1. INTRODUCTION

The concept of the possible amplification of electromagnetic waves in semiconductors with a superlattice was first formulated by Kazarinov and Suris in 1971. Then, this principle was used in 1994 to develop a laser by a team of scientists headed by Federico Capasso, with the laser named that of the quantum-cascade type. At present, high-power compact lasers for the mid- and far-IR spectral range are in high demand for the development of device systems for special and civil purposes. Lasers of this kind are used in the following fields: remote gas analysis; medical diagnostics; optical and space communications; detection of drugs, explosives and other chemical substances; and noncontact chemical tomography.

Effective and compact emitters for the mid- and far-IR spectral ranges, e.g., quantum-cascade lasers (QCLs), are monopolar semiconductor devices based on classical quantum-confinement effects in semiconductor heterostructures, such as resonant tunneling across a potential barrier, the formation of a miniband in short-period superlattices, and optical transitions between quantum-confinement levels in the conduction band. An advantage of QCLs is the possibility of rather widely varying the energy of the radiative transition by only changing the thicknesses of the layers in the nanoheterostructure. The typical lasing wavelengths of QCLs fall within the range 3.4–24 μm. The necessary requirements for fabricating the nanoheterostructure of a high-efficiency QCL are high planarity of heterointerfaces between the layers, the existence of a rather large number of cascades (20 and more), precise control over the thickness and elemental composition of the epitaxial layers, and a large conduction-band offset at the barrier/well heterointerface. At present, all these requirements can be satisfied by the fabrication of QCL nanoheterostructures on GaAs and InP substrates by molecular-beam epitaxy (MBE).

In principle, QCLs are based on intersubband electron transitions between quantum-confinement levels in a semiconductor nanoheterostructure. The wavelength of light emitted by the active region of a QCL (quantum well, QW) is mostly determined by the thickness of the semiconductor layers, rather than by their band-gap width. The effects of resonant tunneling and conduction via the miniband make it possible to create an injector region and connect active zones. The combined set of an injector and active region is named a cascade. Thus, by alternating the active region and the injector region, we can create QCL nanoheterostructures containing a large number of series-connected cascades. Such a cascade-laser design provides a rather simple method for raising the output power of a single device. Overcoming/Upon passing a cascade, an electron emits a photon. When passing through a QCL, a single electron emits a multitude of photons. The larger the number of cascades in a QCL, the greater the number of photons emitted by an electron in a single transit. Consequently, increasing the number of cascades must lead to a higher device output power and a lower lasing threshold. The number of cascades necessary for obtaining a high-efficiency QCL is 40 and above [1, 2]. However, this conclusion is valid only if all the cascades are completely identical. In actual practice, it is difficult to maintain identical parameters of the epitaxial process during the long growth time of a QCL nanohetero-
QCLs for the wavelength range 4–10 μm are grown on InP substrates [3, 4]. The ternary solid solution InAlAs is used as the material of the quantum barrier, and the InGaAs solution, as that of the QW. Two variants of heterostructures are possible: lattice-matched and elastically balanced. In the first case, In$_{0.55}$Ga$_{0.47}$As and In$_{0.55}$Al$_{0.47}$As solid solutions lattice matched with the substrate material are used. In this case, the conduction-band offset $\Delta E_C$ at the heterointerface is approximately 490 meV. In the second case, two solid solutions lattice-mismatched with the substrate material in different directions are used. All the layers forming a quantum-cascade are thin, and, to preclude the formation of mismatch dislocations, it is sufficient to maintain elastic balance, i.e., it is necessary to maintain the average lattice constant of the cascade, which should sufficiently precisely coincide with the lattice constant of the substrate material. In the case of elastically balanced nanoheterostructures, the larger values of $\Delta E_C$ preclude the leakage of electrons via their thermal excitation from the miniband and provide stable operation of the devices at room and higher temperatures. The technological aspects of the fabrication process of specifically these elastically balanced QCLs by MBE and their structural properties are examined in the present study. The number of cascades certainly providing the fabrication of a high-efficiency QCL was found to be 60.

