Thermal and electronic analysis of GaInAs/AlInAs mid-IR QCLs

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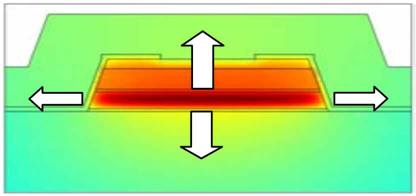
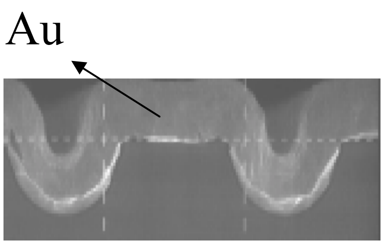
Motivation

- > 10 years progress in the quantum design of *active regions* → high performance QCLs (CW, RT, single mode, high power, at selected mid-IR λ's)
- Real-world applications wants improved performance:
  - e.g. ppb/ppt QCL-based sensor systems compact/portable, affordable, battery-operated, …
- "Typical" QCLs have:
  - Large electrical power (~ 10 W)
  - Low wall-plug efficiencies at room temperature (single-digit %)
- **Heat** generated in the active not efficiently extracted from the device
  - Physical limits → (thermal boundary resistance) (# interfaces)

RT CW mid-IR QCLs fabrication technologies

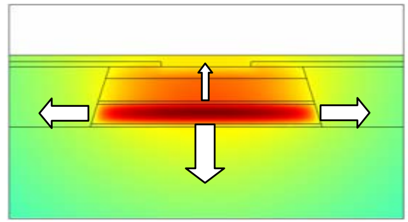
Electroplated *QCLs*





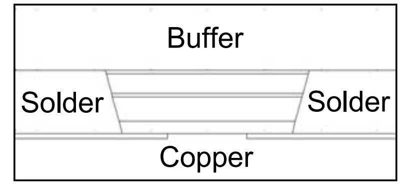
- Heat extraction in all in-plane directions
- Au top contact layer width > 4 μm

InP-buried *QCLs*



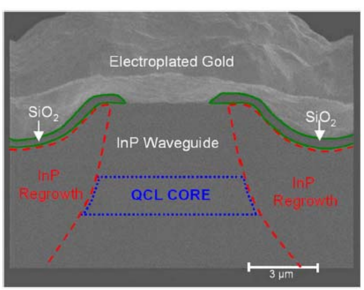
- Lateral heat extraction enhanced
- Require additional growing steps
- May suffer from current leakage

Epilayer-down QCLs



- Better coupling w/ heat sink
- High quality wafer bonding required

State-of-art *[Evans, Slivken, Razeghi et al. APL, Aug.2007]*



Narrow-ridge buried heterostructure waveguides + Electroplating + Thermally optimized packaging

9.3% wall-plug efficiency at RT at 4.7 μm (!)

Outline

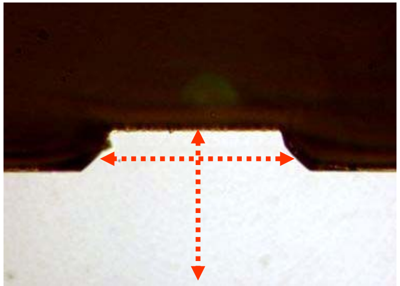
- Review on thermal properties of mid-IR QCLs
  - focus on devices operating in the 3-5 µm window
  - GaInAs/AlInAs
  - GaInAs/AlGaAsSb

- Strategies to improve thermal performance of mid-IR QCLs
  - InAs/InGaAs AlAs/AlInAs smoothed interfaces
  - Improved processing using high-k dielectrics

- Assessment of the electronic and thermal properties of mid-IR QCLs via µ-probe photoluminescence
  - Electron lattice coupling vs conduction band offset
  - Thermal boundary resistance

Experimental approach

- Photoluminescence spectroscopy on the laser *front facets*



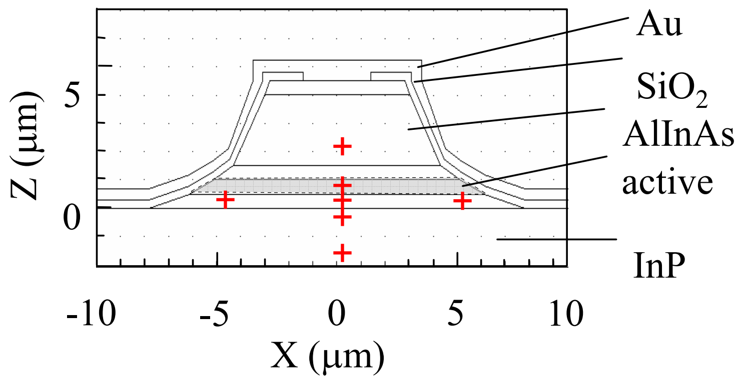
- Exploit
  - *µ-probe* spatial resolution (diffraction limit)
  - No hot-spots or surface e-h recombination (unipolarity)

