High wall plug efficiency THz QCLs: investigation of the optical, electronic and thermal performance

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Outline

- THz Quantum Cascade Lasers (basic concepts and state of art)
- Demonstration of high power and high wall plug efficiency THz QCLs
- Real-time μ-probe photoluminescence →
  - Thermal self-calibrated approach to measure the wall-plug efficiency of QCLs
  - Local lattice temperature (facet + top)
  - Electronic temperature and electron-lattice coupling
  - Dominant role of nm-size abrupt interfaces – TBR
  - Time resolved thermal measurements
- μ-probe Raman spectroscopy →
  - **Non-equilibrium** phonon population

THz QCLs-State of art

Crucial points in the THz range:

- Laser emission at $E < E_{LO}$
- Huge free-carrier absorption $(\sim\lambda^2)$
- Non-radiative lifetimes of intersubband transitions very short

Pisa /(Cavendish)
Neuchâtel / (Neuchâtel)
MIT / Sandia
Teraview / Cavendish
TU Vienna / (Bell Labs)
NRC - Ottawa
Paris 7 / Thales
Bari / Commercial

Quantum designs

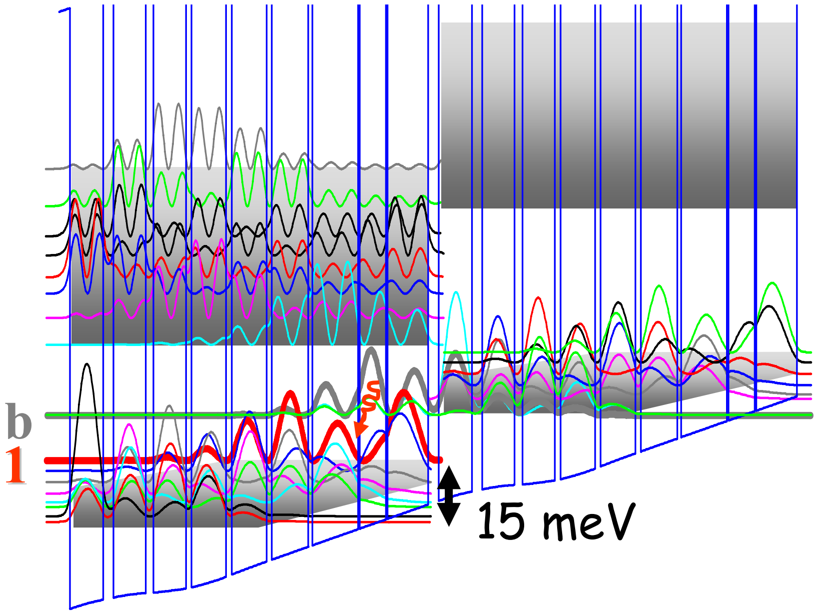
- Chirped superlattices
- Bound-to-continuum
- LO-phonon coupled QW
- Interlaced

State of art - Performance

- T_{max} = 164K (pulsed) 117K (CW)
- ν = 1.2 THz
- P_o = 245 mW @ T=4K
- $\eta_{w\ (max)} \leq 2\%$

Challenges: Increase the **maximum CW operating** temperature, the **optical power** out, the **wall-plug efficiencies**

High Power and High Wall-Plug Efficiency THz QCLs



• Slightly modified version of the bound- to-continuum design (*Barbieri et al. APL 85, 1674 2004)*

• depopulation of the lower radiative state (**1**) via miniband

• upper radiative state (**b**) localized state in the middle of the minigap.

• $E_{b1} = 11.8$ meV

More **diagonal** radiative transition and slightly reduced dipole matrix element $z_{b1} = 9.2$ nm

• **Reduced non radiative scattering** of the upper state into the miniband

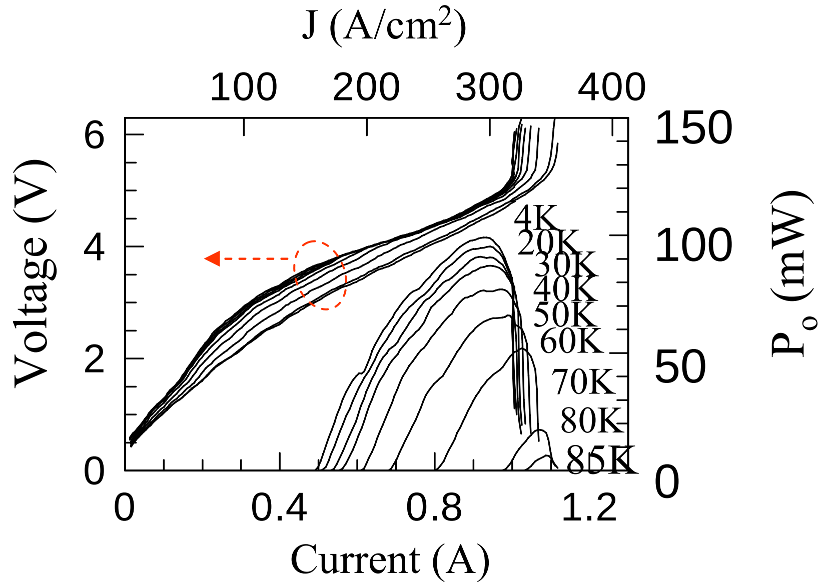
• Reduced coupling from the injector into the lower radiative state→ **improved injection efficiency** η_i

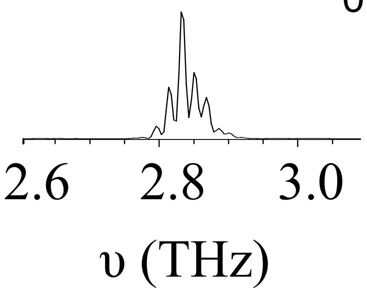
Fabrication and Optical Testing

M.S.Vitiello, G.Scamarcio, V.Spagnolo, S.Dhillon and C.Sirtori 90, 191115 (2007)

- MBE growth
  - *Commercial provider*

- Surface-plasmon optical waveguide
  - ➢ Wet etching
  - ➢ Ni/Ge/Au/Ni/Au - alloyed bottom contact
  - ➢ Ge/Au – alloyed metal stripes
  - ➢ Ni/Au – top not alloyed contact for mode confinement and backside metalization





State of art performance

- High power (~ 100 mW) - a.c.
- Slope efficiency ~ 0.4 W/A ~ 3 times improvement - a.c.
- Record wall-plug efficiency (~ 6 %)
- Differential quantum efficiency: 34 photons for injected electrons at 40 K

