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# Investigation of the Modified Structure of a Quantum Cascade Laser

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**Abstract**—The process of obtaining a modified structure for quantum cascade lasers is studied; this process includes growth using molecular-beam epitaxy, plasma etching, photolithography with the use of liquid etching, and the formation of special contacts for decreasing losses in the waveguide. The use of a special type of structure makes it possible, even without postgrowth overgrowth with a high-resistivity material, to attain parameters satisfying requirements to heterostructures in high-quality quantum cascade lasers at maximal simplification of the entire preparation process.

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## 1. INTRODUCTION

The operation of quantum cascade lasers (QCLs) is based on intraband optical transitions in contrast to the operation of conventional semiconductor lasers with interband transitions and the recombination of charge carriers; the wavelength of emission in QCLs is determined by the band structure of the superlattice in the active region rather than by the material. The wavelength can be chosen in a wide range in relation to applications, one of which is the use of atmospheric optical windows of transparency in the mid-infrared (IR) range (3–5 and 8–13 μm) for high-speed communication systems including those with the involvement of satellites. In the latter case, the effect of absorption and turbulence in the atmosphere is much reduced compared with the visible and near-IR ranges. The structures grown on the InP substrates are used in lasers for wavelengths $\lesssim 5$ μm with InGaAs/AlInAs layers; this is mainly due to considerations of the refractive index, manufacturability, and the availability of a suitable heat sink [1–8].

A critical point in fabricating QCLs, in addition to growth of the active region from superlattices, was found to be postgrowth processing, i.e., the fabrication of mesastrips, contacts, and heat sinks after the laser structure was grown [3]. In order to attain improved QCL characteristics (lowering of thresholds and increasing the differential efficiency), it was assumed to be important to use a material, which overgrows the strip structure, with improved heat removal and increased resistance. High-resistivity indium phosphide which is technologically compatible with InGaAs/AlInAs layers was considered as such a material. Overgrowth made it possible to improve simultaneously both the heat sink from the structure and electrical isolation of the strip walls [4].

We preliminarily showed that, after growth of the structure in the setup for molecular-beam epitaxy (MBE) with the use of the additional technology of metal-organic vapor phase epitaxy (MOVPE), it is possible to perform high quality defect-free overgrowth of the QCL structure with high resistivity indium phosphide (InP) without any special treatment after transfer from the MBE installation and contact with atmosphere [5]. However, the method itself requires the introduction of an additional MOVPE setup and technology into the overall experimental installation; this, undoubtedly, complicated the process and made it longer. In addition, the production of high resistivity material is in itself a nontrivial problem. Due to significant absorption and, as a result, self-heating of a “conventional” QCL structure with continuous contacts, an improved heat sink was required, i.e., the use of diamond and also InP and especially thick (~5 μm) gold contacts was needed [3, 4]. In the structure under consideration, such complications are not needed due to the use of an uncoated surface of the strip (the air–semiconductor boundary with a large refraction index) and to the elimination of absorption in the metal. Such a concept, conventionally referred to as “regrowth-free” and including only a single process of growth in the MBE installation without consecutive overgrowth with indium phosphide produced initially good results with stable single-mode generation without overheating in 2500 h at room temperature [6].

In this publication, we report the fabrication of a modified QCL structure with noncontinuous contacts (with an open surface); the structure is