- Photoluminescence analysis
  - local *lattice and electronic temperatures*

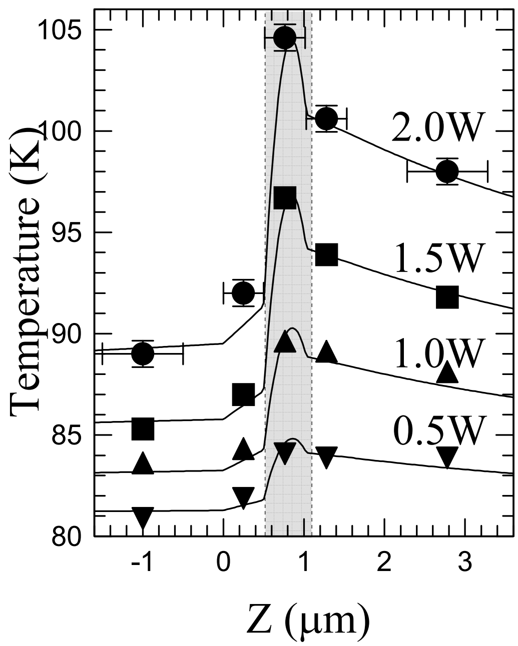
- Facet temperatures close to bulk temperature in QCLs

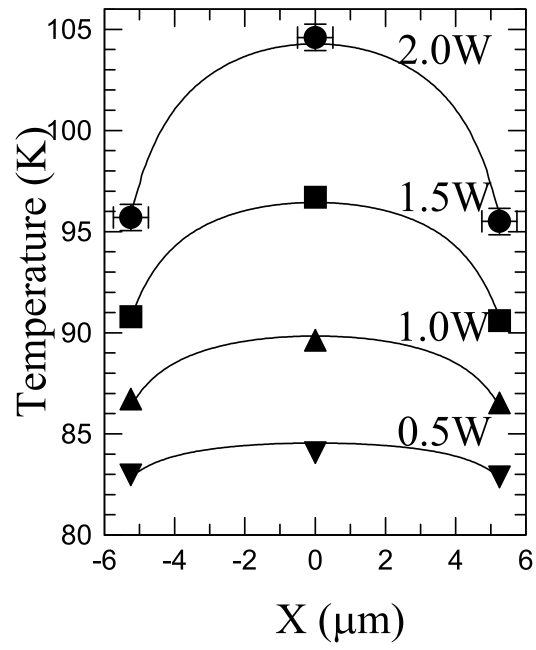
Anisotropic thermal conductivity
2D thermal modeling

[Lops, Spagnolo, Scamarcio, JAP 2006]



