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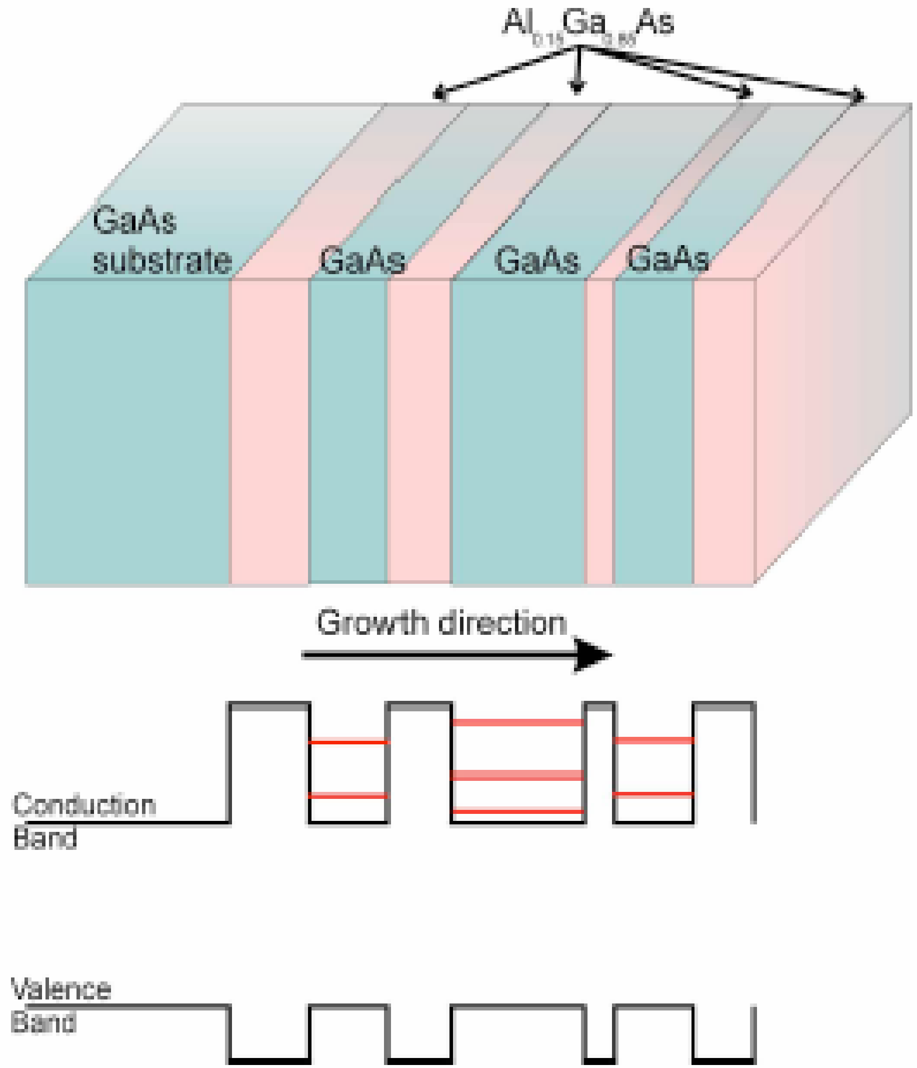
- GaAs and $Al_xGa_{1-x}As$ (or InGaAs/InAlAs) are lattice-matched, can be grown on top of each other defect-free.
- Different gap energies in GaAs and $Al_xGa_{1-x}As$ form quantum wells.
- Molecular Beam Epitaxy (MBE) can grow layer by layer, atomically smooth.
- In essence, with MBE we can design and grow "Artificial Atoms" or " artificial molecules." We can control the size of wells and relative energy levels.



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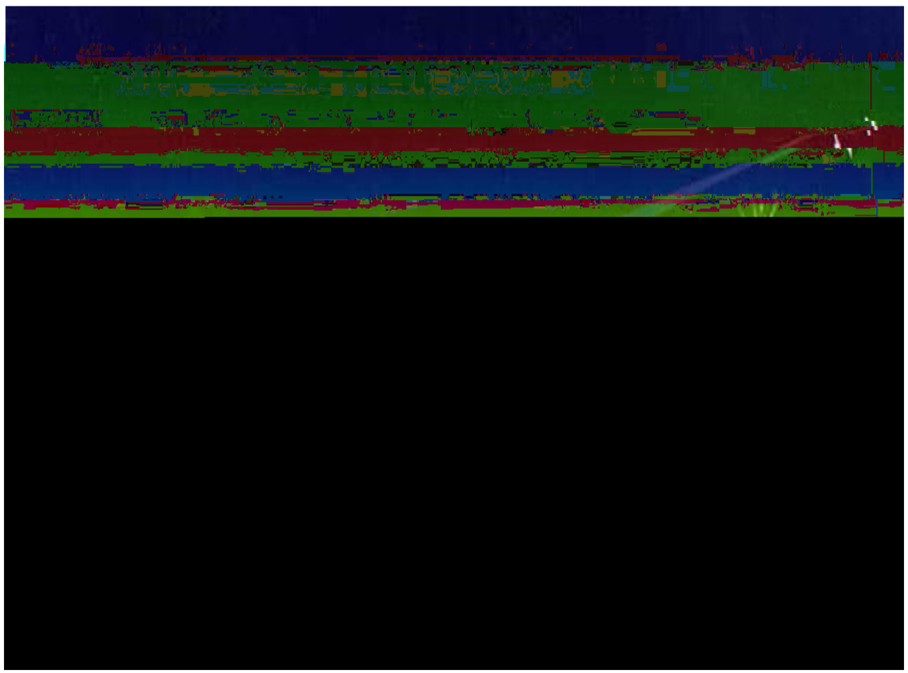 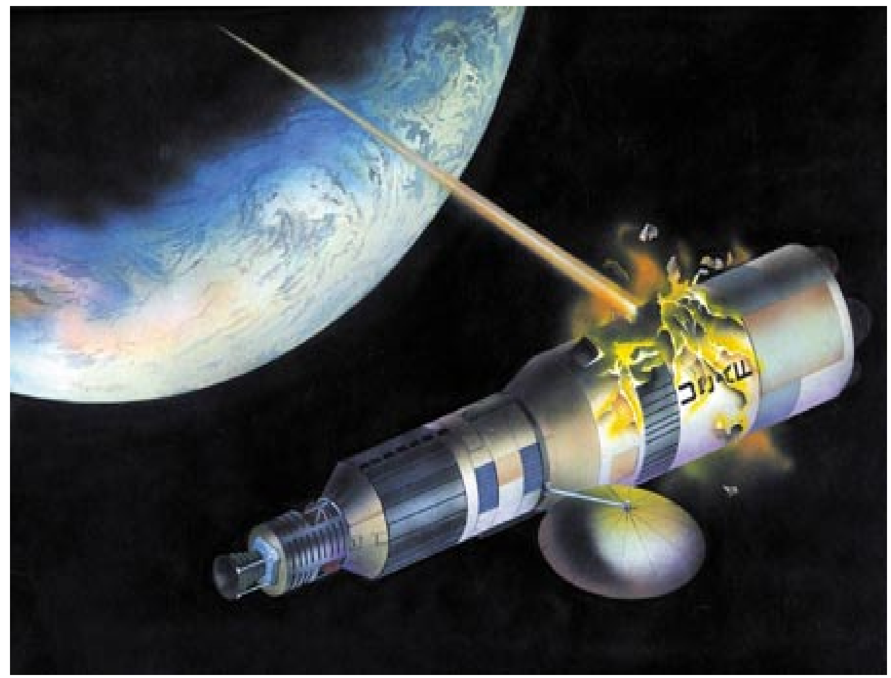

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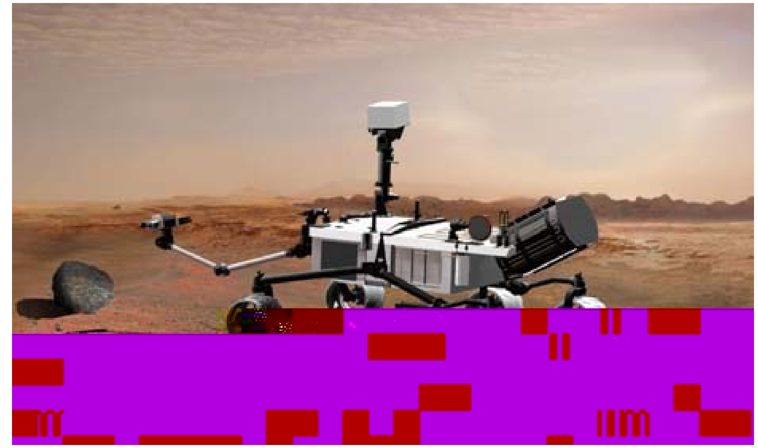
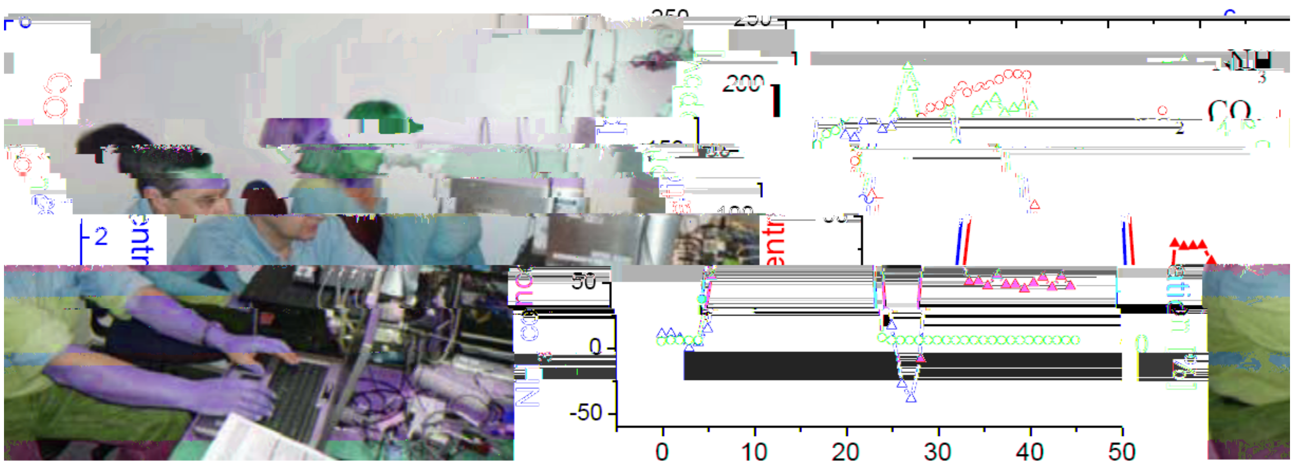
NASA 2011





