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3 THz quantum-cascade laser with metallic waveguide based on resonant-phonon depopulation scheme

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1. Introduction

Terahertz radiation, which frequency belongs to 0.1-10 THz range, is of great importance in various fields of science and engineering. One of the most important applications of THz radiation is the objects visualization and species detection. As this emission penetrates well through clothes and biological tissues and reflects from metals, it can be used in inspection systems for detection of hidden enclosures. At the same time, in contrast to X-ray, THz radiation is safe for living body. Promising sources of this radiation are quantum cascade lasers (QCLs), provided by their compact size, low current and voltage requirements, high brightness as well as relatively low cost. The first THz QCL was fabricated in 2002 [1]. As of today their output optical power reaches more than 200 mW in CW [2] and 1 W in pulse pumping regime [3], wavelength tuning range makes about 3 GHz for CW operation [4] and maximum lasing temperature reaches 200 K (for direct THz-emitted sources) [5]. However, QCL technology is in its infant stage in Russia.

In the present work we have fabricated and tested THz QCL having metal-metal waveguide. Heterostructure included 228 $Al_{0.15}Ga_{0.85}As/GaAs$ cascades with resonant phonon based triple quantum well design. Here we present results of studies of voltage-current and light-current characteristics as well as cyclotron resonance, which allowed us to measure the lasing frequency to be about 3 THz.

2. Experiment details

Heterostructure was grown in a molecular beam epitaxy reactor (Riber 21) on a semi-insulating GaAs (100) substrate. The active region was a 228-period superlattice $Al_{0.15}Ga_{0.85}As/GaAs$. Each cascade involved three tunnel-coupled quantum wells (QW) and had resonant-phonon design. The thicknesses of the layers in the cascade in Angstroms are <u>43</u>/89/<u>24.6</u>/81.5/<u>41</u>/160 (one period has 439.1 Å nominal thickness), where underlined are the dimensions of $Al_{0.15}Ga_{0.85}As$ layers. The complete width of the heterostructure was about 10 μm. Schematic band diagram at an applied bias corresponding to the lasing threshold is shown in Fig. 1a. Active transition is a transition between levels 2 and 3 with a nominal radiation frequency of 3 THz and calculated oscillator strength 0.3 at a bias field of 12 kV/cm^2. Transition 4-1 corresponds to passing of electrons between cascades (injection/extraction) and is carried out with a resonant optical phonon emission.

Growth rate was about 0.8 monolayers per second. The reactor was equipped with high speed shutters with 150 ms actuation, thus spreading of the interfaces did not exceed 0.4 Å. Layer-by-layer structure description is presented in Fig. 1b. Contact layers and the middle QW were doped with silicon concentrations of 5 x 10^{18} cm^{-3} and 5 x 10^{16} cm^{-3}, respectively. The growth was conducted in stabilized As-flow conditions; deposition temperature was controlled by IR pyrometer. The surface condition was monitored *in situ* by high-energy electron diffraction, and as grown wafer was examined by X-ray diffraction and photoluminescence technique, which spectra were compared with simulated one.

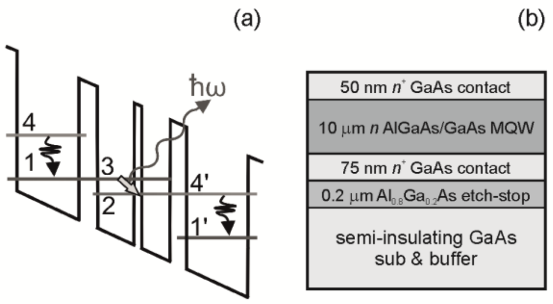

Fig. 1. (a) Schematic band diagram of QCL, (b) layer-by-layer structure description

Next metal-metal waveguide was fabricated that comprised the active region [6]. Postgrowth processing included thermal-compression bonding of the initial wafer epi-side to receptor n$^+$-GaAs substrate using Au-Au interlayer. QCL ridges of 100 microns width were fabricated by means of etching of the initial wafer down to the active region as well as electron lithography and dry etching of the active region through the upper metallization mask.

