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Heterostructures of quantum-cascade lasers with nonselective overgrowth by metalorganic vapour phase epitaxy

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The possibility of fabrication of 4.6 μm spectral range quantum-cascade laser heterostructures by molecular-beam epitaxy technique with non-selective overgrowth by the metalorganic vapour-phase epitaxy is shown. The active region of the laser was formed on the basis of a heteropair of $In_{0.67}Ga_{0.33}As/In_{0.36}Al_{0.64}As$ solid alloys. The waveguide claddings are formed by indium phosphide. The results of surface defects inspection and X-ray diffraction analysis of quantum-cascade laser heterostructures allow to conclude that the structural quality of the heterostructures is high and the estimated value of the root mean square surface roughness does not exceed 0.7 nm. Lasers with four cleaved facets exhibit lasing at room temperature with a relatively low threshold current density of the order of 1 kA/cm^2.

Keywords: superlattices, quantum-cascade laser, epitaxy, indium phosphide.

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When creating high-power quantum cascade lasers (QCL) operating in continuous current pumping mode, an urgent problem that needs to be solved is the removal of heat from the heterostructure in both horizontal and vertical directions. To remove heat along the layers of the heterostructure, the technique of overgrowing a strip laser with semi-insulating layers of indium phosphide [1] is used. For the heat sink in the vertical direction, thick layers of doped InP are used along with the installation of a QCL crystal on an AlN or diamond-based heat sink [1,2]. At the same time, thin InGaAs layers have historically been used to increase the overlap factor of the optical mode with the layers of the active region (Γ-factortorus) when forming waveguide plates. However, a detailed calculation carried out by the finite element method shows that the use of additional InGaAs layers in the layers of the waveguide plates leads to a weak increase in the Γ-factor of the torus from 64 to 65% [3,4]. At the same time, the thermal conductivity of the InGaAs triple solid solution is 12 times lower than the thermal conductivity of Insb [3]. Thus, to increase the efficiency of the QCL heat sink in the vertical direction, it is more preferable to use waveguide plates completely formed on the basis of indium phosphide [2,3].

Since the method of molecular beam epitaxy (MPE) allows you to create sharper heterogeneities than the metalorganic vapour phase epitaxy technology (MOVPE) [5], two epitaxy technologies [1,6,7] are combined to implement lasers with record characteristics: the MPE method is used to grow the active region, and to form indium phosphide layers forming the upper lining of the waveguide, the MOGFE method is used.

In this paper, the results of non-selective overgrowth by the MOGFE method of heterostructures of QCL of the spectral range 4.6 μm grown by the MPE method are presented.

The QCL heterostructure has been grown on the InP substrate with the (001) orientation by the „Connector Optics" company on the Riber 49 molecular beam epitaxy unit of the industrial type [8,9]. The active region of two types of QCL heterostructures is formed from 30 and 45 cascades based on a heteroparticle of solid solutions $In_{0.67}Ga_{0.33}As/In_{0.36}Al_{0.64}As$ [10]. After growing the layers of the active region, an InP layer with a thickness of 100 nm was formed (doping level $n = 1.0 \cdot 10^{17}\,cm^{-3}$). After preliminary characterization of the structural quality in clean rooms, non-selective overgrowth of the heterostructure was carried out by the MOGFE method. Trimethylgallium, trimethylindium, phosphine and arsin were used as initial reagents. The growth temperature was 600−670°C. The samples were pre-annealed in a phosphine atmosphere (PH_3) at a temperature of 600°C for 5 min. The typical growth rate for InP was 1.8 μm/h, for $In_{0.53}Ga_{0.47}As$ — 0.3 μm/h. Thus, on the surface of the heterostructure grown by the MPE method, using the MOGFE method, The density of normal and oval defects, as well as the value of the parameter for QCL heterostructures after overgrowth by the MOVPE technology