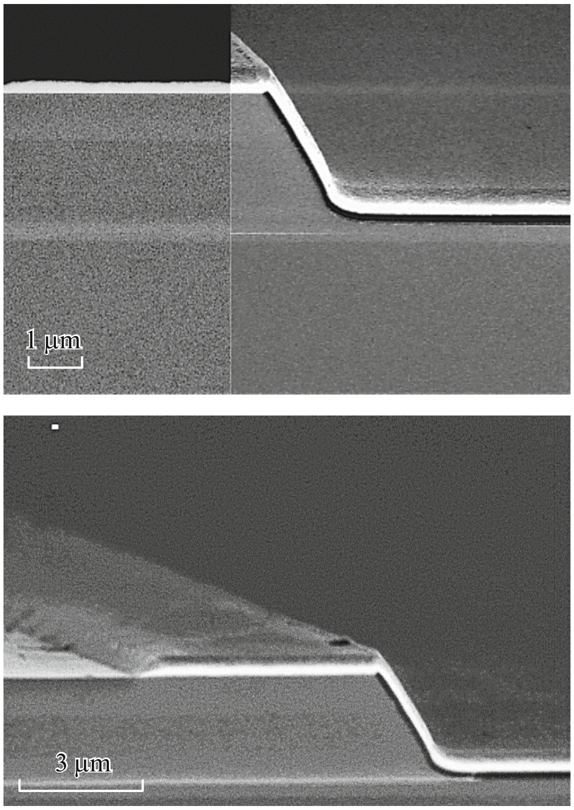


**Fig. 1.** View in an electron microscope of a cleavage of the QCL heterostructure after plasma etching and deposition of an insulator with metal.

intended to be used at a wavelength of ~5 μm, is based on AlInAs/GaAlAs strain-compensated superlattices with a four-well configuration of the active region, and is grown by MBE on InP substrates. In this study, we investigate the growth, postgrowth treatment, and characteristics of a laser structure, which is grown by MBE and has an active region similar to that in [7]. The aim of the study is the development of all necessary operations for the fabrication of high-quality QCL devices on the basis of equipment available at the Ioffe Institute.

At present, quantum cascade lasers, which operate in the wavelength range of 3–5 μm and are grown on indium-phosphide substrates, feature mainly the ridge-waveguide structure with a width of 5–50 μm; the structure is etched to the InP substrate and has dielectric insulation and a continuous ohmic contact on the front and rear sides [3, 4, 8].

In the case under consideration, the processed structure constitutes a ridge waveguide with an almost completely open upper surface and contacts at the ridges of the ridge waveguide (Figs. 1 and 2).

Such a structure not only considerably simplifies but also brings the cost the of entire process of fabrication down in comparison with other structures as a result of reduced expenditure of materials and a shorter duration of the MBE process due to exclusion of the growth of thick emitters and of difficulties related to the fabrication of high-resistivity material (InP) with the use of special technology (MOVPE) [5]. The entire sequence of technological operations is a preliminary one for the fabrication of a laser with distributed feedback and with the extraction of radiation through a diffraction grating deposited onto the surface of the ridge waveguide.

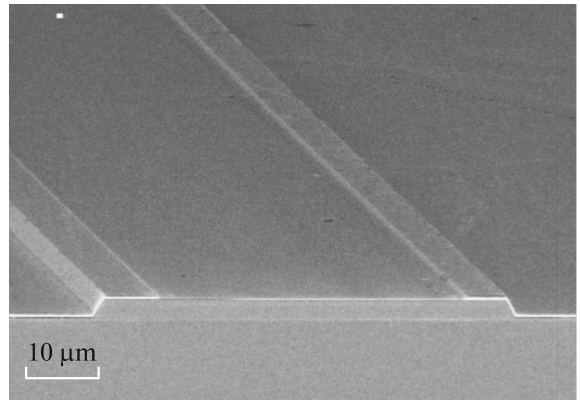


**Fig. 2.** General view of a cleavage of the QCL in an electron microscope on a reduced scale.

## 2. EXPERIMENTAL

### *2.1. Growth of Heterostructures*

The laser heterostructures were grown by molecular-beam epitaxy using a RIBER-Compact 21TM installation. The active regions of the laser structures were grown at 500°C; the conditions of slight stabilization of the surface with arsenic were applied during growth. The developed laser structure included a strain-compensated active region (similarly to [7]) and was deposited onto an *n*-InP substrate doped with $2 \times 10^{17}$ cm$^{-3}$ of Sn. The heterostructures' active regions $GaIn_xAs/AlIn_yAs$ were grown in the strain-compensated variant to increase the band discontinuity at the heteroboundaries in order to suppress the losses of free charge carriers to the continuum. The strain-compressed well regions with an indium content of $x = 0.60$ and strain-extended barriers with an indium content of $y = 0.44$ bring about a total strain in the structures of no larger than $10^{-3}$. The active region of the quantum cascade laser included 30 periods. Each period involved the actively emitting zone proper consisting of four quantum wells and an injection region with a strain-compensated superlattice. One period contained a sequence of 20 alternating AlInAs/GaInAs layers (with thicknesses in nm): 4.2/1.3/1.4/5.0/1.4/4.4/1.5/3.9/2.4/2.9/1.9/2.6/2.0/**2.3/2.1/2.2/2.3**/2.1/3.0/2.1 with GaInAs well layers (underscored) and layers doped with silicon to a level of $n = 4 \times 10^{17}$ cm$^{-3}$ (the thicknesses of these levels are shown in bold). The entire structure (the sequence from the substrate in the growth direction) consisted of the following layers (the doping levels are given in brackets): a $Ga_{0.53}In_{0.47}As$ waveguide layer ($6 \times 10^{16}$ cm$^{-3}$) with a thickness of 340 nm, an active region with a thickness of 1530 nm (30 periods), a $Ga_{0.53}In_{0.47}As$ waveguide layer ($6 \times 10^{16}$ cm$^{-3}$) with a thickness of 500 nm, and an upper "subcontact" heavily doped $Ga_{0.53}In_{0.47}As$ layer ($2 \times 10^{18}$ cm$^{-3}$) with a thickness of 400 nm.

