Quantum-cascade lasers in the 7-8 μm spectral range with full top metallization

A S Kurochkin1,2, A V Babichev1,2,3, D V Denisov4, L Ya Karachinsky1,2,3, I I Novikov1,2,3, A N Sofronov4, D A Firsov4, L E Vorobjev4, A Bousselsou5 and A Yu Egorov1,2

1 Connector Optics LLC, St. Petersburg 194292, Russia
2 ITMO University, St. Petersburg 197101, Russia
3 Ioffe Institute, St. Petersburg 194021, Russia
4 Peter the Great St. Petersburg Polytechnic University, St. Petersburg 195251, Russia
5 Center of Nanoscience and Nanotechnology (C2N), Univ. Paris Sud and Paris-Saclay, 91405 Orsay cedex, France

E-mail: alexander.kurochkin@connector-optics.com

Abstract. The paper demonstrates the generation of multistage quantum-cascade lasers (QCL) in the 7-8 μm spectral range in the pulse generation mode. The active region structure we used is based on a two-phonon resonance scheme. The QCL heterostructure based on a heteropair of In0.53Ga0.47As/Al0.48In0.52As solid alloys was grown by molecular beam epitaxy and includes 50 identical stages. A waveguide geometry with top cladding with full top metallization (surface-plasmon quantum-cascade lasers) has been used. The developed QCLs have demonstrated multimodal generation in the 7-8 μm spectral range in the pulse mode in the 78-250 K temperature range. The threshold current density for a 1.6 mm long laser and a 20 μm ridge width amounted to ~ 2.8 kA/cm2 at a temperature of 78 K. A temperature increase to 250 K causes a long-wave shift of the wavelength from 7.6 to 7.9 μm and a $j_{th}$ increase to 5.0 kA/cm2.

1. Introduction

Quantum-cascade lasers (QCL) that emit in the 7-8 μm spectral range can be effectively applied for remote gas analysis. In particular, the lasers with a 7.3-7.9 μm wavelength are used for detection of SOx, CH4, H2S, C2H2, N2O, and trinitrotoluene [1-3].

Methane detection (at a 7.8 μm lasing wavelength) based on QCL is used for remote leak control at gas pipelines and chemical plants. Detection of various liquids at precipitation on the QCL surface is also of interest [4].

A number of structures of a QCL active region emitting in the 7-8 μm spectral range have been described in literature. Most frequently mentioned structures are based on a two-phonon [5] and a three-phonon resonance [6].

The main technologies for growing QCL heterostructures are molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD). MBE makes it possible to implement lasers with a higher efficiency [7]. The use of industrial MBE production systems has a positive effect on the structural quality of the developed heterostructures [8-10] and enables implementation of multistage
QCL heterostructures with a high identity of the chemical composition and thicknesses of the cascade-forming layers.

This paper presents the results on generation and optical characteristics of multistage QCLs that emit in the pulse mode in the 7-8 μm spectral range in the 78-250 K temperature range.

2. Experiment and results

The QCL heterostructure was fabricated by Connector Optics LLC using a Riber 49 MBE production system with a valved As cracker source and ABI 1000 brand sources for generating gallium and indium flows. The InP substrate with a (100) orientation was doped with sulfur to a level of 3·10^{18} cm^{-3}. The waveguide bottom cladding was developed based on InP (2 μm thick) and In_{0.53}Ga_{0.47}As (0.5 μm thick) layers, which were grown on a substrate in succession. The active region with 50 quantum stages was developed based on lattice-matched In_{0.53}Ga_{0.47}As quantum wells with Al_{0.48}In_{0.52}As potential barriers. The cascade was developed using the two-phonon resonance charge-carrier extraction. After the development of the cascades, In_{0.53}Ga_{0.47}As layers with 1·10^{17} cm^{-3} and 1·10^{19} cm^{-3} doping levels and with 0.1 μm and 0.02 μm thicknesses, respectively, were formed in succession. A detailed description of the QCL heterostructure design is shown in [10].

A waveguide geometry with top cladding with full top metallization (surface-plasmon quantum-cascade lasers) has been used for QCL generation [11, 12]. Such a waveguide design is promising for photonic crystal laser generation.

