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

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Jean-Yves Bengloan. AMELIORATION DES PERFORMANCES DES LASERS A CASCADE QUANTIQUE - ETUDE DU CONFINEMENT OPTIQUE ET DES PROPRIETES THERMIQUES. Physique Atomique [physics.atom-ph]. Université Paris Sud - Paris XI, 2005. Français. NNT: . tel-00084018

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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

J-Y Bengloan

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

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1. Introduction

2. Waveguide Optimisation in GaAs/AlGaAs QCLs

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

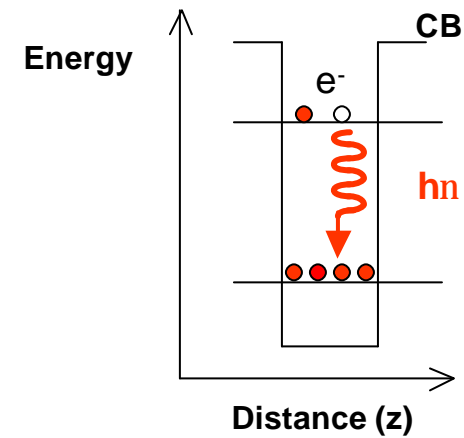
3. Enhancement of thermal dissipation properties of GaInAs/AlInAs/InP QCLs

Selective current injection by proton implantation
Thick electro-plated gold

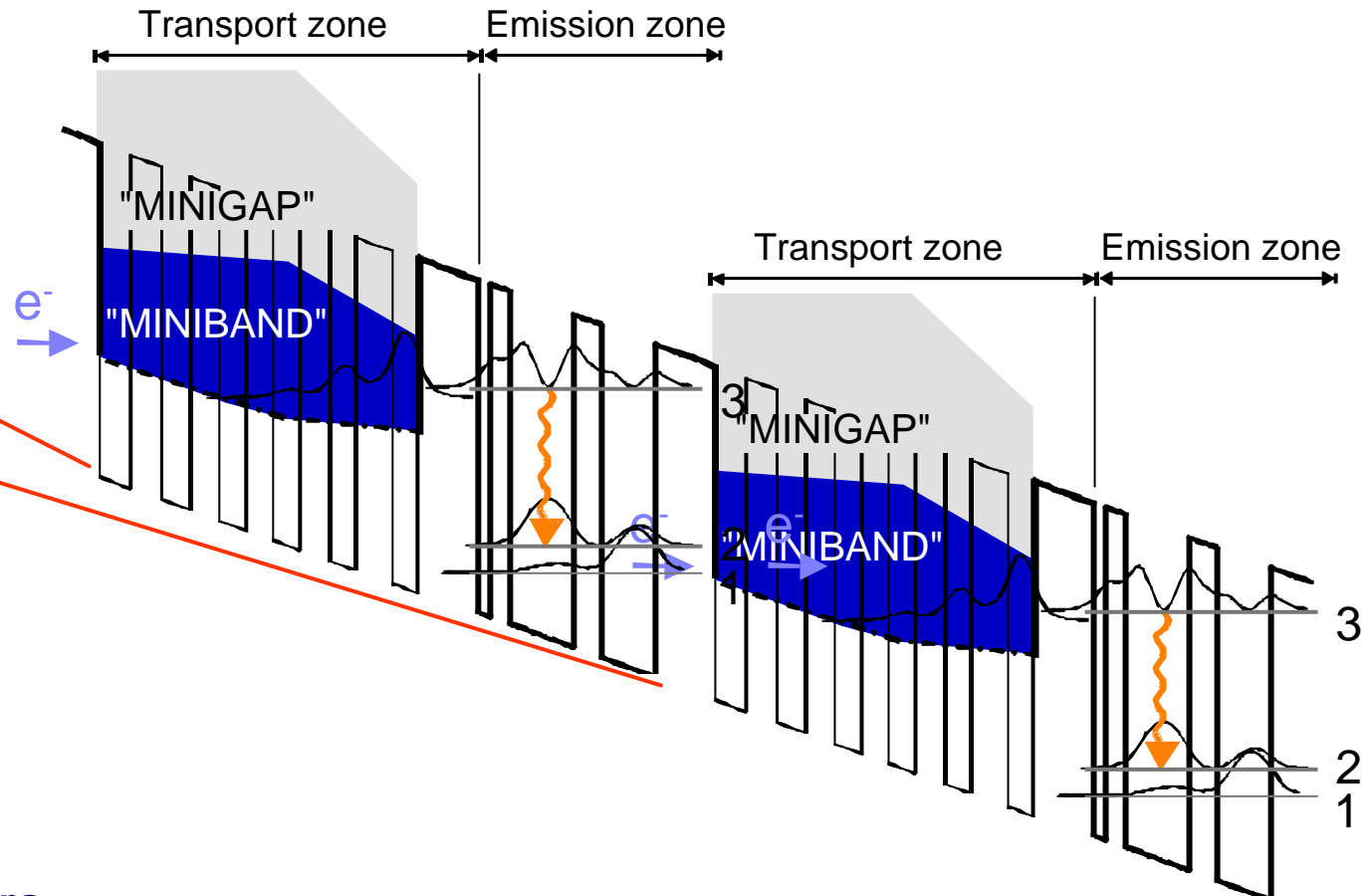
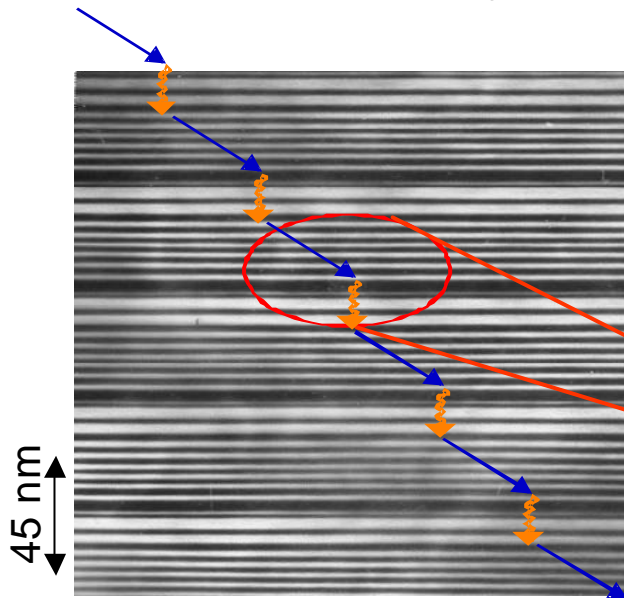
4. Conclusion

Main Properties

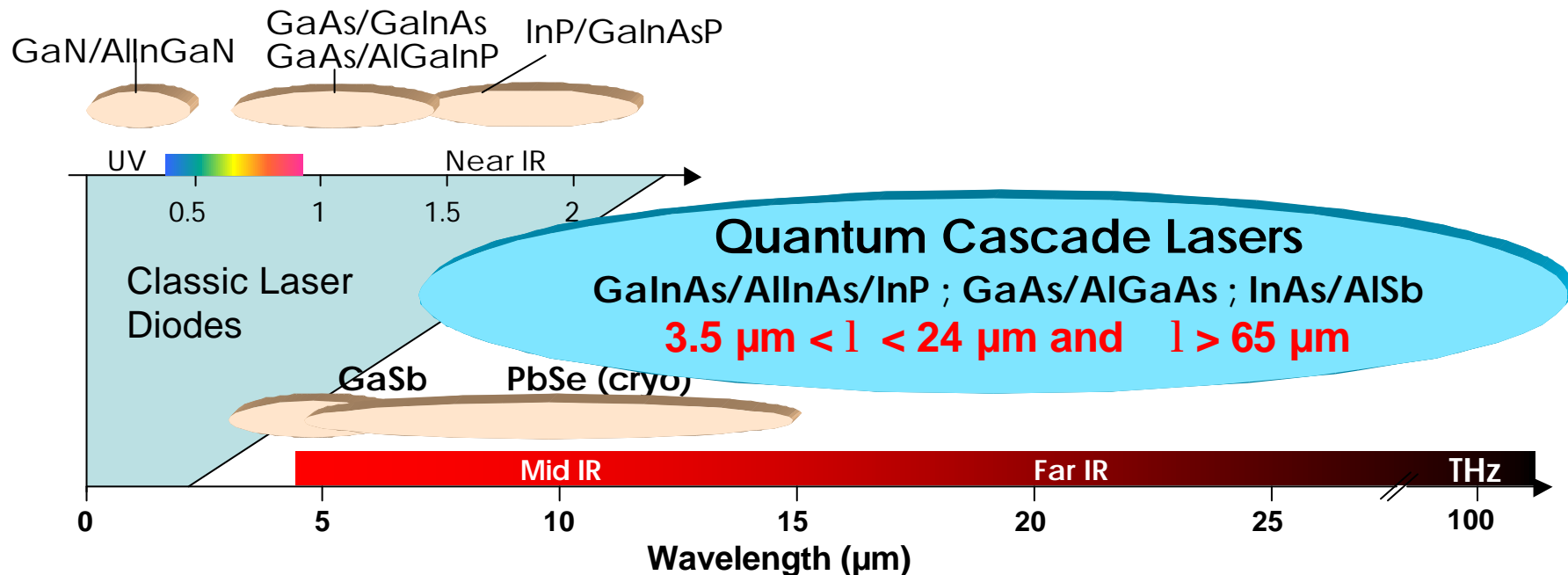
- **INTERSUBBAND** transitions
- **UNIPOLAR** : only one type of carrier used (e^-)



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

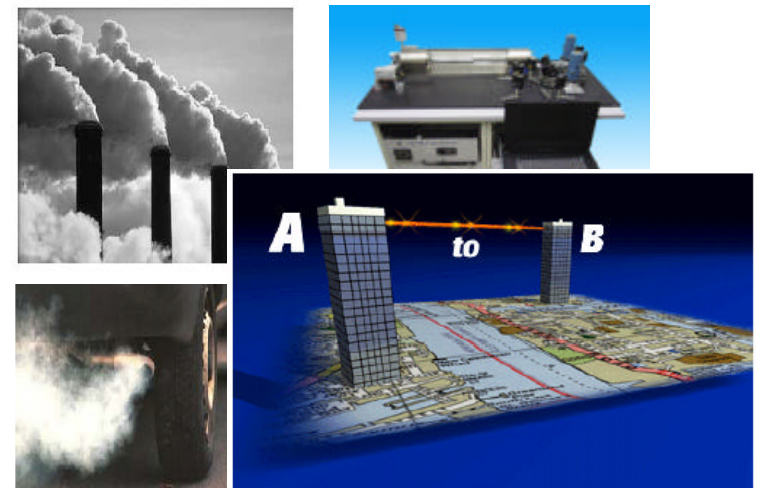


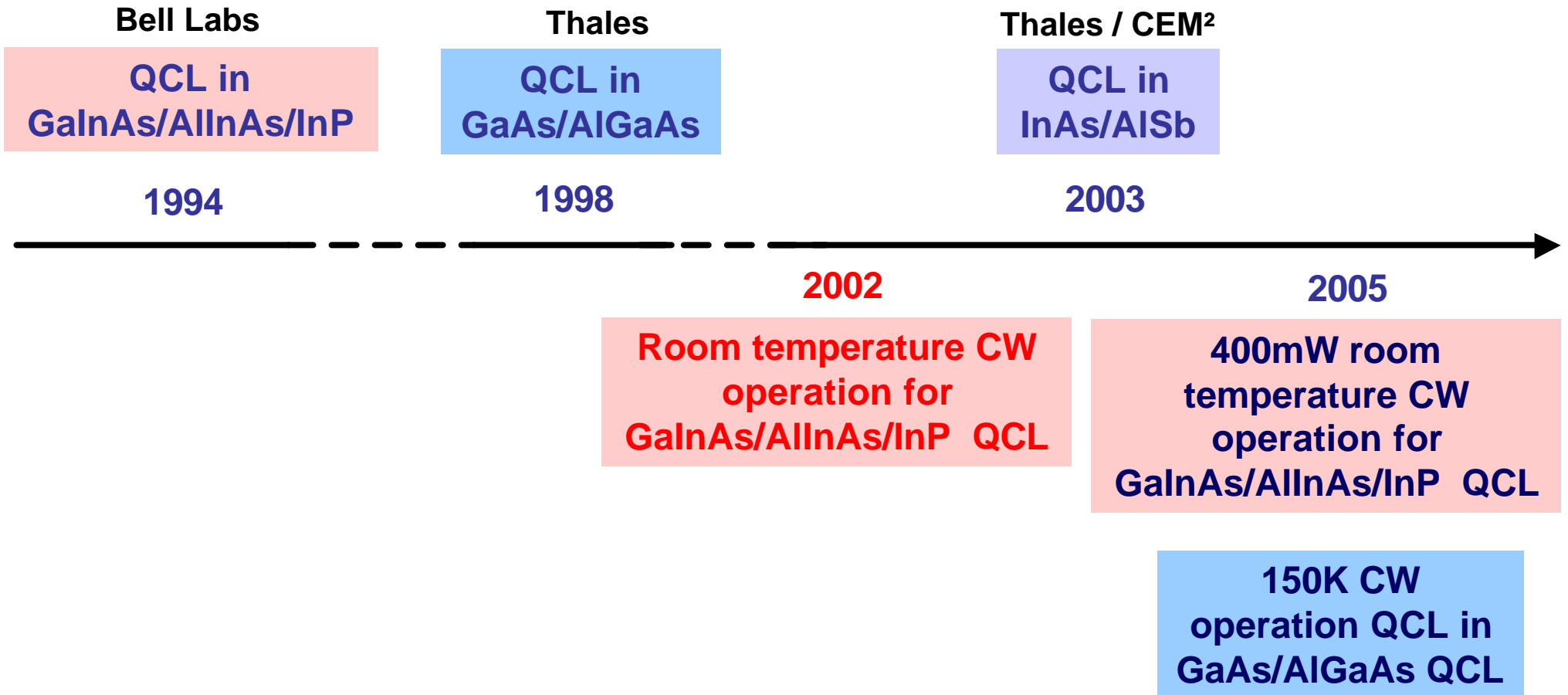
- **CASCADE scheme :**
 Recycling of carriers
 N periods = N photons per carrier



Applications:

