BNL-114266-2017-JA

Cascade Pumping of 1.9–3.3 μm Type-I Quantum Well GaSb-Based Diode Lasers

L. Shterengas, A. Stein

Submitted to IEEE Journal of Selected Topics In Quantum Electronics

March 2017

Center for Functional Nanomaterials

Brookhaven National Laboratory

**U.S. Department of Energy
USDOE Office of Science (SC),
Basic Energy Sciences (SC-22)**

Notice: This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE- SC0012704 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Cascade Pumping of 1.9–3.3 μm Type-I Quantum Well GaSb-Based Diode Lasers

Leon Shterengas, Gela Kipshidze, *Member, IEEE*, Takashi Hosoda, Rui Liang, Tao Feng, Meng Wang, Aaron Stein, and Gregory Belenky, *Fellow, IEEE*

Abstract—Cascade pumping of type-I quantum well gain sections was utilized to increase output power and efficiency of GaSb-based diode lasers operating in spectral region from 1.9 to 3.3 μm . Coated devices with $\sim 100\text{-}\mu\text{m}$ -wide aperture and 3-mm-long cavity demonstrated continuous wave (CW) output power of 1.96 W near 2 μm , 980 mW near 3 μm , 500 mW near 3.18 μm , and 360 mW near 3.25 μm at room temperature. The corresponding narrow ridge lasers with nearly diffraction limited beams operate in CW regime with tens of mW of output power up to 60 $^{\circ}\text{C}$. Two step shallow/deep narrow/wide ridge waveguide devices showed lower threshold currents and higher slope efficiencies compared to single step narrow ridge lasers. Laterally coupled DFB lasers mounted epi-up generated above 10 mW of tunable single frequency CW power at 20 $^{\circ}\text{C}$ near 3.22 μm .

Index Terms—GaSb, type-I QW, midinfrared, semiconductor lasers, cascade lasers, high power, narrow ridge, DFB.

I. INTRODUCTION

COMPACT and efficient high power lasers operating in mid-infrared region of spectra are in demand for various applications including pumping of novel mid-infrared solid-state and semiconductor lasers, pumping of midinfrared nonlinear wavelength converters, LIDAR seeding, infrared scene illumination, infrared countermeasures, medical treatment and surgery, and spectroscopy. GaSb-based type-I quantum well (QW) diode lasers can operate in CW regime at room temperature (RT) in spectral range from 1.9 to 3.5 μm , see for instance [1]. The corresponding heterostructures utilize GaIn(As)Sb QWs with bandgap adjustable by varying indium composition and well thickness. The barriers are made of either AlGaAsSb quaternary or AlGaInAsSb quinary alloys depending on

Fig. 1. Power-current characteristics measured in CW regime at RT for 2- or 3-mm-long 100- μm -wide coated lasers. Inserts show corresponding device emission spectra as well as generic laser band diagram overlapped with fast axis near field distribution.

operating wavelength. The quinary barriers can confine holes in QWs with high In and As contents - a decisive factor in the development of high power diode lasers emitting near and above 3 μm [2]. Currently, diode lasers emitting in the range of 1.9–2.5 μm , generate above 1 W of CW output power from 100- μm -wide apertures and demonstrate threshold current densities near 100 A/cm². High power diode lasers operating near 3 μm generate ~ 350 mW of CW output power and have RT thresholds of 220 A/cm². The diode lasers operating at longer wavelength near and above 3.3 μm demonstrate higher threshold current densities and lower CW output power levels approaching ~ 500 A/cm² and below 100 mW, respectively. Fig. 1 and plots the typical light-current characteristics measured for 100- μm -wide ridge waveguide multimode diode lasers designed and fabricated at Stony Brook University and illustrates the generic design of the regular non-cascade laser heterostructure. Laterally coupled distributed feedback narrow ridge lasers based on non-cascade heterostructures developed at Stony Brook University and operating near 2.05 [3] and 3.27 μm [4] in CW regime at RT have been demonstrated. Several other research groups reported on efficient GaSb-based type-I QW high power and single mode diode lasers.

Recently cascade pumping of type-I QW gain sections was utilized to increase output power and efficiency of GaSb-based diode lasers [5]. Cascade pumping design scheme can address

Manuscript received February 17, 2017; revised March 21, 2017; accepted March 22, 2017. This work was supported in part by the National Science Foundation under Grant ECCS-1408126US, in part by the Army Research Office under Grant W911NF1110109, and in part by the U.S. Department of Energy, Office of Basic Energy Sciences, through the Center for Functional Nanomaterials, Brookhaven National Laboratory, under Contract DE-SC0012704. (Corresponding Author: Leon Shterengas.)

L. Shterengas, G. Kipshidze, T. Hosoda, R. Liang, T. Feng, M. Wang, and G. Belenky are with the Department of Electrical and Computer Engineering, State University of New York at Stony Brook, Stony Brook, NY 11794-2350 USA (e-mail: leon.shterengas@stonybrook.edu; gela.kipshidze@stonybrook.edu; takashi.hosoda@stonybrook.edu; liangr85@gmail.com; tao.feng@stonybrook.edu; meng.wang.2@stonybrook.edu; gregory.belenky@stonybrook.edu).