When choosing the quantity of periods in the active region, it was necessary to take into account the dependence of the threshold current density on the losses, gain, and the confinement factor, i.e.,

$$J_{\rm th}(N_p) = (\alpha_m + \alpha_w)/g\Gamma(N_p).$$

Here, $J_{\rm th}(N_p)$ is the threshold current density, $\alpha_m$ are the losses due to reflection ($\alpha_m = (1/L)\ln R$, where $L$ is the cavity length and $R$ is the coefficient of reflection at the mirrors), $\alpha_w$ are the losses in the waveguide, $g$ is the optical gain, $\Gamma(N_p)$ is the coefficient of optical confinement, and $N_p$ is the amount of periods in the active region. It was found that the lasers with $N_p < 6$ do not produce generation at room temperature. As the number of periods is increased from 12 to 75, the threshold current density at 300 K decreases from 16 to 8 kA/cm$^2$, respectively; theoretical predictions are in good agreement with the experiment and yield $J_{\rm th} \le$ 10 kA/cm$^2$ at a number of periods of >20 [8]. In addition, the threshold current density becomes independent of temperature and of the number of periods at $N_p \ge 20$ with the characteristic temperature $T_0 \ge 100$ K. The quantum cascade lasers behave in relation to temperature as conventional semiconductor lasers with the threshold current density

$$J_{\rm th}(T) = J_0 \exp(T/T_0),$$

but with the value of $T_0$ between 100 and 300 K, which is a very high temperature for other semiconductor lasers (the typical value is $T_0 < 100$ K).

In addition, the differential quantum efficiency becomes >1 at $N_p \ge 12$, while the operating voltage does not become in this case "too" high (3–10 V at 10–40 periods) [8]. Thus, the optimal number of periods is bound to be in the range of 20–40 in order to satisfy all existing requirements.

The technical difficulties encountered with increasing total number of layers in the periods (up to ~600) are determined by the potential of the installation and are not an unsolvable problem for a typical MBE installation. However, from the point of view of time spent, amount of used materials, and wear-and-tear of the installation, it is desirable to reduce the number of layers; thus, we arrive at the minimal necessary number of periods ~30. This number was chosen in our structures.

In addition, as was shown experimentally by Babichev et al. [9], the use of a larger number of periods is not necessary. It was noted in [9] that "the growth of 60 periods does not bring about the desired increase in the quantum efficiency and optical power, but only gives rise to an increase in the operating voltage and to additional self-heating of the laser; cascades at the periphery do not in fact operate". This was also known from study [8] of originators of QCLs as far back as in 2001.

### *2.2. Postgrowth Processing*

The process of postgrowth processing consisted in sequential technological stages, which led to the formation of a mesaridge waveguide structure coated partially with metal (at the edges of the ridge waveguide). The ridge waveguides were etched off to the lower waveguide layer, were coated with an insulator on the side walls, the substrate was thinned, the upper and lower metal layers were deposited, a part of the metal was removed from the upper contact to the middle of the ridge waveguide, and the ridge waveguides were split into chips with a length of 1, 2, and 3 mm (as in a conventional semiconductor laser, without the introduction of additional complicating operations). The only difference consisted in the fact that the upper contact was not continuous and did not cover the entire upper surface of the ridge waveguide.