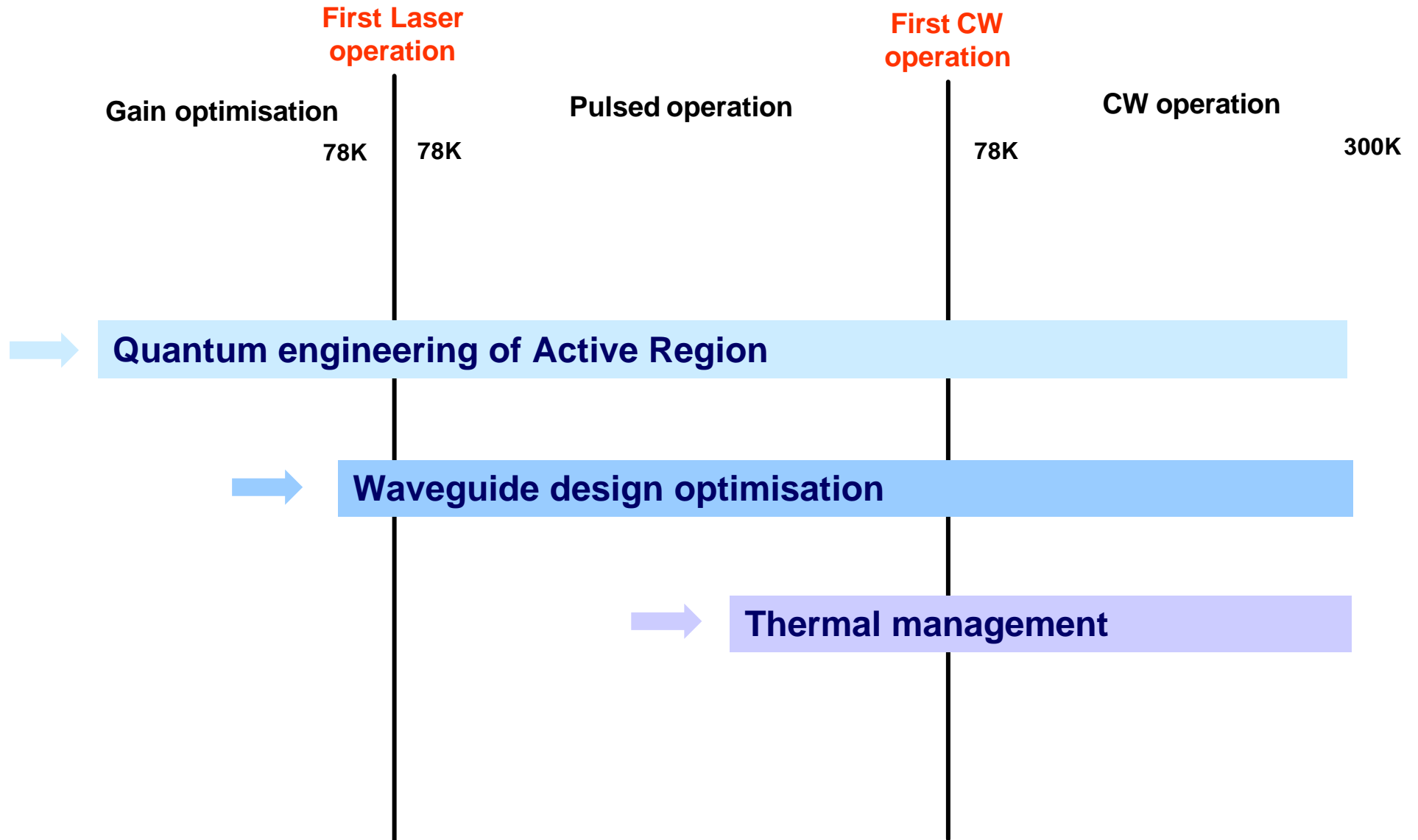
- Spectroscopy and high sensitive Gas detection
Environmental, Medical, Security
- Free space optical communication
Atmospheric transparency windows : 3- 5 μm and 8-12 μm
- Optical countermeasures



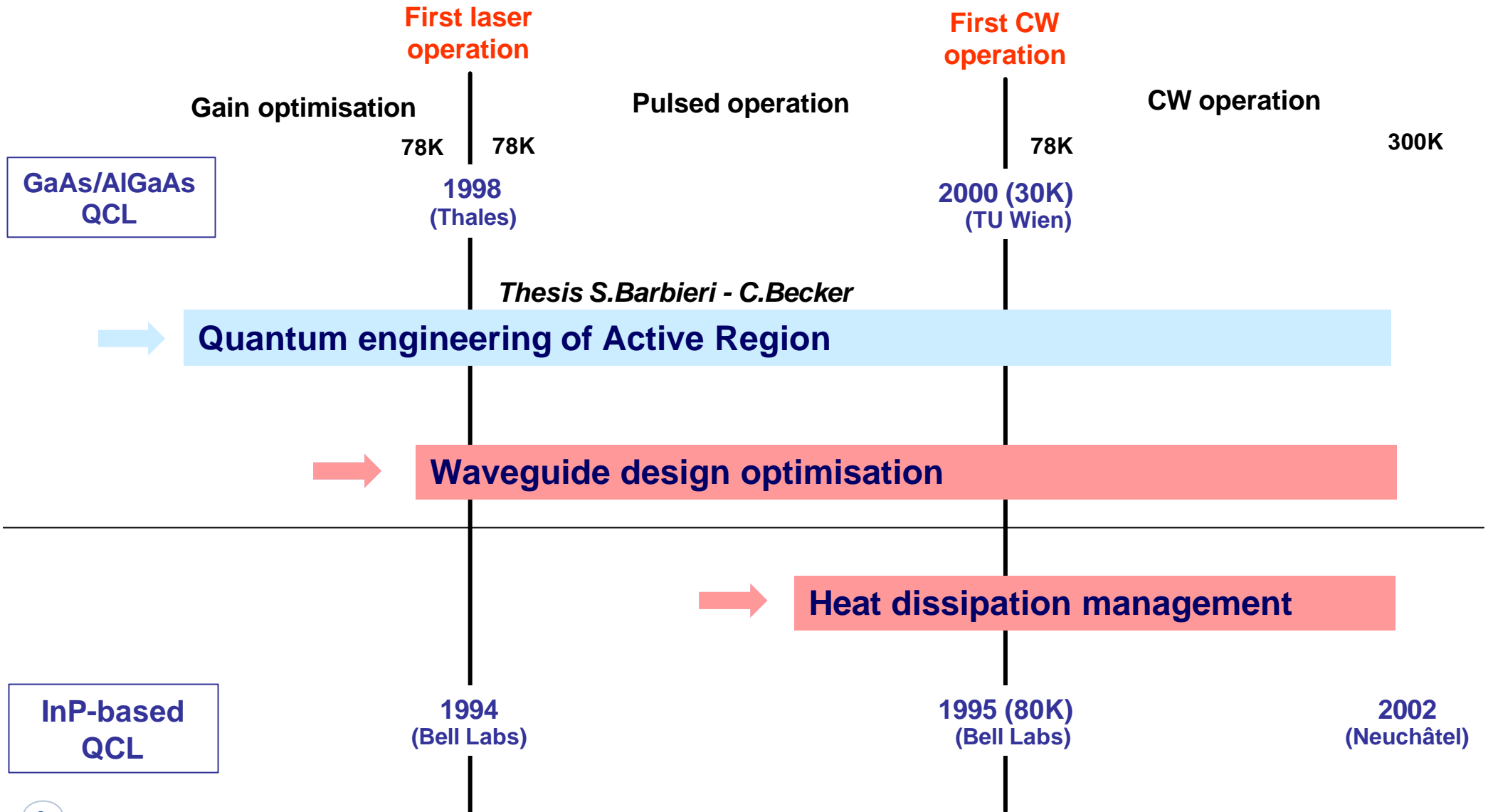


CW: Continuous Wave

From intersubband emission to CW laser operation



From intersubband emission to CW laser operation



1. Introduction

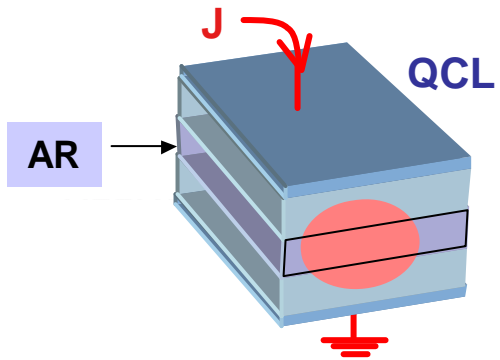
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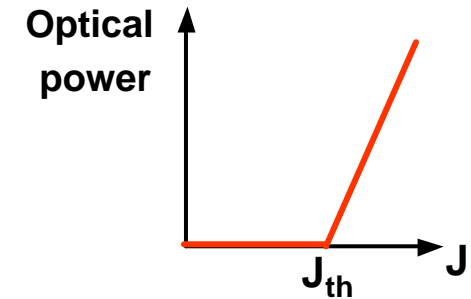


Pulsed operation QCL development: Reduction of the threshold current density J_{th}

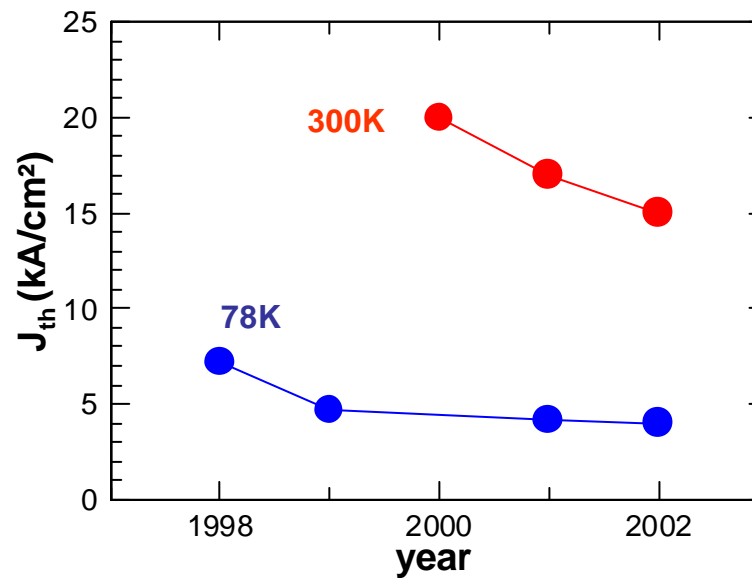
$$J_{th} = (a_{wg} + a_m) / g G$$

Quantum engineering of Active Region : g

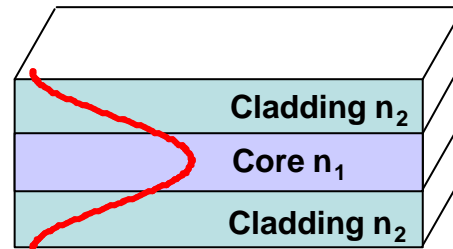
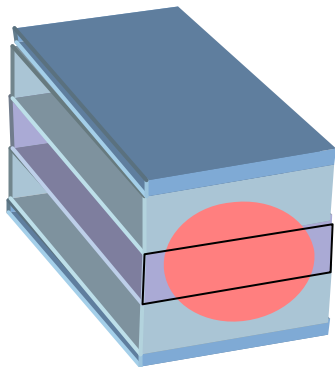
Waveguide design optimisation : a_{wg}, G



GaAs based QCL



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

GaAs Plasmon enhanced waveguide with highly doped cladding layers

$n_{\text{eff}}=3.19$
 $a = 17 \text{ cm}^{-1}$
 $G = 28\%$
 $l = 9.4 \mu\text{m}$

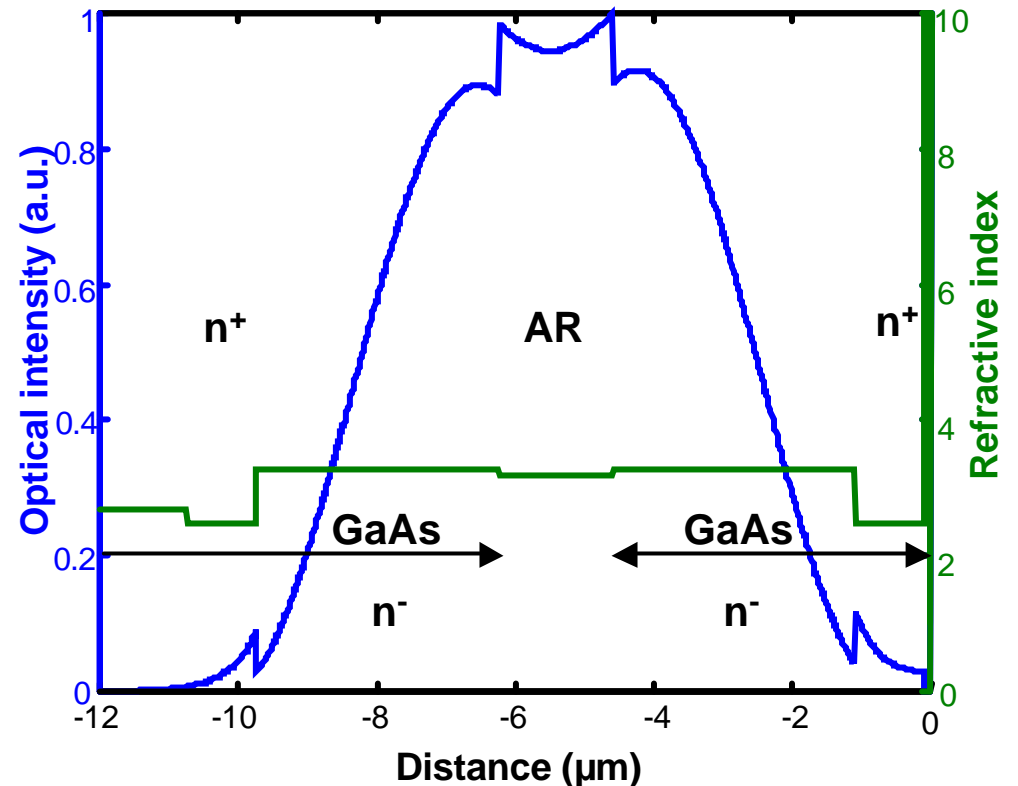
$C = 1.7$
 $J_{\text{th}} = 15 \text{ kA/cm}^2$

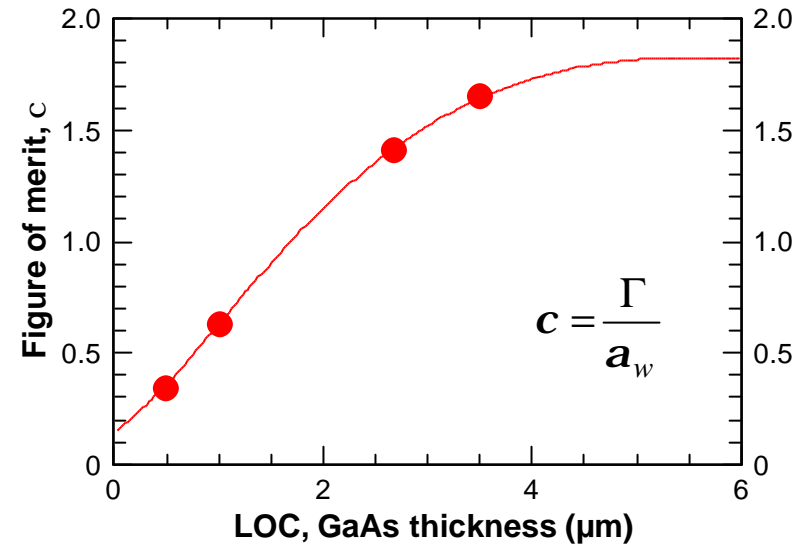
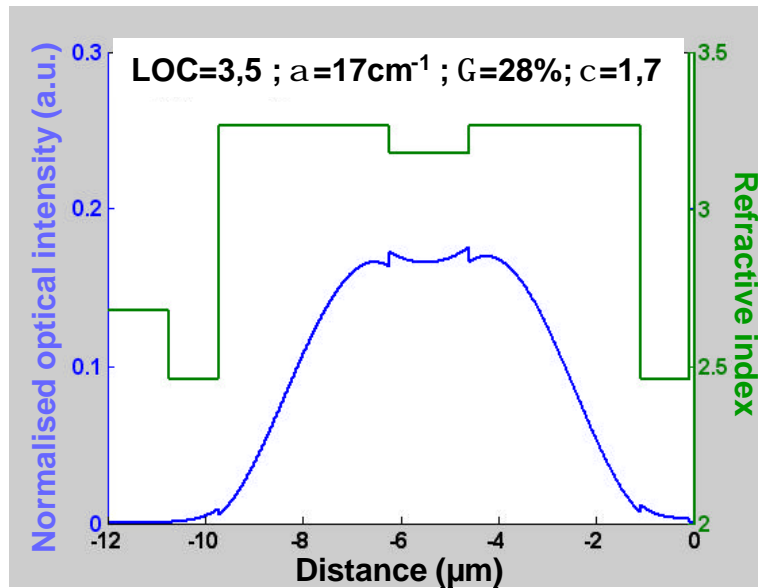
→ Advantages