A. Stein is with the Center for Functional Nanomaterials, Brookhaven National Laboratory, Upton, NY 11973-5000 USA (e-mail: stein@bnl.gov).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/JSTQE.2017.2687763

Fig. 2. Schematic band diagram the heterostructure designed for transport of electrons from valence band of AlGaInAsSb layer to conduction band of the next AlGaInAsSb layer. Insert shows magnified section containing InAs/AISb chipped superlattice. Left bottom corner shows band alignment at the interface between GaSb and InAs grown on GaSb.

fundamental challenge associated with mid-infrared diode laser development. Namely, it provides an efficient way to minimize the QW threshold carrier concentration, hence, to minimize the effect of Auger recombination. Cascade pumping comprises a method to connect active QWs in series. Series connection of QWs maximizes the optical confinement factor avoiding carrier transport limitations characteristic of standard multiple-QW stack. Possibility to minimize the threshold current and simultaneously to increase the device internal efficiency makes cascade pumping an enabling design solution. Initially cascade pumping scheme was applied to laser heterostructures utilizing gain sections based on either intersubband [6] or type-II interband [7] electron transitions, see for instance [8]–[10]. Cascade pumping of the type-I QW interband gain section through tunnel Esaki junction was reported previously [11] and led to improvement of the performance parameters of vertical cavity surface emitting lasers [12], [23]. In those devices the heavily doped tunnel junctions were placed at optical field nodes thus minimizing associated absorption loss. We have shown [13] that, at least within antimonide material system, the cascade pumping scheme is compatible with type-I QW interband gain sections. Carriers are recycled between stages yielding internal efficiencies above 100% and leading to improved high power operation of edge emitting diode lasers. Fig. 2 illustrates one possible design solution to implement efficient connection of the GaSb-based laser active regions in series.

In Fig. 2 illustration the electrons are assumed to be injected from n-contact into the AlGaInAsSb layer containing QWs (not shown) of the first gain section. The electron-hole recombination in the QWs is followed by interband tunneling which transfers the electrons from the valence band of the first gain section to the conduction band of the second gain section. The electron transfer between stages takes place at the tunnel junction made of 10-nm-thick GaSb layer, 2.5-nm-thick AISb and first InAs QW of the chipped InAs/AISb superlattice (SL). The AlGaAsSb ~ 100 -nm-wide graded composition layer was introduced to stop the electron and to promote the hole transport in the first gain

Fig. 3. Slope efficiency measured in short pulse regime for 2.2–3.3 μm emitting 1-mm-long uncoated two-stage cascade (solid circles) and reference single stage diode lasers (open circles). Top insert illustrates the design concept behind the first generation of the cascade diode lasers.

section. Chirped AISb/InAs SL stopped hole transport from and promoted the electron transport to the second gain section.

Utilization of the injector heterostructure shown in Fig. 2 led to demonstration of the two-stage cascade lasers with slope efficiencies nearly doubled compared to benchmark non-cascade lasers operating in the same spectral regions. Fig. 3 illustrates the design approach and plots the single facet slope efficiencies of the cascade and non-cascade uncoated 1-mm-long 100- μm -wide lasers emitting in spectral region from 2.4 to 3.3 μm . Fig. 3 design led to improved output power levels in 2.4 – 3 μm spectral region [5]. However, this type of series connection of the whole MQW laser active regions is more appropriate for light emitting diodes (LED) rather than for lasers. Indeed, five and ten stage cascade LEDs demonstrated proportional increase of the output power level in spectral region near 3.3 μm compared to single stage devices. The design, fabrication, and results of characterization of type-I QW cascade LEDs will be discussed elsewhere.

For lasers, the further adjustments were applied to better realize the potential of the cascade pumping scheme to lower the device threshold current density and improve power-conversion efficiency. Namely, the separations between active QWs and the injector have been minimized to maximize optical confinement and reduce the parasitic voltage drop [14]. The concept adopted was like the one used in regular MQW diode lasers (insert to Fig. 1) and ICLs [10] where multiple active QWs connected either in parallel or in series were stacked together and placed into the center of waveguide core, i.e. near the maximum of the transverse fundamental optical mode. Fig. 4 plots the CW power-current characteristics obtained for 100- μm -wide ridge 3-mm-long coated two- and three-stage cascade lasers indium-soldered epi-side-down onto gold plated polished copper blocks. Comparison between Figs. 1 and 4 data shows that cascade pumping enhanced the maximum CW power level available from semiconductor lasers operating in spectral region from 1.9 to 3.3 μm . The power conversion efficiencies were improved nearly twofold in cascade lasers operating near and above 3 μm [14]. The cascade lasers operating near 2 μm demonstrated power conversion efficiency values similar to those of the

Fig. 4. Power-current characteristics measured in CW regime at RT for 3-mm-long, 100- μm -wide, coated lasers. Inserts show corresponding device emission spectra as well as schematic diagram illustrating cascade pumping approach where QWs connected in series are located near maximum of fundamental mode. Insert shows the optical image of the AR coated mirror of laser soldered epi-side down.

benchmark diode lasers due to excessively increased device operating voltages.

