Performance Dependence on Doping of THz Quantum-Cascade Lasers

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***Abstract*—We present the effects of dopant concentration on the performance of 2.75 THz quantum-cascade lasers. The sheet density was varied from 5.4e9 to 1.9e10 cm^{-2} by growing 4 identical LO-phonon depletion scheme structures and additionally an undoped structure. The threshold current density J_{th} and maximum current density J_{max} scaled linearly with doping concentration while the applied field for the onset of lasing and cessation of lasing remained independent. The maximum operating temperature for all structures was ~140K. These results suggest that within this doping range free carrier absorption is not limiting performance for THz quantum-cascade lasers. Additionally, an undoped structure is expected to have a J_{th} of zero and a J_{max} of 70 A/cm^2.**

***Index Terms*— Doping in Lasers, Quantum-Cascade Lasers, Semiconductor lasers, Terahertz lasers.**

I. Introduction

With the realization of the first THz quantum-cascade laser (QCL) [1] there has been great progress in available emission frequencies down to 1.6 THz [2], reduction of threshold current J_{th} to 1 A/cm^2[3], and maximum operating temperature up to 164K [4]. This has been accomplished through the improvement of QCL active region and waveguide designs: chirped superlattice [1] and bound-to-continuum [5] (low threshold designs), LO-phonon depopulation scheme [6] (high-temperature design), surface plasmon and double metal waveguides.

A previous study into the doping characteristics of the LO-phonon THz QCL structures [7] used a delta doping gradient, created by stopping sample rotation, producing within the same sample a doping variation of 3-5e10 cm^{-2} or +/-20%. In this paper, we investigate four uniformly doped samples over a wide range with approximately +50% differences between doping concentrations, including an additional undoped THz QCL.

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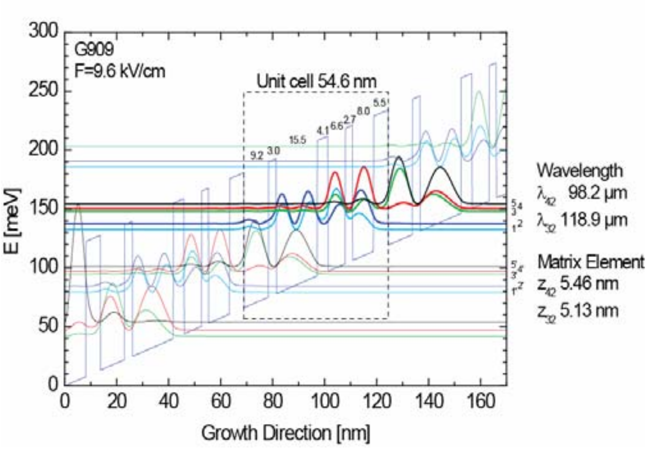

Fig. 1. Calculated band structure at a field of 9.8 kV/cm. The box denotes one unit cell of the 15 µm active retgion. The barriers are $Al_{0.15}Ga_{0.85}As$ and the wells are GaAs. Lasing is between levels 4 and 2 and 3 and 2, depending on the applied field. The lower laser state is depopulated into the ground states 5', 4', and 3' of the next cascade by an LO phonon.

II. Experiment

Five LO-phonon depopulation 2.75 THz QCL structures were grown by solid-source molecular-beam epitaxy (MBE) as in Ref. [8], shown in Fig. 1, with 271 cascade cells for a 15 µm thick active region to minimize waveguide losses. This design uses $Al_{0.15}Ga_{0.85}As$ barriers with GaAs wells to define the upper and lower laser states as well as an LO-phonon resonance with the lower laser level to rapidly deplete the electrons and prevent thermal back filling. The doping in the widest well in the five samples was 5.4e9, 8.2e9, 1.2e10, 1.9e10 cm^{-2}, and undoped. The accuracy of the structure was determined by high-resolution x-ray diffraction. The samples were processed with an Au-Au double metal waveguide for high mode confinement and the laser sidewalls and facets were etched, instead of cleaved, by inductively coupled reactive ion etching (ICP-RIE). The dimensions for each laser bars are 120µm x 1mm.

Device measurement was performed in pulsed mode operation with a pulse length of 100 ns, chosen to prevent additional device heating, and a repetition rate of 1 kHz for the integral measurements and 5 kHz for spectral measurements.

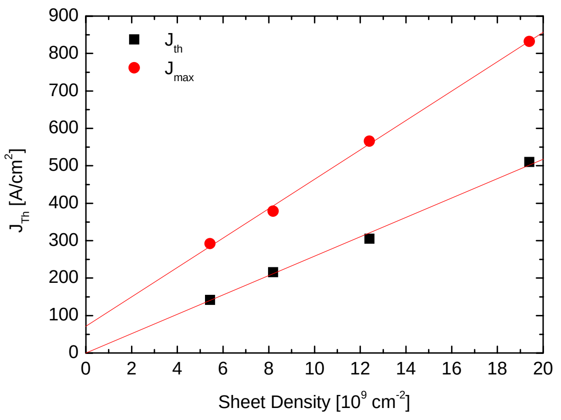

Fig. 2. Plot of threshold current density J_{th} and maximum current density J_{max} vs doping sheet density for the four doped structures. Both J_{th} and J_{max} show a linear dependence on doping density.

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III. Results and Conclusions

The undoped sample shows similar electrical characteristics as the four doped samples. The band structure aligns at 9 kV/cm and then misaligns at a current density of 60 A/cm^2, just below the predicted 70 A/cm^2 from the linear fit to the doped data points. This may indicate a lower doping or impurity limit of the MBE or in a naive approach this corresponds to an overall background doping of 1-2e14 cm^{-3} for the 22 hour growth.

Lasing, except for the undoped sample, in the structures starts at an applied field of 8 kV/cm, where the alignment of the cascades begins and the I-V has a reduced slope. The threshold current density J_{th} increases linearly with carrier concentration. The maximum current density J_{max} also increases linearly with carrier concentration. Thus the carrier concentration also increases the operating range of the laser. While the J_{th} converges on zero A/cm^2, the J_{max} converges on 70 A/cm^2. This is in contrast with Ref. [7], where non-linear behavior was observed for the similar LO-phonon design with higher dopant concentration. The non-linearity was attributed to free-carrier absorption and a strong dependence of T_{max} on carrier density. The T_{max} was ~145K for all samples in our study.

The linearity of the J_{th} and J_{max} with respect to doping and the independent nature of T_{max} leads to the conclusion that free carrier absorption and/or impurity scattering is not yet limiting performance in these THz QCLs. The doping can be changed to directly produce lower J_{th}, although lower doping results in lower output power.

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