Effect of Quantum Well Compressive Strain Above 1% On Differential Gain and Threshold Current Density in Type-I GaSb-Based Diode Lasers

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***Abstract*—InGaAsSb/AlGaAsSb quantum well (QW) diode laser structures with either 1% or 1.5% compressively strained QWs were grown on GaSb substrates by molecular beam epitaxy. Wide-stripe lasers fabricated from structures of both types have room-temperature operating wavelengths near 2.3 microns. The room-temperature threshold current density of 1-mm-long uncoated devices with 1.5% strained QWs was lower than threshold current density of the 1.0% strained QW devices by nearly a factor of two (120 A/cm^2 versus 230 A/cm^2). Experiment shows that the reduction in threshold current density with increasing QW strain is related to the increase in differential gain and decrease in transparency current density. Optical gain calculations prove that improvement of the QW hole confinement reduces the threshold carrier concentration in laser structures with heavily strained low arsenic content quantum wells.**

***Index Terms*—Mid-infrared, GaSb-based, type-I, high power, heavy compressive strain, differential gain, hole confinement.**

I. Introduction

HIGH-POWER room-temperature-operated GaSb-based diode lasers can serve as light sources for wide range of applications including tunable laser spectroscopy, medical diagnostics and therapy, material processing, infrared illumination, and countermeasures. Significant progress has been achieved in technology of type-I GaSb-based quantum well (QW) diode lasers. Watt class continuous wave (CW) output power levels were obtained from single laser emitters in spectral region from 2.3 to 2.8 μm at room temperature [1]–[7]. Recently, devices operating near 3 μm at room temperature with more than 100 mW of CW output power were reported [8]. These achievements indicate that presence of nonradiative Auger recombination is not a limiting factor for development of the room-temperature-operating type-I QW diode lasers in spectral region above 3 μm. However, it is expected that Auger recombination processes should contribute to the threshold current density of mid-infrared devices so that the laser design should take special care to minimize such a contribution.

InGaAsSb/AlGaAsSb heterostructures are characterized by strong misbalance between conduction and valence band offsets, i.e., the conduction band offset usually exceeds the one in the valence band. Hence, in spite of large difference between the band gaps of AlGaAsSb and InGaAsSb alloys, used correspondingly as barrier and QW materials, in QW laser heterostructures the holes might be poorly confined while the electron confinement is more than adequate. There are experimental justifications that type-I GaSb-based QW laser heterostructures suffer from insufficient hole confinement [9], [10]. Hole delocalization from QWs at elevated temperatures can adversely affect both laser threshold and injection efficiency. Hole confinement can be improved by either adjustment of the barrier layer composition [10], [11] or by using InGaAsSb QWs with low arsenic contents, i.e., heavily compressively strained QWs. Introduction of compressive strain in active QWs is also known to improve the laser differential gain through the reduction of the hole density of states (DOS), i.e., through balancing the DOS in the joint electron and hole lasing subbands [12].

In this paper we present detailed experimental and theoretical analysis of the laser threshold in type-I mid-infrared lasers with compressively strained QWs. For this purpose, we have designed and fabricated two laser heterostructures with differently strained QW layers of different compositions which presumably are characterized by different hole confinements. Both structures were emitting at 2.3 μm at room temperature and had the same waveguide and contact layer designs. Increase of the QW compressive strain from 1% to 1.5% resulted in nearly twofold reduction of the room-temperature threshold current from 230 A/cm^2 down to 120 A/cm^2 for 1-mm-long uncoated diode lasers.

Experimental characterization of the lasers included measurements of the laser threshold current, slope efficiency, optical loss and differential gain with respect to current—all in the temperature range from 100 K to over 300 K. Theoretical calculations were based on the 8-band electron energy spectrum model which included strain-induced band structure modification and Coulomb band bending caused by the charge redistribution in the structure. Experimental and theoretical results conclusively demonstrate that improvement of the hole confinement is primarily responsible for the observed enhancement of the optical gain and twofold reduction of the threshold current density in laser structures with heavily strained QWs.

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Strain-induced balancing of the subband DOS was of secondary importance in these structures. It was also noticed that Coulomb attraction of holes to the electrons strongly localized in conduction-band QWs and resulting band bending cannot fully compensate for the lack of hole confinement in GaSb-based laser heterostructures.