GaInAs/AlInAs mid-ir QCLs @ 8.1 μm



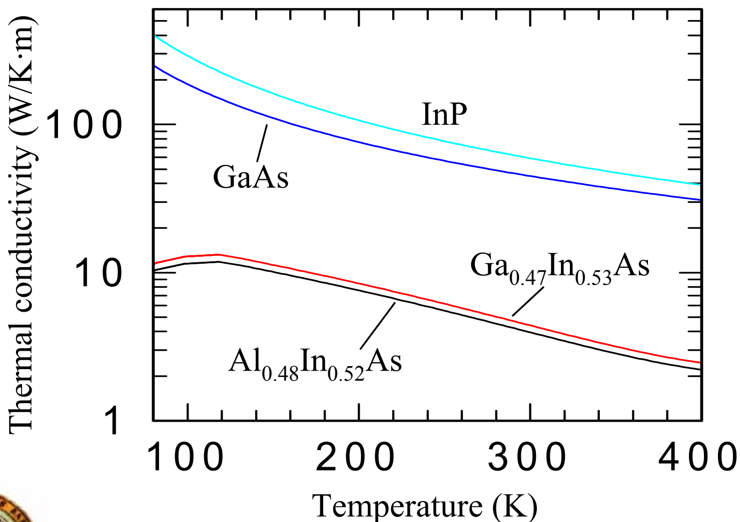


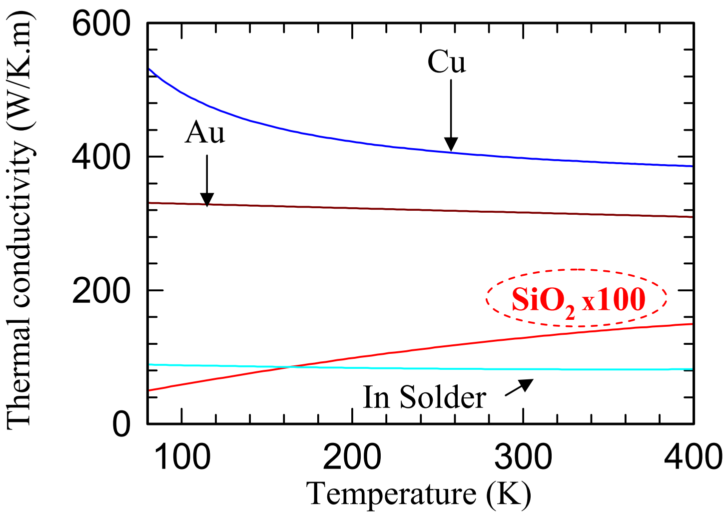
- $T_L > T_H$; Temperature overshoot in the active region → $k_\perp$
- ΔT across the active → different heat fluxes towards AlInAs cladding and InP substrate
- Modeling → $k_\perp$ = 0.6 W/K m ***one order of magnitude smaller than bulk (!?!?!)***
- $k_{//}$ → bulk

Thermal conductivity extraction

$$-\nabla \cdot (k \nabla T) = Q$$

- 2D-heat transport eq. solved and fitted to the exp data
- Boundary conds.: $T=T_H$; no heat escapes through the sides or top of the laser
- Known conductivities for all bulk-like layers considered
- Temperature influence and doping influence included
- Only fitting parameters: $k_{\perp}$ and $k_{//}$ in the active region





Thermal resistivity in heterostructures

a, b: well, barrier thickness

interfaces

$$R = \frac{a}{a+b}R_a + \frac{b}{a+b}R_b + \frac{N}{a+b}TBR$$

Thermal boundary or Kapitza resistance

weigthed average of bulk resistivities

interface thermal resistivity

- If N small → interface contribution to R is negligible
- Our experiments in THz and mid-IR QCLs:
  - *bulk contribution never accounts for the measured values*
  - Interface thermal resistivity dominant
- Comparing experimental R with calculated bulk contributions → TBR

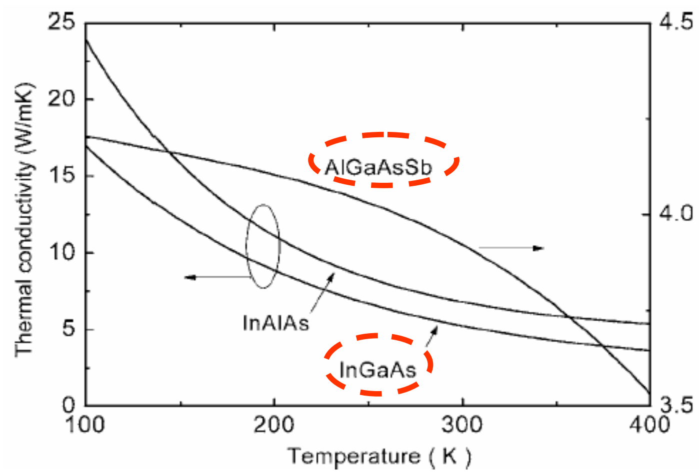
Can we improve the thermal conductivity of mid-IR QCLs ?

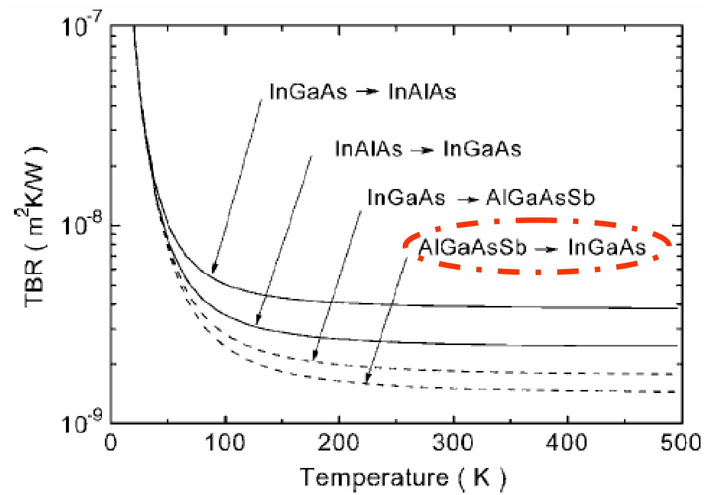
- Design active regions with reduced TBR
  - material choice
  - reduce interface sharpness
- Improve device fabrication
  - use of high-*k* dielectrics

Influence of material:

the case of InGaAs/AlGaAsSb active regions

[calculations by C. Zhu et al. JAP (2006)]