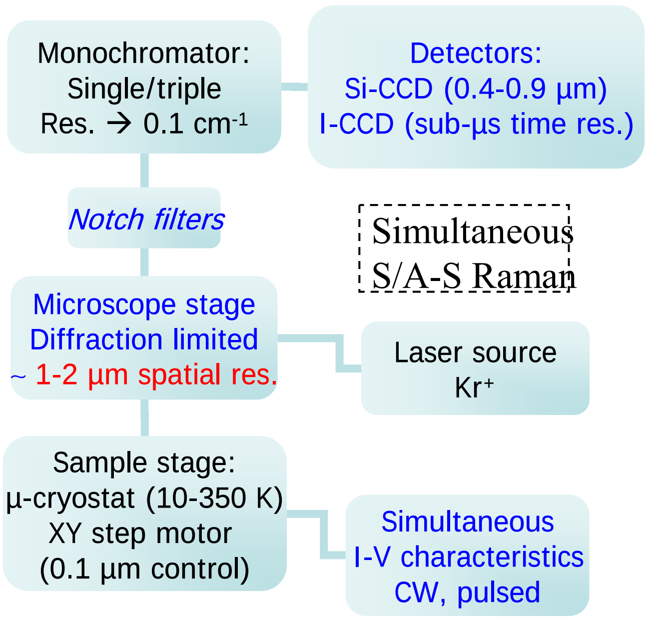
CW performance

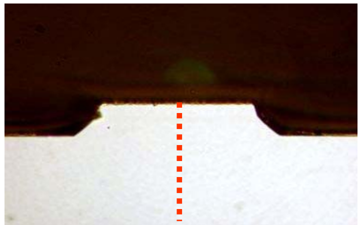
J_{th} = 215 A/cm^2 @ T_{H1}= 20K

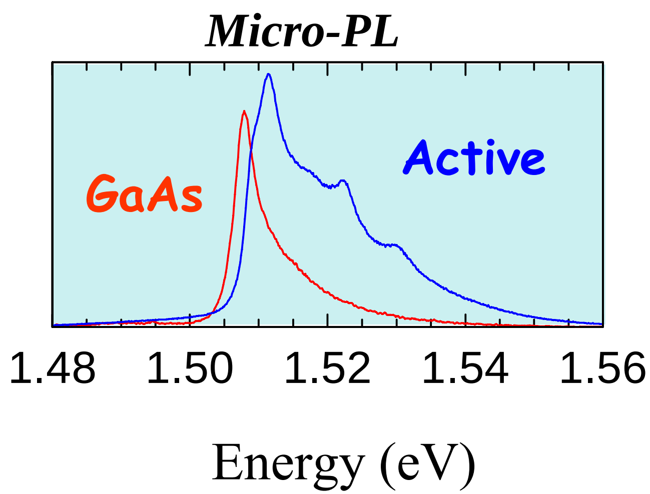
P_o ~ 24 mW @ T_{H1} =20K

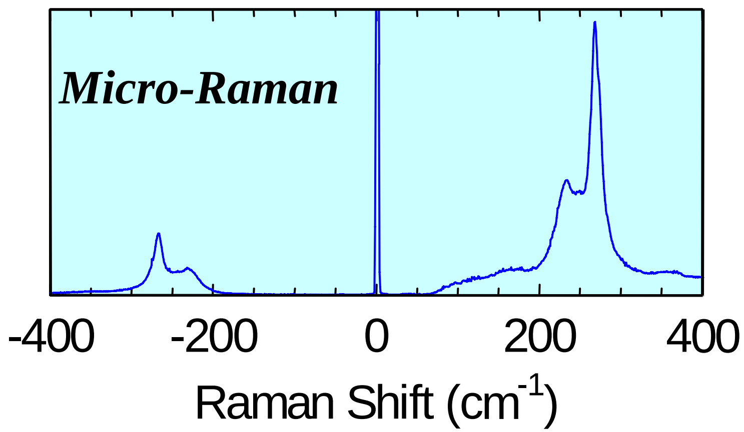
Slope efficiency ~ 0.34 W/A

µ-probe spectroscopy on operating QCLs







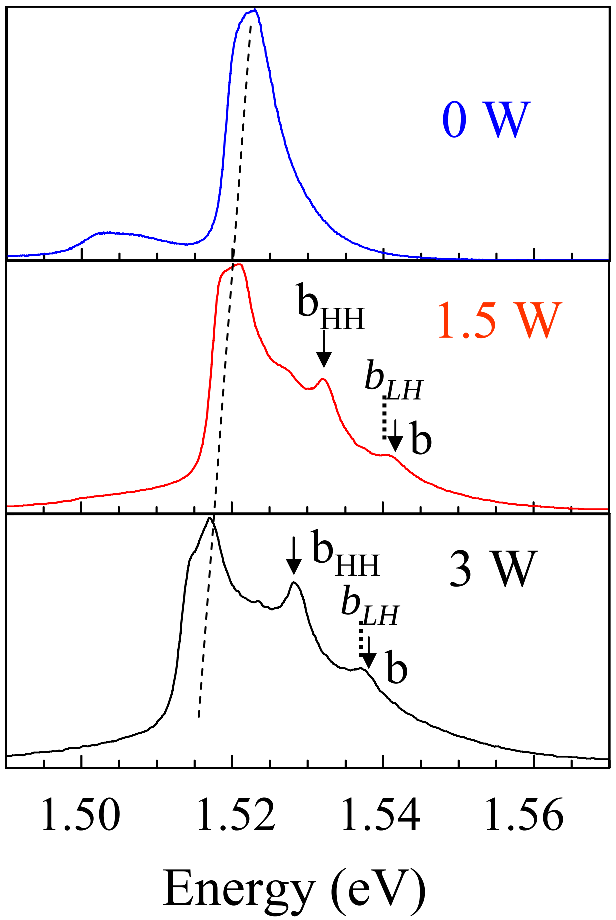


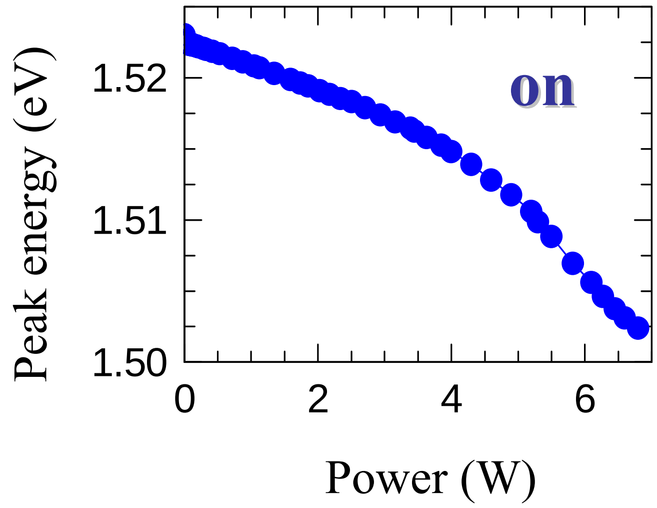
- Material/layer selectivity
- PL shift / calibration → direct thermometric property
- Thermal resistance
- Wall-plug efficiency
- Temperature mapping
- Thermal conductivity
- High-energy slope → electronic temperature → gain

