AMELIORATION DES PERFORMANCES DES LASERS A CASCADE QUANTIQUE - ETUDE DU CONFINEMENT OPTIQUE ET DES PROPRIETES THERMIQUES

Jean-Yves Bengloan

Amélioration des performances des Lasers à Cascade Quantique : Étude du confinement optique et des propriétés thermiques

J-Y Bengloan

Thèse de doctorat de l'Université de Paris XI – Sud (Orsay)

Thèse effectuée à Thales Research & Technology (TRT)

à l'Université de Paris VII

Performance optimisation of Quantum Cascade Lasers:
Investigation of the optical confinement and thermal properties

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PLAN

1. Introduction

2. Waveguide Optimisation in GaAs/AlGaAs QCLs

GaAs based guides (plasmon enhanced) / Limitations
AlGaAs and GaInP Guides

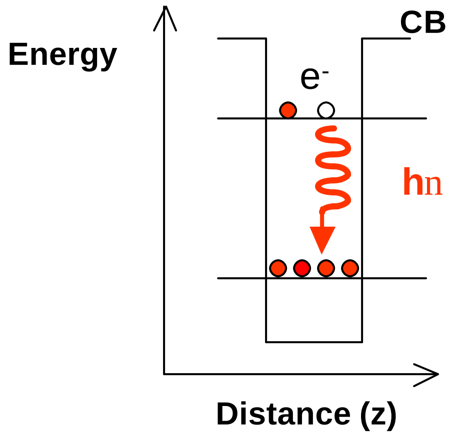
3. Enhancement of thermal dissipation properties of GaInAs/AlInAs/InP QCLs

Selective current injection by proton implantation
Thick electro-plated gold

4. Conclusion

Quantum Cascade Lasers (QCLs)

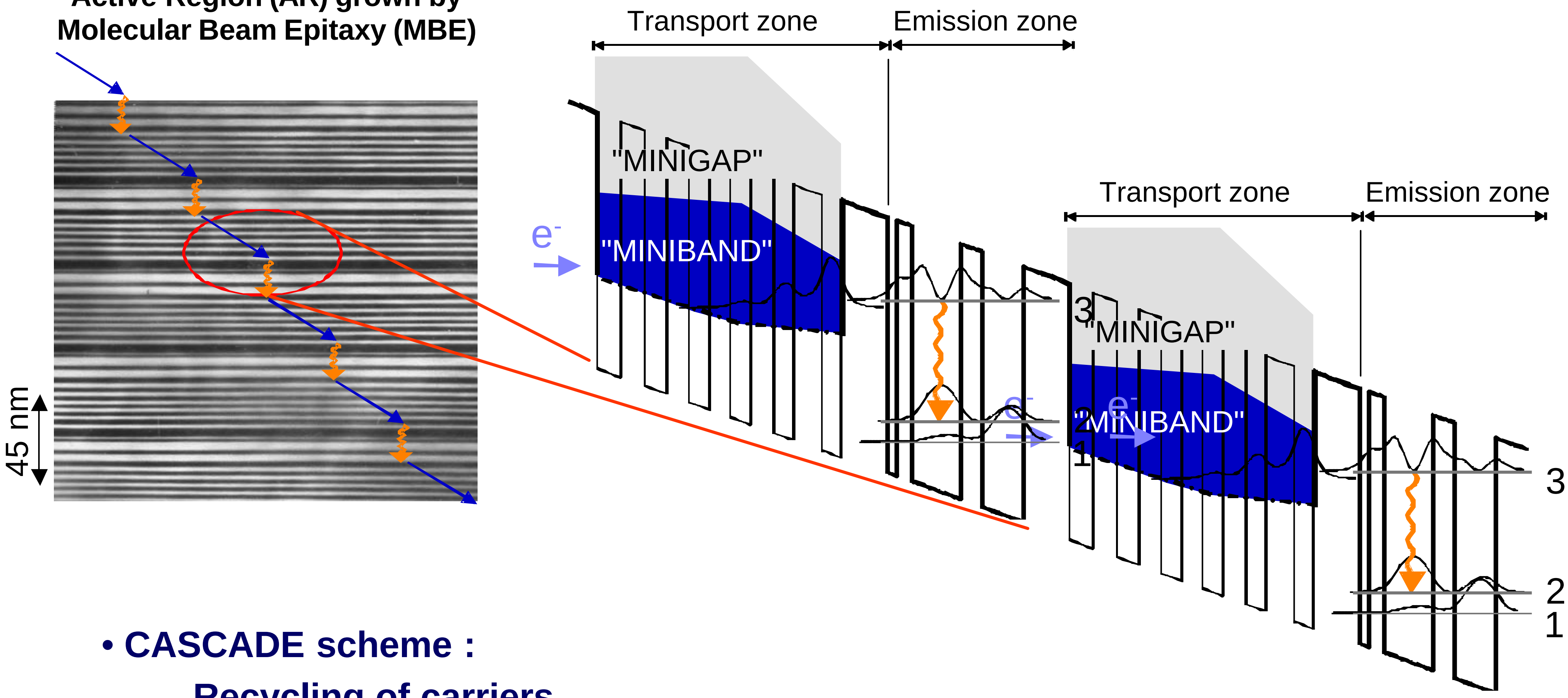
Main Properties



- INTERSUBBAND transitions
- UNIPOLAR : only one type of carrier used (e^-)

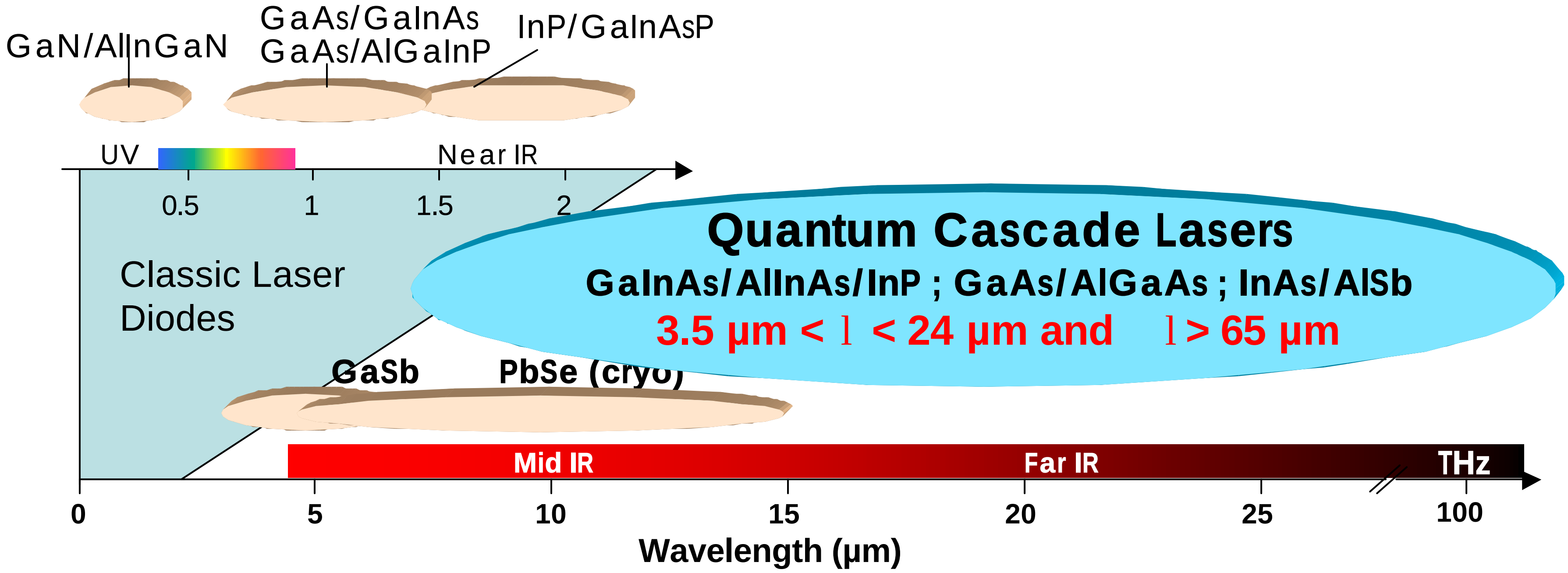
Quantum Cascade Lasers (QCLs)

Active Region (AR) grown by Molecular Beam Epitaxy (MBE)



- **CASCADE scheme :**
  Recycling of carriers
  N periods = N photons per carrier

Spectral range of QCLs



Applications:

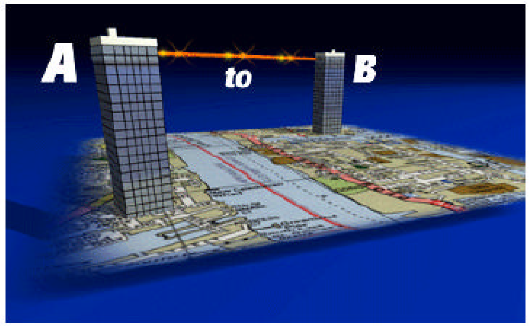
- **Spectroscopy and high sensitive Gas detection**

  Environmental, Medical, Security

- **Free space optical communication**

  Atmospheric transparency windows : 3- 5 µm and 8-12 µm

- **Optical countermeasures**



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QCL History

Bell Labs
QCL in GaInAs/AlInAs/InP
1994

Thales
QCL in GaAs/AlGaAs
1998

2002
Room temperature CW operation for GaInAs/AlInAs/InP QCL

Thales / CEM²
QCL in InAs/AlSb
2003

2005
400mW room temperature CW operation for GaInAs/AlInAs/InP QCL

150K CW operation QCL in GaAs/AlGaAs QCL

CW: Continuous Wave

From intersubband emission to CW laser operation

First Laser operation

First CW operation

Gain optimisation

78K

78K

Pulsed operation

78K

CW operation

300K

Quantum engineering of Active Region

Waveguide design optimisation

Thermal management

From intersubband emission to CW laser operation

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First laser operation

First CW operation

Gain optimisation | Pulsed operation | CW operation

GaAs/AlGaAs QCL

- 78K – 78K – 1998 (Thales)
- 78K – 2000 (30K) (TU Wien)
- 300K

Thesis S.Barbieri - C.Becker

Quantum engineering of Active Region

Waveguide design optimisation

Heat dissipation management

InP-based QCL

- 1994 (Bell Labs)
- 1995 (80K) (Bell Labs)
- 2002 (Neuchâtel)

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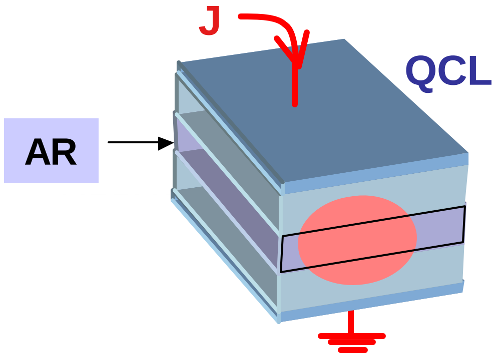
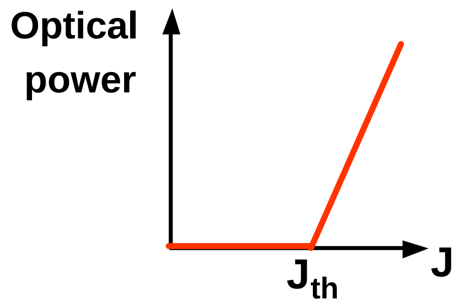


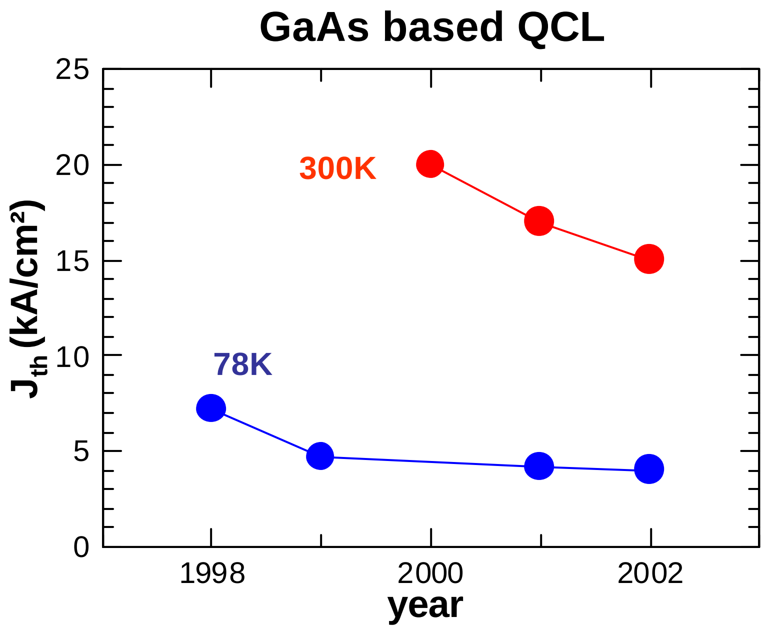
Pulsed operation QCL devevopment: Reduction of the threshold current density J_{th}

$$J_{th} = (a_{wg} + a_m) / g\,G$$

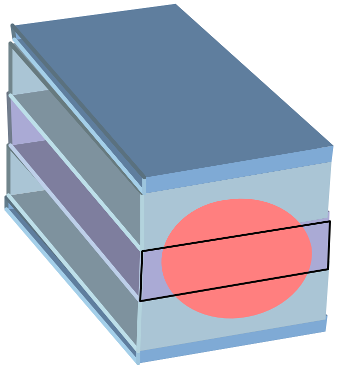


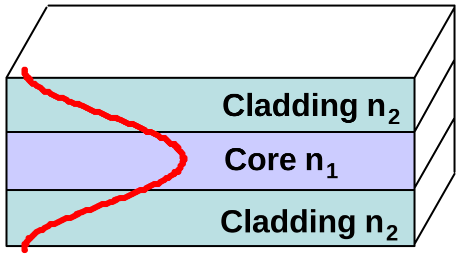
Quantum engineering of Active Region : g

Waveguide design optimisation : a_{wg}, G



Waveguide principle





Guiding condition : $n_1 > n_2$

Waveguide optimisation by numerical simulations :

- **1D Simulations :** **Transfer Matrix Method (TMM)**

choice of appropriate layer compositions and thicknesses → **Increase figure of merit** $c = G / a_w$ → **Decrease** $J_{th} = (a_{w} + a_{m}) / gG$

