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MPQ

UNIVERSITÉ Paris 7 Denis DIDEROT

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

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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

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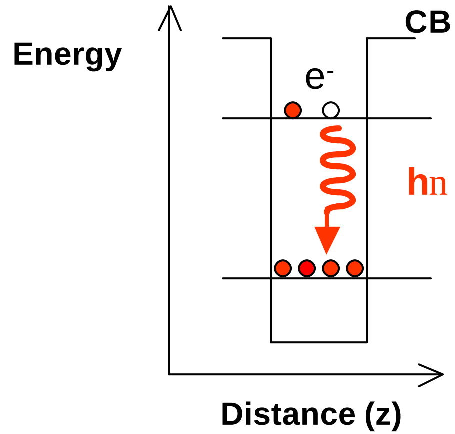
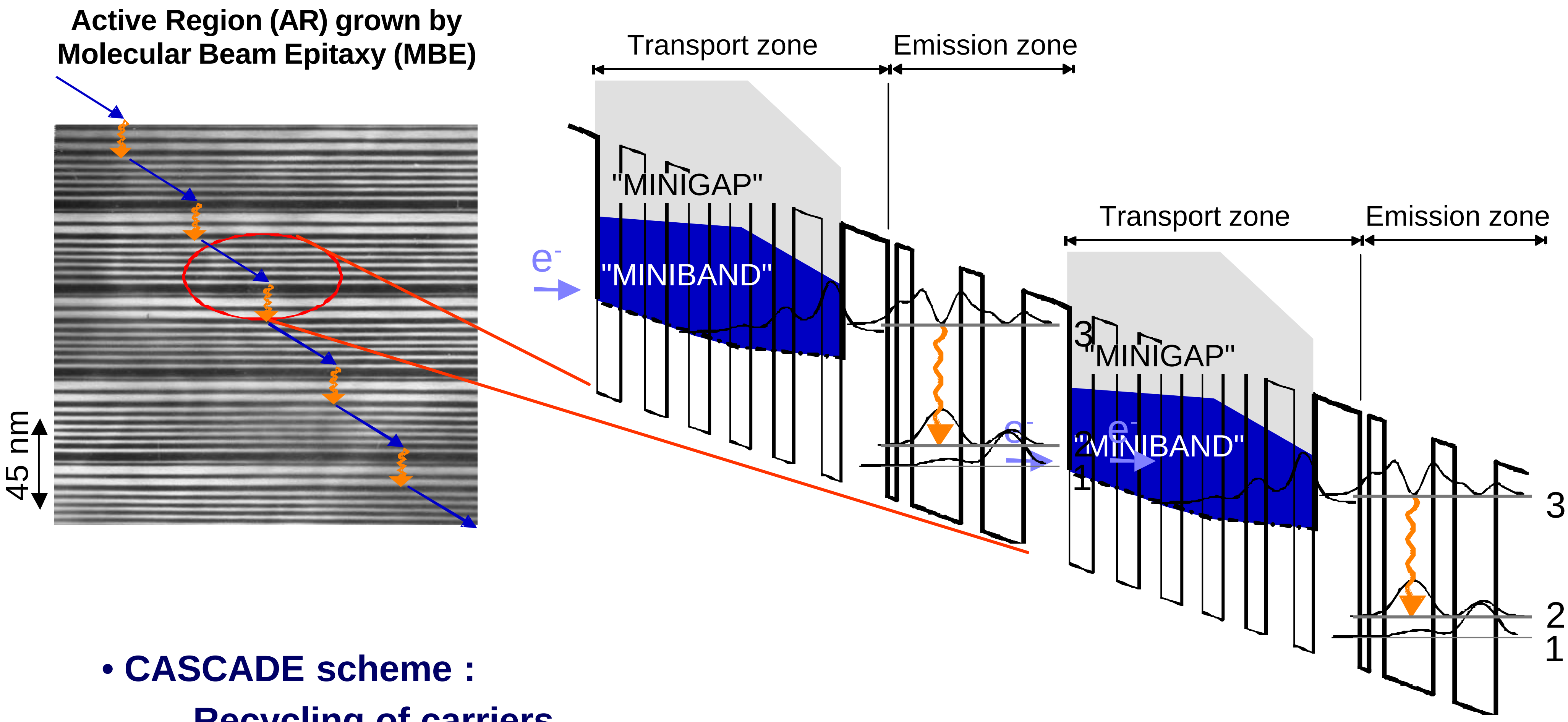
Main Properties

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



Quantum Cascade Lasers (QCLs)



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

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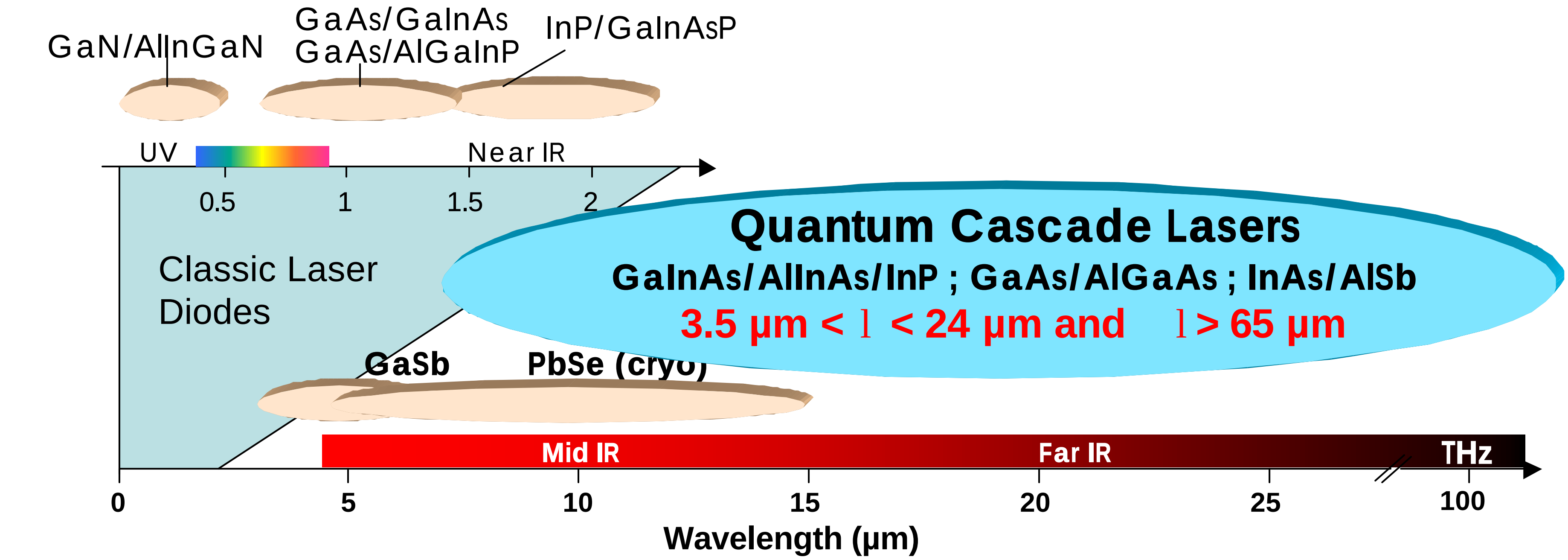
Spectral range of QCLs



Applications:

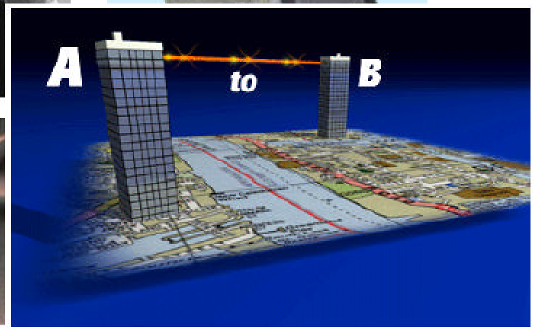
- **Spectroscopy and high sensitive Gas detection**

  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

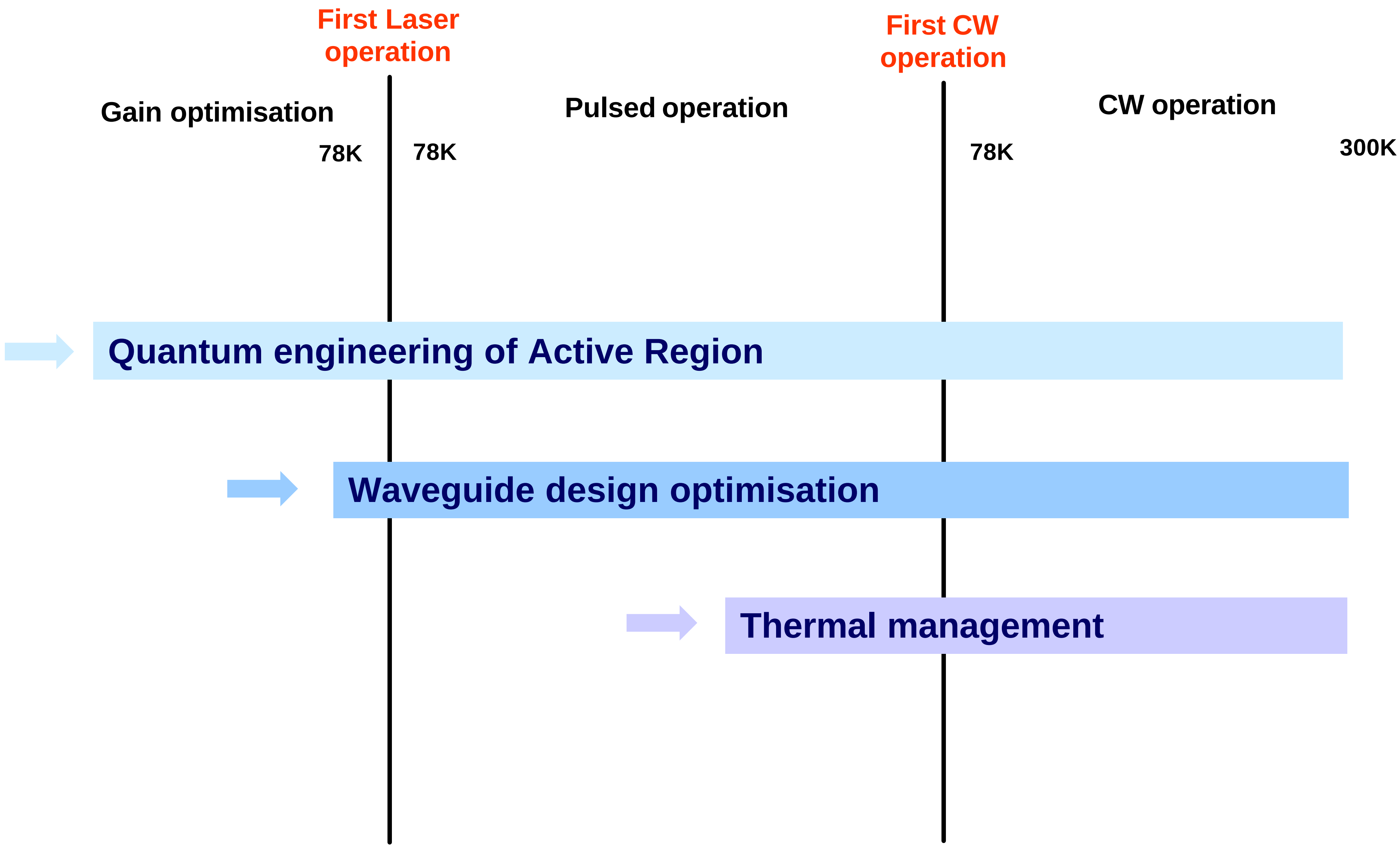
Thales / CEM²
QCL in InAs/AlSb
2003

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

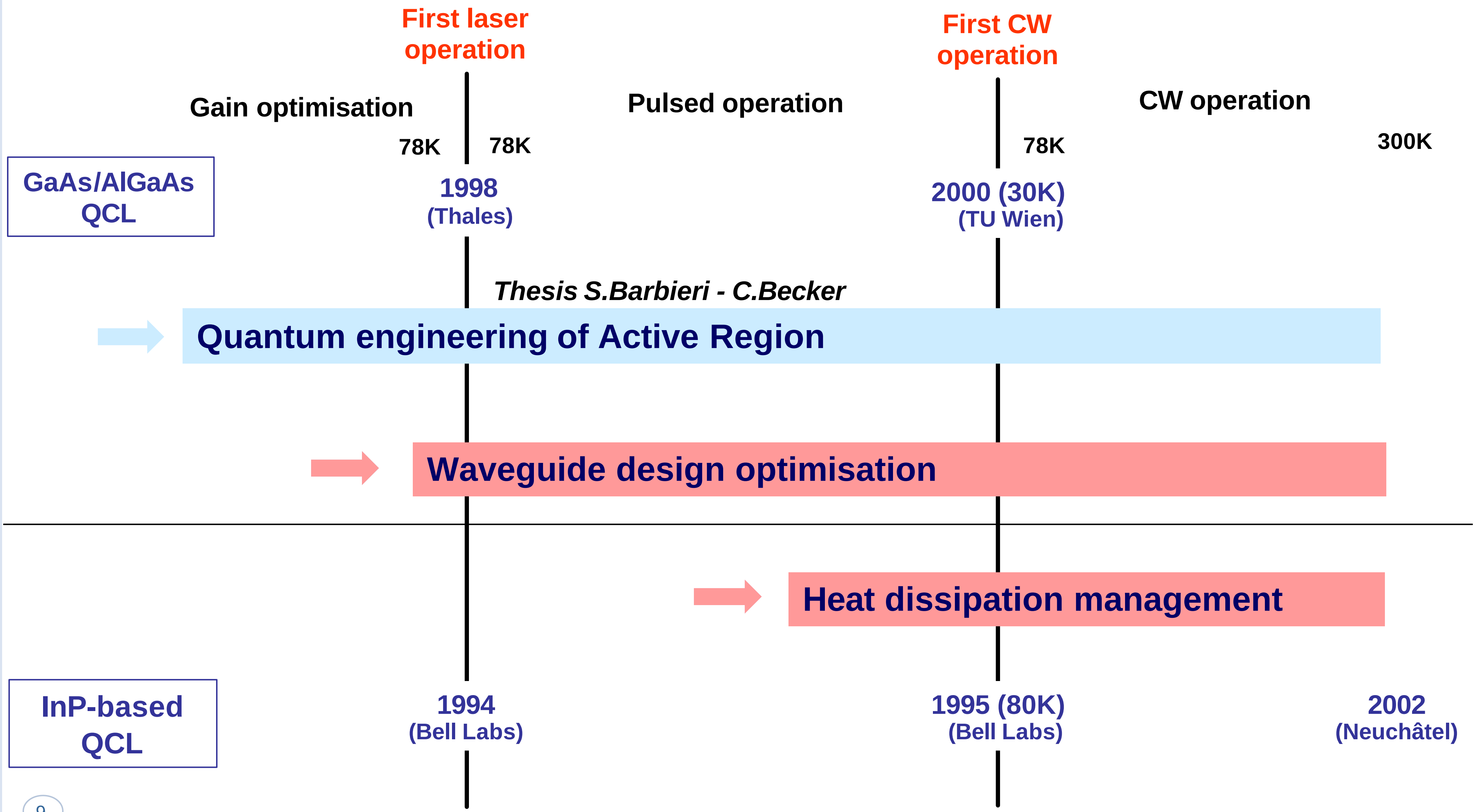
150K CW operation QCL in GaAs/AlGaAs QCL