- Stokes/A-Stokes → phonon population

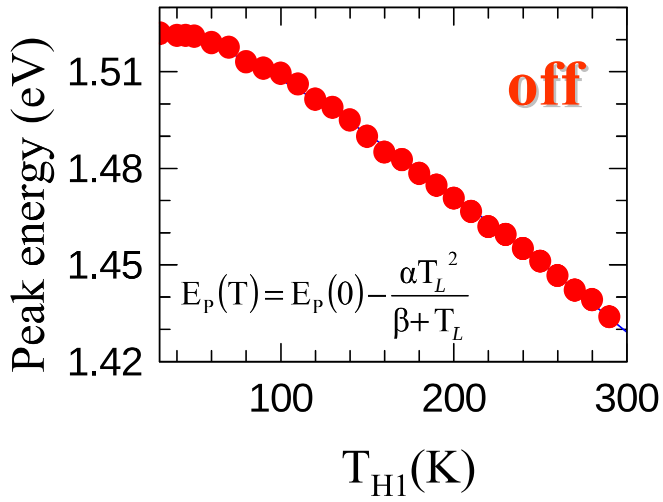
PL spectra - 2.83 THz QCLs

Lattice temperature → PL shift





Calibration curve



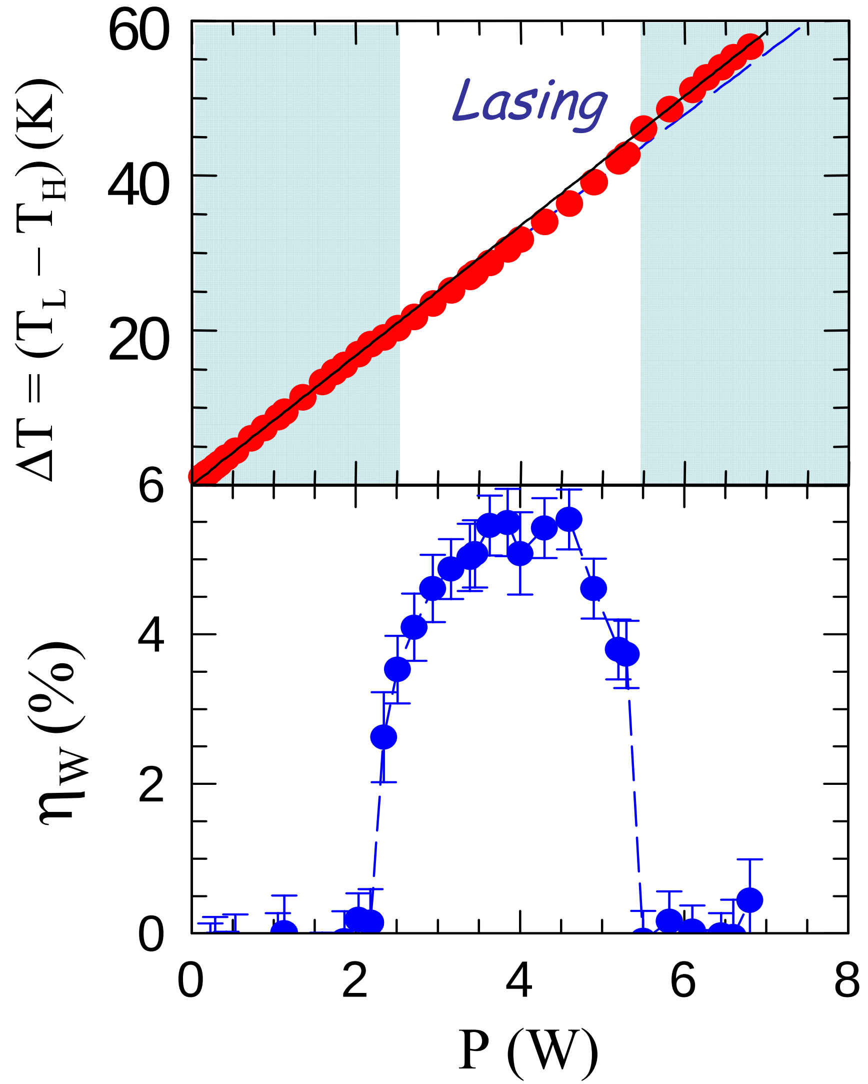
Wall-plug efficiency- Assessment issues

M.S.Vitiello, G.Scamarcio, V.Spagnolo, S.Dhillon and C.Sirtori 90, 191115 (2007)

$P_{in} = P_{optical} + P_{thermal}$; $\eta_W = P_{opt}/P$

$$\eta_w = 1 - \Delta T/(P_{in} \times R_L)$$

Thermal resistance



- Conventional optical measurements in THz QCLs affected by
  - Large beam divergence
  - small collection efficiency $\eta_c \sim 0.3$
  - detector calibration

Our self-calibrated approach

- Thermometric properties measured by μ-PL
- Deviations from the thermal resistance trend in the lasing range → $P_{thermal}$ → η_W
- η_{Wmax} **= (5.5 ± 0.4) %**

Injection Efficiency

experimental

$$\eta_w = 2\frac{dP_o}{dI}\frac{1}{V - \Delta V}\left(1 - \frac{I_{th}}{I}\right)$$

$$\frac{dP_o}{dI} = \frac{1}{2}N_P\frac{h\nu}{q_o}\frac{\alpha_m}{\alpha_m+\alpha_w}\tau$$

where

$$\tau = \eta_i\left[1-\frac{\tau_1}{\tau_2}\left(\frac{1}{\eta_i}-1\right)-\frac{\tau_1}{\tau_{21}}\right]\frac{\tau_2}{\tau_1+\tau_2[1-(\tau_1/\tau_{21})]}$$

From our data $\Rightarrow$ $\dfrac{\alpha_m}{\alpha_m+\alpha_w}\tau = 0.77 \pm 0.21$

As a a rough estimate, assuming:

- $\tau_1 \ll \tau_2, \tau_{12}$ as confimed from the discontinuity in the differential resistance
- α_w in the range 2-6 cm^{-1}
- $\alpha_m = 5.85\ cm^{-1}$