In this paper, we review some elements of the development of the lasers heterostructures yielding the devices with record output power levels presented in Fig. 4. Section II describes the design of the cascade lasers emitting near 2 μm . Section III summarizes results for lasers emitting near and above 3 μm . Section IV discussed the peculiarities of the development of the corresponding narrow ridge diffraction limited and distributed feedback narrow spectrum lasers. Section V summarizes the results and discusses further prospects.

II. GASB-BASED CASCADE DIODE LASERS WITH λ NEAR 2 μm

Laser heterostructures discussed in this work were grown by solid-source molecular beam epitaxy on tellurium doped GaSb-substrates using cracked arsenic and antimony sources. Fig. 5 (top) shows schematic band diagrams of the two-stage laser heterostructure designed to emit just below 2 μm . The devices had $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}_{0.07}\text{Sb}_{0.93}$ cladding layers and 400-nm-wide $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}_{0.03}\text{Sb}_{0.97}$ waveguide core layers on both sides of the active region containing two 8-nm-wide $\text{Ga}_{0.75}\text{In}_{0.25}\text{Sb}$ QWs. The non-cascade laser heterostructure would contain about 20 nm or so of waveguide core material between QWs [15]. The cascade lasers considered in this work had tunnel junction and carrier injector layers connecting QW1 and QW2 in series. The graded composition AlGaAsSb and InAs/AlSb chirped SL were optimized for laser operation near 2 μm [16]. Firstly, the thickness of the first InAs QW in chirped SL structure was selected to be 3 nm to shift the energy of direct optical transition from InAs valence band to the first quantized state above 640 meV ($\lambda \sim 1.95 \mu\text{m}$). Secondly, the initial composition and doping of graded AlGaAsSb layer were selected to be 80% Al and about 10^{17} cm^{-3} nominal Be to suppress thermionic conduction band transport from QW1 to SL injector. Variation

Fig. 5. Schematic band diagrams of the laser heterostructure under flat band condition. Inserts enlarge parts of laser heterostructure containing beryllium doped (nominal $5 \times 10^{16} \text{ cm}^{-3}$) AlGaAsSb compositionally graded layer grown as a random alloy and tellurium doped (nominal $5 \times 10^{17} \text{ cm}^{-3}$ in InAs layers only) AlSb/InAs/.../InAs/AlSb chirped superlattice electron injector.

Fig. 6. Power-current-voltage characteristics measured in short pulse regime for 1-mm-long, 100- μm -wide, uncoated 1.95 μm lasers based on different cascade heterostructure designs. The data for benchmark non-cascade 2-QW diode operating at $\lambda = 2 \mu\text{m}$ are shown for comparison.

of the Fig. 5 design included reduction of the Al composition in the cladding layers from 80 to 60% to minimize the tendency of the exposed non-passivated cladding material to oxidation in atmosphere. This simplifies device processing such as mirror coating and formation of the narrow ridges and laterally coupled DFB laser cavities. Another variation included additional waveguide core broadening to minimize overlap with doped cladding materials and addition of the extra cascade stages to further increase the device slope efficiency.

Fig. 6 plots light-current-voltage characteristics of the 1-mm-long, 100- μm -wide uncoated test lasers based on those varied designs. Devices marked in Fig. 6 as 2Al80 were based on heterostructure shown in Fig. 5. Devices 3Al80 had one more cascade added. Lasers marked 2Al60 differ from 2Al80 only in reduced aluminum composition in cladding –60%, while 2Al60B have waveguide core broadened from 400 nm to 700 nm on each side of active QWs.

TABLE I
PARAMETERS OF 2 μm EMITTING LASERS MEASURED AT 20 $^{\circ}\text{C}$

	I_{th} mA	η_{ext} %	T_0 K	T_1 K	α_{tot} cm^{-1}	dg/dI cm^{-1}/A
3A180	76	140	57	224		
2A180	76	122	65	280	~ 17	414
2A160	83	94	60	275	~ 19	396
2A160B	135	100	57	290	~ 20	260
diode	~ 80	~ 60	90–100	290	15–17	455

Table I lists the operation parameters for these devices measured at 20 $^{\circ}\text{C}$ in short pulse regime. The cascade lasers demonstrate increased external efficiencies compared to benchmark 2-QW diodes. The improvement correlated with number of cascades. All cascade lasers operated in CW regime with watt level output and lasers based on structure 2A180 demonstrated record ~ 2 W CW output power level (Fig. 4). Fast axis beam divergence was about 55 degrees full-width-at-half-maximum (FWHM). The three stage lasers 3A180 had higher efficiency than 2A180 devices but suffered from excessive voltage drop leading to premature thermal rollover of CW power-current characteristics.