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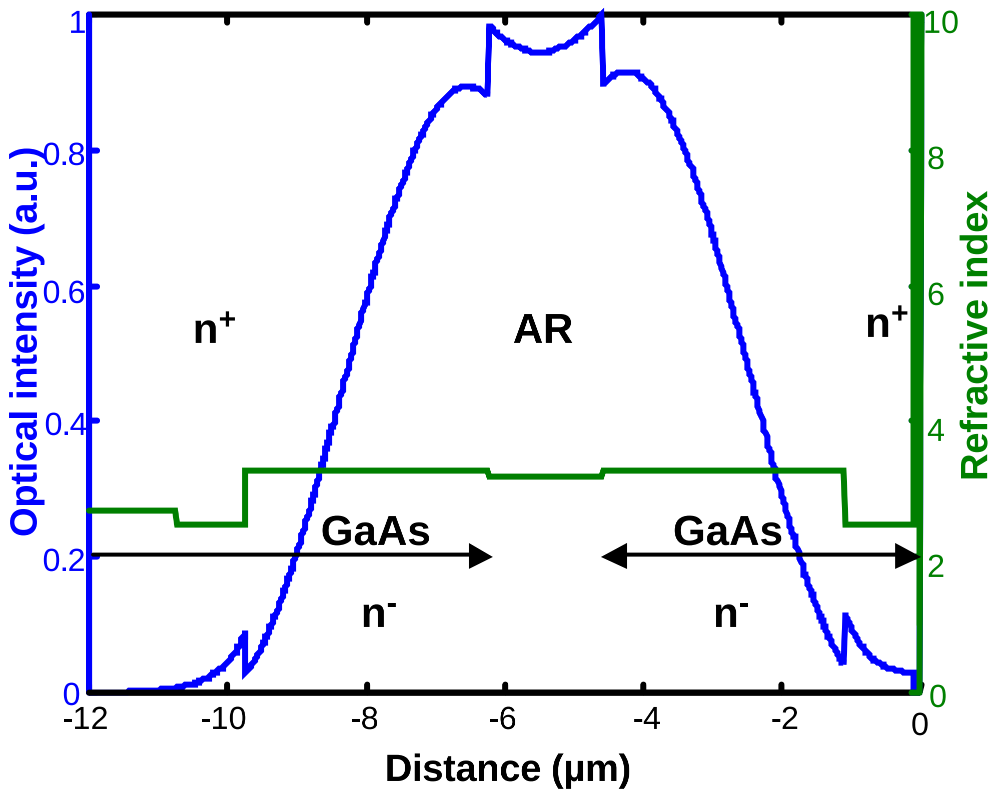
Current GaAs QCL waveguides (1)

GaAs Plasmon enhanced waveguide with highly doped cladding layers

n_{eff}=3.19
a = 17 cm^{-1}
G = 28%
l = 9.4µm

c= 1.7
J_{th}=15kA/cm^2



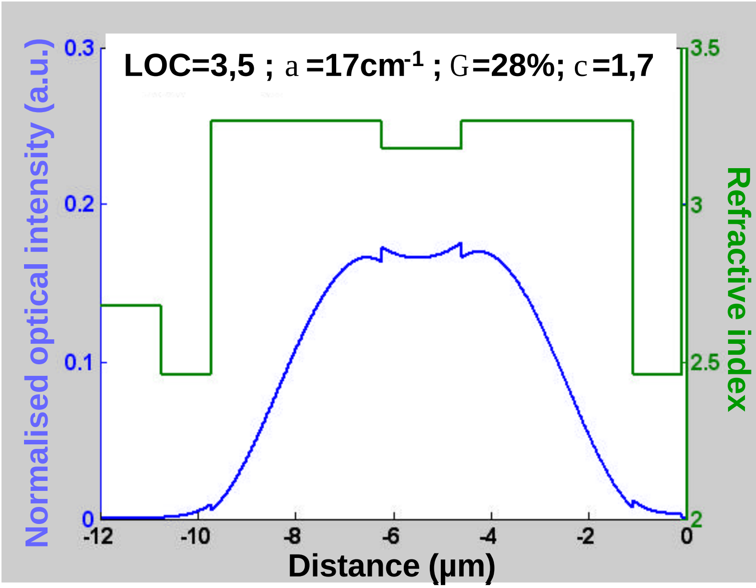
➔ **Advantages**

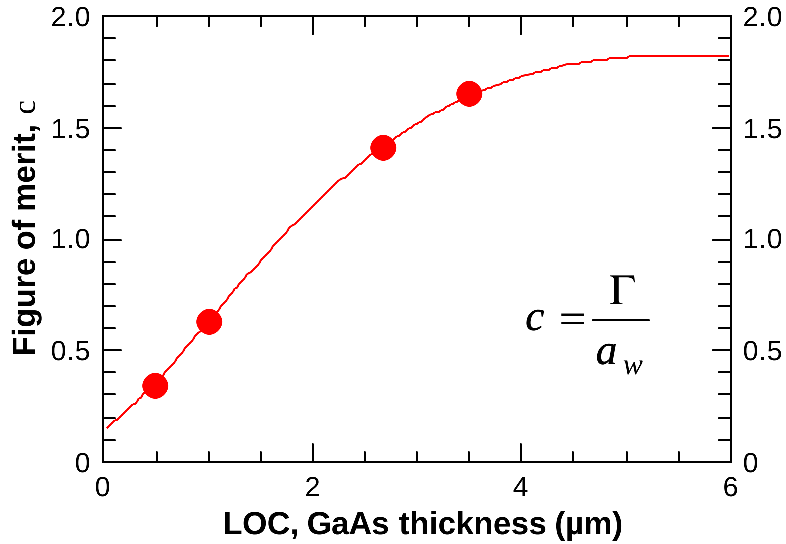
- straight-forward MBE growth
- good electrical characteristics

➔ **Drawbacks**

- free carrier absorption (FCA) losses in highly doped layers

Current GaAs QCL waveguides (2)





The χ optimisation is a trade-off between :

- Γ, decreasing with the GaAs thickness
- a **, mainly due to FCA**

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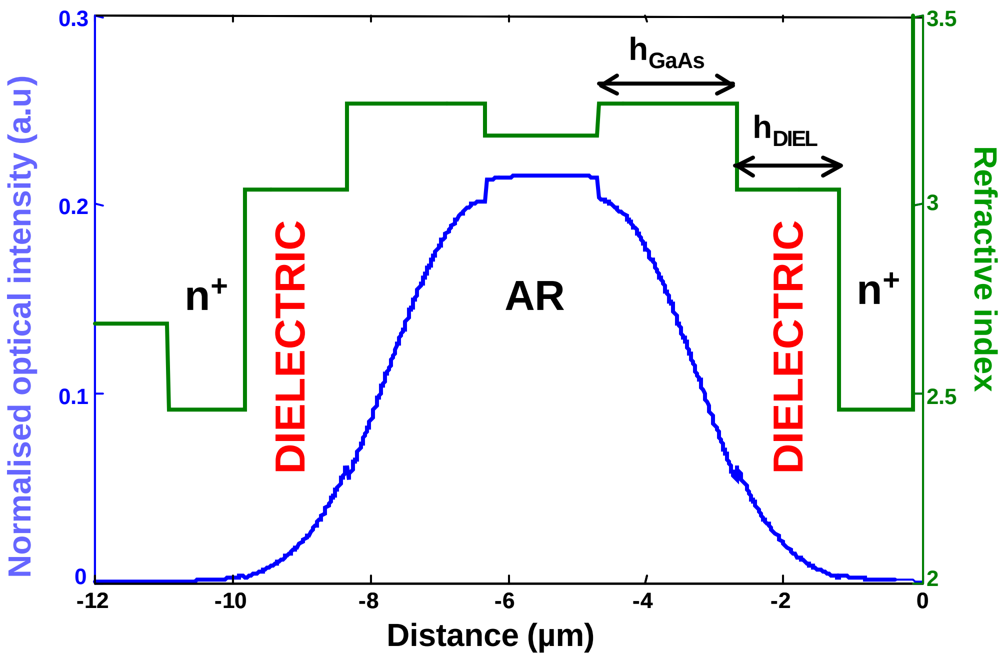
Dielectric waveguide optimisation

NECESSITY TO REDUCE OPTICAL LOSSES FROM CLADDINGS



➔ **Plasmon enhanced waveguide strengthened by dielectric layers :**

- ❑ **AlGaAs layers**
- ❑ **GaInP layers**

Maximum growth thickness ~10µm

➔ $h_{GaAs}+h_{Diel}$=3,5µm

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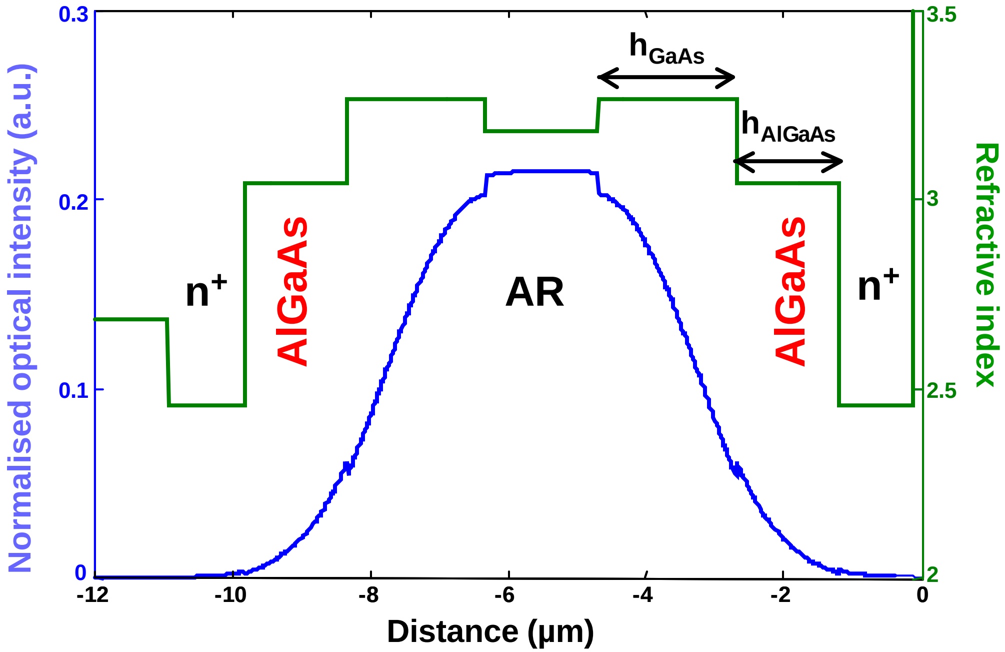
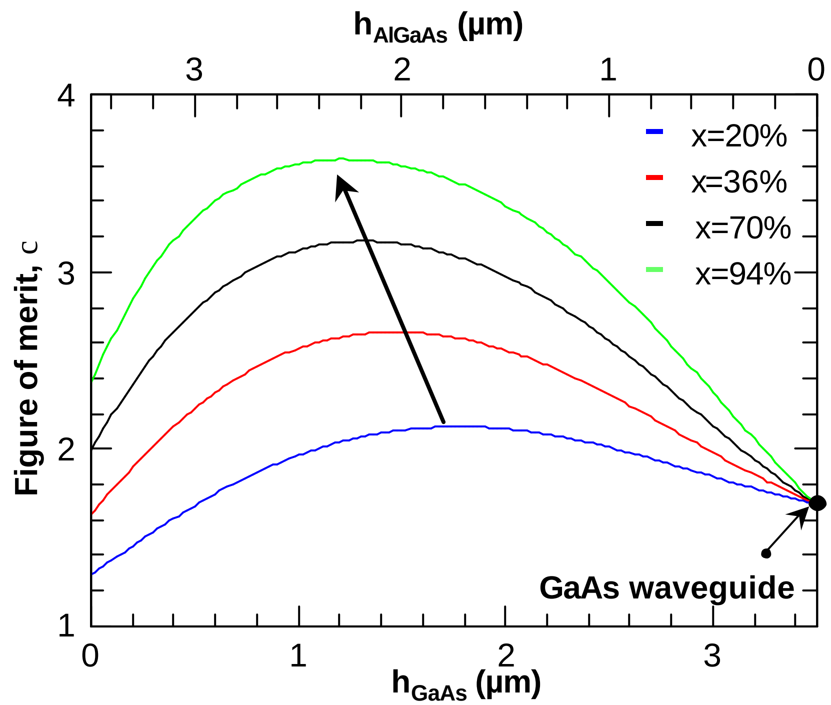
$Al_xGa_{1-x}As$ cladding waveguides

With x_{Al} ↗:

Þ $\Delta n_{GaAs/AlGaAs}$ ↗ Þ Γ ↗
Þ α ↘ (mode overlap with highly doped layers reduced)

} Þ c=G/a ↗





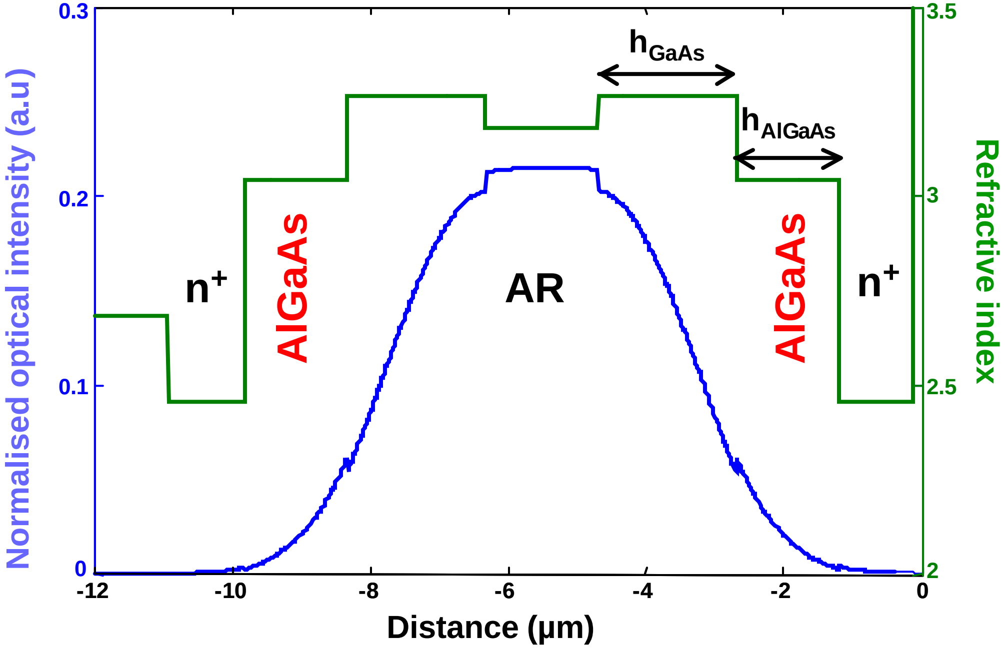
$Al_xGa_{1-x}As$ cladding waveguides

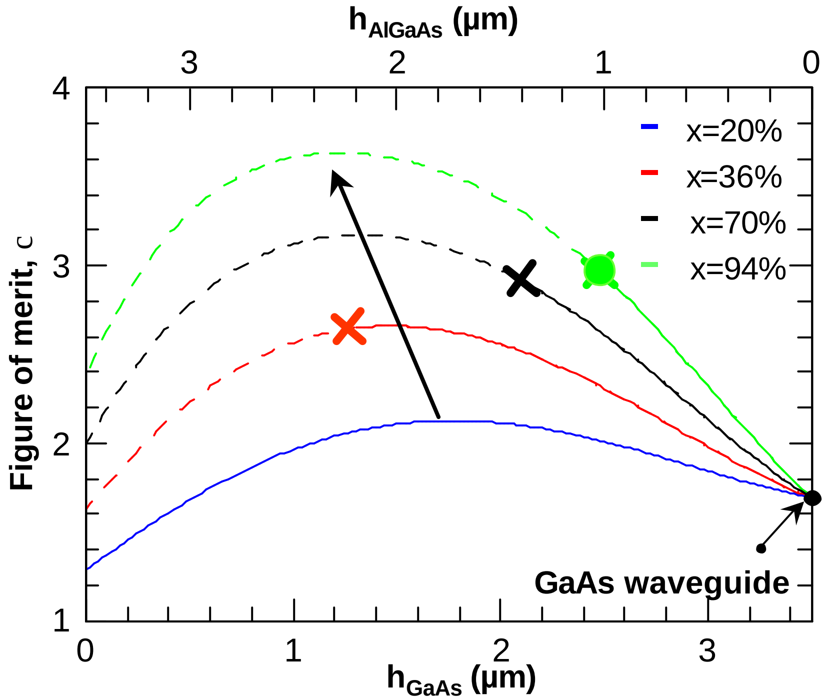
With x_{Al} ↗:

- Þ $\Delta n_{GaAs/AlGaAs}$ ↗ Þ Γ ↗
- Þ α ↘ (mode overlap with highly doped layers reduced)

} Þ $c = G/a$ ↗

! <u>Limitations :</u> lattice mismatch constraint ➔ $Al_xGa_{1-x}As$ thickness limit ~$1/x_{Al}$





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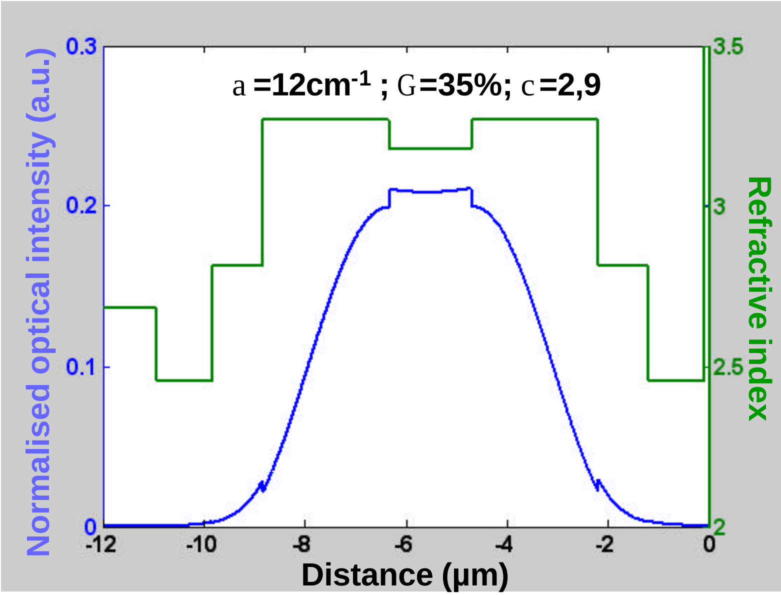
$Al_{0.94}Ga_{0.06}As$ cladding waveguides / QCL AL94

$Al_{0.94}Ga_{0,06}As$ cladding waveguide



c=2.9

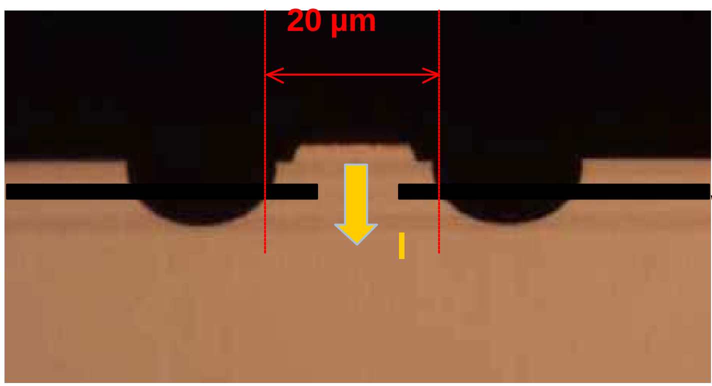
➔ J_{th} ~2 times smaller than that of the GaAs plasmon enhanced waveguide.

2 devices grown and processed identically:

➔ **GaAs : GaAs waveguide**

➔ **AL94 : $Al_{0.94}Ga_{0.06}As$ waveguide**

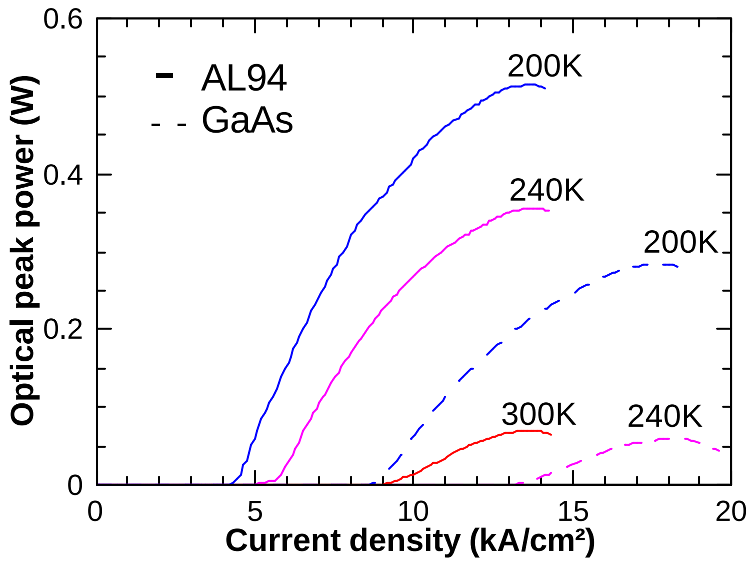
- Identical 3 quantum-well AR (same growth set)
- Double trench ridge devices
- H^+ implanted for selective current channelling
- Low duty cycle to avoid device heating



H^+ implantation (insulating)

QCL AL94

5kHz-100ns

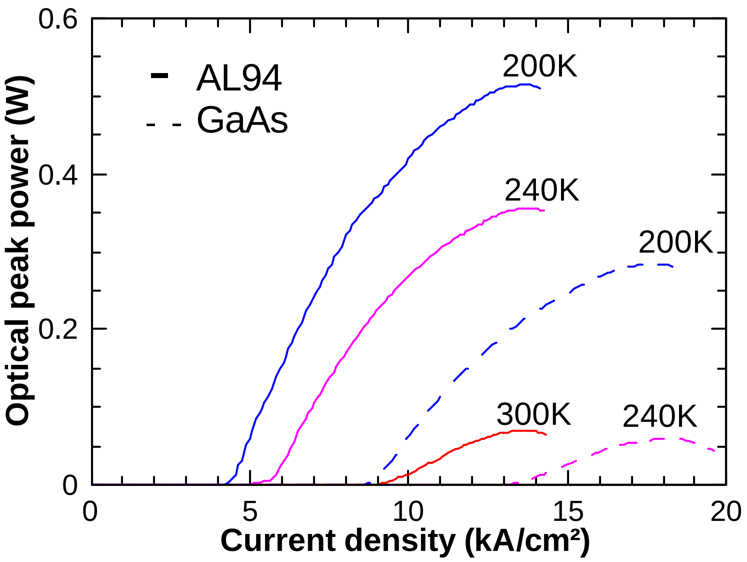


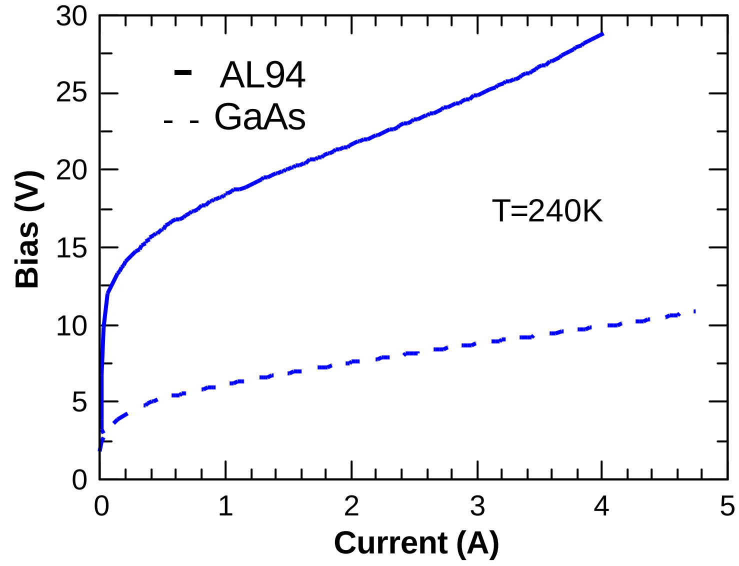
<u>Good optical performances for QCL AL94:</u>

- ➔ **Significant reduction of J_{th}**
- ➔ **Agreement with simulations:**
  $J_{th}(GaAs) / J_{th}(AL94) \approx \chi(AL94) / \chi(GaAs) \approx 2$
- ➔ **Higher optical peak power**

QCL AL94

5kHz-100ns





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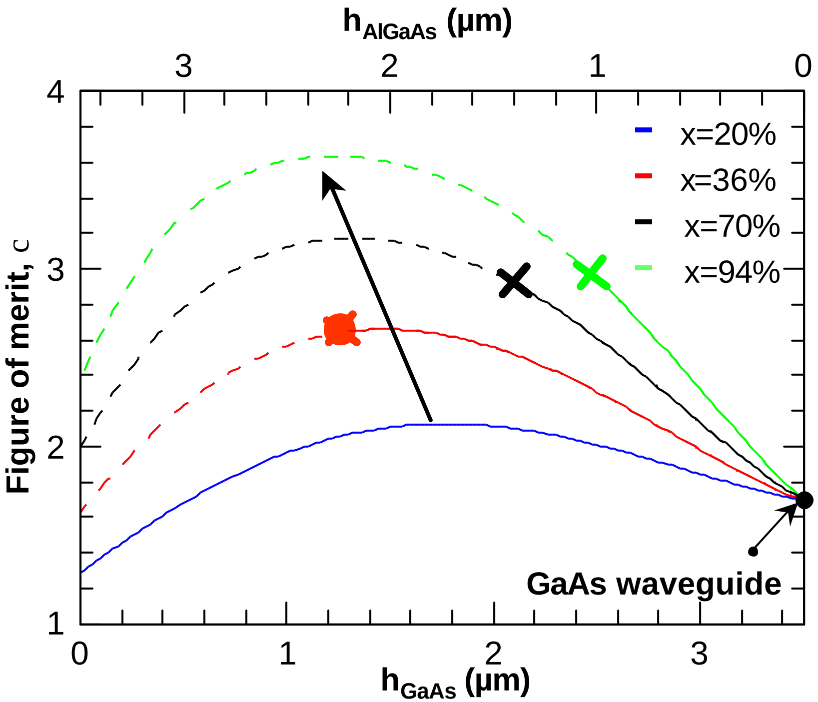
- ➔ **Agreement with simulations:**
  - ***J_{th}(GaAs) / J_{th}(AL94) $\approx$ χ(AL94) / χ(GaAs) $\approx$ 2***
- ➔ **Higher optical peak power**
- ➔ **300K operation**

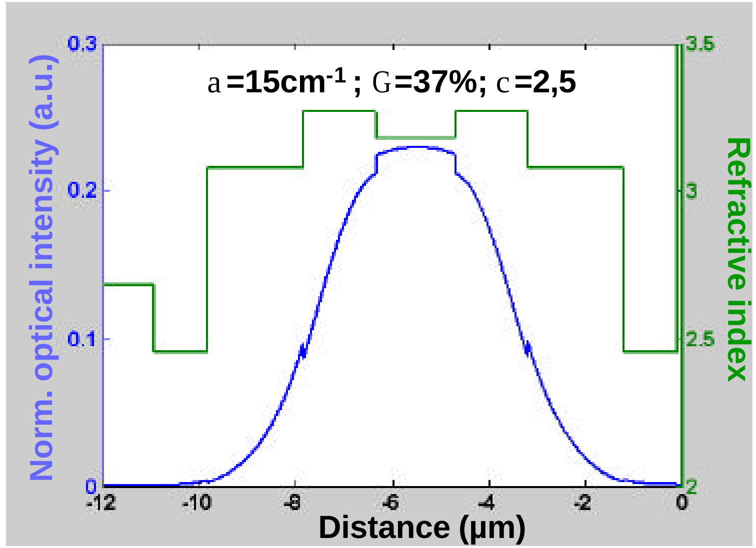
Poor electrical characteristics for QCL AL94:

- ➔ **Abnormally high knee: V_c=14V (V_c(GaAs)=5V)**
  - ***Bad ohmic contacts?***
  - ***Bad grading between GaAs and AlGaAs layers?***
- ➔ **Higher differential resistances**
  - ***3x higher for AL94 device compared to GaAs QCL***
- ➔ **High operating voltage**

$Al_{0.36}Ga_{0.64}As$ cladding waveguides



$Al_{0.36}Ga_{0.64}As$ cladding waveguide



c =2,5

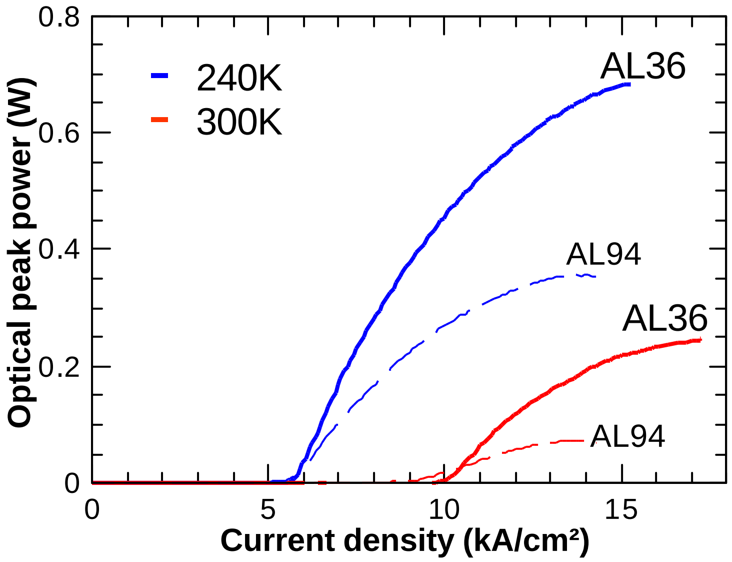
Electrical conductivity better than $Al_{0,94}Ga_{0,06}As$ layers:

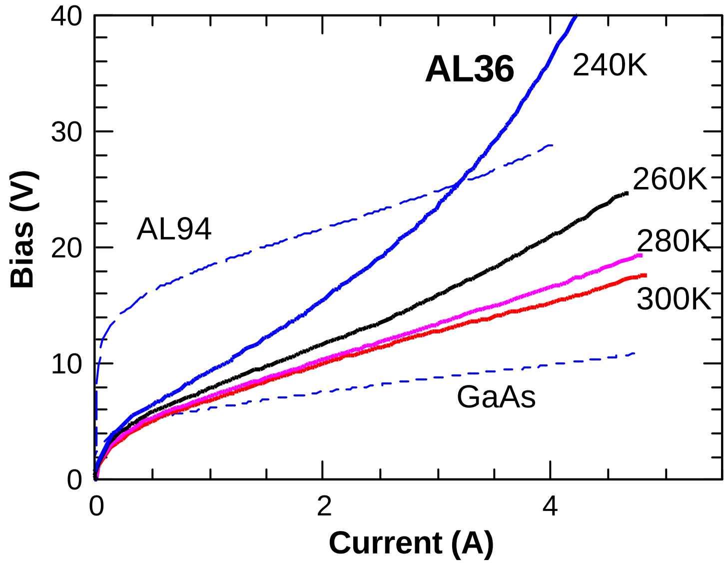
better e^- mobility

lower effective mass

QCL AL36

5kHz-100ns





Good optical performances for QCL AL36:

- ➔ J_{th} significantly lower than J_{th}(GaAs)
- ➔ J_{th} slightly higher than J_{th}(AL94)
- ➔ Higher optical peak power

P_{max}(AL36)=250 mW at 300K

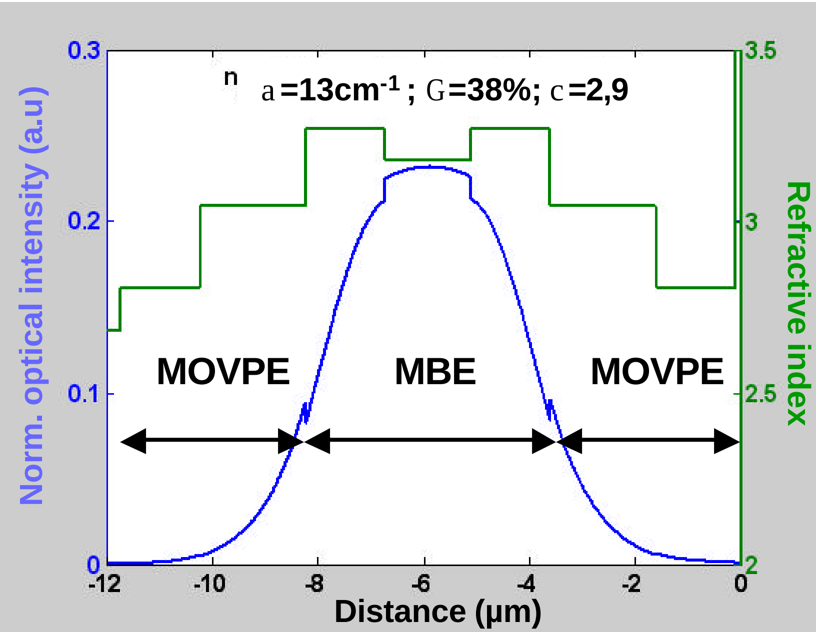
Electrical characteristics dependant on the temperature:

- ➔ Higher differential resistances
- ➔dV/dI= f (T) for AL36 QCL: E_{act}=132meV
- ➔ High operating voltage for T<260K

$Ga_{0.51}In_{0.49}P$ cladding waveguides

- **$Ga_{0.51}In_{0.49}P$ refractive index @ $Al_{0.45}Ga_{0.55}As$ refractive index**
  - ➔ Good $\Delta n_{GaAs/GaInP}$ for improved confinement: c **=2,9**
- **Good electrical conductivity**
- **$Ga_{0.51}In_{0.49}P$: lattice matched to GaAs**
  - ➔ no thickness limitation

c **=2,9**



Drawback : $Ga_{0.51}In_{0.49}P$ re-growth by MOVPE at Thales

➔ **growth in 3 steps**

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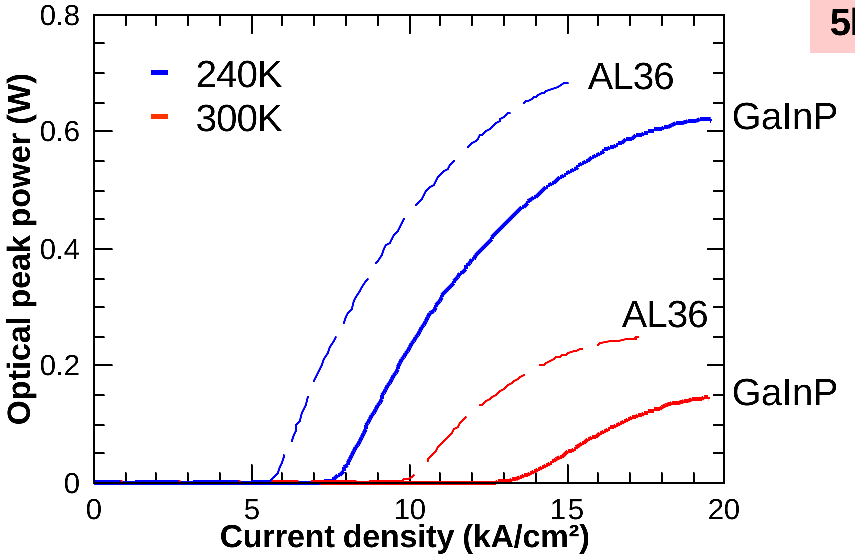
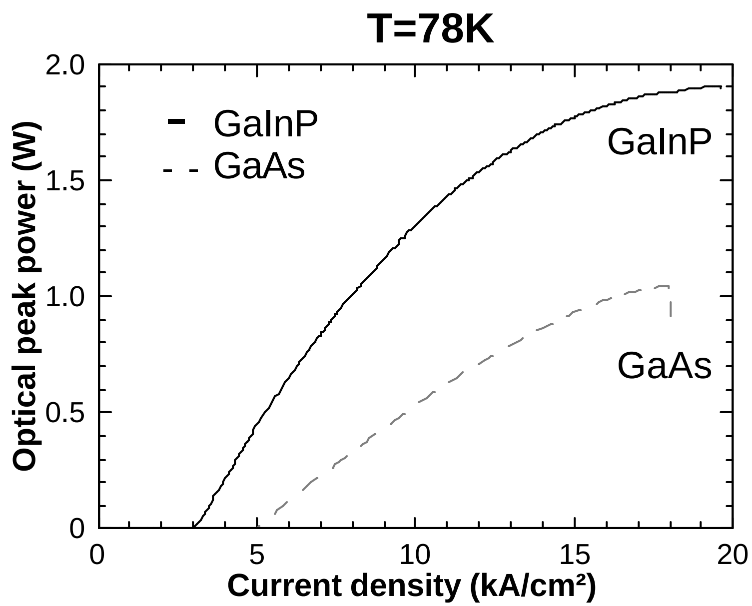
QCL GaInP

5kHz-100ns





Good optical performances for QCL AL36:

- ➔ J_{th} significantly lower than J_{th}(GaAs)
- ➔ J_{th}(GaInP) higher than J_{th}(AL36)
- ➔ High optical peak power at 78K

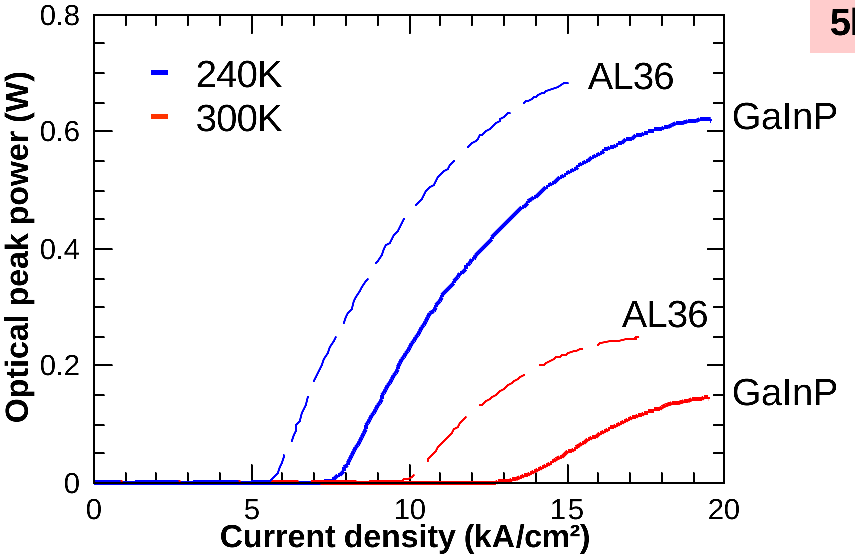
  P_{max}(GaInP)=1,9W at 78K

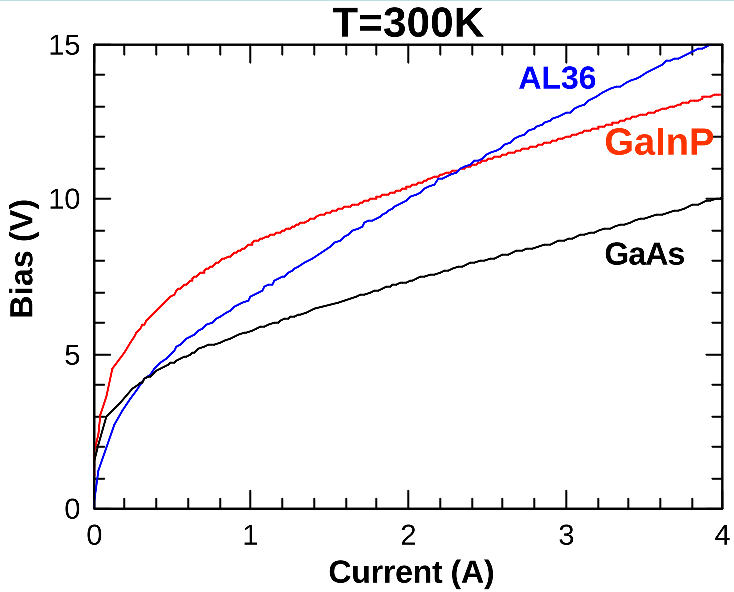
- ➔ Optical peak lower than QCL AL36 at RT

  P_{max}(GaInP)=150 mW at 300K

QCL GaInP

5kHz-100ns





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- ➔ J_{th}(GaInP) higher than J_{th}(AL36)
- ➔ High optical peak power at 78K

  P_{max}(GaInP)=1,9W at 78K

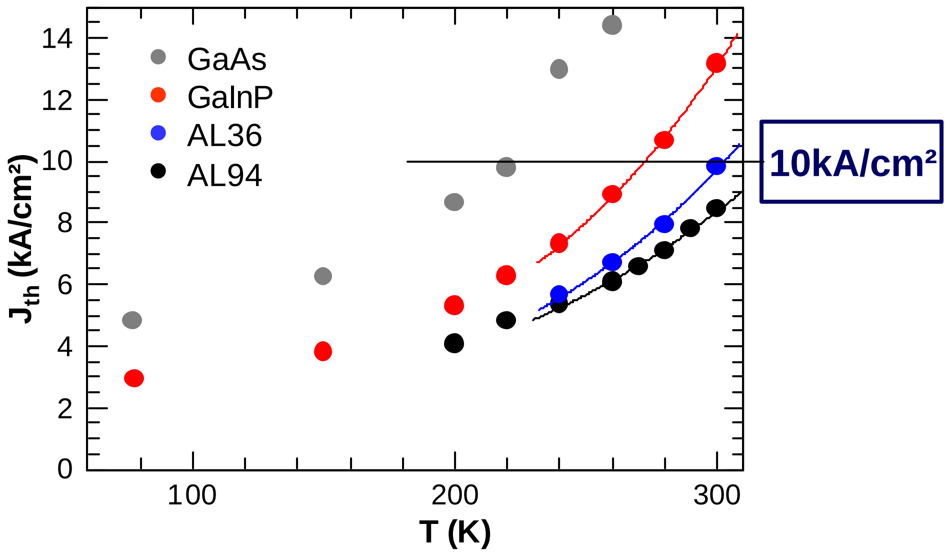
- ➔ Optical peak lower than QCL AL36 at RT

  P_{max}(GaInP)=150 mW at 300K

Electrical characteristics :

- ➔ Higher knee bias: V_c=7V (V_c(GaAs)=5V)
- ➔ Lower differential resistance than AL36
- ➔ Higher operating voltage than GaAs

Summary of laser performances

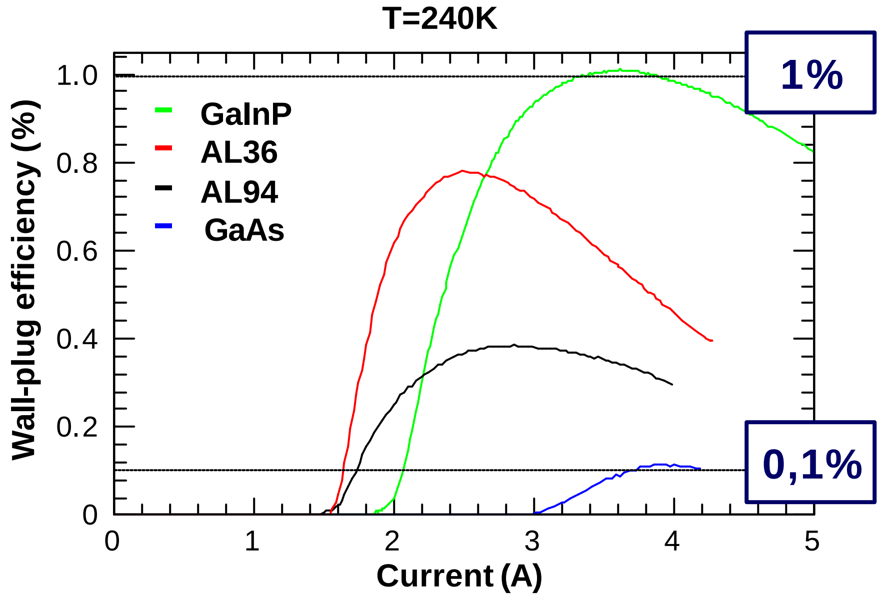


Reduction of threshold current densities:

- ➔ Low J_{th}
- ➔ Agreement with our predictions for AL94 and AL36:

J_{th}(GaAs) / J_{th}(Diel.) @ c(Diel.) / c(GaAs)

Best waveguide device :
QCL AL36



Better Wall-Plug efficiencies than LCQ GaAs

➔WP(GaInP)=1%= 10xWP(GaAs) at 240K

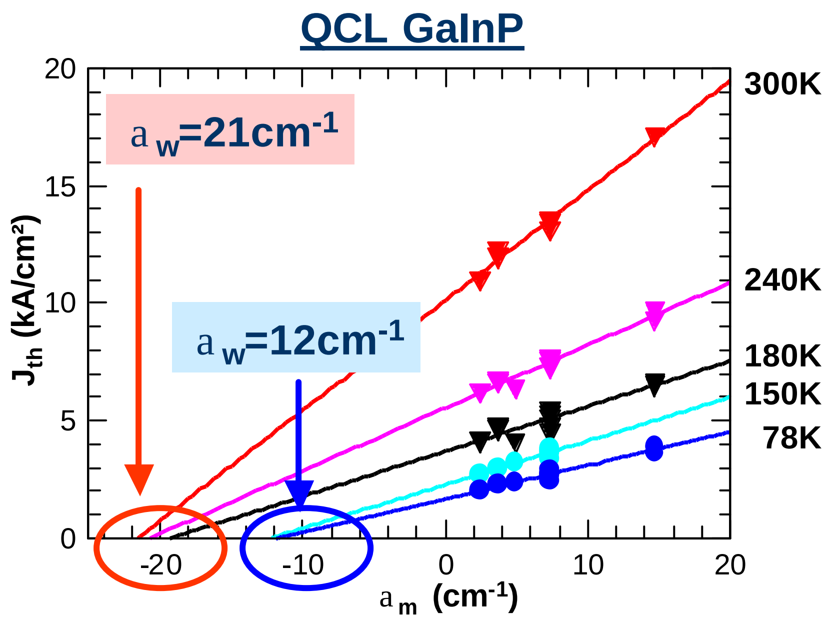
Optical performances improvements	>	Electrical degradations

Best QCLs :
QCL AL36 for T> 250 K
QCL GaInP for T< 250 K

Waveguide loss measurements

Waveguide losses a_w determined from $J_{th}=f(a_m)$ plot:

$$J_{th}=(a_m+a_w)/gG$$



	a_w	
	T<180K	T^{3} 180K
AL36	-	19 cm^{-1}
GaInP	12 cm^{-1}	21 cm^{-1}
GaAs	20 cm^{-1}	-

a_w increase at T^{3} 180K

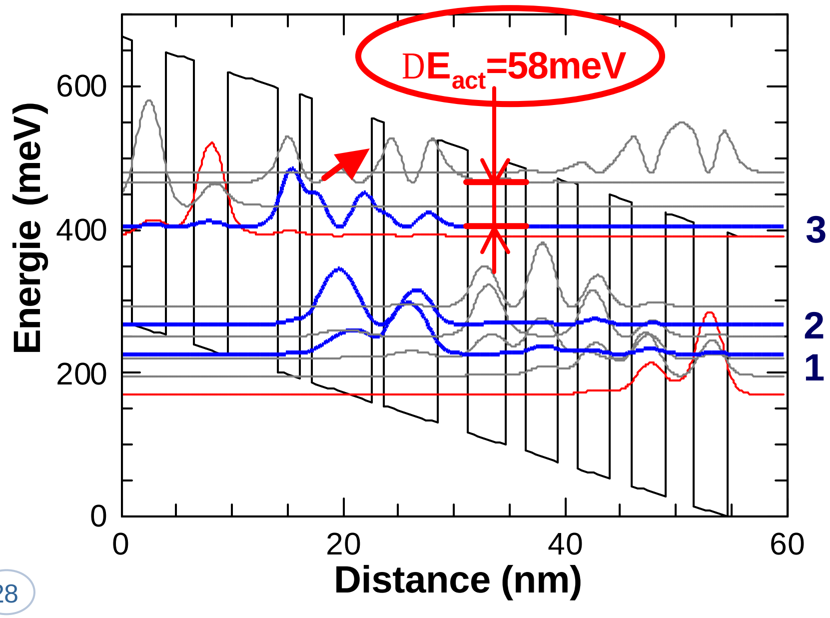
Reduction of a_w at low temperature compared to QCL GaAs

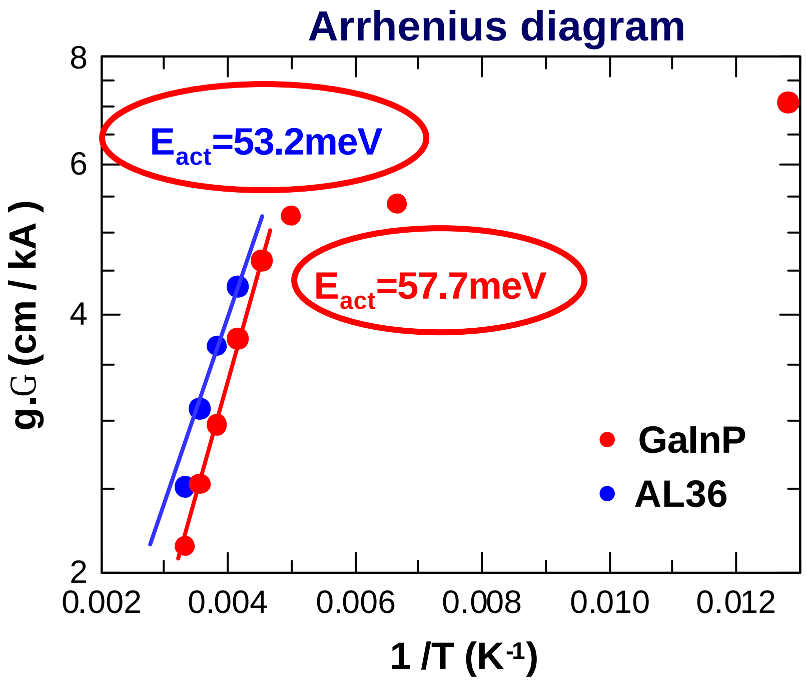
Gain coefficient

$J_{th}=f(\alpha_m)$ plot ⇨ $gG = f(T)$

➡ Observation of 2 operating regimes

Carrier leakage into the continuum ?





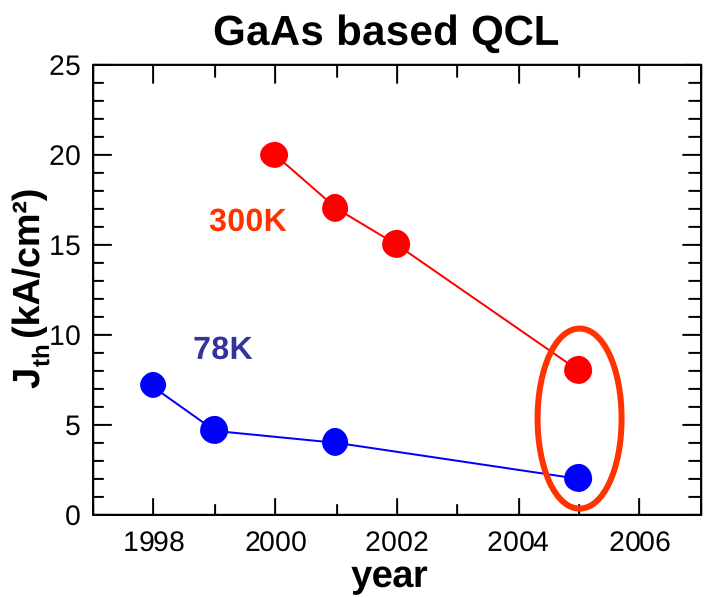
➡ **Carrier leakage into the continuum**

Limitation of the conduction band discontinuity of GaAs/AlGaAs for room temperature operation

Waveguide study conclusion

- Significant reduction of J_{th}
- Best performances (J_{th}, P_{max}) on GaAs-based QCLs

Application of these waveguides on a bound-to-continuum AR QCL



- Degradation of the electrical transport
- Limitation from the conduction band discontinuity of GaAs/AlGaAs underlined for room temperature operation
- High optical losses at Room Temperature

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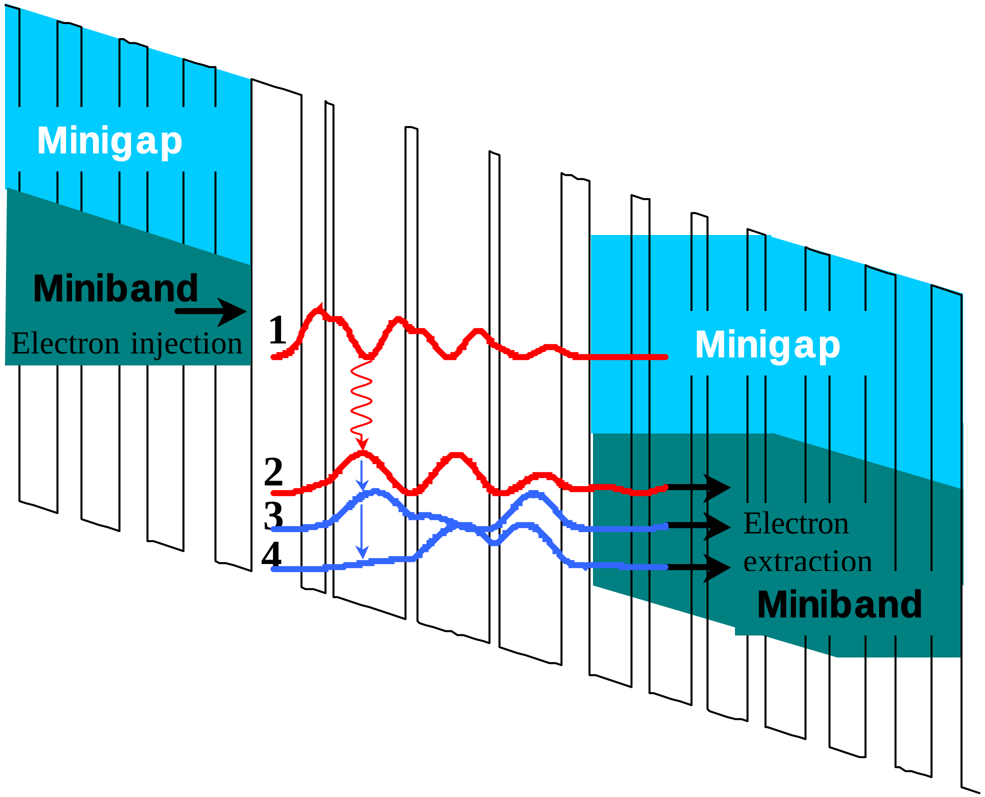
Selective current injection by proton implantation
Thick electro-plated gold

4. Conclusion

Application to InP-based QCLs

Active Region: l ~9µm

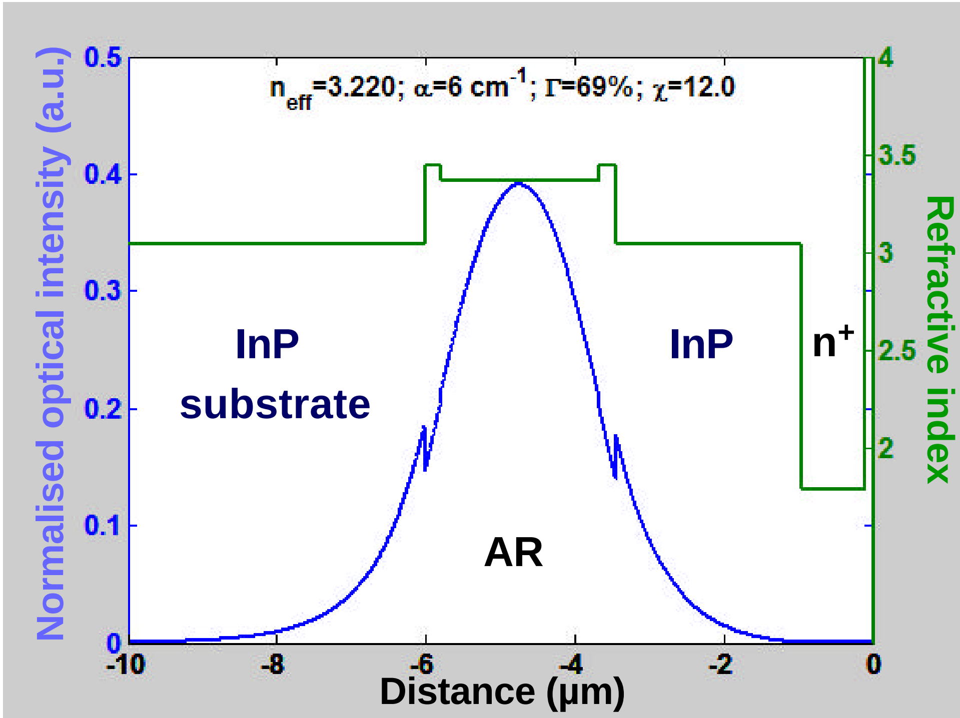
4 Quantum Wells



Vertical Waveguide Structure: c~12

G~69%

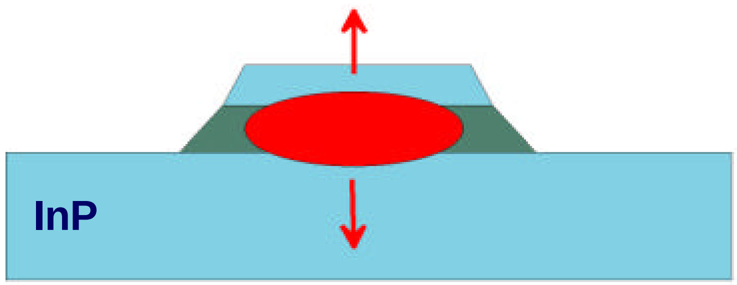
a ~6 cm^{-1}



Beck et al., Science **295**, 301, (2002)