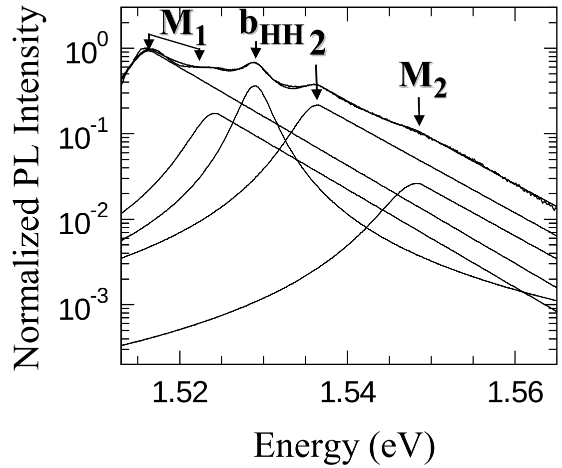
Injection efficiency $\eta_i > 0.75$

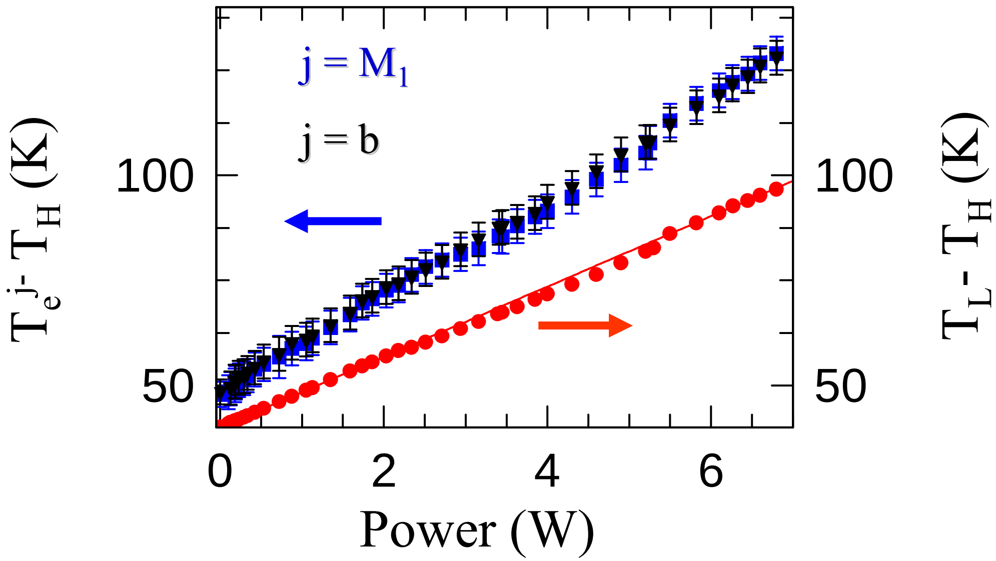
- –Internal quantum efficiency (LI)
- –Gain modeling

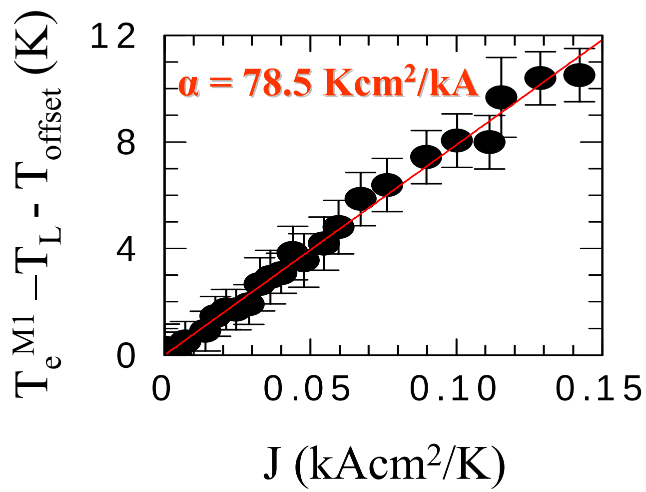
Electronic and lattice temperatures -2.83 THz QCLs

M. Vitiello, G. Scamarcio and V. Spagnolo, J. Nanophoton.,1, 013514 (2007)

- Lattice temperature → PL shift
- Electronic Temperature → high energy slope analysis
- Features of μ-PL spectra in THz QCLs
  - both ground and <u>excited</u> subbands
  - band-to-band and/or excitonic transitions







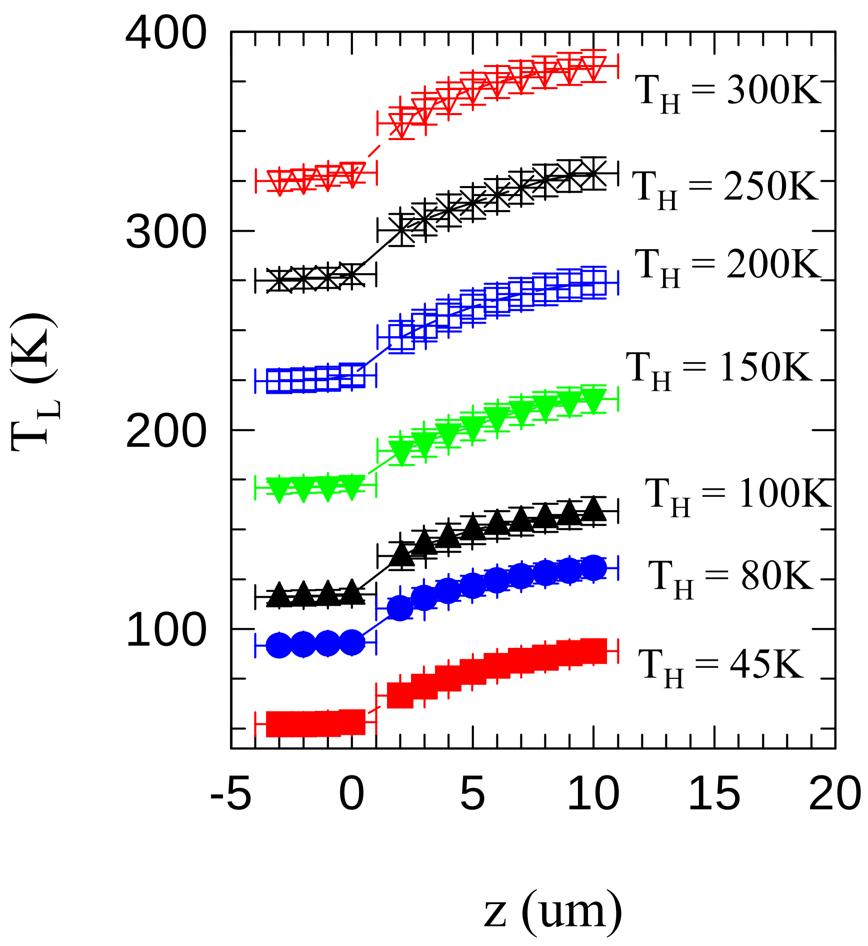
The electrons in the active region share the same T_e

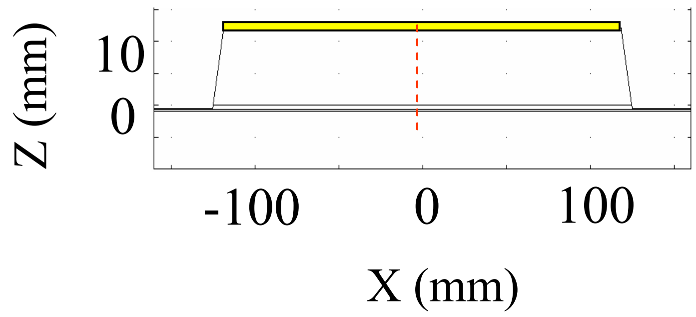
R_e = 12.0 K/W > R_L = 8.37 K/W

Most of the electrons dissipate excess energy via slow ***acoustic phonons*** assisted transitions

