Wafer-fused 1300 nm VCSELs with an active region based on superlattice

Sergey Blokhin,1 Andrey Babichev,2 Andrey Gladyshev,2 Leonid Karachinsky,2 Innokenty Novikov,2 Alexey Blokhin,1 Sergey Blokhin,1 Wafer-fused 1300 nm VCSELs with an active region characteristics can be obtained by increasing the differential gain of the active region based on InGaAs/InGaAlAs superlattice [8]. Further improvement of the modulation characteristic of InP-based VCSELs [8] by optimization of the cavity photon lifetime, which in turn enables error-free data transmission rate at 25 Gbps.

The 1300 nm range vertical-cavity surface-emitting lasers with the active region based on InGaAs/InGaAlAs superlattice are fabricated using molecular-beam epitaxy and the double wafer-fusion technique. Lasers with the buried tunnel junction diameter of 5 μm have shown single-mode CW operation with the output optical power of ~6 mW at 20°C. The use of InGaAs/InGaAlAs quantum wells allows creating sharp heterointerfaces, which made it possible to implement an active region based on SL for InP-based VCSELs in comparison with the InGaAs QW-based active region [10]. Here, we report on the realization of 1300 nm MBE-grown double wafer-fused VCSELs with an active region based on InGaAs/InGaAlAs SL, which demonstrate the output optical power of 6 mW in a single-mode CW regime. Small and large-signal modulation experiments revealed the possibility of efficient stable operation at 10 Gbps.

Device structure: The VCSEL heterostructure was fabricated by double wafer fusion of InGaAs/InGaAs DBRs grown on GaAs substrate on both sides of the InGaAs/InP optical cavity grown on the InP substrate. The InP-based and GaAs-based heterostructures were grown using the MBE technique. A double intra-cavity contacted the VCSEL design with buried junction (BTJ) for current confinement which was applied as our basic device design [11]. Figure 1 shows a cross-sectional scanning electron microscope (SEM) image of the completed VCSEL heterostructure in the microcavity region and the corresponding distribution of the electromagnetic field intensity of the cavity mode along with the refractive index profile. GaAs-based VCSEL heterostructure consists of a bottom DBR based on 35.5 pairs of quarter-wave Al0.53Ga0.47As/GaAs layers, a bottom intra-cavity n-InP contact layer with a thin heavily doped n-InGaAs contact layer, an active region based on SL (24 periods of 0.8 nm-thick In0.53Ga0.47As/0.2 nm-thick In0.53Ga0.47As/0.2 nm-thick In0.53Ga0.47As), a p-In0.52Al0.48As contact layer, and a p-In0.52Al0.48As emitter. The use of InGaAs/InGaAlAs superlattice in comparison with the InGaAs QW-based active region was placed at its antinode to increase the optical confinement factor. The BTJ layers and heavily doped contact layers were placed at the node of the electromagnetic field intensity of the cavity mode to reduce optical absorption loss, whereas the active region was placed at its antinode to increase the optical confinement factor.
and the differential resistance, calculated at half rollover current, is only 11% at 70°C and by 22% at 90°C. The threshold voltage is 1.9

Fig. 2 LIV characteristics. Inset shows a spectra at different currents

only 11% at 70°C and by 22% at 90°C. The threshold voltage is 1.9 V and the differential resistance, calculated at half rollover current, is ~85–90 Ω due to the optimized doping profile and a high quality of the wafer-fused interfaces. The wall-plug efficiency also reaches high values up to ~30%. Single-mode operation over the entire current range with a side-mode suppression ratio (SMSR) of a least 40 dB is revealed. Inset in Figure 2 shows a spectra at different currents.

To estimate the high-speed performance of the present VCSELs, the small-signal modulation response $S_{21}(f)$ was measured using the Keysight N4375D 26.5 GHz lightwave component analyser. The RF signal was combined with the direct current bias through a 45 GHz bias tee and fed to on-wafer VCSELs at a high-frequency ground-source-ground probe head. The results of small-signal modulation analysis for VCSELs at different bias currents are presented in Figure 3. The −3 dB cut-off frequency modulation bandwidth reaches a value of ~8 GHz at about 10 mA with a modulation current efficiency factor of ~2.9 GHz/mA$^{0.5}$, then saturates at 8 GHz and drops down to 5 GHz at higher currents (near rollover current). According to the corresponding $S_{21}(f)$ fits by the three-pole transfer function, the resonance frequency $f_0$ significantly exceeds the −3 dB cut-off modulation bandwidth at high currents, while the $K$-factor, derived from the dependence of the damping coefficient on the squared resonance frequency, is about 0.4 ns (a further decrease in the value is possible only by reducing the length of the optical cavity). The parasitic cut-off frequency reaches only ~4 GHz and hence the high-speed performance of the developed VCSELs is limited by an electrical parasitic.

