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1300 nm VCSELS with active region based on InGaAs/InGaAlAs superlattice for long-distance transmission

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Abstract. We present the comprehensive study of laser performance of 1300 nm wafer-fused vertical-cavity surface-emitting lasers. Lasers with 5μm buried tunnel junction diameter demonstrate a stable single mode operation in the wide temperature range with maximal output optical power of 6 mW and above 1.5 mW at 20 °C and 80 °C respectively. Based on small-signal analysis the maximal modulation frequency of 8 GHz at 20 °C was estimated. Further increase of the temperature up to 85 °C led to dropping of maximal small-signal modulation frequency down to ~6 GHz at -3dB level despite of remaining of rather high current modulation efficiency about ~2.7 GHz/mA$^{0.5}$.

Keywords: vertical-cavity surface-emitting lasers, molecular-beam epitaxy, buried tunnel junction

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Материалы конференции
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Вертикально-излучающие лазеры спектрального диапазона 1300 нм с активной областью на основе сверхрешетки InGaAs/InGaAlAs для передачи данных на большие расстояния

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Аннотация. Представлены результаты комплексных исследований статических и динамических характеристик вертикально-излучающих лазеров спектрального диапазона 1300 нм, созданных по технологии спекания пластины оптического резонатора с пластинами распределенных отражателей, выращенных методом молекулярно-пучковой эпитаксии. Лазеры с диаметром мезы заращенного туннельного перехода 5 мкм продемонстрировали одномодовую лазерную генерацию в широком температурном диапазоне с максимальной выходной мощностью 6 мВт и 1,5 мВт при 20 °C и 85 °C соответственно. Достигнута максимальная частота модуляции 8 ГГц при температуре 20 °C. Дальнейшее увеличение температуры до 85 °C приводит к уменьшению максимальной частоты модуляции до ~6 ГГц на уровне модуляции -3дБ.

Ключевые слова: вертикально-излучающие лазеры, молекулярно-пучковая эпитаксия, заращенный туннельный переход.

Финансирование: Работа авторов из Университета ИТМО выполнена при поддержке Министерства науки и высшего образования Российской Федерации, проект тематики научных исследований № 1442-2019 (код научной темы FSER-2020-0013) в части исследований статических характеристик, при финансовой поддержке программы «Приоритет 2030» в части экспериментов по исследованию малосигнальной модуляции, а также САБ благодарит за поддержку Российский фонд фундаментальных исследований (Проект № 20-52-12006) в части измерения спектральных характеристик и в части экспериментов по прямой модуляции лазеров большим сигналом.

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Introduction

Nowadays, there has been a significant increase in the volume of digital data requires to be long-distance transmitted. In this regard, the increase in the number of optical communication channels and information processing lead to a significant growth in energy consumption in the world due to necessity to maintain the quantity and quality of transmitted information at high level [1]. The solution of this problem can be found through the development of the new effective laser sources and a vertical-cavity surface-emitting lasers (VCSELs) looks very perspective for this goal. VCSELs in the telecommunication spectral range of 1300 nm can be widely used for optical data transmission over long distances (more than 1 km). Gas sensors [2] and Light Detection and Ranging systems (LIDAR) [3,4] are also belonged to the perspective field of application of these lasers. Development an effective 1300 nm VCSELs requires combining an active region with a high optical gain and a high quality distributed Bragg reflectors (DBR) with a reflection coefficient close to 100%. However, now there are several problems associated with InGaAlAs/GaAs and InGaAlAsP/InP material systems. These problems include insufficient electron localization energy in the InGaAsP quantum well (QW) of the active region [5], large thickness and low thermal conductivity of the InGaAlAsP DBR layers. All these factors lead to weak temperature stability of the output laser's characteristics. One of the ways to solve this problem is to use a wafer-fused (WF) technology for of the active region heterostructures grown on InP substrate and DBRs grown on GaAs substrates, [6, 7], together with the use of a buried tunnel junction (BTJ) as a current and optical confinement [8, 9]. The most important challenge in the development of this approach, to create the very high efficient active gain media based on InP substrates which is able to provide data transfer speeds of tens of Gbit/s.

In this work we present a studies of static and dynamic performance of 1300 nm VCSELs with original design of active gain media based on InGaAs/InGaAlAs superlattice that were fabricated using of molecular-beam epitaxy (MBE) and wafer-fusion technologies.

