Conference Paper

GaInAs/AlInAs Heteropair Quantum Cascade Laser Operating at a Wavelength of 5.6 μm and Temperature of Above 300K

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Abstract

A quantum cascade laser based on a strain-compensated $Ga_{0.4}In_{0.6}As/Al_{0.58}In_{0.42}As$ heteropair is developed, which operates in a pulse mode in the wavelength range of 5.5–5.6 μm at a temperature of up to 350 K. Such characteristics are obtained due to increased quantum well depth and a two-phonon depopulation mechanism for the lower laser level. The laser epitaxial heterostructure was grown by the MOVPE method. Investigation by the high-resolution X-ray diffraction technique confirmed a high quality of the heterostructure. The threshold current density is 1.6 kA/cm^2 at 300 K. The characteristic temperature is T_0 = 161 K for the temperature range of 200–350 K. For a laser of size 20 μm × 3 mm with cleaved mirrors, the maximum pulse power is 1.1 W at 80 K and 130 mW at 300 K.

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1. Introduction

Quantum cascade laser (QCL) is a unipolar radiation source based on intersubband transitions of charge carriers in a semiconductor nanoheterostructure [1, 2]. The radiation wavelength of QCL is determined by both quantum well size and the heteropair employed, which determines the band offset that is the quantum well depth. Presently, by varying these two parameters and the material composition, QCLs are created, which cover a wide spectral range of 3–250 μm. For operation in the actual middle IR spectral range of 4–6 μm, a strain-compensated GaInAs/AlInAs heteropair is used and the multilayer nanoheterostructure is grown, as a rule, by the molecular beam epitaxy method. The MOVPE (metal organic vapor phase epitaxy) epitaxial method suggested in [3–5] possesses such advantages as high rate of growth and the possibility of growth of the phosphorous-containing materials. However, a drawback of this method is the interface sharpness problem due to a higher growth temperature.

In the present article, a laser heterostructure based on a strain-compensated $Ga_{0.4}In_{0.6}As/Al_{0.58}In_{0.42}As$ heteropair was grown by the MOVPE method. High quality of the structure is confirmed by X-ray diffraction spectra. The structure design corresponds to the emission wavelength of about 5.4 μm and utilizes a two-phonon scheme for lower laser level depopulation. In the pulsed regime, the temperature of QCL operation reached 350 K and the radiation power was above 1.1 W at 80 K.

2. Design of Laser Heterostructure

It is well-known that almost perfect match of lattice constants during epitaxial growing of $Ga_{1-x}In_xAs$ and $Al_{1-y}In_yAs$ solid solutions on a InP substrate is reached at x = 0.53 and y = 0.52. The band offset in the conduction band for these compositions is ΔE = 0.52 eV. Such a depth of quantum well in the heterostructure is insufficient for obtaining a radiation wavelength shorter than ~ 6 μm, especially for QCL with the two-phonon depopulation mechanism for a lower laser level. Hence, for increasing the depth of quantum well, a heteropair is used, which is not matched to the InP substrate lattice constant [6]. With this purpose, in the $Ga_{1-x}In_xAs$ solid solution the contents of In is increased and in the $Al_{1-y}In_yAs$ solid solution it is reduced. As a result, epitaxial layers become, correspondingly, compressed or stretched with respect to the InP substrate. With such changed compositions of the considered solid solutions, the conduction band offset in the heterojunction noticeably increases and slightly reduces due to the sign of arising mechanical stresses. Finally, the conduction band offset in such a strain-compensated heteropair increases and for chosen parameters x = 0.60 and y = 0.42, we obtain approximately ΔE = 0.68 eV. The estimate of the band offset is based on the idea of the 'electron affinity' [7] for pseudomorphic grown solid solutions with the aforementioned compounds on an InP substrate. In the estimates, dependences of the forbidden band gap, lattice constant, values of deformation, elastic constants, and deformation potentials on the composition content were used [8–10].

