Vertical cavity surface emitting lasers of 1.3 μm spectral range based on the InGaAs/InGaAlAs superlattice

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Abstract. Vertical-cavity surface-emitting lasers of 1.3 μm spectral range with the active region based on the InGaAs/InGaAlAs superlattice were studied. VCSEL heterostructure was formed by a wafer-fusion of the heterostructure with an active region and two DBRs grown by molecular-beam epitaxy on InP and GaAs substrates respectively. Fabricated VCSELs have shown threshold current below 1.6 mA and frequency of small signal modulation near 9 GHz at 20°C.

1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) of 1.3 μm spectral range are promising light sources for different telecommunication systems, various hybrid optical interconnections and silicon photonics. The development of long-wavelength VCSELs faces with a number of fundamental problems, including rather large free carrier absorption, especially in p-doped contact layers. One of the possible solutions is associated with the use of intra-cavity (IC) contacts and a tunnel junction (TJ). However, in InGaAlAs/InP material systems it is impossible to form an oxide aperture for an effective current confinement similar to InGaAlAs/GaAs material systems, as a result use of an air aperture in the tunnel junction layer for a lateral confinement of the carrier injection region leads to a stronger self-heating effect in VCSELs monolithically grown on the InP substrate due to the deterioration of heat dissipation from active region [1]. Wafer fusion technique makes it possible to combine the advantages of an InP-based active region (high material gain) and a GaAs-based distributed Bragg reflectors (DBR, high thermal conductivity) [2]. Yet, the implementation of a GaAs intra-cavity contacts and oxide-confined AlGaAs apertures is associated with problems of the formation of an additional potential barrier and recombination centers in case of the current flow through the fused GaAs-InP interfaces [3]. As a partial solution the design with a buried tunnel junction (BTJ) and intra-cavity n-type contact layers in optical microcavity grown on InP substrate can be used [4].

Optimization of the active region has always been the base of progress in the development of semiconductor lasers. Recently we have shown that using of InGaAs/InGaAlAs superlattice (SL) as a VCSEL’s active region is very promised to substitute VCSELs active regions based on highly strained quantum wells (QW) and it can help to increase the modal gain of the device [5]. It was shown that the
variation of the ratio of QW and barrier-layer thicknesses in the InGaAs/InGaAlAs SL allows to control the shift of the photoluminescence peak position and to precisely control detuning in VCSELs [6].

In this paper, we present the results of the study of 1.3 μm VCSELs formed by a wafer fusion technique with an active region based on the InGaAs/InGaAlAs superlattice and n-type IC-contact layers inserted in the optical microcavity grown on the InP substrate.

2. Heterostructure

The schematic cross-section of the 1.3 μm InGaAs/InGaAlAs SL VCSEL is shown in Figure 1. The completed VCSEL heterostructure was fabricated by a double wafer fusion of the InP-based optical microcavity with two GaAs-based DBRs: first, a top 21.5 pairs Al_{0.9}Ga_{0.1}As/GaAs DBR wafer with the InAlGaAs/InP optical microcavity wafer and, after a selectively removing the InP substrate, with a bottom 35.5 Al_{0.9}Ga_{0.1}As/GaAs DBR wafer. The total thickness of an InAlGaAs optical microcavity was 3λ. The n\textsuperscript{++}-InGaAs/p\textsuperscript{++}-InGaAs/p\textsuperscript{++}-InGaAlAs TJ as well as heavy doped contact layers were placed at the node of the electromagnetic field intensity of the optical cavity mode to reduce an absorption losses. An InP/InGaAs layer re-growing of the surface relief (with an etching depth of 25 nm), which created in the TJ layer an 8-μm BTJ diameter, was carried out during the second growth step. Note that the molecular-beam epitaxy (MBE) was used as an epitaxial method for all heterostructures and growth steps. The active region consisted of a 24-period In_{0.57}Ga_{0.43}As/In_{0.53}Ga_{0.27}Al_{0.2}As SL with layer thicknesses of 0.8 nm and 2 nm, respectively, was placed at the peak of the electromagnetic field. The wavelength of the photoluminescence peak of an active region test was about 1280 nm at 20°C (Figure 2). The resonance wavelength of the double wafer fused VCSEL heterostructure measured by optical reflectance was near 1300 nm, which corresponds to a negative gain-to-cavity detuning of about 20 nm as shown in Figure 2.

