence band should exist. Its value increases with increasing In composition in the heavily strained QW’s. At the present time, therefore, we are unable to confirm the exact cause of the mechanism leading to degradation of lasing parameters with increasing wavelength at high temperature range. Further experiments including studies of the 2.6–2.7-μm laser-transistors should clarify this question.

**REFERENCES**