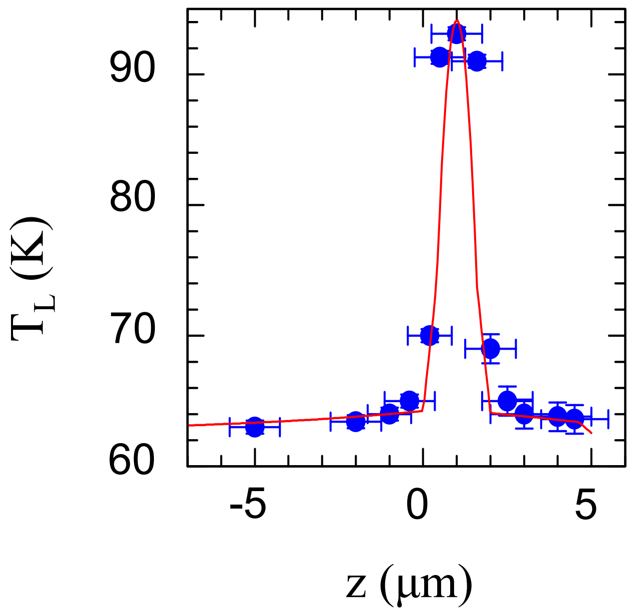


- K (AlGaAsSb) ≅ ¼ K(InGaAs), K(InAlAs)

  however
- Better matching of phonon properties in InGaAs/AlGaAsSb
  - phonon dispersion; acoustic impedance (mass density x sound velocity); phonon DOS; Debye temperature
- → TBR (InGaAs/AlGaAsSb) < TBR (InGaAs/AlInAs)

InGaAs/AlGaAsSb QCLs

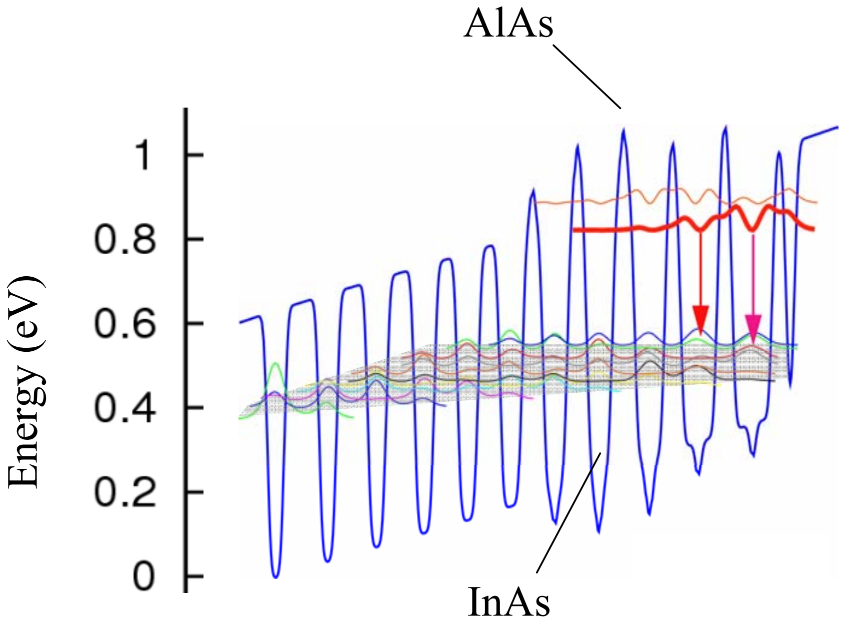
[Vitiello, Scamarcio, Spagnolo, Yang, Wagner et al. APL, 2007]



- Emission wavelength $\lambda = 4.9\ \mu m$
- # interfaces = 550
- $k_\perp = 1.8$ W/K·m
- Interface contribution to thermal resistivity = 63 %
- TBR = 0.75×10^{-9} K/W·m^2
  - Comparable with GaAs/AlGaAs
  - ~ 5 times better than GaInAs/AlInAs

