Performance Dependence on the Doping of THz Quantum-Cascade Lasers

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Motivation

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.

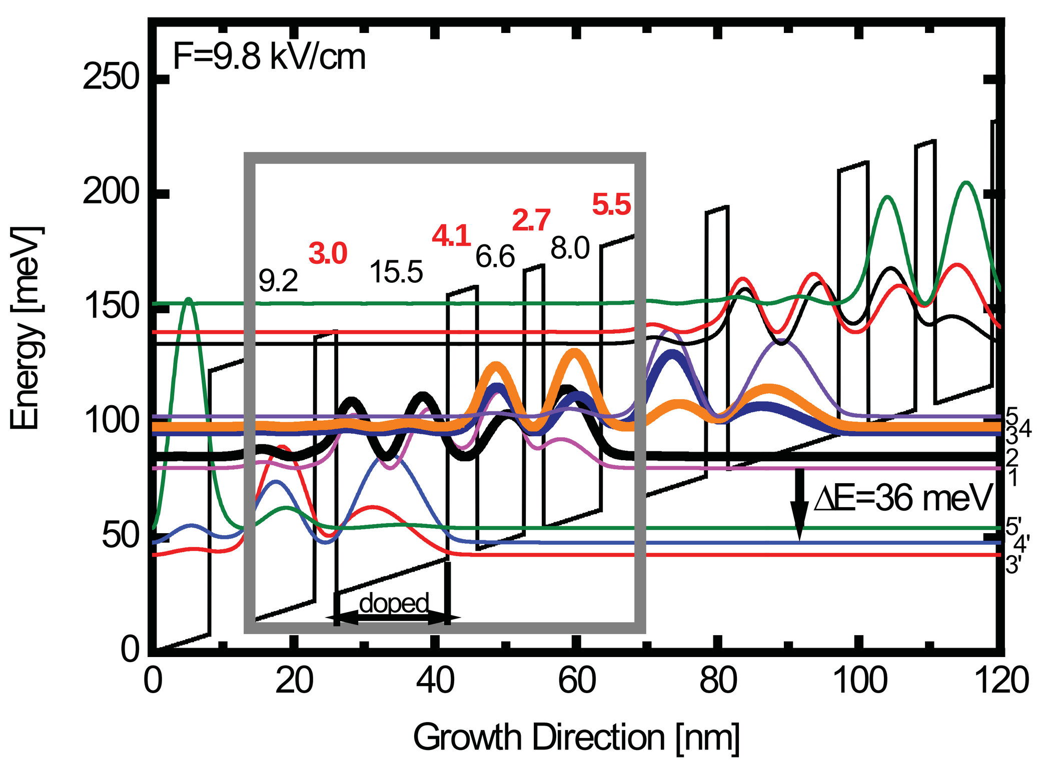
The only previous study into the doping characteristics of the LO-phonon THz QCL structures [7] used a delta doping gradient within one sample, created by stopping sample rotation, producing within the same sample a doping variation of 3-5 10^{10} cm^{-2} or +/-20% of the target doping concentration.

Here, we investigate five uniformly doped samples over an order of magnitude, with approximately +50% increase in doping concentration between samples, including an additional undoped THz QCL.

Sample Summary

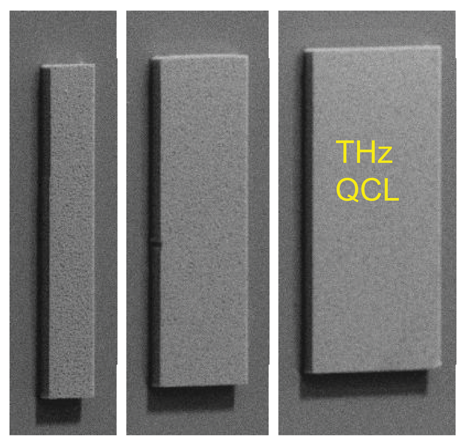
Sample	A	B	C	D	E
Doping of widest well (10^{15} cm^{-3})	2.80	4.24	6.40	10.00	25.00
Sheet density (10^{10} cm^{-2})	0.43	0.66	0.99	1.55	3.88
Average doping density (10^{15} cm^{-3})	0.79	1.20	1.82	2.84	7.10
J_{th} (kA/cm^2)	0.142	0.216	0.305	0.510	1.55
J_{max} (kA/cm^2)	0.292	0.379	0.566	0.832	2.01
T_{max} (K)	145	147	133	140	140

