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1550 nm high-speed VCSELS based on compressively strained In(Al)GaAs QWs

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Abstract. High-speed vertical-cavity surface-emitting lasers of 1550 nm spectral range based on ten compressively strained In(Al)GaAs QWs were fabricated by molecular-beam epitaxy and direct double wafer-fusion technique. The devices demonstrate threshold current of 2 mA and maximum output optical power of 4.8 mW. The effect of saturable absorber was observed at a temperature above 50 °C. Small signal analysis revealed that modulation bandwidth f_{-3dB} and the resonant frequency f_R of 8 GHz and 12 GHz, respectively, can be reached for presented VCSELs design. The NRZ-mode data rate up to 20 Gbps at 20 °C across the distance of 1000 meters was demonstrated.

Keywords: VCSEL, molecular-beam epitaxy, wafer fusion, data transmission, tunnel junction, strained quantum wells

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Материалы конференции
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Высокоскоростные вертикально излучающие лазеры 1550 нм на основе напряженных In(Al)GaAs КЯ

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Аннотация. Были изготовлены высокоскоростные вертикально излучающие лазеры (ВИЛ) спектрального диапазона 1550 нм на основе 10 напряженных In(Al)GaAs КЯ с использованием метода молекулярно-пучковой эпитаксии и двойного прямого молекулярного спекания эпитаксиальных пластин. Приборы демонстрируют пороговый ток 2 мА и максимальную выходную оптическую мощность 4,8 мВт. Эффект насыщающегося поглотителя наблюдался при температуре выше 50 °С. Малосигнальный анализ показал значения ширины полосы модуляции f_{-3dB} и резонансной частоты f_R 8 ГГц и 12 ГГц, соответственно. Была продемонстрирована скорость передачи данных до 20 Гбит/с в режиме NRZ при 20 °С на расстояние 1000 метров.

Ключевые слова: ВИЛ, молекулярно-пучковая эпитаксия, спекание пластин, передача данных, туннельный переход, напряженные квантовые ямы

Финансирование: Работа авторов из Университета ИТМО выполнена при поддержке Министерства науки и высшего образования Российской Федерации, проект тематики научных исследований № 2019-1442, в части исследований статических характеристик, при финансовой поддержке программы «Приоритет 2030» в части экспериментов по исследованию малосигнальной модуляции. И. А. Мельниченко благодарит Программу фундаментальных исследований НИУ ВШЭ за поддержку в части измерений спектров генерации. С.А. Блохин выражает благодарность программе CAS PIFI в части экспериментов по прямой модуляции лазеров большим сигналом.

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Introduction

To date, the growing needs for data storage, processing centers, information and computing systems require new light sources that can increase the bandwidth of fiber optic communication links [1]. Long-wavelength vertical-cavity surface-emitting lasers suitable for single-mode operations are among the most promising laser sources due to their relatively low threshold currents and the possibility of implementing high-frequency signal modulation [2]. Of great importance is the possibility to form 1D and 2D arrays based on VCSELs, as well as the possibility of integration with silicon, which is of interest for silicon-based radio photonics devices and their hybrid integration [3].

There are two main approaches to the creation of single-mode long-wavelength 1300–1550 nm VCSELs. The first approach uses an active region on an InP substrate with dielectric distributed Bragg reflectors (DBR) [4] formed by magnetron sputtering and requires specific materials (AlF_3, ZnS, CaF_2) to form hybrid DBR mirrors and removal of the InP substrate before sputtering. This approach has limitations such as relatively low obtained single-mode maximal output optical power at room temperature, as well as increased requirements for the optical uniformity and roughness of dielectric DBRs interfaces [4–6].