The active region of QCL comprises four quantum wells with a 'weakly-diagonal' optical transition. The calculation is performed for the following structure of the active region: **4.0**/1.3/**1.3**/5.1/**1.3**/4.5/**1.4**/4.0/**2.3**/3.1/**1.8**/2.8/**1.9**/2.5/**2.0**/2.4/**2.2**/2.3/**2.8**/2.2, where starting from the injection barrier the widths of epitaxial layers are given in nanometers for a single cascade. Here, barrier widths are given in bold face and quantum well widths are in ordinary face; doped layers are indicated by underline. The design of heterostructure was aimed at obtaining the radiation wavelength near 5.4 μm. Electron energy levels and wave functions are found by solving a one-dimensional Schrodinger equation. The problem stated was solved numerically (by the finite-difference method). Since the heterostructure is aimed at room-temperature operation, the calculation parameters were chosen for T = 300 K: the conduction band offset ΔE_c= 0.68 eV, barrier band gap is 1.75 eV, quantum well gap is 0.68 eV, effective electron mass in the barrier is $0.1m_0$ and in well it is $0.04m_0$, where m_0 is the free electron mass. A nonparabolicity of the conduction band was also considered.

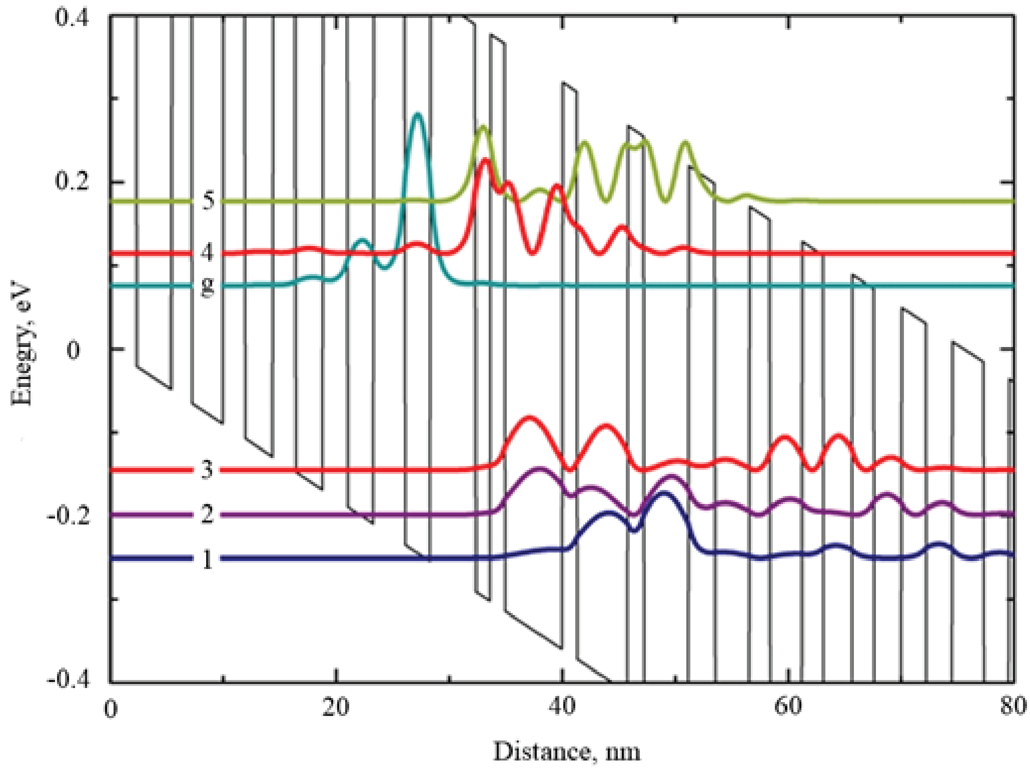

Figure 1: Calculated energy diagram of the active region of QCL based on heteropair $Ga_{0.4}In_{0.6}As/Al_{0.58}In_{0.42}As$. The electric field applied is 80 kV/cm. Square absolute values of the wave functions are shown.

Calculated energy diagram of QCL is shown in Figure 1. One can see that the main transition from the upper laser level 4 to the lower laser level 3 is 'weakly-diagonal', and the energy difference is E_{43} = 230 meV, which approximately corresponds to the radiation wavelength of 5.4 μm. The energy difference between lower laser level 3 and levels 2 and 1 is, correspondingly, 43.3 and 42.6 meV. Since the ground level of injector is below level 1, the obtained voltage defect is above 100 meV. Level 5 is the nearest to upper level 4, and the distance between them is 58.5 meV, which exceeds the heat energy of $2k_0T$ and gives a hope to obtain the operation temperature of 300 K.

