Simulation and optimization of 2.6-2.8 μm GaSb-based vertical-cavity surface-emitting lasers

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***Abstract*–We present the simulation results of threshold operation of mid-infrared GaSb-based vertical-cavity surface-emitting lasers obtained with the use of comprehensive fully self-consistent optical-electrical-thermal-recombination numerical model. The results show that by a proper design of the active region it is possible to achieve the stable single-fundamental-mode low-threshold operation with emission wavelengths longer than those reported so far for similar devices.**

I. INTRODUCTION

Mid-infrared vertical-cavity surface-emitting lasers (VCSELs) have a great potential as low cost, ultralow threshold, small beam divergence light sources in distant air monitoring. Although there are several important gases, like C_2O, N_2O, H_2S, CH_4 in the mid-infrared spectral range, the longest wavelength reported to date for electrically pumped room temperature (RT) continues-wave (CW) VCSELs is 2.62 μm [1]. In this work we present the results of numerical analysis carried out for devices designed to emit the light from the 2.6–2.8 μm wavelength range. Due to the fact that the single-fundamental-mode operation is particularly suitable for absorption spectroscopy, we concentrate on suppression of the higher-order transverse modes in the modeled devices.

II. THE LASER STRUCTURE AND THE NUMERICAL MODEL

The structure under consideration was the GaSb-based multi-quantum-well (MQW) GaInAsSb/GaSb VCSEL similar to the device presented in [2]. Its active region is assumed to be composed of 8-nm $Ga_{1-x}In_xAs_{0.15}Sb_{0.85}$ QWs (In content x is equal to 0.43 and 0.49 for 1.6% and 2.0% compressively strained QWs, respectively) separated by 10-nm GaSb barriers. The active region is embedded in $Al_{0.15}Ga_{0.85}As_{0.01}Sb_{0.99}$ waveguide and sandwiched by p- and n-type GaSb spacers. Above p-type spacer, the tunnel junction (TJ) composed of p^{++}-GaSb and n^{++}-$InAs_{0.91}Sb_{0.09}$ is located. Upper spacer is manufactured from n-GaSb. The 3-λ cavity with several n^+-GaSb current spreading layers situated in cavity nodes is terminated on both sides by distributed-Bragg-reflectors (DBRs). The diameter of the bottom DBR (24 pairs of n-$AlAs_{0.08}Sb_{0.92}$/n-GaSb) is assumed to be equal to 100 μm, whereas the diameter of the top DBR (4 pairs of α-Si/SiO_2) is larger by 10 μm than TJ diameter. The top contact is produced in a form of a ring of 5 μm width, whereas the bottom one covers the whole bottom surface of the n-GaSb substrate.

Our three-dimensional optical-electrical-thermal-gain self-consistent model has been adapted to simulate the CW operation of the GaSb-based VCSELs. The detailed description of the numerical algorithm applied in our model can be found in [3], whereas in [4] the method to calculate the shifts in the conduction and valence bands due to strain effects is presented. Values of all necessary material parameters can be obtained with the use of formulas given in [5].

III. RESULTS

In Fig. 1. we present the values of the threshold current I_{th} for various ambient temperatures T_{amb} calculated for 2.6-μm VCSEL with the strain in the QW equal to $\varepsilon = -1.6\%$. As can be seen, with the increase of the T_{amb} the threshold current increases for all considered TJ diameters. This behavior can be explained with the use of Fig. 2 in which we present the gain spectra calculated for VCSELs designed to emit the light from the 2.6–2.8 μm wavelength range. For the 2.6-μm device the gain peak is shifted to a longer wavelength than the emission one. To achieve the threshold operation for higher T_{amb} it is necessary to obtain the similar value of gain in the active region (in our calculations the threshold gain slightly increases which is a result of temperature influence on absorption coefficients taken into account). However, for higher temperatures, gain calculated for a fixed carrier concentration decreases. Therefore, it is necessary to increase the carrier concentration in the active region which leads to the higher I_{th}. From Fig. 1. it can be also seen that for wider apertures the