CW: Continuous Wave

From intersubband emission to CW laser operation



From intersubband emission to CW laser operation



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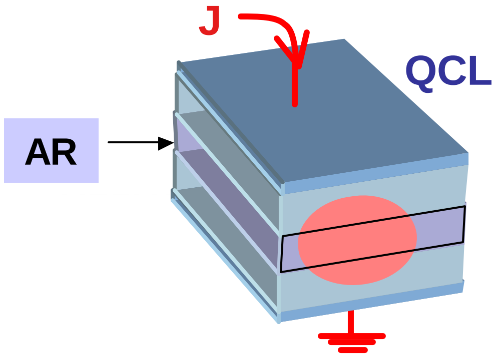
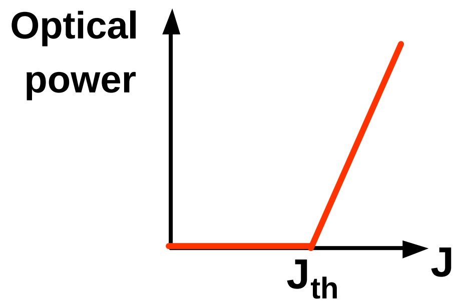


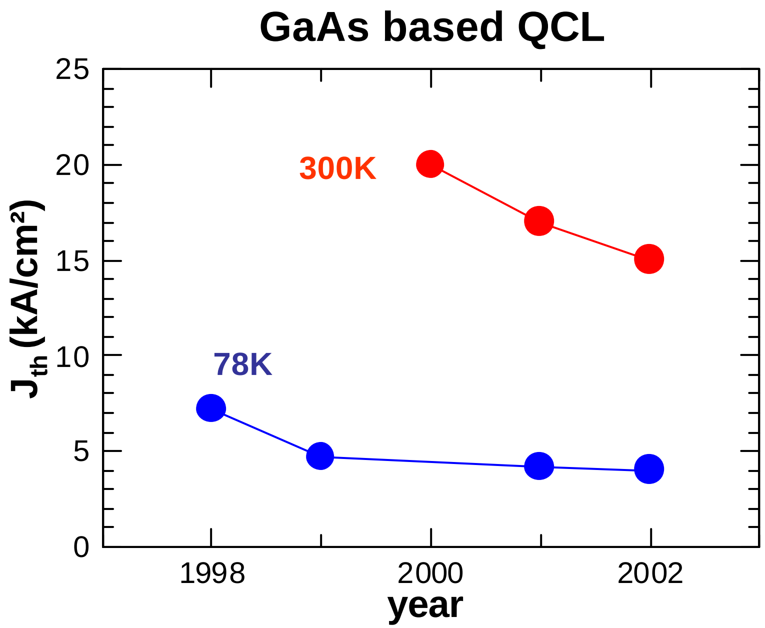
Pulsed operation QCL devevopment: Reduction of the threshold current density J_{th}

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

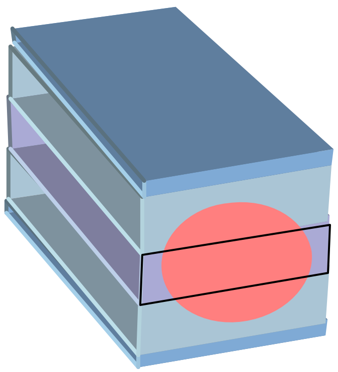


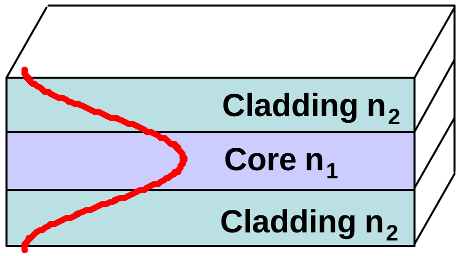
Quantum engineering of Active Region : g

Waveguide design optimisation : a_{wg}, G



Waveguide principle





Guiding condition : $n_1 > n_2$

Waveguide optimisation by numerical simulations :

- **<u>1D Simulations :</u> 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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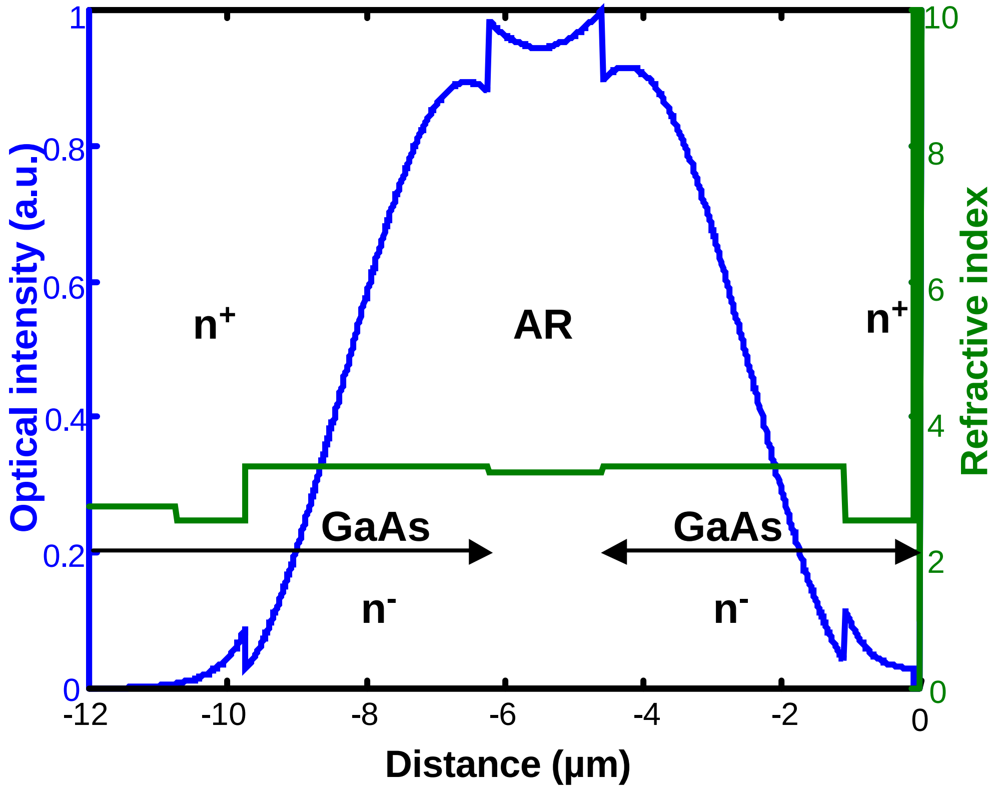
Current GaAs QCL waveguides (1)

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

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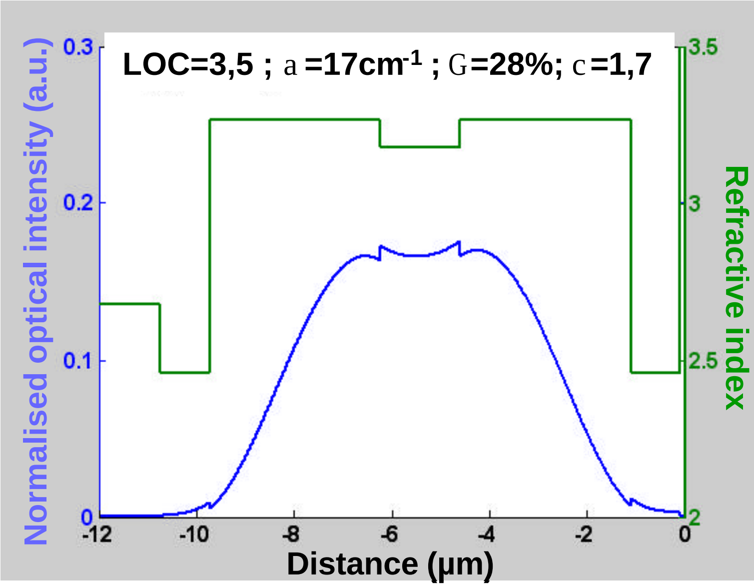
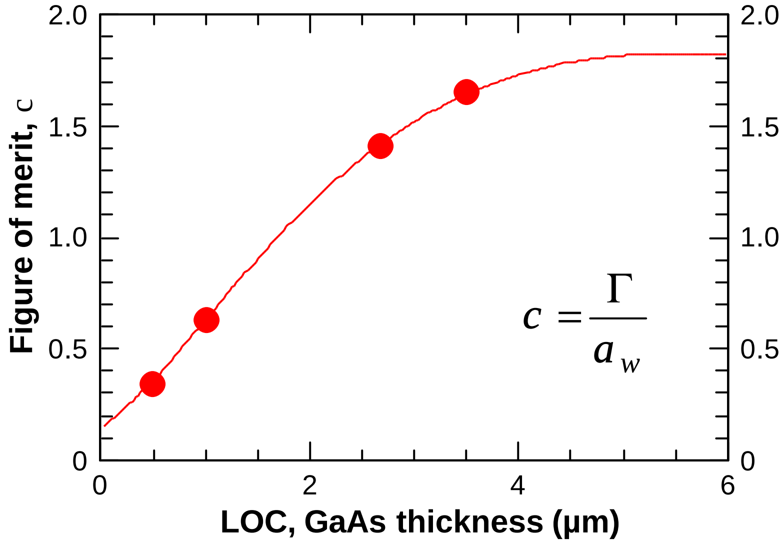
Current GaAs QCL waveguides (2)





The χ optimisation is a trade-off between :

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

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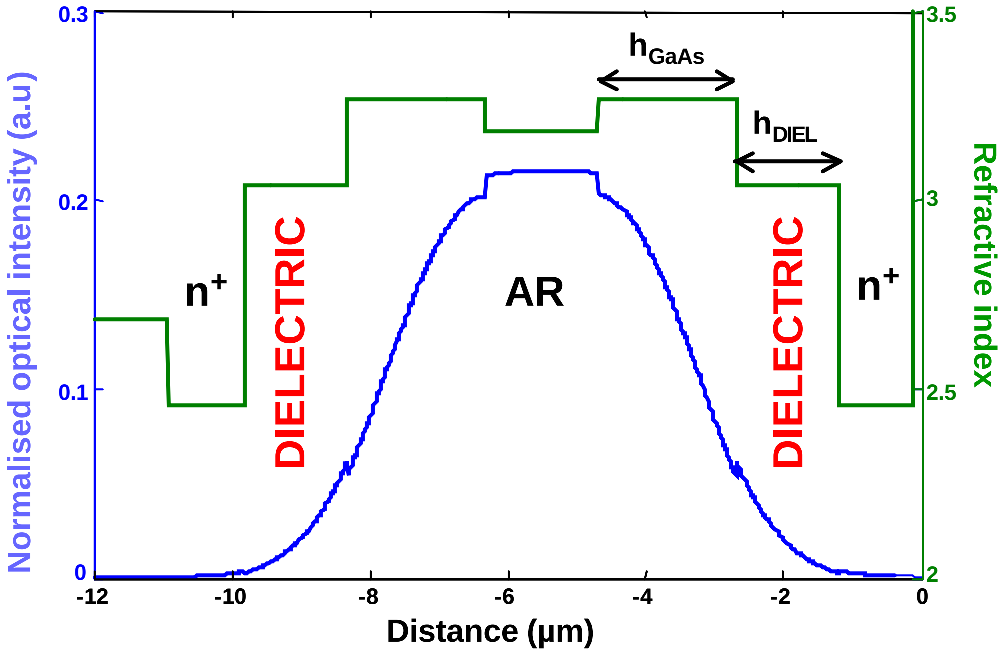
Dielectric waveguide optimisation

NECESSITY TO REDUCE OPTICAL LOSSES FROM CLADDINGS



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

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

Maximum growth thickness ~10µm

➔ $h_{GaAs}+h_{Diel}=3{,}5\mu m$

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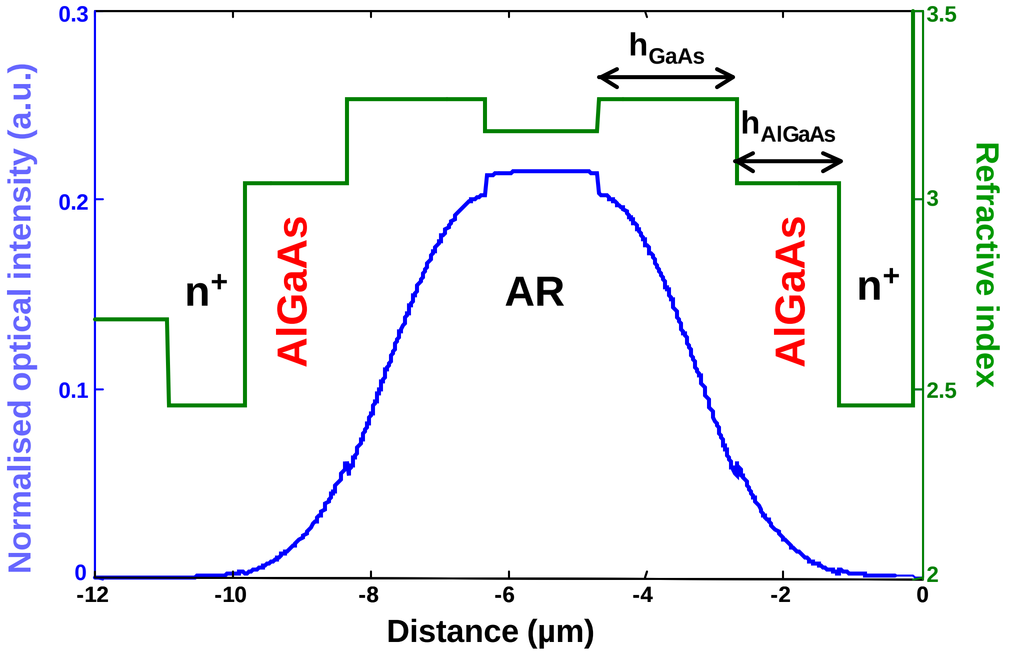
$Al_xGa_{1-x}As$ cladding waveguides

