Performance of Phonon Depopulated Terahertz Quantum Cascade Lasers

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In this contribution we present experimental results of optimized active regions for terahertz quantum cascade lasers. The optimization was achieved by employing a Non-equilibrium Green's Functions model. Theoretical results suggested to revise the extraction barrier of the current design in order to increase the peak gain. Measurements showed an improved dynamic range and also an increased operating temperature of 145 K.

Introduction

The mid-infrared (MIR) quantum cascade laser was demonstrated in 1994 [1] and 8 years later the concept was successfully extended to the terahertz region [2]. So, the terahertz quantum cascade laser (THz QCL) might be the long wavelength relative but not for operating temperatures, which in contrast to room temperature-working MIR QCLs still requires cryogenic cooling [3].

Terahertz radiation has lots of potential applications (spectroscopy, imaging, medical diagnostics, etc.), which means solid-state, compact and efficient sources would be very desirable. At the moment only quantum cascade lasers fulfill these criteria and a lot of effort is put into pushing the operating temperatures at least to 240 K. Such temperatures are accessible with thermoelectric cooling stages.

Theory

Unlike in ordinary semiconductor band gap lasers, the energy levels in a quantum cascade laser are formed only in the conduction band of a semiconductor heterostructure. Consequently, one is no longer limited by the naturally given band gap of a material, in fact one can now tailor the optical transition energy by changing the width of the wells and barriers. The difficulty in realizing a terahertz quantum cascade laser is the small energy spacing of the lasing transition (1 THz is equivalent to 4 meV) and to establish population inversion in the presence of phonons. One successful realization is the so-called phonon depopulation scheme [4]. It is a combination of resonant tunneling and sub-picosecond emission of a longitudinal optical phonon for an efficient depopulation of the lower laser state. In a previous study we showed that the threshold current density can be significantly reduced with a lower doping density [5]. Unfortunately not only the threshold is reduced but also the dynamic range. The limiting factor is the onset of a negative differential resistance region. One design strategy for reaching higher operating temperatures is to extend the dynamic region. In a collaboration a newly developed transport code based on Non-equilibrium Green's Functions (NEGF) [6] was used to improve the design of the active region. This realistic description of the transport in such a heterostructure can be used to obtain an energy-resolved density distribution and to calculate the peak gain of the active region (Fig. 1). Simulations focused on the barrier responsible for the resonant tunneling out of lower laser state suggested to reduce the anticrossing of the involved states. This is done by thickening the barrier from 4.1 to 5.2 nm.

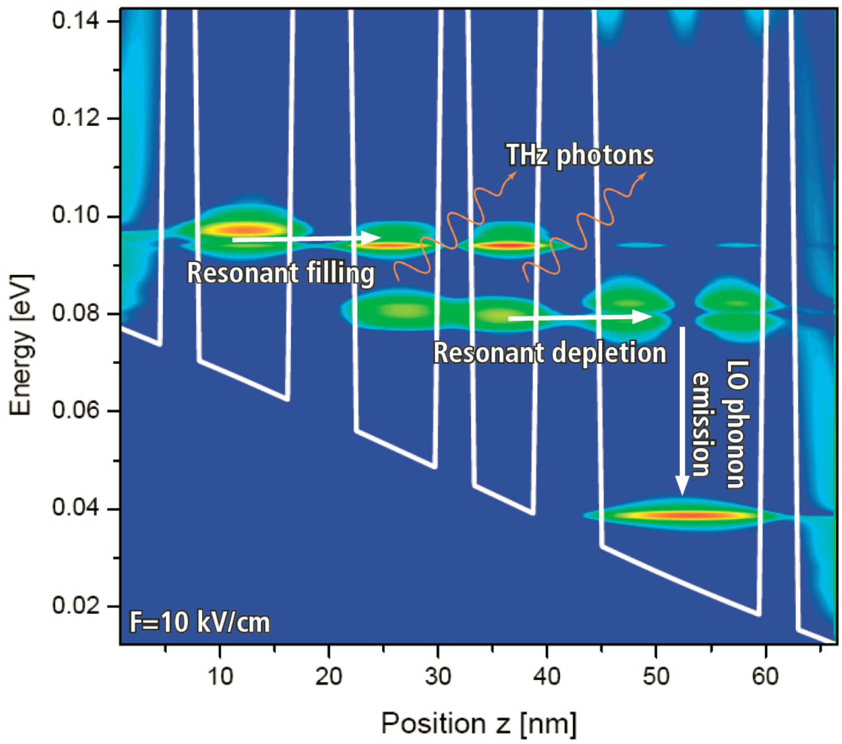

Fig. 1: Simulation results gained from the NEGF based transport model. The energy-resolved local density of states is color coded. The white lines represent the conduction band profile [6].

Experimental

Sample Preparation

The active region designs were realized in the GaAs/$Al_{0.15}Ga_{0.85}As$ material system by molecular beam epitaxy (MBE). The 15 µm thick heterostructure is then processed into a so-called double-metal waveguide, very similar to a microstrip transmission line.