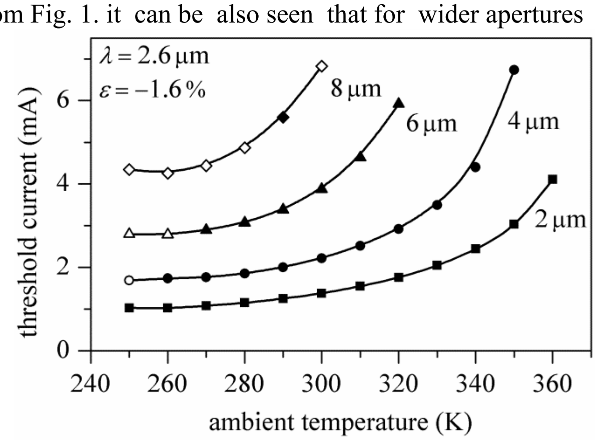

Fig. 1. Calculated threshold current vs. ambient temperature for 2.6-μm VCSEL with 1.6% compressively strained QWs. Filled and empty symbols correspond to LP_{01} and LP_{11} mode operation, respectively.

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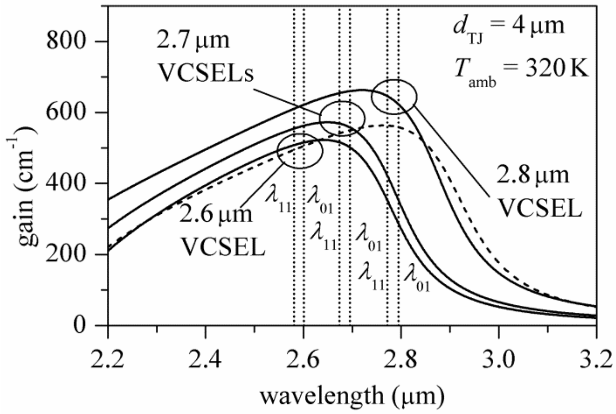

Fig. 2. Gain spectra calculated for VCSELs with 4-μm TJ diameter emitting in the 2.6–2.8 μm wavelength range with 1.6% (solid lines) and 2.0% (dashed line) compressively strained QWs. Wavelengths corresponding to the LP_{01} and LP_{11} modes have been additionally shown.

temperature range, in which the LP_{01} mode operation is achieved, decreases. This can be explained by the fact that for wider apertures the LP_{11} mode losses calculated in respect to LP_{01} mode become smaller.

For the device with the same active region but designed to emit the wavelength of 2.7 μm by increasing the thicknessess of DBR layers and the optical length of the cavity, we obtained the stable LP_{01} mode operation only for the TJ with the smallest aperture (Fig. 3a). As can be seen from Fig. 2, for 2.7-μm VCSEL and ε = –1.6%, due to the shift of gain spectrum towards the longer wavelengths, the value of gain for the wavelength corresponding to LP_{11} mode is higher than the one for LP_{01} mode. This leads to the significant reduction of the LP_{11} mode losses, and therefore we observe LP_{11} mode operation for all considered apertures wider than 2 μm, for which the LP_{11} mode losses are still enough high to provide LP_{01} mode emission. We performed analogous calculations for 2.8-μm VCSEL with the strain in the QW equal to ε = –1.6%. For this device LP_{11} mode operation is more favorable than for the 2.7-μm VCSEL with the same active region (Fig. 2). The values of the threshold current which, we do not report here, follow the same trend where the threshold current increases and the temperature range, for which LP_{01} mode operation is observed, decreases. As a result, for the 2.8-μm VCSEL, we obtained the stable fundamental mode operation only for device with TJ diameter of 2 μm.