Cross-plane thermal conductivity in THz QCLs

M. Vitiello, G. Scamarcio and V. Spagnolo, submitted to JSTQE (2007)

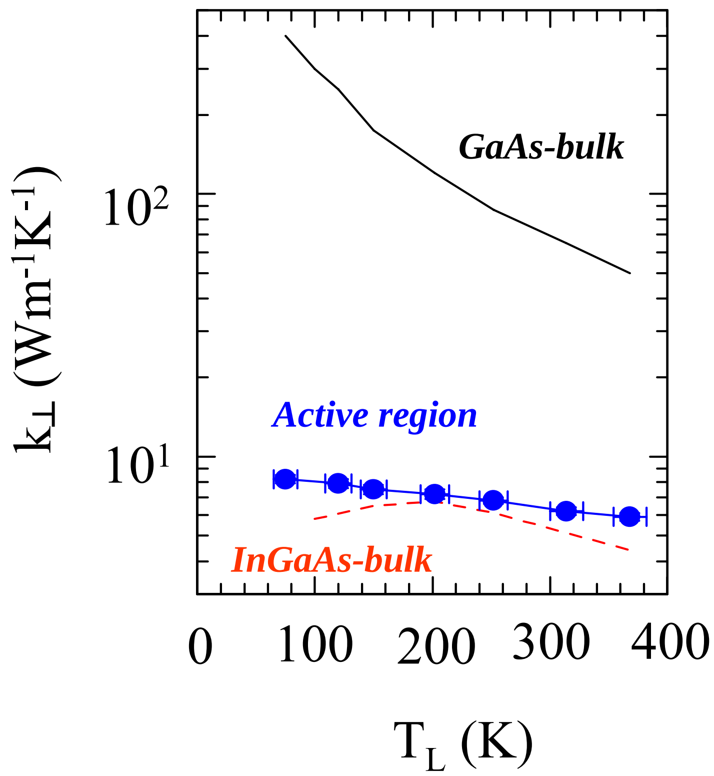




- Lack of lateral heat flow channels → T increases *monotonically* in the active
- Heat flux 100% → substrate
- $k_\perp$ extracted directly from the experimental data, taking advantage from the monotonic trend of the temperature profile and the absence of lateral heat extraction channels

$$k_\perp = \left(\frac{T_{max}(active) - T(sub)}{P} \times \frac{S}{d} \right)^{-1}$$

Bulk and Interface conductivity in THz QCLs



$k_\perp$ decreases monotonically as T is decreased

$k_\perp$ ~ one order of magnitude lower than the relevant bulk ones at comparable T

a, b: well, barrier thickness

\# interfaces

Thermal boundary or Kapitza resistance

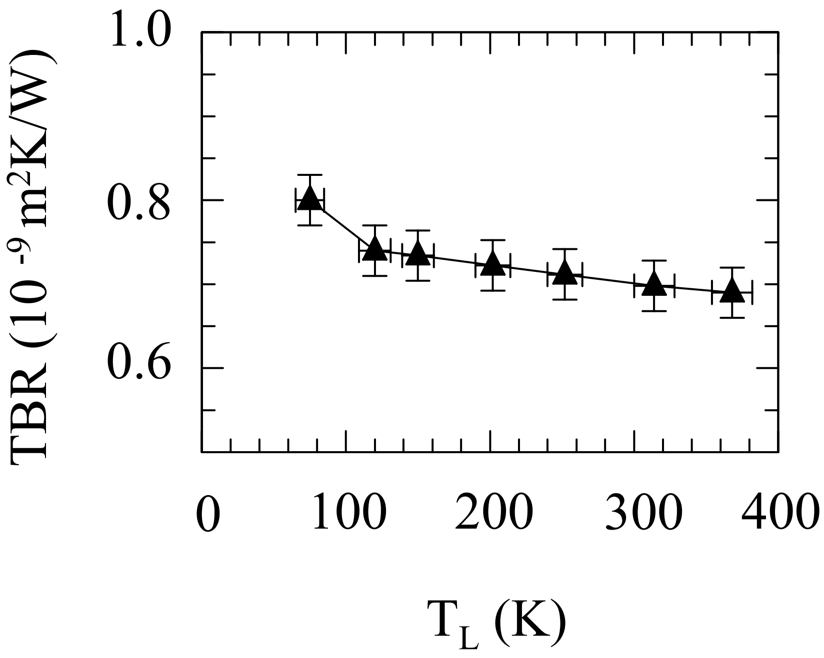
$$k_\perp^{-1} = \underbrace{\frac{a}{a+b}R_a + \frac{b}{a+b}R_b}_{\text{weigthed average of bulk resistivities}} + \underbrace{\frac{N}{a+b}TBR}_{\text{interface resistivity}}$$

- TBR arises from the mismatch in:
  - Acoustic impedances (mass density x sound velocity)
  - Phonon energy dispersion and densities of states

- If N small → interface contribution to R is negligible
- In QCLs:
  - bulk contribution never accounts for the measured values
  - **Interface thermal resistivity dominant**

Thermal boundary resistance

Comparing experimental $k_\perp$ with calculated bulk contributions → **TBR**



TBR decreases with temperature

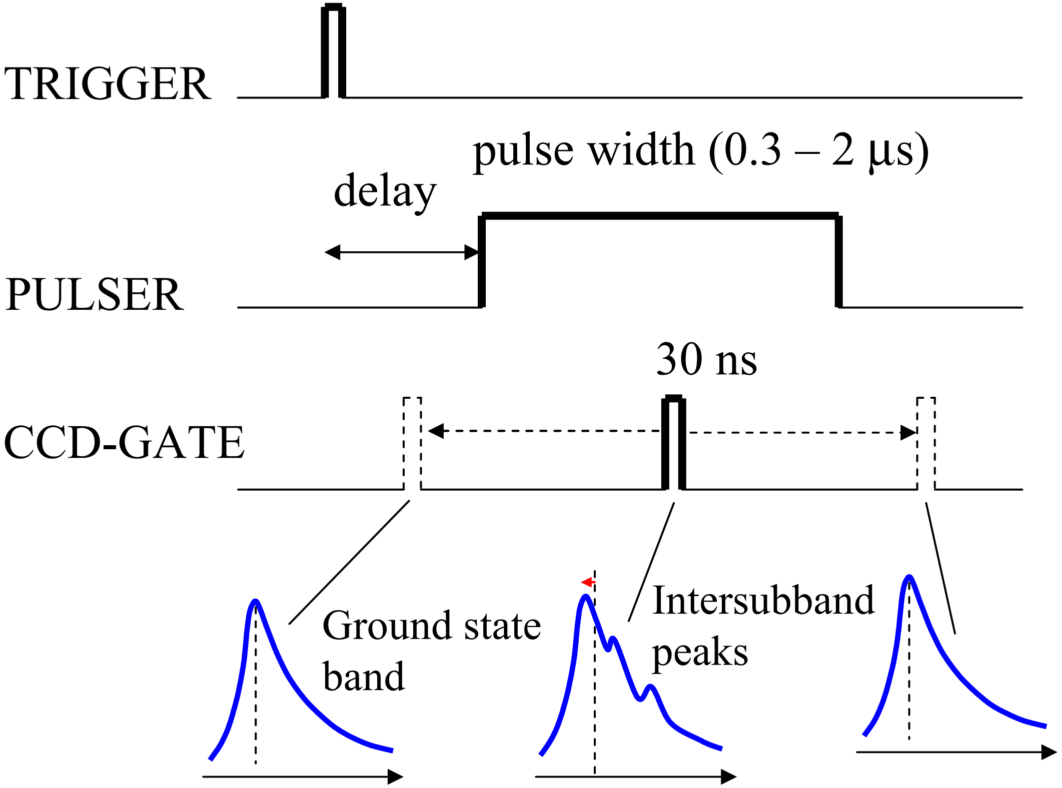
Why ?