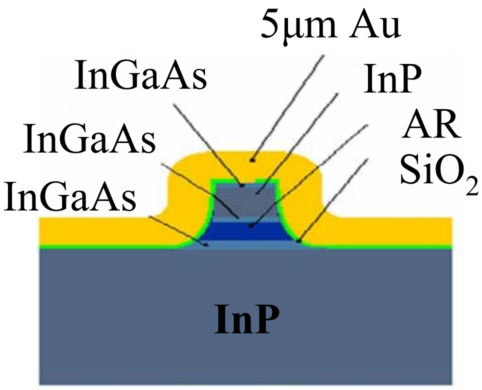
Influence of interface structure

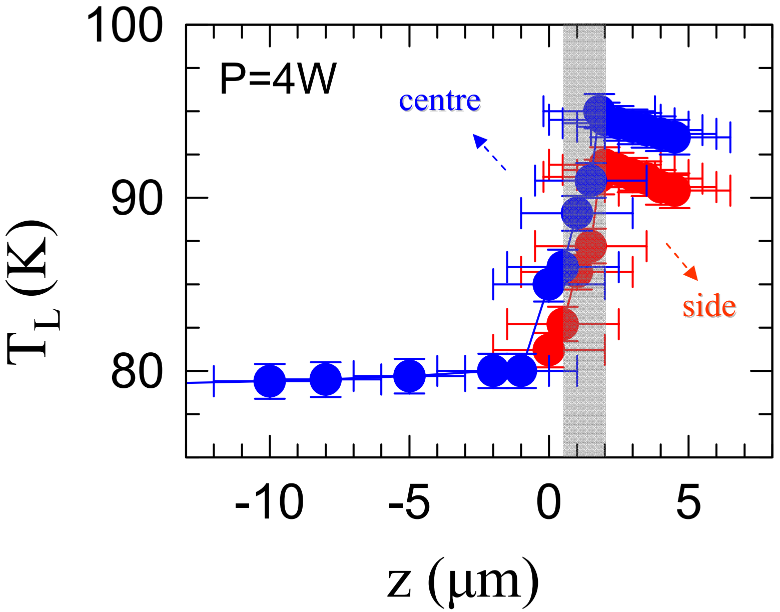
[Vitiello, Gresch, Spagnolo, Scamarcio,Faist et al. , submitted APL, 2007]



- strained $In_{0.61}Ga_{0.39}As/In_{0.45}Al_{0.55}As$ QCLs
- InAs or AlAs δ-layers (0.2 nm) to increase the conduction band discontinuity in the active layers
- 1ML broadening at IFs included in the design
- Emission wavelength λ= 4.78 μm
- Peak optical power: 0.55 W @ 323K; T_{MAX}(CW) = 243 K

Temperature mapping





- $k_{\perp}$ = 2.0 W/K·m
- # interfaces = 600 / 1325
- TBR = 0.5 – 1.1 x 10^{-9} K/W·m^2
  – Comparable with GaAs/AlGaAs

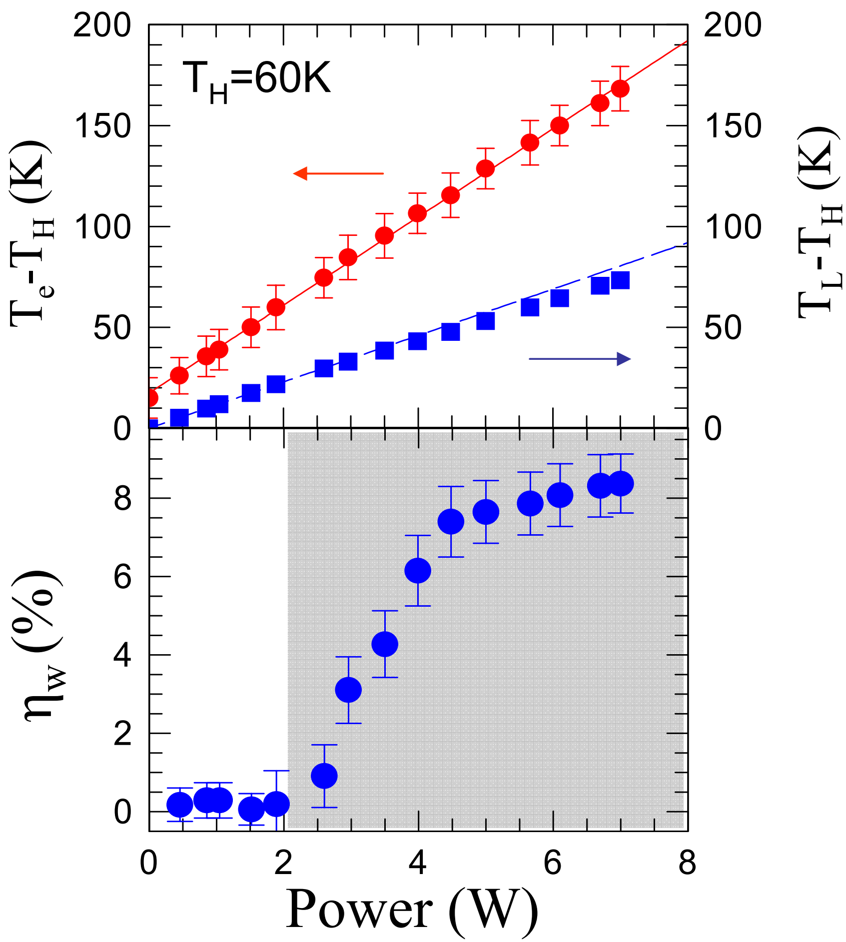
Mid-ir InGaAs-based and GaAs-based QCLs

QCL active region	λ (μm)	T_H(K)	$k_\perp$ (W/(K × m))	TBR (10^{-9}K/W×m^2)
InGaAs/AlInAs	8	80	0.6	4.4
InGaAs/InGaAsSb Epilayer down	4.9	60	1.8	0.75
InGaAs/InGaAsSb Epilayer up	4.9	60	1.8	0.75
InGaAs/AlInAs InAs, AlAs δ-layers	4.8	60	2	0.5 – 1.1
$GaAs/Al_{0.33}Ga_{0.67}As$	9.4	90	5.5	0.48

