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Design and fabrication of terahertz quantum cascade laser with double metal waveguide based on multilayer GaAs/AlGaAs heterostructures

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Abstract. We have designed multilayer heterostructure (MH) based on three quantum well GaAs/Al0.15Ga0.85As active module with diagonal transitions and optimized oscillator strength – 0.425. Furthermore, we have developed a method for the fabrication of terahertz quantum cascade laser (THz QCL) with double metal waveguide via low-temperature In-Au wafer bonding followed by SI-GaAs substrate removal. ICP RIE in BCl3/Ar has been used to obtain laser ridges (widths 50-200 mkm) with vertical sidewalls. We investigate the dependence of the MH energy band structure on the electric field and thermal properties of terahertz quantum cascade lasers (THz QCL) under different operation conditions.

1. Introduction

The development of technology for manufacturing of devices operating in THz range can give the global medical science new principles and theoretical approaches in early diagnosis and healing of chronic diseases (especially tumors). Relevance of these developments are also linked to the existence of the problem of countering terrorism in public places and transport because there is pentup demand reliable, but also safe for human inspection systems.

Among various techniques for THz generation [1-3], THz quantum cascade lasers (THz QCL) are compact solid-state source with electrical pump. Thus, THz QCL are considered to be the most promising THz source. THz QCL based on AlGaAs/GaAs heterostructures operate in the range 1.2-5.4 THz with output powers of more than 100 mW in continuous wave regime [4] and a peak powers of more than 1 W in the pulsed mode [5]. The spectral width of a THz QCL with distributed-feedback (DFB) is equal to ~10 kHz, it allows the use of THz QCL as a local oscillator for heterodyne detection [6]. Frequency comb based on THz QCL with a spectral bandwidth of more than 1 THz was demonstrated, which enables the development of THz spectrometers with a large S/N ratio [7,8]. One of the key desired THz QCL characteristic is RT operation, but it has not been achieved yet.

In the present article we have proposed the design of GaAs/Al$_{0.15}$Ga$_{0.85}$As multilayer heterostructure (MH) with optimized oscillator strength and investigated thermal properties and energy band profile of THz QCL under different operation conditions.

2. Results and discussion

On the basis of the calculation of the oscillator strength for the transitions between quantum-well levels two MH based on the three coupled quantum well (3QW) with resonant-phonon depopulation scheme (RP) were grown by molecular beam epitaxy (MBE). The layer sequences, starting from the injector barrier, are 43/75.6/24.6/69.3/41/136 (MH-1); 43/89/24.6/81.5/41/160 (MH-2) in Åangstrom. In Ref [9] the results of X-ray diffraction and photoluminescence spectroscopy characterization of the grown MH are presented.

3QW MH with four electron levels (see figure 1) is investigated. Levels E_2 and E_3 in the double quantum well are active laser states. Difference $E_3 - E_2$ corresponds to the energy and frequency of the emitted THz radiation. Levels E_1 and E_4 in the wide QW correspond to the injector and extractor levels, respectively. The THz QCL generation is possible for the following level alignments: (1) injector E_1 is aligned with higher laser state E_3, (2) lower laser state E_2 is aligned with extractor state $E_{4'}$ in the next period. The heterostructure is designed in such a way that difference $E_4 - E_1$ is equal to optical phonon energy ($E_{LO} = 32$ meV for GaAs) to provide resonant electron extraction.

Figure 2 shows the first level alignment of the lower injector state (E_1) with the upper injector state in the next stage ($E_{4'}$) occurs under 8.5 kV/cm (calculated within a Schrodinger-Poisson approach [10,11]). In that case the electrons tunnel through "lasing double-well" without emission of THz photons. The second level alignment occurs under 12.5 kV/cm and indicates alignment of the lower injector state (E_1) with the upper laser level (E_3). At higher bias THz QCL band structure is totally misaligned.