ath analysis facility
St. Luke's Hospital

Sensor response @ 45oC

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III-V ` E ˮl ʮ

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IV-IV

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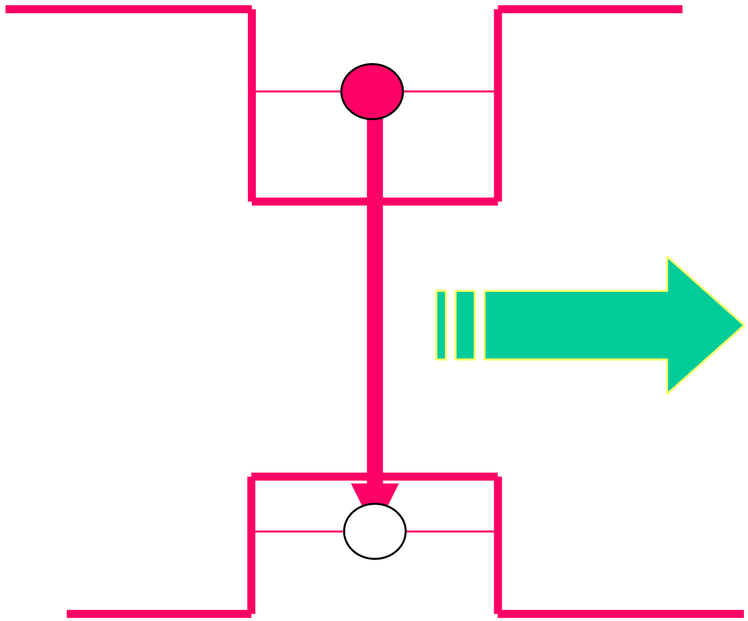
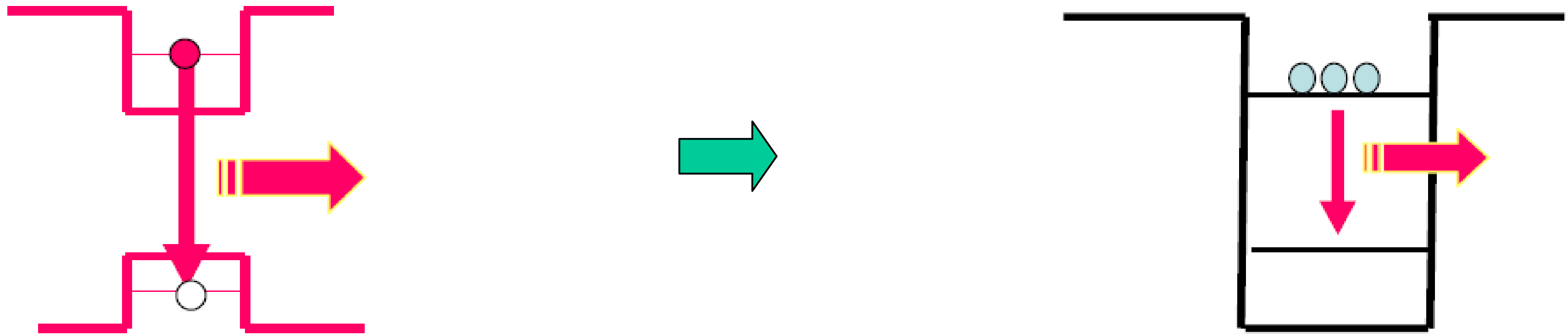
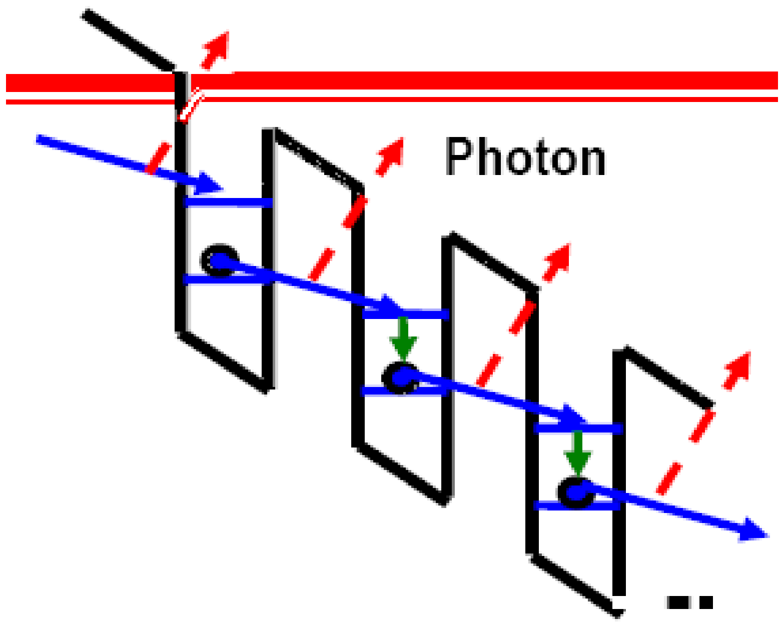
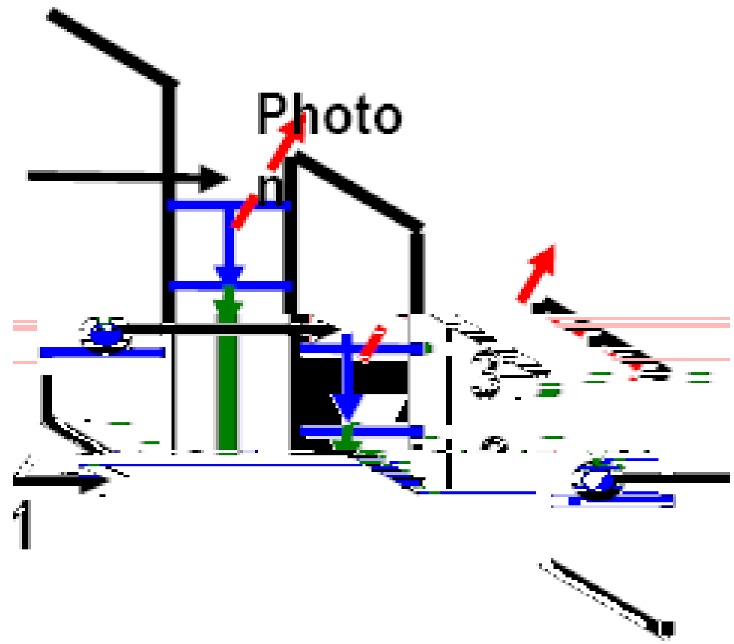




R. F.Kazarinov, R.A.Suris,Sov. Phys.Semicond. 5, 707 (1971)





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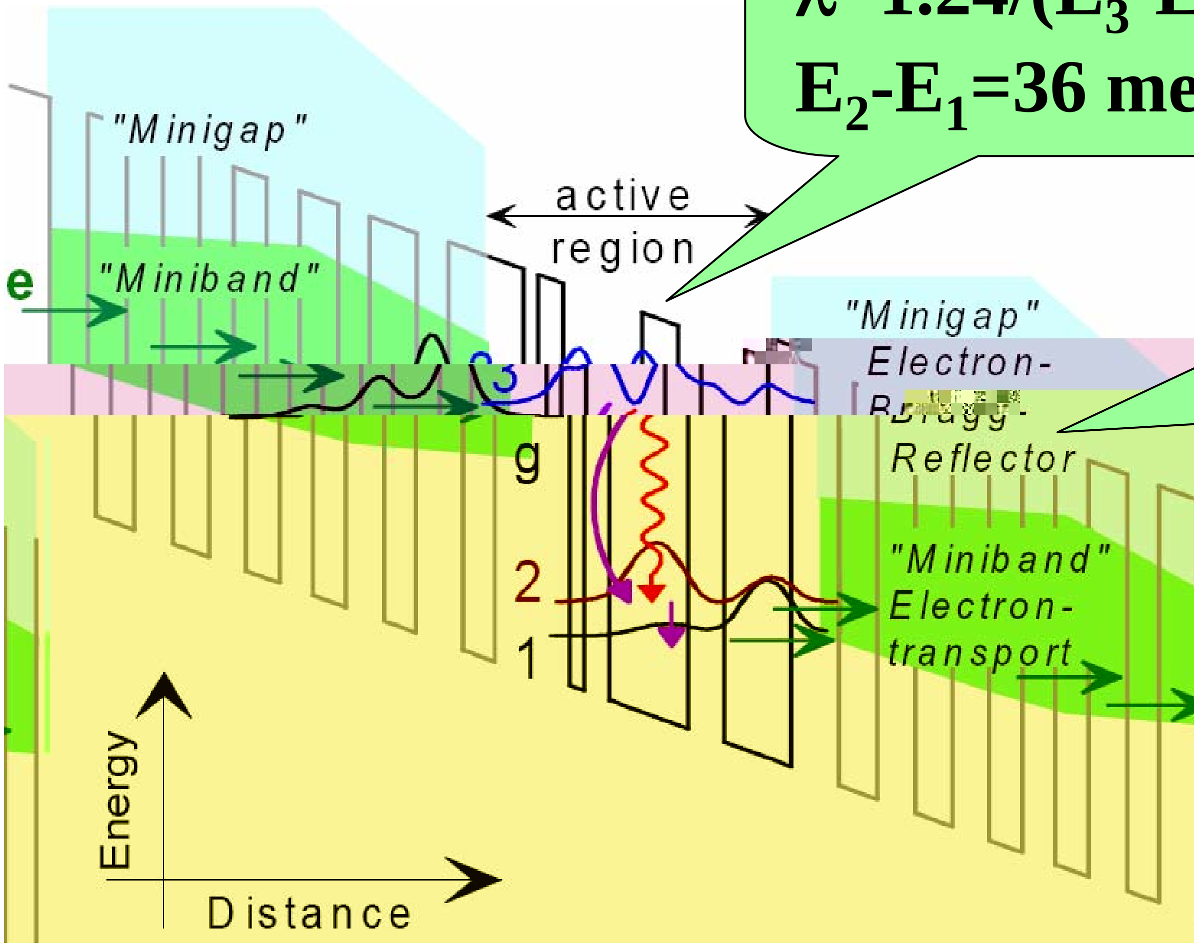
ˮl ʎ(QCL) ɔ ʮ

λ=1.24/(E_3-E_2)