- straight-forward MBE growth
- good electrical characteristics

→ Drawbacks

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



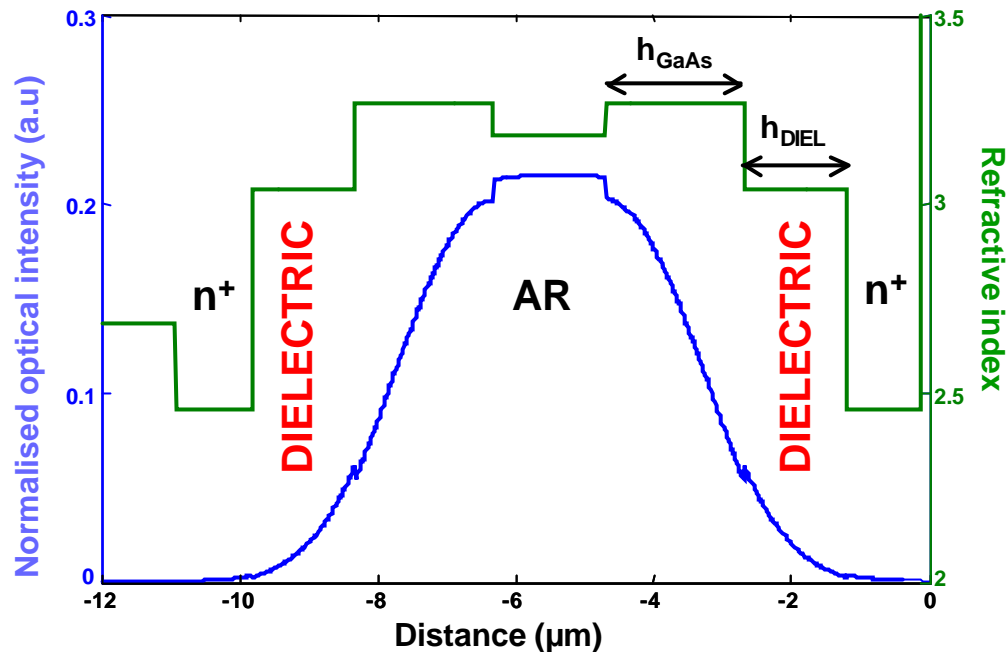


The χ optimisation is a trade-off between :

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

NECESSITY TO REDUCE OPTICAL LOSSES FROM CLADDINGS

→ Plasmon enhanced waveguide strengthened by dielectric layers :



- AlGaAs layers
- GaInP layers

Maximum growth thickness $\sim 10\mu\text{m}$

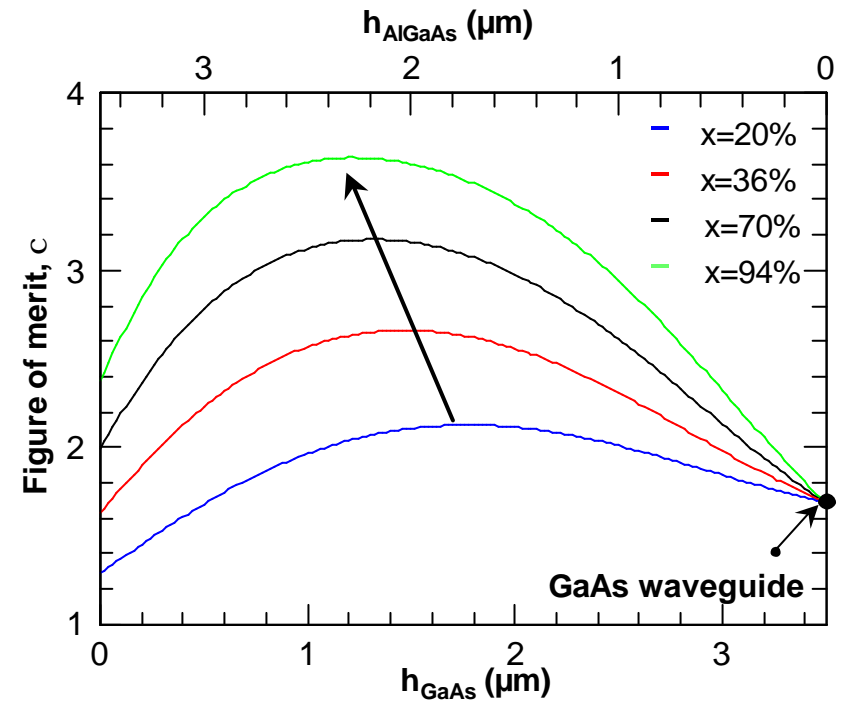
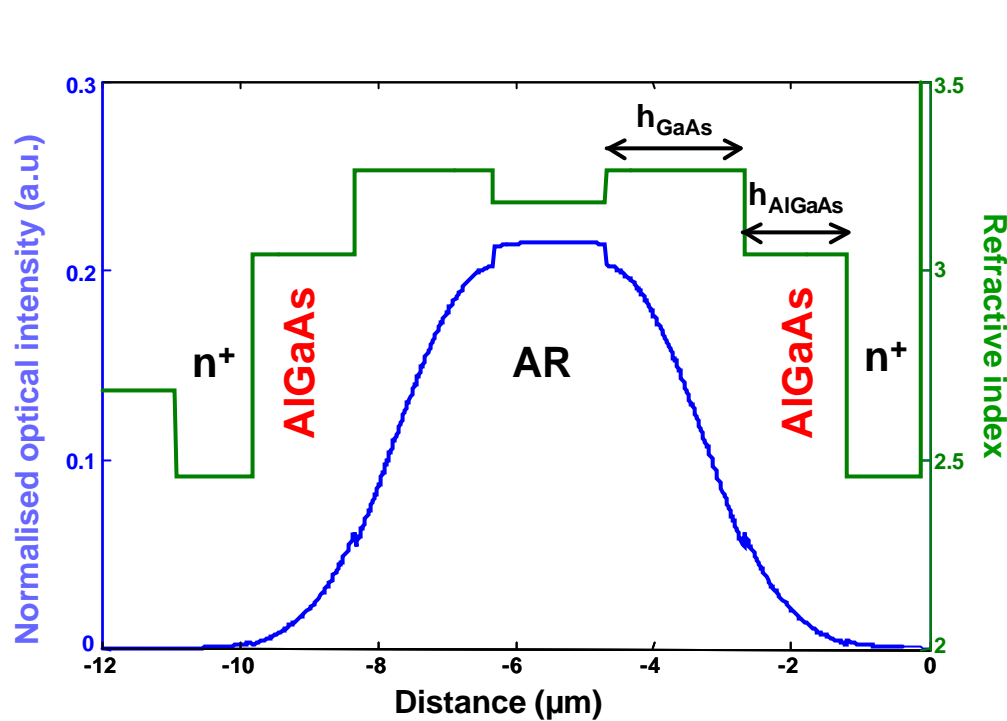
→ $h_{\text{GaAs}} + h_{\text{Diel}} = 3,5\mu\text{m}$

With $x_{Al} \nearrow$:

$\Delta n_{GaAs/AlGaAs} \nearrow$ $\Gamma \nearrow$

$\alpha \searrow$ (mode overlap with highly doped layers reduced)

$c=G/a \nearrow$

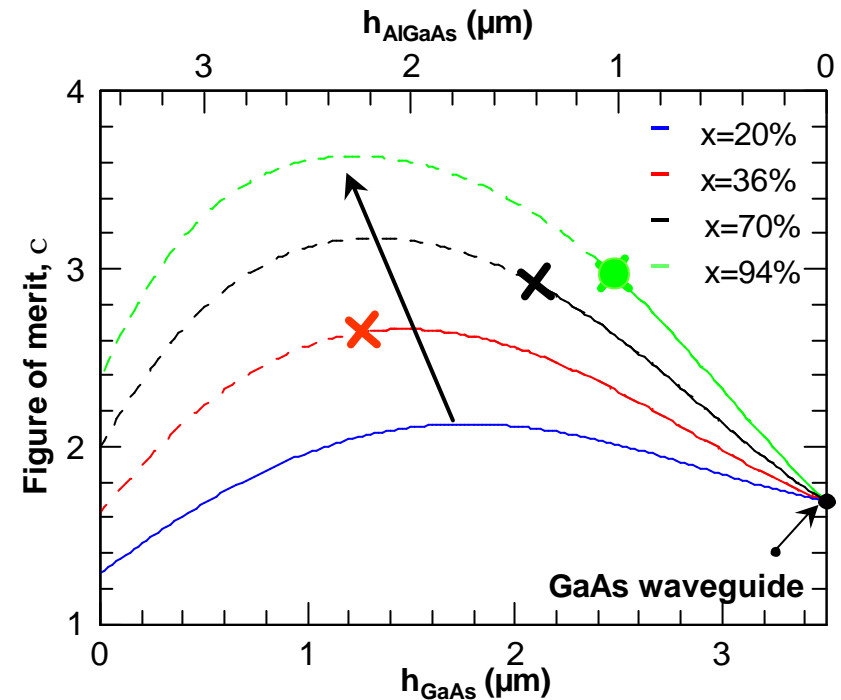
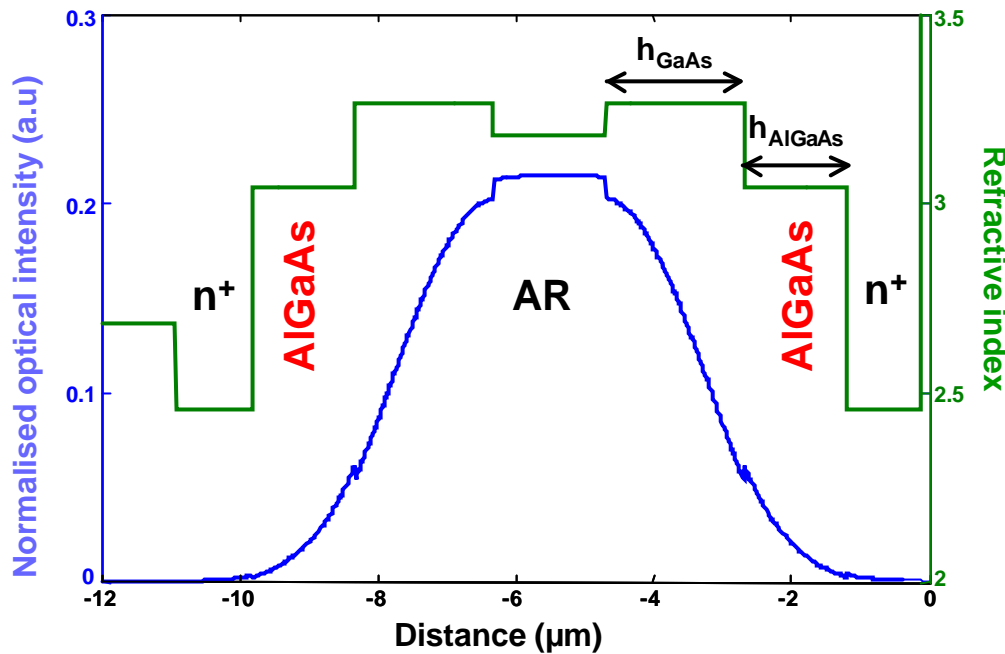


With $x_{Al} \nearrow$:

$\bar{P} \Delta n_{GaAs/AlGaAs} \nearrow \bar{P} \Gamma \nearrow$
 $\bar{P} \alpha \searrow$ (mode overlap with highly doped layers reduced)
 }
 $\bar{P} c=G/a \nearrow$

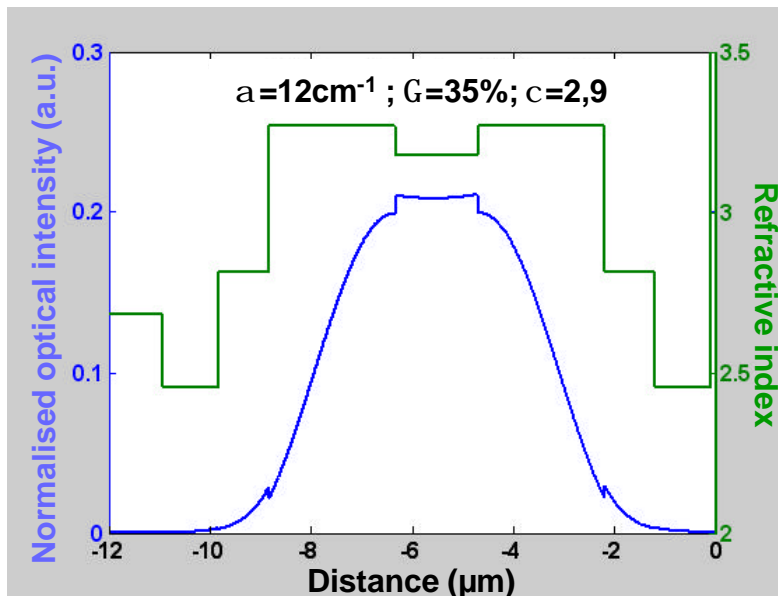


Limitations : lattice mismatch constraint \rightarrow Al_xGa_{1-x}As thickness limit $\sim 1/x_{Al}$



$\text{Al}_{0.94}\text{Ga}_{0.06}\text{As}$ cladding waveguides / QCL AL94

$\text{Al}_{0.94}\text{Ga}_{0.06}\text{As}$ cladding waveguide



$c=2.9$

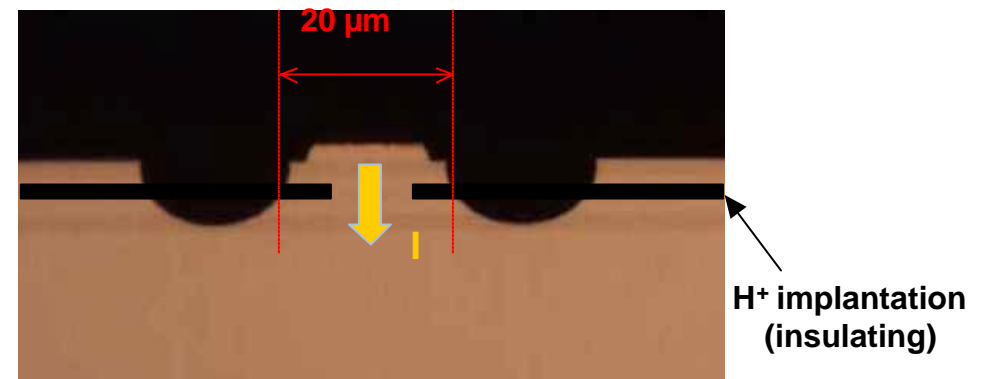
→ J_{th} ~2 times smaller than that of the GaAs plasmon enhanced waveguide.