The second approach uses the wafer fusion technology to bond the active region based on InP and DBRs based on GaAs [7]. This approach effectively combines the advantages of the active region on the InP substrate and the high reflectivity DBR on GaAs substrates based on AlGaAs/GaAs materials. Recently, we have demonstrated the successful application and adjustment of the wafer fusion technique for a long-wavelength VCSELs fabrication [8–10]. Within this approach the current and optical confinement were ensured by a tunnel junction (TJ) [11] with a following overgrowth with an InP layer. One of the main advantages of this approach is the stability of the devices to meet the requirements of the GR-468-CORE Telcordia standard [12]. Previously, we proposed an original design of the buried tunnel junction (BTJ) n^{++}-InGaAs/p^{++}-InGaAs/p^{++}-InAlGaAs using the molecular-beam epitaxy (MBE) method both for the creation of active-region and DBRs heterostructures and for the overgrow of the TJ [13].

In this paper, we present the results on fabrication and study of 1550 nm single-mode VCSELs formed by molecular-beam epitaxy and a direct dry double wafer fusion of an active region based on compressively strained In(Al)GaAs quantum wells (QWs) with a n^{++}-InGaAs/p^{++}-InGaAs/p^{++}-InAlGaAs BTJ and GaAs DBRs.

Materials and methods

The schematic cross-section of the 1550 nm VCSEL is shown in Fig. 1. The heterostructure of the In(Al)GaAs/InP active region on InP substrate, including a microcavity, as well as heterostructures of distributed Bragg reflectors on GaAs substrates, were formed by the MBE method using an Riber 49 [14]. Each technical step of a direct dry double wafer fusion was performed with a modified EVG 501 wafer bonding system.

The In(Al)GaAs/InP optical cavity consisted of an active region with ten compressively strained $In_{0.74}Ga_{0.26}As/In_{0.53}Al_{0.26}Ga_{0.21}As$ QWs/barriers of 2.6 nm and 7 nm-thick, respectively, sandwiched by bottom intra-cavity (IC) layer with a heavily doped InGaAs contact layer from one side and a p-InAlAs emitter, a composite BTJ n^{++}-InGaAs/p^{++}-InGaAs/p^{++}-InAlGaAs with layers doped up to 5×10^{19} cm^{-3} and a top IC from the other side. The optical resonator was geometrically constructed to place $In_{0.74}Ga_{0.26}As$ QWs with a lattice mismatch parameter of ~ 1.4% and the composite BTJ in the maximum and minimum of the calculated electromagnetic field distribution, respectively (Fig. 2). The total thickness of microcavity was 3λ. The top and bottom DBRs consisted of 22.5 and 35.5 pairs of $Al_{0.9}Ga_{0.1}As$/GaAs layers, respectively. Note that gain-to-cavity detuning was performed to red shift microcavity resonance on the value of ~ 25 nm.

The composite BTJ mesa with a diameter of 6 μm was formed by a chemical etching, the first mesa was formed by a dry etching and inductively coupled plasma, the second mesa was formed by a two-step selective wet etching, the dielectric passivation was performed by a plasma enhanced chemical vapor deposition of Si_3N_4 and metallization of Ti/Pt/Au contacts was performed by a lift-off process to form ground-source-ground contacts topology.

Results and Discussion

Fig. 3 shows light-current-voltage (L-I-V) characteristics for the 1550 nm VCSEL based on compressively strained In(Al)GaAs in the temperature range of 20 to 90 °C. Temperature change

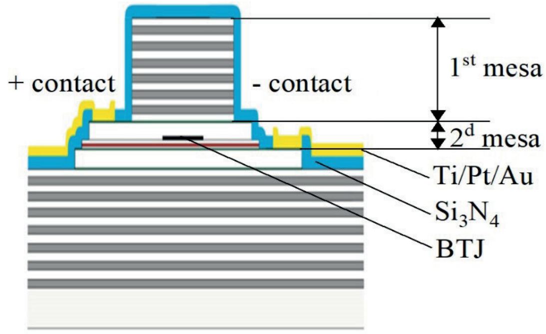

Fig. 1. Cross-section of the 1550 nm VCSEL based on compressively strained In(Al)GaAs QWs