Number of cascades in the structure	Density of normal defects, cm^{-2}	*Haze* in the range $0.6-10\,\mu m^2/\delta$, ppm/nm	Density of oval defects, cm^{-2}	*Haze* in the range $10-250\,\mu m^2/\delta$, ppm/nm
30	253	147/0.7	104	114/0.6
30	181	127/0.7	49	96/0.6
30	165	130/0.7	53	103/0.6
45	222	128/0.7	69	105/0.6
45	191	136/0.7	65	110/0.6
45	161	120/0.6	47	94/0.6
45	176	143/0.7	56	109/0.6

layers of the upper lining of the waveguide with a total thickness of $2.9\,\mu m$ based on indium phosphide were formed (with a variable doping level in the range of $1.0 \cdot 10^{17}-3.0 \cdot 10^{18}\,cm^{-3}$). The thickness of the contact layer $In_{0.53}Ga_{0.47}As$ with the doping level of $2.5 \cdot 10^{19}\,cm^{-3}$ was 200 nm. The formation of a crystal of 4-cleaved QCL was carried out by a method similar to that described earlier [11]. The sizes of 4-chipped lasers were 360×360 and $340 \times 340\,\mu m$ for QCL structures with an active region based on 30 and 45 cascades, respectively. Installation of the laser crystal was carried out with an epitaxial surface down onto a copper heat sink using an indium solder.

The structural quality of the heterostructure, as well as the thickness of the layers in the cascades were evaluated by X-ray diffractometry. Measurements of X-ray diffraction spectra were carried out near the symmetric reflex (004) InP on a PANalytical X'pertpro diffractometer in parallel geometry of the X-ray beam.

The study of maps of surface defects of QCL heterostructures was carried out on an automated system for monitoring the condition of the surface and determining the density of defects of substrates and structures Surfscan KLA Tencor. The density of normal defects (with sizes in the range of $0.6-10\,\mu m^2$) for structures including 30 cascades, before the process of accretion by the MOVPE technology, was in the range of $57-74\,cm^{-2}$, and the density of oval defects (with sizes in the range of $10-250\,\mu m^2$) did not exceed $5\,cm^{-2}$. The value of the parameter *haze* characterizing the roughness in the range of $0.6-10\,\mu m^2$ did not exceed the value of 16 ppm, which corresponds to the estimated value of the RMS surface roughness δ, not exceeding 0.2 nm. The parameter δ was evaluated using the expression [12]:

$$\delta = (\lambda/4 \cdot \pi)(H/R_0)^{0.5},$$

where R_0 — the reflection coefficient of the material, H — the value of *haze*, λ — the pumping wavelength in the surface condition monitoring system and determining the density of defects of substrates and structures Surfscan KLA Tencor, which was 488 nm. The value of the parameter *haze* in the range of $10-250\,\mu m^2$ is close to zero, which characterizes the absence of root-mean-square surface roughness δ.

The density of normal defects for structures comprising 45 cascades before the process of overgrowth by the MOVPE technology was in the range of $81-88\,cm^{-2}$, and the density of oval defects did not exceed $10\,cm^{-2}$. The value of the parameter *haze* in the range of $0.6-10\,\mu m^2$ did not exceed the value of 20 ppm, which corresponds to the estimated value of δ, not exceeding 0.3 nm. The value of the parameter *haze* in the range of $10-250\,\mu m^2$ did not exceed the value of 2 ppm, which corresponds to the estimated value of δ, not exceeding 0.1 nm.

The results of assessing the density of defects after overgrowth are presented in the table.