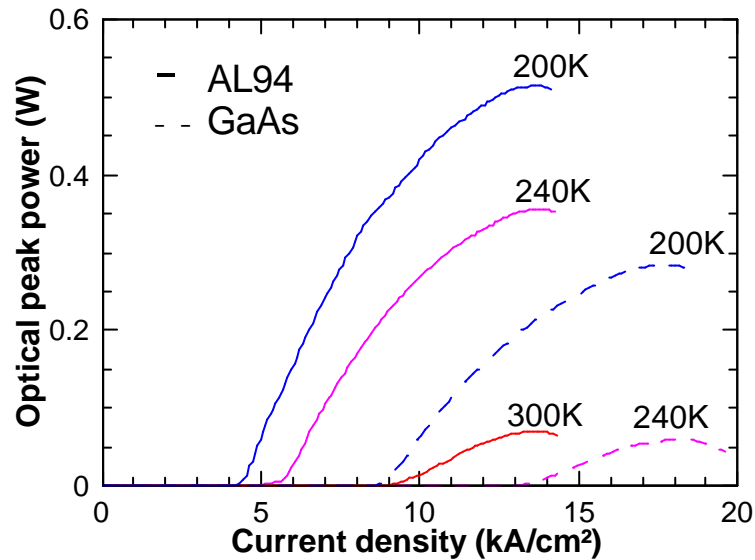
2 devices grown and processed identically:

→ **GaAs** : GaAs waveguide

→ **AL94** : $\text{Al}_{0.94}\text{Ga}_{0.06}\text{As}$ 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

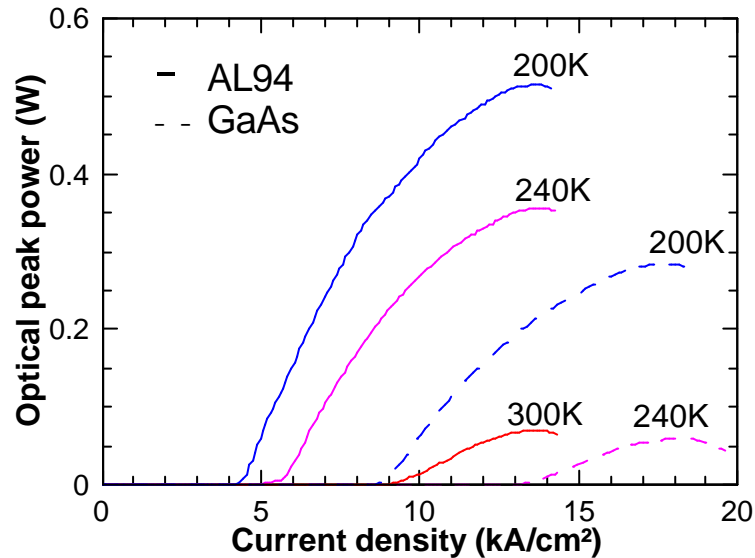




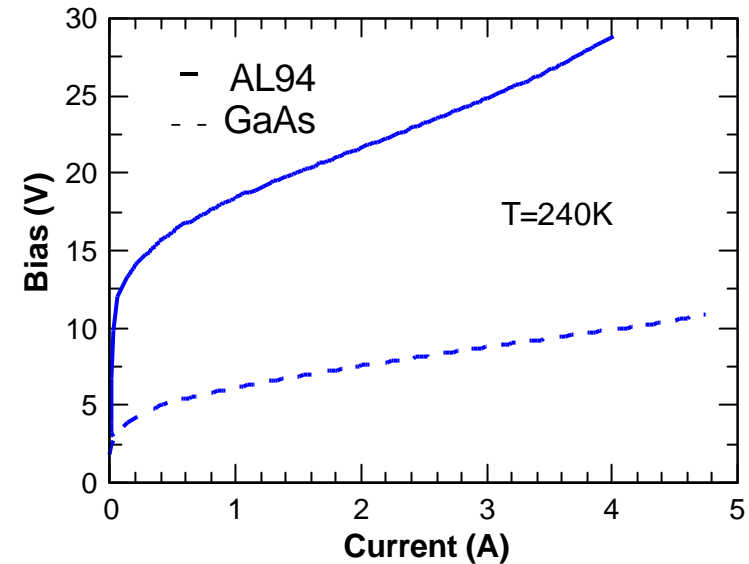
5kHz-100ns

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



5kHz-100ns



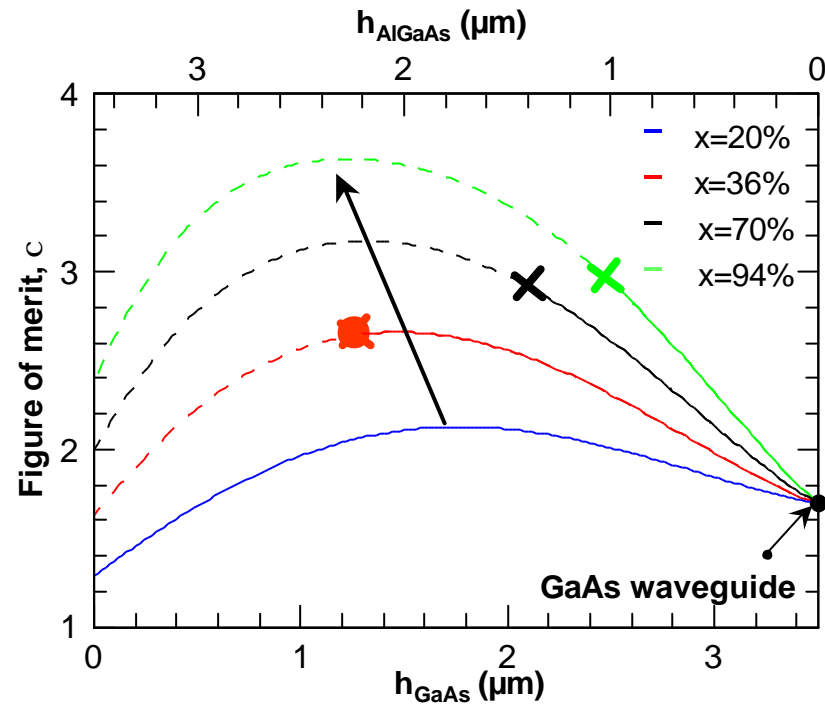
Good optical performances for QCL AL94:

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- Agreement with simulations:
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- Higher optical peak power
- 300K operation

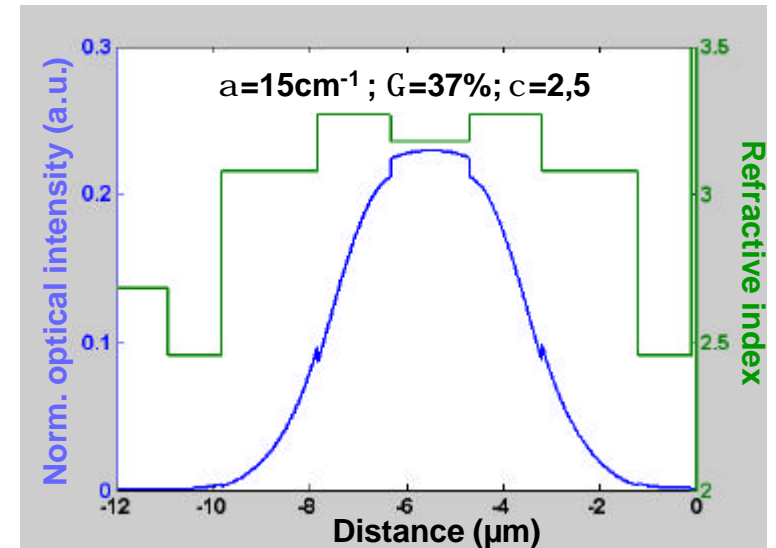
Poor electrical characteristics for QCL AL94:

- 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

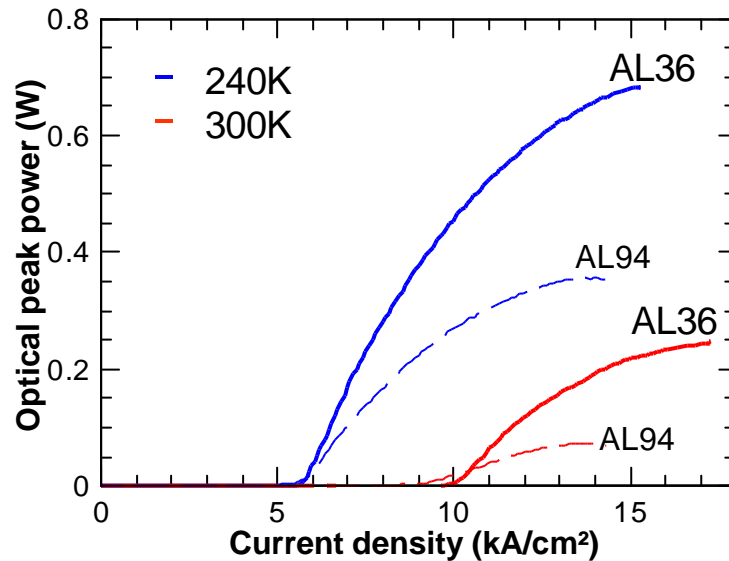


Al_{0.36}Ga_{0.64}As cladding waveguide

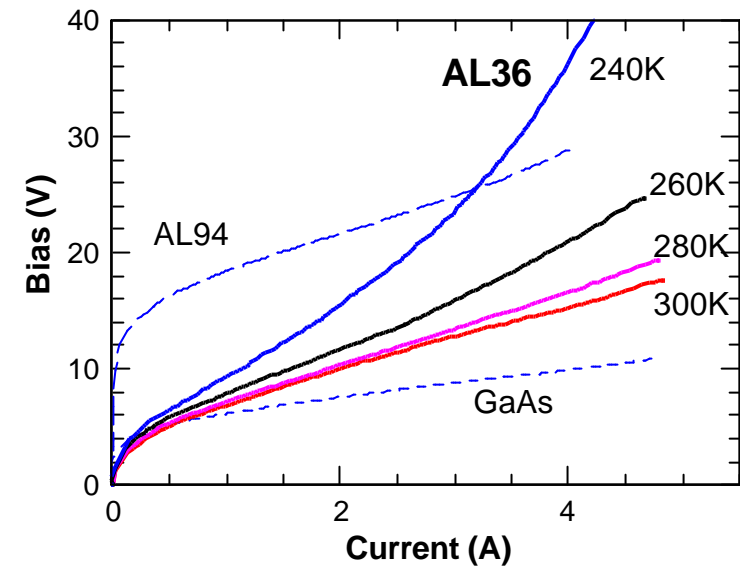


c=2,5

Electrical conductivity better than Al_{0,94}Ga_{0,06}As layers:
better e⁻ mobility
lower effective mass



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

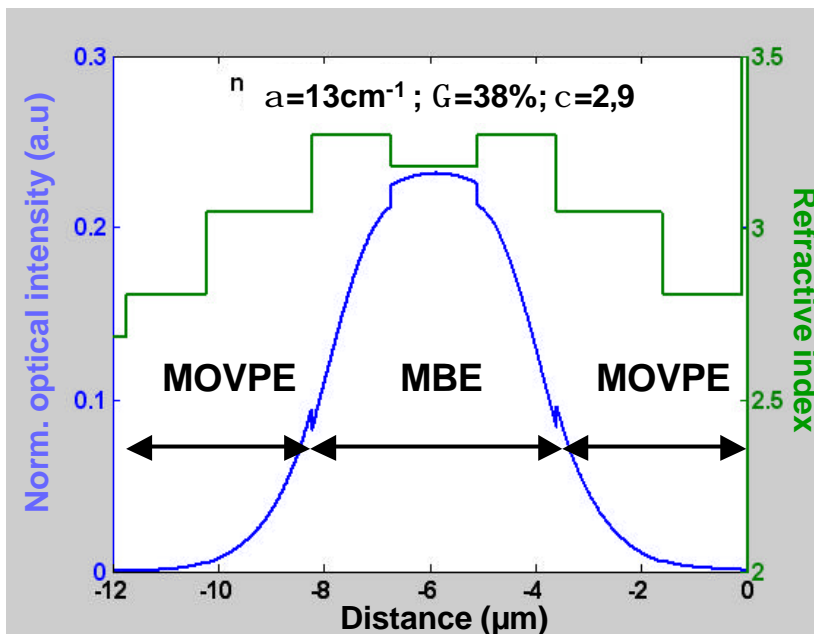
$P_{max}(AL36)=250\text{ mW at }300K$

Electrical characteristics dependant on the temperature:

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

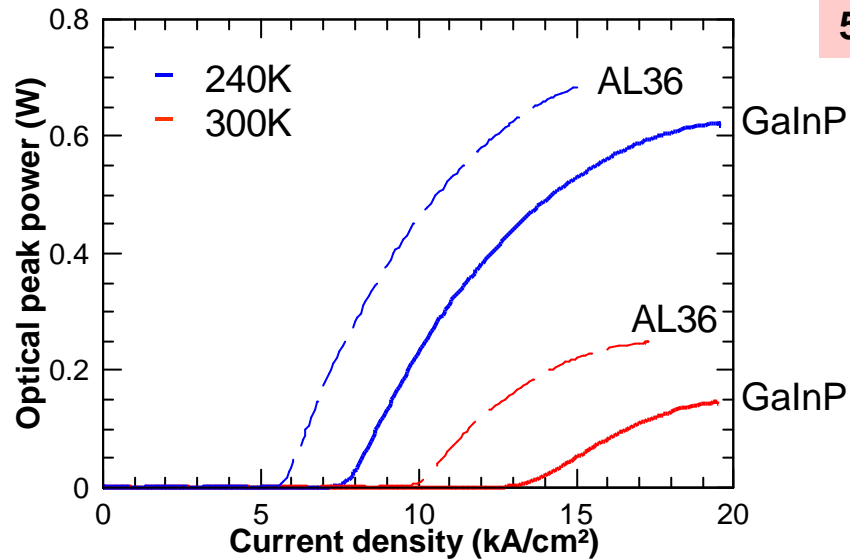
- **Ga_{0.51}In_{0.49}P refractive index @ Al_{0.45}Ga_{0.55}As refractive index**
 → Good $\Delta n_{\text{GaAs/GaInP}}$ for improved confinement: $c=2,9$
- **Good electrical conductivity**
- **Ga_{0.51}In_{0.49}P : lattice matched to GaAs**
 → no thickness limitation

c=2,9



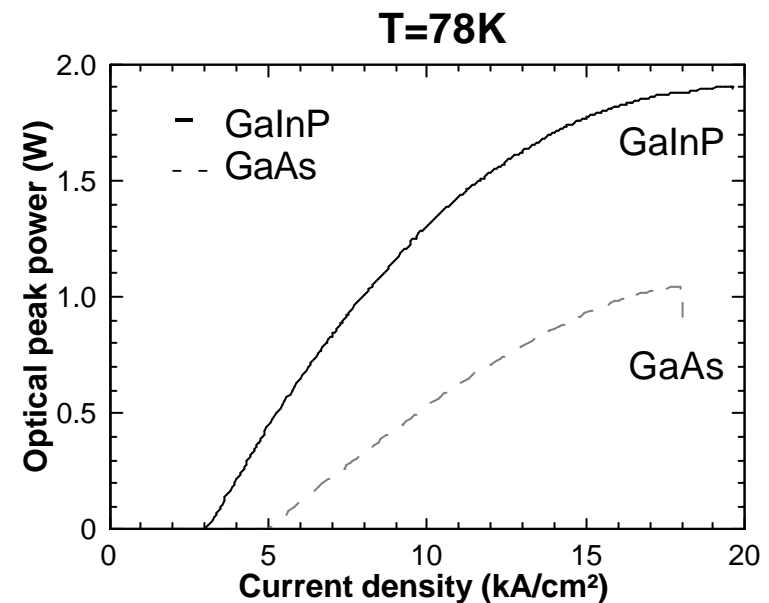
Drawback : Ga_{0.51}In_{0.49}P re-growth by MOVPE at Thales