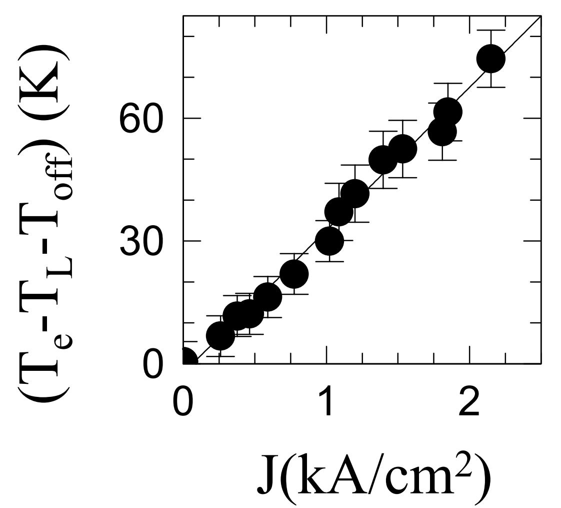
- Developing new design strategies of QCLs including *smoothed interfaces* and/or *phonon matched* materials will pay off
  - TBR reduction
  - improved thermal management

Electronic properties / wall plug efficiency

[strained $In_{0.61}Ga_{0.39}As/In_{0.45}Al_{0.55}As$ QCLs + InAs, AlAs δ-layers]



α = 34.3 Kcm^2/kA



- $R_E = T_E / P$ = 22.0 K/W
- $R_L = T_L / P$ = 11.5 K/W

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

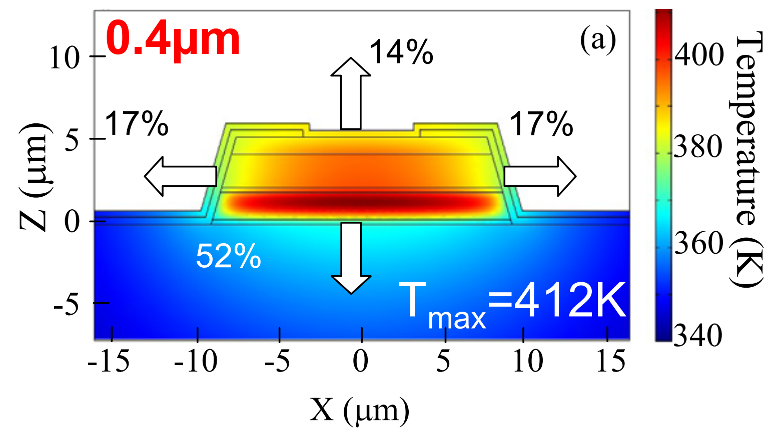
- η_{Wmax} = (8.4 ± 0.7) %

Electron-lattice coupling

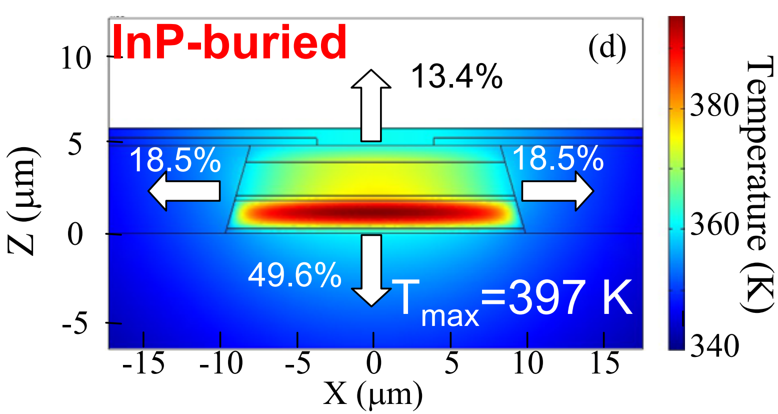
Heterostructure	λ (μm)	ΔE_C (eV)	**α (Kcm²/kA)**
$GaAs/Al_{0.45}Ga_{0.55}As$	12.6	0.39	44.7
GaAs/AlAs	11.8	1	29.0
$Ga_{0.47}In_{0.53}As/Al_{0.62}Ga_{0.38}As_{1-x}Sb_x$ epilayer-side	4.9	1.2	10.4
$Ga_{0.47}In_{0.53}As/Al_{0.62}Ga_{0.38}As_{1-x}Sb_x$ substrate side	4.9	1.2	10.8
InGaAs/AlInAs InAs, AlAs δ-layers	4.8	0.62-0.95	34.3