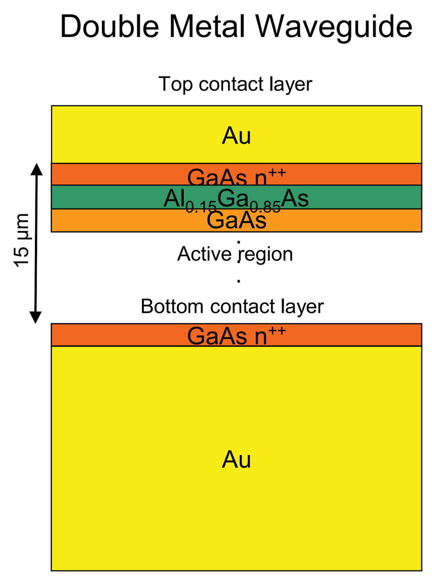
Bandstructure and Waveguide

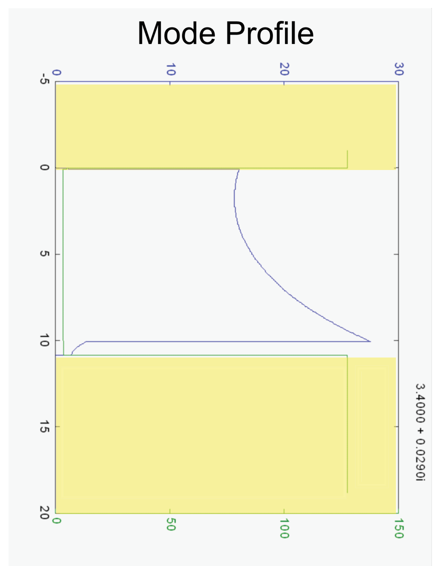


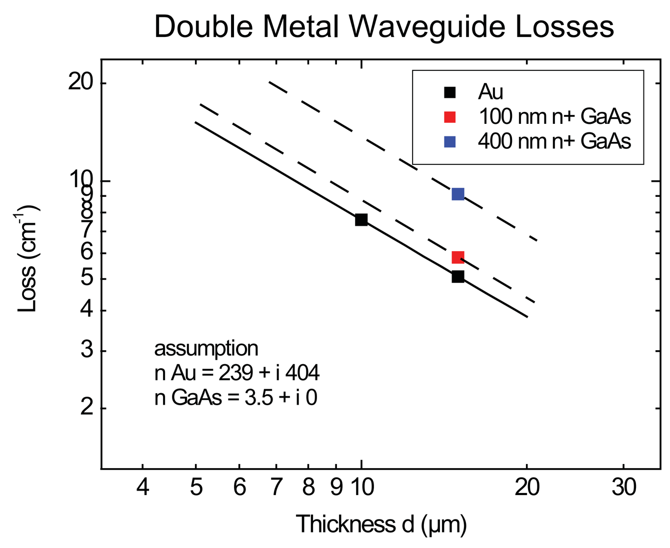
The 2.8 THz QCL structure used is made from a repeated GaAs/$Al_{0.15}Ga_{0.85}As$ heterostructure based on the LO phonon depopulation of the lower laser state [8]. One cascade consists of four wells with the doping in the widest well.