Fig. 6 shows that operating voltage increases twofold in two-stage and threefold in three-stage $\lambda \sim 2$ μm cascade lasers compared to non-cascade devices. The lower voltage drop increase would be expected in ideal case since voltage drop across claddings should not scale up with number of cascades. Further optimization of (a) the p-doping profile of the graded composition layer and (b) n-doping profile and layer thicknesses of the chirped superlattice are required. Another indication of the unresolved carrier transport issues could be found in similar values of the differential gain (determined from Hakki-Paoli data [17]) and threshold current of the best cascade and diode lasers. The threshold currents did not improve in cascade lasers as could be expected for series connection of the QWs. Temperature sensitivity of the laser parameters also did not improve in cascade lasers compared to benchmark diodes.

The laser heterostructure 2A180 was utilized for the development of the narrow ridge single spatial mode lasers. Fig. 7 plots light-current-voltage characteristics measured in short pulse and in CW regime for 2-mm-long AR/HR coated lasers soldered epi-side-up.

The laser threshold current was about 35 mA, which corresponded to about 115 A/cm^2 if ~ 15 - μm -wide current aperture is assumed. This is higher than nominal threshold current density measured for 100- μm -wide multimode ridge lasers (75–80 A/cm^2). External efficiency of two step ridge lasers was somewhat reduced and became $\sim 100\%$ versus $\sim 120\%$ in 100- μm -wide multimode emitters. Both increased optical loss and surface recombination at the deep etched sidewall can contribute to observed increase of threshold current density and decrease of external efficiency. The lasers generated above 180 mW of CW power in nearly diffraction limited beam. Devices mounted epi-side down (not shown) generated record 250 mW thanks to improved thermal contact [18]. The ridge waveguide geometry contained two steps – ~ 5 - μm narrow shallow etched ridge and ~ 15 - μm wide deep etched ridge (insert

Fig. 7. Power-current-voltage characteristics measured in short pulse and CW regime for 2-mm-long coated two-step ridge waveguide lasers based on 2A180 designs. Inserts show the SEM of laser facets, laser spectra and slow axis far field patterns at different currents.

in Fig. 7). The benefits offered by this geometry compared to narrow deep or shallow ridges will be discussed in more details in Section IV.

III. CASCADE DIODE LASERS WITH λ NEAR AND ABOVE 3 μm

Devices emitting near and above 3 μm utilized 12-to-13-nm-wide GaInAsSb QWs with nominal In composition in the range from 55 to 58% and compressive strain of $\sim 1.5\%$. The quinary AlGaInAsSb alloy was used in place of AlGaAsSb waveguide core (Fig. 5). The composition and thickness of the AlGaAsSb graded layer and chirped SL were adjusted to match the electron states in active QWs. The operation of the injector was more efficient for devices emitting near and above 3 μm compared to 2 μm emitters leading to improved laser power conversion efficiencies. We have reported two-stage cascade lasers emitting near 3 μm [14]. The barrier and waveguide core layers were nominally undoped $\text{Al}_{20}\text{Ga}_{55}\text{In}_{25}\text{As}_{23}\text{Sb}_{77}$. The devices demonstrated threshold current densities about 100 A/cm^2 , which corresponded to twofold reduction compared to benchmark 2-QW diode lasers. The device maximum CW output power and peak power conversion efficiency improved nearly twofold as well and were reaching values of 650 mW and 16% at RT. The corresponding shallow etched narrow ridge waveguide lasers demonstrated more than 100 mW of power in nearly diffraction limited beam [19]. Laterally coupled distributed feedback 2.9 μm lasers for hydroxyl radical spectroscopy were based on similar two-stage cascade laser heterostructure and demonstrated above 10 mW in stable single spectral mode beam [20]. The addition of one more stage to the laser heterostructure further improved device slope efficiency leading to nearly 1 W CW level from 100- μm -wide aperture (Fig. 4). However, the threshold current density and differential gain at 20 $^{\circ}\text{C}$ did not improve further compared to two-stage lasers indicating unresolved issues with carrier transport below threshold in multistage cascade laser heterostructures. Above threshold the proportional improvement in device efficiency confirmed carrier recycling between three stages. Internal

Fig. 8. Power-current characteristics (bottom left) and peak modal gain vs current (bottom right) measured in short pulse regime for 1-mm-long 100- μ m-wide uncoated lasers based on three different laser heterostructures. Top inserts show the band diagram of the 3QW1 design yielding devices with the best overall performance parameters.

efficiency of about 190% were estimated for three-stage 3 μ m lasers at RT while two-stage lasers showed $\sim$ 145%. The parameter T_0 was somewhat improved from $\sim$ 40 to $\sim$ 50K when number of stages increased from two to three.

In order to increase the wavelength of the lasers above 3 μ m we utilized Al₃₀Ga₄₀In₃₀As₂₈Sb₇₂, i.e. increased aluminum and indium composition of the barrier to accommodate for lowered valence band in QWs with $\sim$ 58% of indium composition. It was also shown experimentally that the increase of the number of cascades from two to three led to critical enhancement of the differential gain and reduction of the threshold current density [21]. Two-stage device demonstrated gain saturation with current below threshold. Three-stage cascade lasers operating near 3.15 μ m demonstrated 500 mW CW at RT from 100- μ m-wide aperture (Fig. 4).