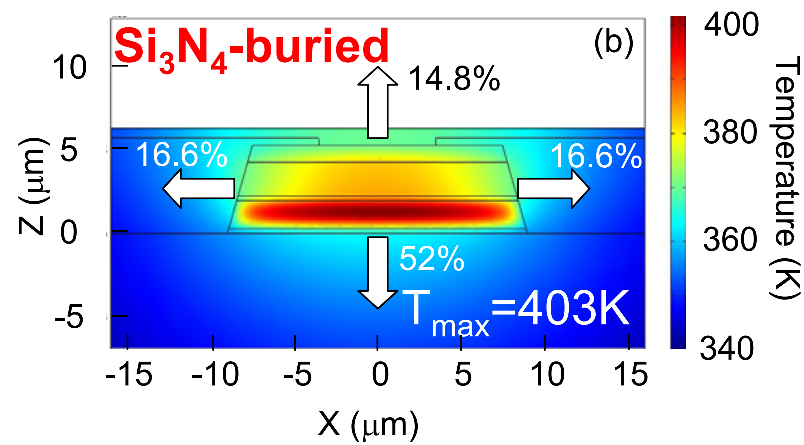
- Comparable active region mean doping in the range 1.5-4.5 cm^{-3}
- The electron-lattice coupling increases with the conduction band offset

Planarization w/dielectrics

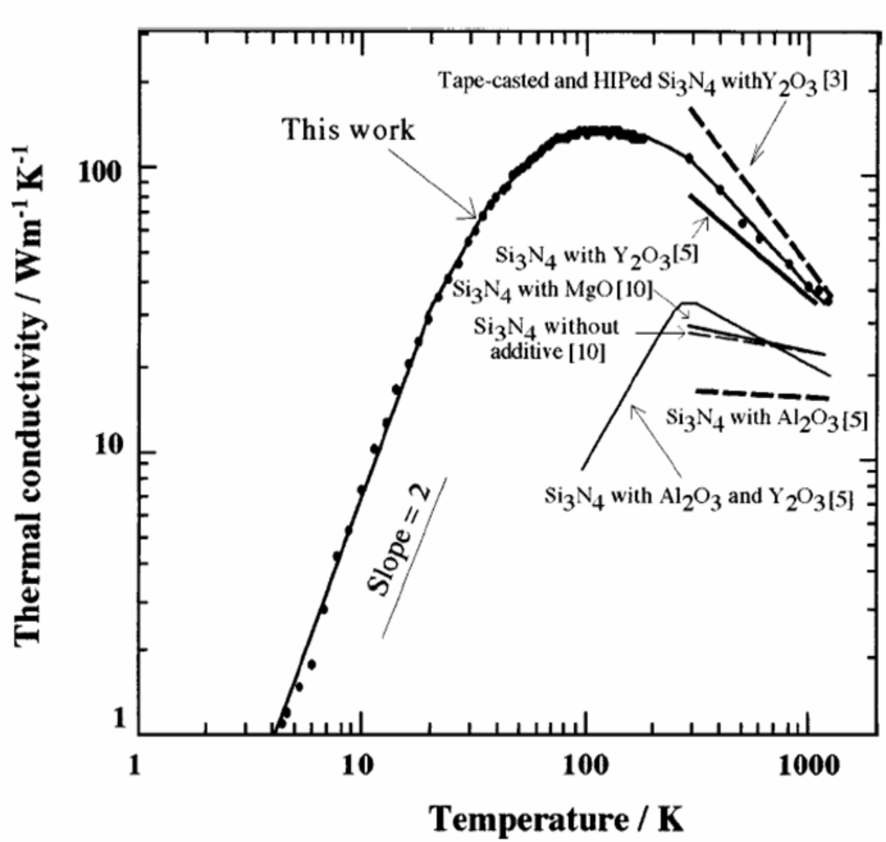


- Core structure as in Yu, Razeghi et al., APL (2003), T_H=298 K, P=7W
- Thermal performance comparable with InP-buried devices





Thermal conductivity of Si_3N_4:Y_2O_3



InP (300K)

