Growth and optical characterization of 7.5 μm quantum-cascade laser heterostructures grown by MBE

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Abstract. We present the results on growth, characterization and optical properties of quantum-cascade laser heterostructures grown by molecular-beam epitaxy. The double-phonon resonance design for forming of active region together with thick InP-based top cladding was used to increase the quantum-cascade laser performance. The results of electroluminescence studies of 4-cleaved samples are presented. The room temperature lasing at 8.0 um with threshold current density about 1.98 kA/cm² was achieved.

1. Introduction
Quantum-cascade lasers (QCL) emitting in the spectral range of 7-8 μm can be effectively used for medical applications and remote gas analysis. In particular, lasers with a wavelength of 7.3-7.9 μm are using for the detection of SO₂, CH₄, H₂S, C₂H₂, N₂O, and TNT. SO₂ is one of the most common impurities present in the medical gas supply lines in hospitals. Due to the high toxicity of SO₂, the special attention is paid to the development of compact systems for bedside monitoring of this oxide that can be based on QCLs [1]. In turn, using the QCLs is possible for effective remote monitoring of the CH₄ leaks in gas pipelines and chemical plants. Moreover, the presence of CH₄ in human exhale can indicate a number of diseases of the gastrointestinal tract [2].

2. Samples and experimental setup
The QCL heterostructures were grown by Connector Optics LLC using a production molecular-beam epitaxy system Riber 49 [3]. The Riber 49 is equipped with a solid-state source of arsenic and ABI 100 cells for forming of gallium and indium fluxes. The InP substrate with orientation (001) was doped with sulfur to a level of 1 × 10¹⁷ cm⁻³. The lower confinement layer was formed by thick In₀.₅₃Ga₀.₄₇As layer (0.5 μm thick). An active region including 50 quantum cascades consisted of unstrained In₀.₅₃Ga₀.₄₇As quantum wells and Al₀.₄₈In₀.₅₂As barrier layers. A double-phonon resonance design was used to fabricate the cascades [4]. The top cladding layers were formed by InP and In₀.₅₃Ga₀.₄₇As layers with a doping level of 1 × 10¹⁷ cm⁻³ and thicknesses of 3.9 μm and 0.1 μm, respectively. The contact In₀.₅₃Ga₀.₄₇As consisted of heavy doped layer (doping level is about 1 × 10¹⁹ cm⁻³) and had thickness of 20 nm.
Recently, we have shown that multi-cascade heterostructures with thin top cladding allows to reach room-temperature lasing [5]. Here in, we proposed the modified structure, in relation with Ref. 4, with thick top cladding based on binary solid alloy (InP). It is well known that InP solid alloy has better thermal conductivity that allows to increase the efficiency of heat removal from multi-cascade active region. QCL heterostructures were characterized by XRD and TEM.

The optical quality of QCL heterostructure was verified by fabrication of four-cleaved laser samples, based on well-known approach presented in ref. 6,7. The top metallization was formed by deposition of Ti/Pt/Au. The bottom metallization based on AuTe/Au was used after the lapping of substrate down to 150 μm. Laser chips with typical size of 0.5×0.5 mm$^2$ were mounted on copper heatsinks.

The samples were measured in a cryostat with ZnSe optical window with 70% optical transmission in the desired spectral range. The bias was applied to the structure in the form of 0.05 – 0.4 μs pulses at a frequency of 1-5 kHz with gate circuit based on the power MOSFET. Sample in the cryostat was physically connected to the circuit with low-impedance micro-strip line. Current through the sample was controlled as the voltage on the series-connected 1 Ohm resistor. Waveforms of voltage and current through the sample were recorded with digital oscilloscope.

The spectral measurements were performed with the Bruker Vertex 80v Fourier spectrometer operating in a step-scan mode with a liquid nitrogen cooled HgCdTe photodetector. Sample in the cryostat was placed in the focus of the spectrometer input port. The photodetector signal was measured with a boxcar averager in the case of spontaneous emission studies, and directly recorded with the spectrometer ADC in the case of stimulated emission (experimental setup schematics is presented in [8]). Spectral resolution was 8 cm$^{-1}$ (0.98 meV) and 0.2 cm$^{-1}$ (0.025 meV) for spontaneous and stimulated emission measurements, respectively. The total dynamic range of the experimental setup is more than 4 orders of magnitude.

3. Experimental Results

TEM cross-section is presented on Figure 1. Obtained results indicate the high structural quality and precision of the applied growth technique. Fluctuations of composition and thickness were less than 1% for studied heterostructure.

![Figure 1. The dark-field TEM image of the one cascade of QCL heterostructure (cross section (1-10)). (a) low magnification. (b) high magnification.](image)
The typical \(L-I-V\) dependences are presented in Figure 2a. Threshold voltages of 15 V and 18 V are measured at 80 and 300 K, respectively. These values are in coincidence with the previous published results for the same active region QCL [9]. The temperature dependence of threshold current density, \(j_{th}\), is presented on Figure 1b (inset) and can be approximated by expression (1) [10]:

\[
 j_{th}(T) = j_0 \exp \left( \frac{T}{T_0} \right)
\]

where \(T_0\) is the characteristic temperature and \(j_0 = j_{th}(0)\). The determined values of \(T_0\) and \(j_0\) are 146 K and 0.26 kA/cm\(^2\), respectively. The threshold current density measured at 300 K is about 1.98 kA/cm\(^2\). This value is higher than values that have been published for long ridge lasers based on the same design of active region [11,12].

The below-threshold intersubband electroluminescence spectrum at 80 K is shown on Figure 2b. The full-width at half maximum (FWHM) of the spectrum is 13 meV that in a good agreement with previous published results [10].

![Figure 2. (a) The typical L-I-V curves of 7.5 μm quantum-cascade laser. Pulse duration – 50 ns, frequency – 5 kHz; (b) Intersubband electroluminescence spectra measured at \(T = 80\) K. Pulse duration – 400 ns, frequency – 5 kHz, current = 0.92 A. Inset depicts \(j_{th}(T)\) dependence (logarithmic scale).](image)

The lasing spectra measured at different temperatures are shown on Figure 3a (low pumping current case) and Figure 3b (high pumping current case). Increase the temperature results in wavelength red shift. The emission wavelength shifts from 7.5 μm up to 8.0 μm at low pumping current and from 7.7 μm to 8.0 μm at high pumping current. Small red shift of wavelength measured at 80 K with increase of current from 1.3 A to 2.9 A can be related with heating of sample. The typical FWHM of lasing spectra is 1.5 – 2 nm (0.03-0.04 meV).
Figure 3. (a) Lasing spectra at different temperatures. Pulse duration – 50 ns, frequency – 5 kHz. Intensities are normalized; (b) Lasing spectra at different temperatures. Pulse duration – 50 ns, frequency – 5 kHz. Intensities are normalized.

Conclusions

QCL heterostructures was grown by MBE. The high structural quality of grown heterostructures were proved by X-ray diffraction and transmission electron microscopy studies (fluctuations of composition and thickness < 1%). The heterostructures were used for manufacturing of 4-cleaved lasers sized 0.5×0.5 mm². Laser samples mounted on copper heatsinks have shown room temperature lasing at ~ 8 μm. The threshold current density measured at 300 K was about 1.98 kA/cm². The estimated values of T₀ and j₀ were 146 K and 0.26 kA/cm², respectively.

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