Doping in Terahertz Quantum-Cascade Lasers

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We present the effects of the doping concentration on a set of terahertz quantum-cascade-lasers emitting around 2.75 THz. The threshold current density decreases linearly with the doping. The output power drops monotonically.

Introduction

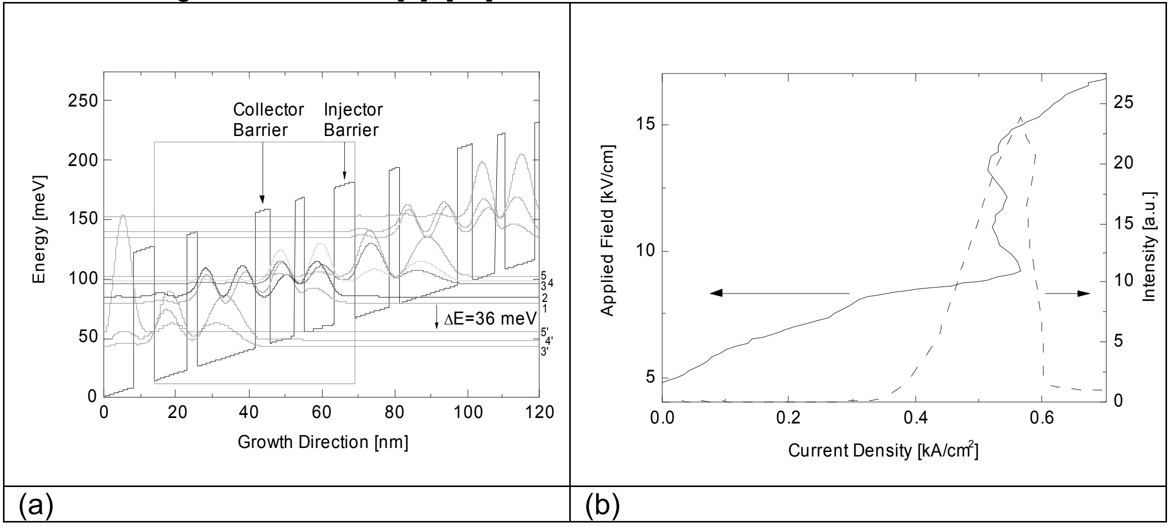
Since the first reported quantum-cascade-laser (QCL) in the terahertz (THz) spectral region by Köhler et. al. [1] there has been significant progress. The available frequencies are as low as 1.39 THz [2], also extremely low threshold current densities of 1 A/cm^2 can be achieved [3]. Single-mode emission at well defined frequencies is available [4]. Also the non-radiative scattering processes are well understood, mainly due to measurements performed in a magnetic field [2], [3], [5]. Three different designs for the active region are competing each other, the chirped superlattice [1], the bound-to-continuum [4] and the longitudinal-optical (LO) phonon depopulation scheme [6]. We have chosen the last one for our studies as it shows the best temperature performance.

Sample	(a)	(b)	(c)	(d)
Doping of the widest well [cm^{-3}]	1.25e16	8e15	5.3e15	3.5e15
Sheet density [cm^{-2}]	1.9e10	1.2e10	8.2e9	5.4e9
Threshold current density J_{Th} [A/cm^2]	510	305	216	142
Maximum working temperature [K]	145	147	133	140
Growth deviation [%]	+1.3	+2.6	+1.9	+5.5

Tab. 1: The doping concentration, threshold current density, maximum working temperature and growth deviation obtained by X-ray-diffraction analysis for all samples. The X-ray diffraction results show a splitting for sample (c).

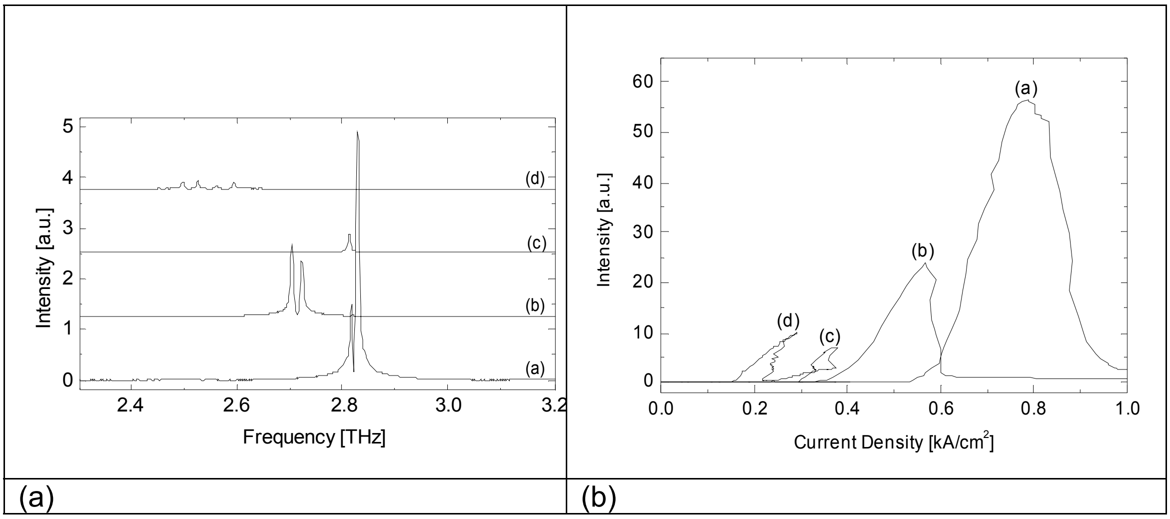
We present here a systematical study on the effects of the doping concentration on the performance of THz-QCLs. The design is nearly identical to the one published by Kumar *et al*. [7], it consist of a MBE grown GaAs/Al$_{0.15}$Ga$_{0.85}$As-superlattice. One cascade is built up by four wells. A simulation of the structure at lasing field is shown in Fig. 1(a). Only the widest well of the structure is homogeneously doped. The rest of the cascade remains undoped, thereby minimizing the scattering inside the optically active part of the cascade. To be able to change the doping concentration in a wide range, four identical structures have been grown. To guarantee that all samples have a comparable quality, all of them have been analyzed by X-ray-diffraction measurements.