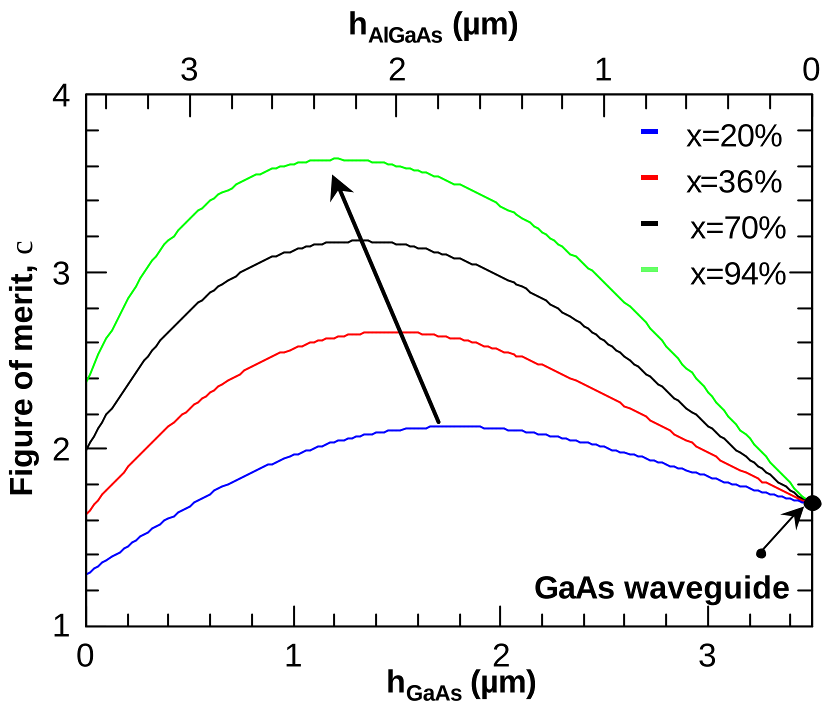
With x_{Al} ↗:

Þ $\Delta n_{GaAs/AlGaAs}$ ↗ Þ Γ ↗

Þ α ↘ (mode overlap with highly doped layers reduced)

} Þ c=G/a ↗





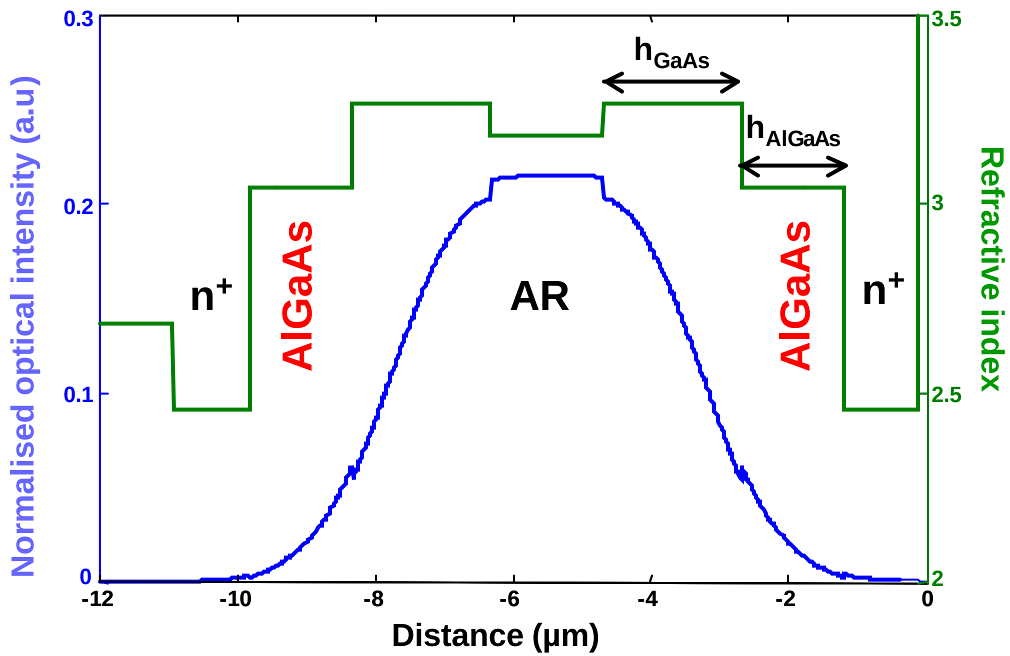
$Al_xGa_{1-x}As$ cladding waveguides

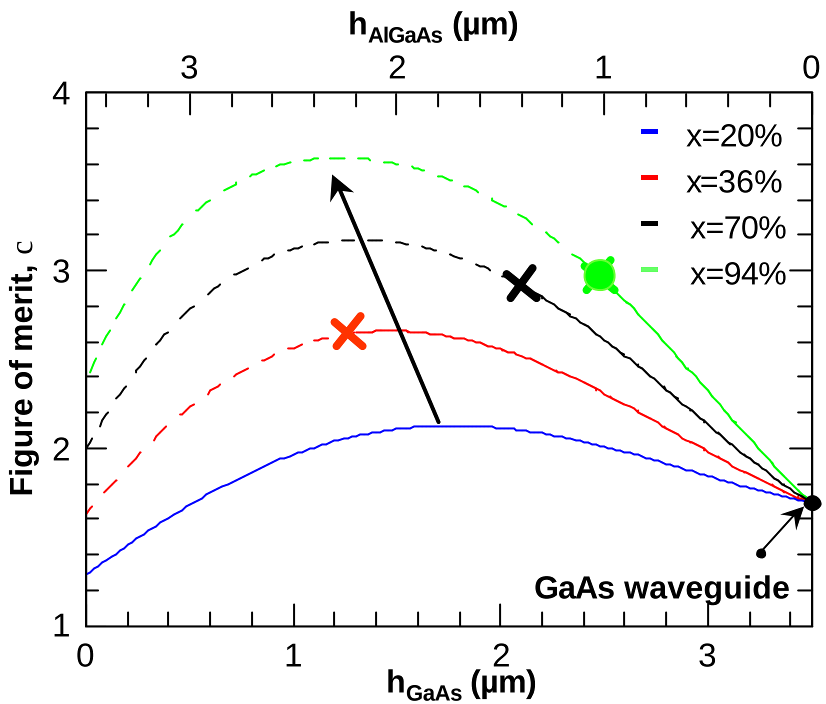
With x_{Al} ↗:

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

!

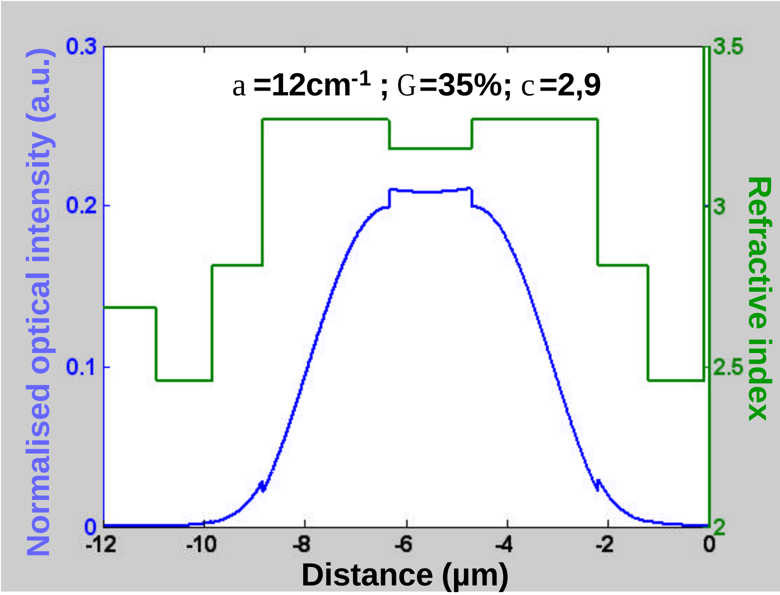
<u>Limitations :</u> lattice mismatch constraint ➔ $Al_xGa_{1-x}As$ thickness limit ~$1/x_{Al}$





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

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



c=2.9

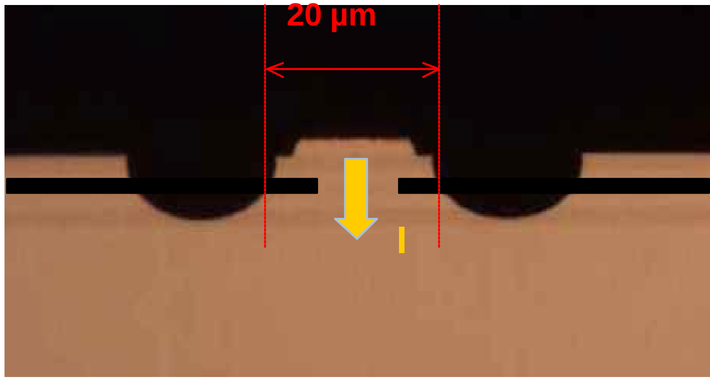
➔ J_{th} ~2 times smaller than that of the GaAs plasmon enhanced waveguide.

2 devices grown and processed identically:

➔ **GaAs : GaAs waveguide**

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

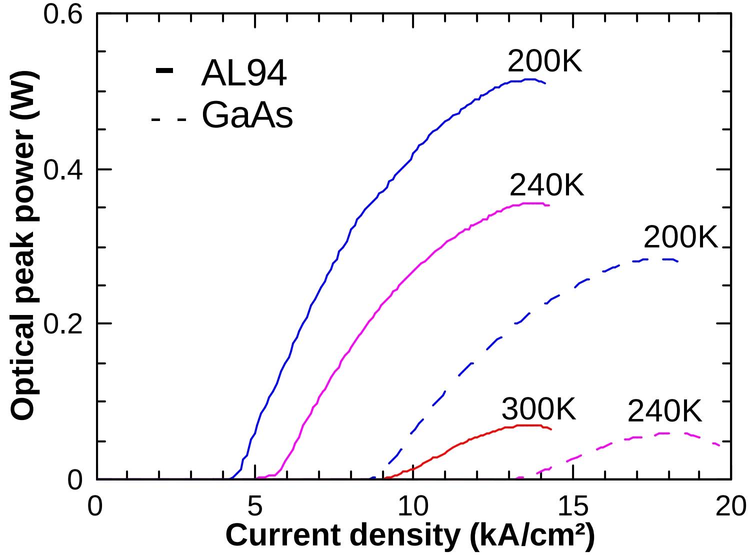
- Identical 3 quantum-well AR (same growth set)
- Double trench ridge devices
- H^+ implanted for selective current channelling
- Low duty cycle to avoid device heating



H^+ implantation (insulating)

QCL AL94

5kHz-100ns



Good optical performances for QCL AL94:

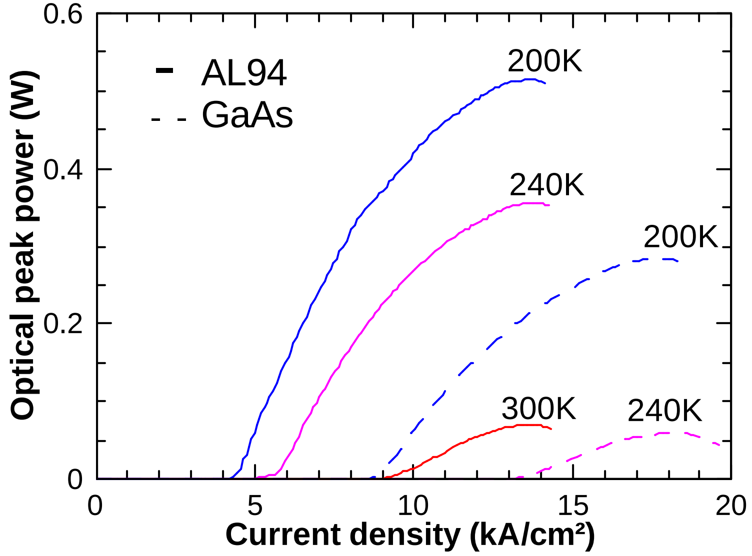
➔ **Significant reduction of J_{th}**

➔ **Agreement with simulations:**

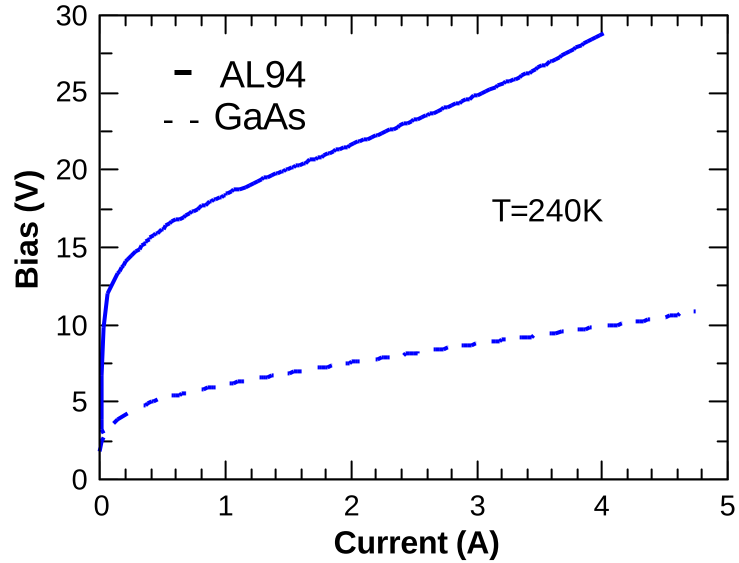
$J_{th}(GaAs) / J_{th}(AL94) \approx \chi(AL94) / \chi(GaAs) \approx 2$