First of all, a piece of the device wafer and the receptor wafer (n+ doped) are prepared with a thick gold layer (~ 1 µm) for thermocompression bonding. The bonding takes place at 330 °C and under constant pressure of 200 bar. Afterwards the device substrate is removed by polishing, followed by selective wet etching stopping at the underlying etch stop layer of the heterostructure. Another selective wet etching step removes this etch stop layer. Now, since the active region is accessible again, standard processing methods can be applied. Ridge resonators are lithographically defined, a gold top contact is sputtered and the mesas are formed by reactive ion etching in a $SiCl_4/N_2$ plasma environment.

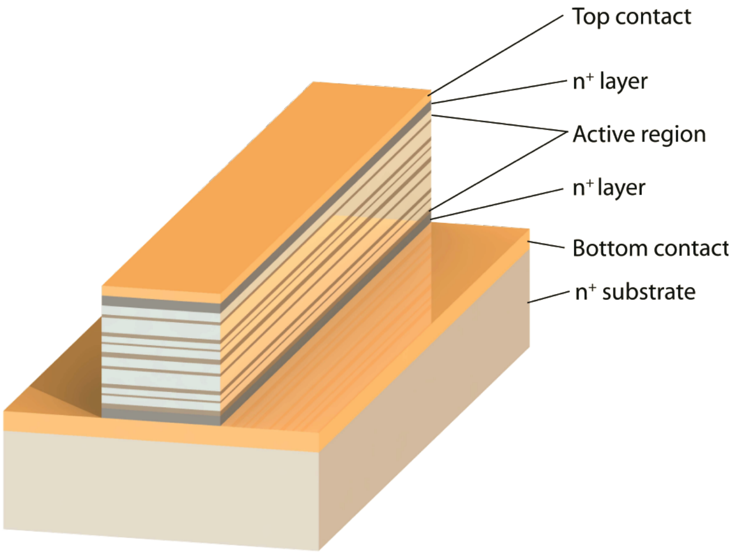

Fig. 2: Schematic of the processed double-metal ridge laser. The active region is sandwiched between two layers of gold which function as waveguides and electrical contacts.

Measurements

The samples are mounted on the cold finger of a cryostat and the terahertz radiation is collected by an off-axis parabolic mirror. The collinear beam is guided through a Fourier transform spectrometer and detected with a liquid helium cooled silicon bolometer. In pulsed operation a lock-in detection technique is applied to increase the signal-to-noise ratio.

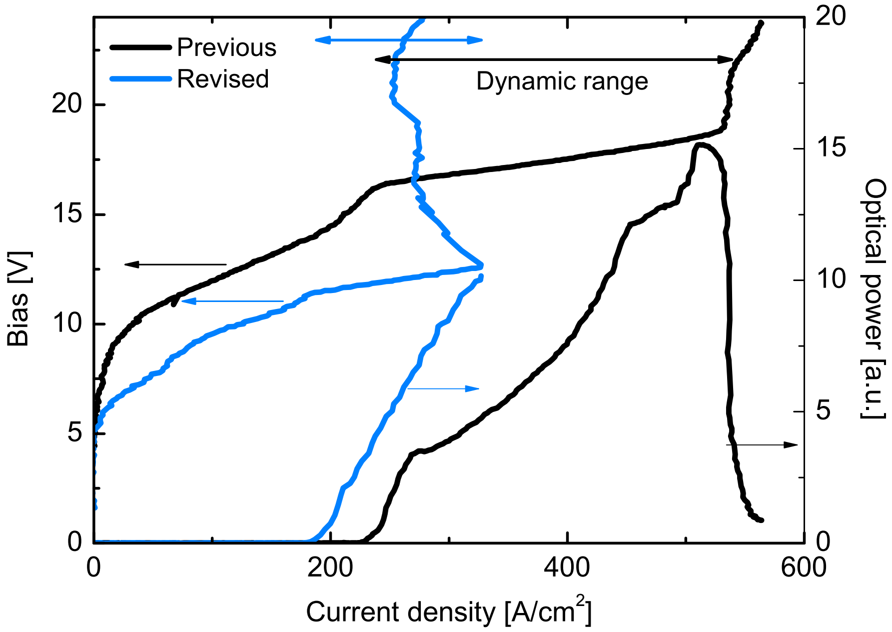

Fig. 3: LIV characteristics - comparison of the previous and the revised structure. The double arrows on top clearly show the improved dynamic range.

Figure 3 shows the electrical characteristics and optical power of the previous and the revised design. The previous design features a pronounced negative differential resistance (NDR) region which limits the operation at higher current densities. After redesigning the extraction barrier, the current transport is no longer limited by an NDR region and the dynamic range is almost extended by a factor of 2.5. However, the influence on the maximum operating temperature was not that dramatic, raising it from 140 K to 145 K.

Conclusion

We were able to improve the active region design of a terahertz quantum cascade lasers by using a sophisticated transport theory based on Non-equilibrium Green's Functions. The revised design exhibits an extended (more than doubled) dynamic range and therefore reaches slightly higher operating temperatures.

Acknowledgements

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