Materials and Methods

The active region and top/bottom DBRs heterostructures for 1300 nm VCSELs were grown using MBE Riber 49 system. The active region with optical cavity and active gain media was grown on the InP substrate. It consisted of (see Fig. 1) a bottom intracavity n-InP contact layer with a thin heavy n-doped InGaAs contact layer inside, an active gain media based on a 24-period InGaAs/InAlGaAs SL, a *p*+-InAlAs emitter and composite *n*++-InGaAs/*p*++-InGaAs/*p*++-InAlGaAs BTJ.

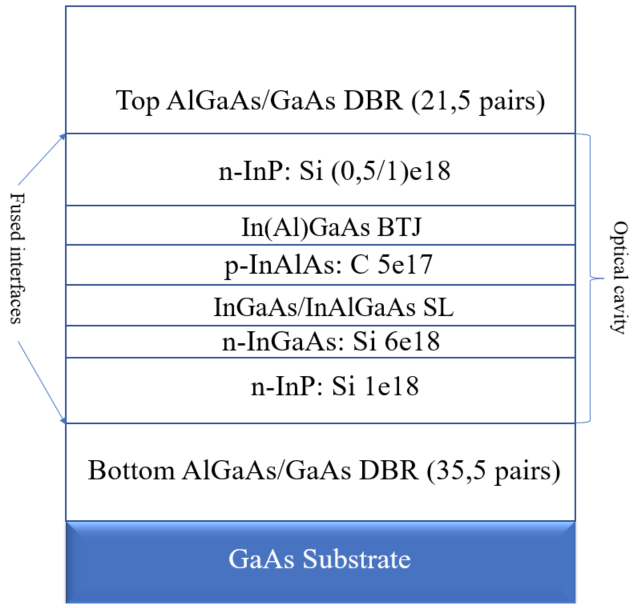

Fig. 1. Schematic representation of the resulting 1300 nm VCSEL heterostructure

The tunnel junction mesa was regrown by *n*-InP layer to form the BTJ. The thickness of the InGaAs layer in SL was 0.8 nm thick, and 2 nm thick for InAlGaAs barrier layers. These values were selected to achieve the photoluminescence peak at a wavelength of 1280 nm at room temperature. The DBR heterostructures were formed by MBE on GaAs substrates. Bottom DBR consisted of 35.5 pairs of $Al_{0.91}Ga_{0.09}As$/GaAs quarter-wave layers and the top DBR consisted of 21.5 pairs. Double wafer fusion of heterostructures at 600°C was carried out using a EVG 510 bonding system under high vacuum conditions. The contact force about 7 kN was applied during the whole bonding process. All thicknesses of the layers were corresponded with the calculated values to ensure resonance peak at 1300 nm. Fig. 2 shows the refractive index profile of the resulting heterostructure. The fabrication of VCSEL chips was carried out by an inductive coupled plasma etching of the top DBR mesa and a selective wet etching of optical cavity layers. Passivation with a SiN dielectric layer was carried out by a plasma-enhanced chemical vapor deposition. The diameter of BTJ mesa was 5 μm.