The density of normal defects for all studied heterostructures after the process of overgrowth by the MOVPE technology did not exceed $260\,cm^{-2}$, and the density of oval defects — $104\,cm^{-2}$. The value of the parameter *haze* in the range of $0.6-10\,\mu m^2$ did not exceed 150 ppm, which corresponds to the estimated value of δ, not exceeding 0.7 nm. The value of the *haze* parameter in the range $10-250\,\mu m^2$ did not exceed 115 ppm, which corresponds to the estimated value of δ, not exceeding 0.6 nm. Previously, for QCL heterostructures of the spectral range $4.6\,\mu m$, fully grown by the MPE [10], the density of normal defects did not exceed $140\,cm^{-2}$, and the density of oval defects — $25\,cm^{-2}$. The value of the parameter *haze* in the range $0.6-10\,\mu m^2$ did not exceed 100 ppm, which corresponds to the estimated value of δ, not exceeding 0.6 nm. The value of the parameter *haze* in the range of $10-250\,\mu m^2$ did not exceed 66 ppm, which corresponds to the estimated value of δ, not exceeding 0.5 nm.

Fig. 1 shows experimental swing curves of QCL heterostructures with an active region based on 30 and 45 cascades. The measurements were carried out after the process of overgrowth by the MOVPE technology. The X-ray diffraction curves show a complete coincidence of the zero peak of the satellite structure with the position of the peak from the InP substrate. This fact indicates the exact compliance of the chemical composition of the epitaxial layers with the specified values given in the

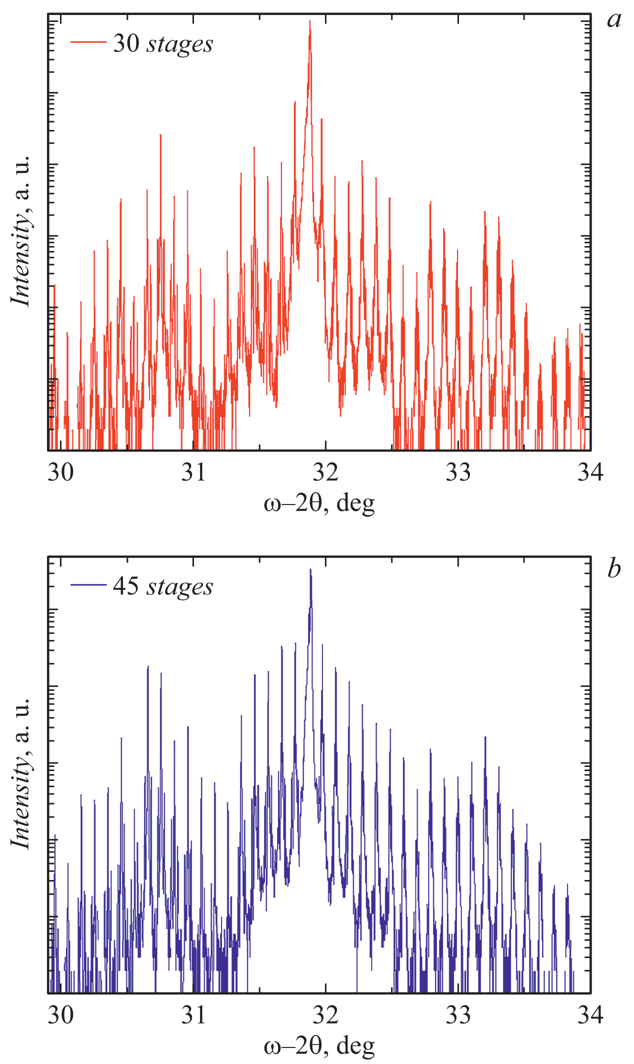

Figure 1. X-ray diffraction curves of QCL heterostructures with nonselective accretion by the MOVPE technology. *a* — QCL with an active region based on 30 cascades, *b* — QCL with an active region based on 45 cascades.

growth specification. A large number (on the order of 40) of peaks are observed on the swing curves- of high-order satellites characteristic of the periodic structure of cascades. Curve analysis gives a fairly small value of the average width at half-height (FWHM) of peaks-of satellites $13 \pm 2''$, which indicates a high uniformity of the composition and thicknesses of various cascades in the obtained heterostructures and correlates with the results of [10]. Based on the position of 20 satellite peaks, the average thickness of the cascade period was estimated, which was 50.8 ± 0.2 and 50.5 ± 0.4 nm for QCL heterostructures with an active region based on 30 and 45 cascades, respectively. Thus, the data of X-ray diffraction analysis indicate a high structural perfection of QCL heterostructures with active regions grown by the MPE method, followed by the formation of layers of the upper lining of the waveguide and contact layers by the MOVPE technology.