![Figure 1. Schematic cross-section of 1.3 μm InGaAs/InGaAlAs VCSEL.](image)

![Figure 2. Photoluminescence (PL) spectra of the optically-pumped InGaAs/InGaAlAs SL-based active region test at 20°C (red dot-line) and optical reflectance (OR) spectra of the double wafer fused VCSEL heterostructure (black line).](image)
3. Experiment

Figure 3 shows typical continuous wave light-current-voltage characteristics measured in the temperature range of 20 to 100°C for the VCSELs with 8-μm diameter BTJ. VCSELs demonstrate a slope efficiency of 0.6 W/A and a maximum output optical power of about 8.8 mW at 20°C. The threshold current is less than 1.6 mA despite high output losses and the use of InGaAs-based BTJ, which can be explained by relatively low internal optical losses. Raising the heat-sink temperatures up to 70°C reduces the output optical power down to 3.2 mW, and the threshold current increases to 2.8 mA. The devices lase at 90°C with threshold current of 4.2 mA and output optical power of 1.3 mW, which still suited for uncooled-laser applications. According to the linear extrapolation of the maximum output optical power versus temperature (Figure 4), the lasing is possible up to 100°C. The obtained poor temperature stability of the static characteristics can be associated with a relatively small gain-to-cavity detuning in created VCSELs. The obtained results are comparable to the 1.3 μm wafer-fused VCSELs based on InAlGaAs QWs with InAlGaAs BTJ [2]. Note that devices start lasing via the fundamental mode with the subsequent switching to the multi-mode lasing at higher bias currents. It can be explained by an insufficient planarization of the surface relief during MBE regrowth that leads to the strong lateral waveguide effect.

![Figure 3. Light output power-current-voltage (L-I-V) characteristics for 1.3 μm InGaAs/InGaAlAs SL VCSEL with 8-μm BTJ diameter.](image1)

![Figure 4. Extracted threshold current and maximum optical power at different heat-sink temperature for 1.3 μm InGaAs/InGaAlAs SL VCSEL with 8-μm BTJ diameter.](image2)

To estimate the dynamic performance of the developed VCSELs a small signal modulation analysis $S_{21}(f)$ dependences on various forward bias currents and a heat-sink temperature were carried out by using Keysight N4375D 26.5 GHz light wave component analyzer. Figure 5 shows the -3dB modulation frequency as a function of bias current and the corresponding relaxation resonance frequency extracted from the fit of the conventional three-pole transfer function to the modulation response $S_{21}(f)$. At the temperature of 20°C, the -3dB modulation frequency reaches ~7 GHz at 10 mA with a modulation current efficiency factor of ~2.4 GHz/mA$^{1/2}$ and then saturated at 9 GHz near thermal roll-over. Temperature increase up to 85°C does not sufficiently effect on modulation current efficiency factor (~2.3 GHz/mA$^{1/2}$), but the maximal value of -3dB modulation frequency falls down to 5.8 GHz. For both temperatures, the -3dB modulation frequency saturates only near the thermal rollover current, while the resonance relaxation frequency demonstrates linear growth of the square-root of bias current above threshold. On the one hand, the current-induced self-heating can lead to an excessive damping and a fast saturation of the -3dB modulation frequency with a current as compared to that for the relaxation resonance frequency. On the other hand, the parasitic cut-off frequency estimated from the $S_{11}$ data is only about 4-5 GHz. Thus, the electrical parasitic has a significant impact on VCSEL’s high-speed performance and limits the achievable modulation bandwidth.
Figure 5. Estimated -3 dB modulation bandwidth ($f_{-3dB}$) and the extracted relaxation resonance frequency ($f_R$) as functions of the square-root of bias current above threshold at the temperature of 20°C (a) and 85°C (b) for 1.3 μm InGaAs/InGaAlAs SL VCSEL with 8-μm BTJ diameter.

4. Conclusion
We have studied fully MBE-grown double wafer-fused 1.3 μm VCSELs based on InGaAs/InGaAlAs SL active region. Lasers with 8-μm BTJ diameter have demonstrated the threshold current of about 1.6 mA and the maximum output optical power of 8.8 mW at 20°C. Rising of the heat-sink temperature up to 85°C reduces the output optical power down to 1.8 mW and increases the threshold current up to 3.8 mA, which is still suitable for uncooled-laser applications. According to the small signal modulation response the -3dB modulation bandwidth of 9 GHz and 5.8 GHz can be achieved in the developed VCSELs at temperatures of 20°C and 85 °C, respectively. The proposed design of the heterostructure can be used in VCSELs for telecom applications with a data rate up to 10 Gbit/s.

We believe that the further optimization of the InGaAs/InGaAlAs SL design, BTJs refractive index step and BTJs diameter as well as the photon cavity lifetime will lead to a better dynamic performance of 1.3 μm SL-based VCSELs compared to the InP-based VCSELs with InAlGaAs QWs [2].

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References
[1] Park M. R. et al. 2006 IEEE photonics technology letters 18 1717
[2] Mereuta A. et al. 2015 Journal of Crystal Growth 414 210
[3] J. Ram, J. J. 1995 Journal of Applied Physics 78 4227
[4] Blokhin S. A. et al. 2020 Technical Physics Letters 46 854
[5] Karachinsky L. Y. et al. 2019 Optics and Spectroscopy 127 1053
[6] Rochas S. S. et al. 2020 Technical Physics Letters 46 1128