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An 8-μm quantum cascade laser produced by the metalorganic vapour phase epitaxy method

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***Abstract*. An 8-μm quantum cascade laser is fabricated by the metalorganic vapour phase epitaxy method. A scheme of vertical transitions in a structure consisting of three quantum wells is used. The laser operates in a pulsed regime at temperatures up to 250 K. The threshold current density was about 3 kA cm^{-2} at 77 K and increased up to 6 kA cm^{-2} at 250 K. The 1-μs pulse power in the multimode regime was 45 mW at 77 K.**

Keywords: *quantum cascade laser, metalorganic vapour phase epitaxy, quantum well.*

Since the advent of a quantum cascade laser (QCL) [1], the heterostructures for it have been mainly grown by the molecular-beam epitaxy (MBE) method. Recently, the metalorganic vapour phase epitaxy (MOVPE) method came into wide use for this purpose [2, 3]. This method provides the heterostructure parameters compared to those obtained by the MBE method. The MOVPE method is characterised by higher growth rates (up to 5 μm h^{-1}) and lower defect densities (10–20 cm^{-2}) compared to the MBE method and can be used to grow high-quality phosphide layers, including the second cladding InP layer. In addition, MOVPE is a technology for semi-industrial production, which promises the reduction of the QCL cost in the future. An important problem of the MOVPE method is the production of sharp interfaces.

In this paper, we report the development of an 8-μm QCL based on the lattice-matched GaInAs/AlIn As/InP heterostructure grown by the MOVPE method. We used a working scheme with vertical radiative transitions occurring inside one quantum well. In this case, the influence of the interface on the half-width of the spontaneous emission line is minimal, whereas for a diagonal transition (through the interface) the linewidth is twice as large. This is important because the interface blur upon MOVPE is expected to be greater than that upon MBE. To obtain the emission wavelength near 8 μm ($E_3 - E_2 = 0.155$ eV, Fig. 1), we chose the active region structure [4] **3.8**/2.1/**1.2**/6.5/**1.2**/5.3/**2.3**/4.0/**1.1**/3.6/**1.2**/3.2/1.2/3.0/**1.6**/3.0, where the layer thickness is indicated in nanometers, beginning from the injection barrier. Here, the thickness of the $Al_{0.48}In_{0.52}As$ barriers is indicated in bold and the thickness of the $Ga_{0.47}In_{0.53}As$ quantum wells – by usual type. The working quantum wells are the wells of thickness $L_z = 2.1$, 6.5 and 5.3 nm. The right part of the structure is an injector with three layers doped with Si up to the concentration 2×10^{17} cm^{-3} (underlined).

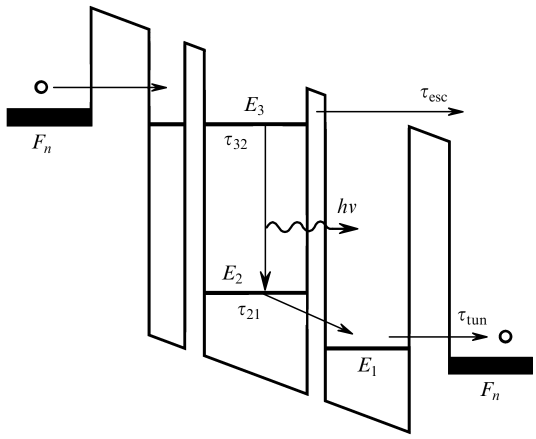

Figure 1. Scheme of electronic transitions in three tunnel-coupled wells upon electric bias.

The first (narrow) well ($L_z = 2.1$ nm) contains a level resonant with the Fermi level F_n in the injector and with the upper laser level E_3 in the second, relatively broad ($L_z = 6.5$ nm) quantum well. This allows one to increase the overlap of the wave functions for the upper laser level and the ground state of the injector and simultaneously to decrease the overlap of the wave functions of the ground state of the injector and lower states E_2 in the second well and E_1 in the third well. As a result, the injection efficiency increases, the elastic and inelastic scattering of electrons directly to the ground state decreases, and the matrix element for vertical transitions in the second well increases.