A laser heterostructure was grown by the MOVPE method on an InP substrate with the electron concentration of 2x10^{18} cm^{-3}. The electron concentration in the doped layers of active region was 1x10^{17} cm^{-3}. The number of cascades was 35. The thickness of n-InP waveguide layers was 2.5 μm, and the electron concentration in these layers was 5x10^{16} cm^{-3}.

X-ray structure analysis was performed on a diffractometer of the type DRON-8. A diffraction scan Ω-2θ of the heterostructure studied has a set of well-resolved satellites on each side of the substrate peak. The zero-order satellite is actually in matched position with that of the substrate. The interference period corresponds to the cascade thickness of 50.5 nm that is close to the technology value of 51.2 nm.

Stripes of width 20 μm were formed on the grown heterostructure by the photolithography technique, and then the plate was totally covered from the side of layers by a dielectric Si_3N_4 layer. Then the dielectric was opened by photolithography technique in the strips for further formation of ohmic contacts. With this purpose, contacts Ti(50 nm)/Au(250 nm) were evaporated onto the heterostructure after chemical etching and then it was plated by Au of thickness 2–3 μm. From the side of substrate, the structure was grounded by chemical-mechanical polishing to a thickness of about 0.15 mm, and Ti/Au contacts were evaporated onto the substrate. Laser crystals chipped with the cavity length of 3 mm were soldered to a copper holder through a thin MD-50 gasket for better matching in the coefficient of linear thermal expansion. Gold current leads were welded on by thermal-compression bonding.

3. Measurement Results and Discussion

An active laser element produced in this way is mounted in a special case that is placed on a heat conductor of a metallic optical cryostat with IR windows made from KBr or BaF_2 for operation in a wide temperature range (7-350 K). For operation near 300 K, the laser was placed into a compact optical unit with a Peltier cooler.

Temperature dependences of the threshold current density were measured in a pulsed mode (τ = 1 μs, f = 170 Hz). A gold-doped germanium photoresistor was used as an integral detector of radiation. The dependence obtained is given in Figure 2. One can see that the operation temperature of 350 K is reached, which is limited by possibilities of the experimental setup. The threshold current density in this case was, at most, 1.8 kA/cm^2. The threshold current density was 1.6 kA/cm^2 at 300 K. Thus, the two-phonon mechanism of depopulation of the lower laser level is efficient, and the quantum well is sufficiently deep to reduce transition of electrons from upper level to continuum.

The dependence of the threshold current density on temperature cannot be approximated by a single exponent in the whole range of temperature variation 7-350 K. In the range 200–350 K, it is approximated by the exponent J_{th} = 0.2exp(T/161) with the characteristic temperature T_0 = 161 K.