Device fabrication began with the formation of a mesa-ridge-waveguide structure with a width of ~55 μm. Using the method of ion-beam etching, the mesa was etched (through the mask of a photoresist) to a depth corresponding to the shut-down of the etching process at the lower $Ga_{0.47}In_{0.53}As$ waveguide layer with a thickness of 340 nm, which is clearly seen in Fig. 1. We used the $TiO_2/SiO_2$ films to obtain a dielectric coating. Our experience shows that the layers of such an insulator are denser compared with the layers of silicon dioxide; therefore, the necessary thickness of the protective coating can be chosen smaller (≤0.2 μm) than in the case of $SiO_2$ layers, which provides better heat removal.

When using ion beam etching, the damaged layer remains at the side surface of the mesa as a result of bombardment of the semiconductor structure with Ar atoms; this layer can bring about the appearance of leakages. In order to remove this layer, we used an etchant based on a heavily diluted solution of HBr and $H_2O_2$ in water with a very low etching rate $V$ = 0.05 μm/min, which provides the same etching rate for structure layers differing in composition and, as a result, a smooth surface of the side wall of the ridge waveguide. Removal of the damaged layer from the laser structure was performed directly after dry etching; the depth of treatment was ~0.1 μm.

After the above operations, we passivated the side wall of the mesa with an insulator. A $TiO_2/SiO_2$ dielectric coating was deposited onto the sample by the method of magnetron sputtering using a BAS450 Bal-

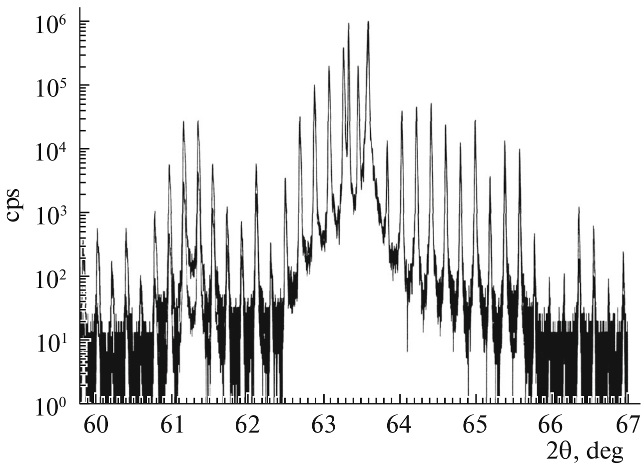


**Fig. 3.** Diffraction pattern of the QCL structure at the center of the plate and at the edge in the range 60°–67° (the Cu$K_\alpha$ radiation, the wavelength $\lambda = 0.154$ nm).

zers installation. The following parameters were chosen: the temperature of the process was equal to 200°C and the optimal thickness of the coating ~180 nm. Subsequent removal of the photoresist mask using organic solvents brings about vacation of the contact layer on top of the ridge waveguide; in this case, the side wall of the mesa is coated with an insulator. The use of a single photoresist mask for both etching of the mesa and passivation of its side wall makes it possible to reduce the number of photolithographic operations.

We then thinned the substrate to a thickness of ~170 μm. A continuous AuGe-Ni-Au *n*-type rear contact with a total thickness of 300 nm was deposited by the method of thermal evaporation in vacuum using a VUP-5M installation. In order to obtain ohmic characteristics of the contact, we performed rapid thermal annealing for $t = 30$ s in a $H_2$ atmosphere at a temperature of 370°C. In order to improve heat removal and reduce the resistance, we strengthened the contact by the additional deposition of Au (200 nm); as the material for the adhesion layer with a thickness of ~20 nm we used Cr.

The upper contact was not continuous; it had the following configuration: metal covers the side wall of the ridge waveguide above the insulator and forms two strips with a width of 6–7 μm on the surface of the contact layer at its edges (Fig. 2). This makes it possible to attain good contact characteristics and leaves a wide zone free of metal or a “window” in order to exclude the absorption of laser radiation in the metal (~75% of the surface). In the future, such a structure will make it possible to fabricate a diffraction grating on the free surface for the extraction of single-mode radiation, i.e., to form the basis for the fabrication of a laser with distributed feedback.

In order to form such a topology of the upper contact, we used the method of explosive photolithography. A part of the ridge waveguide, where it was required to form a “window”, was covered with the photoresist mask and metal was deposited by sputtering; then, the resist was removed using organic solvents and simultaneously a “window” was formed. The layer of metal deposited by sputtering is bound to be fairly thick taking into account the subsequent formation of high-quality soldered connections of the chips; therefore, in order to make easier the “explosion”, we used a two-layer mask with a special lift-off resist. As a material to contacts, we chose the following system: a Cr adhesion layer (20 nm) and a thick Au layer (450 nm). The contact was not fired in.