The dependence of the lifetime of nonequilibrium electrons in a perfect crystal quantum well on their scattering involving a longitudinal optical phonon is used in the construction of laser levels [5] by choosing the distance $E_2 - E_1$ between the first and second levels equal

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to or more than $h\nu_{LO} \approx 35$ meV, which leads to subpicosecond electron scattering times ($\tau_{21} = 0.2 - 0.4$ ps). Because the $E_3 - E_2$ transition energy is about 160 meV, a large wave vector is required for scattering. In this connection the electron lifetime τ_{32} at the upper laser level reaches 2 – 5 ps, which provides the population inversion. The population inversion is achieved also because the upper laser level falls within the injector gap for the specified electric field strength, i.e. the time of electron scattering from this level directly to the injector is relatively large ($\tau_{esc} \sim 15$ ps). However, the internal radiation yield between the levels is small: $\eta_i \sim \tau_{32}/\tau_r \sim 3 \times 10^{-4}$ because the radiative lifetime τ_r lies in the nanosecond region. In this connection the active region is cascaded many times (in our case, 30 times) and is separated by the doped injector.

Laser structures were grown on a modernised MOVPE setup with a horizontal quartz reactor and rotating graphite susceptor. The growth was performed on n-InP (100) substrates of diameter 50.8 mm at temperatures 620 – 690 °C and pressures in the reactor 40 – 15 mbar. The typical growth rate was 11 nm min^{-1}. As the sources of the third group elements, we used triethyl gallium, trimethyl indium and trimethyl aluminium. The sources of the fifth group elements were phosphine and arsine. The n-type layers were doped in the injector by using monosilane in a mixture with hydrogen.

In the first samples, as transmission electron microscope images showed, heteroboundaries obtained between layers were blurred, although satellites in the X-ray diffraction pattern were present. To improve the quality of the active region of the QCL, it was necessary to optimise the growth regime. For this purpose, we additionally updated the gas scheme of the growth setup to minimise parasitic non-blow-through volumes. The reduction of the growth rate of the active region and consumption of reagents allowed us to obtain a working heterostructure, for which the rocking curve is shown in Fig. 2. The curve exhibits a periodic structure containing numerous satellites, although the general shape of the curve is somewhat asymmetric. The size of the active region (44.3 nm), obtained from the distance between satellites, well agrees with its technologically specified value. Thus, X-ray measurements allow one to estimate the quality of heterostructures for QCLs already at the first stage of their testing. This is important because transmission electron microscope measurements are very prolonged and expensive.

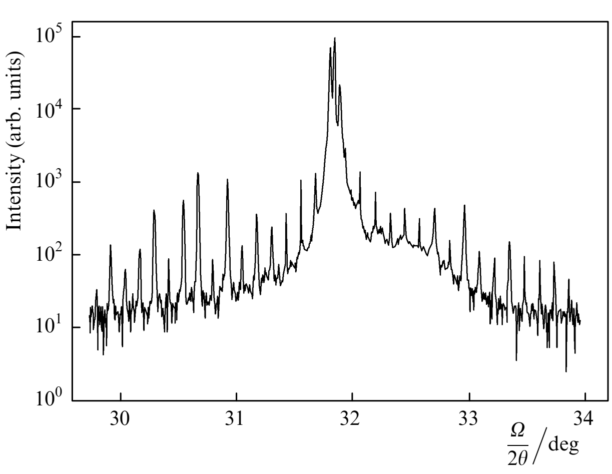

Figure 2. Rocking curve for diffraction reflection from InP (004). The upper emitter and waveguide are removed.

The cladding InP layers were doped up to the concentration 3×10^{17} cm^{-3}, the thickness of the buffer and upper layer being 0.2 and 2.9 μm, respectively. On the heterostructure the Cr ($\sim$ 50 nm) and Au ($\sim$ 0.5 μm) contacts were deposited in vacuum. Then, a 1.5 – 2-μm-thick gold layer was deposited electrolytically. The stripe laser structure (of width 50 μm) was fabricated by photolithography by uncovering stripes in the insulating Al_2O_3 layer deposited by electron-beam sputtering. The laser resonator length was $L = 3$ mm. The laser crystal was soldered from the heterostructure side to a contact plate made of an MD-50 material matched in the linear thermal expansion coefficient with the laser crystal. The upper contact with the laser crystal was provided with the help of a copper stripe connected with a kovar lead.

