Doping density dependent performance of short-wavelength InP-based quantum-cascade lasers

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***Abstract*—We report on a doping study on strain compensated quantum cascade lasers grown on indium phosphide substrates by gas source molecular beam epitaxy. In detail we investigate the power outputs, threshold densities and far field patterns utilizing doping densities between 7×10^{16} cm^{-3} and 4×10^{17} cm^{-3}. Further the temperature dependent laser performance as a function of injector doping density is investigated.**

***Index Terms*—Quantum cascade laser, Doping density, Short wavelength, Indium phosphide.**

I. Introduction

Development of quantum-cascade lasers (QCLs) which operate in 3-5 µm spectral region is driven by several applications including chemical and medical uses as well as free space communication and military countermeasures.

Several groups demonstrated short-wavelength QCLs by incorporating InP-based material systems with a very large conduction band offset [1], [2]. However, to improve the performance of such devices, especially towards continuous wave operation at room temperature, and to understand better the limitations of particular designs, further investigation of the influence of relevant physical parameters is required.

The effect of the QCL active region doping variation on the laser performance has been studied both experimentally and theoretically by several authors [3]. So far, most of the studies deal with a fairly narrow doping range only, where one usually observes a monotonic reduction of laser threshold with reduced doping level [3]. Given the boundary condition that QCLs with no doping do not lase (i.e. threshold is infinite), it becomes obvious that the threshold vs. doping level must experience a minimum at some point. Such an optimal doping level was observed experimentally for GaAs/AlGaAs QCLs at λ ~ 10 µm [4]. Of course, optimized doping level is expected to depend on the particular QCL design and the operation wavelength. In this

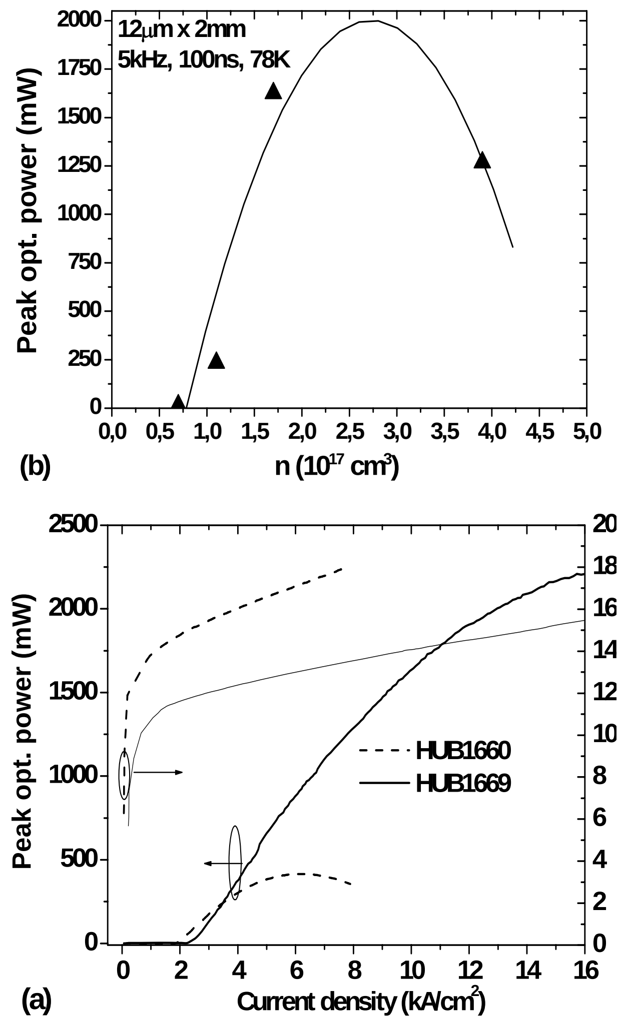

Fig. 1(a) Peak optical power vs. doping density characteristics of 2 mm long and 12 µm wide devices driven with 100 ns x 5 kHz current pulses, recorded under pulsed bias at a heat sink temperature of 78 K. The symbols denote experimental data and the solid line is their quadratic fit. The doping levels are 0.7×10^{17} cm^{-3}, 1.1×10^{17} cm^{-3}, 1.7×10^{17} cm^{-3} and 3.9×10^{17} cm^{-3} (corresponding to samples HUB1664, HUB1660, HUB1658 and HUB1669, respectively).

(b) Light output and voltage vs. current density characteristics of two ~2 mm long and 18 µm wide devices, recorded under pulsed bias at a heat sink temperature of 78 K. The solid lines belong to sample HUB1669 with the highest doping level (3.9×10^{17} cm^{-3}) and is compared to the lower doped HUB1660 (1.1×10^{17} cm^{-3}; broken line).

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presentation we analyze the effect of the active region doping variation between 7×10^{16} cm^{-3} and 4×10^{17} cm^{-3} on the performance of a short-wavelength, λ~3.8 µm, InP-based strain compensated QCL.

II. Samples

The QCL structures were grown by using gas-source molecular-beam epitaxy on a low doped InP substrate, which is used as the lower cladding layer. The 30-period strain-compensated In-Ga-As/In-Al-As/AlAs active region is sandwiched between two In-Ga-As spacers. The upper cladding is provided by an InP layer followed by an In-Ga-As contact. This sequence and the material compositions are well described in [5].

The grown material was processed into 10 to 20 µm wide ridges where the side walls of the lasers were defined by 5.3 µm deep and 10 µm wide trenches via a reactive ion etching process. A silicon nitride layer, serving as electrical insulation, was deposited by plasma enhanced chemical vapour deposition technology and was opened along the ridges. Extended contact pads were sputtered on top and a lift off process was used to electrically insulate the ridges from each other. The back contact was evaporated and annealed. The laser emission was studied using pulse-mode operation with a width of 100 ns and a repetition rate of 5 kHz at different temperatures. By means of a Fourier-transform spectrometer with a spectral resolution of 0.2 cm^{-1} the infrared spectra were recorded.

III. Results

Four samples were characterized, showing a clear dependence of optical power and threshold current on doping density. Fig. 1(a) shows a maximum of the optical power at doping level of ~$0.7\text{x}10^{17}$ cm^{-3}. Similarly, the maximum operating current increases linearly with doping concentration. Thus, the doping value determines the current laser's dynamic range. Fig 1(b) shows a trend of increased threshold current density with higher doping. We estimated waveguide losses by measuring threshold currents for different laser lengths. The results of the complete doping study by means of threshold behavior, power output, losses, far fields and temperature performance of various ridge widths will be presented.

IV. Conclusion

We have studied the influence of varying doping density on transport and lasing properties of strain-compensated InP-based quantum cascade lasers. In this case, especially for the short wavelength regime, determining the optimal doping density is the best way of improving lasing performance, yielding a continuous wave operation at room temperature.

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