The laser ridge generation started with wet etching of a deep mesa (based on HBr:HNO_{3}:H_{2}O solution). The etching mask was a silicon oxide layer etched locally in a fluorine-based plasma chemical deposition. The windows in the Si_{3}N_{4} layer were opened for metallization by reactive ion etching in a CHF_{3}/O_{2} gas mixture under a photoresist mask. The top metallization was performed through a photoresist mask by electron beam deposition of consecutive layers of titanium and gold with 20 and 200 nm thicknesses, respectively. Before the bottom contact metallization, the substrate was lapped down to a thickness of 150 μm. For bottom metallization, a sequence of titanium/gold layers was used with 20 and 200 nm thicknesses, respectively. The ridges were obtained by mechnical cleavage. The ridge laser width (near the heterostructure surface) amounted to 20 μm. The ridge laser length amounted to 1.6 mm. No high-reflection and anti-reflection coating was applied to the laser facets. Mounting was performed “heterostructure up” onto a silver-plated copper heatsink.

Studies of the experimental QCL samples mounted on a heatsink were performed in the 78-250 K temperature range. The current-voltage characteristics were measured at current pulses flashing with a 100 ns duration and an 84 kHz frequency (the duty cycle of the pulses was 0.84 %). The QCL lasing spectra were recorded using a Fourier spectrometer and an HgCdTe photodetector.

Figure 1 shows the current-voltage and power-voltage characteristics measured at various temperatures. The threshold current density, \( j_{th} \), for the examined QCL amounted to 2.8 kA/cm^2 at a temperature of 78 K. A temperature increase up to 250 K leads to a \( j_{th} \) increase up to 5.0 kA/cm^2. The threshold voltage, \( V_{th} \), amounts to 14 and 17 V at \( T = 78 \) K and 250 K, respectively.

The approximation of experimental values \( j_{th} \) corresponding to various temperatures is based on the \( j_{th}(T) = j_{0}\exp(T/T_0) \) expression and provides an evaluation of the characteristic temperature of threshold current stability, \( T_0 = 94 \) K, and the threshold current density at zero temperature, \( j_0 = 2.1 \) kA/cm^2. The intermodal distance between extensional modes, \( \Delta \lambda \), is \( \sim 0.0053 \) μm. The mirror loss factor, \( \alpha_m = \ln(R_{eff})/L \), is 7.3 cm^{-1}. Figure 2 demonstrates the generation spectra measured at various temperatures. Multimode laser generation has been demonstrated. With a temperature increase, a shift of the maximum intensity of the stimulated radiation spectrum to a long-wave region is observed, which is due to a decrease in the conduction band offset with a \( T \) increase.
Figure 1. The current-voltage characteristics and power-voltage characteristics measured at various temperatures.

![Current-Voltage Characteristics](image1.png)

Figure 2. The stimulated radiation spectra of QCL samples measured at various temperatures.

![Stimulated Radiation Spectra](image2.png)

Conclusions

Lasing of multistage quantum-cascade lasers in the 7-8 μm spectral range in the pulse generation mode has been demonstrated. The active region structure based on the two-phonon resonance scheme has been used. The heterostructure of the quantum-cascade laser based on a heteropair of In0.53Ga0.47As/Al0.48In0.52As solid alloys was grown by molecular beam epitaxy and included 50 identical stages. A waveguide geometry with top cladding with full top metallization (surface-plasmon quantum-cascade lasers) has been used. The developed QCLs have demonstrated multimodal generation in the 7-8 μm spectral range in the pulse mode in the 78 - 250 K temperature range. The threshold current density amounted to ~ 2.8 kA/cm² at a temperature of 78 K. A temperature increase to 250 K causes a long-wave shift of the wavelength from 7.6 to 7.9 μm and a $j_{th}$ increase to 5.0 kA/cm². The determined $j_{th}$ values are comparable with the results presented previously for a
similar structure of the active region of a QCL heterostructure grown by MOCVD [12]. Further optimization of the conditions for epitaxial growth of QCL heterostructures and the selection of new contact types to enhance the laser performance are required.

Acknowledgments
The research was partly supported by the Russian Foundation of Basic Research (grant № 16-29-03289) and the Ministry of Education and Science of the Russian Federation (state assignment №3.933.2017/4.6).

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