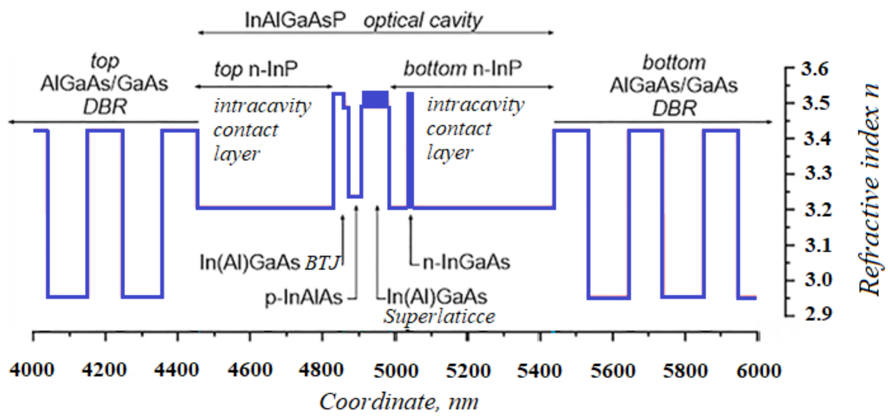

Fig. 2. Refractive index profile of the resulting 1300 nm VCSEL heterostructure

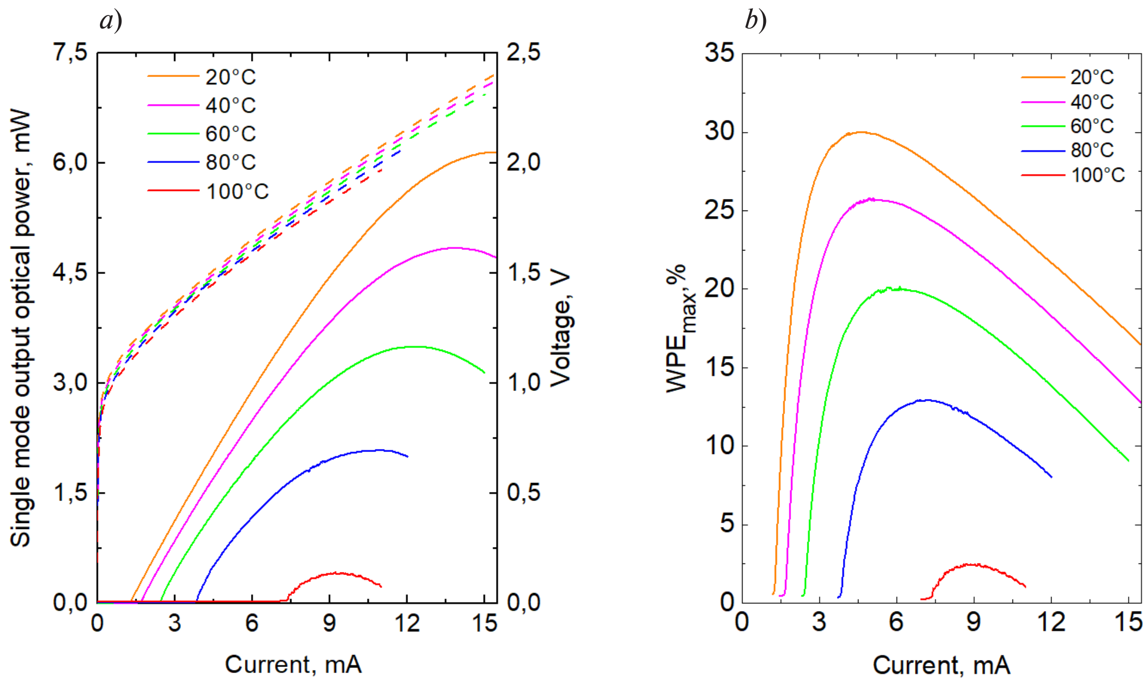

Fig. 3. LIV characteristics of the 1300 nm VCSEL measured at different temperatures (*a*), and dependence of wall-plug efficiency on current (*b*)

Results and Discussion

The statistic characteristics of the fabricated VCSELs were investigated. The continuous-wave (CW) light-current-voltage (LIV) characteristics of 1300 nm wafer-fused VCSEL were measured in a temperature range 20—100 °C (see Fig. 3,*a*). Lasers have shown the threshold current below 1.5 mA, slope efficiency more than 0.6 W/A and wall-plug efficiency about 30% at room temperature. Analysis of the optical losses in 1300 nm WF VCSELs was discussed in detail early in [10].

The threshold current growths at higher temperatures above the room temperature. At temperatures above 60 °C, an abrupt growth of the threshold current with temperature appears. Moreover, one can see that slope efficiency become the function of the pumping current and this effect increases with the temperature. This may be due to optical absorption at the resonant wavelength of the resonator in the non-pumped parts of the active region. The maximal achieved values of wall-plug efficiency (WPE_{max}) were (see Fig. 3,*b*): 30% at room temperature and 9% at 100 °C.

An emission spectra analysis (see Fig. 4) revealed that the VCSELs show stable single-mode lasing for the entire operating range of drive currents and temperatures. As a result, the 1300 nm VCSELs demonstrate a single-mode output optical power more than 6 mW and 1.5 mW at a temperature of 20 °C and 85 °C, respectively, with a side mode suppression ratio more than 40 dB.