Final laser bars are definded by ICP-RIE etching







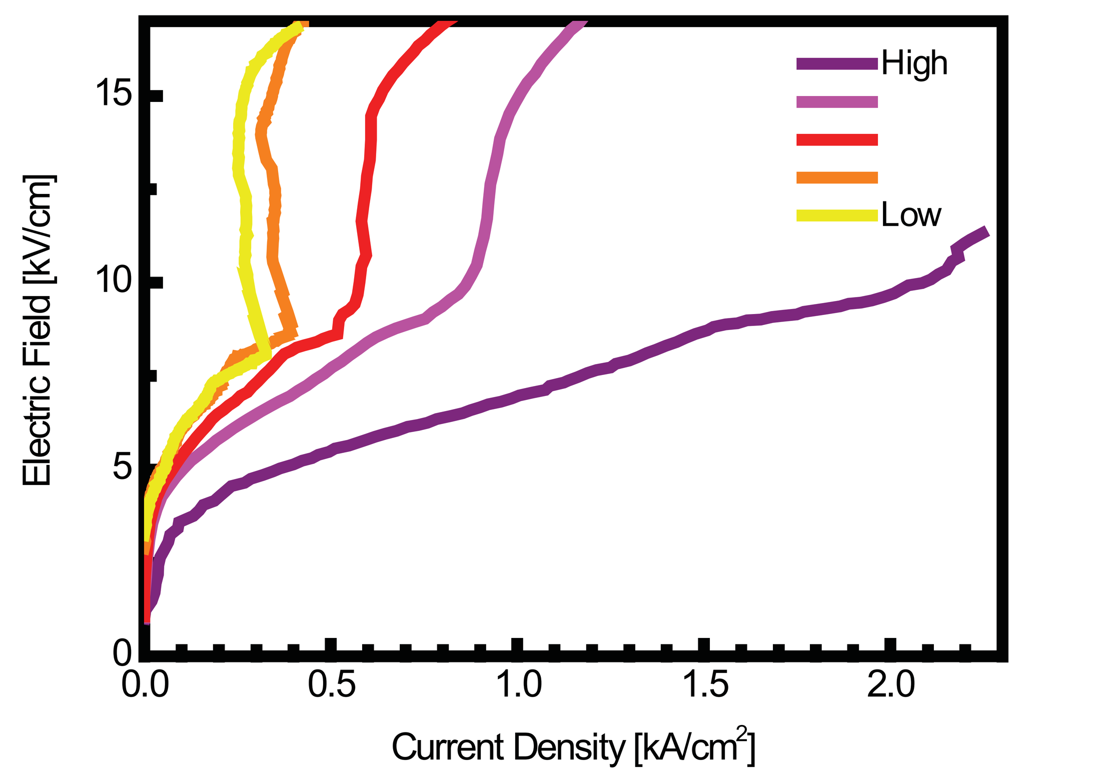


M.A. Ordal *Appl. Optics* 22, 1099 (1983)
G.Brandli *Phy. Rev. B* 5, 3550 (1972)

Surface plasmon waveguides are easy to process, but the poor mode confinement limits the potential performance of the THz laser. A double metal waveguide significantly improves mode confinement, but it introduces high waveguide losses.