To estimate the thermal properties of THz QCL under the different operation conditions (power and cooling modes) modeling of heat flow processes in these devices was carried out [12]. The results for continuous wave regime for THz QCL are shown in figure 3. Due to the high value of thermal conductivity of the MH and In−Au bonding layer, thermal resistance of the device is dominated by the temperature drop inside the active region, and spreading resistance in the substrate.

The thermal dynamics of a THz QCL operating in pulse mode is investigated. In figure 4 maximum values of active region temperature T_{AR} under the different operation conditions (pulse repetition frequencies and duty cycles) are shown. Temperature-time profile for a standard ridge waveguide (inset figure 4) showing that T_{max} is stabilized for a time of about 2 ms and the further operation of the device remains unchanged.
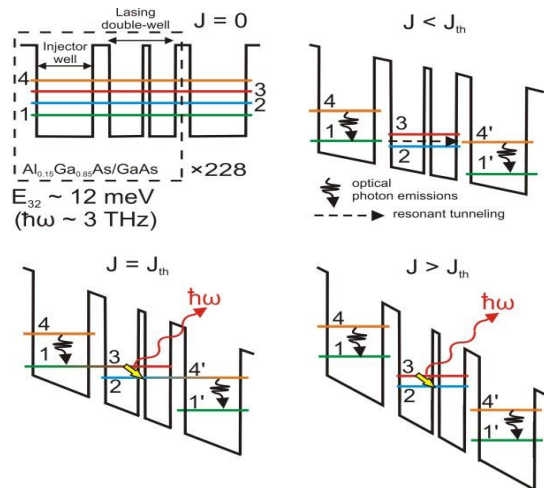

Figure 1. Schematic diagram of conduction-band of the 3QW MH based on RP scheme at different biases. A single quantum cascade stage is marked by a box. The radiative transition and LO photon emission is from 3 to 2 and from 4 to 1, respectively.
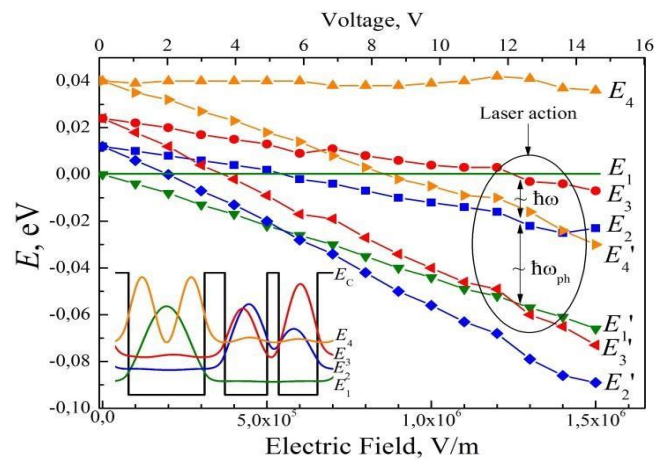