➔ **Higher optical peak power**

QCL AL94



5kHz-100ns



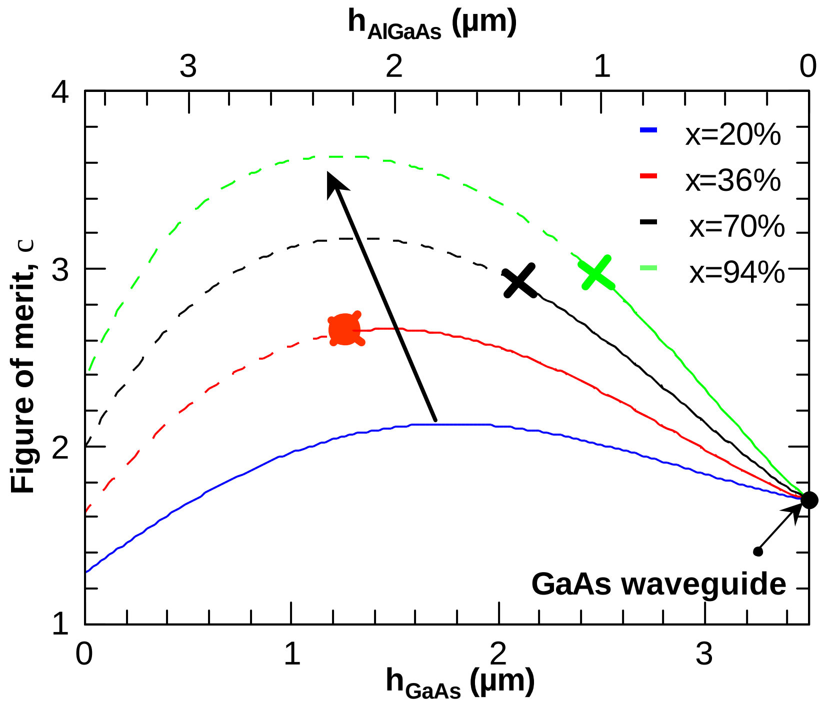
Good optical performances for QCL AL94:

- ➔ **Significant reduction of J_{th}**
- ➔ **Agreement with simulations:**
  - ***J_{th}(GaAs) / J_{th}(AL94) @ c(AL94) / c(GaAs) @ 2***
- ➔ **Higher optical peak power**
- ➔ **300K operation**

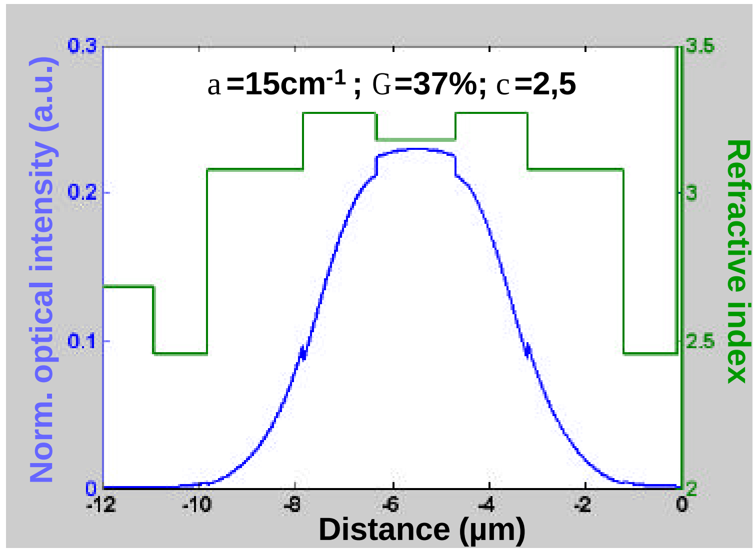
Poor electrical characteristics for QCL AL94:

- ➔ **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

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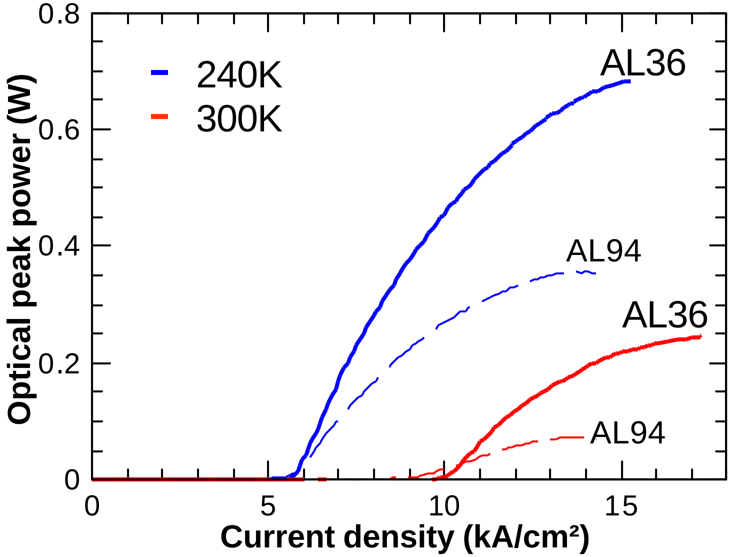
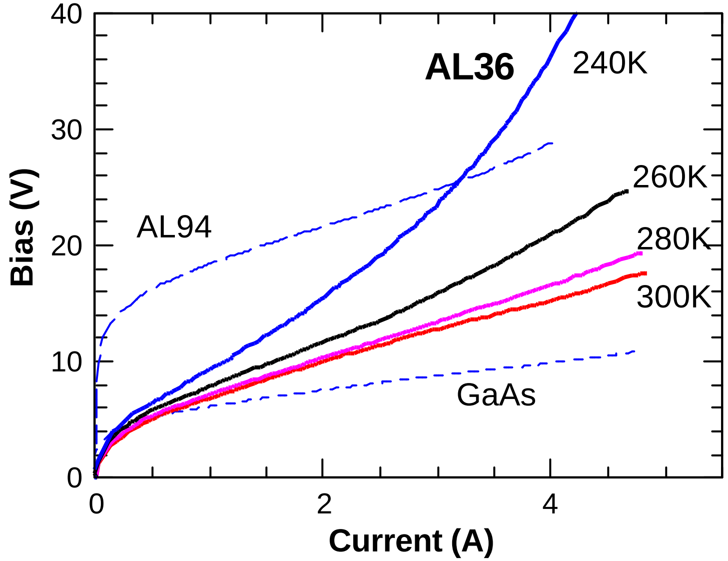
QCL AL36



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

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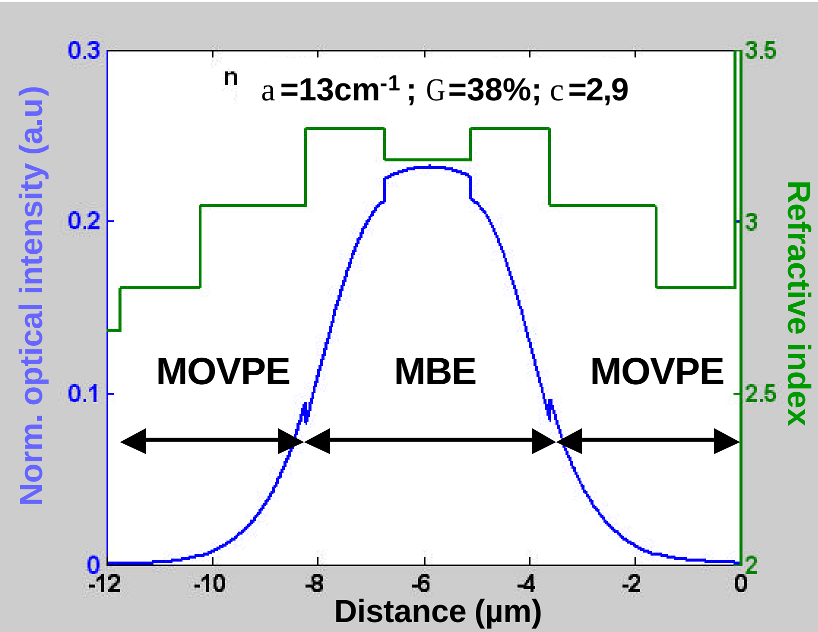
$Ga_{0.51}In_{0.49}P$ cladding waveguides

- **$Ga_{0.51}In_{0.49}P$ 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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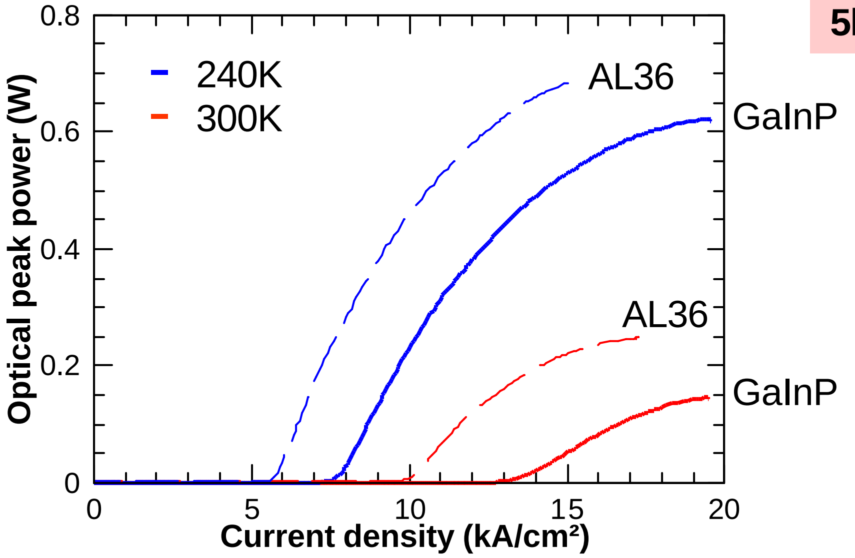
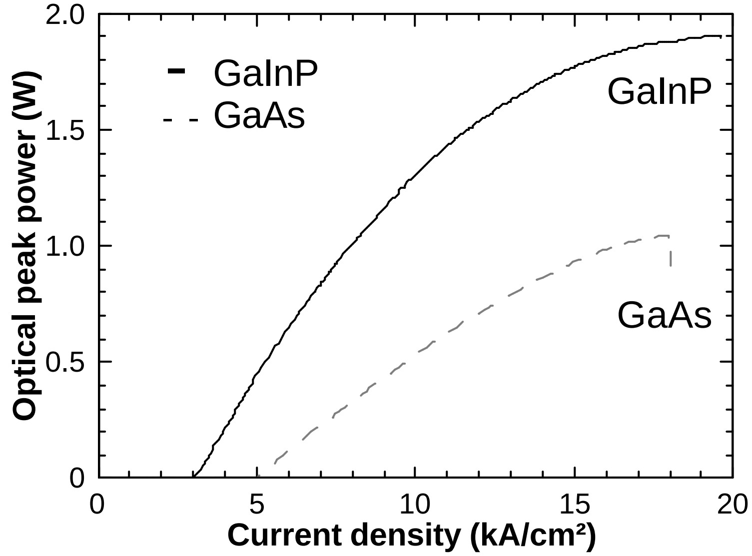
QCL GaInP

5kHz-100ns



T=78K



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**

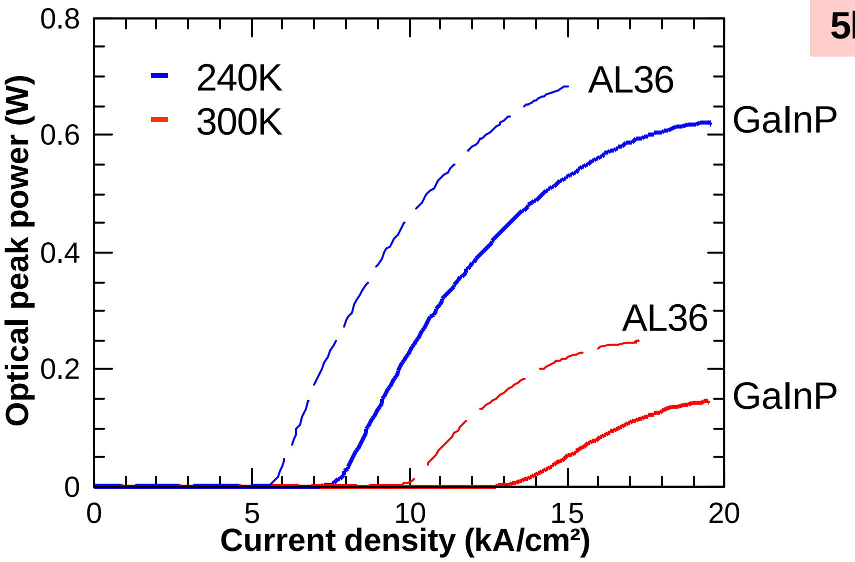
  P_{max}(GaInP)=1,9W at 78K

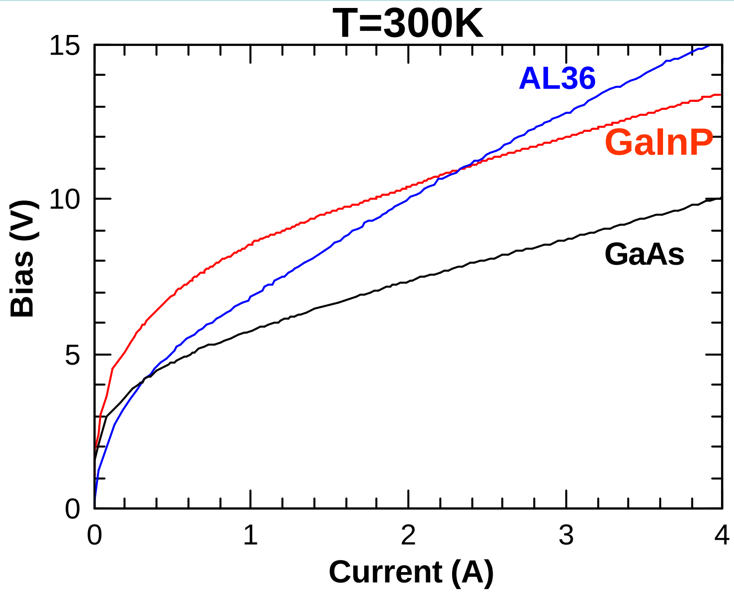
- ➔ **Optical peak lower than QCL AL36 at RT**

