Optical characterization of mid-infrared range quantum-cascade laser structures grown by MBE

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Abstract. Optical characteristics of quantum-cascade laser structures were studied in this work. Current-voltage characteristics and dependencies of photoresponse signal on current through the structure were measured together with the spontaneous and stimulated emission spectra. The stimulated emission with wavelength close to 9.56 μm with optical power of tens of milliwatt was observed in a pulsed mode.

1. Introduction
Quantum-cascade lasers (QCL) are extensively developed optoelectronic devices. However, the growth of the multi-stage structures with highly controlled parameters, as well as precise post-processing are still the challenges for nowadays technology.

Basic technologies to create QCL heterostructures are metal-organic vapour-phase epitaxy (MOVPE) and molecular beam epitaxy (MBE). MOVPE allows one to create heterostructures with a greater growth speed. MBE allows implementation of lasers with higher quantum efficiency [1]. Additional improvement of quantum efficiency of QCL is possible to achieve by implementing multi-stage QCL heterostructures containing up to 100 stages [2]. Manufacturing of such multi-stage QCL heterostructures requires maintaining the high identity of chemical composition and thickness of layers throughout the whole long process of epitaxy [3]. The utilization of industrial MBE system satisfies these requirements, as demonstrated by a number of research groups [4-7]. The use of state of the art multi-substrate industrial MBE systems such as Riber 49-7000, Veeco Gen 200-2000 and Oxford VG Semicon V80H-V150 substantially increases the overall yield.

In this work, we present the results of detailed optical characterization of the multi-stage quantum-cascade lasers with emission wavelength close to 9.5 μm at liquid nitrogen temperature. We studied spontaneous emission spectra for below-threshold currents, and time-resolved stimulated emission spectra in pulsed operation mode with different current pulse durations.
2. Samples and experimental setup

The design with the active region based on three-phonon resonance scheme [8] was used. QCL heterostructures were grown by molecular-beam epitaxy on InP (100) substrates using the Riber 49 MBE machine. It contains the 40 stages active region based on $\text{In}_0.53\text{Ga}_0.47\text{As}/\text{Al}_0.49\text{In}_0.52\text{As}$ heteropair. The bottom cladding is formed by silicon-doped InGaAs layer (thickness $\sim 2000$ nm). The top cladding is based on InGaAs and InAlAs solid alloys with thickness of 1830 and 4000 nm, respectively. Contact n++ InGaAs layer is fabricated on heterostructure surface. Grown QCL heterostructures were studied by XRD and TEM. Obtained results indicate high structural quality and precision of the growth technique. Fluctuations of layer composition and thickness were less than 1% for studied structures. To study electroluminescent characteristics, the QCL heterostructures were processed into 22-µm-stripe-width lasers. Cavity length of $\sim 1.5$ mm was chosen. Lasers were mounted on copper heatsinks.

The experimental setup for optical studies is schematically shown in Figure 1. 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 0.1 – 2.0 µs pulses at a frequency of 0.1 – 10 kHz with gate circuit based on the power MOSFET. 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 Lock-In amplifier in the case of spontaneous emission studies, and directly recorded with the spectrometer ADC in the case of stimulated emission. Spectral resolution was 16 cm$^{-1}$ and 0.4 cm$^{-1}$ for spontaneous and stimulated emission measurements, respectively. The time resolution of the experimental setup was limited by the photodetector bandwidth (approximately 100 ns). The total dynamic range of the experimental setup is more than 4 orders of magnitude. The average output optical power was estimated with a calibrated mid-infrared power-meter and recalculated to the pulse power taking into account the pumping duty cycle.

![Figure 1. Experimental setup schematics.](image-url)
3. Experimental Results

The typical current-voltage and current-intensity characteristics are presented in Figure 2(a). The typical threshold current values were found to be in the range of 700 – 800 mA. The spectra of spontaneous emission (Figure 2 (b)) demonstrate a single emission peak with a width at half maximum of about 50 cm\(^{-1}\) with a center at 1030-1040 cm\(^{-1}\) with slight blue shift with the increase of the current. A typical lasing spectrum measured for the same sample under 200 ns current pumping is plotted in the inset of Figure 2(b). Stimulated emission demonstrates a single line at the frequency of 1043 cm\(^{-1}\) (wavelength 9.588 µm).

![Figure 2](image)

**Figure 2.** (a) The typical current-voltage and current-intensity characteristics. (b) Typical spontaneous and stimulated (inset) emission spectra at different currents.

The time-resolved measurements of the stimulated emission spectra with relatively long current pulses allowed us to study the temporal evolution of the lasing. The typical lasing transients are plotted in Figure 3 under 800 ns current pulses at different current values.

The characteristic feature of the plots in Figure 3 is a slight tilt of the generation line in the ‘time-frequency’ domain. It shows the slight red shift of the lasing frequency that is related to the heating of the structure with the current. At higher currents lasing demonstrates jumps of the generation frequency due to mode competition in the Fabry-Perot cavity.
Figure 3. Typical time-resolved lasing spectra (lasing intensity is in arb. units) at pump current values of 682 mA (a) and 722 mA (b).

The typical output optical power at the one facet of the laser structure is estimated as tens of milliwatts.

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