- low T ⟶ λ phonon long ⟶ umklapp scattering frozen out and boundary scattering dominates

- T increases ⟶ λ phonon decreases and ~ size of the defects ⟶ defect scattering dominates

- high T ⟶ λ phonon shorter (larger wavevectors) ⟶ umklapp scattering dominant

Time resolved μ-PL



ADVANTAGES

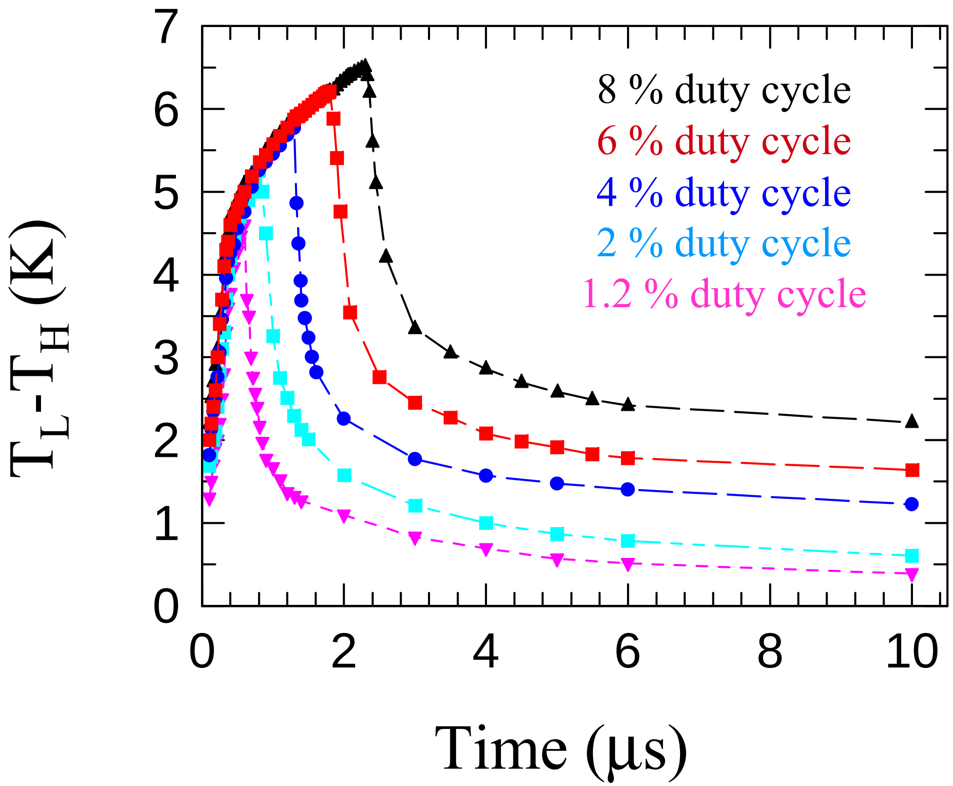
<u>Low mean power dissipated</u>

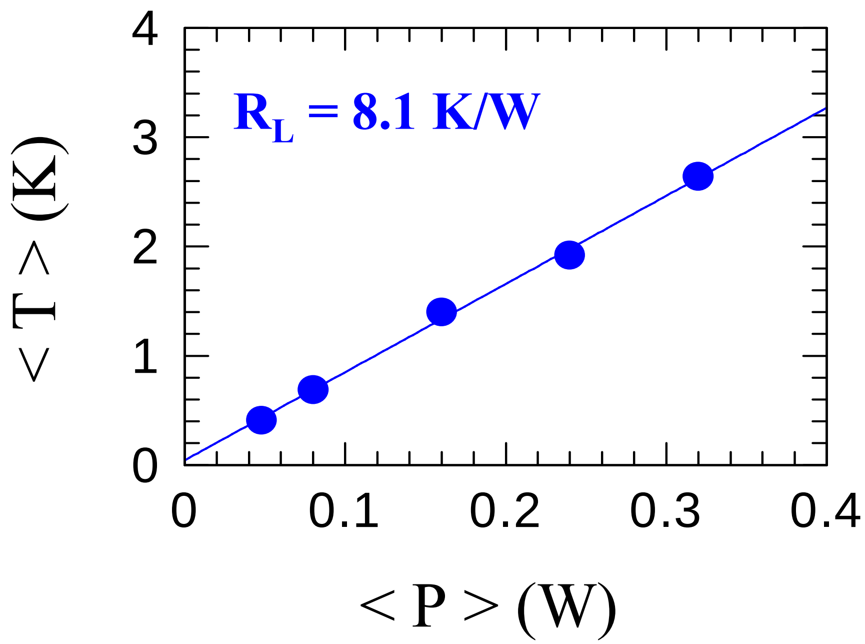
- Investigation of QCL thermal dynamics under <u>pulsed operation</u> well above laser threshold and roll-off
- QCL dynamics at very high operating temperatures

OUTCOME

Heat diffusion dynamics

Thermal dynamics under pulsed operation @ T = 80K



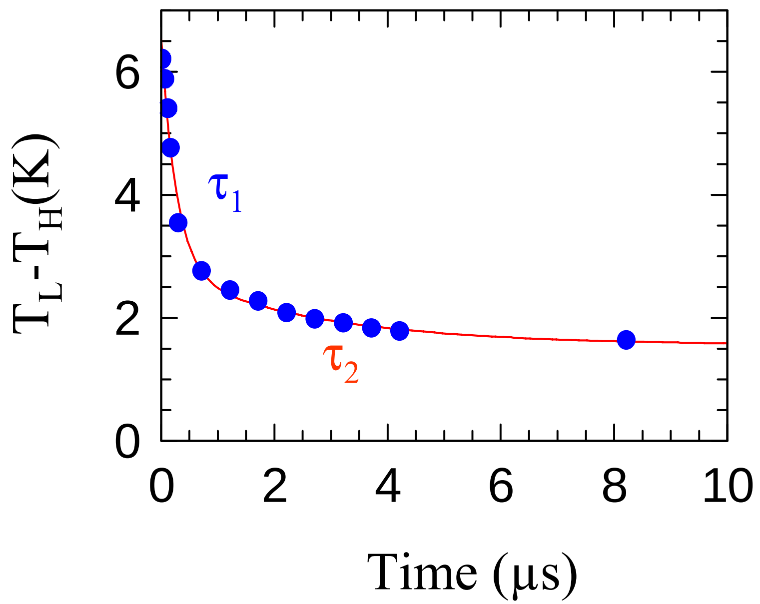


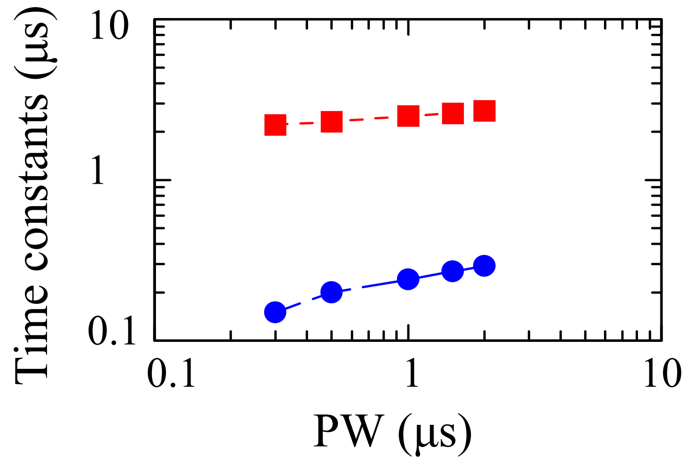
$< T > = T_{max} \times \text{duty} + T_{off} \times (1\text{-duty})$