E_2-E_1=36 meV



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n=3 Bragg ɻ ʎ˘
n=1 à 2 Â

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1 à 2 ˘
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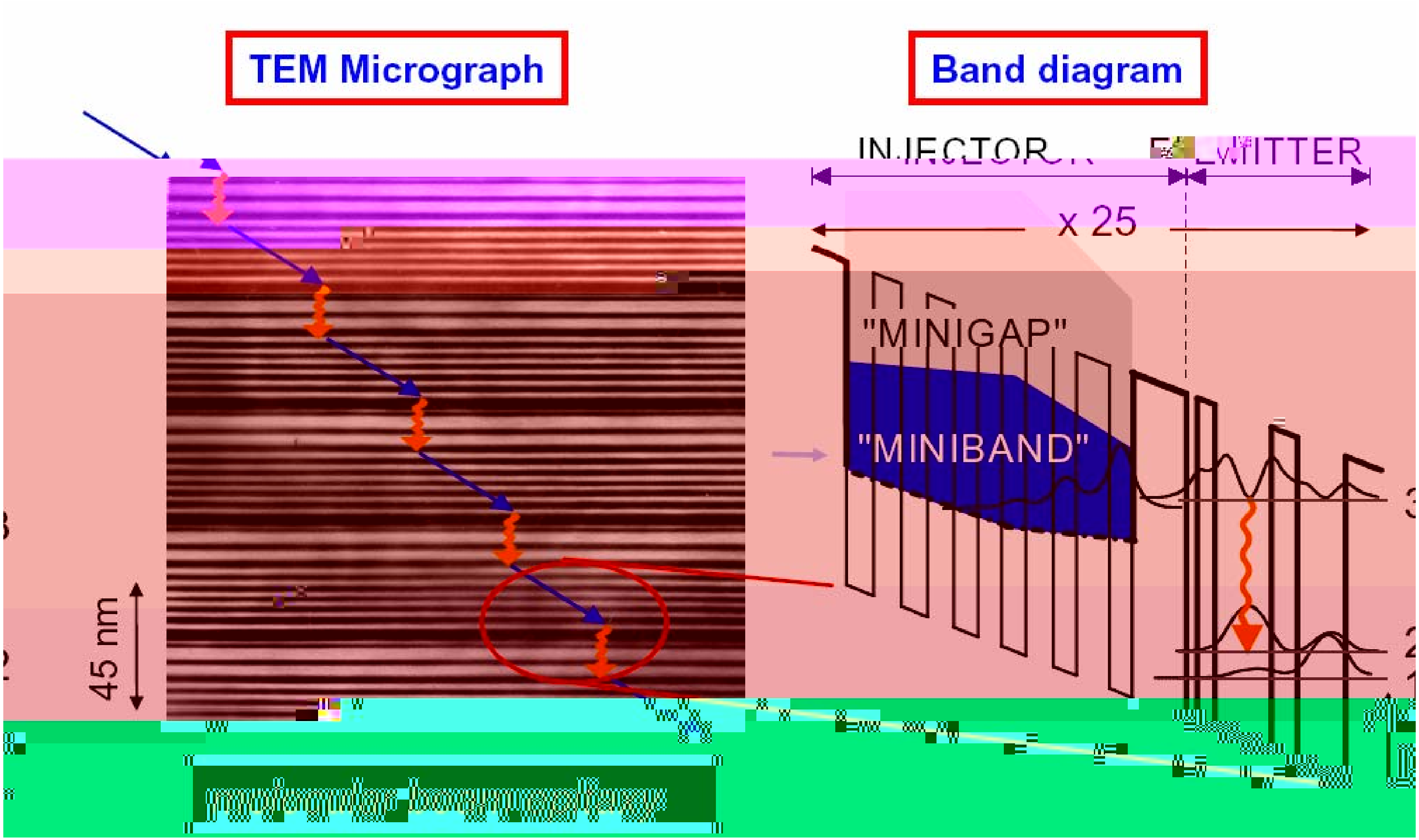

TEM Micrograph
Band diagram
INJECTOR
x 25
"MINIGAP"
"MINIBAND"
45 nm

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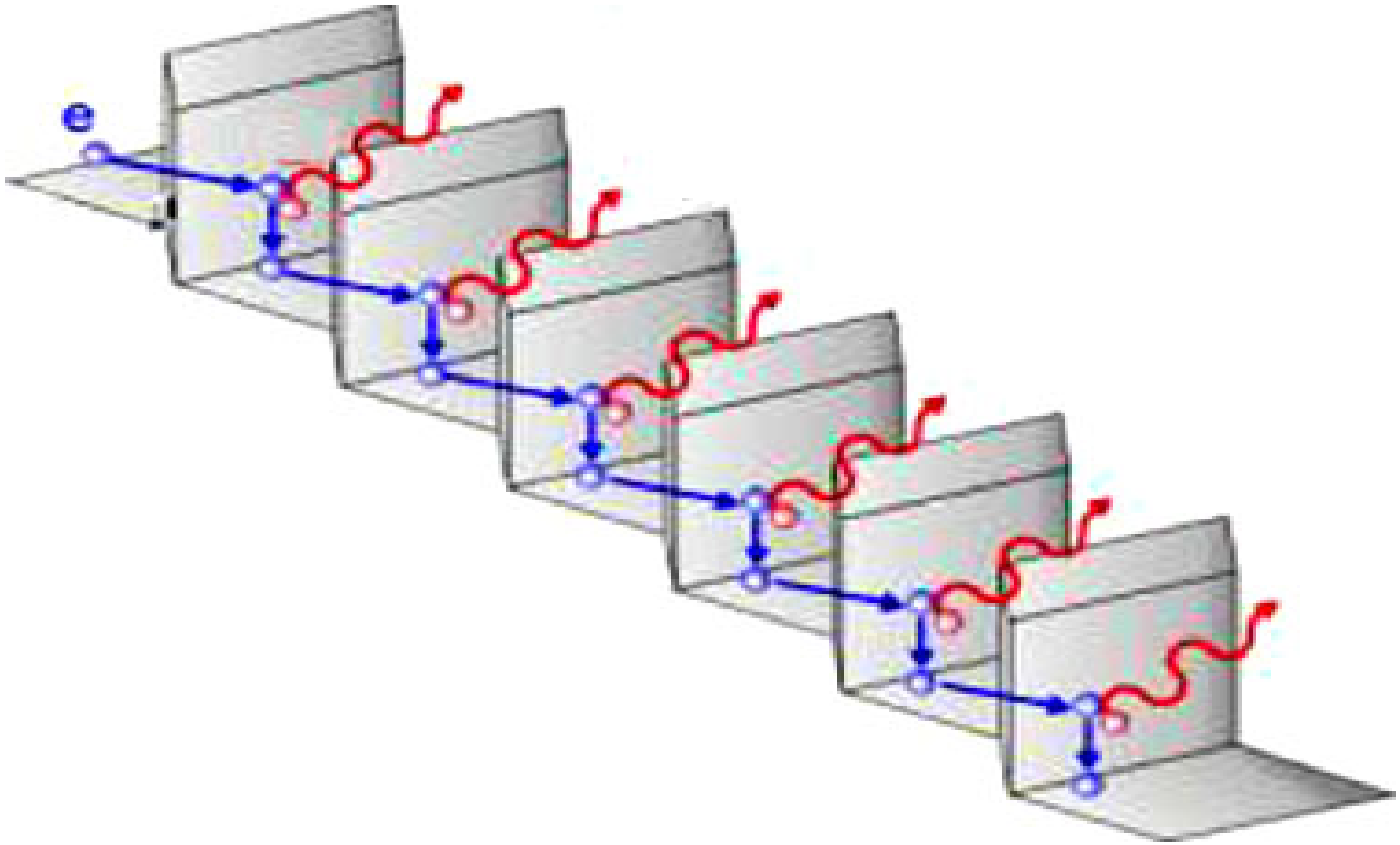

