Continuous wave operation of diode lasers at 3.36 μm at 12 °C

L. Shterengas, G. Belenky, T. Hosoda, G. Kipshidze, and S. Suchalkin
Department of Electrical and Computer Engineering, State University of New York at Stony Brook, New York 11794, USA

(Received 14 April 2008; accepted 11 June 2008; published online 8 July 2008)

GaSb-based type-I quantum-well diode lasers emitting at 3.36 μm at 12 °C with 15 mW of continuous wave output power are reported. Devices with two or four InGaAsSb compressively strained quantum wells and AlInGaAsSb quinternary barriers were fabricated and characterized. It was shown that increase in the quantum-well number led to improved laser differential gain and reduced threshold current. © 2008 American Institute of Physics. [DOI: 10.1063/1.2953210]

The growing demand for light emitters capable of high power room temperature operation in spectral region from 3 to 3.5 μm encourages intensive search for appropriate design approach to fabricating such photonic devices. Both monopolar and bipolar lasers based on cascade and multiple quantum well (QW) active region designs are being extensively researched for this purpose (see, for instance, Refs. 1 and 2). GaSb-based type-I QW diode lasers operate in continuous wave (cw) at room temperature in spectral region above 3 μm.3,4 Diode lasers grown by molecular beam epitaxy on GaSb substrates and operating up to 3.1 μm at room temperature in cw mode have been recently reported by our group.5 Further increase in the operating wavelength of type-I QW GaSb-based lasers faces two major complications (a) gradual decrease in the valence band offset between InGaAsSb QW and Al containing barrier layers when In and As concentrations in QW are increased6 and (b) possible increase in the nonradiative Auger recombination rate when QW bandgap decreases. The latter is thought to be fundamental in nature.

The lack of valence band offset in GaSb-based heterostructures can be overcome by introduction of heavy compressive strain above 1% into InGaAsSb QWs7 and utilization of the quinternary AlInGaAsSb barrier material.8,9 The contribution of the Auger recombination processes to threshold current can be minimized by a reduction in the threshold carrier concentration through improvement of the hole confinement itself and by increase in the number of QWs in device active region.

In this work we report on the development of the 3.36 μm emitting lasers with strained active region and quinternary barrier material. We demonstrate that increase in the number of QWs from two to four decreases the device threshold current through improvement in the laser differential gain (with respect to current). Diode lasers with four QW active regions operate in cw mode at 12 °C with 15 mW of output power at 3.36 μm.

Laser heterostructures were grown at State University of New York at Stony Brook by solid-source molecular beam epitaxy using Vecco GEN-930 reactor equipped with As and Sb valved cracker sources. Te and Be were used for n- and p-doping, respectively. Laser active region contained either two or four 16 nm wide 1.5% compressively strained InGaAsSb QWs with nominal In composition of 54%. The interwell spacings were 40 and 20 nm in two-QW and four-QW devices, respectively. The waveguide (total width of 1 μm) and barrier materials were Al0.20In0.25Ga0.55As0.26Sb0.74. The cladding material was Al0.9Ga0.1As0.07Sb0.93. Graded bandgap heavily doped transition layers were introduced between the substrate and n cladding and between the p cladding and GaSb p cap to assist carrier injection. The wafers were processed using silicon nitride dielectrics to form 100 μm wide gain guided lasers. Lasers were neutral-reflection [(NR) ~ 30%] and high-reflection [(HR) ~ 95%] coated, In-soldered epiepisode down onto Au-coated polished copper heatsinks, and mounted either onto a closed cycle cryostat cold finger or onto a water cooled copper block for characterization. Thermal resistance of the packaged diode lasers was estimated as ~5 K/W.