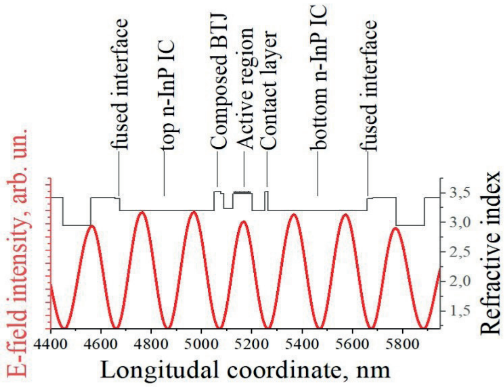

Fig. 2. Vertical distribution of electromagnetic field intensity along the refractive index of the 1550 nm VCSEL based on compressively strained In(Al)GaAs QWs

was carried out with a Peltier module. The studied devices at 20 °C demonstrated threshold current of ~ 2 mA with a slope efficiency of ~ 0.47 W/A and a maximum output optical power of ~ 4.8 W at the thermal roll-over current of ~ 18 mA. Rising the temperature resulted in reducing of the maximum output optical power with a disproportionate increase in the threshold current and a sharp increase in the optical power value at the beginning of the lasing, which can be explained by the effect of so-called saturable absorber, which we earlier observed in 1300 nm and 1550 nm VCSELs with a diameter of BTJ mesa lower than critical value [15]. Thus, rising temperature up to 60 °C leads to a rise in threshold current up to ~ 4.6 mA and at the temperature of 90 °C the threshold current reaches the value of 10.2 mA. Note that despite of the non-linearity of L-I-V characteristics for the all bias currents the single-mode operation is observed (inset to Fig. 2) which eliminates the possibility of the effect of a saturable absorber due to mode competition. According to lasing spectra fabricated VCSELs are suitable for 1550 nm window (also called third window) of optical fiber, namely for L band.

The estimation of the dynamic performance of the 1550 nm VCSEL based on compressively strained In(Al)GaAs QWs was carried out with a small signal modulation analysis $S_{21}(f)$ at a various forward bias currents using Rodhe & Schwarz ZVA 40 network analyzer and a 25 GHz New Focus 1434 photodetector. The classical method of three-pole transfer function was used to determine laser response to sinusoidal pump current modulation.

Fig. 4 shows the -3dB modulation bandwidth (f_{-3dB}) at the temperature of 20 °C. At the bias current of 3 mA the f_{-3dB} reaches 5 GHz and at the bias current of 6 mA the f_{-3dB} reaches 7.6 GHz and then saturates at the level of ~ 8 GHz with higher currents.

The corresponding to the f_{-3dB} saturation point modulation current efficiency factor is of ~ 3.6 GHz/mA0.5 (Fig. 5). The *D*-factor which demonstrates the rise of the resonant frequency (f_R) with a current and the differential gain level is at the level of 3.2 GHz/mA0.5. One can see that at high bias currents relaxation resonance frequency f_R reaches more than ~ 12 GHz (Fig. 5).

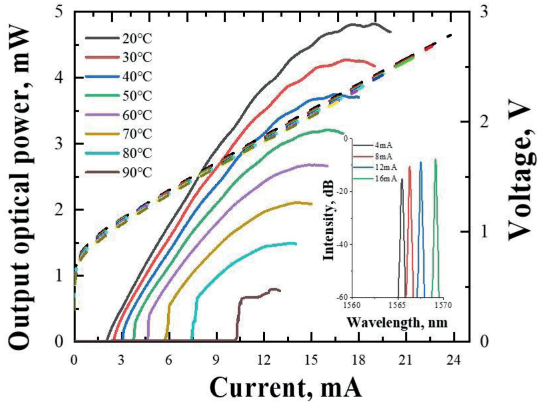

Fig. 3. *L-I-V* characteristics of the 1550 nm VCSEL based on compressively strained In(Al)GaAs QWs, inset shows lasing spectra at the temperature of 20 °C