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QCL

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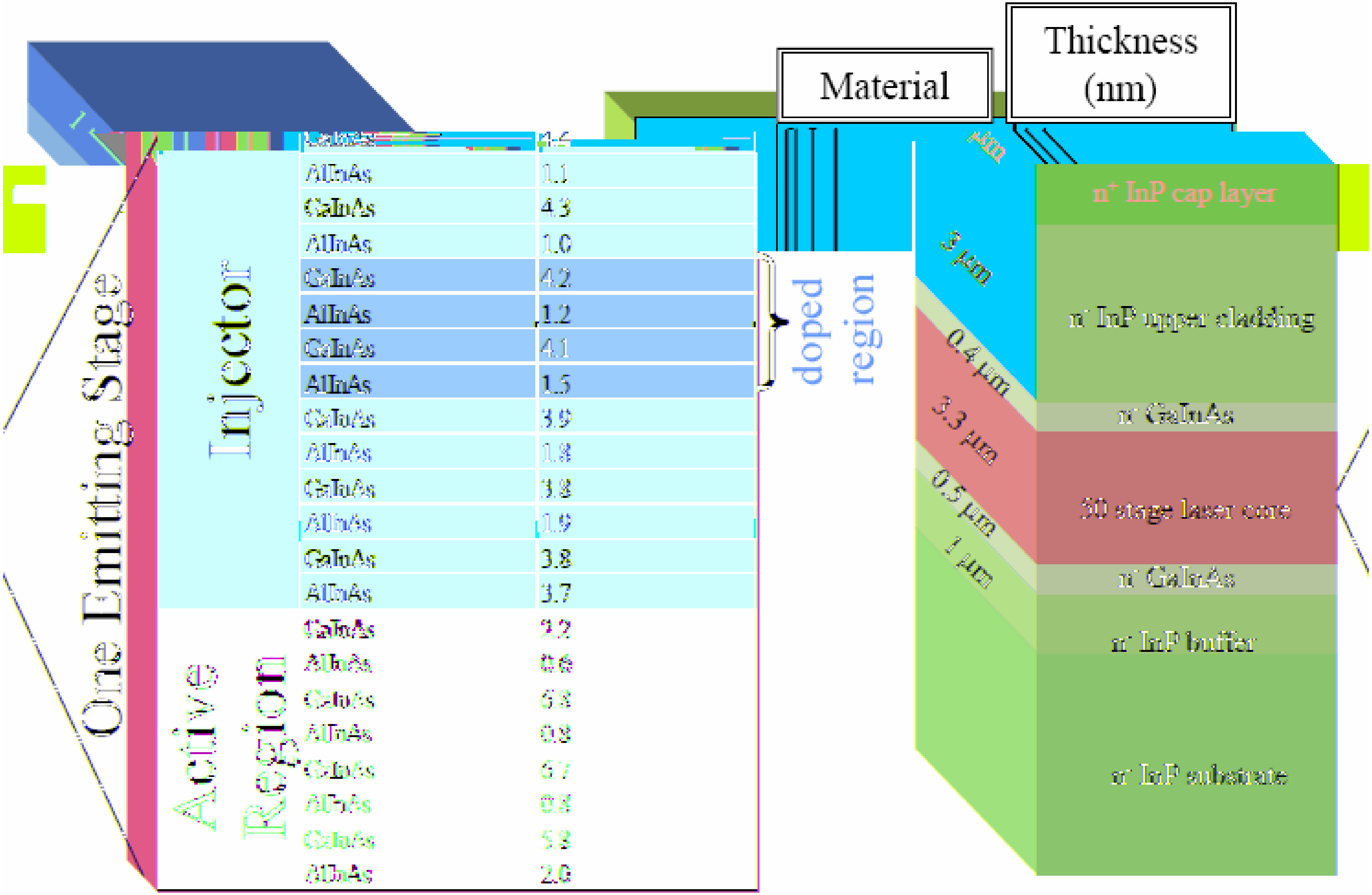
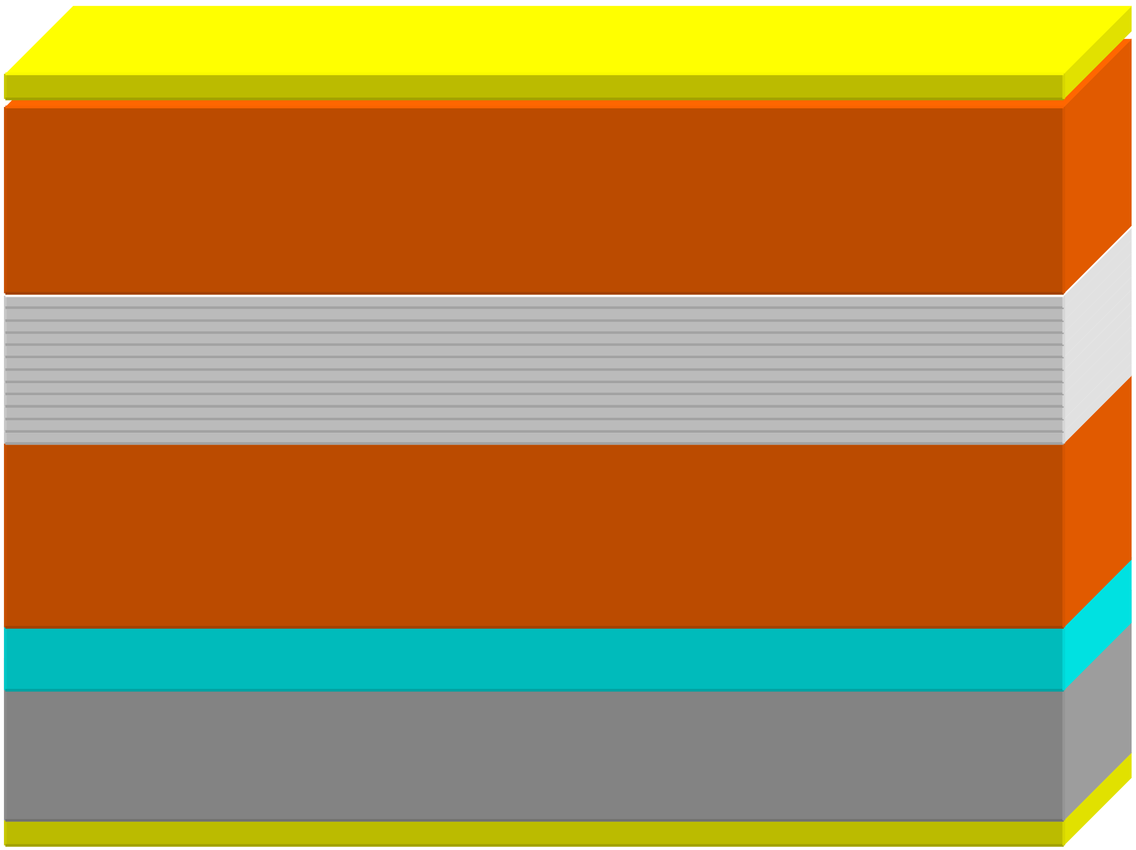
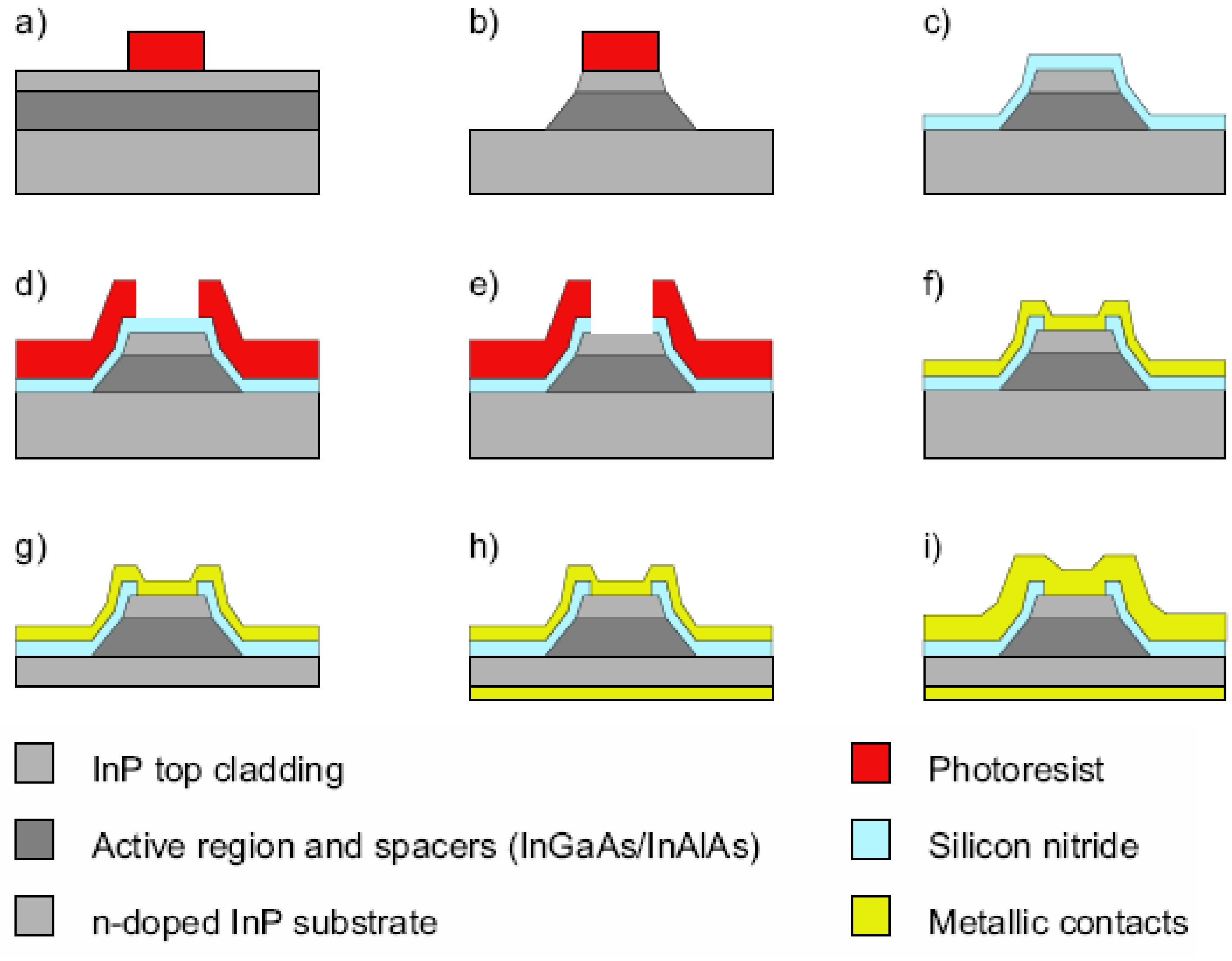
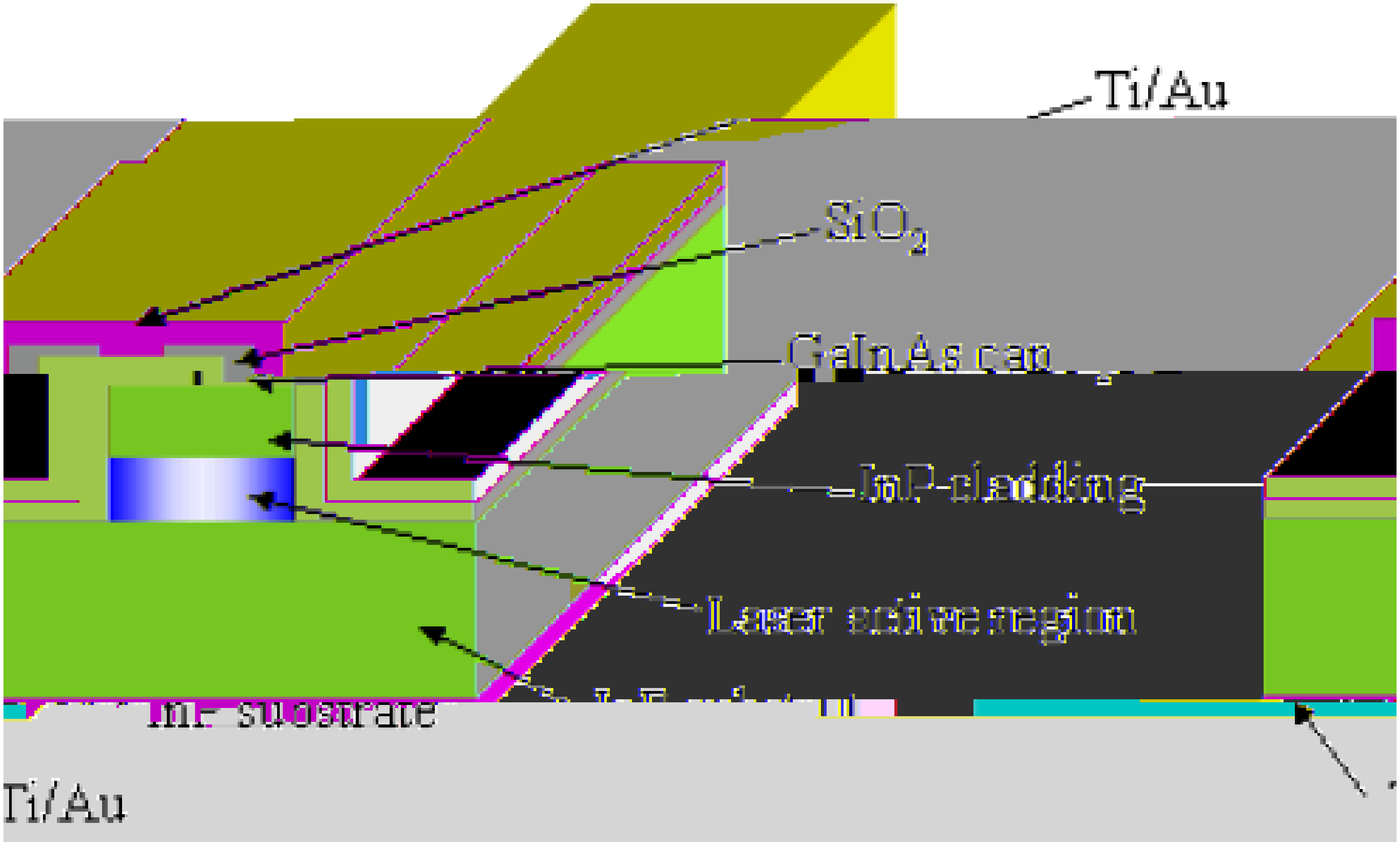
SiGe/Si E Â



Material
Thickness (nm)
One Emitting Stage
Injector
Active Region
AlInAs 1.1
GaInAs 4.3
AlInAs 1.0
GaInAs 4.2
AlInAs 1.2
GaInAs 4.1
AlInAs 1.5
GaInAs 3.9
AlInAs 1.8
GaInAs 3.8
AlInAs 1.9
GaInAs 3.8
AlInAs 3.7
GaInAs 2.2
AlInAs 0.6
GaInAs 6.8
AlInAs 0.8
GaInAs 6.7
AlInAs 0.8
GaInAs 5.8
AlInAs 2.0
doped region
n^+ InP cap layer
n InP upper cladding
n GaInAs
50 stage laser core
n GaInAs
n InP buffer
n InP substrate
3 µm
0.4 µm
3.3 µm
0.5 µm
1 µm




a)
b)
c)
d)
e)
f)
g)
h)
i)
InP top cladding
Active region and spacers (InGaAs/InAlAs)
n-doped InP substrate
Photoresist
Silicon nitride
Metallic contacts