The characteristics of the QCL were studied in the pulse mode. The duration of the pumping pulses was 200 ns at a repetition rate of 25 kHz. To obtain the dependence of the QCL radiation intensity on the pumping current, the laser radiation was collimated using a high-aperture lens and recorded by a cooled Vigo PVI-4TE-10.6 photodetector connected to an Agilent 54835 oscilloscope. The pass band of both devices was 1 GHz. Parallel recording of photoresponse pulses and pump current pulses on an oscilloscope allowed simultaneous recording of data for constructing a pulsed volt-ampere characteristic, as well as the dependence of the pulse intensity of the QCL radiation on the pump current. The dependences of the pulse intensity of radiation, as well as the volt-ampere characteristics of 4-chipped QCL are shown in Fig. 2. The value of the threshold current density was of the order of 1.0 kA/cm^2, which correlates with the previously obtained results for QCL of the spectral range 4.6 μm, fully grown by the MPE [10] method. The threshold voltage in the lasers was 7.5–8.0 and 12 V for QCL with an active region based on 30 and 45 cascades, respectively. Registration of the QCL generation spectra was carried out using a vacuumed Fourier spectrometer BrukerVertex 70v. A typical laser generation spectrum is represented by a group of optical modes in the spectral range 4.65–4.70 μm (see insert in Fig. 2).

Thus, in the course of research, results were obtained on the creation and study of the QCL characteristics of the spectral range 4.6 μm. Combining two epitaxy technologies to create heterostructures of QCL made it possible to implement 4-cleaved lasers demonstrating threshold current densities comparable to the results for similar QCL struc-

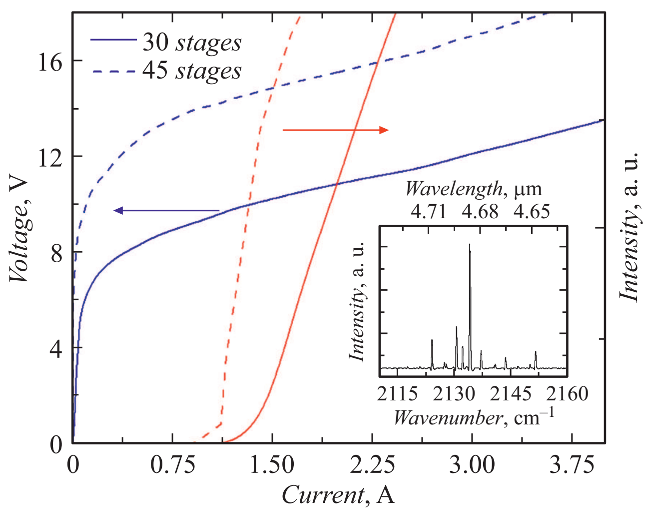

Figure 2. Volt-ampere characteristics (left axis) and the dependence of the pulse radiation intensity on the pump level (right axis) for 4-cleaved QCL with an active region based on 30 (solid lines) and 45 (dashed lines) cascades. In the insert — a typical generation spectrum near the threshold value for a QCL with an active region based on 30 cascades.

tures fully grown by the MPE [10] method. Considering the fact that strip QCLs made from heterostructures fully grown by the MPE method demonstrate high optical output power (at the level of 10,W) [13,14], it can be concluded that the combined approach in epitaxy of heterostructures is promising to implement powerful QCLs of the spectral range 4.6 μm. At the same time, increasing the number of cascades to 45 can further increase the output optical power in comparison with the previously presented results [14], which is the subject of further research.

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Conflict of interest

The authors declare that they have no conflict of interest.

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