The doping concentrations and other characteristics of the samples are given in Tab. 1. The active region is 15 µm thick; it consists of 271 identical cascades, and is processed into a high-confinement double-metal waveguide using an Au-Au thermocompression bonding [8]. The top-gold is used as a self-aligned etch mask for reactive-ion-etching (RIE). The sidewalls and the facets are etched, thereby ensuring a comparable quality and dimension for all devices. This processing and the waveguide used results in devices with high-Q resonators [9], [10].



(a) (b)

Fig. 1: A calculated bandstructure at a field of 9.8 kV/cm of the samples and an LV/IV-curve. (a) One cascade is marked with a box. The growth sequence in nm starting from the left is 9.2/**3.0**/15.5/**4.1**/6.6/**2.7**/8.0/**5.5**, where the barriers are marked with bold letters and the doped well is underlined. The optical transition happens between the wavefunctions marked with 3, 4 (upper lasers states) and 2 (lower laser state). (b) The IV shows two kinks, the first one when the structure aligns, the lasing starts, and the second one when the structure misaligns, the lasing ceases.



(a) (b)

Fig. 2: Spectra of all samples at a comparable electric field and LI-measurements for the 4 samples. (a) The emission of sample (d) is slightly shifted due to a growth deviation of +5.5%. (b) The threshold and J_{max} drops linearly with a lowered doping. The peak output power decreases monotonically with the reduced doping, except for sample (c), which shows a splitting in the X-ray diffraction analysis.

Experimental Results

The first characterization of a QCL are the measurements light-versus-current (LI) and field-versus-current (IV), the results for sample (b) are shown in Fig. 1(b). A comparison of the LI and the IV reveals that the IV shows the first kink when the QCL starts to lase and the second one at maximum emission. The first one corresponds to the alignment of the cascades and therefore to an efficient transport, the second one to the misalignment of the cascades. All samples emit around 2.75 THz; the spectra are shown in Fig. 2(a). The emission of sample (d) is slightly shifted due to a growth deviation of +5.5%.

The doping concentration is a crucial factor for a working QCL as it determines the number of available carriers inside the active region. A high number of carriers in the upper laser state allows for a strong population inversion and thereby to a high gain, which scales with the doping density n. At the same time also the free-carrier absorption is increased, which scales with n^2. All our QCLs show a linear dependence of the threshold current density J_{Th} on the doping concentration. A lower doping leads to a lower threshold. Also J_{max}, the current density where maximum emission happens, drops linearly with the doping. The LIs of all samples are shown in Fig. 2(b). Beside the changes in J_{Th} and J_{max} also a drop in peak output power with a lowered doping is observable.

The relationship between the threshold current density and the temperature is an exponential one for all samples. It can be approximated with the phenomenological expression:

$$J_{Th} = J_0 + J_1 \cdot \exp\left(\frac{T}{T_0}\right). \qquad (1)$$

The parameter J_{max} on the other hand is independent of the temperature. The QCLs work up to a temperature where J_{Th} and J_{max} become equal. Unlike other publications [11] we don't see a connection between the doping and the maximum working temperature. All samples are lasing up to approx. 140 K; at this temperature the thermal energy k_BT is equal to the energy of the laser transition of 12 meV. The best results so far show a slightly higher T_{max} of 164 K [12].

A monotonical and a linear relationship between the threshold current density and the doping concentration has already been reported for THz-QCLs [11], [13]. It has been explained with the reduced waveguide losses due to the reduced free-carrier absorption in the active region. Measurements for a 10 µm thick double-metal waveguide and a sheet density for the active region of 3.2e10 cm^{-2} show a waveguide loss of 5 cm^{-1} [14]. This doping concentration is still a factor of 1.5 higher than our highest doped sample. Our simulations show a waveguide loss of 5 cm^{-1} for an undoped active region. At the extremely low doping concentration in a THz-QCL, the losses are dominated by the two gold layers and the thin n^+-contact layers and not by the free-carrier absorption in the active region. Therefore we don't attribute the increase of the threshold with a higher doping to the increased waveguide losses but to the fact that QCLs are designed to lase at a certain field and not at a certain current. Before a QCL can lase, the cascades have to be aligned properly. Therefore a higher number of available carriers, determined by the doping, leads to a higher current to establish the required field. All our samples lase strongly in a field region between 8 and 9 kV/cm independently of the doping. According to our simulations that is the field region where the coupling between the upper and the lower laser state is strong and the lower laser state is separated from the ground state by 36 meV, which corresponds to the energy of an LO-phonon in GaAs. Thereby an efficient depopulation of the lower laser level is ensured.

Conclusion

We have varied the doping concentration of a THz-QCL emitting at 2.75 THz from 5.4e9 to 1.9e10 cm^{-2}. There was no effect on the maximum working temperature observable. All samples lased up to approx. 140 K in pulsed mode operation. The threshold current density and J_{max} scaled linearly with the doping concentration. That was attributed to the fact that a QCL needs a certain field for lasing. If the doping is higher also the current has to be higher to establish that field. The output power raised monotonically with a higher doping.

Acknowledgements

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