The QW threshold carrier concentration can be reduced by increase of the optical confinement factor. Optical confinement factor can be increased by either utilization of the large number of cascades with single QW in each of them or by using increased number of QWs in each cascade. We tested three types of laser heterostructures emitting above 3.2 μ m, namely: two-stage with 2 QWs per stage (2QW2), three-stage with 2 QWs per stage (3QW2) and three stage with 1 QW per stage (3QW1). The heterostructures using 2 QWs per stage were similar in all aspects to three-stage designs used for development of 3.15 μ m emitters [21]. The QWs in each stage were separated by 20 nm of Al₃₀Ga₄₀In₃₀As₂₈Sb₇₂. In three-stage structure with 1 QW per stage the AlGaInAsSb layer between n-cladding and QW1 was replaced with lightly tellurium-doped GaSb. High refractive index of the GaSb (above 3.8 near 3 μ m) helps to improve QW optical confinement factor. The hole confinement in QW1 was achieved by adding InAs/AlSb superlattice insert between GaSb and QW1. Fig. 8 (left) plots the power-current characteristics measured in short pulse regime for 1-mm-long, 100- μ m-wide uncoated lasers based on three designs. Insert (top) plots the

band diagram of the 3QW1 heterostructure yielding devices with the best performance parameters.

Two-stage devices with 2 QW per period (2QW2) demonstrated adequate differential gain in contrast to what was observed previously for two-stage lasers with 1 QW per period. Increase of the number of periods in structure 3QW2 improved differential gain further and led to reduced threshold current compared to 2QW2 design. However, the devices based on 3QW2 structure demonstrated higher internal loss and thus showed limited overall improvement compared to 2QW2. The three-stage devices (3QW1, top insert in Fig. 8) with 1 QW per stage demonstrated much improved transparency current and had low enough internal loss $\sim$ 6cm⁻¹. So despite lower differential gain compared to 3QW2, the devices based on structure 3QW1 demonstrated the lowest threshold and the highest efficiency characterized by parameters T_0 and T_1 of $\sim$ 40 and $\sim$ 80 K, respectively. There is apparent difference in measured transparency currents between 3QW2 and 2QW2 lasers. In ideal case the transparency currents should be similar. The measurement error and growth-to-growth variation contribute to the observed difference. However, it could also be interpreted as an indication of the different population of the QWs with electron and holes in different structures, i.e. non-optimized transport. Devices based on 3QW1 when AR/HR coated and mounted epi-side down generated above 350 mW near 3.25 μ m (Fig. 4). Lasers based on structures 3QW2 and 2QW2 generated less than 200 mW (not shown). Thus we selected the 3QW1 structure for development of the narrow ridge and DFB single mode lasers.

IV. NARROW RIDGE AND DFB LASERS WITH λ NEAR 3.25 μ m

The lasers with 100- μ m-wide ridge width (Fig. 4) generate multimode beams with correspondingly limited brightness. The ridge geometry can be adjusted for the waveguide to support only the fundamental mode. For instance, the etching depth determining lateral index step can be selected shallow enough for a certain ridge width to yield single mode cold cavity. The complicated laser current and photon dynamics can change the cavity properties above threshold and promote multimode operation. The situation with shallow etching becomes even more complicated if lateral current spreading is taken into account. In devices prone to severe current spreading and with insufficient lateral index step the gain guiding can become dominant often leading to very inefficient and multimode laser operation. The current path in lateral direction can be constrained by deep etching. Then the ridge width should be reduced until the single mode cavity operation is established. The deep etching approach is widely used for various cascade lasers having strongly enhanced anisotropy between lateral and vertical carrier transport. In narrow deep etched interband ridge lasers the surface recombination at the ridge sidewalls can severely degrade the device performance.

Often the deep etched lateral waveguide width does not have to be reduced until cold cavity supports only one mode. The laser single spatial mode operation can be achieved utilizing lateral mode competition based on higher scattering loss for all modes except the fundamental one. Even, in case of relatively shallow ridges the lateral mode competition can provide effective

Fig. 9. SEM images of as cleaved narrow ridge laser facets. The top line illustrates the three types of narrow ridge devices studied: left – etched down to top of waveguide core (DR1); center – etched down to bottom cladding (DR2); and right – two-step ridge (TSR). The bottom line shows the DR1 devices with variable ridge width.

mechanism to ensure waveguide single spatial mode operation. However, shallow etching can lead to strong mismatch between lateral mode profile and lateral current path especially if laser structure is prone to current spreading. In reference [22] there was proposed and realized a combined two-step etching approach. Namely, narrow shallow etching defined modal profile and contributed to mode competition while wide deep etching confined current. Fig. 7 shows the power-current characteristics of the $2\ \mu\text{m}$ lasers fabricated following that approach. Near $2\ \mu\text{m}$ the simple deep etched ridges would have to be narrower than $5\ \mu\text{m}$ to ensure single mode operation and that would increase both laser loss and surface current [18]. As an additional benefit the two-step narrow/wide design also yields narrower slow axis far-field pattern compared to narrow deep ridges. For devices operating at longer wavelength near and above $3\ \mu\text{m}$ it was not apparent if the two-step etching would be the best solution and we tried both two-step (TSR) and deep etched devices with variable ridge width. We also tested two different deep etching profiles: (1) through the p-cladding and just into waveguide core but not through QWs (DR1); and (2) all the way through the laser core down to bottom cladding (DR2). Fig. 9 shows the scanning electron microscope (SEM) images of the cleaved facets of the narrow ridge lasers with different ridge waveguide geometries. The width of the single step ridges was varied from ~ 7 to $\sim 14\ \mu\text{m}$ while TSR were fabricated with fixed widths of the narrow ($\sim 4.5\ \mu\text{m}$) and wide ($\sim 14.5\ \mu\text{m}$) sections.