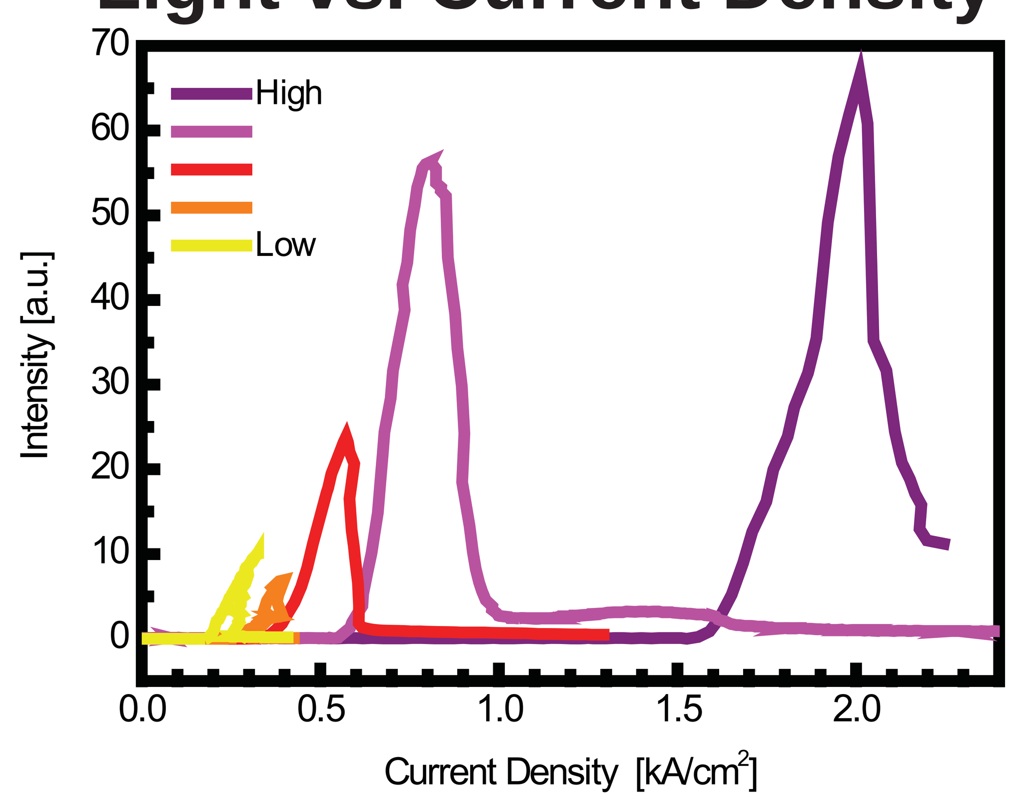
The waveguide losses can be significantly reduced by increasing the active region from 10 to 15 µm thick, which requires 271 cascades and 24 hours to grow. To additionally reduce the losses thin contact layers are used.

Voltage vs. Current Density



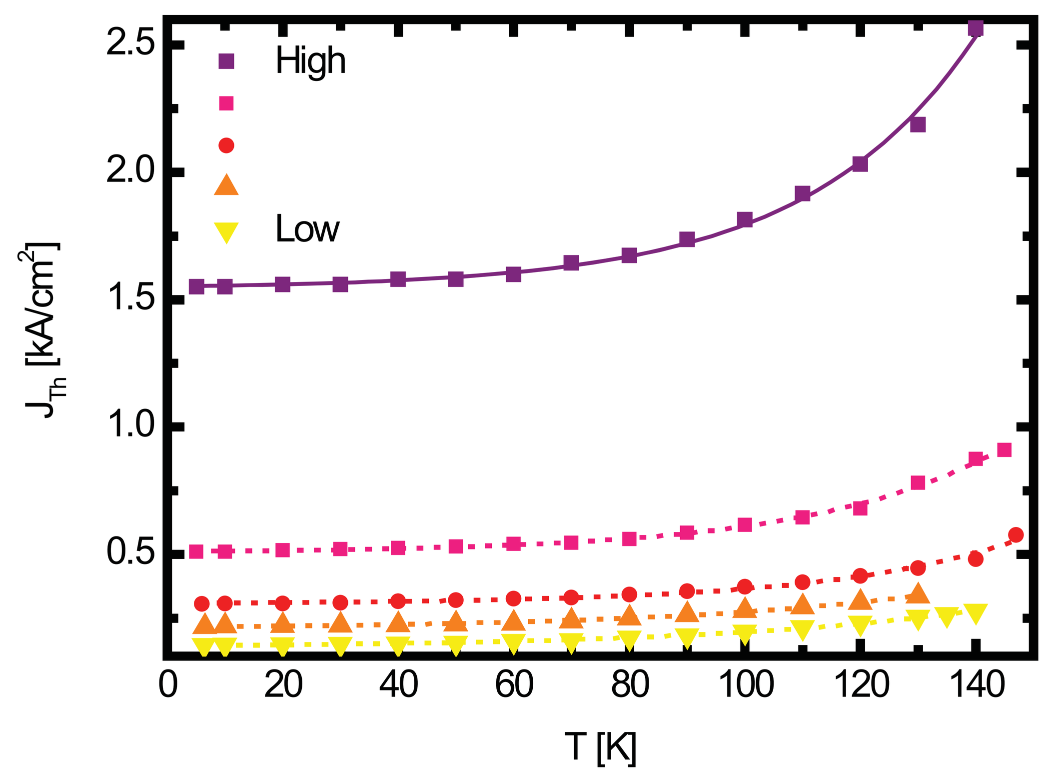
All IV curves show two kinks which correspond to the alignment and misalignment of the QCL structure. An electric field of about 8 kV/cm for alignment is constant, independently of the doping concentration.