Small-signal modulation experiments were performed at various bit rates to determine the data transmission capacity of the fabricated devices. The Keysight MS195A 65 Gbps arbitrary waveform generator was used to generate a non-return-to-zero bit pattern (pseudo-random bit sequence with a pattern length of $2^n - 1$). The Keysight 86100D Infinium DCA-X wide-bandwidth oscilloscope combined with a 20 GHz optical module was used to record the large-signal modulation. The VCSEL was biased at 10 mA with 0.7 V peak-to-peak modulation voltage at 20°C. The eye amplitude is weakly changing with bit rate increase up to 10 Gbps, however beyond this rate a decrease in the eye height is observed. The inset in Figure 3 shows a typical eye diagram at 10 Gbps.

Conclusions: We have studied 1300 nm MBE-grown wafer-fused VCSELs with the InGaAs/InGaAlAs SL-based active region and a BTJ diameter of 5 μm. Single-mode CW operation with the output optical power of 6 mW and SMSR > 40 dB at 20°C has been obtained. Small-signal modulation more than 8 GHz and clearly opened eye diagrams up to 10 Gbps were observed. We believe that further optimization of the length of the optical cavity, SL design and the photon lifetime, as well as reduction of the parasitic capacitance, would lead to better dynamic characteristics of VCSELs with the SL-based active region compared to the results of InP-based VCSELs with AlGaNAs QWs.

Acknowledgements: This work was supported by the Ministry of Science and Higher Education of the Russian Federation (project no. 2019-1442).

© 2021 The Authors. Electronics Letters published by John Wiley & Sons Ltd on behalf of The Institution of Engineering and Technology This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited. Received: 10 April 2021 Accepted: 6 May 2021 doi: 10.1049/el.2012.12232

References

1 Murty, M.V.R., et al.: Development and characterization of 100 Gb/s data communication VCSELs. IEEE Photonics Technol. Lett. 1–1 (2021). https://doi.org/10.1109/LPT.2021.3069146

2 Park, M.-R., et al.: All-epitaxial InAlGaAs-InP VCSELs in the 1.3–1.6-μm wavelength range for CWDM band applications. IEEE Photonics Technol. Lett. 18(16), 1717–1719 (2006). https://doi.org/10.1109/lpt.2006.879040

3 Riechert, H., et al.: Development of InGaAsN-based 1.3 μm VCSELs. Semicond. Sci. Technol. 17(8), 892–897 (2002). https://doi.org/10.1088/0268-1242/17/3/318

4 Gębski, M., et al.: Baseline 1300 nm dilute nitride VCSELs. OSA Continuum 3(7), 1952–1957 (2020). https://doi.org/10.1364/osaac.396242

5 Nishiyama, N., et al.: Long-wavelength vertical-cavity surface-emitting lasers on InP with lattice matched AlGaNAs-InP DBR grown by MOVCD. IEEE J. Sel. Topics Quantum Electron. 11(5), 990–998 (2005). https://doi.org/10.1109/JSTQE.2005.853841

6 Muller, M., et al.: InP-based 1.3 μm and 1.55 μm short-cavity VCSELs suitable for telecom- and datacom-applications. In: Proceedings of 14th International Conference on Transparent Optical Networks (ICTON), Coventry (2012). https://doi.org/10.1109/icton.2012.6254394

7 Ohiso, Y., et al.: 1.3-μm buried-heterostructure VCSELs with GaAs/AlGaAs metamorphic DBRs grown by MOVCD. Electron. Lett. 56(2), 95–97 (2020). https://doi.org/10.1049/el.2019.3995

8 Sirbu, A., et al.: Reliability of 1310 nm wafer fused VCSELs. IEEE Photonics Technol. Lett. 25(16), 1555–1558 (2013). https://doi.org/10.1109/lpt.2013.2271041

9 Caliman, A., et al.: 25 Gbps direct modulation and 10 km data transmission of 1310 nm waveband wafer fused VCSELs. Opt. Express 24(15), 16329–16335 (2016). https://doi.org/10.1364/oe.24.016329

10 Karachinsky, L. Y., et al.: Optical gain in laser heterostructures with an active area based on an InGaAs/InGaAlAs superlattice. Opt. Spectrosc. 127(6), 1053–1056 (2019). https://doi.org/10.1134/s0030400x19120099

11 Babichev, A. Y., et al.: 6-mW single-mode high-speed 1550-nm wafer-fused VCSELs for DWDM application. IEEE J. Quantum Electron. 53(6), 1–8 (2017). https://doi.org/10.1109/JQE.2017.2752700