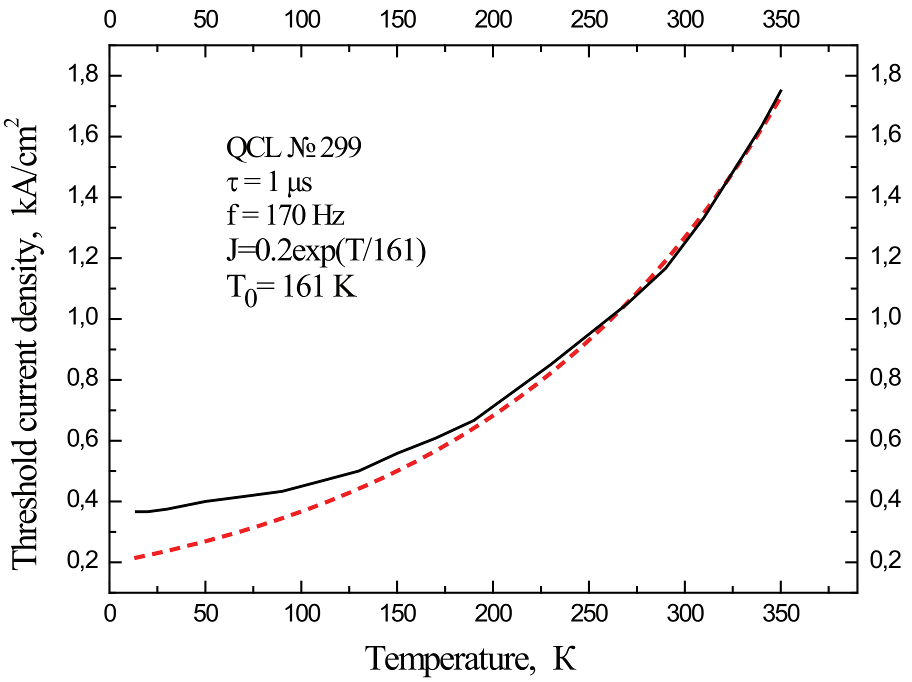

Figure 2: Temperature dependence of current density for QCL No. 299.

In measuring the watt-ampere characteristic, the laser operated in pulsed mode as well (τ = 1 μs); however, at the pulse repetition frequency of 10 kHz. The average radiation power was measured by a calorimeter of type OPHIR with a head 3A at the three temperatures: 80, 200, and 300 K. Results of measurements are show in Figure 3. One can see that the laser of size 20 μm x 3 mm with cleaved mirrors has the maximal radiation power of 1.1 W at 80 K and 130 mW at 300 K. This again testifies the efficiency of the active region of a QCL based on a strain-compensated $Ga_{0.4}In_{0.6}As/Al_{0.58}In_{0.42}As$ heteropair.

Emission spectra of QCL were measured by a Vertex-70 Fourier spectrometer operated in the step mode scanning with a resolution of 0.2 cm^{-1}. This provided the possibility to reliably resolve a mode structure of emission spectra. Measurement results for 80 K and various injection currents are presented in Figure 4. One can see a great

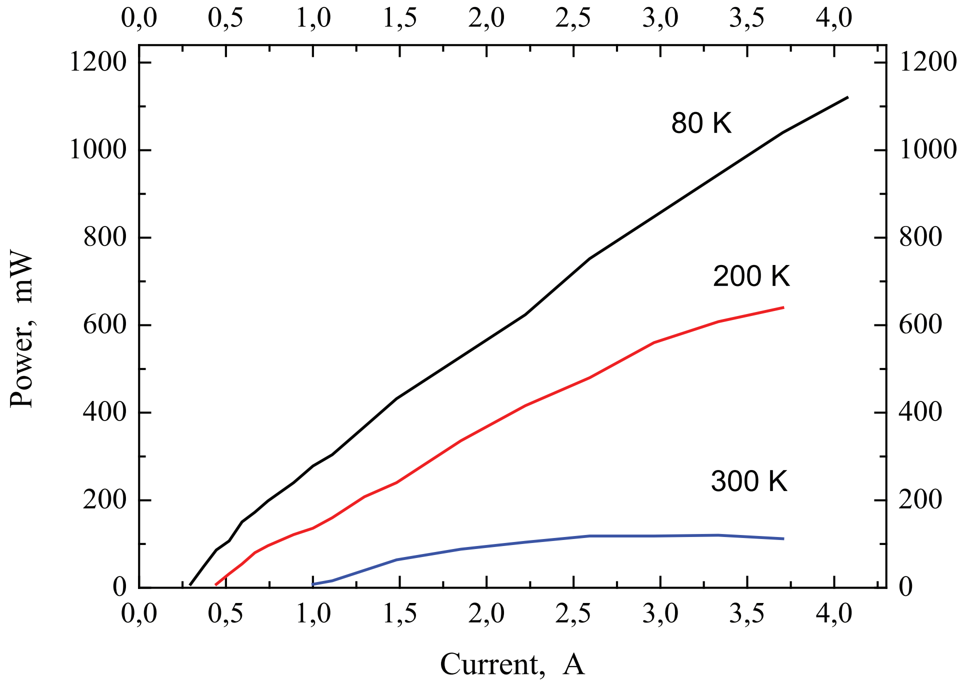

Figure 3: Watt-ampere characteristic of QCL No. 299.

number of longitudinal modes starting from 10–15 modes near the threshold and up to 20 modes at the two-fold excess over the threshold value. In further current increase, the number of modes can reach hundreds, that is, the gain width is greater than 50 cm^{-1} (1810–1860 cm^{-1}). The mode separation is 0.505 cm^{-1}. From this value one can find the effective refractive index for the active region $N^* = (2\Delta kL)^{-1} = 3.30$, where Δk is the mode separation and $L = 3$ mm is the cavity length.