II. Sample Preparation

Laser heterostructures were grown by solid-source molecular beam epitaxy using Veeco GEN-930 modular system equipped with valved cracker cells for both As and Sb. Two heterostructures with different QW compositions and widths have been grown on n-GaSb substrates doped with Te. The cladding layers were 1.5-μm-wide $Al_{0.90}Ga_{0.10}As_{0.07}Sb_{0.93}$ doped with Te (n-side) and Be (p-side). Graded bandgap heavily doped transition layers were introduced between the substrate and n-cladding and between the p-cladding and p-cap to assist carrier injection. The nominally undoped $Al_{0.25}Ga_{0.75}As_{0.02}Sb_{0.98}$ waveguide layer with a total thickness of about 800 nm contained two $In_{0.35}Ga_{0.65}As_xSb_{1-x}$ QWs centered in the waveguide and spaced 20 nm apart. The thick waveguide and cladding layers were lattice matched to GaSb substrate. The laser heterostructures used in this work closely corresponded to designs of high-power 2.3–2.5 μm diode lasers with above 1 W CW output power at room temperature [7], [13].

The structure that will be referenced in this text as the "moderately strained" one contained 10 nm QWs with compressive strain of 1%. Structure two, the "heavily strained" one, contained 12 nm QWs with compressive strain of 1.5%. The difference in strain was achieved by changing QW arsenic contents from about 9% (heavily strained) to about 17% (moderately strained). The QW width was reduced from 12 to 10 nm for moderately strained structure in order for both lasers to operate at the same wavelength (near 2.3 μm at room temperature).

Both wafers were processed into 100-μm-wide oxide confined gain guided lasers using pulse anodization (PA) technique [14], [15]. In this technique, native oxide layer was grown in the p-side transition and cladding layers to define the current stripes. The wafers with photo resist mask were attached to a glass holder with clear wax and put into a beaker filled with electrolyte (40% ethylene glycol, 20% deionized water, and 1% phosphoric acid). The current pulses (100 mA/cm^2, 700 μs/50 Hz) were sent through the circuit consisting of wafer as an anode, electrolyte bath, platinized titanium as a cathode, and 100 Ohm resistor. An oscilloscope probe connected across the 100 Ohm resistor was used to observe temporal development of the current amplitude and the oxidation process was stopped when the tailing edge current saturated. The electrolytically grown native oxide thickness was about 100 nm. Standard metallization was applied to p- and n-sides of the wafers. One-mm-long uncoated diode lasers were In-soldered epi-side up onto Au-coated polished copper blocks. The mounted devices were bolted either onto thermoelectrically cooled test station or onto cold finger of liquid nitrogen cooled cryostat and characterized in pulsed mode (200 ns/1 MHz).

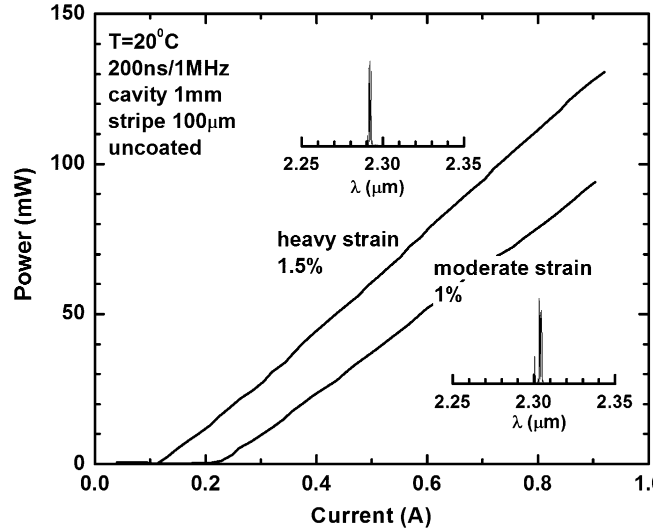

Fig. 1. Pulsed (200 ns/1 MHz) light-current characteristics of 1-mm-long uncoated lasers with 1% and 1.5% of compressive strain in InGaAsSb QWs. Inset shows room-temperature laser spectra near threshold.