Light-current characteristics measured in short pulse regime at $20\ ^\circ\text{C}$ for 1-mm-long uncoated lasers from each group is shown in Fig. 10. The TSR devices demonstrated the lowest threshold current ($\sim 35\ \text{mA}$) and the highest external efficiency ($\sim 75\%$) at $20\ ^\circ\text{C}$. The deep etched ridge lasers from both groups (DR1 and DR2) showed about 5-10% smaller efficiencies for ridge width of near and above $10\ \mu\text{m}$. When ridge width gets below $10\ \mu\text{m}$ the deep etched device external efficiencies decrease further (more rapidly for DR2 lasers). Threshold currents of DR2 lasers remains near $55\ \text{mA}$ for ridge width varied from ~ 7 to $\sim 13\ \mu\text{m}$. The threshold currents of DR1 lasers (not etched through QWs) are higher and tend to increase from ~ 65 to $\sim 75\ \text{mA}$ when ridge width increased from ~ 7 to $\sim 14\ \mu\text{m}$. Notably, the deep etched lasers DR2 show lower thresholds than not so deep etched DR1 devices. The lateral current spreading in the cascade active region can explain this observation. This

Fig. 10. Power-current characteristics measured in short pulse regime for 1-mm-long uncoated narrow ridge lasers based on 3QW1 laser heterostructure with different lateral waveguide geometries. The inserts show the lateral far field patterns (bottom) for DR1 $9.5\text{-}\mu\text{m}$ -wide, DR2 $10.5\text{-}\mu\text{m}$ -wide and TSR lasers and dependence of its FWHM on ridge width (top).

Fig. 11. Current dependences of the peak modal gain measured for DR2 $8.5\text{-}\mu\text{m}$ -wide and TSR narrow ridge lasers plotted together with scaled version of the corresponding dependence obtained for reference $100\text{-}\mu\text{m}$ -wide ridge lasers. The right side shows the modal gain spectra measured for several below threshold currents for DR2 $8.5\text{-}\mu\text{m}$ -wide and reference $100\text{-}\mu\text{m}$ -wide ridge lasers.

also allows speculating that surface recombination current at the etched sidewalls makes smaller contribution to the device threshold than aforementioned lateral current spreading. Inserts in Fig. 10 shows the slow axis far field patterns measured near $100\ \text{mA}$ for all devices and dependence of its full-width-at-half-maximum (FWHM) on ridge width for DR1, DR2 lasers (FWHM for TSR devices is shown as horizontal solid line). The near field pattern for DR1 $9.5\text{-}\mu\text{m}$ -wide and TSR devices are almost identical with FWHM ~ 14 degree. Deeply etched DR2 lasers demonstrate the current independent but more divergent slow axis far field patterns. The TRS and DR1 lasers show somewhat increased beam divergence at high currents above threshold. Devices having ridge width near and above $12\ \mu\text{m}$ demonstrate tendency to multiple spatial mode operation at elevated currents. Fig. 11 (left) plots the current dependencies of

Fig. 12. CW power-current characteristics measured in temperature range from 20 to 50 °C for 2-mm-long AR/HR coated 9.5- μm -wide DR1 deep etched cascade lasers mounted epi-down on copper blocks. Inserts show the laser lateral far field patterns and different currents as well as laser spectra at temperature and currents specified.

the peak modal gain of TSR and DR2 8.5- μm -wide 1-mm-long uncoated lasers together with scaled version of the data for reference 100- μm -wide deep ridge lasers (Fig. 8, 3QW1 lasers). The current values in the dependence measured for 100- μm -wide devices were scaled down by factor (8.5/100).

If the edge effects in deep etched lasers were marginal the properly scaled version of the data of 100- μm -wide lasers would match the data obtained for DR2 8.5- μm -wide lasers. Fig. 11 shows that DR2 devices demonstrate nearly twice higher transparency current and roughly twice lower differential gain than it could be expected from scaling. The optical loss (as determined from long wavelength part of the gain spectra) increased in DR2 lasers by about 2 cm^{-1} compared to reference 100- μm -wide devices (right part of Fig. 11). Notably, the peak modal gain dependence on current measured for TSR lasers closely resembles the scaled version of the data for 100- μm -wide devices. Thus one can speculate that the role of the surface recombination at the deep etched sidewalls is suppressed in TSR lasers by shallow etching of the $\sim 4.5\text{-}\mu\text{m}$ -wide ridge (200 nm or less of low doped p-cladding material is left outside of the ridge section).