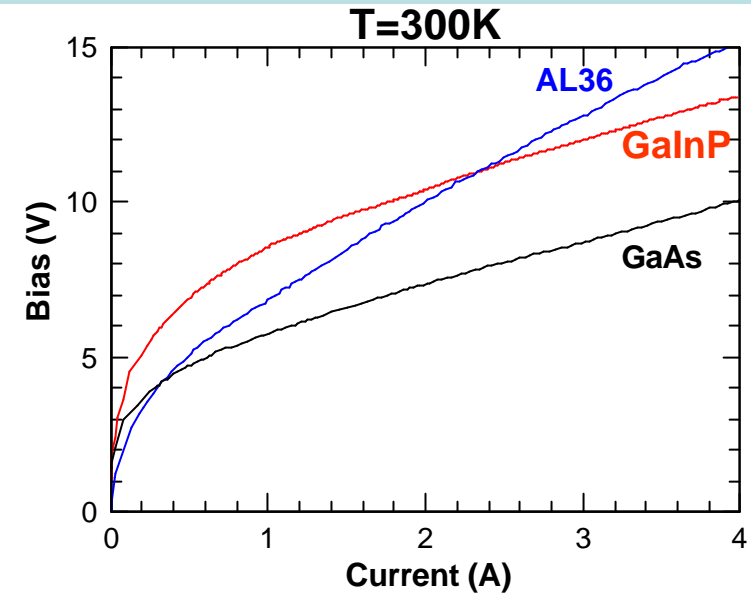
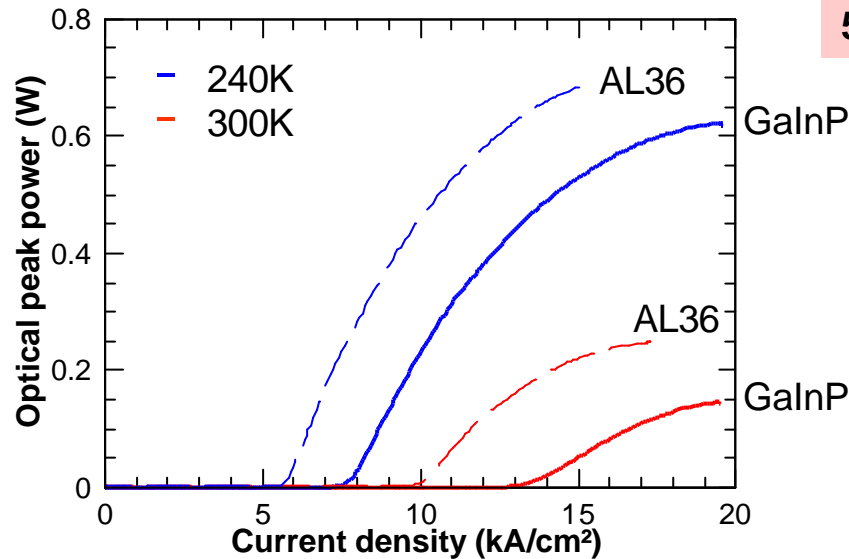
→ growth in 3 steps



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





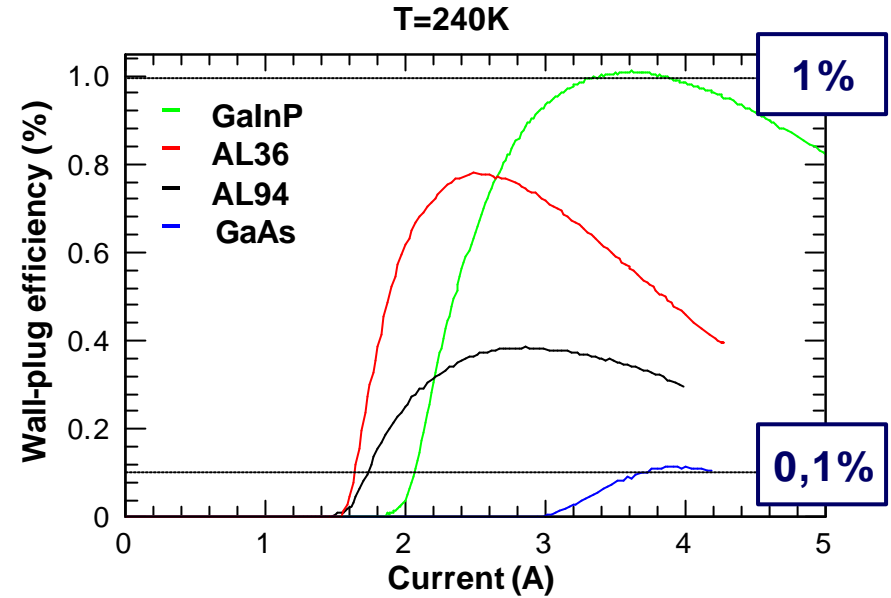
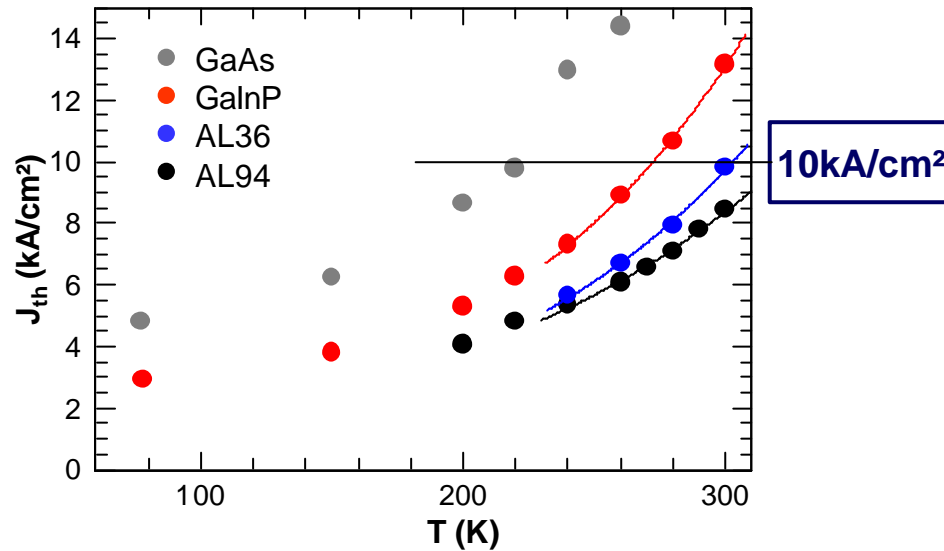
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- High optical peak power at 78K
 $P_{max}(GaInP)=1,9W$ at 78K
- Optical peak lower than QCL AL36 at RT
 $P_{max}(GaInP)=150$ mW at 300K

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(GalnP)=1%= 10xWP(GaAs) at 240K

Optical performances improvements



Electrical degradations

**Best QCLs :
QCL AL36 for T > 250 K
QCL GalnP for T < 250 K**

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

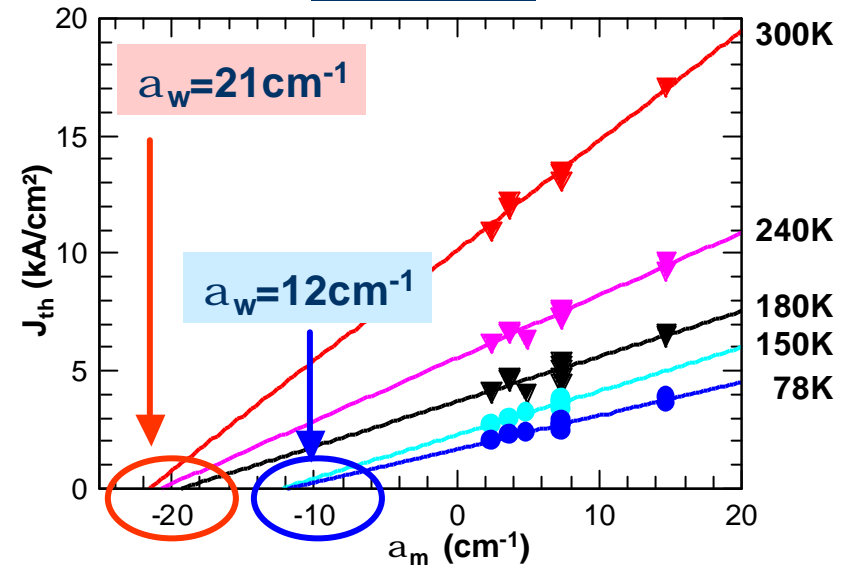
$$J_{th}=(a_m+a_w)/gG$$

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

$\rightarrow a_w$ increase at $T \geq 180K$

\downarrow
Reduction of a_w at low temperature compared to QCL GaAs

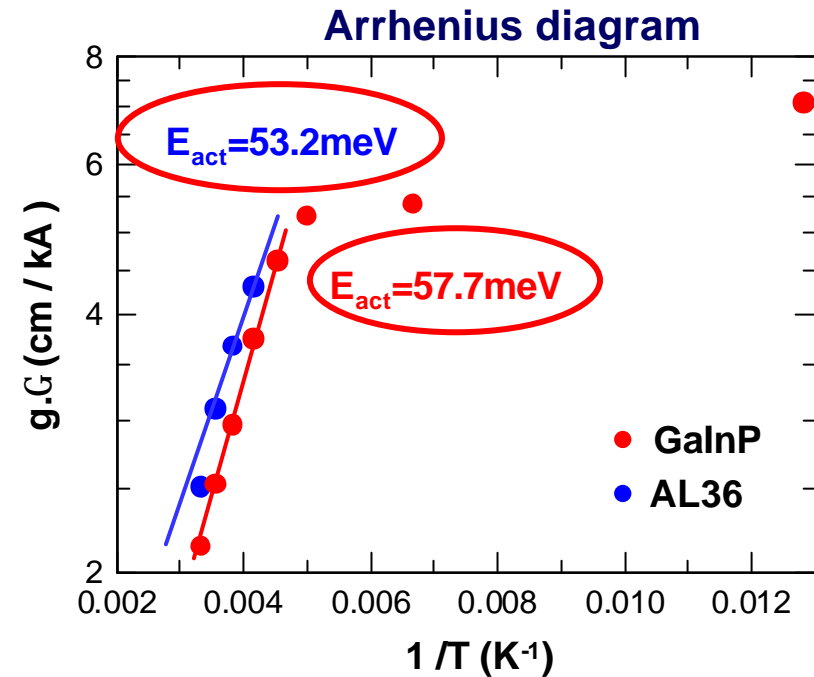
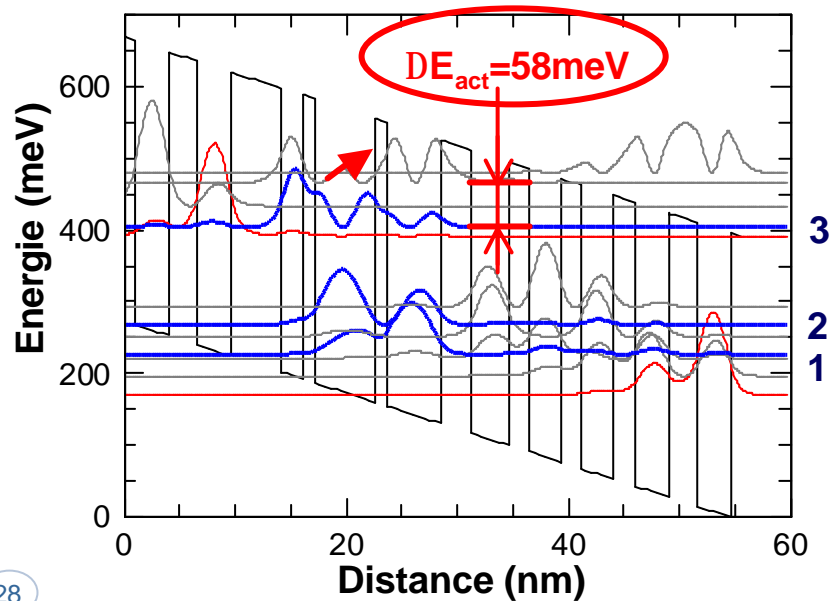
QCL GaInP



$$J_{th} = f(a_m) \text{ plot} \Rightarrow gG = f(T)$$

➔ Observation of 2 operating regimes

Carrier leakage into the continuum ?