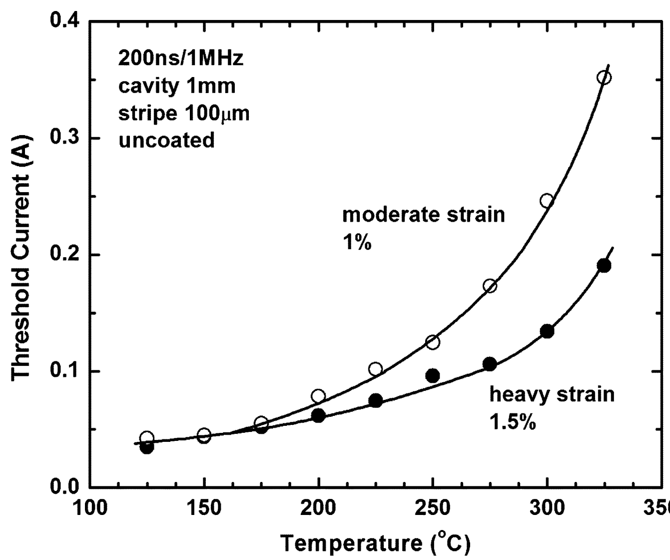

Fig. 2. Temperature dependences of the laser threshold current for moderately and heavily strained lasers.

III. Experiment

Fig. 1 shows the light-current characteristics measured at room temperature (20 °C) for moderately strained and heavily strained diode lasers. Threshold current density of about 230 A/cm^2 was measured for moderately strained lasers and only 120 A/cm^2 for heavily strained devices. (Five devices from each group were characterized at 20 °C and threshold currents in the range 120–140 mA and 230–260 mA were measured for heavily strained and moderately strained lasers, correspondingly). Heavily strained devices also tend to have higher slope efficiency (0.16 W/A per facet) than low strain ones (0.14 W/A per facet).

At low temperatures (Fig. 2), the threshold currents for both structures become nearly identical and equal to 40 mA (20 A/cm^2 per QW) at 150 K. At 200 K, the threshold current of heavily strained lasers is already slightly larger than

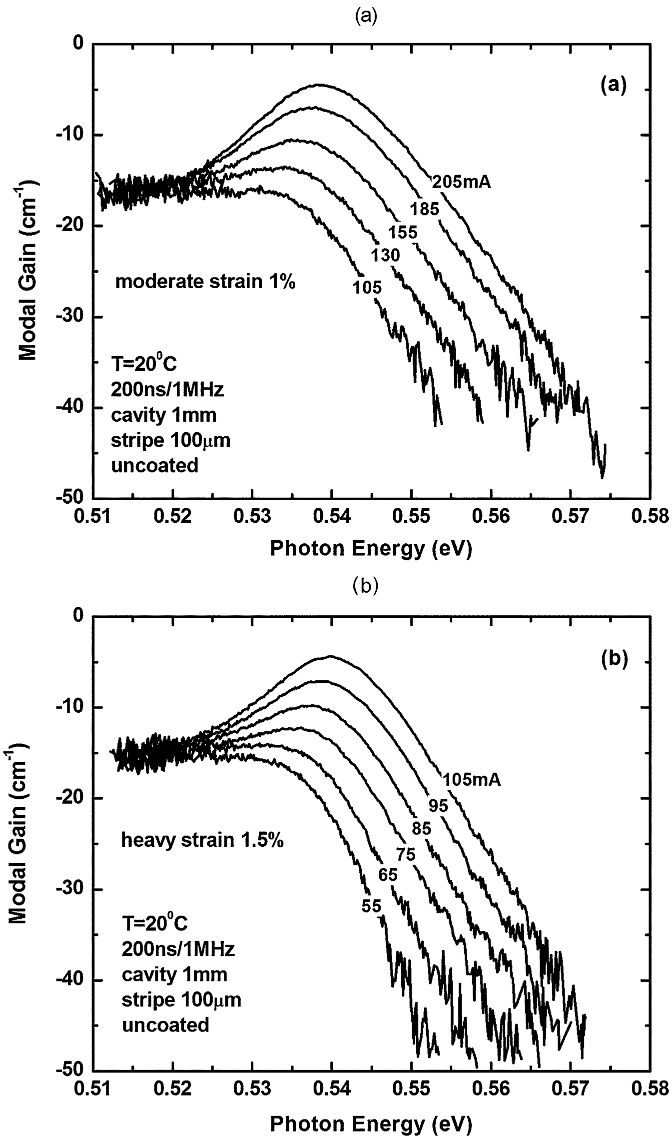

Fig. 3. Current dependences of the gain spectra measured at 293 K for (a) moderately strained and (b) heavily strained lasers.