Elastically balanced QCL nanoheterostructures based on In$_{0.44}$Al$_{0.56}$As and In$_{0.65}$Ga$_{0.35}$As solid solutions on a conducting InP substrate were fabricated by MBE on a Riber 49 industrial MBE machine. Three wafers with a diameter of 2 in were fabricated in a single epitaxial process. The chosen elemental composition of the solid solutions of the In$_{0.44}$Al$_{0.56}$As/In$_{0.65}$Ga$_{0.35}$As heteropair provided the necessary elastic balance in the QCL cascades and a band offset $\Delta E_C$ of no less than 630 meV at the heterointerface.

Preserving the high crystal perfection of the nanoheterostructure from the first to the last cascade when fabricating elastically balanced QCLs is an important technological task. First, it is necessary to maintain with extremely high precision the fluxes of Group-III elements to the epitaxial surface. For this purpose, it is necessary to provide precise control over the temperature of the effusion sources, with deviations not exceeding ±0.5°C. In addition, particular attention should be given to maintaining the ambient temperature in the room with the epitaxial apparatus, with deviations not exceeding ±0.5°C, so that the fluxes can be maintained with an accuracy of no worse than ±2%. In the case of stronger fluctuations of the ambient temperature for which an industrial system is employed, the fluxes may deviate beyond the above limits during epitaxial growth of the nanoheterostructure.

2. EXPERIMENTAL

Preliminarily, prior to the fabrication of a multiperiod QCL structure, we produced, to precisely calibrate the thicknesses and elemental composition of the epitaxial layers, test samples with an elastically balanced superlattice (10 cascades) formed by In$_{0.44}$Al$_{0.56}$As/In$_{0.65}$Ga$_{0.35}$As and In$_{0.32}$Al$_{0.68}$As/In$_{0.72}$Ga$_{0.28}$As heteropairs. X-ray diffraction analysis of the superlattices demonstrated that the samples formed on the basis of the In$_{0.44}$Al$_{0.56}$As/In$_{0.65}$Ga$_{0.35}$As heteropair at an epitaxial temperature of 500 ± 5°C show diffraction curves close to those calculated, with a comparatively narrow diffraction-peak width. The samples based on the In$_{0.32}$Al$_{0.68}$As/In$_{0.72}$Ga$_{0.28}$As heteropair grown at the same temperature are characterized by diffraction curves with strongly broadened peaks, which indicates that the heterointerfaces are blurred and regions enriched in indium are possibly formed during epitaxy of the In$_{0.72}$Ga$_{0.28}$As solid solution. Therefore, lower epitaxial temperatures should be used to fabricate QCLs based on the In$_{0.32}$Al$_{0.68}$As/In$_{0.72}$Ga$_{0.28}$As heteropair. Upon performing the test epitaxial processes, we fabricated a QCL nanoheterostructure with 60 cascades at an epitaxy temperature of 500 ± 5°C. The heterostructure was grown on an InP (100) substrate, with a 100-nm-thick lattice-matched Si-doped InGaAs layer grown on the substrate prior to fabrication of the cascades. After the cascades were formed, a thick Si-doped InAlAs cap layer with a thickness of 1500 nm and a thin Si-doped InGaAs conducting layer with a thickness of 50 nm were grown.

3. RESULTS AND DISCUSSION

Information about the structural perfection of the QCL heterostructure and coincidence of the real layer thicknesses with the required values was furnished by transmission electron microscopy (TEM) and high-resolution X-ray diffraction analysis. The surface uniformity of an epitaxial wafer with a diameter of 51 mm was examined by the photoluminescence (PL) method. The design of the nanoheterostructure is illustrated by the table.

3.1. TEM Study of the QCL Nanoheterostructure

The layer thicknesses of the QCL sample were determined by the TEM analysis of cross sections of the structures using a JEOL JEM2100F transmission electron microscope (Japan). Samples in the cross-sectional configuration were prepared by grinding and subsequent thinning via milling with Ar$^+$ ions at ener-