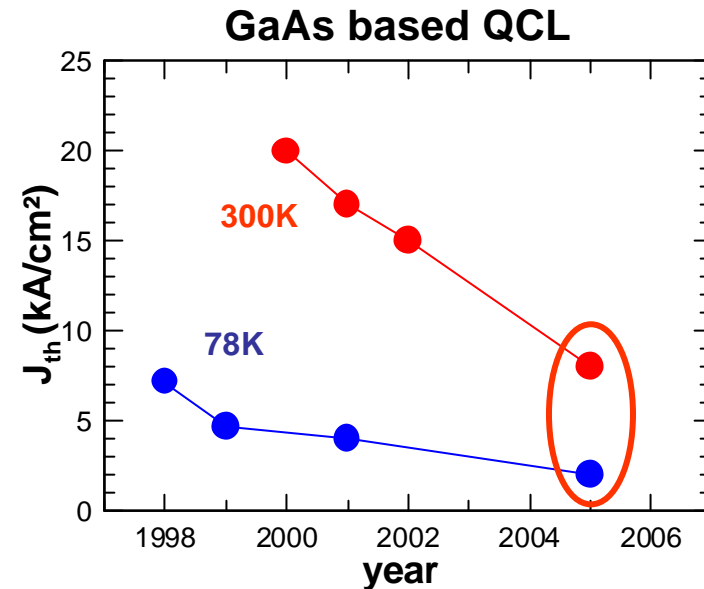


➔ Carrier leakage into the continuum

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

- ➔ 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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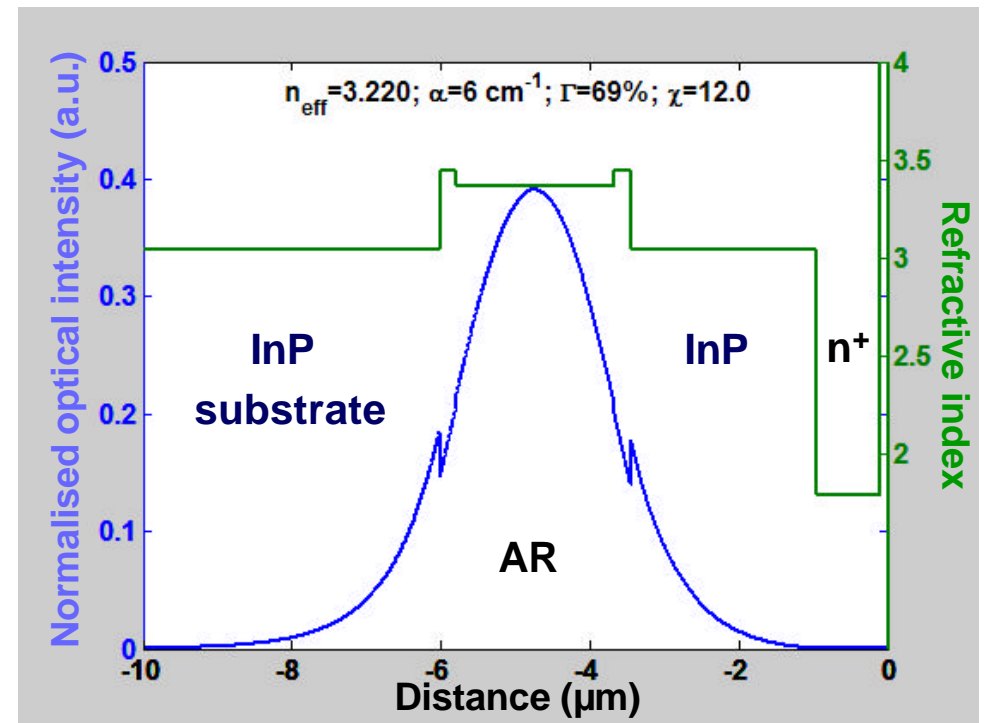
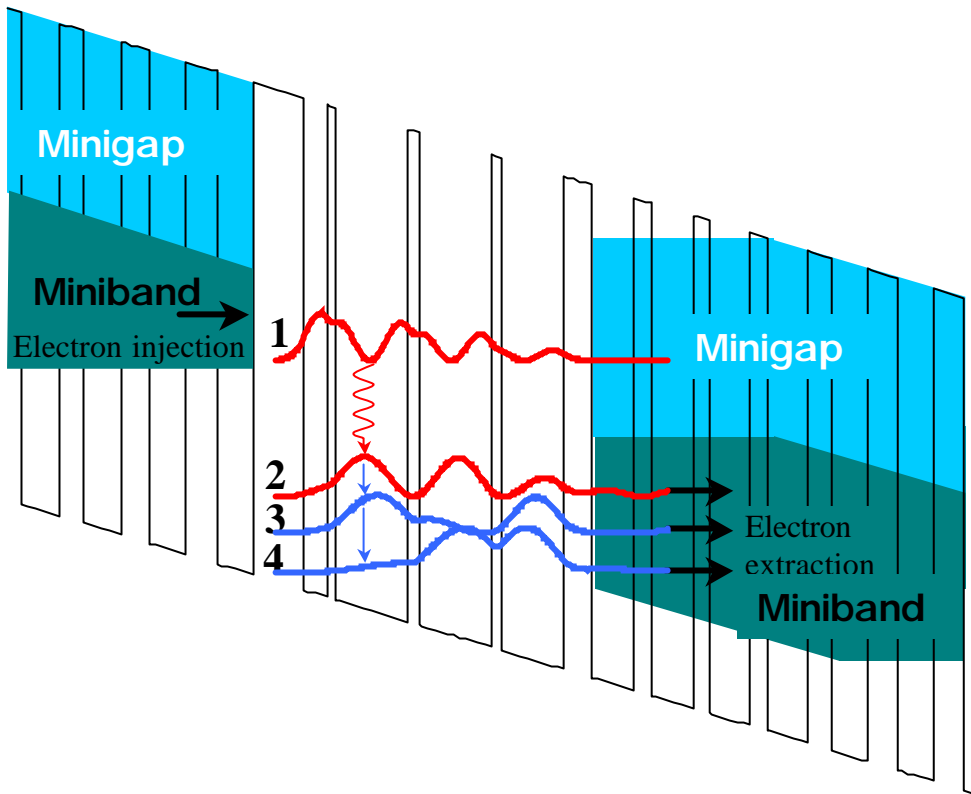
Selective current injection by proton implantation
Thick electro-plated gold

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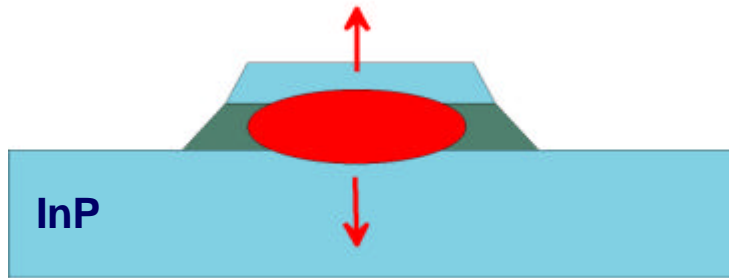
Application to InP-based QCLs

Active Region: 1 ~9 μ m
4 Quantum Wells

Vertical Waveguide Structure: $c \sim 12$
 $G \sim 69\%$
 $a \sim 6 \text{ cm}^{-1}$



Standard ridge waveguide

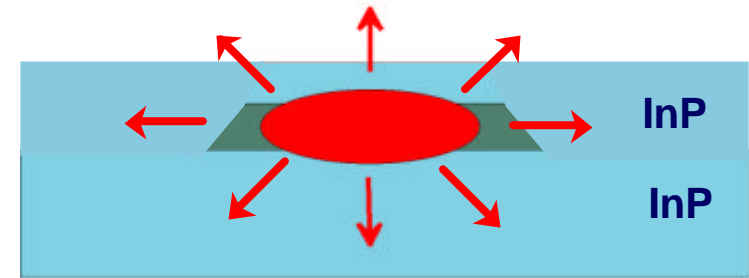


No lateral heat dissipation

InP based QCLs



Buried heterostructure

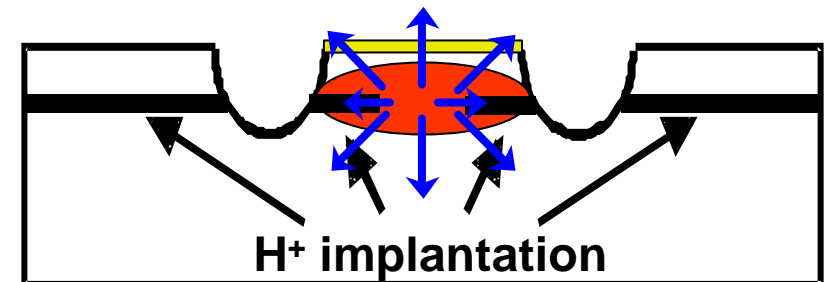


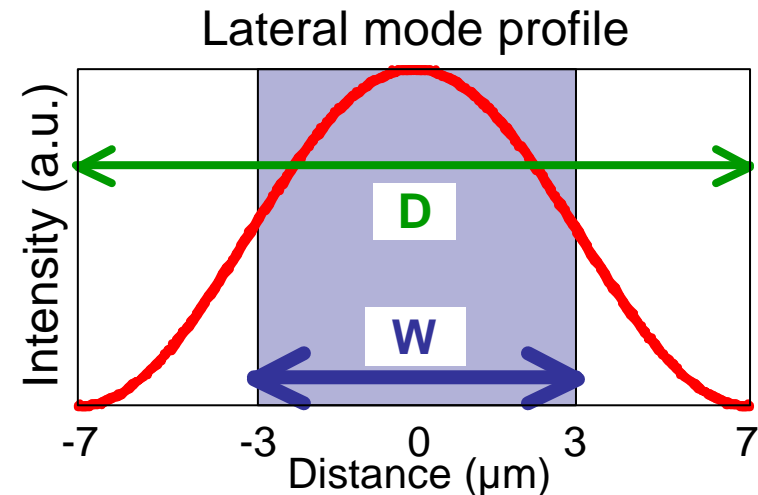
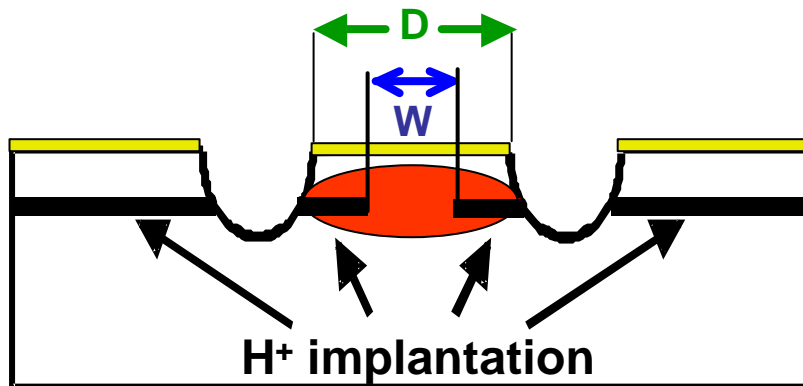
Good lateral heat flow

GaAs based QCLs



Selective current injection





Semi-insulating layers using proton implantation

➔ decrease electrically pumped area

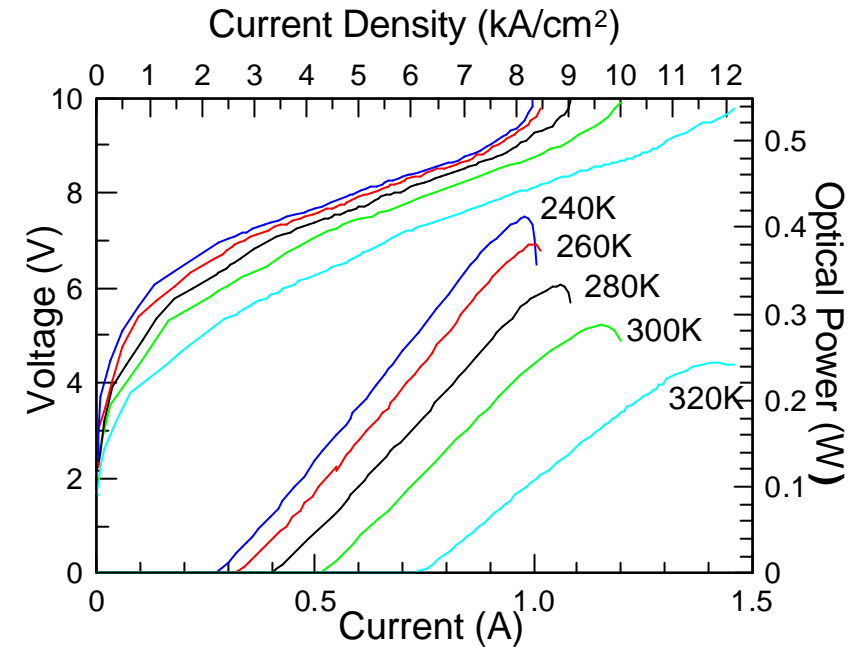
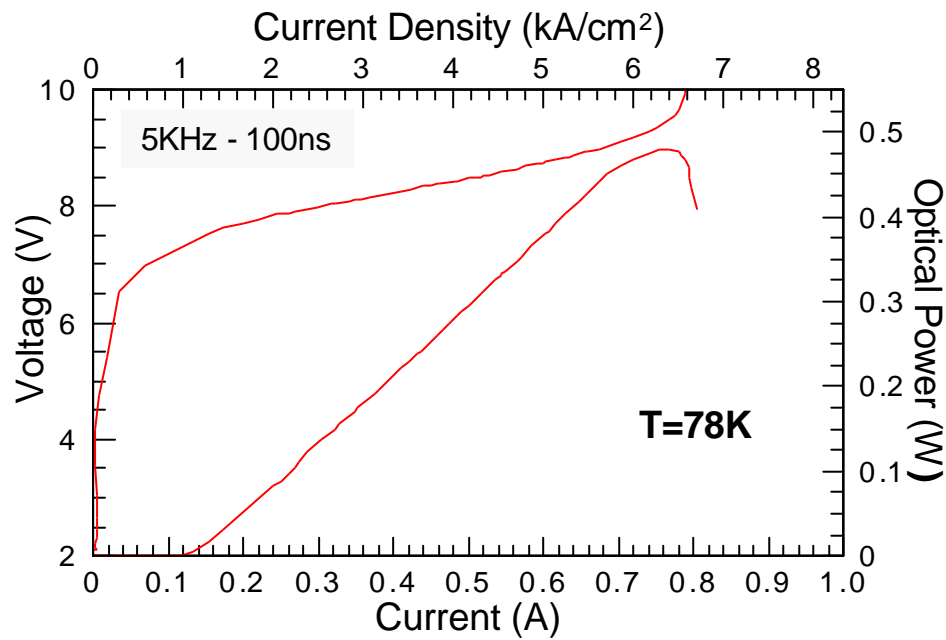
For $\frac{W}{D} = \frac{6}{14} \approx 0,5$

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



Decrease of injected electrical power

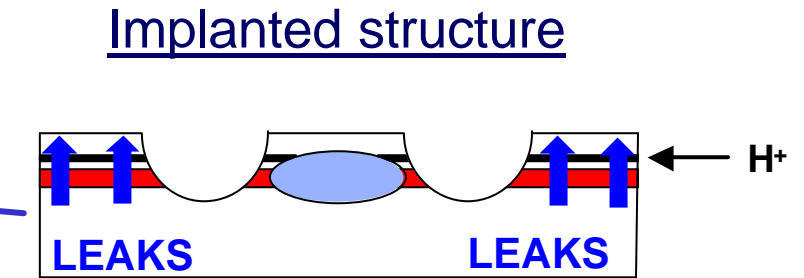
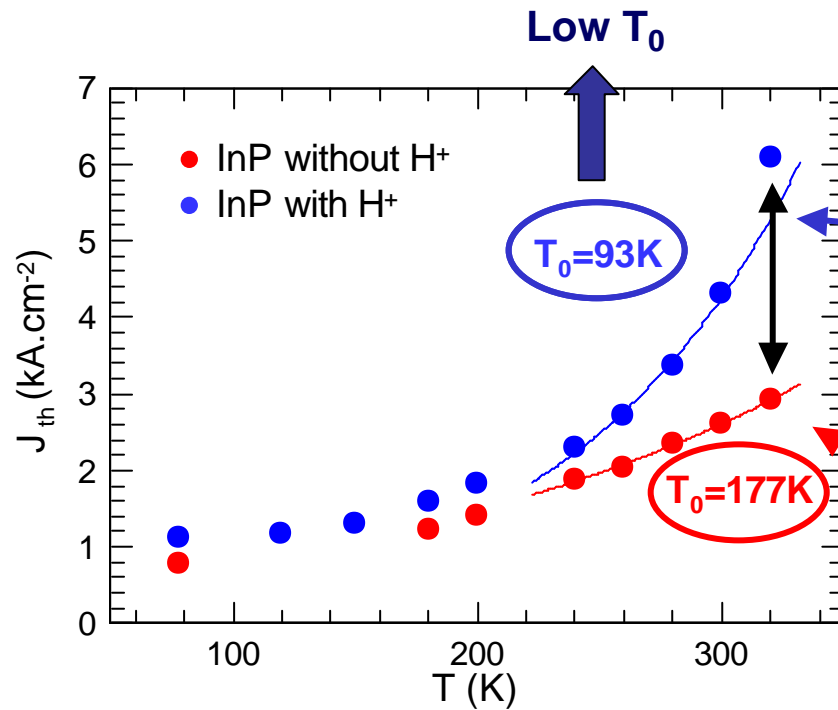
Selective current injection in InP QCLs: L-I-V pulsed characteristics