Figure 1 shows the temperature dependence of cw light-current characteristics for 2-mm-long lasers. At 200 K both types of devices (two- and four-QW) have very similar light-current characteristics and their output power is well above 100 mW at 3.15 μm (see inset in Fig. 2). Once the temperature increases above 240 K the four-QW lasers tend to provide more power than two-QW ones. At 12 °C the two-QW lasers do not turn on in CW mode while four-QW ones still demonstrate output power above 15 mW at 3.36 μm (see inset in Fig. 2). The voltage drop across four-QW laser heterostructure at 12 °C is 1.5 V at 3 A of cw current. Figure 2 plots the temperature dependence of the cw threshold current for two- and four-QW lasers. At temperatures below 200 K...

FIG. 1. CW light-current characteristics measured in temperature range from 200 to 285 K for 2 mm long, 100 μm wide, NR/HR coated lasers with two- and four-QWs.
the two-QW devices demonstrate lower threshold currents than four-QW ones. The threshold current increases with temperature faster for two-QW devices and at 250 K four-QW lasers demonstrate lower thresholds. In short pulse mode (160 ns/10 kHz) (Fig. 3), when thermal effects are negligible, both types of devices operate at 12 °C (285 K) with more than 150 mW of output power. Pulsed threshold current of two-QW lasers is about 2 A while four-QW devices have lower threshold of about 1.5 A.

In order to identify the reason for the observed dependence of the laser threshold current on the number of QWs, the device modal gain spectra were measured at several currents below the threshold. Modal gain spectra were obtained using Hakki–Paoli method\(^9\) supplemented by spatial filtering optics to separate the on-axis mode of the multimode gain guided lasers. Insets in Fig. 4 show the current dependences of the modal gain spectra for 100-μm-wide 2-mm-long coated lasers measured at 285 K. Total optical losses can be determined from the low energy part of the modal gain spectra where the spectra measured at different currents converge. Modal gain in the low energy limits approaches −17 cm\(^{-1}\) for two-QW and −19 cm\(^{-1}\) for four-QW lasers. Difference in total optical losses cannot explain higher threshold current of two-QW lasers. In fact the two-QW lasers tend to have lower total losses than four-QW devices. The transparency current of two-QW lasers is also lower than that of four-QW devices, i.e., about 400 mA versus about 700 mA. Nearly twofold difference in transparency currents can be expected since it generally tends to scale with number of QWs in active region.\(^{10,11}\)

The reason for decrease in the threshold current with increase in QW number from two to four is the higher overall differential gain with respect to current observed in four-QW devices. Figure 4 plots the current dependences of the modal gain peak for both types of lasers measured at 285 K. Initially the optical gain is higher in two-QW devices due to lower transparency current but it tends to roll over and become inferior to that of four-QW lasers. Differential gain with respect to current for four-QW 2-mm-long 100-μm-wide devices can be estimated as 20 cm\(^{-1}\)/A. This observation can be explained either by domination of nonradiative Auger recombination or by the effect of hole delocalization from QW. Both of these effects or, possibly, their self consistent combination should become more pronounced at increased QW carrier concentrations. Losses measurements demonstrate that in both two-QW and four-QW lasers nearly the same active region gain is required to reach the threshold. Since the QW threshold carrier concentration should be lower in four-QW devices, the role of the mechanisms leading to super linear dependence of current on carrier concentration (such as Auger and/or hole delocalization) should become less pronounced.

Summarizing, diode lasers with above 15 mW cw and more than 200 mW pulsed output power at 12 °C were designed and fabricated within GaSb-based type-I QW technology. The use of 1.5% of compressive strain in InGaAsSb QWs, quinternary AlInGaAsSb barrier material, and increased number of QW from two to four led to improved differential gain and reduced threshold carrier concentration. The experimental results demonstrate that there is no fundamental limitation for development of high power cw room
temperatures operated interband diode lasers for spectral region from 3 to 3.5 $\mu$m.

This work was supported by the National Science Foundation under Grant No. DMR071054, by New York State under NYSTAR contract, and by US Army Research Office under Contract No. W911NF0610399.