# Thermal modelling of terahertz quantum-cascade lasers

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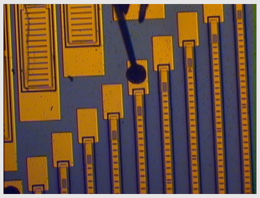
## Introduction

- The thermal properties of THz QCLs play a crucial role in determining the device performance.
- THz QCLs have inferior temperature performance compared to MIR devices due to the difficulty in achieving selective injection and depopulation of the upper and lower laser levels at higher temperatures.
- Additionally, since the photon energy is less than the LO phonon energy, at high temperatures, thermally activated LO phonon emission can seriously reduce the upper laser level lifetime.
- Coupled with these facts, the cross-plane thermal conductivity of QCL active regions is reduced compared to bulk due to their multilayer nature and makes heat extraction from the active region difficult.
- THz QCLs particularly suffer due to the large active region thickness and increased number of interfaces which increases the thermal resistance.
- The optical waveguide configuration also plays an important role in determining the thermal properties of the device.

## Theory and Experiment

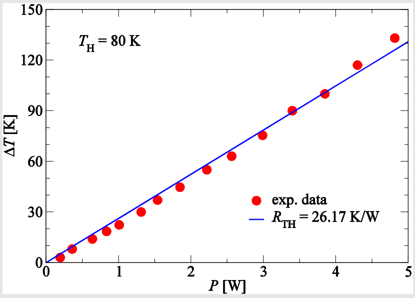


- Investigated the thermal properties of a surface-emitting THz QCL with metal-metal (MM) optical waveguide.
- Local-lattice temperature measured on top of the device active region using a microprobe band-to-band PL technique [1].
- Calibration curves obtained at 'device-off' by measuring PL while varying $T_H$.
- Comparing the shift of the main PL peak with the calibration curves allows the lattice temperature to be extracted.

$$\nabla \cdot \left[ \kappa \nabla T \right] + Q = 0$$

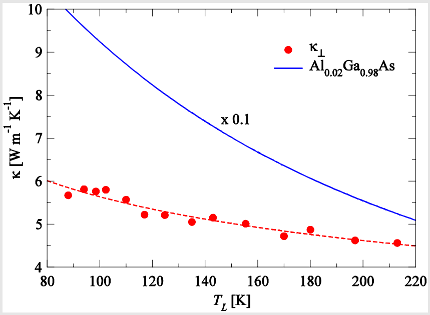
- Heat flow simulated using steady-state two- and three-dimensional anisotropic thermal models.
- Solved using a finite-difference method and successive over-relaxation technique.
- Model takes in account temperature and doping dependent thermal conductivities.

## Device Thermal Resistance



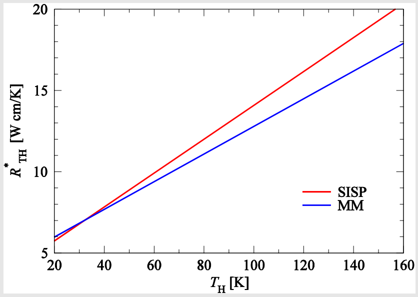
- Lattice temperature rise measured in central aperture of DFB at a heat sink temperature of $T_H$= 80 K for a range of electrical powers*.
- Linear fit to data gives rise to a thermal resistance of 26.17 K/W.
- Similar to previously extracted values of thermal resistance for edge-emitting THz QCLs with MM optical waveguides [2].

## Cross-plane Thermal Conductivity



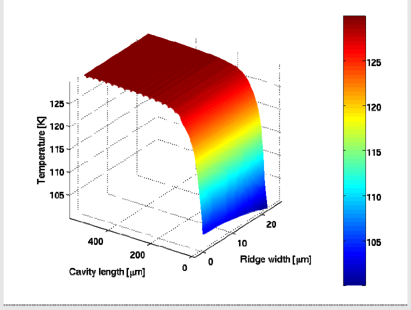
- Temperature dependent cross-plane thermal conductivity extracted by fitting simulations to measured data – $k = 21.20T^{-0.288}$ W/(m K).
- Good agreement with measured values of GaAs/AlAs superlattices [3].
- Decreasing function of temperature could be limiting factor in the temperature performance of all GaAs-based QCLs?

## Comparison of Optical Waveguides



- Normalised ($R^* = R \times S/d$) thermal resistances of MM and semi-insulating surface-plasmon (SISP) optical waveguides simulated.
- At low heat sink temperatures, SISP waveguides have smaller $R_{TH}$ due to higher thermal conductivity of the SI substrate.
- MM waveguides get progressively better at higher values of $T_H$.

## Longitudinal Temperature Distribution



- Longitudinal temperature distribution simulated at $P$ = 2.1 W.
- Insulator/metal covered facets open up longitudinal heat flow channels.
- Suggests electroplated Gold on sidewalls could improve temperature performance although this will depend on the ridge aspect ratio.

### References

[1] V. Spagnolo *et al.*, *Appl. Phys. Lett.,* vol. 15, no. 15, p. 2095, 2001.
[2] M. S. Vitiello *et al., Appl. Phys. Lett.,* vol. 86, no. 021111, p. 1, 2006.
[3] W. S. Capinski *et al., Phys. Rev. B,* vol. 59, pp. 8105-8113, 1999.

* Experimental data taken from G. Scamarcio, M. S. Vitiello, V. Spagnolo, S. Kumar, B. S. Williams, and Q. Hu, accepted for publication in *Physica E*, 2007.

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