## 3. MAIN PART

### *3.1. Study of the Structure of the Quantum Cascade Laser by the Method of X-Ray Diffractometry*

We performed X-ray diffraction studies using a D8 Discover Bruker (Germany) diffractometer. The source of radiation with a power of 6 kW was an X-ray tube with a rotating copper anode (the wavelength $\lambda = 0.15406$ nm). The diffraction curves were obtained in the three-crystal geometry using a Bartels four-fold flow-through crystal–monochromator and a three-fold flow-through crystal–analyzer Ge(220). The half-width of the primary beam was no larger than 12″. The entire plate with a diameter of 5 cm was studied after growth, before splitting and performing the process of photolithography.

The diffraction curves were obtained by $2\theta/\theta$ scanning in the region of the reflection angle from the (004)InP plane. The obtained diffractograms are shown in Fig. 3. The developed interference pattern is observed in a wide range of angles, >10° over the $2\theta$ scale, which indicates that the interfaces forming the periodic structure are planar and continuous. The peaks in the thickness oscillations feature a small half-width without splitting, which corresponds to the constancy of composition and periods of the “superlattice”. In general, the observed diffraction pattern indicates high structural perfection of the QCL. Deviation from the calculated values amounted to 30 periods (~0.4% for the thickness), which corresponds to ~1.6 monolayers (ML) (Fig. 3). The natural precision (by the nature of MBE) cannot exceed one monolayer.

### *3.2. Study of the Electrical Characteristics of the Structure*

In order to preliminarily estimate the electrical characteristics, we measured the current–voltage ($I$–$V$) characteristics without soldering the samples to the heat sink and using only a pressing probe. The $I$–$V$ characteristics were measured at room temperature in the pulsed mode (duration of the pulses was 100 ns and the pulse-repetition rate was ~5 kHz). The length of the ridge waveguide was $L = 1.5$ mm, the thickness of it was $W = 50$ μm, and the temperature was 300 K

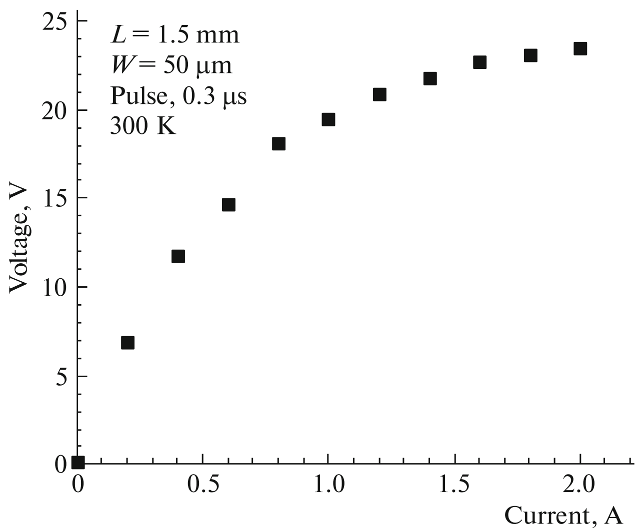


**Fig. 4.** Current–voltage characteristic of the QCL structure under study. The parameters are indicated.

(Fig. 4). The voltages sustained by the structure appear sufficient for initiating tunneling and entering the mode of generation (typical voltages referred to in available relevant foreign publications amounted to 10–15 V). On the other hand, these voltages are close to those in the structures grown in Russia [9]. The results of a more detailed study of the structure's characteristics will be reported in a special subsequent publication.

## 4. CONCLUSIONS

In this study, we investigated the modified structure of a quantum cascade laser (QCL) grown by molecular-beam epitaxy and formed using photolithography and plasma (and liquid chemical) etching; the structure does not include thick emitters. It is shown that the equipment available at the Ioffe Physical–Technical Institute makes it possible to attain all required QCL parameters with simplification of the process compared with the "standard" one known before. The obtained structures will make it possible in the future to change to the fabrication of a laser with distributed feedback; these structures conform to all requirements imposed on the heterostructures of high-quality QCLs.

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