One of methods to increase the LP_{11} mode losses and therefore to obtain laser operation in the LP_{01} mode is to shift the gain spectrum toward the longer wavelength. In VCSELs, for the situation when the wavelength corresponding to the gain peak is longer than the emission wavelength, the LP_{01} mode operation is more favorable than the LP_{11} one. In our calculations we shifted the gain spectrum for the 2.7-μm VCSEL (Fig. 2) by increasing the indium content in the GaInAsSb QWs from 0.43 to 0.49 which was followed by the increase in the value of compressive strain by 0.4%. As a result we obtained the stable LP_{01} mode operation for TJ diameters up to 6 μm (Fig. 3b) with the distinctly lower values of the threshold currents.

In conclusion, it has been shown that by a proper design of the VCSEL structure it is theoretically possible not only to achieve the threshold operation for wavelengths distinctly longer than those reported so far, but also to obtain the desired low-threshold stable single-fundamental-mode operation in these devices within a wide ambient temperature range.

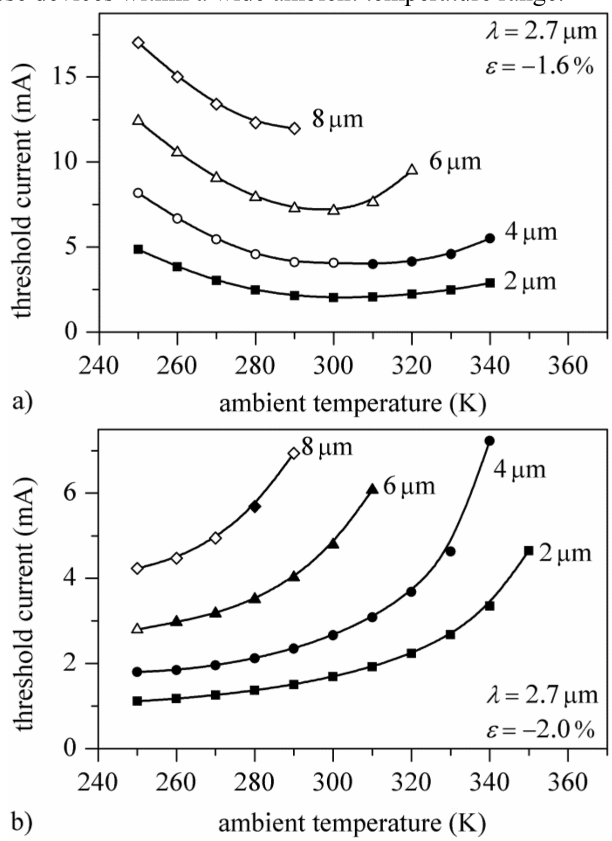

Fig. 3. Calculated threshold current vs. ambient temperature for 2.7-μm VCSEL with a) 1.6% and b) 2.0% compressively strained QWs. Filled and empty symbols correspond to LP_{01} and LP_{11} mode operation, respectively.

Acknowledgment

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References

[1] S. Arafin, A. Bachmann, K. Vizbaras, and M.-C. Amann, "Large-aperture single-mode GaSb-based BTJ-VCSELs at 2.62 μm," *Proc. of the 22nd IEEE International Semiconductor Laser Conference (ISLC)*, 26-30 Sept. 2010, Kyoto (Japan), pp. 47-48.

[2] S. Arafin, A. Bachmann, K. Kashani-Shirazi, and M.-C. Amann, "Continuous-wave electrically-pumped GaSb-based VCSELs at ~2.6 μm operating up to 50°C," *Proc. of the 22nd Annual Meeting of the IEEE Photonics Society (LEOS)*, 4-8 Oct. 2009, Belek-Antalya, Turkey, pp. 837-838, 2009.

[3] R. Sarzała et al., "Numerical self-consistent analysis of VCSELs," *Advances in Optical Technologies*, vol. 2012, id. 689519, 17 pp., 2012.

[4] Ł. Piskorski, L. Frasunkiewicz, and R.P. Sarzała, "Comparative analysis of GaAs- and GaSb-based active regions," *Bull. Pol. Ac.: Tech.*, vol. 63, pp. 597-603, September 2015.

[5] Ł. Piskorski and R.P. Sarzała, "Material parameters of antimonides and amorphous materials for modelling the mid-infrared lasers," *Opt. Appl.,* in press.