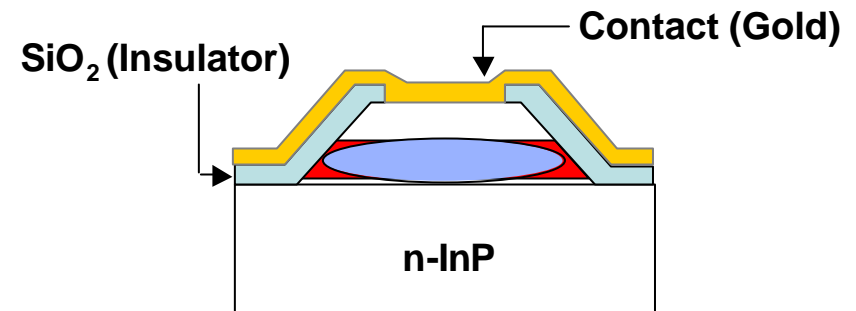
➔ @78K: $I_{th}=135 \text{ mA}$, $J_{th}=1,1 \text{ kA/cm}^2$

➔ @300K: $I_{th}=500 \text{ mA}$, $J_{th}=4,3 \text{ kA/cm}^2$

Abnormally high increase of I_{th} with temperature

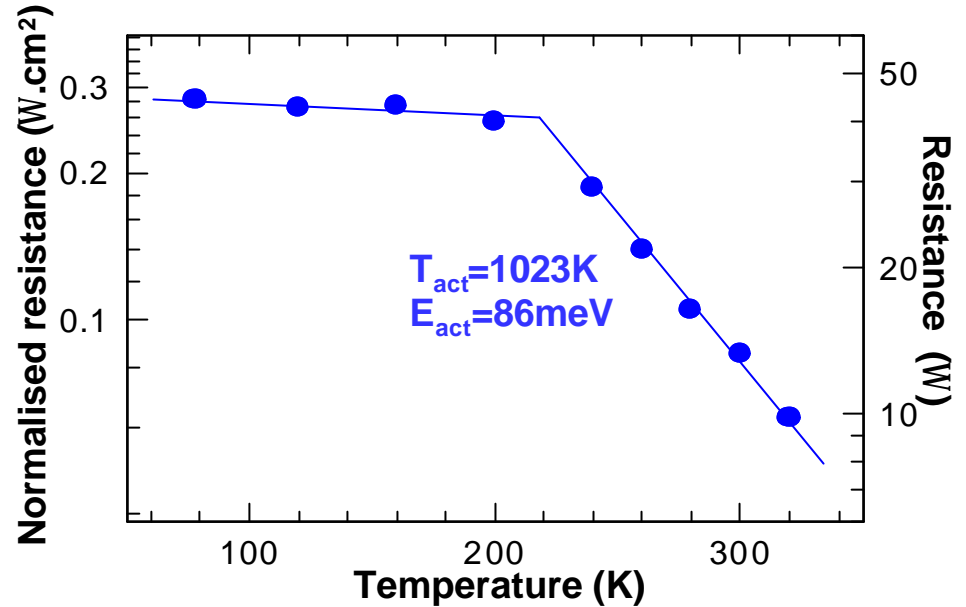
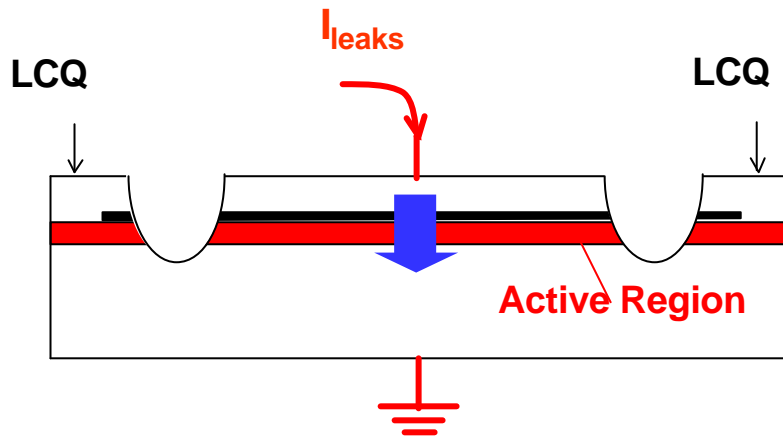


Standard ridge waveguide



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

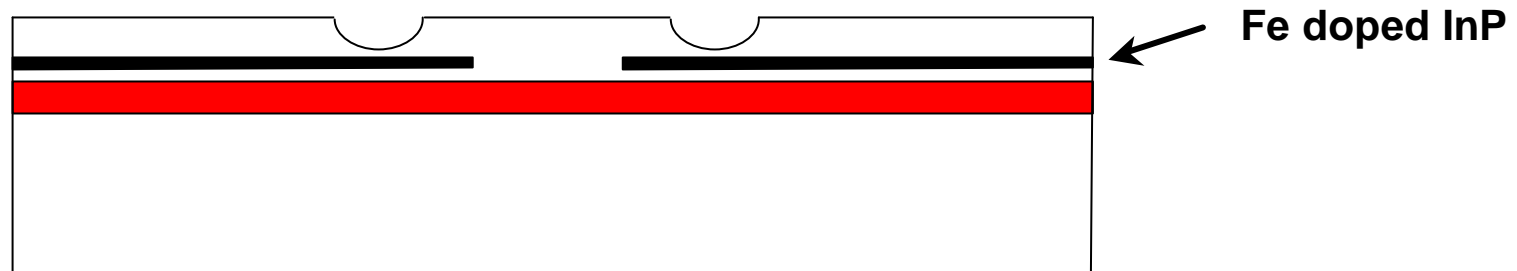


Selective current injection for InP-based QCLs ?

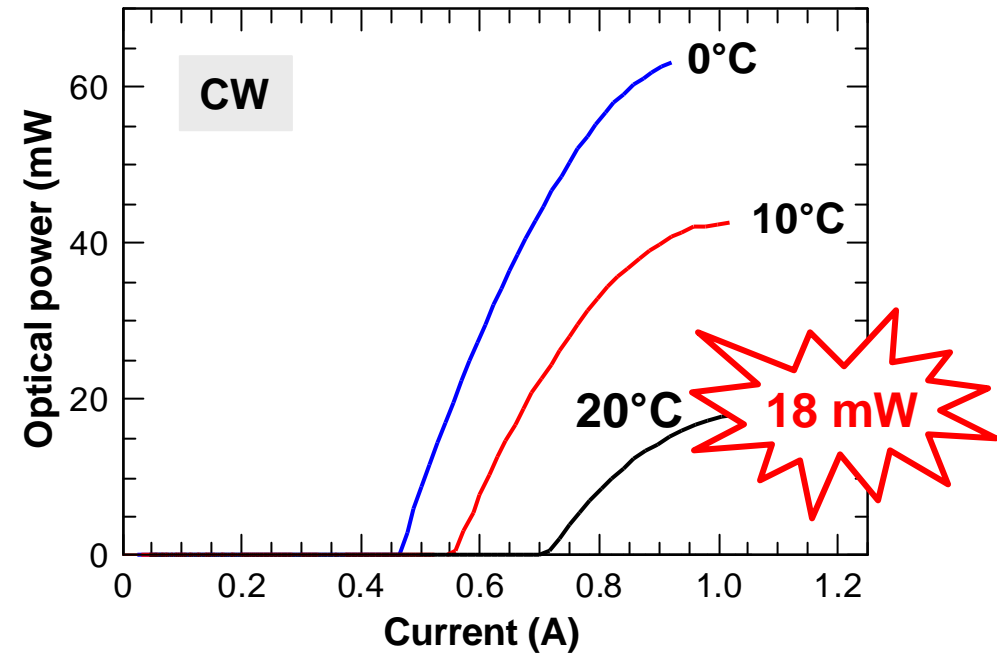
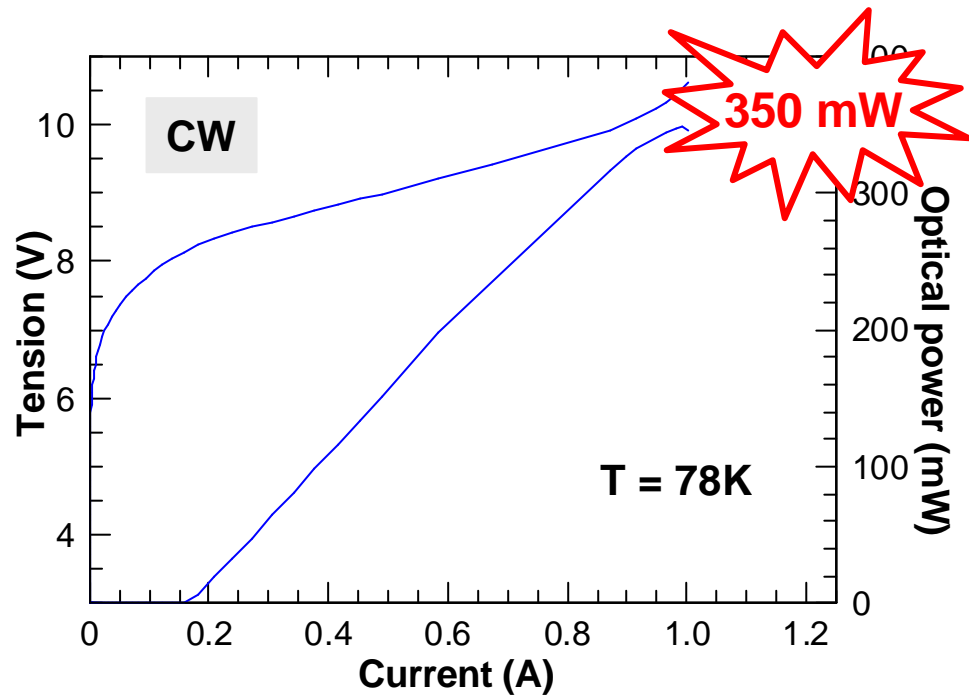
➔ Selective current injection by H⁺ implantation inefficient in InP-based QCLs

➔ 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

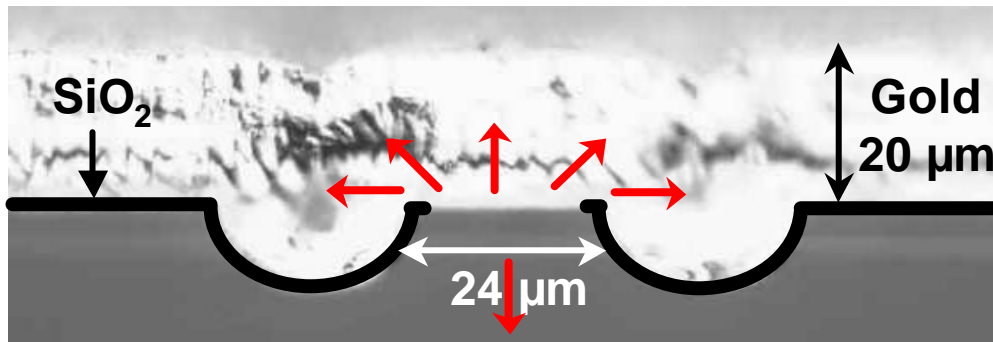


CW operation for H⁺ implanted InP-based QCLs



High Temperature CW operation even with current leakage

Electroplated Au Device

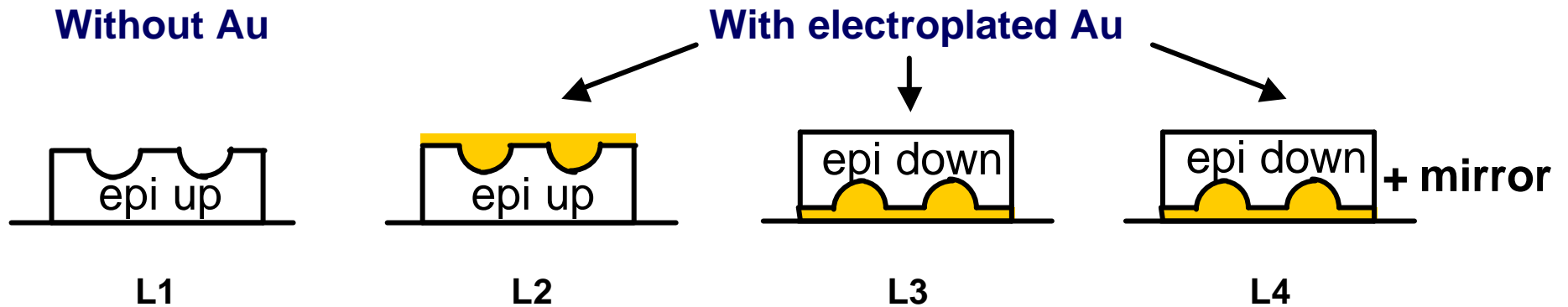


➔ **Very good heat dissipation device**

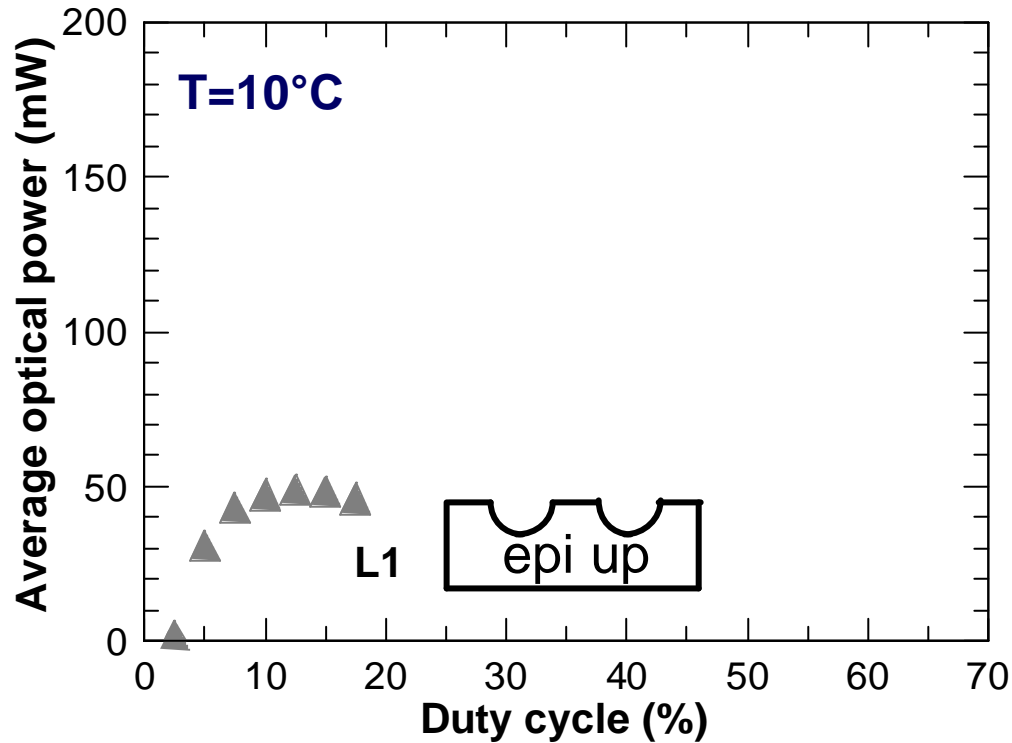
Best performances obtained on QCLs with this type of device