Light vs. Current Density



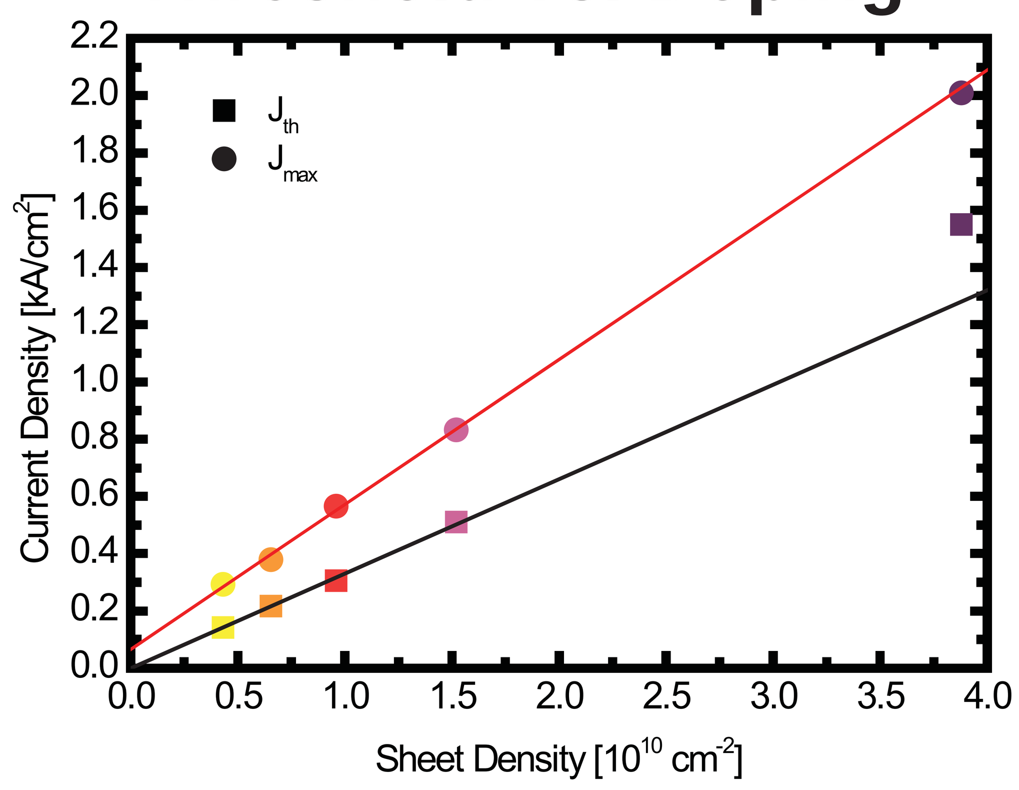
The emitted power and dynamic range is increased with the higher doping. For applications, a compromise between output power and threshold current will have to be made.

Temperature Dependence



The threshold current density of the five doping concentrations show the same exponential behavior. The maximum working themperature is ~140K and the T_0 is ~30K.

Threshold vs. Doping



The threshold current shows linear behavior for the four lowest doped samples. Only the highest doped sample deviates from linearity. The maximum current at the peak power remains linear.

Summary

Threshold current density scales linearly in a broad range. Applied voltage determines the onset of lasing. Free-carrier absorption losses are observable only at the highest doping concentration. The gain must overcome this additional loss. Doping has no effect on the maximum working temperature T_{max} or the characteristic temperature T_0.

References:

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