After thinning of the receptor to about 150 μm the wafer was cleaved to create 1.5 mm long resonators. Next chips were soldered the receptor side down to Cu heatsinks – the bottom contacts to the devices. In turn Au-wires were soldered to the ridges. The devices characteristics (voltage-current, light-current and cyclotron resonance spectra) were measured in pulse pumping regime at a liquid He temperature. To measure integral radiation intensity Ge:Ga photodetector was used. To determine QCL lasing frequency we used variable rejecting filter based on HgTe/CdHgTe QW, which attenuation spectrum depends on magnetic field.

3. Results and discussion

Results of studies of the synthesized structure by high resolution X-ray diffractometry are shown in Fig. 2. The figure also presents calculated rocking curve. Measured superlattice period is 436 Å, differs only by 0.7% from its nominal value. Low full width at half maximum (FWHM) of satellite peaks (15-19″) indicates a high accuracy of the cascades thicknesses within the structure as well as low roughness of the interfaces. Atomic-force microscopy studies indicated the high planarity of the surface even after 10 µm growth. The widths of terraces were 0.7-1.0 µm and RMS roughness was estimated about 0.2 nm.

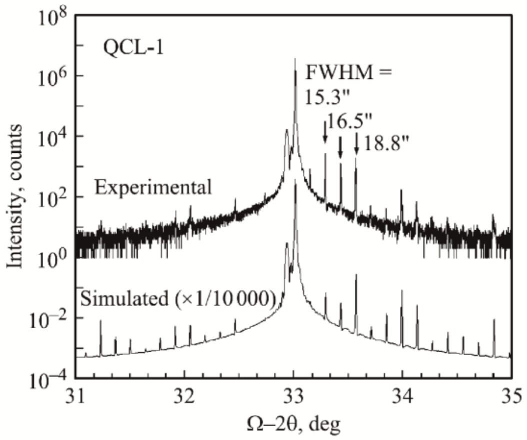

Fig. 2. X-ray rocking curve of the QCL structure near the GaAs (004) reflection and the corresponding simulated curve

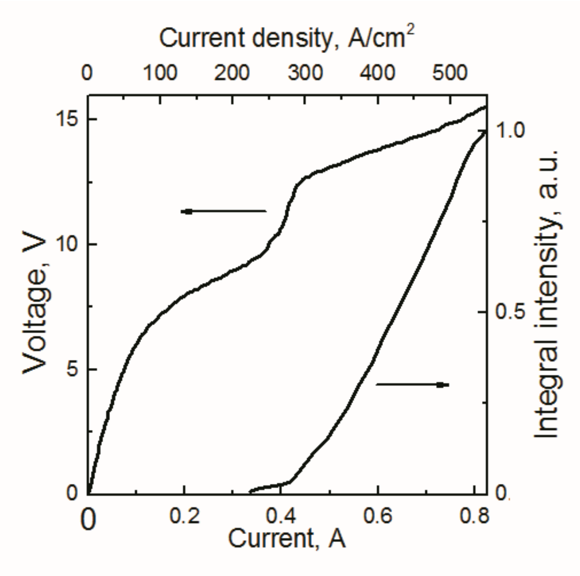

Fig. 3. Voltage-current (solid line) and light-current (dotted line) of the studied THz QCL

The dependence of the radiation intensity on the pumping current of the studied devices had characteristic threshold growth starting from 0.4 A (see Fig. 3), what is typical to the onset of laser generation. The voltage, corresponding to the kink in the light-current curve, about 11 V, is consistent with the calculated value of electric field, at which the levels are aligned, i.e. when the lasing should start (see Fig. 1a). Measurements of the radiation intensity transmitted through the variable filter based on HgTe/CdHgTe QW allowed to determine the lasing frequency of the QCL. The measured value about 3 THz coincides with the nominal frequency.

4. Conclusion

Thus, using fully domestic technological capacities we fabricated THz QCL with the double metal waveguide and the active region based on triple tunnel-coupled QWs with resonant-phonon depopulation scheme of the lower active level. High quality of the synthesized heterostructures was confirmed by high resolution X-ray diffractometry and atomic-force microscopy. Pulsed lasing was demonstrated at a liquid He temperature at 300 A/cm^2 threshold current density and 12 V voltage. The radiation frequency was estimated to be 3 THz, which is consistent with designed value.

Acknowledgements

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