Slivken et al, APL (2004)

4 experimental arrangements:

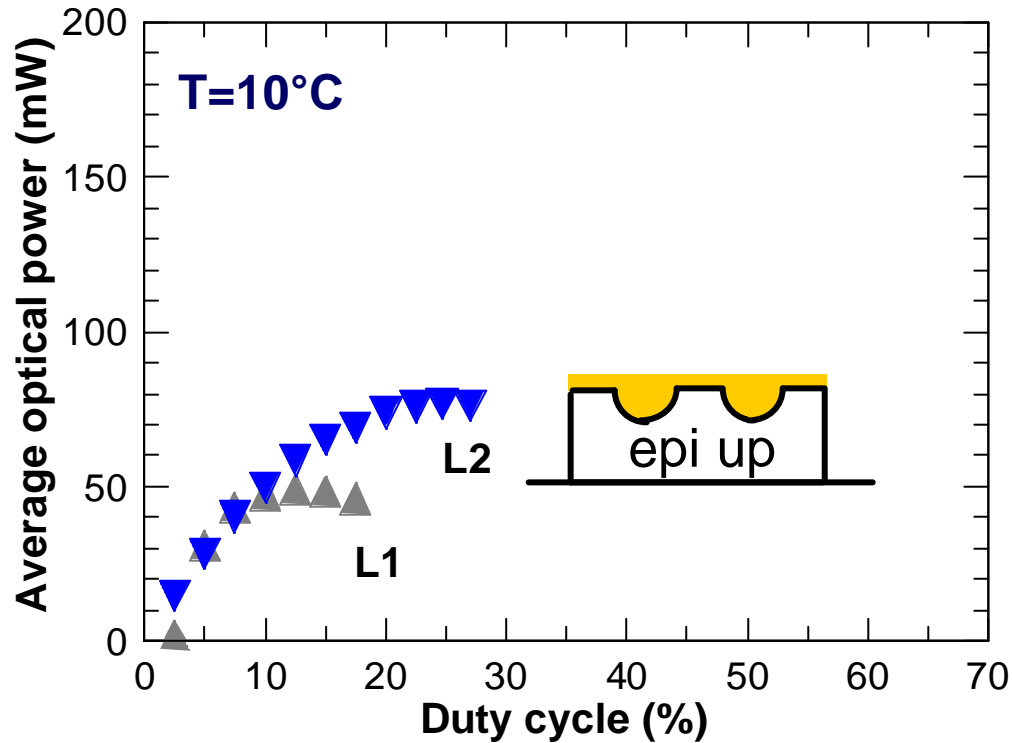


Effect of Thick electroplated Au



L1 → $P_{\max} = 49\text{mW}$ for DC=12%

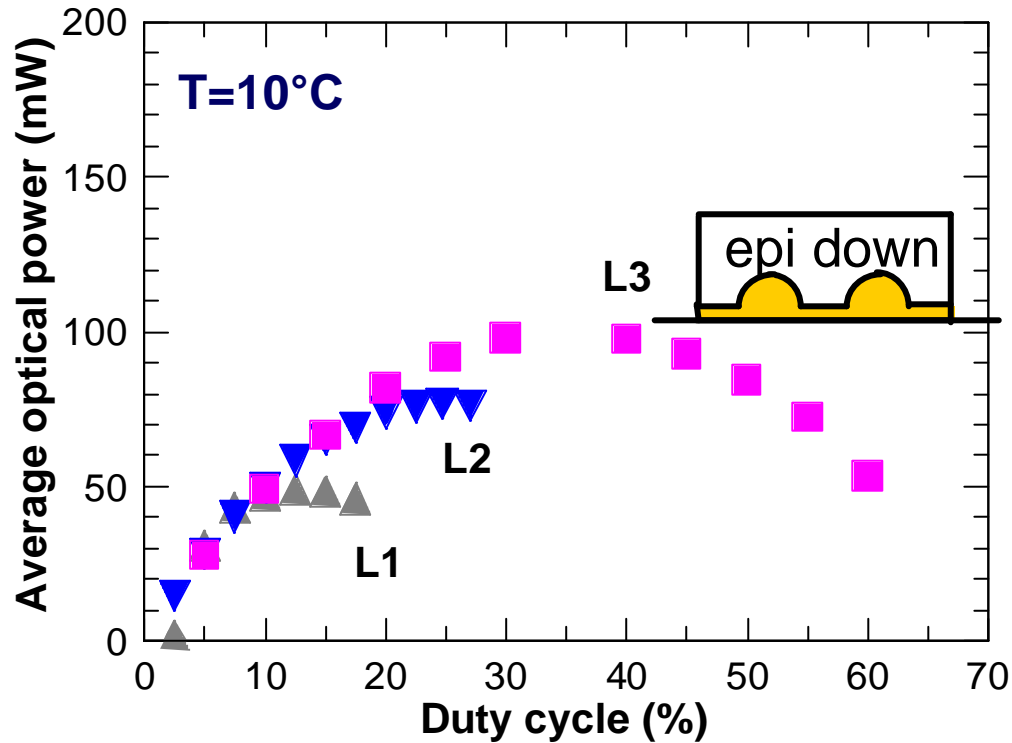
Effect of Thick electroplated Au



L1 → $P_{max} = 49\text{mW}$ for **DC=12%**

L2 → $P_{max} = 78\text{mW}$ for **DC=25%**

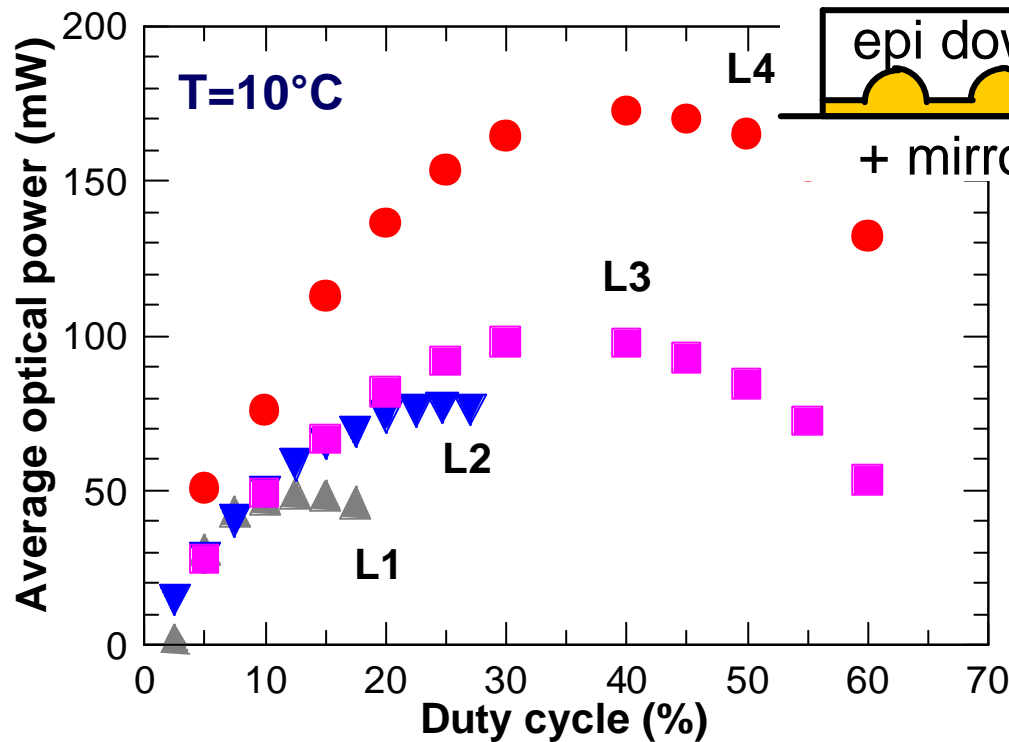
Effect of Thick electroplated Au



L1 → $P_{\max} = 49\text{mW}$ for **DC=12%**

L2 → $P_{\max} = 78\text{mW}$ for **DC=25%**

L3 → $P_{\max} = 102\text{mW}$ for **DC=37%**








L1 → $P_{max} = 49\text{mW}$ for DC=12%

L2 → $P_{max} = 78\text{mW}$ for DC=25%





L3 → $P_{max} = 102\text{mW}$ for DC=37%

L4 → $P_{max} = 175\text{mW}$ for DC=40%

Thick electroplated Au - Summary

		R_{th} (K.cm/ W)	
L1		6	 <p>-50%</p> <p>~ -40%</p>
L2		2,9	
L3		1,8	
L4	 + mirror	1,8	
Buried Heterostructure (Beck et al, Science295, 2002)		1,45	

Thick electroplated Au - Summary

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

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

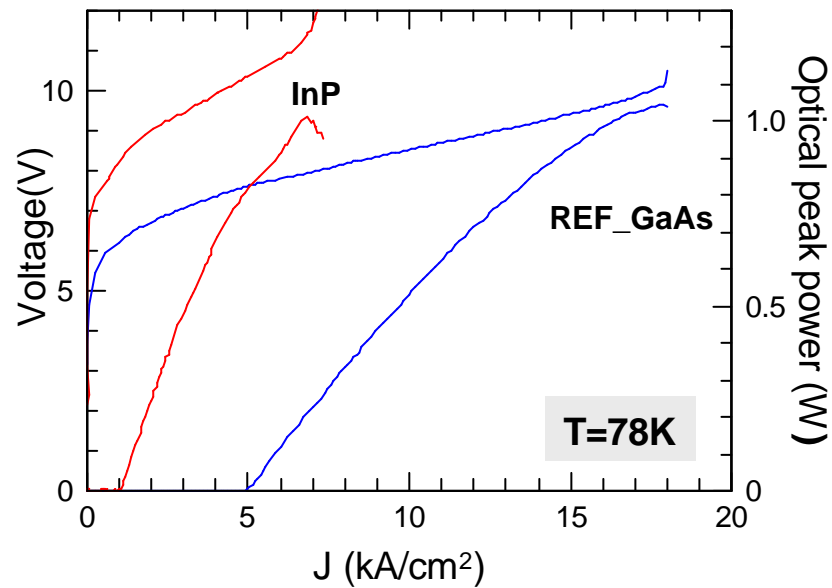
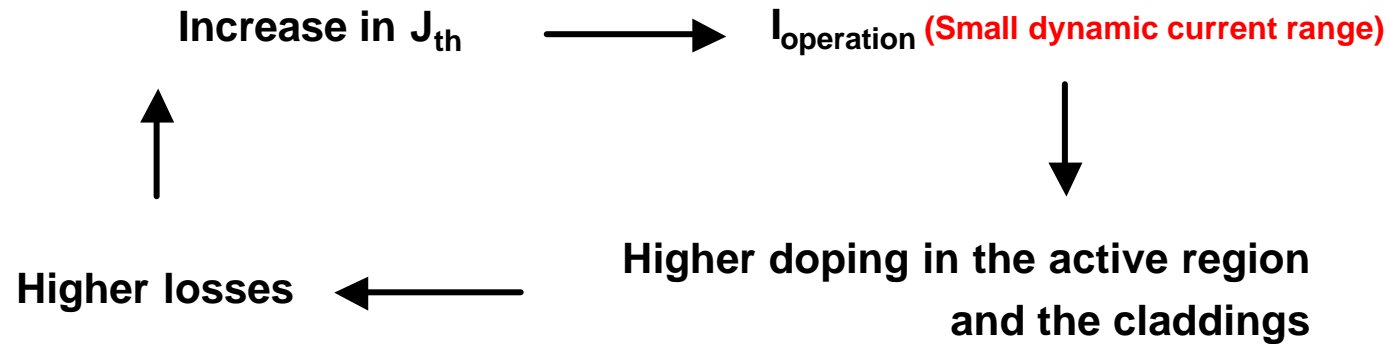
4. Conclusion

- ➔ **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

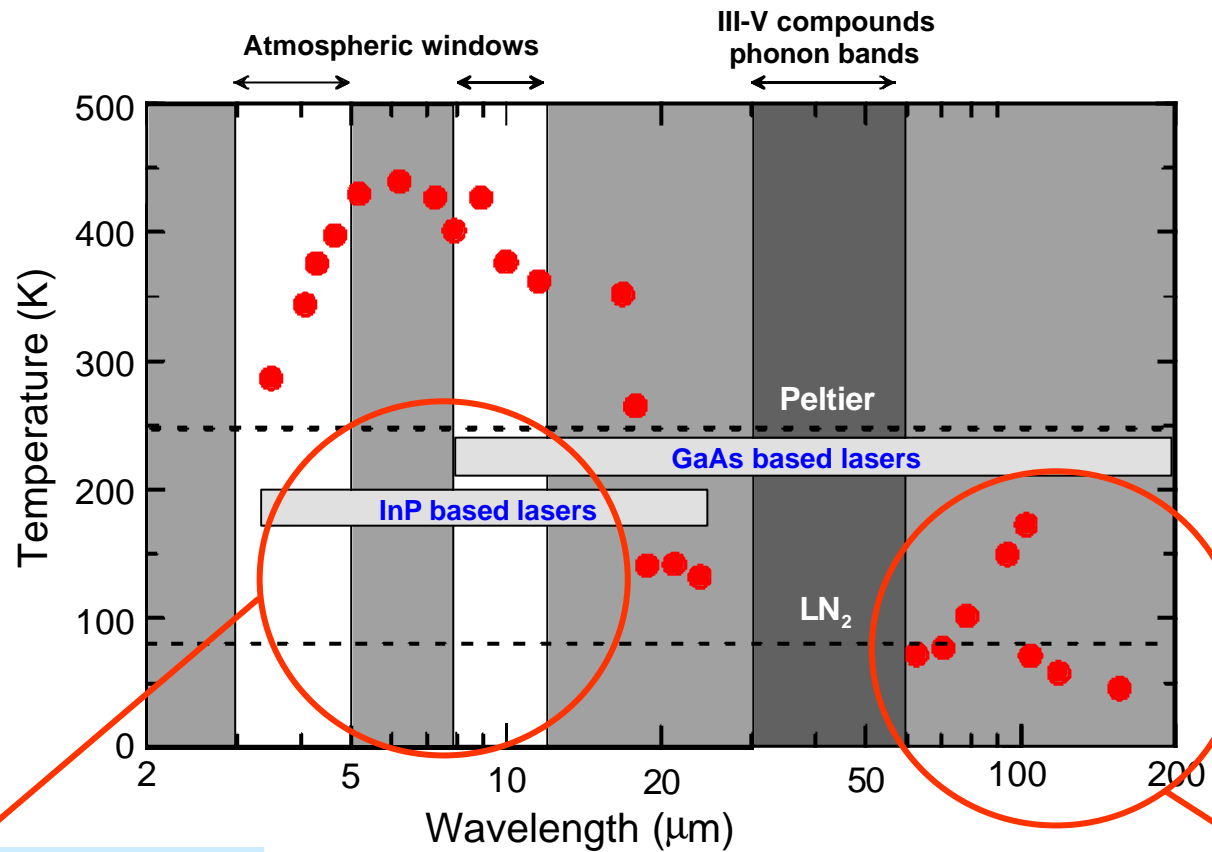


Thick electroplated Au on selective current injection devices

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



Which material for which wavelength ?



Mid Infrared :

AllInAs/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