The 2-mm-long DR1 and TSR lasers were coated AR/HR (5%/95%) and NR/AR (30%/95%), respectively. Fig. 12 plots the CW light-current characteristics of the 9.5- μm -wide DR1 ridges mounted epi-down onto copper blocks. The devices operate in CW regime in wide temperature range in technologically important region of spectra from 3.2 to 3.3 μm and generate tens of mW of power in single lobe beams. Devices mounted epi-up also operated in CW regime and generated in excess of 35 mW at 450 mA at 20 °C (not shown). The DR1 lasers with ridge width of 11.5 μm generated in excess of 80 mW CW at 20 °C in single lobe beam though with current dependent far field pattern

Fig. 13 plots the CW light-current characteristics of the TSR lasers mounted epi-down onto copper blocks. The devices generated 30 mW in CW regime at 20 °C. The far field pattern is more stable compared to that of DR1 device from Fig. 12 indicating more stable single spatial mode operation. The lasers

Fig. 13. CW power-current characteristics measured in in temperature range from 20 to 60 °C for 2-mm-long NR/HR coated two-step (TSR) lasers. Inserts show the laser lateral far field patterns and different currents as well as the laser spectra at temperatures and currents specified.

Fig. 14. CW power-current characteristics measured at different temperatures for 2-mm-long NR/HR coated 2nd order laterally coupled DFB lasers. DFB devices were mounted epi-up on copper blocks. Inserts show the laser spectra at temperatures and currents specified. SEM images of the as cleaved laser facet is also shown.

were coated NR/HR to obtain minimum threshold current of about 50 mA at 20 °C corresponding to less than 100 mW of threshold electrical power. Devices coated AR/HR are expected to have higher slope efficiency and generate output power levels comparable or better than those of DR1 lasers.

We have fabricated 2nd-order laterally-coupled distributed feedback lasers based on heterostructure 3QW1 (Fig. 8) but with 60% aluminum in claddings. The cladding aluminum composition was reduced from 80% to 60% to simplify the device processing and increase the laser reliability. Grating period was selected to be 920 nm corresponding to a calculated effective modal index of 3.50. Fig. 14 shows the light-current-voltage characteristics of the epi-up mounted 2-mm-long NR/HR coated single frequency lasers. Insert shows the laser spectra at different currents at 15 °C and SEM image of the as cleaved laser facet. Lasers generate more than 10 mW of narrow spectrum tunable CW power in epi-up configuration. The laser wavelength

was continuously tunable at the rates of 0.77 nm/mA and 0.31 nm/K. The DFB lasers etching profile closely resembles that of the TSR lasers. This was achieved without any specially added processing steps since the etching inside the mask defining the DFB grating was about 1.5 time slower.

V. CONCLUSION

Recently cascade pumping of type-I quantum well gain sections was utilized to increase output power and efficiency of GaSb-based diode lasers. Carrier recycling between two QWs emitting near 3 μm led to reduction of the threshold current density from ~ 200 down to ~ 100 A/cm² and increase of the maximum CW power level from ~ 350 up to ~ 650 mW compared to non-cascade diodes. Narrow shallow ridge lasers fabricated from the same material demonstrated record 100 mW of CW power in nearly diffraction limited beam. Two-stage cascade diode lasers operating near 2 μm demonstrated threshold current densities ~ 80 A/cm² and CW output power ~ 2 W per 100- μm -wide stripe and ~ 250 mW from ~ 5 - μm -wide narrow ridge apertures. The increase of the number of cascades from two to three led to further improvement of the device CW output power level and 960 mW, 500 mW and 350 mW in multimode beams were obtained near 3, 3.15 and 3.25 μm , respectively. The further increase of the output power level and efficiency of the cascade type-I QW lasers can be achieved following optimization of the carrier transport through injector structures and minimization of the voltage drop per stage.

The corresponding narrow ridge lasers generating nearly diffraction limited beams operate in CW regime above 60 °C. The optimization of the single spatial mode emitting lasers design included fabrication of the two-step shallow narrow and deep wide ridges. Two step design demonstrated the lowest threshold current densities for 2- μm - and 3.25- μm -emitting lasers. For 3.25- μm -emitting lasers the single step deep etched ridges also generated tens of mW of output power level but showed higher thresholds compared to two-step designs. Notably all narrow ridge devices operated also in epi-up configuration generating tens of mW of CW power at 20 °C and above. Laterally coupled DFB lasers mounted epi-up generated above 10 mW of tunable single frequency CW power at 20 °C near 3.22 μm .

ACKNOWLEDGMENT

The author T. Feng acknowledges the China Scholarship Council for the financial support.

REFERENCES

- [1] G. Belenky, L. Shterengas, M. Kisin, and T. Hosoda, "Gallium antimonide (GaSb)-based type-I quantum well diode lasers: Recent development and prospects," in *Semiconductor Lasers: Fundamentals and Applications*, A. Baranov and E. Tournié, Eds. Woodhead Publishing Series in Electronic and Optical Materials, no. 33. Cambridge, U.K.: Woodhead Publishing, pp. 441–486, 2014.