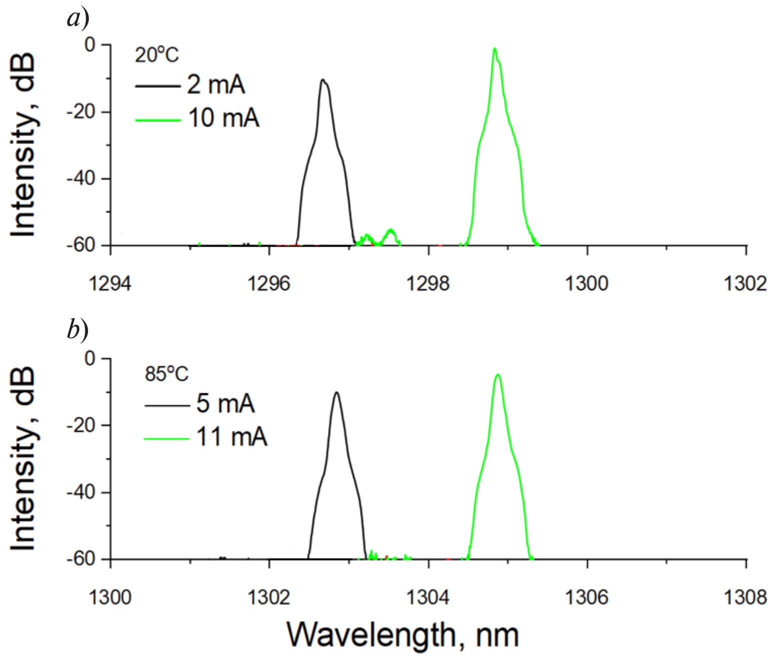

Fig. 4. Optical spectra at different drive current measured at temperatures of 20 °C (*a*), 85 °C (*b*)

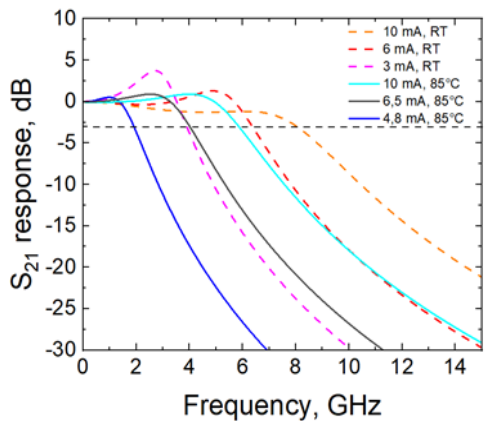

Fig. 5. Small-signal modulation response $S_{21}(f)$ measured at 20 °C and 85 °C

To estimate the dynamic VCSELs performance, the investigation of the frequency response on the small-signal amplitude modulation was carried out. The DC current was combined with the RF-signal through a 45 GHz high frequency bias-tee and was applied to VCSELs via a 40 GHz high-frequency electrical probe. The small-signal frequency response (S_{21}) was measured at temperatures of 20 °C and 85 °C (see Fig. 5). At room temperature, the extracted value of -3 dB modulation bandwidth has reached more 8 GHz at 10 mA and drops to 4-5 GHz at higher currents. At 85 °C temperature, the extracted value of -3 dB modulation bandwidth was only 6 GHz despite of maintaining the reasonable high current modulation efficiency about ~2.7 GHz/mA$^{0.5}$. As mentioned previously [10, 11], the electrical parasitics limit the modulation bandwidth of the studied VCSELs.

Conclusion

The 1300 nm VCSELs with InGaAs/InAlGaAs superlattice acting as active gain media were fabricated using of MBE and wafer-fusion as main technologies for fabrication. Static and dynamic characteristics of developed VCSELs at different temperatures were studied. The lasers with BTJ diameter of 5 μm demonstrated single-mode lasing with side mode suppression ratio more than 40 dB at all investigated temperatures. At temperatures above 60 °C, an abrupt growth of threshold current o temperature appeared, and accompanied by nonlinear behavior of slope efficiency with current, what can be attributed to the optical absorption at the cavity resonance wavelength in the non-pumped parts of the active region (cavity). The maximal modulation frequency reached of 8 GHz at 20 °C. Further increase of the temperature up to 85 °C led to a drop of modulation frequency down to ~6 GHz at -3 dB level despite of remaining of rather high current modulation efficiency value of ~2.7 GHz/mA$^{0.5}$.

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