$< P > = P \times \text{duty}$

Post-pulse temperature decay

Duty cycle	PF (kHz)	PW (μs)	τ_1 (μs)	τ_2 (μs)
1.2%	40	0.3	0.15	2.2
2%	40	0.5	0.23	2.3
4%	40	1	0.24	2.5
6%	40	1.5	0.27	2.6
8%	40	2	0.33	2.7



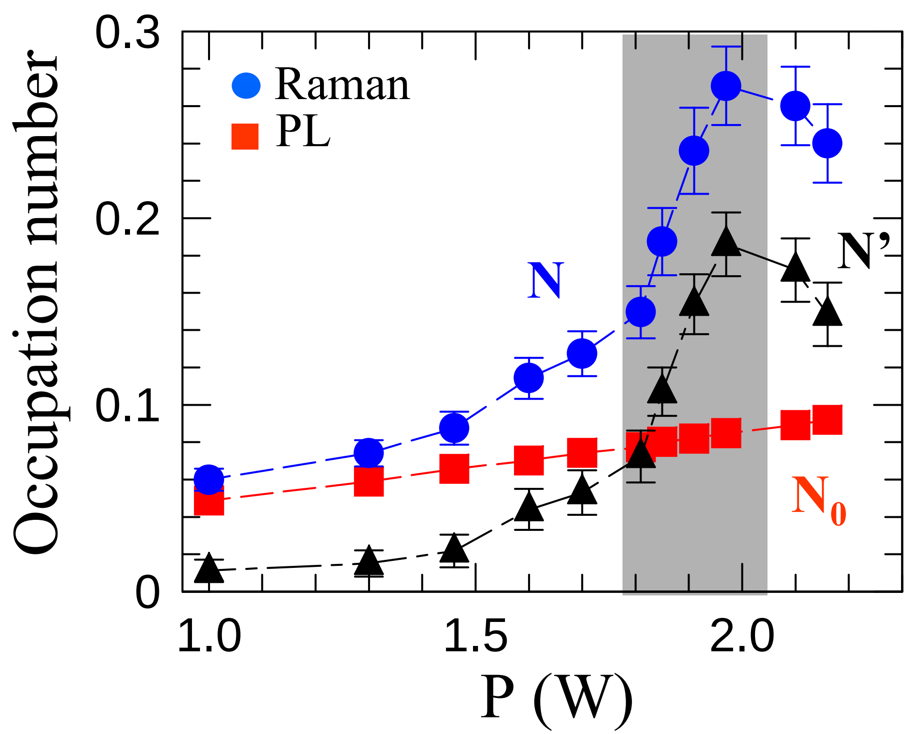


- Bi-exponential decay
  [Evans, Indjin, Harrison, Ikonic et al., 2006]
- Short time constant τ_1 → Heat extraction from the active region
- Long time constant τ_2 → Heat extraction from the substrate

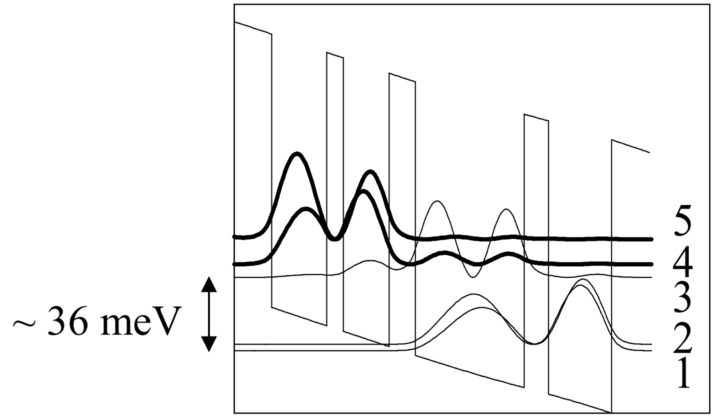
PW increases → τ_1, τ_2 increase due to the temperature dependence of the thermal conductivity