Ti/Au
SiO$_2$
GaInAs cap
InP-cladding
Laser active region
Ti/Au

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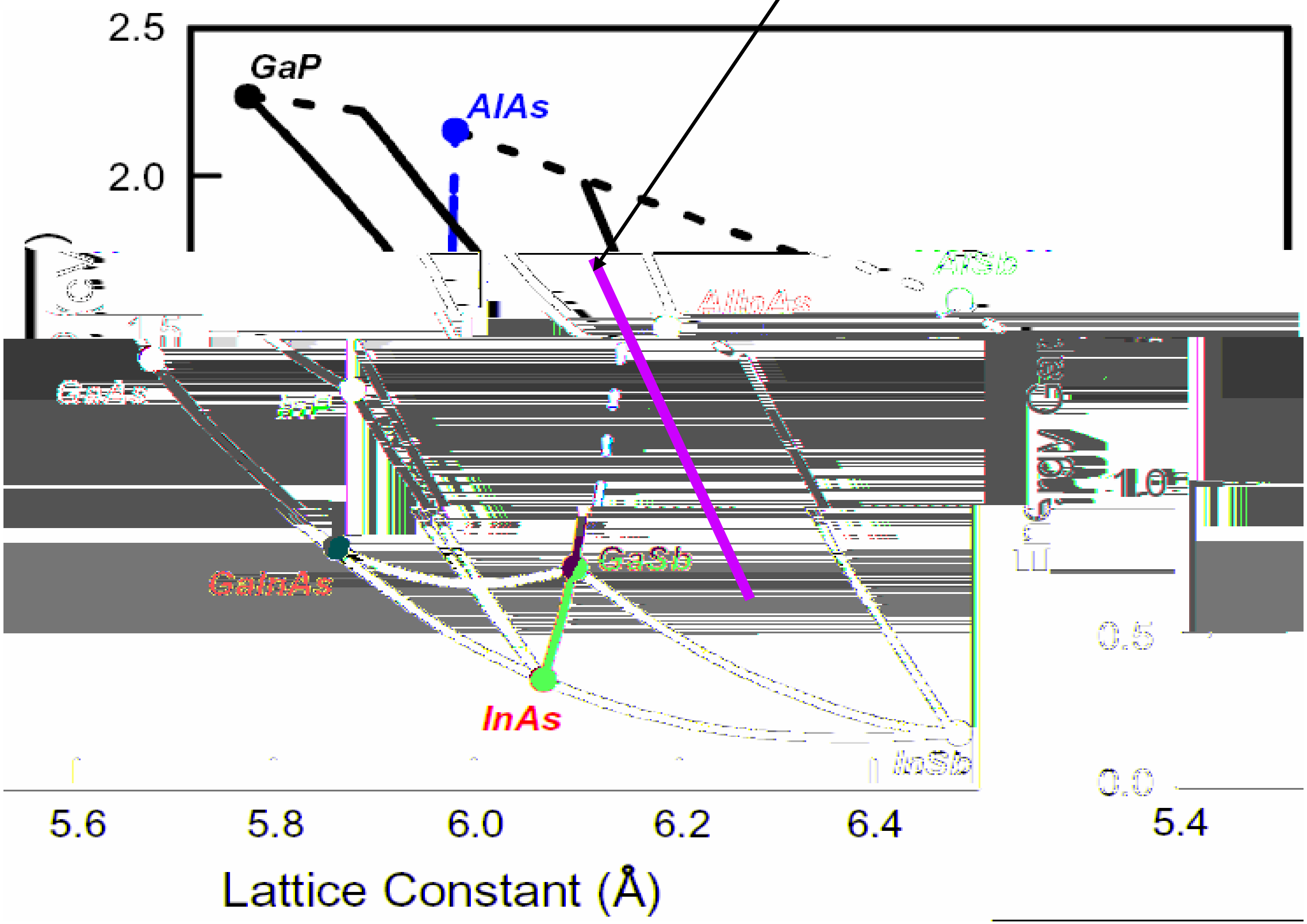
$In_{1-x}Ga_xAs/\ In_{1-y}Al_yAs$



b.

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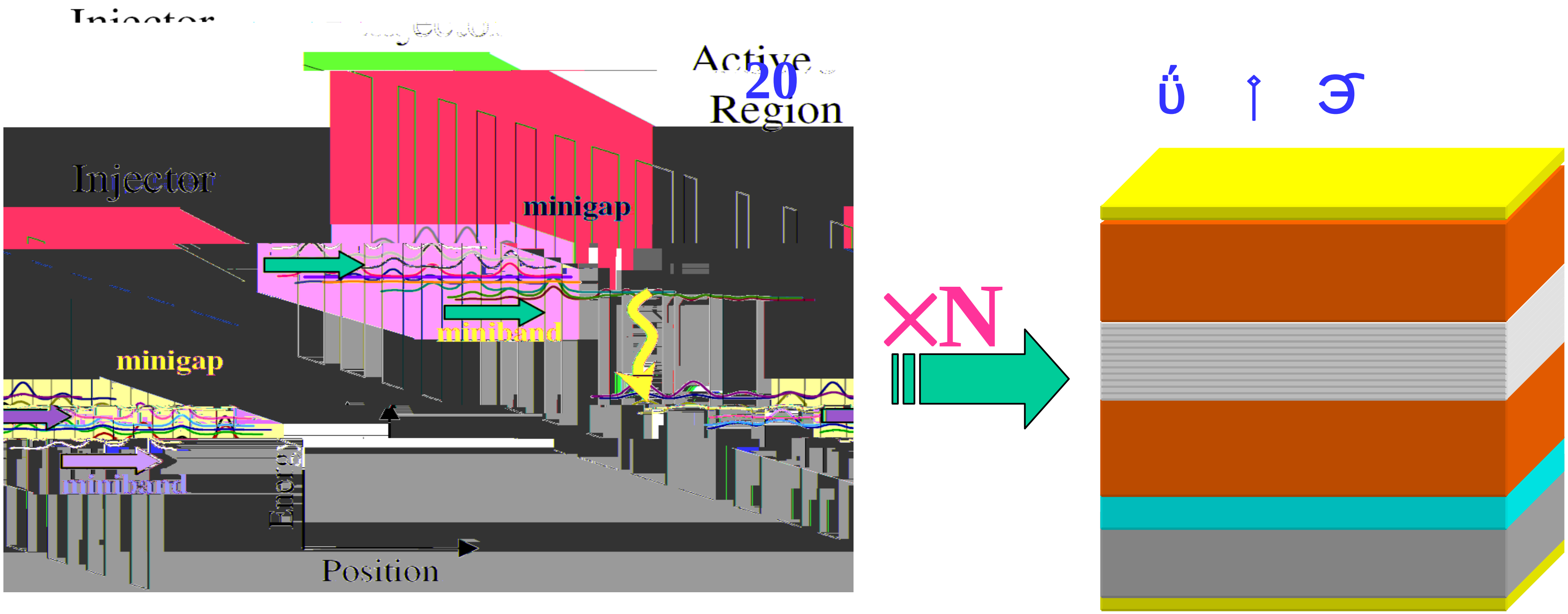
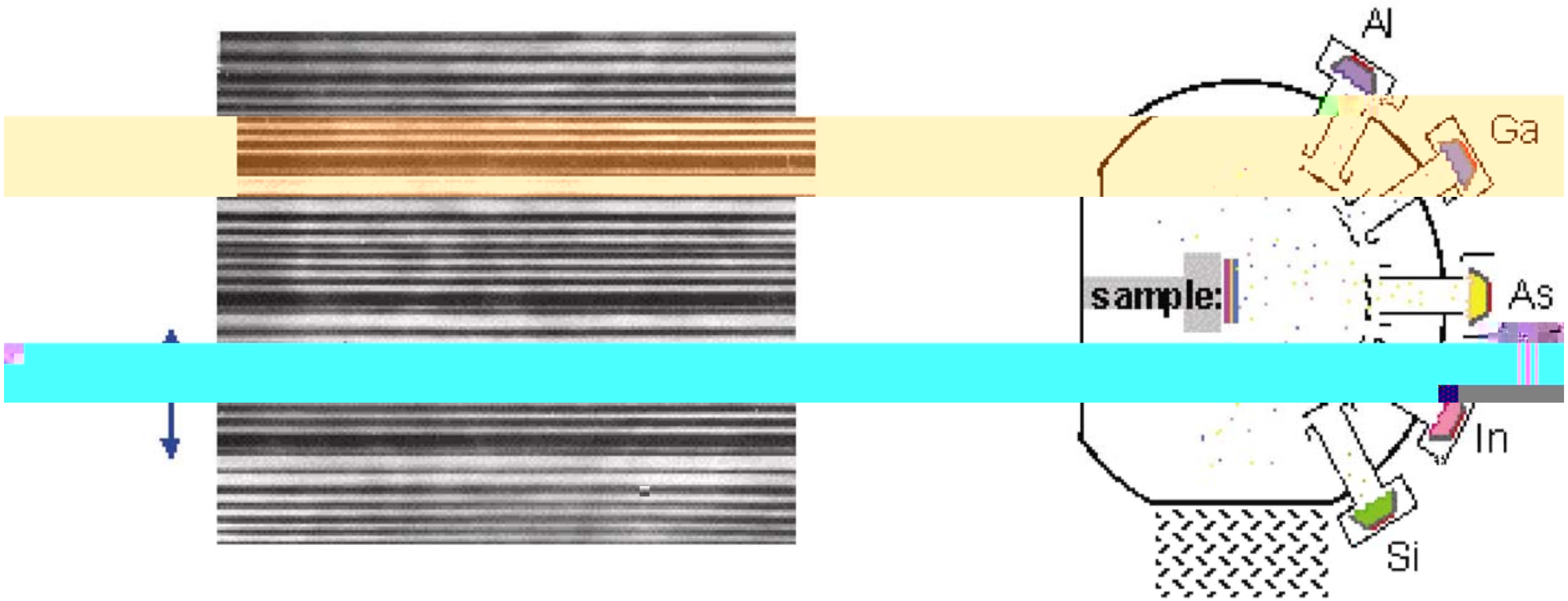


QCL ' 8



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(InGaAs ầ InAlAs)˘ 1nm ¥ 4 э \ ˊ Â
\ ầ \ ầ ` ⁄ ≠ ầ 8
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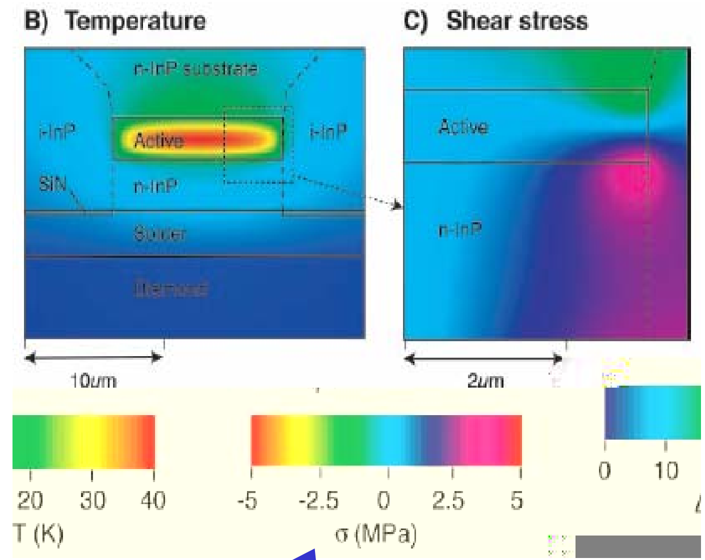
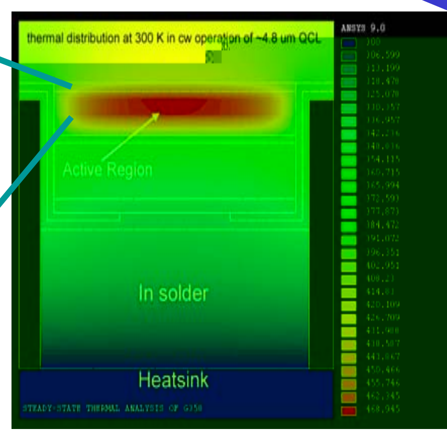
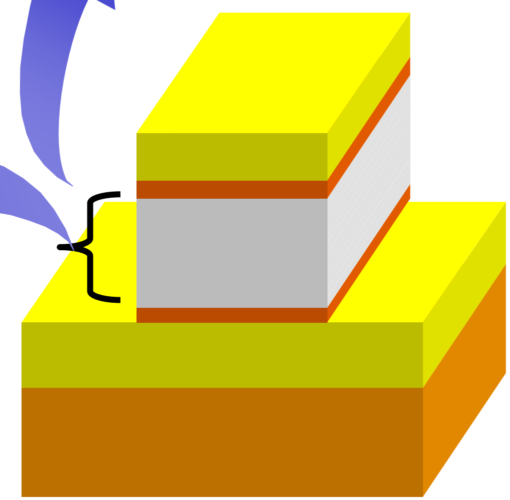