At increased temperature, the QCL emission spectrum shifts to the long-wavelength side, the middle of the spectrum shifts from 1835 cm^{-1} at 80 K to 1780 cm^{-1} at 300 K, that is, from 5.45 to 5.62 μm. Note that at room temperature, the emission wavelength 5.62 μm is greater than the calculated value of 5.4 μm by 0.2 μm. It is explained by a small smearing of interfaces in the nanoheterostructure, which agrees with data from [11], where roughness of interfaces of QCL grown by the MOVPE method was studied by transmission electron microscopy. Such shift effect to the long-wavelength side was also observed in [12], where QCL was also created by the MOVPE method and the corresponding long-wavelength shift reached even 0.5–1 μm.

Thus, a quantum cascade laser is developed on the basis of strain-compensated $Ga_{0.4}In_{0.6}As/Al_{0.58}In_{0.42}As$ heteropair operating in the wavelength range of 5.5–5.6 μm in a pulsed regime at a temperature of up to 350 K. This became possible due to increasing

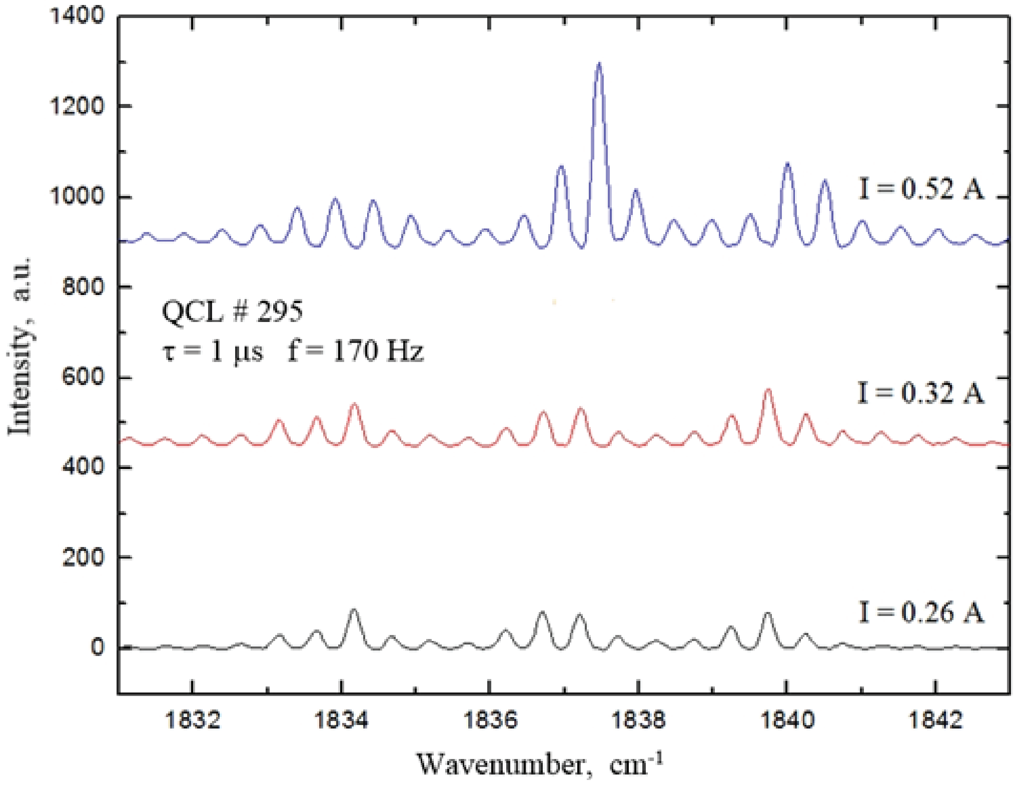

Figure 4: Emission spectra of QCL No. 295 at 80 K and various injection currents.

the depth of the quantum well and employment of the two-phonon mechanism of depopulation of lower laser level. The laser heterostructure of high quality was grown by the MOVPE method. The threshold current density is 1.6 kA/cm^2 at 300 K. The maximal emission power of the laser of size 20 μm x 3 mm with cleaved mirrors is 1.1 W at 80 K and 130 mW at 300 K.

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