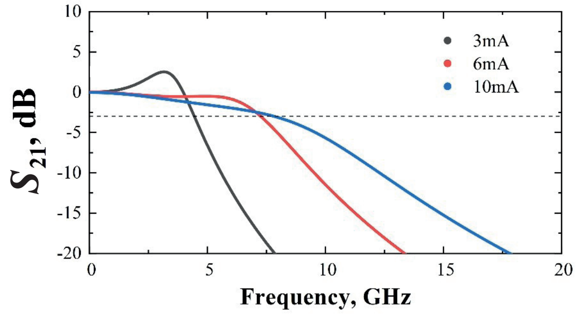

Fig. 4. Small signal modulation analysis $S_{21}(f)$ of the 1550 nm VCSEL based on compressively strained In(Al)GaAs QWs

The estimation of large signal modulation of the 1550 nm VCSEL was carried out with a SHF 12105A bit pattern generator, a 33 GHz Tektronix DPO7OE1 optical probe and Tektronix 59 GHz real time oscilloscope DPO75902SX. The data transmission was carried out in the non-return-to-zero (NRZ)-mode with a pseudo-random binary sequence (PRBS) of 2^7-1 using back-to-back (B2B) configurations over single-mode fiber (SMF) at a distance of 1000 meters.

Fig. 6 shows clear open eye diagram for the studied devices at data rate of 20 Gbps at 20 °C. The jitter value extracted from the bit error rate (BER) = 10^{-12} was 23 ps (~ 0.31 UI) at the 16 mA bias current and 300 mV modulation voltage.

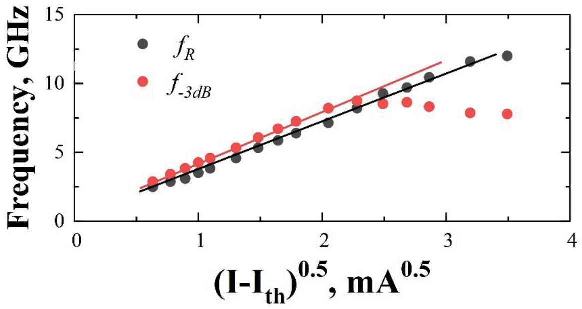

Fig. 5. The -3dB modulation bandwidth (f_{-3dB}) and the extracted relaxation resonance frequency (f_R) versus current at the temperature of 20 °C of the 1550 nm VCSEL based on compressively strained In(Al)GaAs QWs

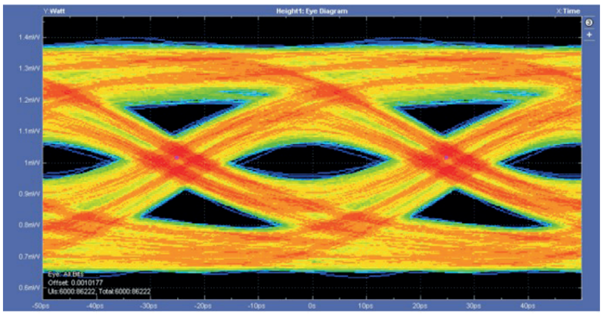

Fig. 6. Eye diagram of the 1550 nm VCSEL at the 16 mA bias current and 300 mV modulation voltage at 20 °C across 1000 meters SMF

Conclusion

We presented the results on fabrication and investigation of MBE-grown wafer-fused 1550 nm VCSELs based on compressively strained In(Al)GaAs QWs. The devices demonstrated the threshold current of about 2 mA and the maximum output optical power of 4.8 mW at 20 °C while increase in the influence of the saturable absorber effect [15] was observed at higher temperatures. According to the small signal modulation analysis $S_{21}(f)$ the -3dB modulation bandwidth f_{-3dB} and the relaxation resonance frequency f_R were 8 GHz and 12 GHz, respectively. The data rate up to 20 Gbit/s was achieved for VCSELs with BTJ mesa diameter 6 μm which is of interest of data transmissions for a large distance across single-mode fibers (e.g. 1000 meters).

We believe that the further improvement of the mesas geometric parameters and temperature stability of the devices (e.g. increase of QW barriers band gap), which is related with suppression of thermal escape of carriers from the QWs, as well as reducing parasitic capacitance to increase the -3dB modulation bandwidth, will lead to a better devices performance.

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