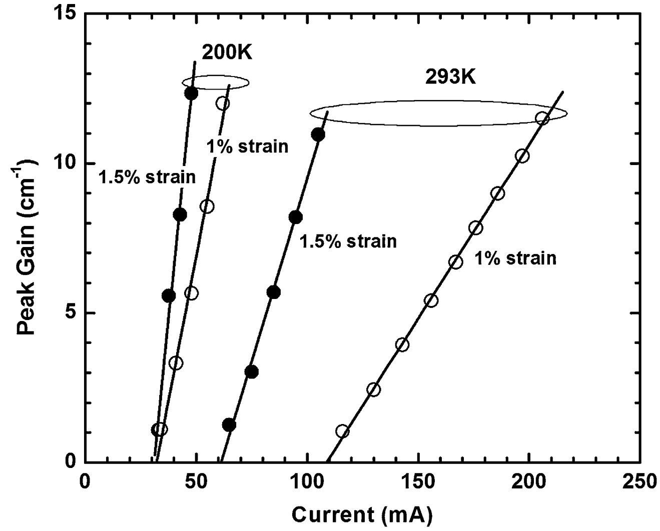

Fig. 4. Current dependences of the peak modal gain measured for moderately and heavily strained devices at 200 K and 293 K.

that of moderately strained ones and the difference tends to increase with temperature. In the room-temperature range, the moderately strained lasers demonstrate nearly twofold higher threshold currents as compared to heavily strained devices.

In order to identify the reason for the observed dependence of the laser threshold current on active region strain, the corresponding laser modal gain spectra were studied. Fig. 3 shows the current dependences of the modal gain spectra for 100-μm-wide 1-mm-long uncoated lasers measured at 293 K. Modal gain spectra were obtained using the Hakki–Paoli method [16] supplemented by spatial filtering optics to separate only the on-axis mode of the multimode gain guided lasers. Internal optical losses can be determined from the low energy part of the modal gain spectra where the spectra measured at different currents converge to total modal losses. Modal gain in the low energy limits approaches about -16 cm^{-1} for both types of lasers. The mirror losses are estimated to be 12 cm^{-1} for a 1-mm-long as-cleaved lasers leaving a value for internal optical loss of 4 cm^{-1}. Internal efficiencies are estimated as 80% and 70% for heavily and moderately strained lasers, correspondingly. Thus, it was confirmed that the internal optical loss value is independent on active region strain and the nearly twofold difference in threshold currents between moderately and heavily strained lasers cannot be attributed to either difference in optical losses or internal efficiencies. Fig. 4 plots the current dependences of the peak modal gain measured at 200 K and 293 K. Room temperature data (293 K) show strong dependence of the differential gain and transparency current on laser active region strain. Heavily strained devices demonstrate increase of the differential gain from 120 cm^{-1}/A up to 250 cm^{-1}/A and reduction of the transparency current from 120 mA down to 60 mA as compared to moderately strained lasers. A twofold difference in the differential gain and transparency current accounts for a twofold lower room-temperature threshold current of the heavily strained devices. At low temperatures the differences in both the differential gain and transparency current between moderately and heavily strained lasers tend to decrease. Fig. 4 shows that at 200 K the transparency current values for both types of the devices are about 30 mA while the differential gain increases up to 730 cm^{-1}/A for heavily strain lasers and up to 390 cm^{-1}/A for moderately strain ones. Despite the difference in differential gains still remains considerable at 200 K (though smaller than at room temperature) the similar values of the transparency currents and high values of the differential gains lead to small relative difference in threshold currents, namely 60 mA for heavily strained and about 80 mA for moderately strain devices. When temperature decreases below 200 K, the difference in threshold currents between moderately and heavily strained lasers tends to disappear.