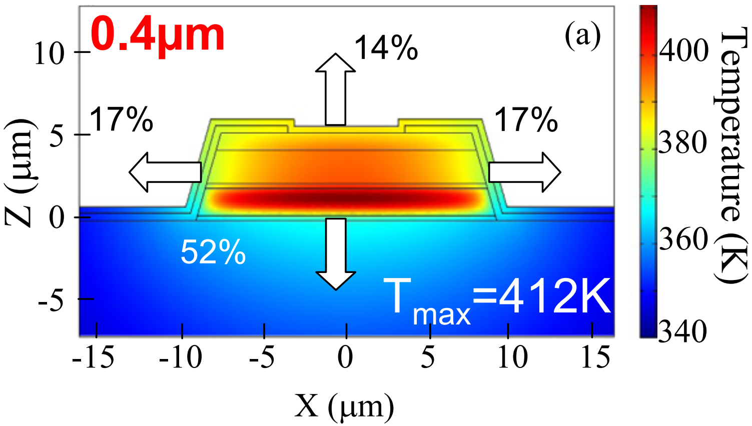
Si_3N_4 (300K)

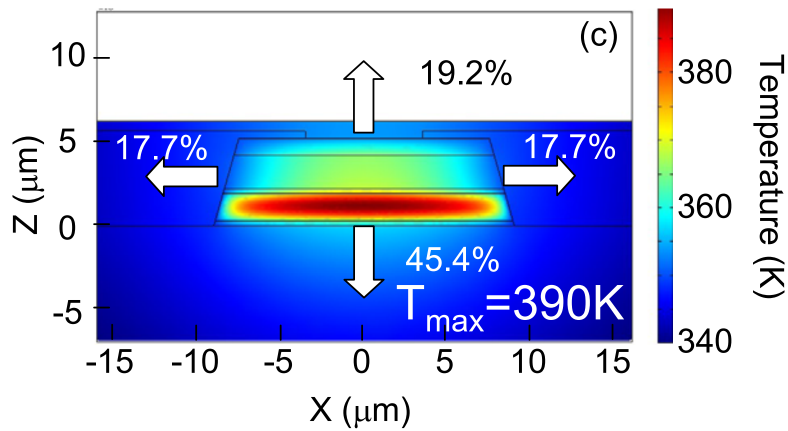
SiO_2 (300K)

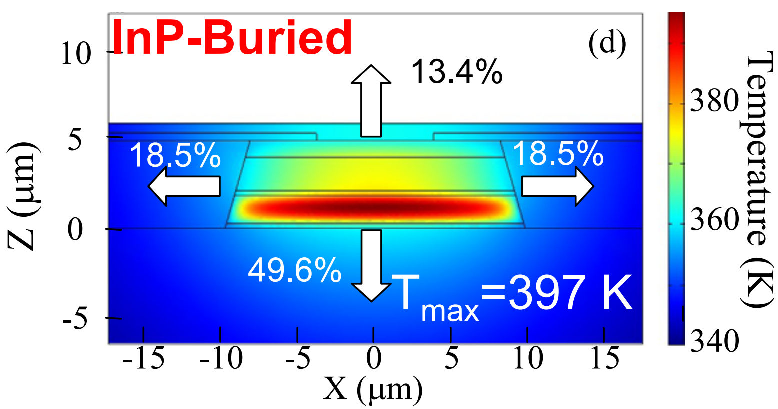
[K. Watari et al. JMS Lett. (1999)]

Planarization of QCLs using $Y_2O_3:Si_3N_4$

[Spagnolo, Lops, Scamarcio, Vitiello, Di Franco, submitted JAP, 2007]







- Improved thermal management
- No lateral current leakage
- Significant reduction in the device thermal resistance

Thermal resistance $R_L=(T_{max}-T_H)/P$

Mounting and processing configuration	Top contact thickness	Insulating material	Planarizing material	R_L (K/W)
“Conventional” Ridge waveguide	0.4 µm	SiO_2	----	17.9
“Conventional” Ridge waveguide	0.4 µm	Si_3N_4	----	16.3
InP-Buried	0.4 µm	Si_3N_4	---	14.1
Au Electroplated	5 µm	SiO_2	---	**13.5**
Planarization	0.4µm	SiO_2	SiO_2	18.4
Planarization	0.4µm	Si_3N_4	Si_3N_4	15.0
Planarization	0.4µm	Si_3N_4	Y_2O_3: Si_3N_4	**13.1**
Planarization + Au Electroplated	5 µm	Si_3N_4	Y_2O_3: Si_3N_4	**11.8**

- Planarization with suitable dielectrics:
  - Thermal performance comparable with conventional buried or electroplated structures
  - 13% reduction of R_L with respect to reference device [Yu, Razeghi et al. APL 83]

Summary

- Comparison of the electronic and thermal properties of mid-IR QCLs via μ-probe PL

- Strategies for the improvement of the thermal performance of mid-IR QCLs operating in the 3-5 μm range:
  - Reduction of the thermal boundary resistance
    - InGaAs/AlGaAsSb
    - InGaAs/AlInAs + (AlAs, InAs) δ-layers
  - Planarization using high-k dielectrics

- *running*:
  - Simultaneous thermal and electrical modeling
  - Design of QCLs w/improved thermal performance