Heat management in QCLs

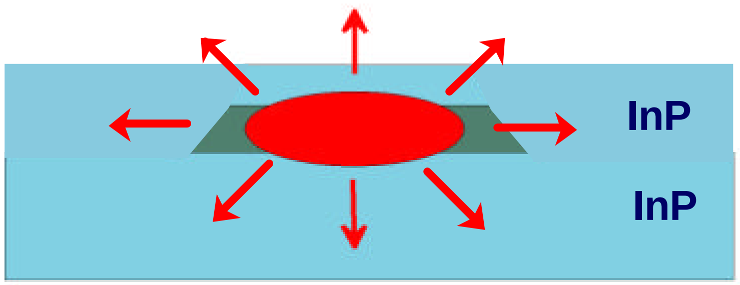
Standard ridge waveguide



No lateral heat dissipation

InP based QCLs

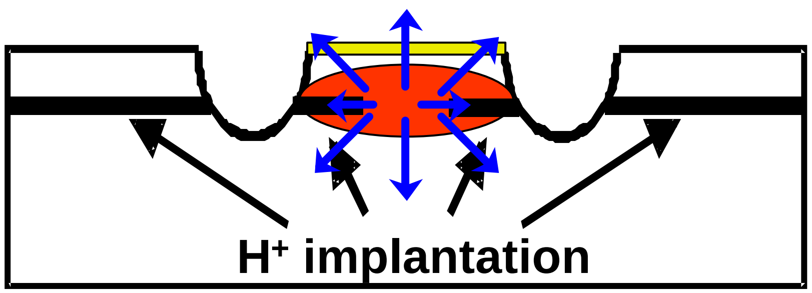
Buried heterostructure



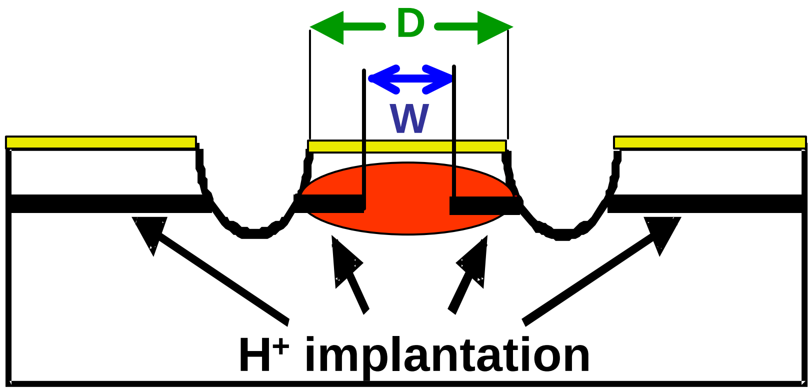
Good lateral heat flow

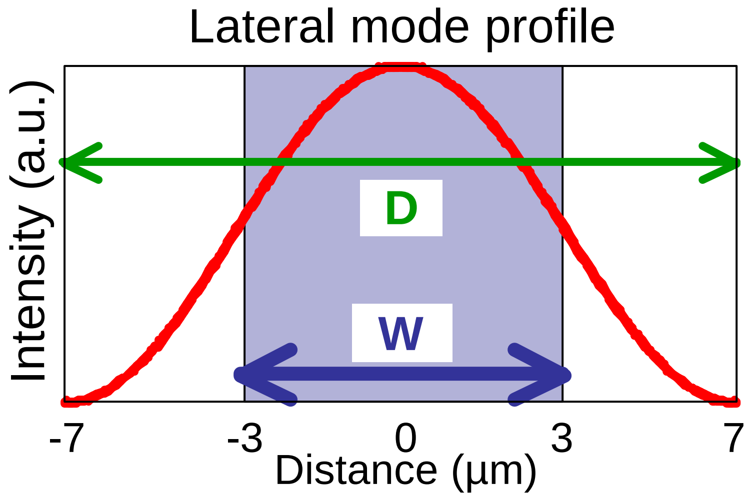
GaAs based QCLs

Selective current injection



Selective current injection





Semi-insulating layers using proton implantation

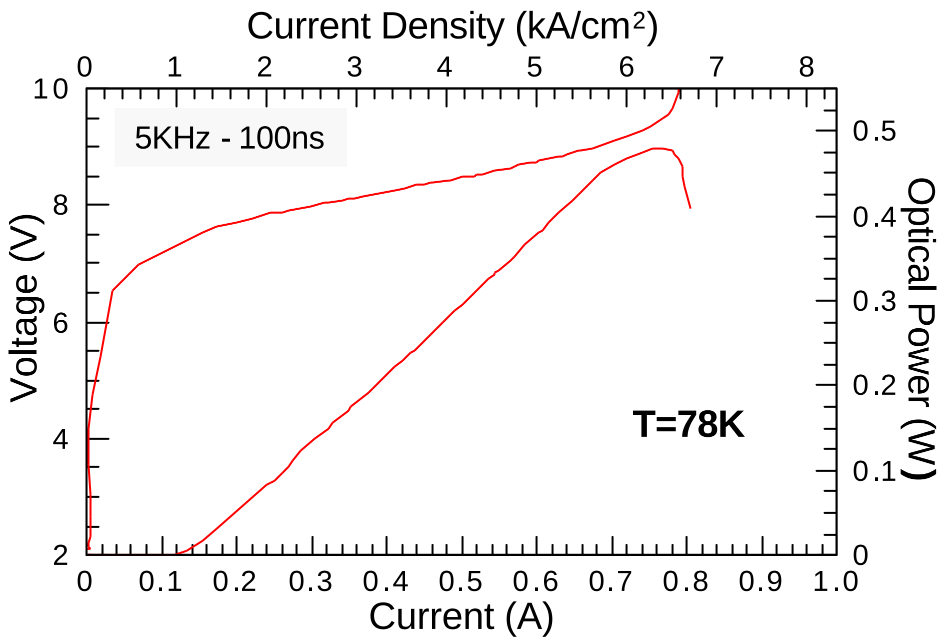
➡ **decrease electrically pumped area**

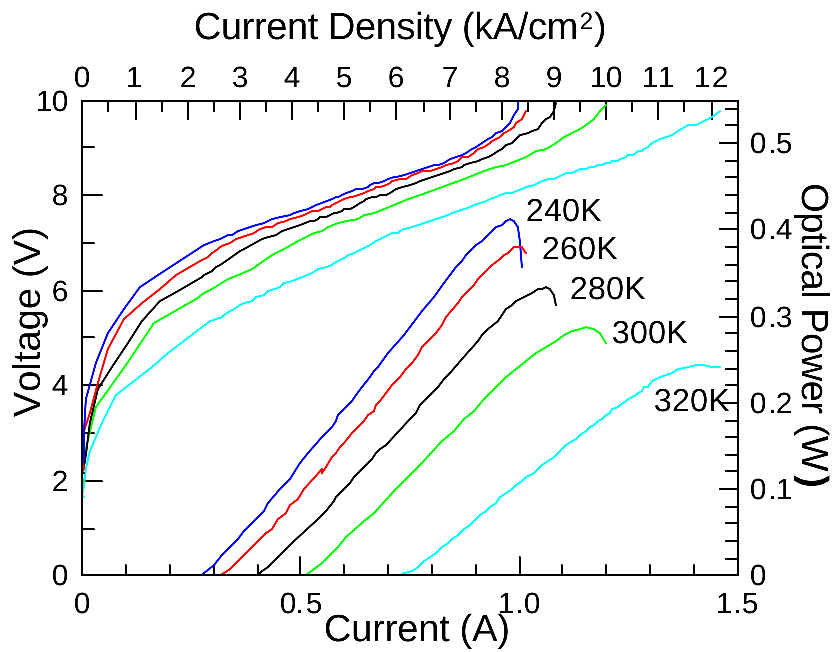
For $\frac{W}{D} = \frac{6}{14} \approx 0,5$

Þ	Pumped area (A)	↘	: -50%
Þ	Mode overlap (Γ)	↘	: -20%
Þ	J_{th} µ 1/Γ	↗	: +20%
Þ	$I_{th} = J_{th} \times A$	↘	**: -40%**

➡ **Decrease of injected electrical power**

Selective current injection in InP QCLs: L-I-V pulsed characteristics



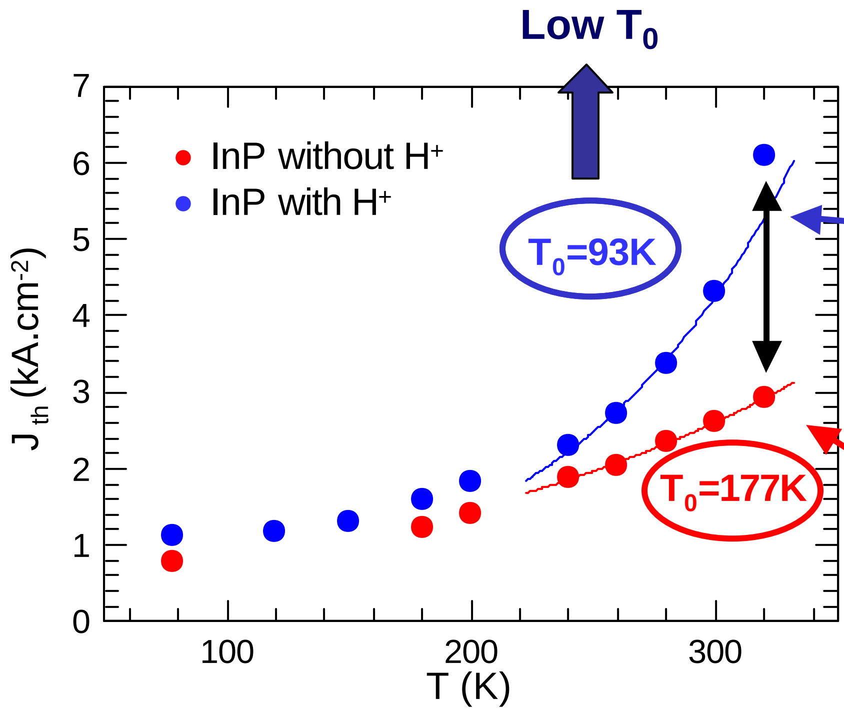


@78K: I_{th}=135 mA, J_{th}=1,1 kA/cm²

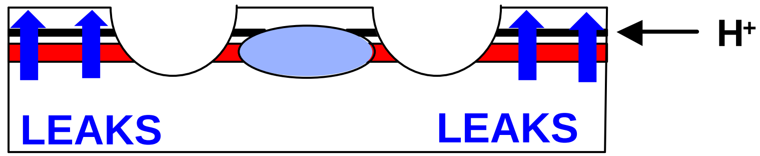
@300K: I_{th}=500 mA, J_{th}=4,3 kA/cm²

Abnormally high increase of I_{th} with temperature

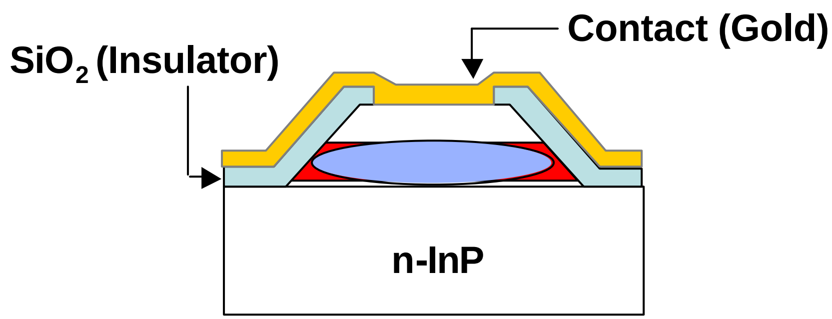
T_0 characteristics



Implanted structure

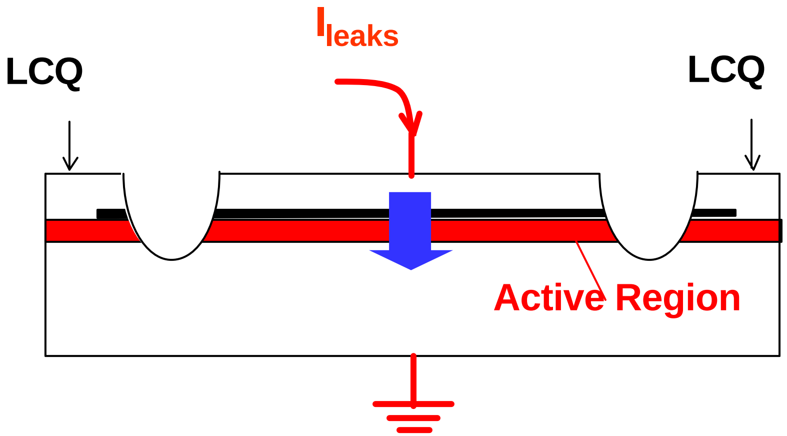


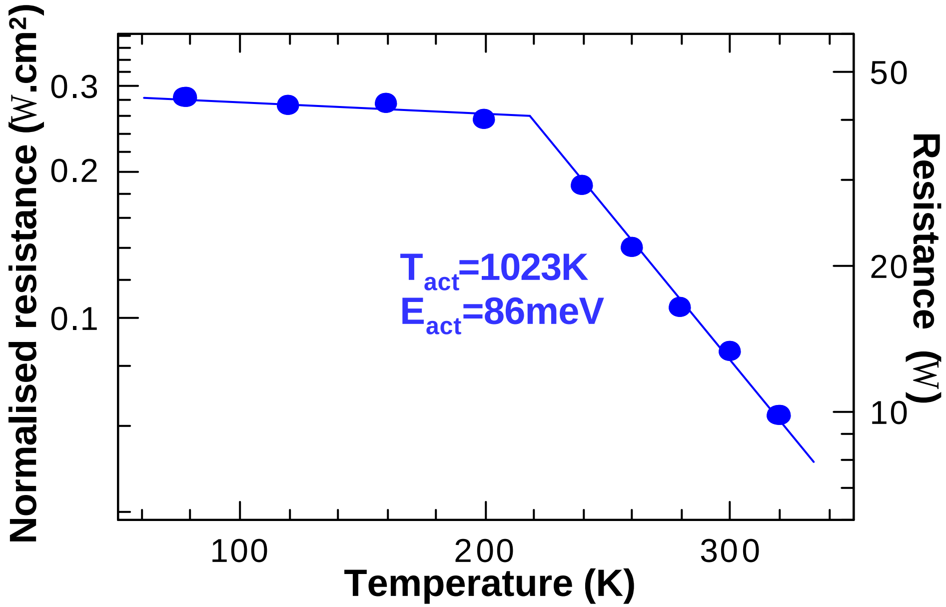
Standard ridge waveguide



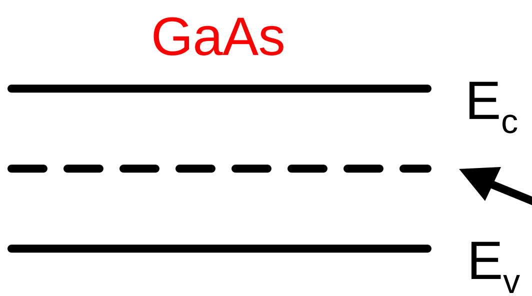
T_0 : Characteristic temperature
from fit : $J_{th} = J_{th0} \cdot \exp(T/T_0)$