IV. Modeling

We illustrate the effect of the strain on the laser performance by calculating the modal optical gain in structures with moderate (1%) and high (1.5%) level of compressive strain in the active QWs. According to our estimation, the hole confinement in the first structure was insufficient, with valence band QW depth for heavy holes of only 35 meV. In the second structure, designed for the same lasing wavelength, the arsenic concentration in QW was decreased thus increasing the QW compressive strain. Due to combined effect of reduced arsenic concentration and increased strain the confining barriers for the heavy holes in the latter structure were increased up to 105 meV. Calculations show that this improvement of the hole confinement is primarily responsible for the enhancement of the optical gain, while the strain-induced subband DOS balancing is only of secondary importance. Our calculations are based on the 8-band model of the electron energy spectrum in cubic semiconductors [17] with included strain-induced modifications of the band edge positions in compressively strained QWs. The resulting 8-band Schrödinger equation system was solved self-consistently with the Poisson equation using the COMSOL software [18]. During each iteration, the hole populations and Fermi distribution functions in each hole subband were recalculated taking into account thermal redistribution of holes between active QWs and waveguide. The iteration cycle was repeated until quasi-Fermi level position in valence band was stabilized which took five to ten iterations depending on the injected hole concentration and carrier temperature. In all the modeled structures, electrons were strongly localized in conduction-band QWs, occupying predominantly the states in the lowest electronic subband.

Fig. 5 illustrates our choice of material compositions for strained QW structures with enhanced hole confinement. Data for binary materials and ternary alloys used in these calculations were taken from review [19]. The quaternary alloy band gaps were calculated using biquadratic interpolation algorithm [20]. Fig. 5(a) shows the arsenic versus indium concentration dependencies for isostrain QW compositions. The compositions with indium contents above 30% are of major interest for the QW MIR-lasers. Fig. 5(b) and (c) shows the calculated energy gaps and heavy-hole band edge positions in quaternary GaInAsSb compositions with different levels of compressive strain. It is readily seen that highly strained indium-rich QW compositions benefit from improved hole confinement while retaining sufficiently low values of the optical gap.

Fig. 6 illustrates the process of strain-induced balancing of the electron and hole DOS in GaSb-based QW heterostructures. Fig. 6(a) shows energy subbands (left panel) and subband DOS (right panel) in an exemplary lattice matched (unstrained) $Al_{0.50}Ga_{0.50}As_{0.04}Sb_{0.96}/Ga_{0.80}In_{0.20}As_{0.20}Sb_{0.80}$ QW heterostructure. Electron and hole subbands have noticeably different DOS in unstrained QW due to the anticrossing between second (heavy-hole) and third (light-hole) valence subbands, which induces strong subband nonparabolicity. Fig. 6(b) demonstrates much better balance between lower electron and upper hole subband DOS in $Al_{0.25}Ga_{0.75}As_{0.02}Sb_{0.98}/Ga_{0.65}In_{0.35}As_{0.09}Sb_{0.91}$ heterostructure (heavily strained laser in Section III) with highly compressively strained QW (strain 1.5%). All three upper hole subbands in this heterostructure are of heavy-hole type in the Brillouin zone center and no anticrossing effects are visible in the subband DOS structure. Bold lines in the lower part of Fig. 6(b) represent the valence subbands (left panel) and