- [2] M. Grau, C. Lin, O. Dier, C. Lauer, and M. C. Amann, "Room-temperature operation of 3.26 μm GaSb-based type-I lasers with quaternary Al-GaInAsSb barriers," *Appl. Phys. Lett.*, vol. 87, no. 24, Dec. 2005, Art. no. 241104.
- [3] S. Forouhar, R. M. Briggs, C. Frez, K. J. Franz, and A. Ksendzov, "High-power laterally coupled distributed-feedback GaSb-based diode lasers at 2 μm wavelength," *Appl. Phys. Lett.*, vol. 100, 2012, Art. no. 031107.
- [4] R. Liang *et al.*, "Distributed feedback 3.27 μm diode lasers with continuous-wave output power above 15 mW at room temperature," *IET Electron. Lett.*, vol. 50, no. 19, pp. 1378–1380, Sep. 2014.
- [5] L. Shterengas *et al.*, "Cascade pumping of GaSb-based type-I quantum well diode lasers," *Proc. SPIE Int. Soc. Opt. Eng.*, 2014, Art. no. 900213.
- [6] R. F. Kazarinov and R. A. Suris, "Possibility of amplification of the electromagnetic waves in a semiconductors with a superlattice," *Fizika i Tekhnika Poluprovodnikov* 5: 797, 1971.
- [7] R. Q. Yang, "Infrared laser based on intersubband transitions in quantum wells," *Superlattices Microstruct.*, vol. 17, pp. 77–83, 1995.
- [8] F. Capasso, "High-performance midinfrared quantum cascade lasers," *Opt. Eng.*, vol. 49, 2010, Art. no. 111102.
- [9] M. Razeghi, "High-performance InP-based mid-IR quantum cascade lasers," *IEEE J. Sel. Topics Quantum Electron.*, vol. 15, no. 3, pp. 941–951, May–Jun. 2009.
- [10] I. Vurgaftman *et al.*, "Interband cascade lasers with low threshold powers and high output powers," *IEEE J. Sel. Topics Quantum Electron.*, vol. 19, no. 4, Jul.–Aug. 2013, Art. no. 1200210.
- [11] R. Q. Yang and Y. Qiu, "Bipolar cascade lasers with quantum well tunnel junctions," *J. Appl. Phys.*, vol. 94, pp. 7370–7372, 2003.
- [12] R. Koda, C. S. Wang, D. D. Lofgreen, and L. A. Coldren, "High-differential-quantum-efficiency, long-wavelength vertical-cavity lasers using five-stage bipolar-cascade active regions," *Appl. Phys. Lett.*, vol. 86, 2005, Art. no. 211104.
- [13] L. Shterengas *et al.*, "Type-I quantum well cascade diode lasers emitting near 3 μm ," *Appl. Phys. Lett.*, vol. 103, 2013, Art. no. 121108.
- [14] L. Shterengas *et al.*, "Cascade type-I quantum well diode lasers emitting 960 mW near 3 μm ," *Appl. Phys. Lett.*, vol. 105, 2014, Art. no. 161112.
- [15] R. Liang *et al.*, "High-power 2.2 μm diode lasers with heavily strained active region," *IEEE Photon. Technol. Lett.*, vol. 23, no. 10, pp. 603–605, May 2011.
- [16] T. Hosoda, T. Feng, L. Shterengas, G. Kipshidze, and G. Belenky, "High power cascade diode lasers emitting near 2 μm ," *Appl. Phys. Lett.*, vol. 108, 2016, Art. no. 131109.
- [17] B. W. Hakki and T. L. Paoli, "Gain spectra in GaAs double-heterojunction injection lasers," *J. Appl. Phys.*, vol. 46, pp. 1299–1306, 1975.
- [18] T. Feng *et al.*, "Two-step narrow ridge cascade diode lasers emitting near 2 μm ," *IEEE Photon. Technol. Lett.*, vol. 29, no. 6, pp. 485–488, Mar. 2017.
- [19] R. Liang *et al.*, "Narrow ridge $\lambda \approx 3$ μm cascade diode lasers with output power above 100mW at room temperature," *IEEE Photon. Technol. Lett.*, vol. 27, no. 23, pp. 2425–2428, Dec. 2015.
- [20] T. Hosoda *et al.*, "Laterally coupled distributed feedback cascade diode lasers emitting near 2.9 μm ," *IET Electron. Lett.*, vol. 52, no. 10, pp. 857–859, Dec. 2016.
- [21] T. Hosoda, M. Wang, L. Shterengas, G. Kipshidze, and G. Belenky, "Three stage cascade diode lasers generating 500 mW near 3.2 μm ," *Appl. Phys. Lett.*, vol. 107, 2015, Art. no. 111106.
- [22] S. Forouhar *et al.*, "Reliable mid-infrared laterally-coupled distributed-feedback interband cascade lasers," *Appl. Phys. Lett.*, vol. 105, 2014, Art. no. 051110.
- [23] D. Sanchez, L. Cerutti, and E. Tournié, "Mid-IR GaSb-based bipolar cascade VCSELs," *IEEE Photon. Technol. Lett.*, vol. 25, no. 9, pp. 882–884, May 2013.