B) Temperature
C) Shear stress
n-InP substrate
i-InP
Active
i-InP
SiN
n-InP
Solder
Active
n-InP
10um
2um
20 30 40
T (K)
-5 -2.5 0 2.5 5
σ (MPa)
0 10



thermal distribution at 300 K in cw operation of ~4.8 um QCL
ANSYS 9.0
Active Region
In solder
Heatsink



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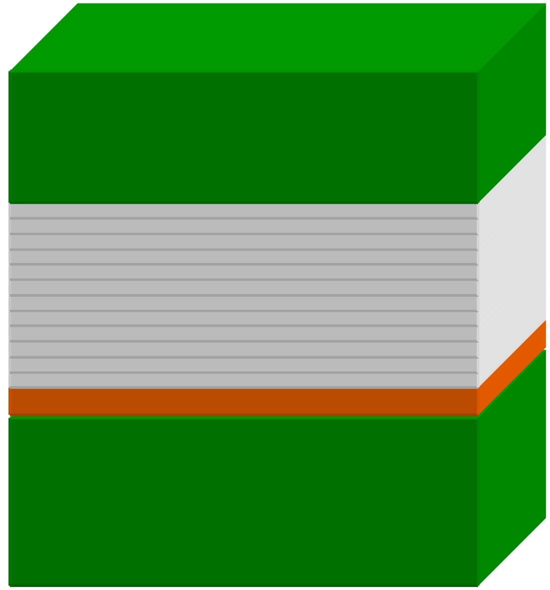
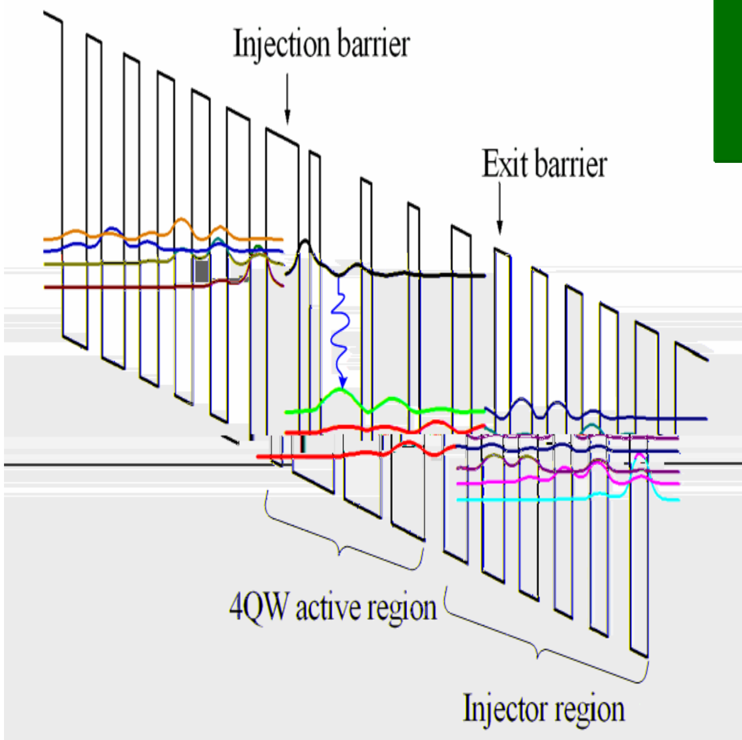
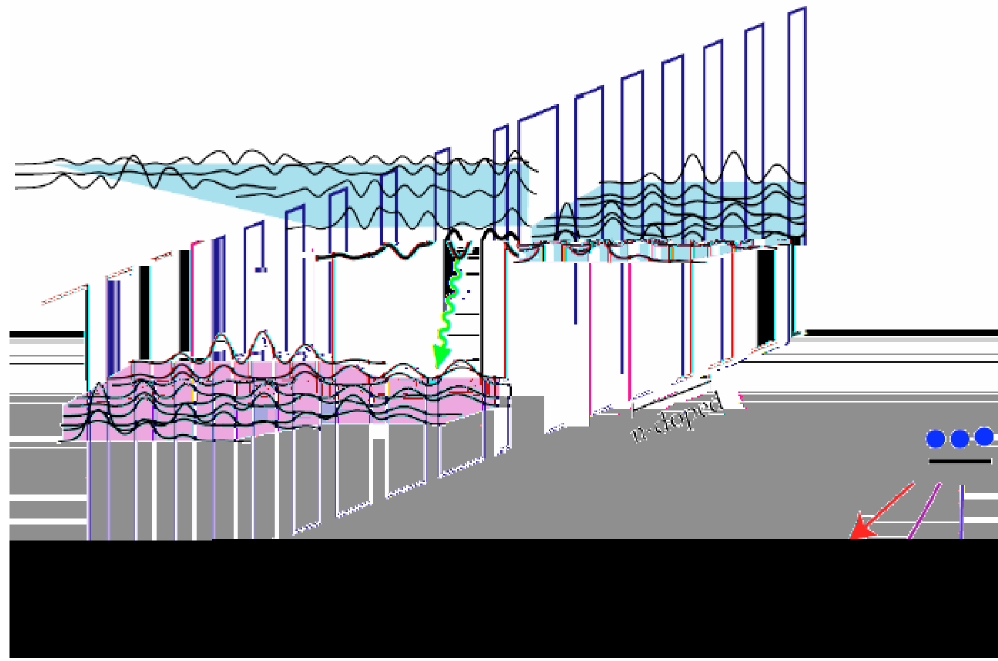
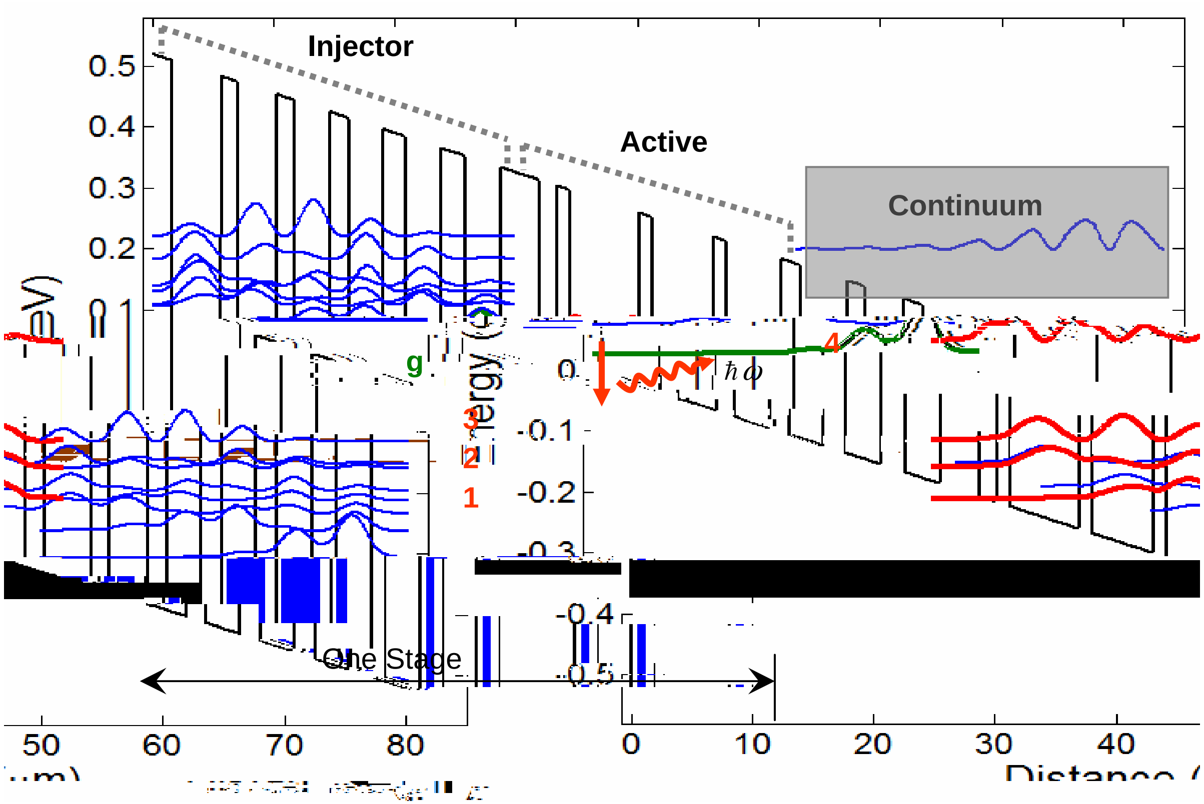



Injection barrier
Exit barrier
4QW active region
Injector region


n-doped

R ʻ



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$In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$˘ 7.8 µm Â