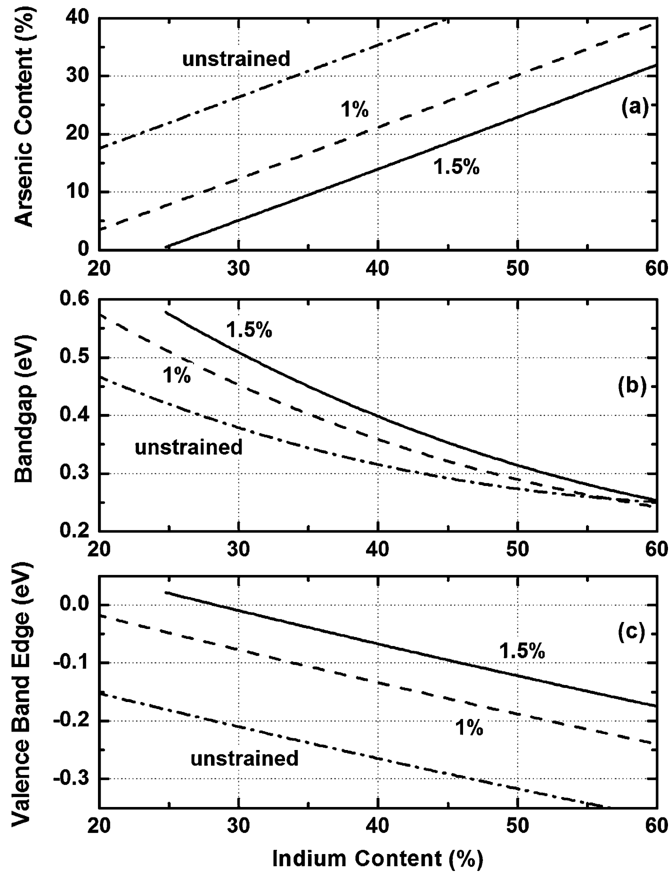

Fig. 5. Isostrain lines in quaternary GaInAsSb alloy system: dash-dotted lines—alloy composition lattice matched to GaSb; dashed lines—composition with 1.0% compressive strain; solid lines—1.5% compressive strain. (a) Arsenic versus indium concentration in InGaAsSb alloys. (b) Fundamental energy gap in InGaAsSb alloys with different strains. (c) Strain-induced modification of the heavy-hole band edge position.

the subband DOS (right panel) for QW with higher arsenic concentration (17%) and lower strain (1%). According to our calculations, this structure is characterized by heavy-hole QW depth of only 35 meV. It is readily seen, however, that the DOS at the upper subband edge in this shallow QW does not differ noticeably from the DOS of the uppermost states in the deeper QW. The main difference between the two structures is the hole confinement which is significantly lower in structure with lower strain and higher arsenic contents.

The QW depth for electrons is more than adequate in both structures so that the electrons predominantly occupy the lowest electronic subband with negligible thermal redistribution into the higher subbands even at room temperature. Deficit of the hole confinement in the moderately strained structure in combination with large value of valence band DOS in bulk waveguide layers leads to strong thermal hole redistribution and reduces the population of the hole lasing states. On the other hand, different spatial distribution of the electrons and holes induces the band bending which to some extent improves the hole confinement in low strain structure [Fig. 7(b)].

Hole redistribution in QW laser heterostructure can noticeably deteriorate the optical gain. Fig. 8 shows peak modal gain calculated at 100 K, 200 K, and 300 K as a function of the injected carrier concentration for structures with moderate