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

QCL GaInP

5kHz-100ns





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*

Electrical characteristics :

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

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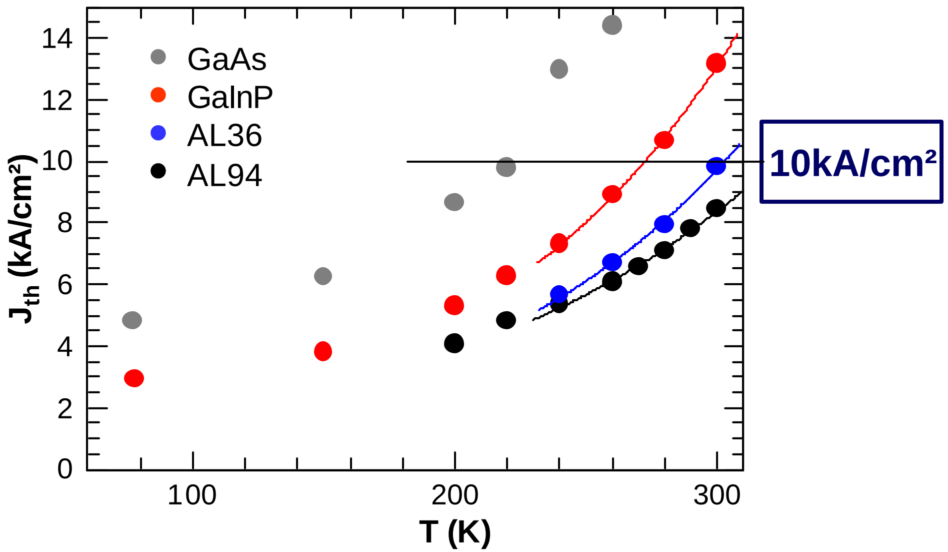
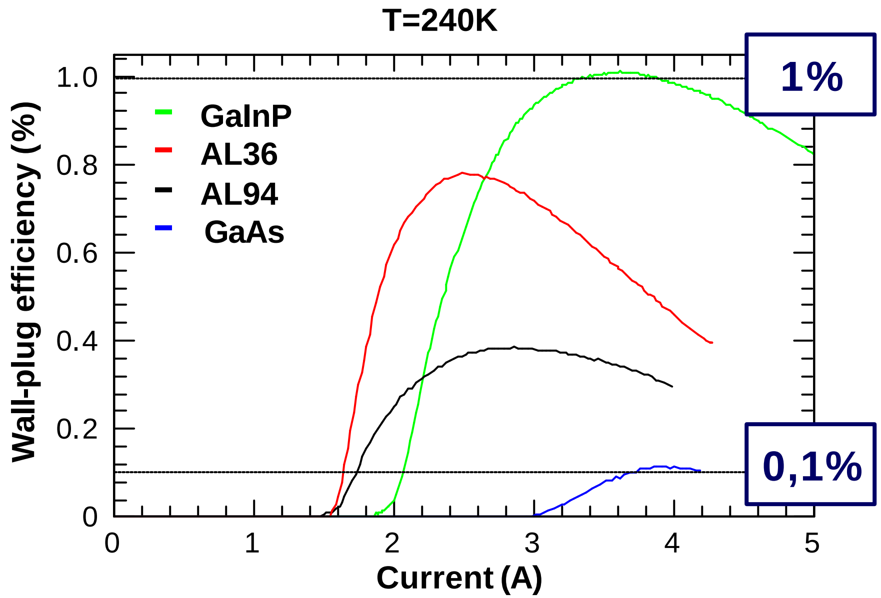
Summary of laser performances





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

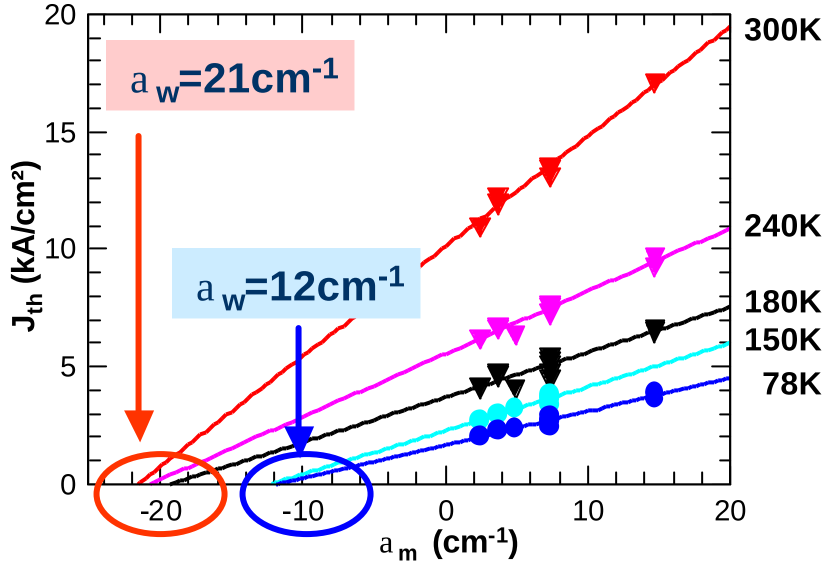
Best QCLs :
QCL AL36 for T> 250 K
QCL GaInP for T< 250 K

Waveguide loss measurements

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

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

QCL GaInP



	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

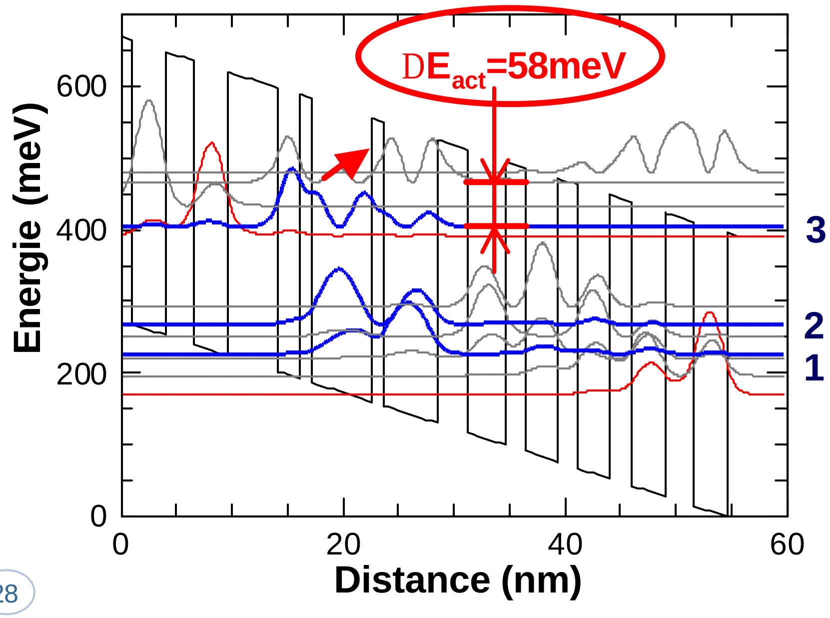
Reduction of a_w at low temperature compared to QCL GaAs

Gain coefficient

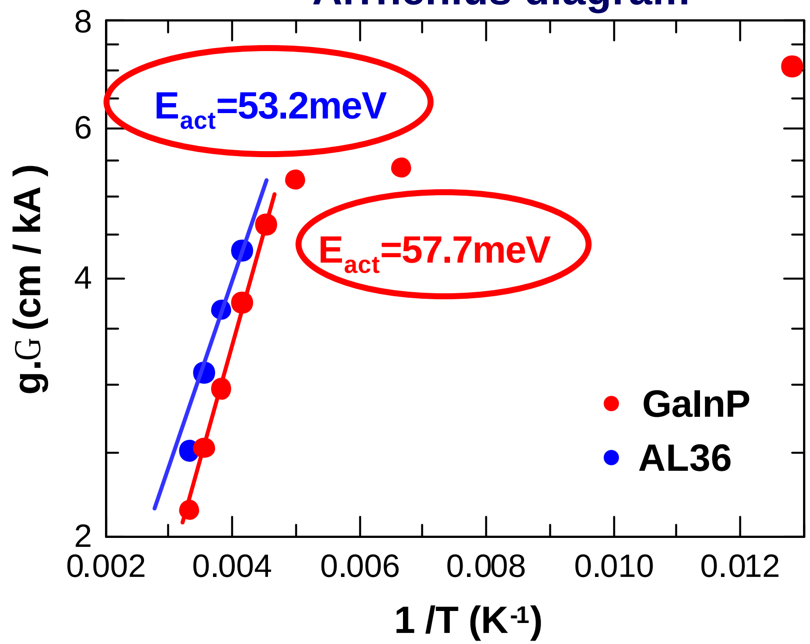
$J_{th}=f(a_{m})$ plot ⇨ $gG=f(T)$

➡ Observation of 2 operating regimes

Carrier leakage into the continuum ?



Arrhenius diagram



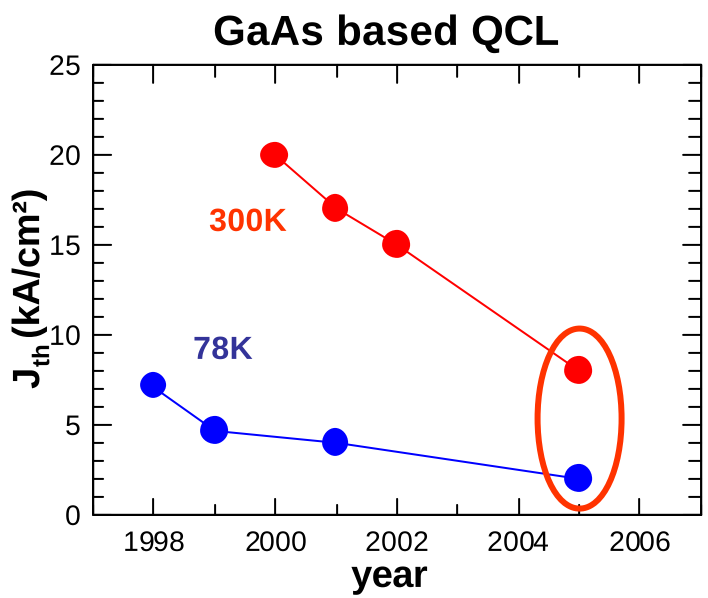
➡ Carrier leakage into the continuum

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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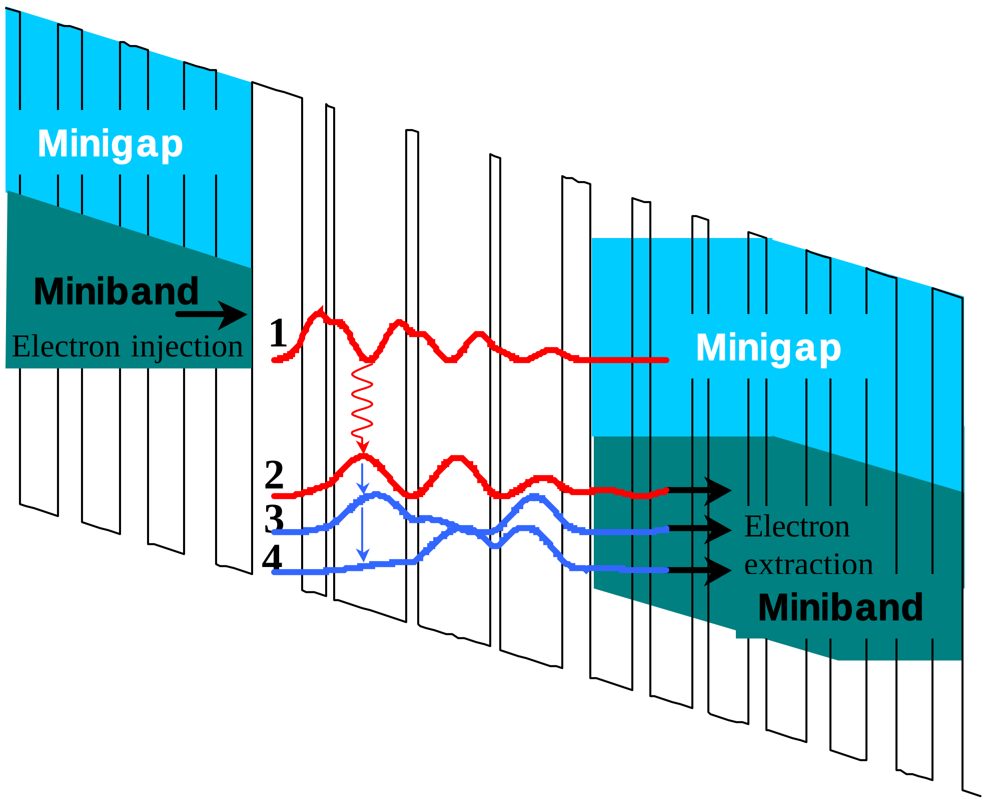
Application to InP-based QCLs