Current leakage – implantation breakdown

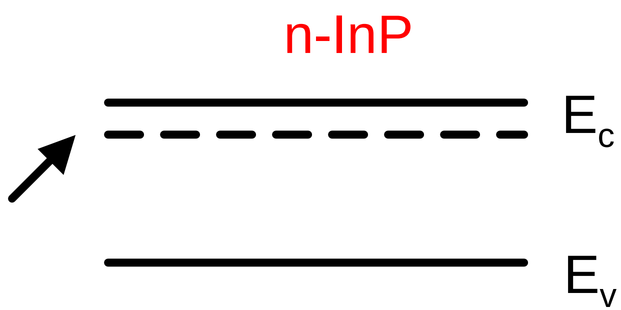




H^+ implantation creates shallow defects in n-doped InP material



H^+ implantation works well in GaAs but not in n-InP

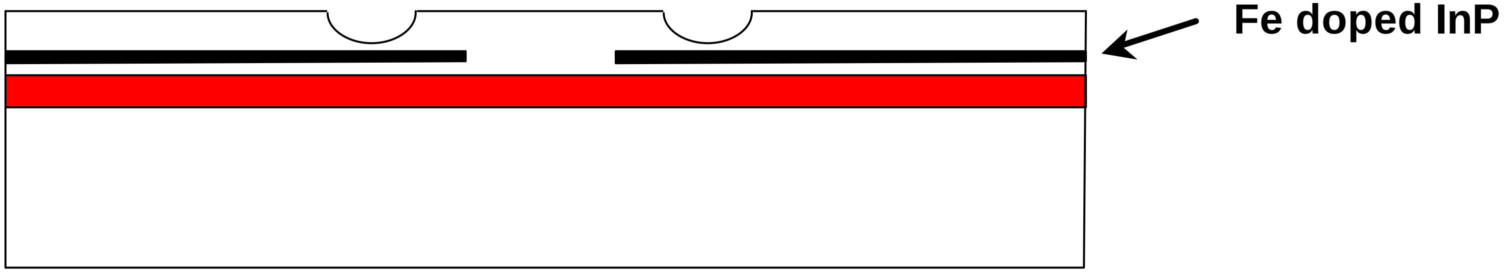


Selective current injection for InP-based QCLs ?

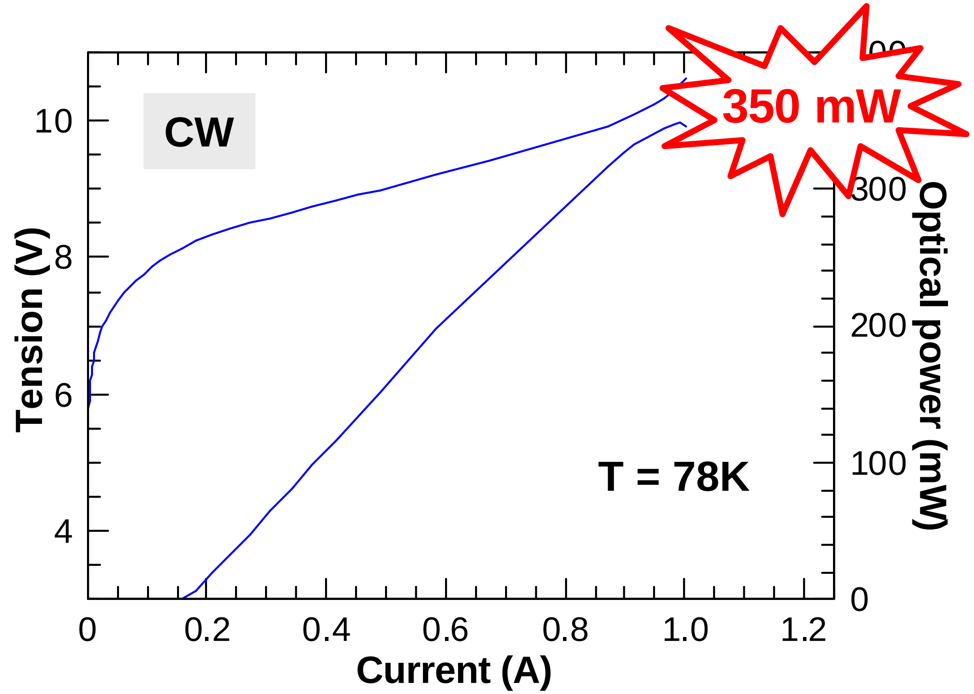
➡ **Selective current injection by H+ implantation inefficient in InP-based QCLs**

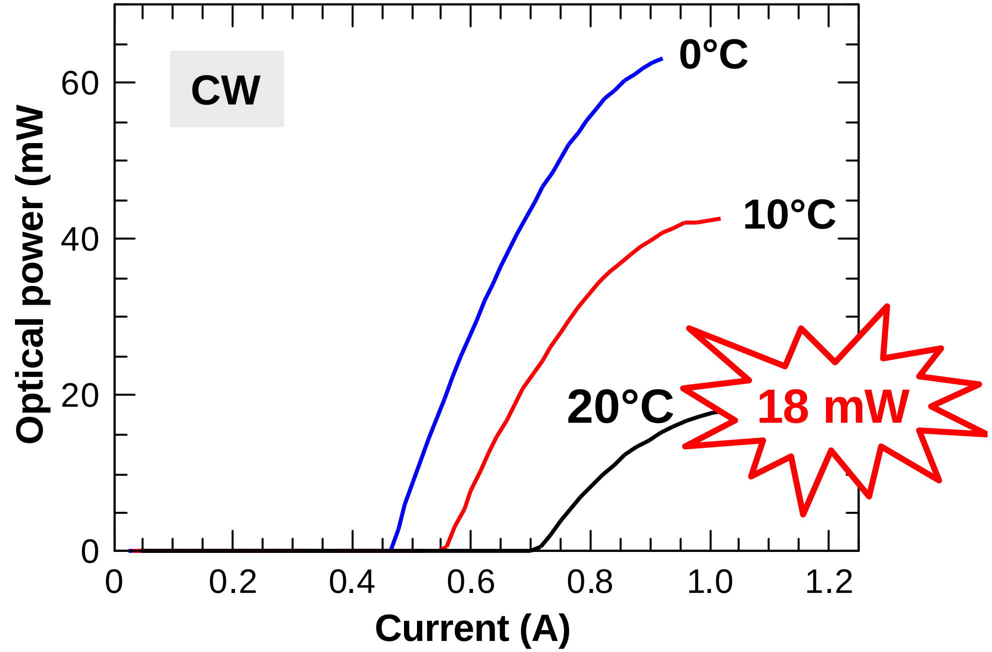
➡ **Future : use of Fe-doped InP as insulating layer**

- **Deep defects in InP bandgap**
- **Fe cannot be deeply implanted ➔ growth of Fe-doped InP layer**



CW operation for H^+ implanted InP-based QCLs



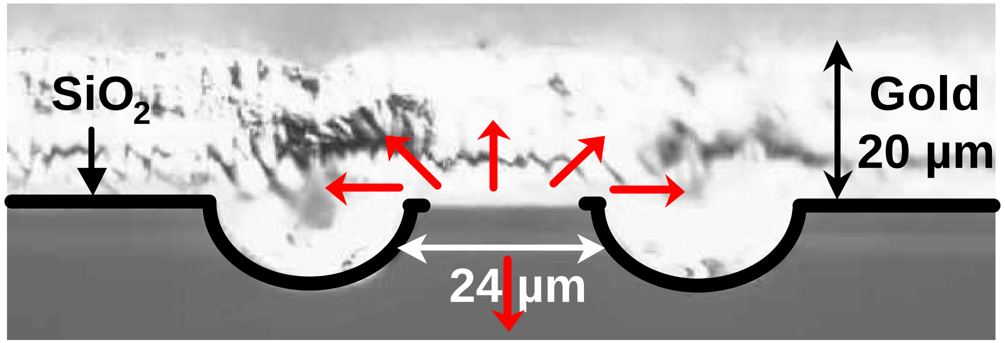


High Temperature CW operation even with current leakage

THALES Research & Technology

Electroplated Gold (Au) devices

Electroplated Au Device

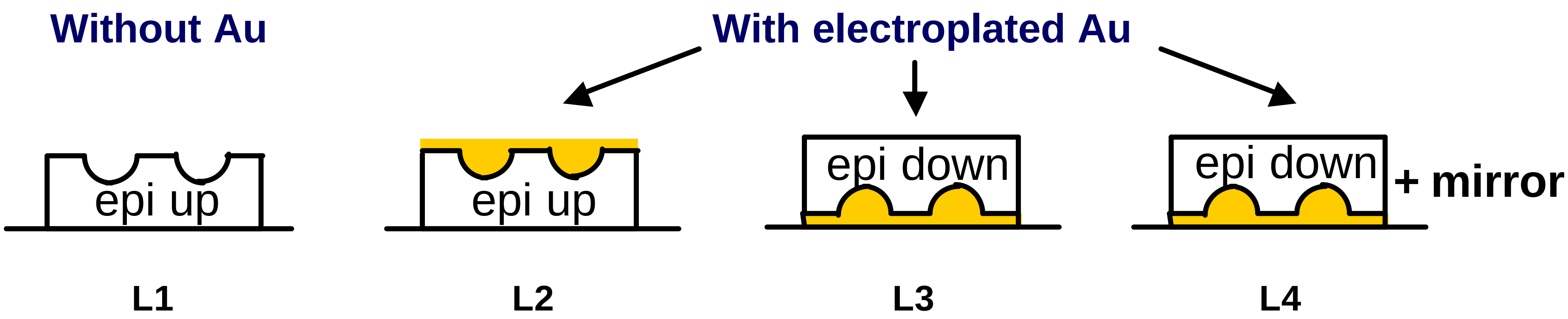


Very good heat dissipation device

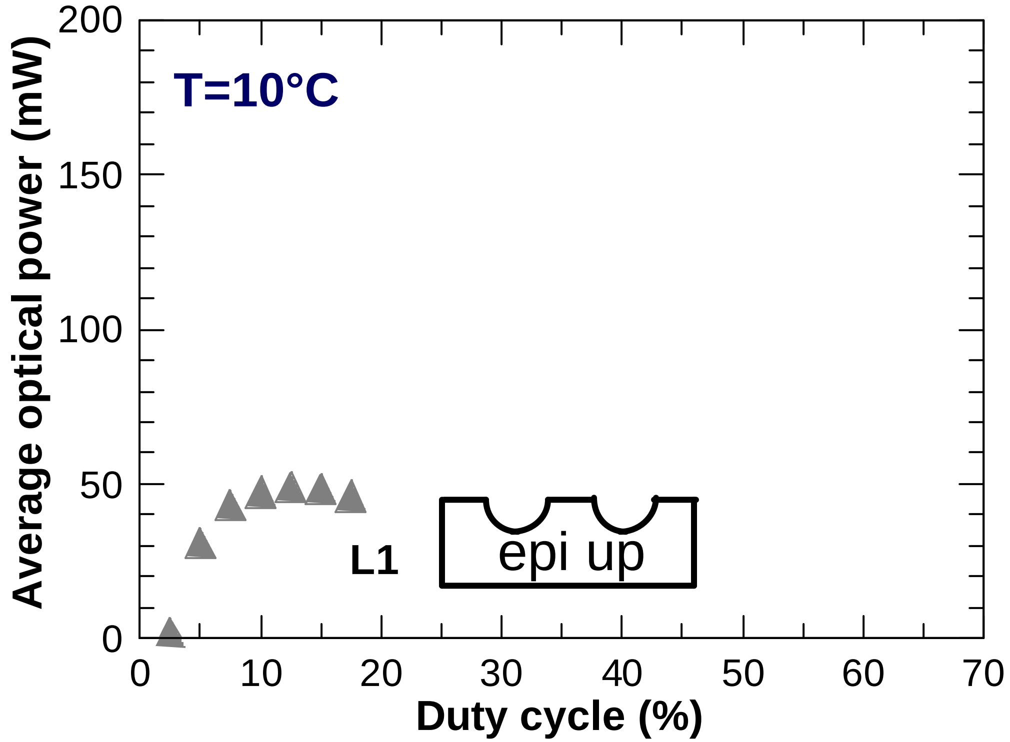
Best performances obtained on QCLs with this type of device

Slivken et al, APL (2004)

4 experimental arrangements:

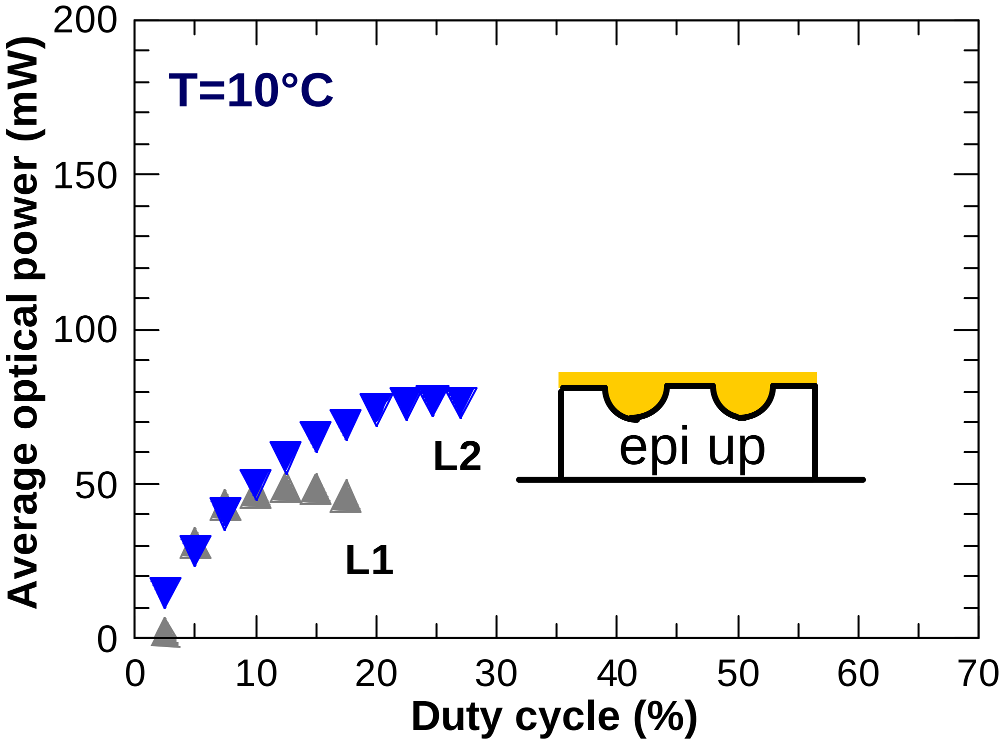


Effect of Thick electroplated Au



L1 ➡ P_{max}= 49mW for DC=12%

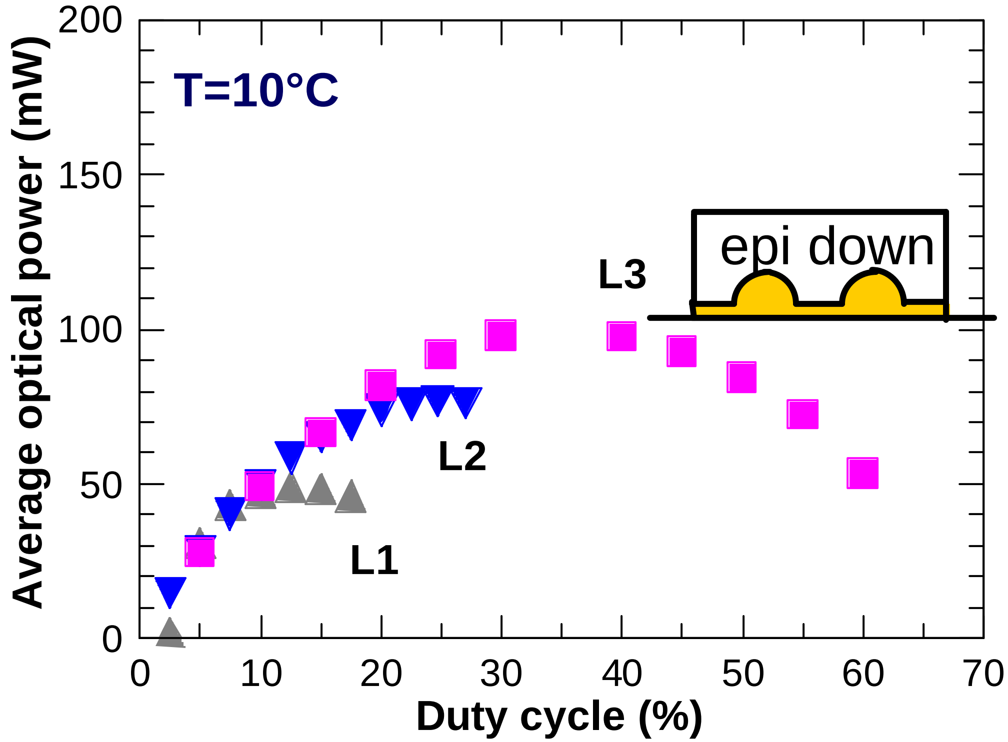
Effect of Thick electroplated Au



L1 ➡ P_{max}= 49mW for DC=12%

L2 ➡ P_{max}= 78mW for DC=25%

Effect of Thick electroplated Au

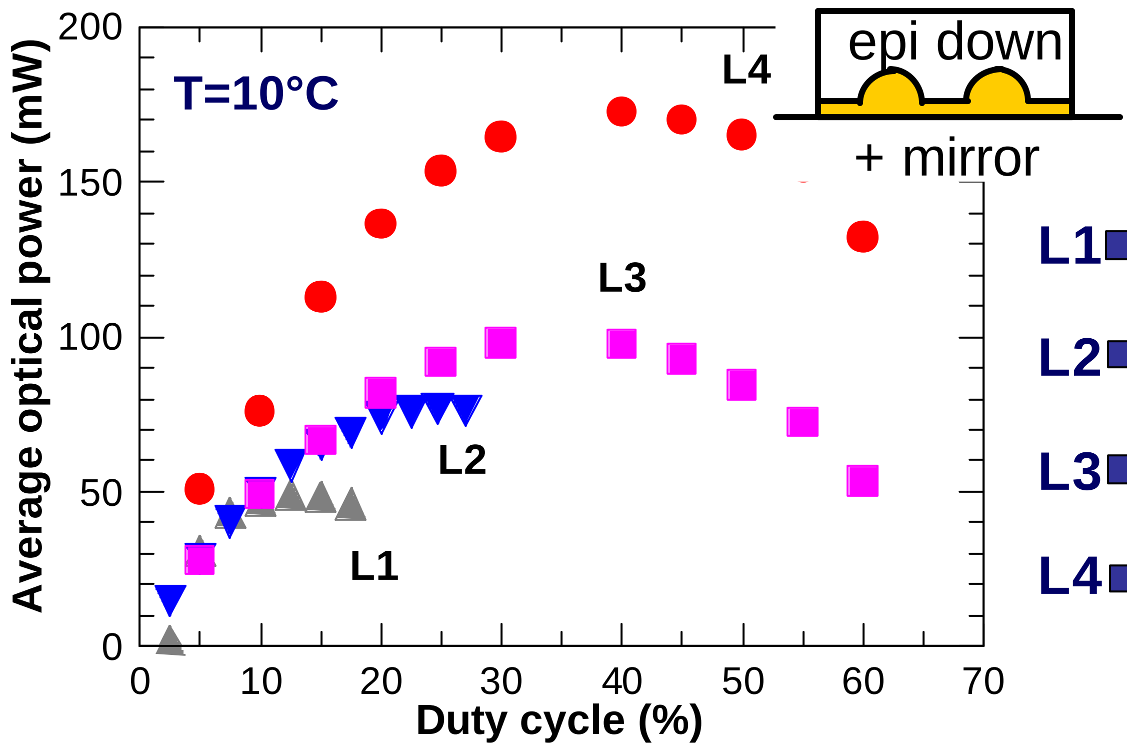


L1 ➔ P_{max}= 49mW for DC=12%

L2 ➔ P_{max}= 78mW for DC=25%

L3 ➔ P_{max}= 102mW for DC=37%

Effect of Thick electroplated Au



L1 ➡ P_{max}= 49mW for DC=12%

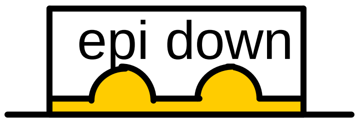
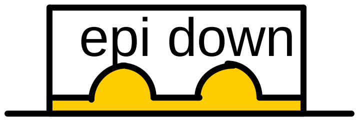
L2 ➡ P_{max}= 78mW for DC=25%

L3 ➡ P_{max}= 102mW for DC=37%

L4 ➡ P_{max}= 175mW for DC=40%

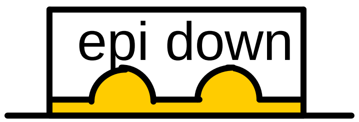
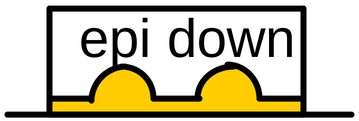
![III-V lab Alcatel-Thales]

Thick electroplated Au - Summary

		R_{th} (K.cm/ W)
L1		6
L2		2,9
L3		1,8
L4	 + mirror	1,8
Buried Heterostructure (Beck et al, Science295, 2002)		1,45

III-V lab
ALCATEL-THALES

Thick electroplated Au - Summary

		R_{th} (K.cm/ W)	Max. CW temperature
L1		6	–
L2		2,9	130K
L3		1,8	240K
L4	 + mirror	1,8	278K
Buried Heterostructure (Beck et al, Science 2002)		1,45	313K

PLAN

1. Introduction

2. Waveguide Optimisation in GaAs/AlGaAs QCLs

   GaAs based guides (plasmon enhanced) / Limitations
   AlGaAs and GaInP Guides

3. Enhancement of thermal dissipation properties of GaInAs/AlInAs/InP QCLs

   Selective current injection by proton implantation
   Thick electro-plated gold

4. Conclusion

Conclusion

- **Significant performance improvements realised in GaAs-based QCLs owing to waveguide optimisation**
  - **Use these waveguide on a bound to continuum structure**
- **Breakdown of selective current injection (H^+ implanted layers) in InP-based QCLs**
  - **Application of Fe-doped InP layer**
- **Significant thermal improvements realised with thick electroplated Au**
  - **R_{th} close to that of buried heterostructure**

Thick electroplated Au on selective current injection devices

Mid IR QCL Material ?

GaAs has an intrinsic lower gain than GaInAs (m*>m*)

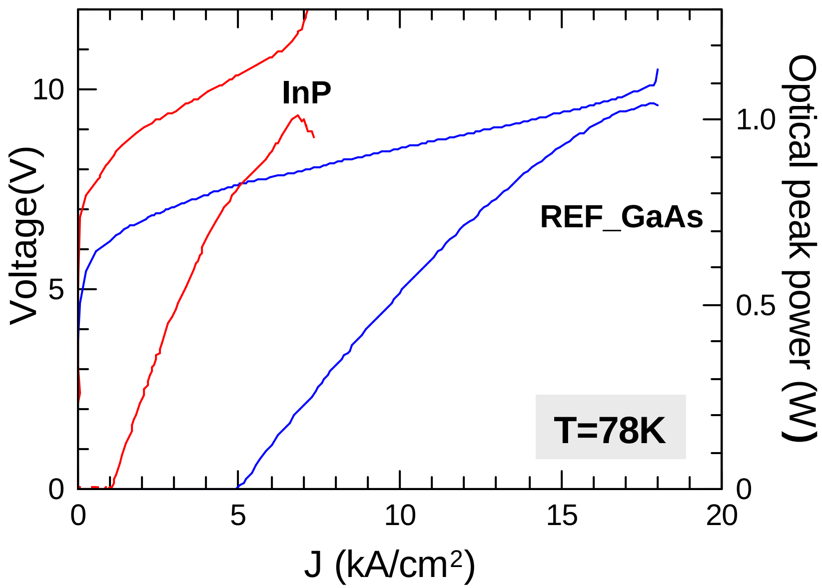
Increase in J_{th} → **$I_{operation}$** **(Small dynamic current range)**

↓

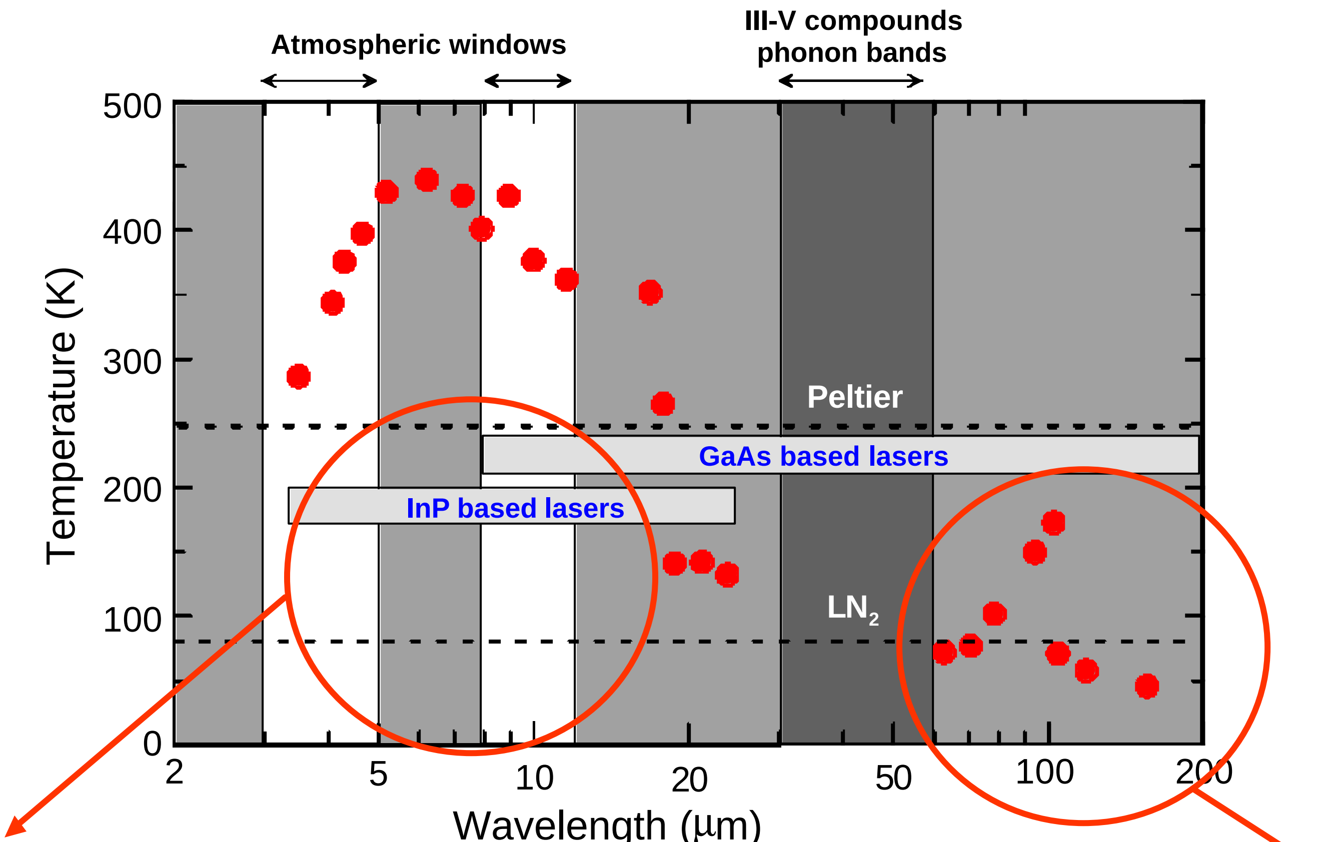
Higher doping in the active region and the claddings

← **Higher losses**

↑ (back to Increase in J_{th})



Which material for which wavelength ?



Mid Infrared :

AlInAs/GaInAs/InP QCLs

InAs/AlSb QCLs

Far Infrared (THz) :

GaAs/AlGaAs QCLs

Contributions to this work...

Thesis directed by Carlo Sirtori

Simulation direction: A. De Rossi

Epitaxy realised by: X. Marcadet (MBE)
M. Lecomte, O. Parillaud (MOVPE)

Devices processing: M. Calligaro, M. Carbonnelle
Y. Robert, C. Darnazian

Characterisations realised with the help of :

C. Faugeras, L. Sapienza,
S. Forget, E. Boër-Duchemin