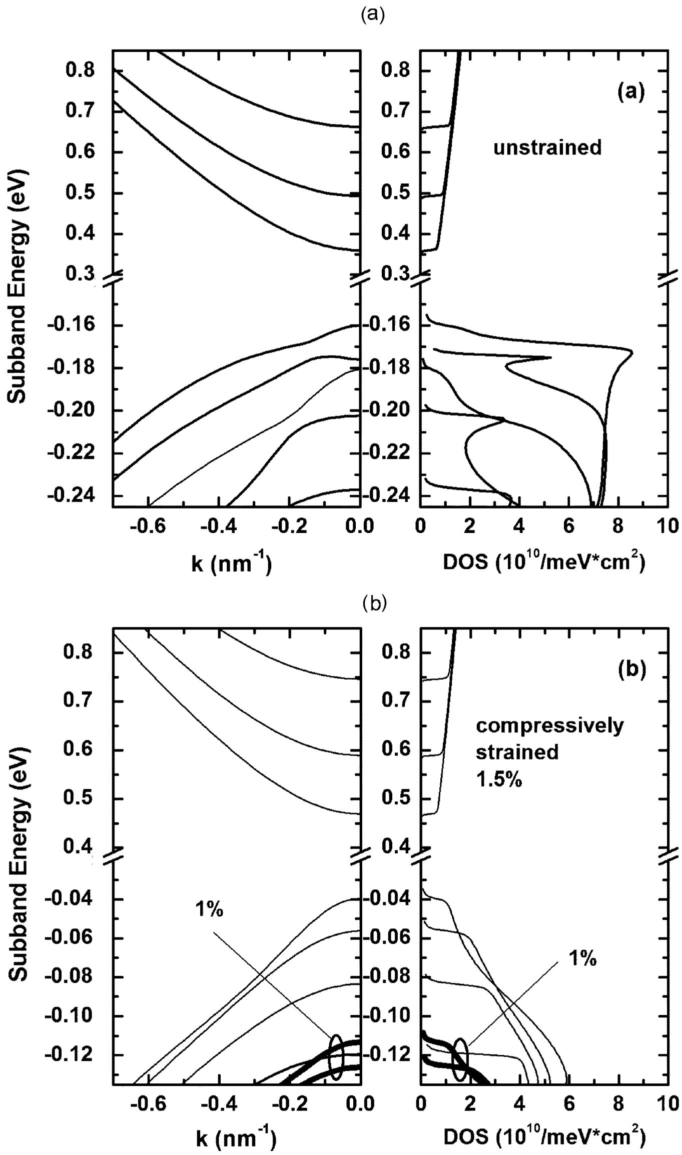

Fig. 6. Strain-induced balancing of electron and hole DOS. (a) Lattice matched $Al_{0.50}Ga_{0.50}As_{0.04}Sb_{0.96}/Ga_{0.8}In_{0.2}As_{0.2}Sb_{0.8}$ QW heterostructure. (b) Strained $Al_{0.25}Ga_{0.75}As_{0.02}Sb_{0.98}/Ga_{0.65}In_{0.35}As_{0.09}Sb_{0.91}$ QW heterostructure with compressively strained QW (strain 1.5%). Left panel of each plot shows the subband dispersion, i.e., the subband energy versus the electron/hole wavevector k; right panel shows the subband DOS (in 10^10/meV*cm^2). Note the difference in energy scale for valence band subbands in (a) and (b). Two bold lines in the lower part of each panel of (b) show valence subbands and DOS for QW composition $Ga_{0.65}In_{0.35}As_{0.17}Sb_{0.83}$ with 1% strain.

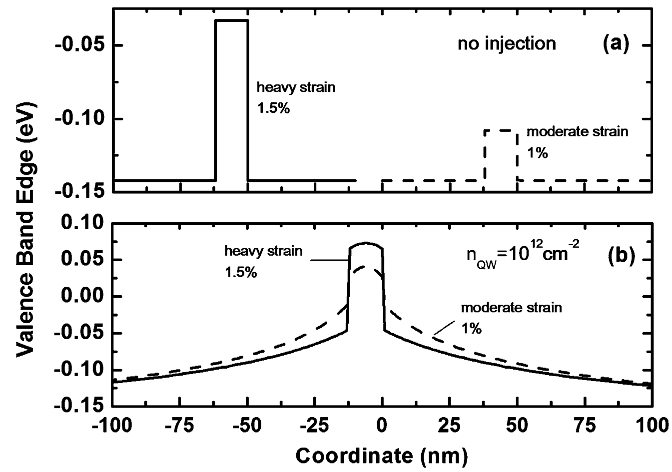

Fig. 7. Valence band profiles for structures with 1% compressive strain (dashed line) and 1.5% strain (solid line): (a) valence band edge position for QWs without injected carriers; (b) self-consistent QW profile for QW carrier concentration 2×10^{12} cm^{-2}.

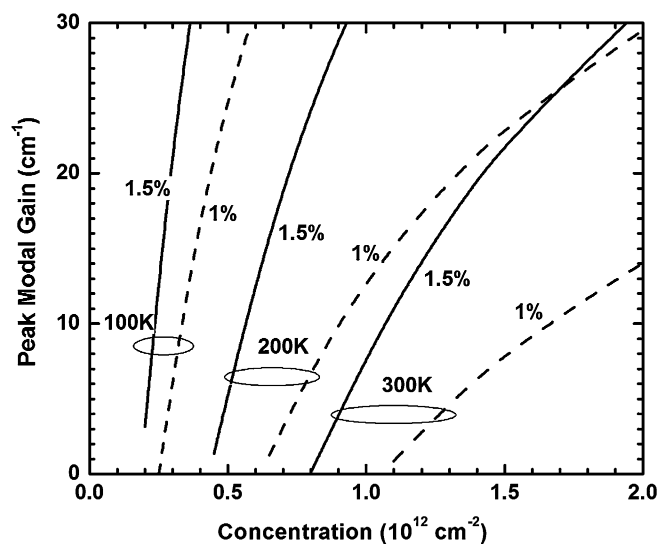

Fig. 8. Peak modal gain as a function of the injected carrier concentration in QW for different temperatures. Dashed lines indicate structure with 1% compressive strain (moderate strain), solid lines indicate structure with 1.5% strain (heavy strain).

strain (dashed lines) and heavy strain (solid lines). The structure with heavily strained QWs and, hence, better hole confinement demonstrates higher differential gain and lower transparency concentration as compared to moderately strained structures.