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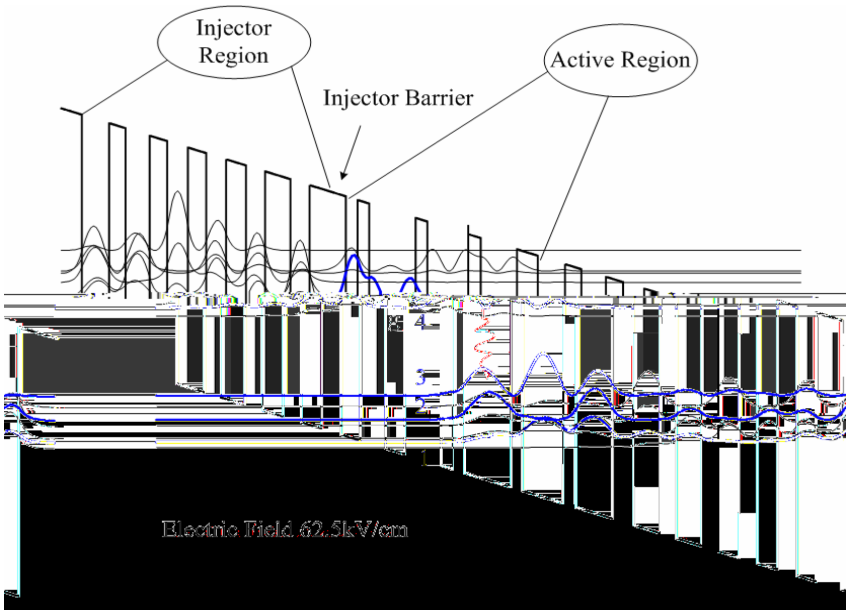
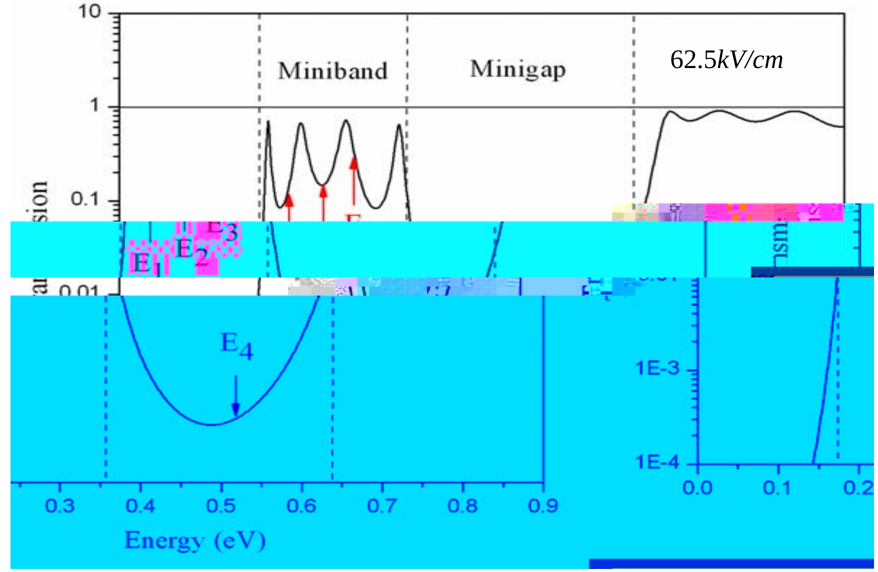
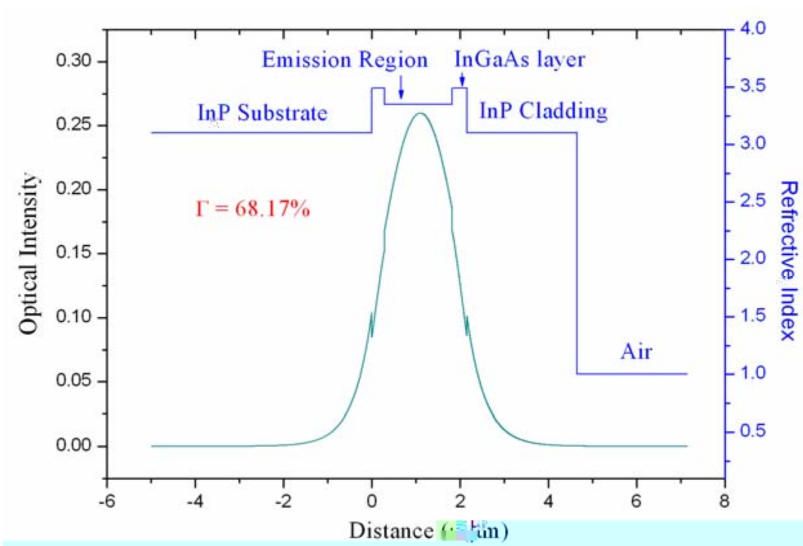
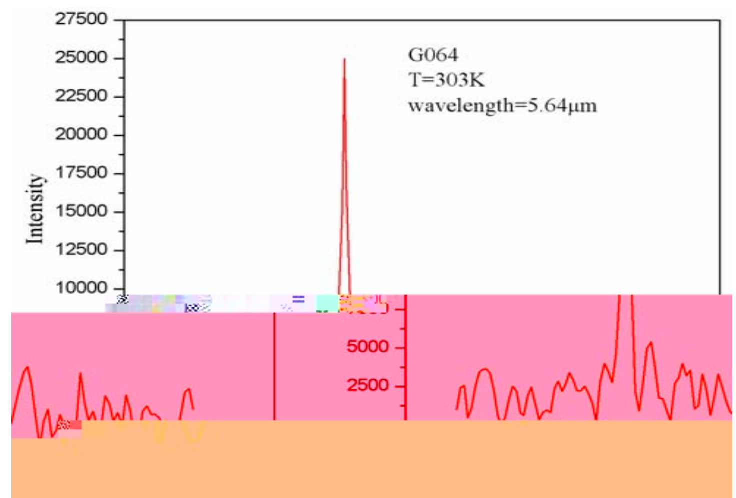
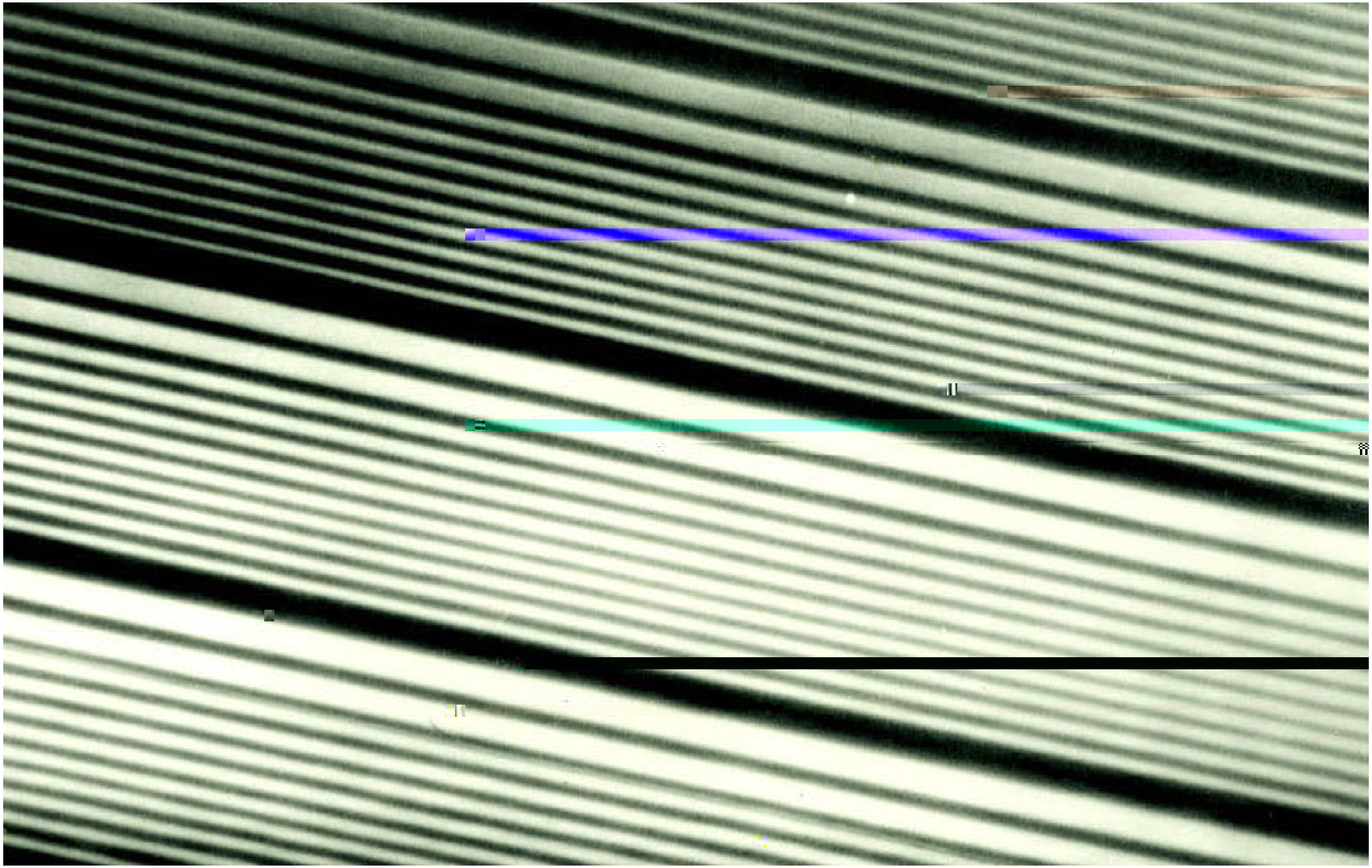
$In_{0.6}Ga_{0.4}As/In_{0.44}Al_{0.56}As$˘ 5.6 µm Â