Because of the presence of cascades, the volt – ampere characteristic of the QCL differs from that of the usual bipolar laser. Figure 3 shows the volt – ampere characteristic of the laser at temperature 77 K. One can see that the cut-off voltage is about 6 V. The calculation of the cut-off voltage $V_c = (h\nu + h\nu_{LO})N_p/e$, where N_p is the number of cascades, gives $(0.16 + 0.04) \times 30 = 6$ V, which is close to the experimental value. The laser resistance, determined from the slope of the straight branch of the characteristic, was 0.4 Ω at 77 K. This value is relatively large and should be reduced. Note that the volt – ampere characteristic of the laser demonstrates a high initial (through) current and several weak breaks. The presence of the through current is explained by the fact that thin (1 – 2 nm) barriers in the heterostructure have defects or blurred heteroboundaries which violate the resonance in the location of levels in the specified electric field.

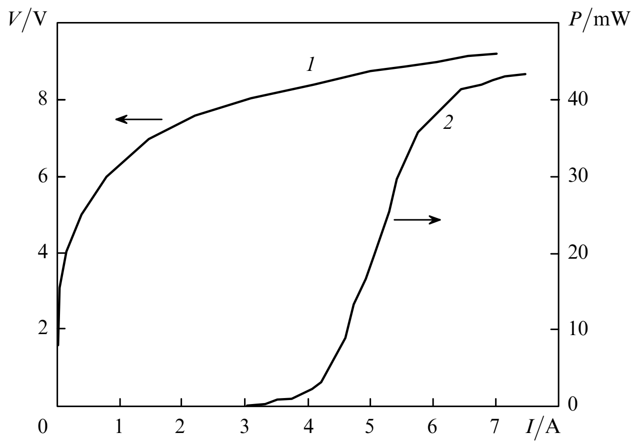

Figure 3. Volt – ampere (*1*) and watt – ampere (*2*) characteristics of the laser at 77 K.

Lasers operated in the pulsed regime at temperatures up to 250 K. Their threshold current density increased from 3 kA cm^{-2} at 77 K to 6 kA cm^{-2} at 250 K. The experimental temperature dependence of the threshold current density is usually described by the expression of the type $J_{th}(T) = J_0 \exp(T/T_0)$. The characteristic temperature is $T_0 = 110$ K, which suggests that the Auger recombination is noticeably suppressed at high temperatures.

The emission spectra of lasers were measured in the pulsed regime ($\tau = 1$ μs, $f = 170$ Hz). One can see from Fig. 4 that near the threshold the laser operates in the single-mode regime. As the current is increased, the emission spectrum shifts and new emission lines appear from the long-wavelength side. The distance between these modes is ~ 2 cm^{-1}, whereas the distance Δk between longitudinal modes should be $1/(2Ln) \sim 0.5$ cm^{-1} (n is the refractive index). The pulsed radiation power of the QCL in the multimode regime achieved 45 mW at 77 K (Fig. 3).

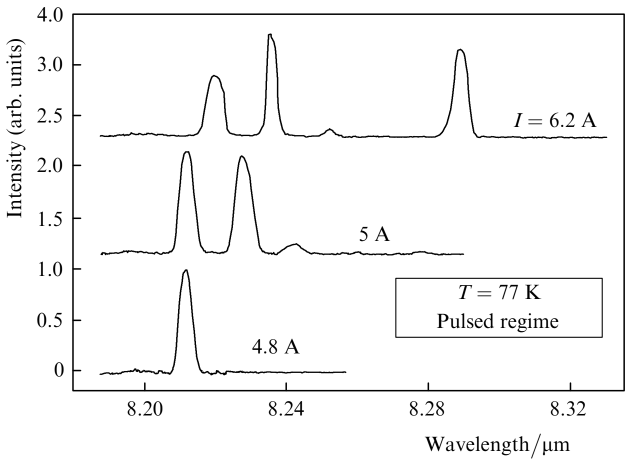

Figure 4. Emission spectra of the laser at 77 K for different currents.

Thus, by using MOVPE method, we have developed the GaInAs/AlInAs heterostructure QCL emitting 45-mW pulses at 77 K. The laser can operate at temperatures up to 250 K.

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