Active Region: l ~9µm

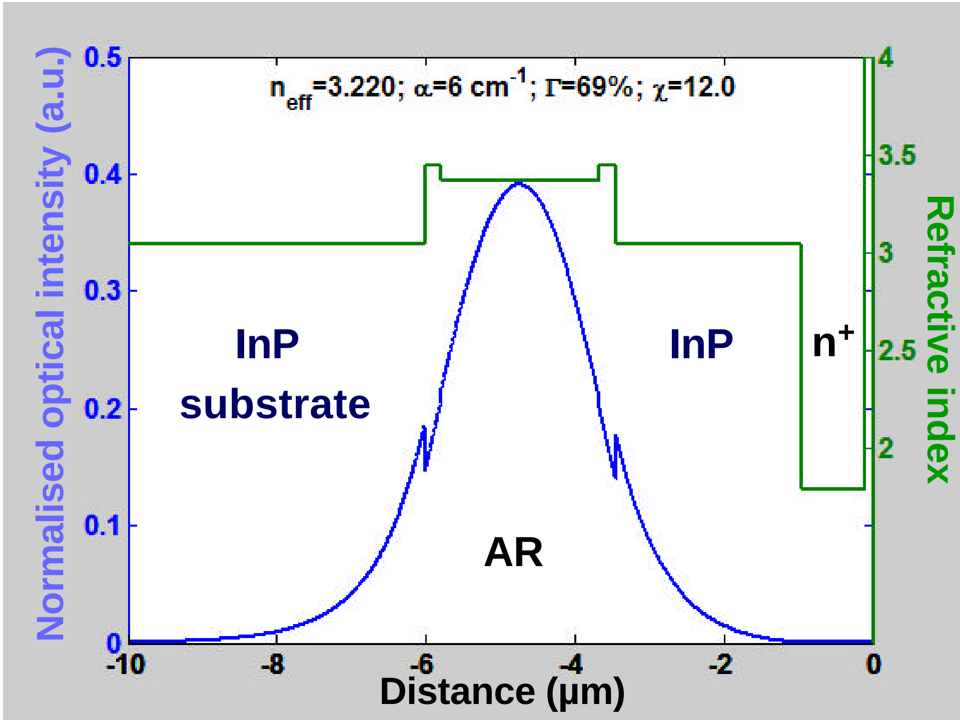
4 Quantum Wells



Vertical Waveguide Structure: c~12

G~69%

a ~6 cm^{-1}



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

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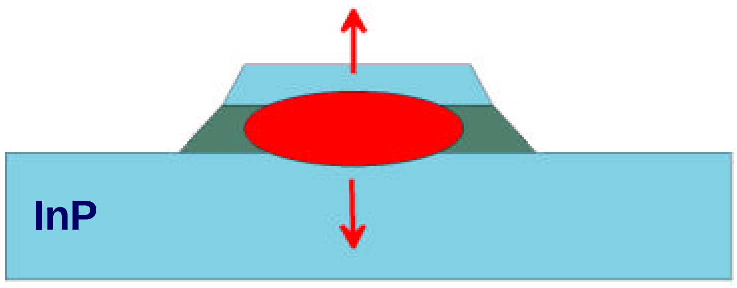
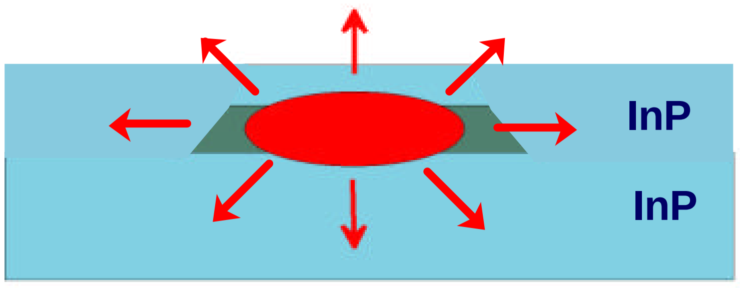
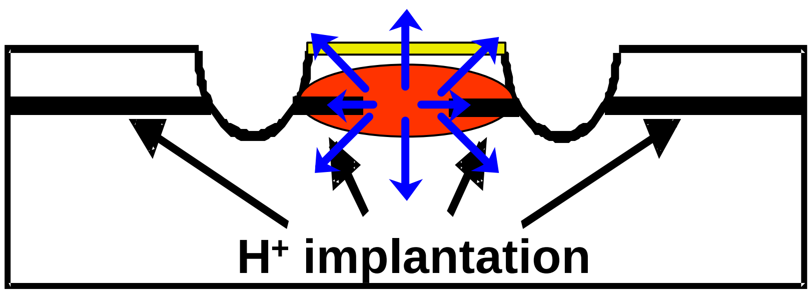
Heat management in QCLs



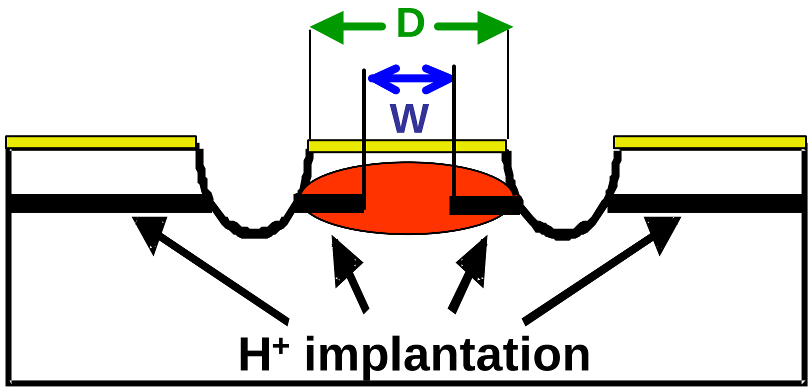
InP based QCLs

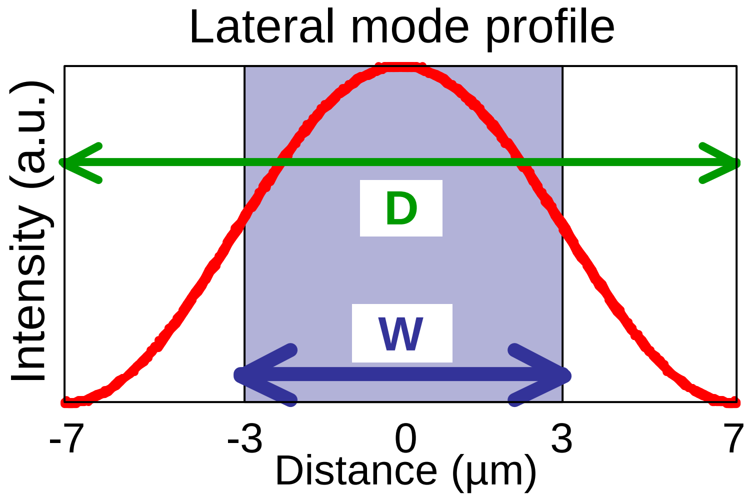


GaAs based QCLs



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**

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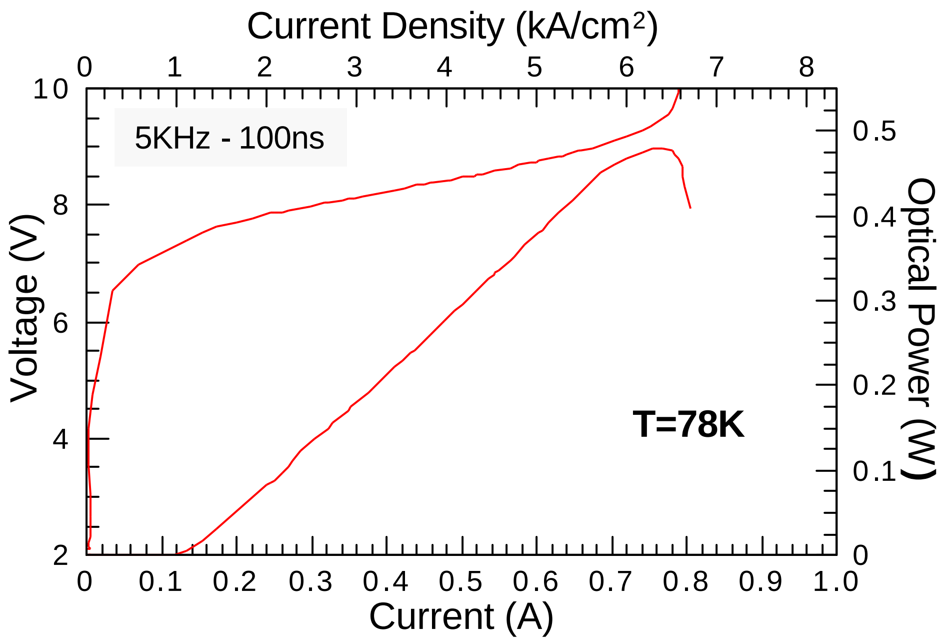
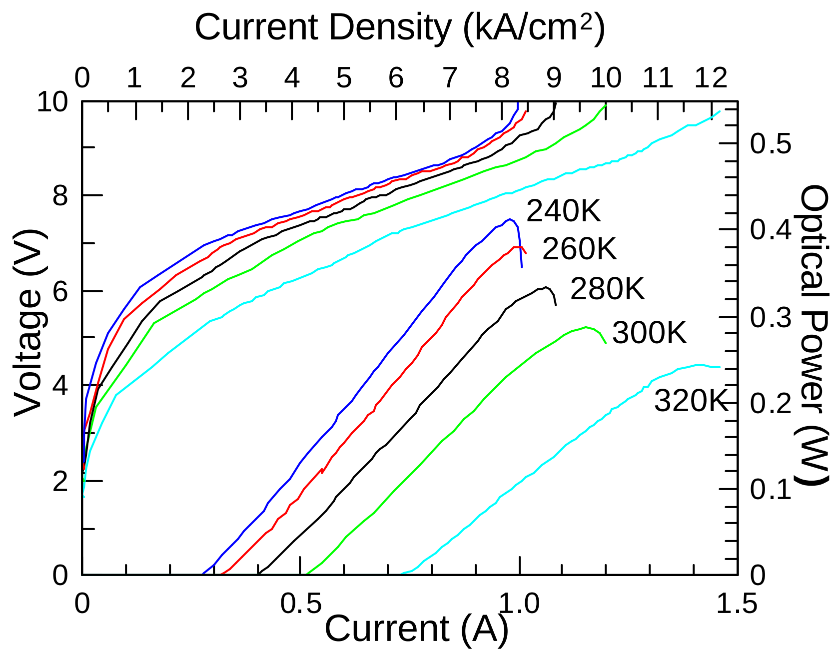
Selective current injection in InP QCLs: L-I-V pulsed characteristics





@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

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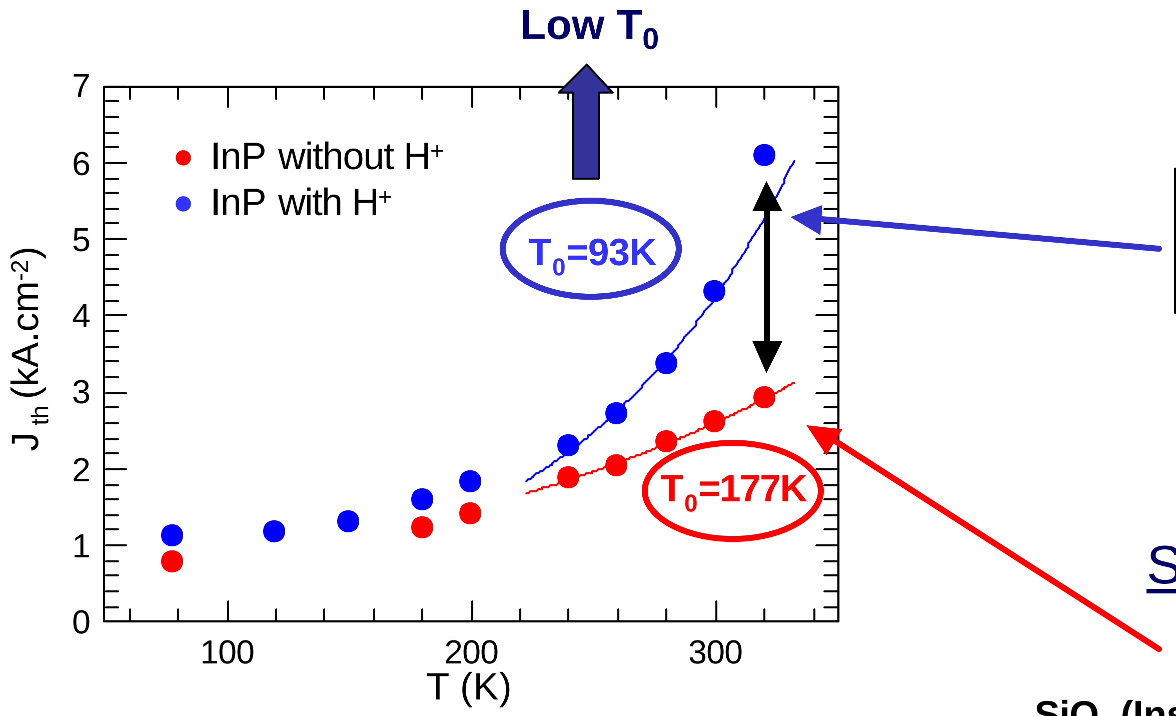
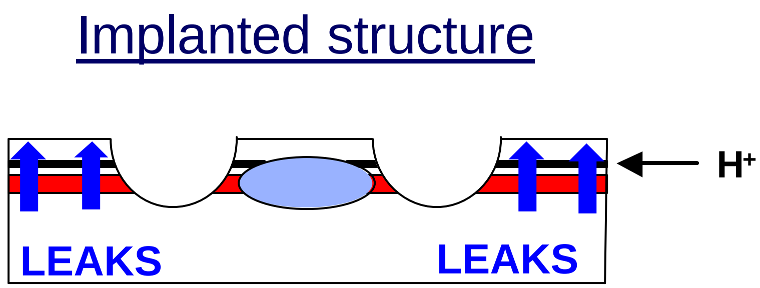
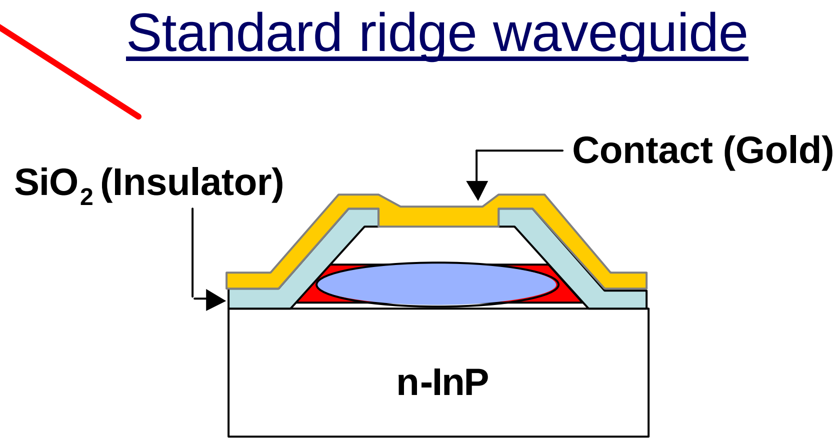
T_0 characteristics