Hot-phonons in resonant-phonon THz QCLs

G. Scamarcio, M. Vitiello, V. Spagnolo, S. Kumar, B. Williams and Q. Hu, Physica E, in press (2007)



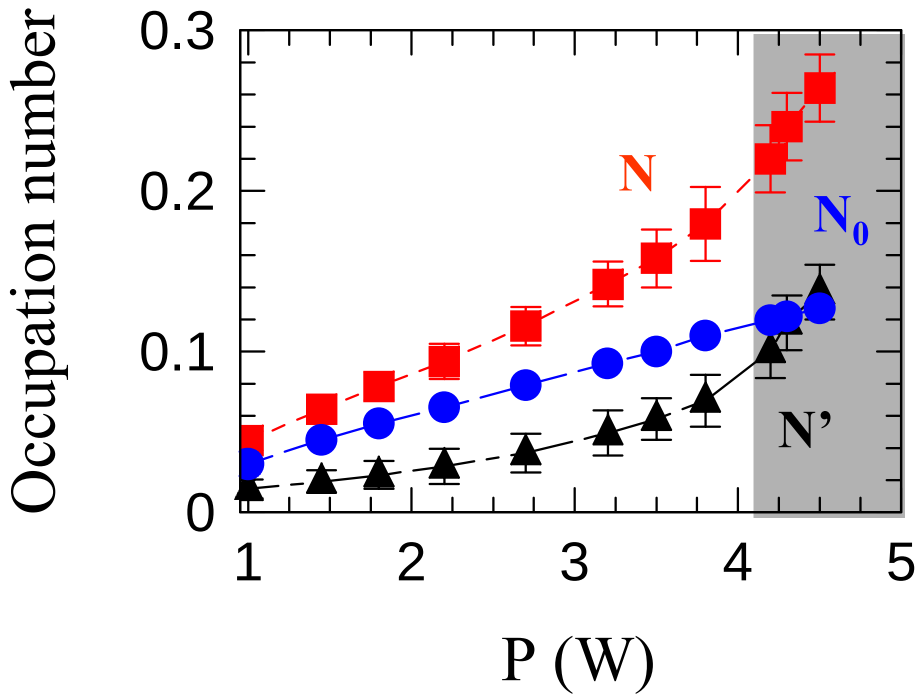
GaAs-IF_{TO} phonons

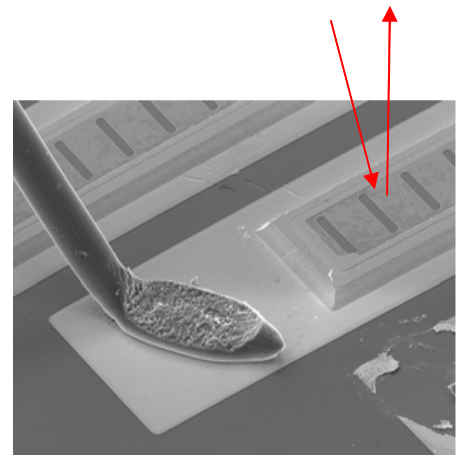


- THz QCLs allow to study all regimes below and above laser threshold
- Superlinear increase of hot phonon population (N'= N-N_0) with power → *stimulated emission of phonons (?)*

What about LO phonons ?

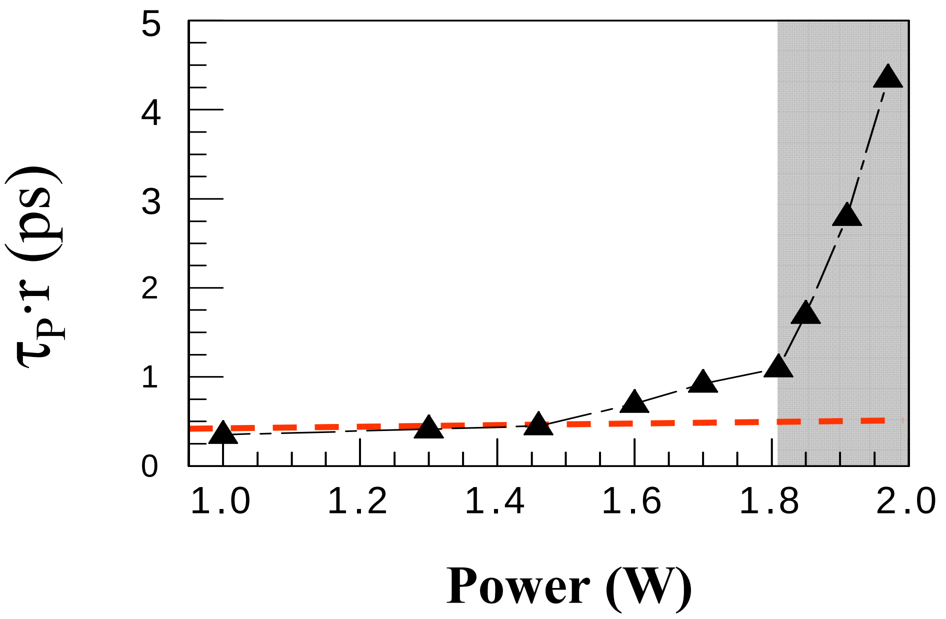
G. Scamarcio, M. Vitiello, V. Spagnolo, S. Kumar, B. Williams and Q. Hu, Physica E, in press (2007)

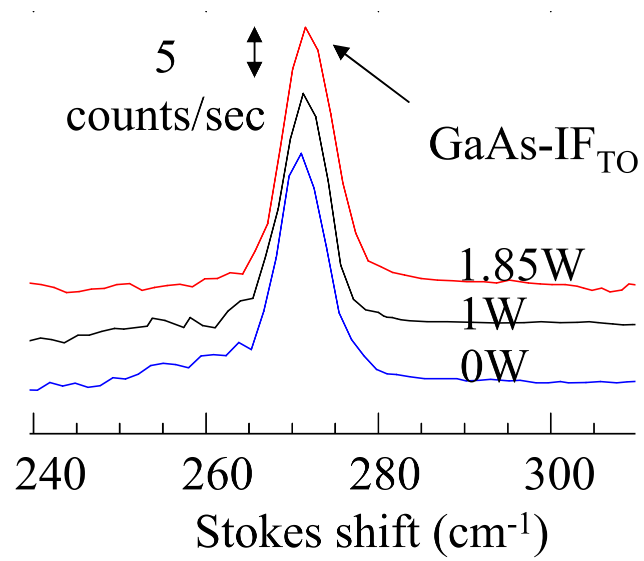


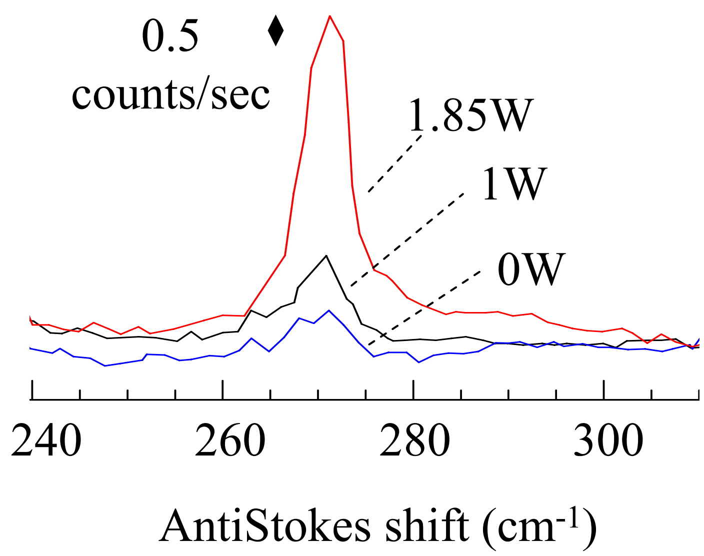


- Raman selection rules requires backscattering from the top facet
- Poorer device efficiency and higher laser threshold does not allow to study above lasing regime

Phonon lifetime and relaxation rate







Rate equation arguments →

$$\tau_p \cdot r = \frac{n_{hot}}{P} \cdot \frac{\hbar\omega}{6\pi^2} Ad \cdot \left[k^3_{Max} - k^3_{Min}\right]$$

- $\tau_p \cdot r$ ~ const if n_{hot} were proportional to P
- Phonon lifetime (τ_P) decreases with T_L→
  in our case phonon relax. rate (r) increases (!)
- Characteristics of *phonon stimulated emission*
- However, *no line narrowing observed (?!?)*

Summary

- Demonstration of **high power** and **high wall-plug efficiency ($\eta_w = 5.5\%$)** bound-to-continuum 2.83 THz QCLs
- Development of a new self calibrated experimental approach to measure the total **wall-plug efficiency** of THz QCLs: estimation of the **injection efficiency**
- μ-probe optical spectroscopy in THz quantum cascade lasers
  - Temperature dependence of the cross-plane thermal conductivity
  - Influence of thermal boundary resistance
  - Time-resolved thermal measurements
  - Non-equilibrium phonon generation

Running:

- Include knowledge on microscopic thermal properties in the design of active regions showing low TBR
- Stimulated emission of phonons