V. Discussion

In InGaAsSb/AlGaAsSb QWs, the band offsets at the heterointerfaces are unevenly distributed between conduction and valence bands, leading to excessive electron and deficient hole confinements. Since the electrons are strongly localized in deep conduction band QWs, the thermal redistribution of holes between the shallow valence band QWs and the optical waveguide layers creates Coulomb barriers which can improve the hole confinement to some extent. Even in this case, however, the bulk heavy-hole states of the waveguide material with high DOS remain energetically close to the lasing states in the uppermost hole subband and, therefore, unfavorably affect the population of the lasing states. This situation can be improved by using the compressively strained QW layers.

It is well known [12] that compressive strain splits the first heavy-hole and first light-hole subbands and reduces the band-edge hole DOS, which otherwise is unfavorably increased by heavy-light subband mixing. This mechanism of gain improvement, however, works well only for compressive strain level up to 1% [21]. Strain values beyond that range have minor effect on the band-edge heavy-hole DOS, since at such a high strain the heavy-hole and light-hole subbands are already well separated in energy. In this work, we have demonstrated that, due to the inherently low valence band offsets at the quaternary InGaAsSb/AlGaAsSb interfaces, the QW compressive strain manifests itself not only through the band-edge hole DOS reduction but, mainly, by increasing the effective barrier height for the quantum-confined hole states. In compressively strained low arsenic content InGaAsSb QWs, the heavy-hole states are moved upwards, thus making the heavy-hole QW deeper. Improved hole confinement, in turn, reduces the thermally activated hole redistribution between the QW subbands and the adjoin bulk barrier states and, therefore, increases the occupation of the uppermost hole subband states participating in the lasing transition. This ultimately enhances the laser differential gain and reduces the threshold current density. The calculations prove that the enhancement of the optical gain in Sb-based lasers through the increased heavy-hole confinement in heavily compressively strained QWs remains efficient for high compressive strain in the 1–2% range while preserving the benefit of the balanced joint DOS achieved at the lower strain level.

Reduction of the laser threshold concentration in structures with heavily strained QWs also minimizes the contribution of the Auger processes though cannot eliminate them completely. The carrier concentration required to reach lasing threshold increases with temperature (Fig. 8). In moderately strained structures with inadequate valence band offset, there is a need for the extra carrier injection that comes from the necessity to occupy a set of closely separated hole subbands with inherently large density of states. Corresponding increase of the threshold carrier concentration triggers Auger processes which in turn increase the laser threshold current density and worsen temperature stability of the device.

It is important to note that physical properties of InGaAsSb/AlGaAsSb/GaSb material system differ in some respects from the properties of well-known InGaAs/InGaAsP/InP material system used in devices with shorter, 1.5-μm range, emission wavelength. For instance, in InGaAs/InGaAsP QW heterostructures, the barriers are lower in the conduction band than in the valence band which prevents strong electron localization and favors the hole confinement. On the contrary, in GaSb-based devices, electrons are strongly localized, while hole confinement can be insufficient which, as we have shown, can deteriorate the laser performance. Therefore, the roles of the compressive strain in these two systems are different. In InGaAsSb, compressive strain moves heavy-hole states upwards thus increasing the QW barriers and improving the heavy-hole confinement. In InGaAs/InP QWs, where the barriers in valence band are already high enough, the compressive strain mostly unfavorably decreases the electron confinement.

VI. Summary

The experiment demonstrates that the use of the InGaAsSb quantum wells with compressive strain above 1% is an effective tool for the reduction of the laser threshold current, especially at room temperatures. Calculations show that strain-induced improvement of the hole confinement is primarily responsible for the observed improvement of the laser performance. In contrast to strain-induced DOS balancing, which is efficient for strain values up to 1%, this mechanism remains efficient at higher compressive strain levels. GaSb-based diode lasers designed for room-temperature operation at 2.3 μm demonstrate nearly twofold reduction of the threshold current density from about 230 A/cm^2 down to 120 A/cm^2 when QW compressive strain is increased from 1% up to 1.5%. Measurements of the device differential gain and transparency current show that the observed improvement of the laser threshold is explained by the twofold increase of the differential gain (with respect to current) and transparency current reduction. At lower temperatures, when the hole confinements become adequate in both 1% and 1.5% compressively strained QWs, the dependence of the laser threshold current on QW compressive strain tends to disappear.

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