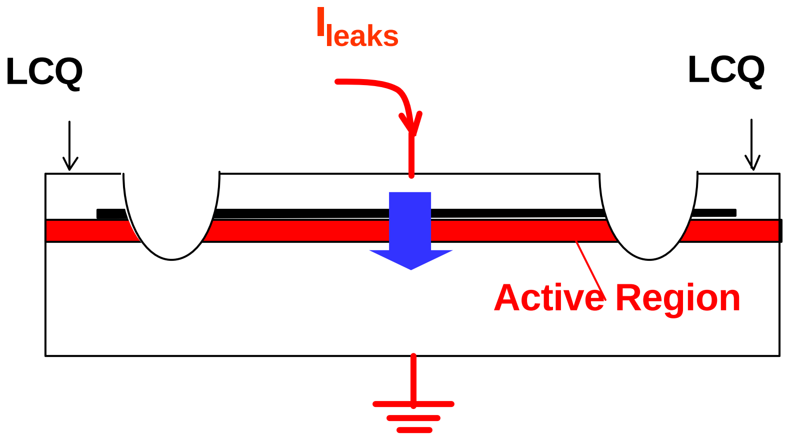


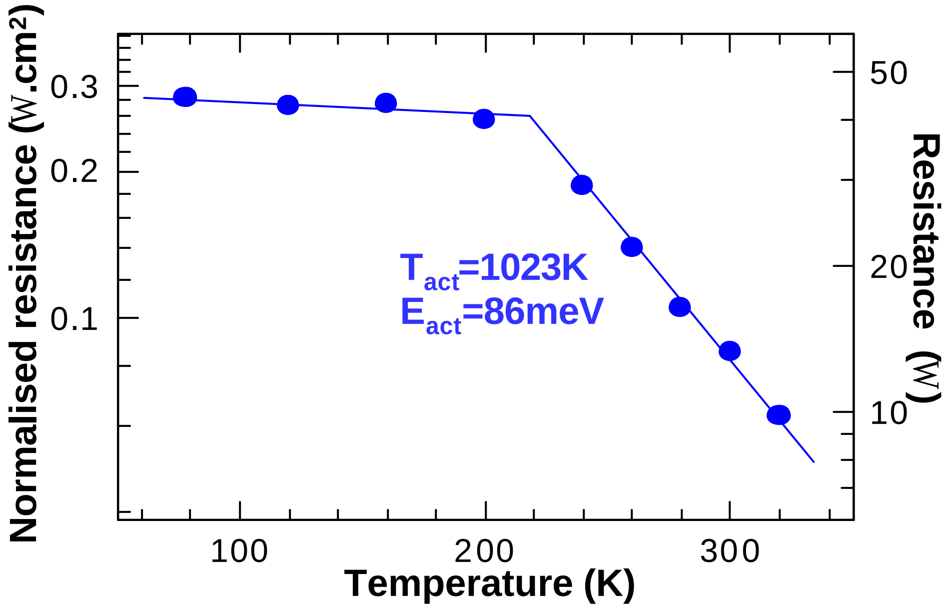




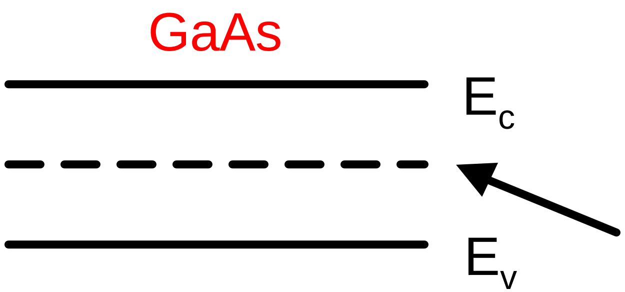
T_0 : Characteristic temperature
from fit : $J_{th} = J_{th0} \cdot \exp(T/T_0)$

Current leakage – implantation breakdown

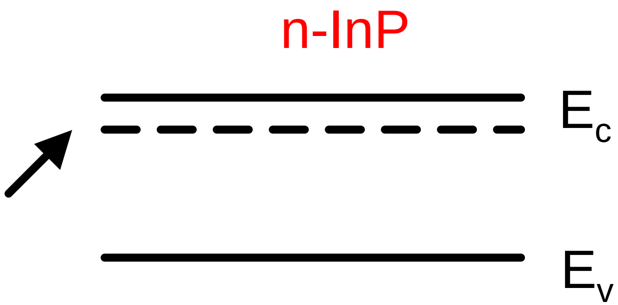




H^+ implantation creates shallow defects in n-doped InP material



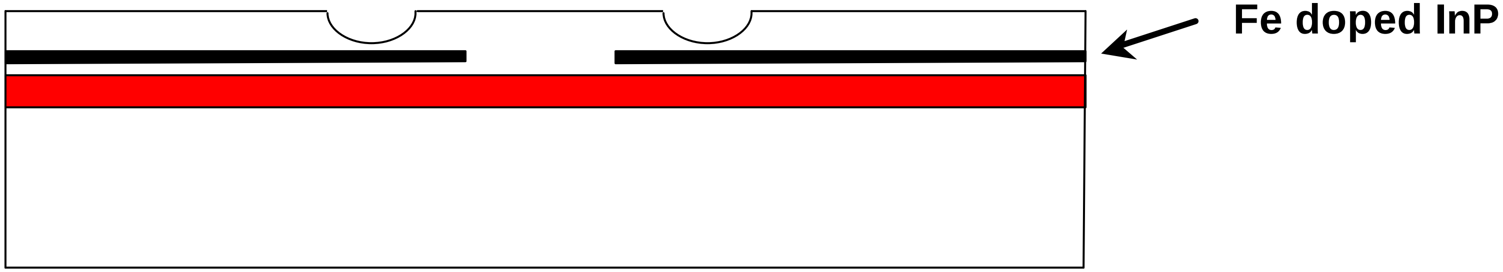
H^+ implantation works well in GaAs but not in n-InP



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



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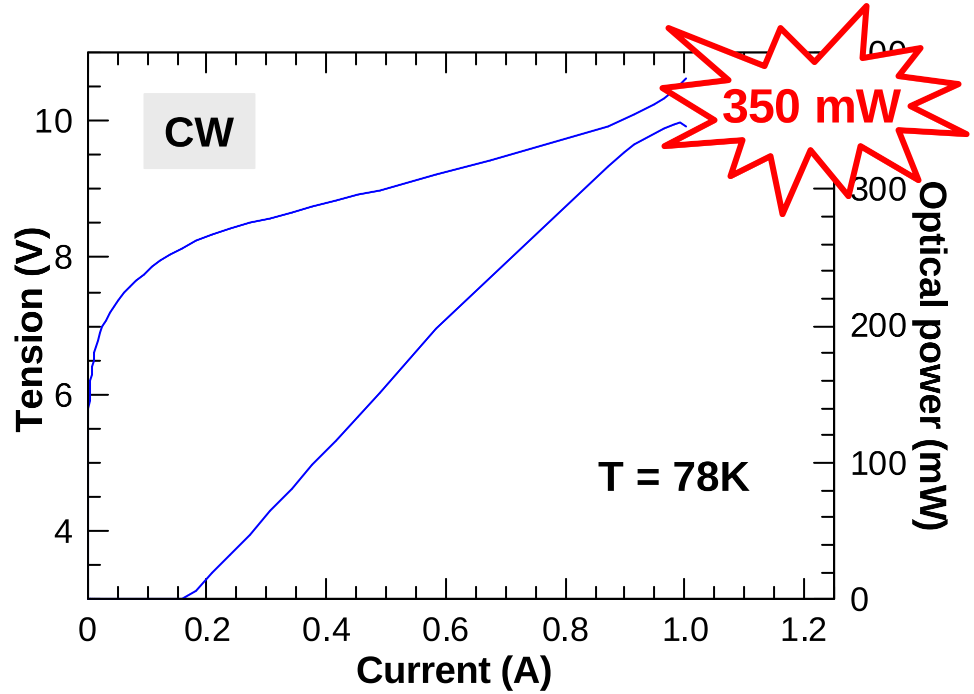
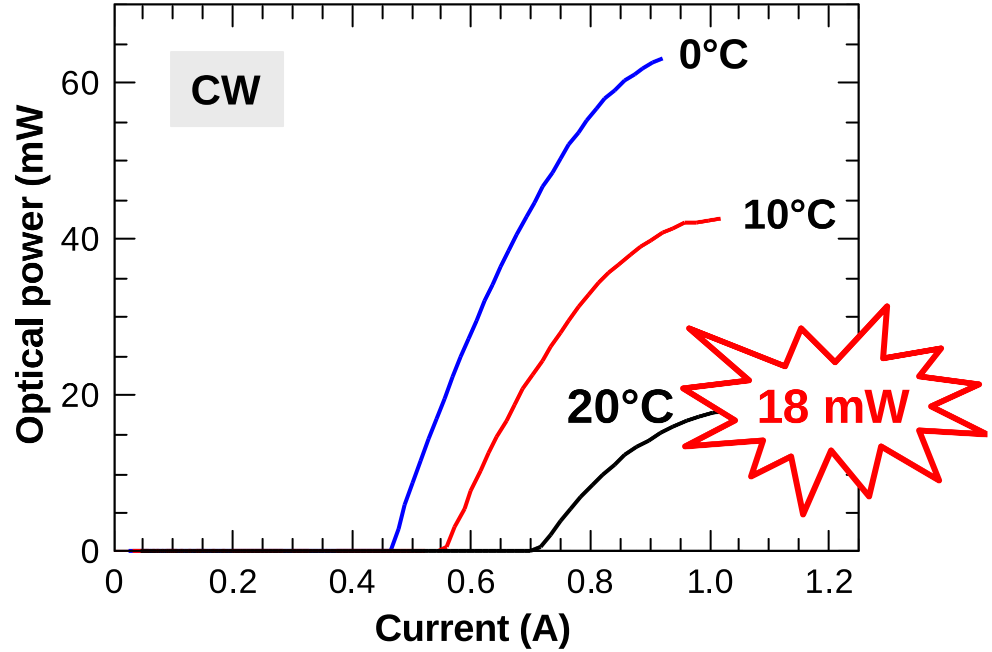
CW operation for H⁺ implanted InP-based QCLs





High Temperature CW operation even with current leakage

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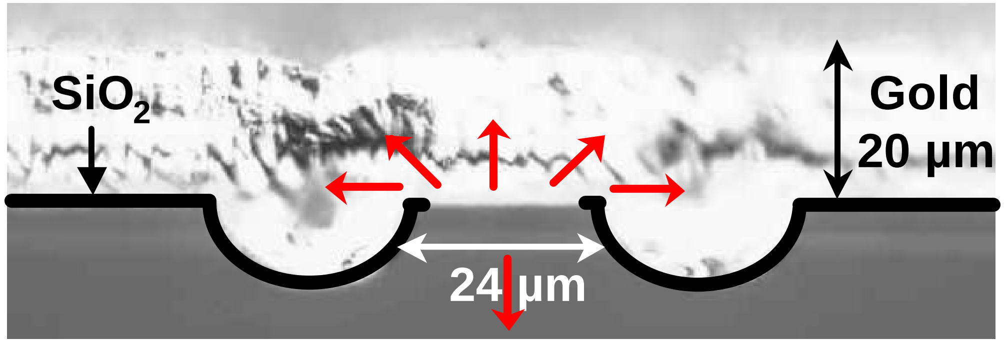
Electroplated Gold (Au) devices

Electroplated Au Device



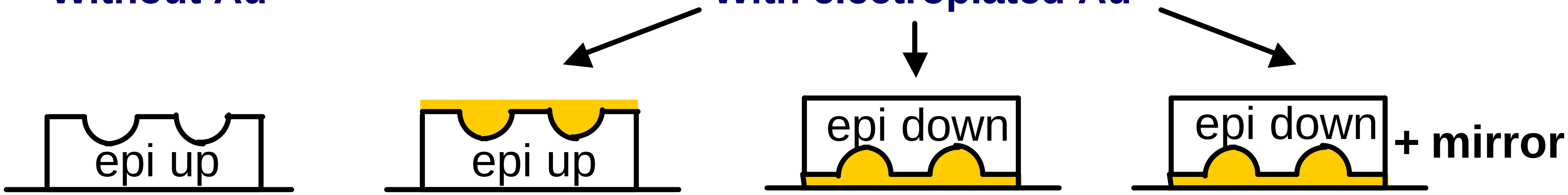
Very good heat dissipation device

Best performances obtained on QCLs with this type of device

Slivken et al, APL (2004)

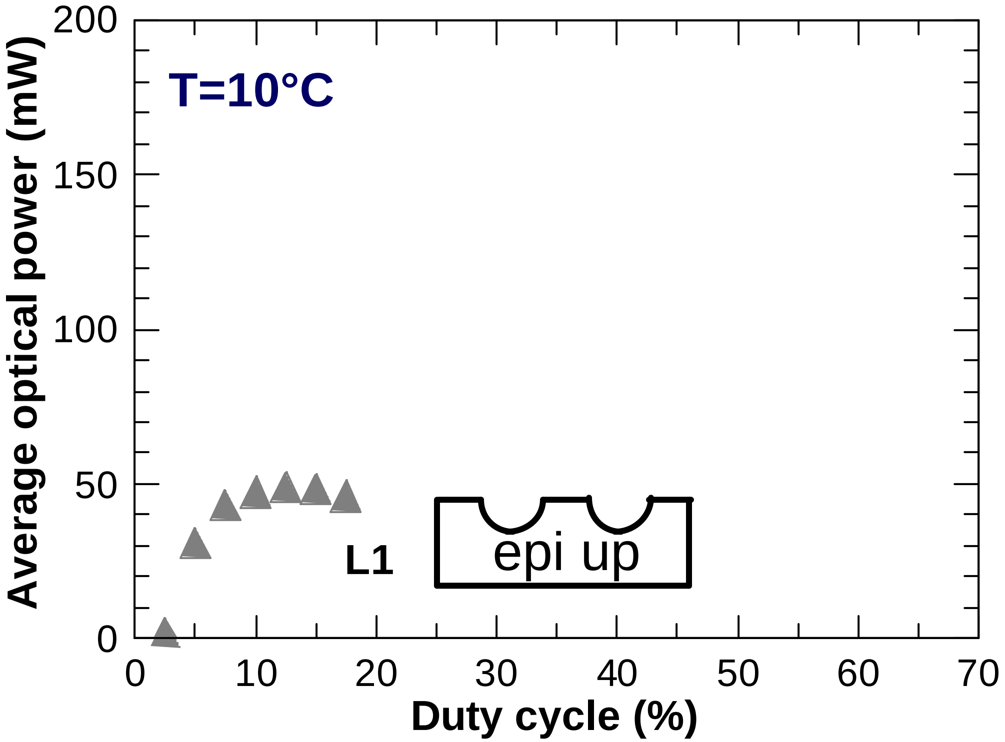
4 experimental arrangements:

Without Au **With electroplated Au**



L1 **L2** **L3** **L4**

Effect of Thick electroplated Au



L1 ➡ P_{max}= 49mW for DC=12%

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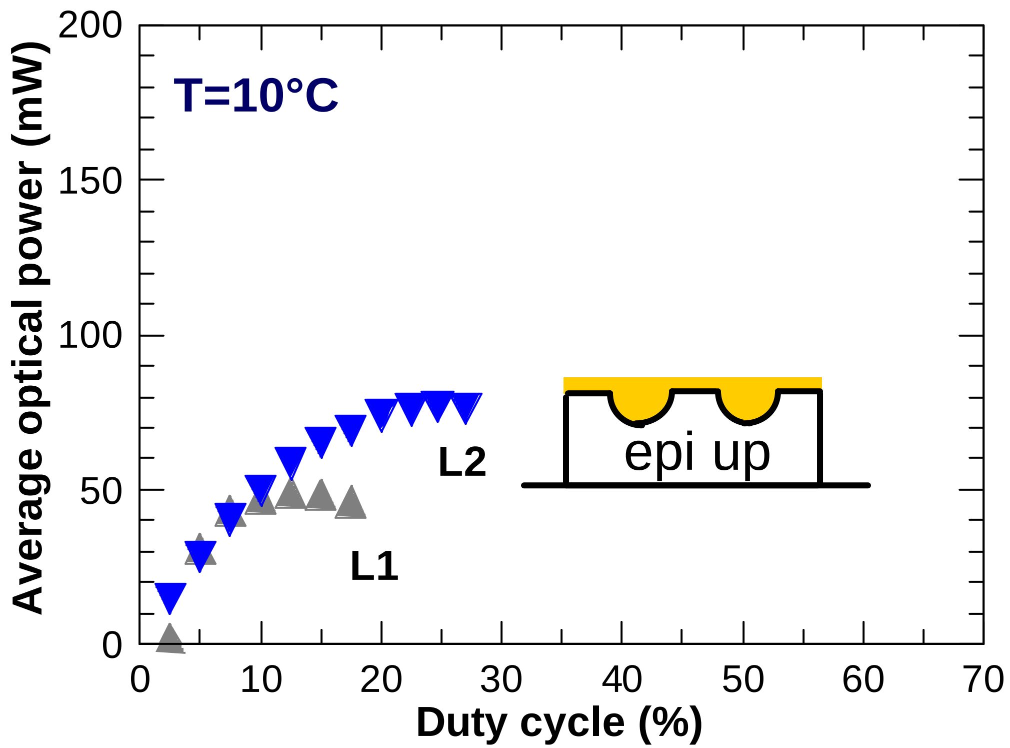
Effect of Thick electroplated Au



L1 ➡ P_{max}= 49mW for DC=12%

L2 ➡ P_{max}= 78mW for DC=25%

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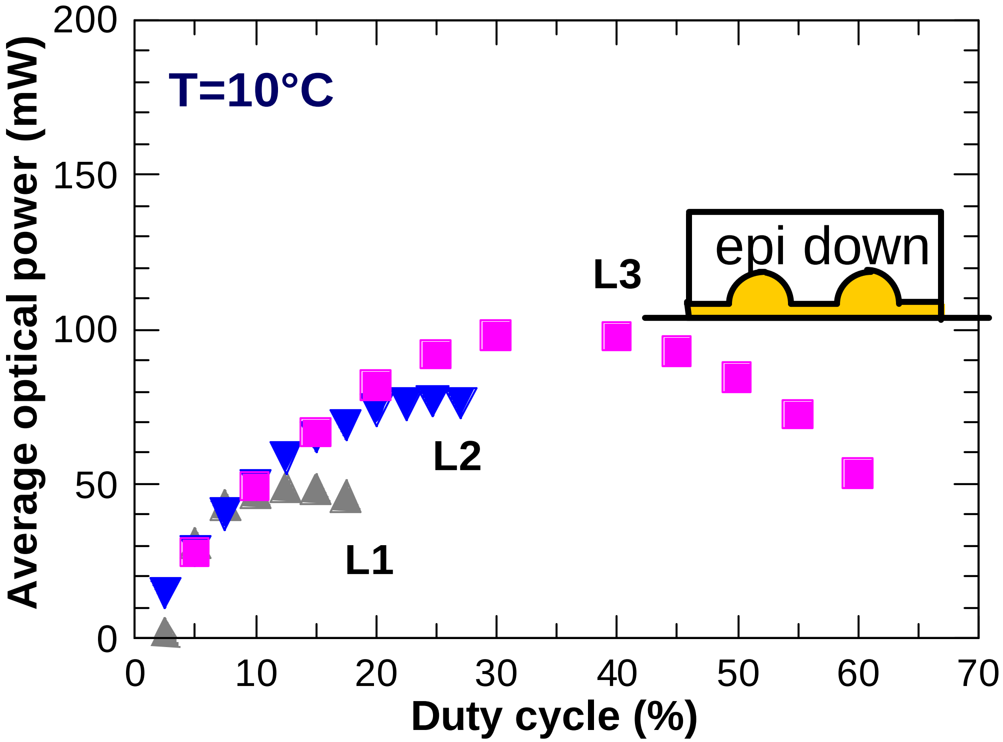
Effect of Thick electroplated Au



L1 ➡ **P_{max}= 49mW for DC=12%**

L2 ➡ **P_{max}= 78mW for DC=25%**

L3 ➡ **P_{max}= 102mW for DC=37%**

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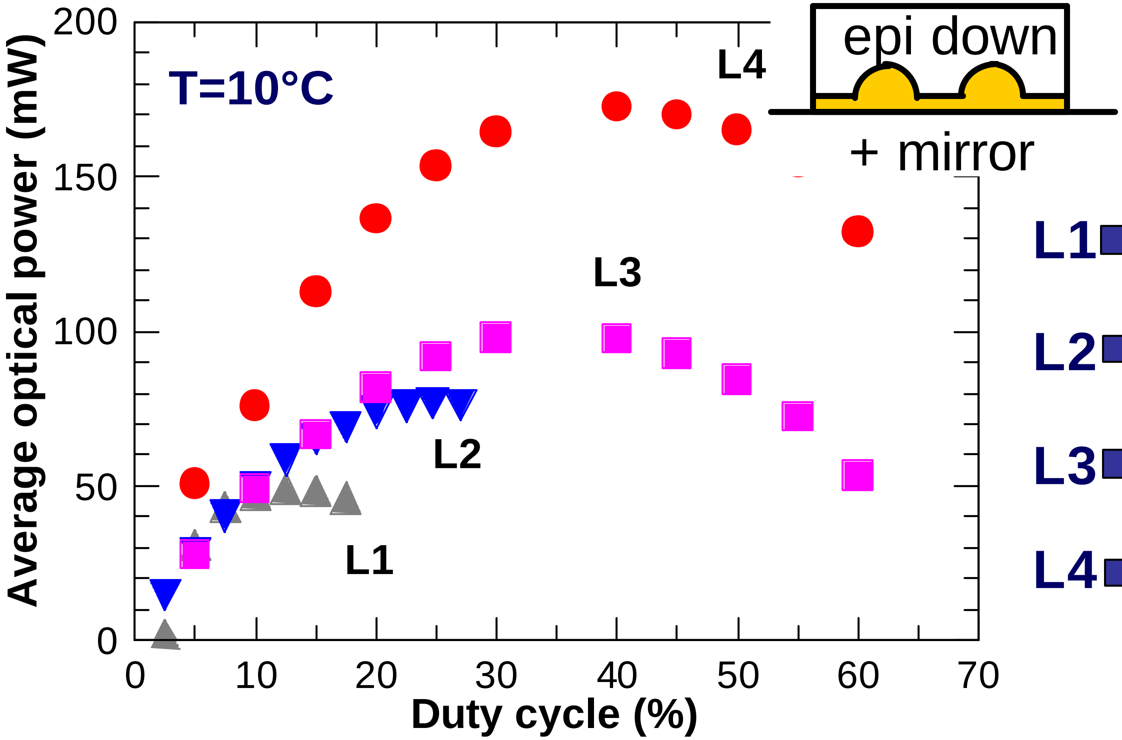
Effect of Thick electroplated Au



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%

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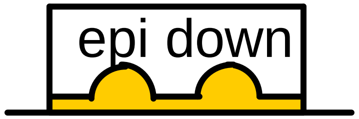
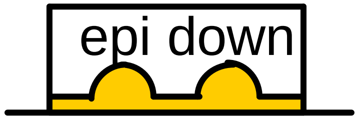
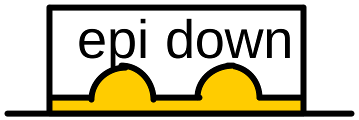
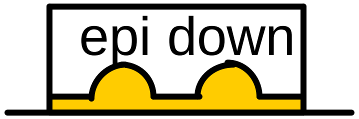
Thick electroplated Au - Summary

		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

-50%

~ -40%

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

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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

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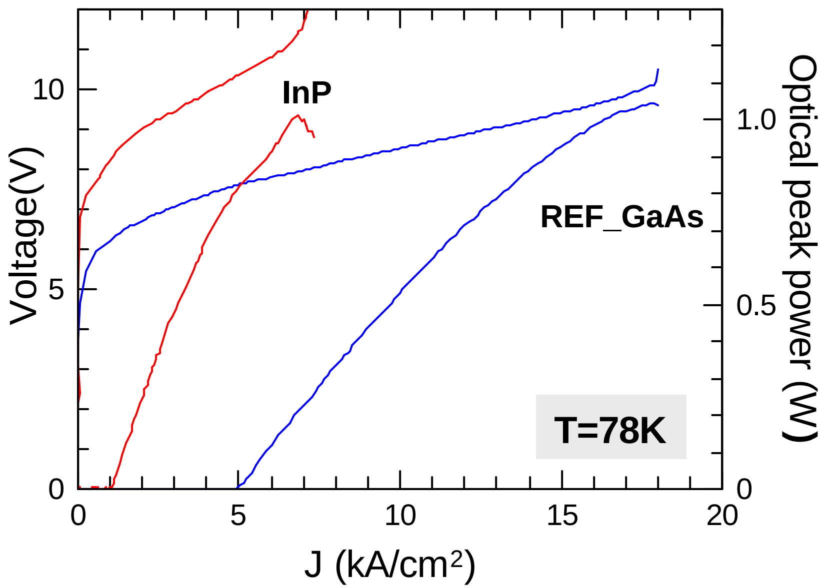
Mid IR QCL Material ?

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

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

↑ ↓

Higher losses ← **Higher doping in the active region and the claddings**



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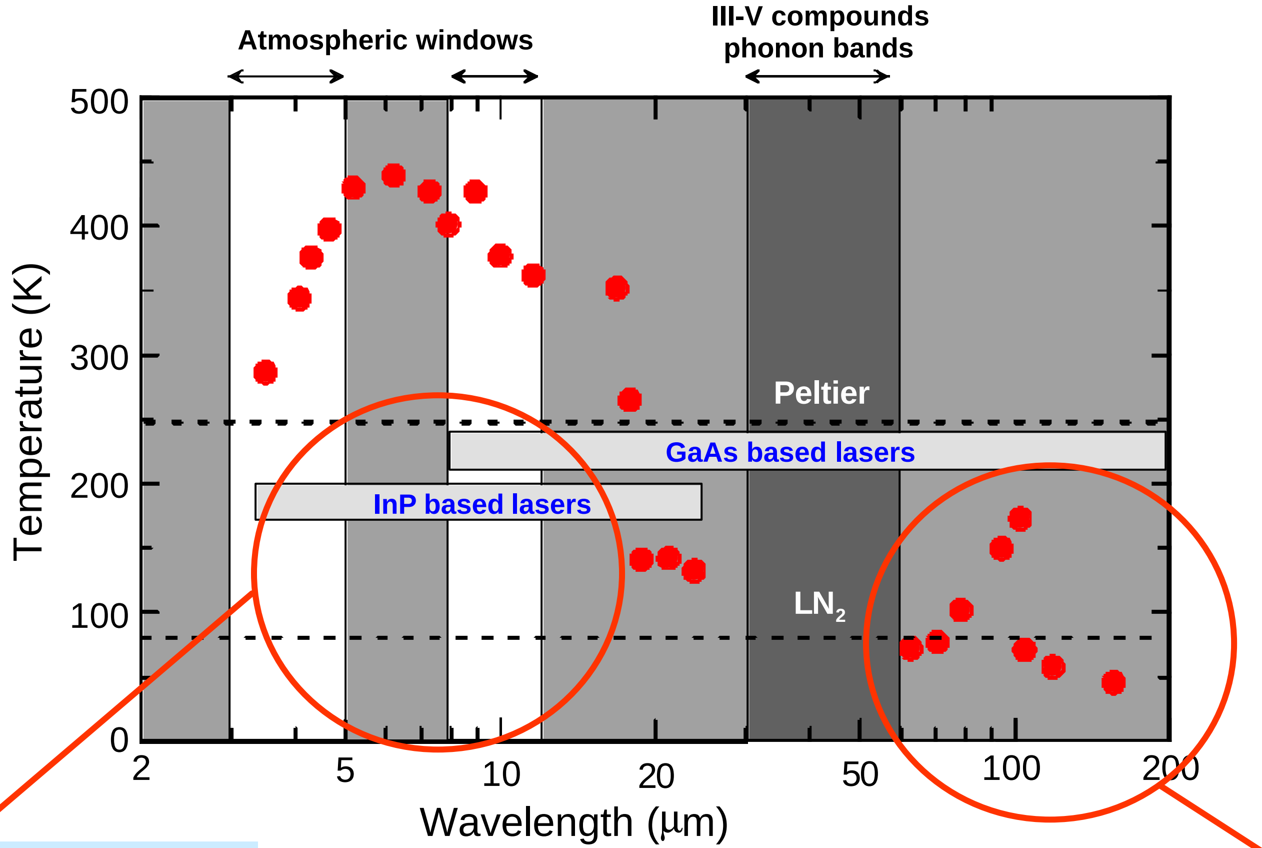
Which material for which wavelength ?



Mid Infrared :

AlInAs/GaInAs/InP QCLs

InAs/AlSb QCLs

Far Infrared (THz) :

GaAs/AlGaAs QCLs

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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