Figure 2. Dependence of the energy level positions in the current E_i and following $E_{i'}$ THz QCL periods on electric field for structure MH-2 (level E_1 is reference); inset – conduction band scheme, electron wave functions and energy levels alignment at zero electric field.
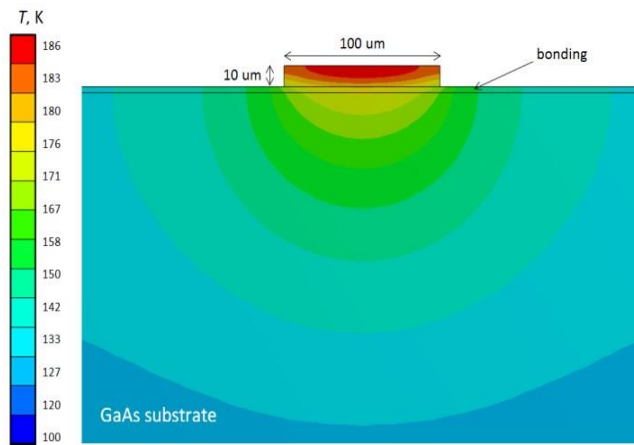
Figure 3. 2D heat flow model of cw THz QCL calculated with finite-element solver. The lower boundary is set to 100 K.
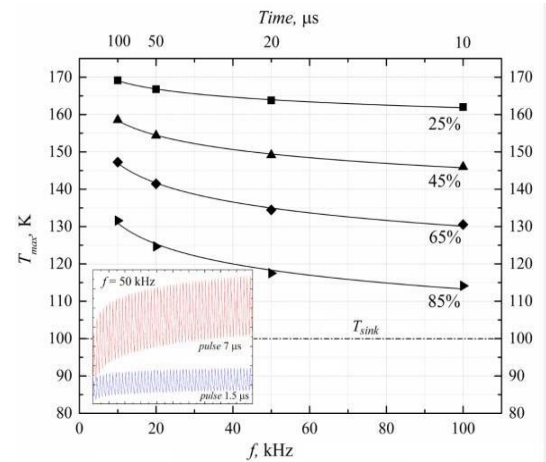
Figure 4. Maximum values of T_{AR} for different pulse repetition frequencies in the range 10-100 kHz and duty cycle 25-85%; inset – temperature-time profile for 1.5 and 7 µs pulse widths at 50 kHz.

We have developed post-growth processing of multilayer heterostructures GaAs/AlGaAs THz QCL with In−Au double metal waveguide [13]. The post-growth processing includes In−Au bonding of the THz QCL on n+-GaAs wafer, mechanical lapping and selective wet etching of the SI-GaAs wafer, and dry etching of the ridge structures using 50-µm, 100-µm and 200-µm-wide Ti/Au contacts as self aligned etch masks. The inductively coupled plasma reactive ion etching regime has been optimized in BCl_3/Ar for vertical sidewalls of the laser ridge with the minimum of Ti/Au mask destruction. Device processing then continued according to the standard recipe.

THz QCL bar is soldered onto Cu blocks, which serves as a heat sink and bottom electrical contact (figure 5). Top QCL contact is made by wire bonding to Ti/Au pads. A scanning electron micrograph of a typical wire bonding 50-µm-wide ridge structure is shown in figure 6. It has been found that n+-GaAs receptor must be thinned to ~100 µm to obtain a good quality of laser facet.

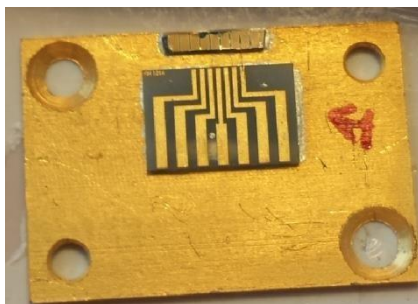Light-current curves and spectral characteristics of fabricated lasers are presented in [14,15].

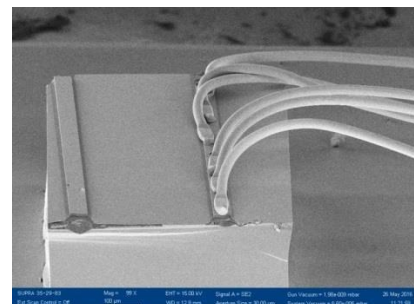**Figure 5**. THz QCL bar is mounted onto C-mount (Cu blocks).

Figure 6. SEM photograph of a processed 100-µm-wide laser ridge with wire bondings.

3. Conclusion

We have proposed the multilayer heterostructure based on three quantum well GaAs/Al0.15Ga0.85As with optimized oscillator strength – 0.425. Energy band calculations and thermal modelling of THz QCL under different operation conditions were carried out. THz QCL with 50 and 100 -μm-wide ridge structure were fabricated.

Acknowledgements

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