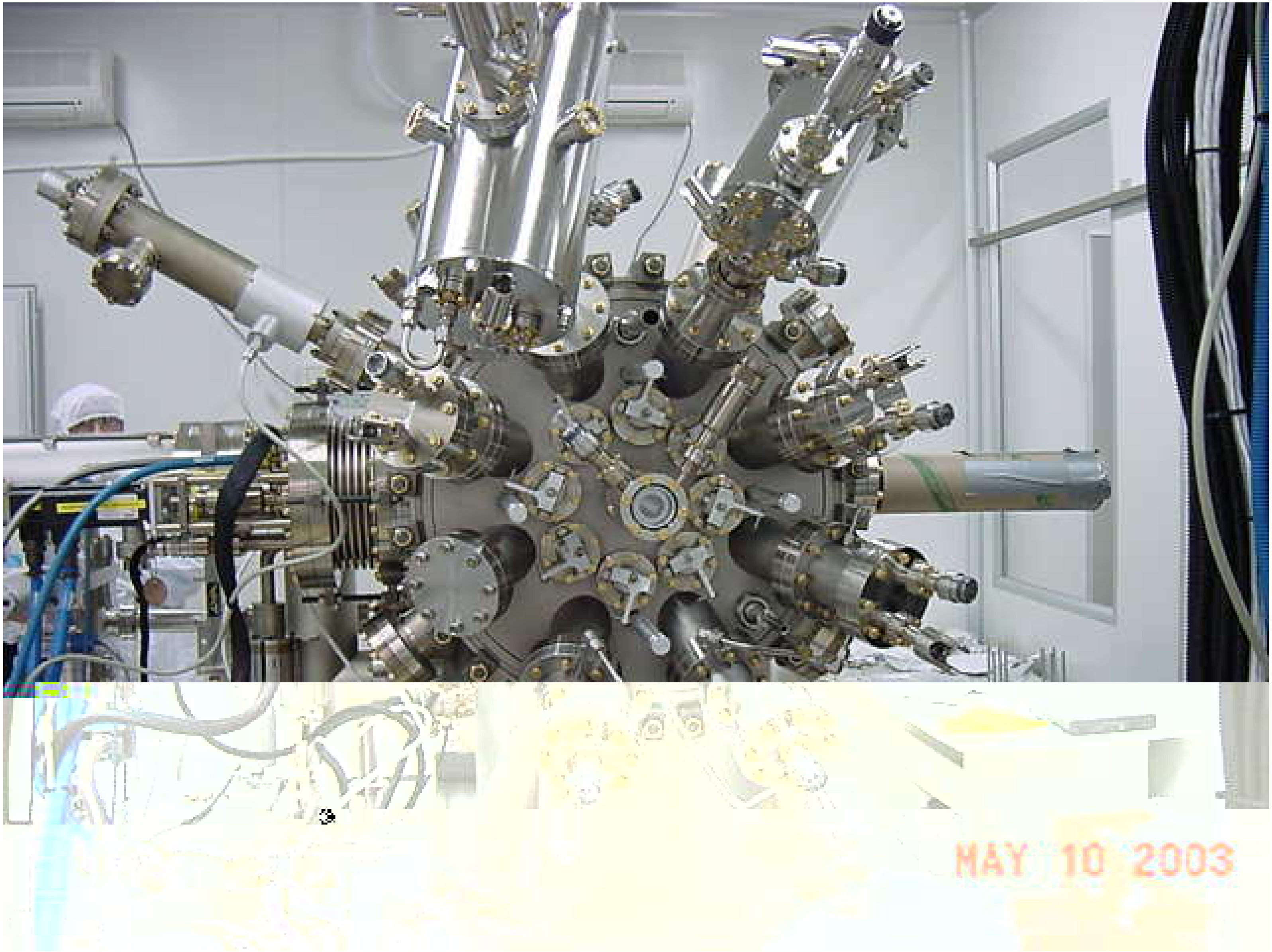






ή QCL ש SEM

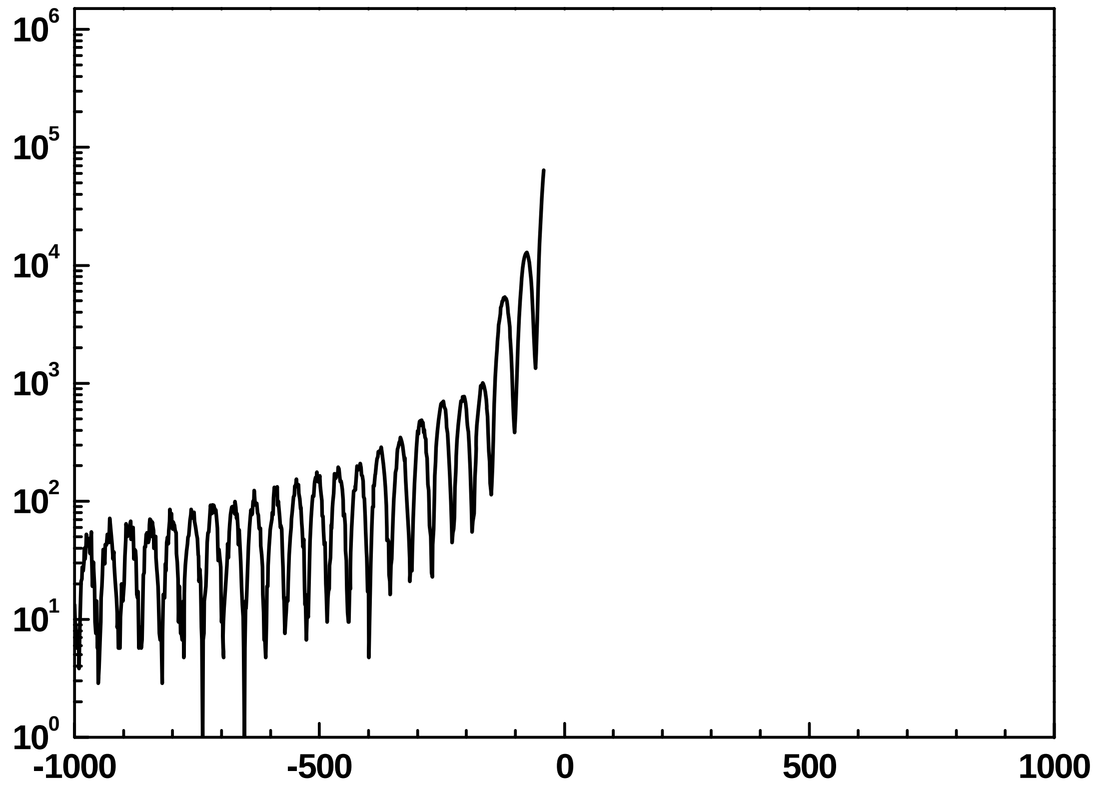
Semicond. Sci. Technol. 15_ L44(2000)



As, P, In, Ga, Al, Si

QCL

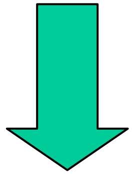
1. Compositions (InGaAs, InAlAs)
2. Growth rates
3. Doping
4. InP growth
5. Strain-compensation
6. QCL structures



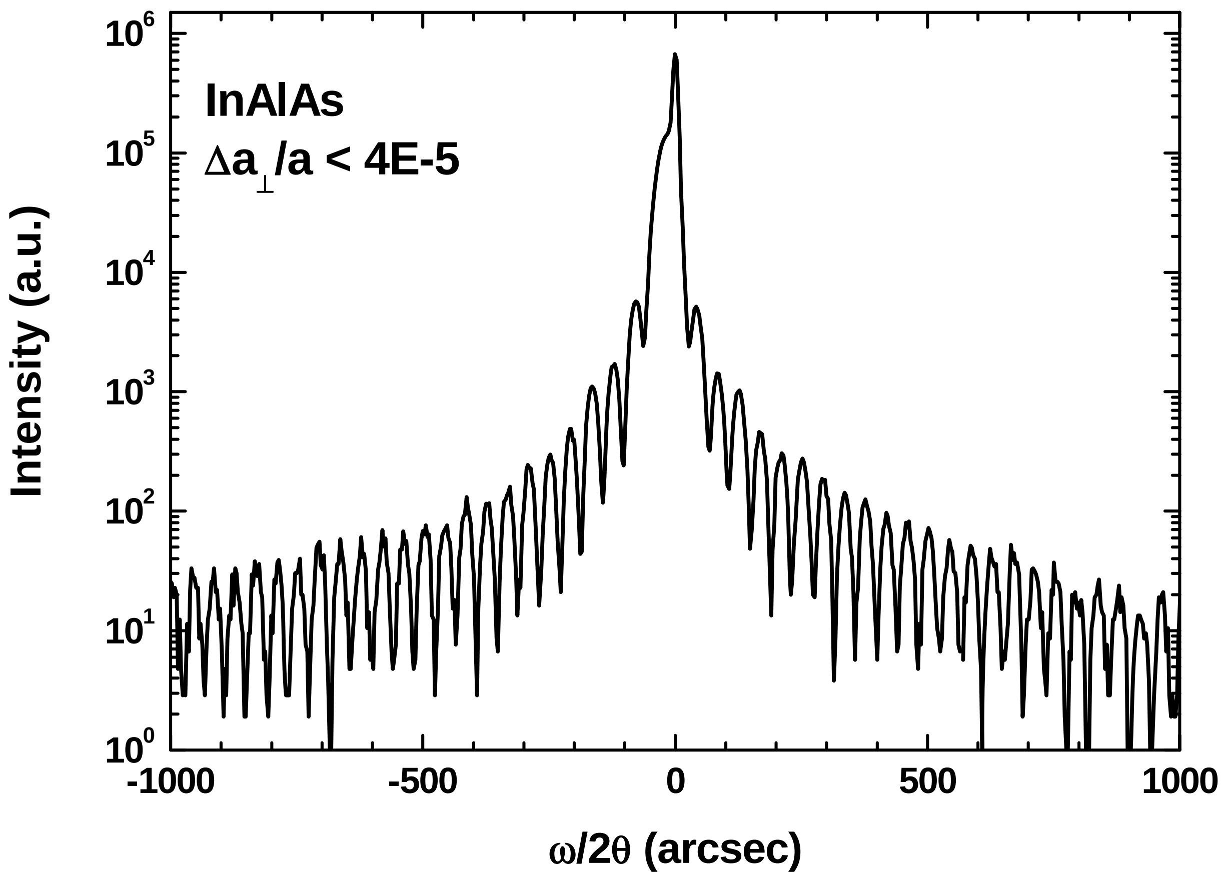
10^6
10^5
10^4
10^3
10^2
10^1
10^0
-1000
-500
0
500
1000

Composition: $In_{0.52}Al_{0.48}As$
V/III ration 20, Sub =515°C

By djusting In/Al ratio,

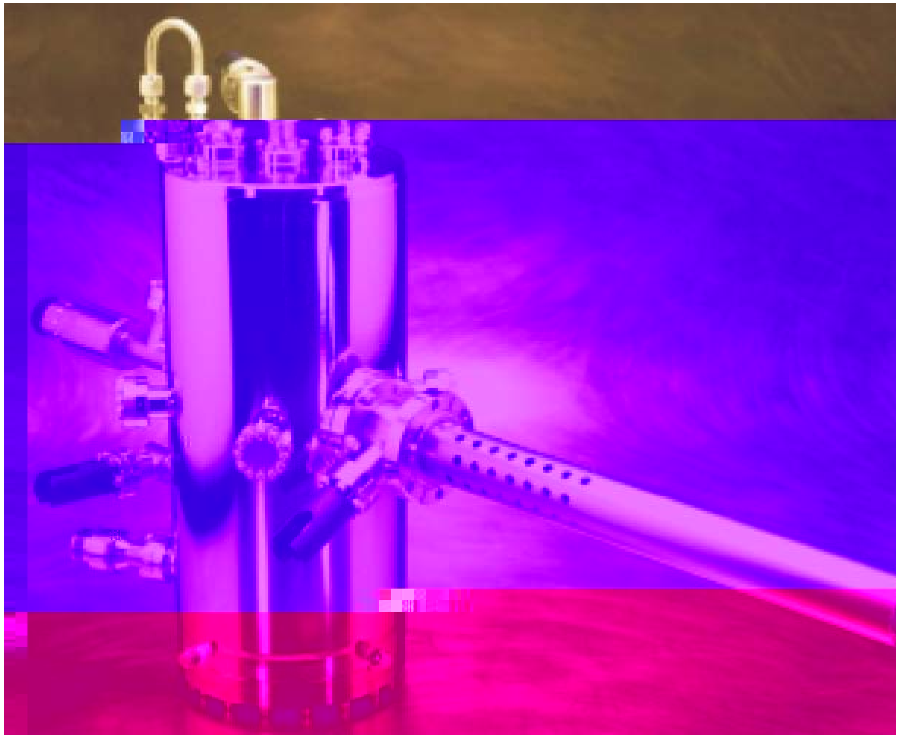


Anticipated composition



Double crystal X-ray diffraction result

InP growth



valved cracker of P

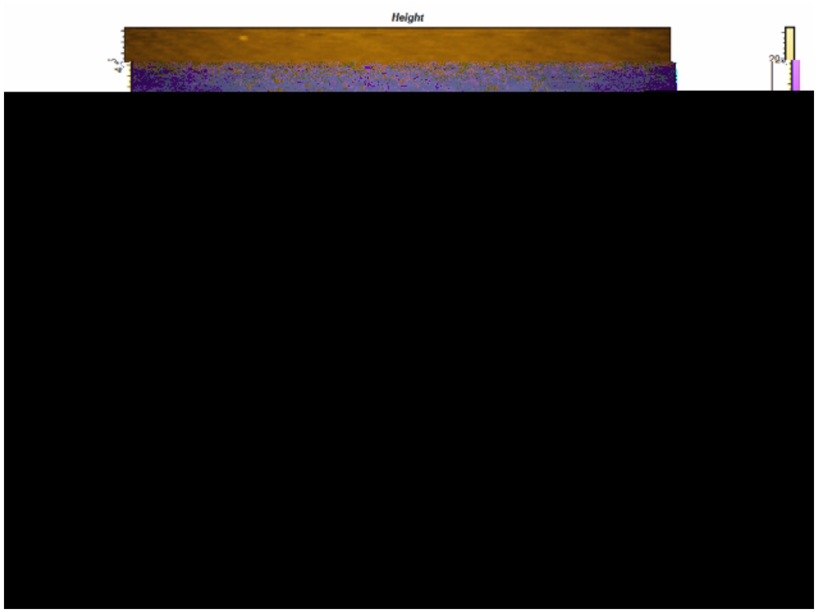
Cracker: 950°C, conversion P_4 to P_2.

Red p: 350-360°C

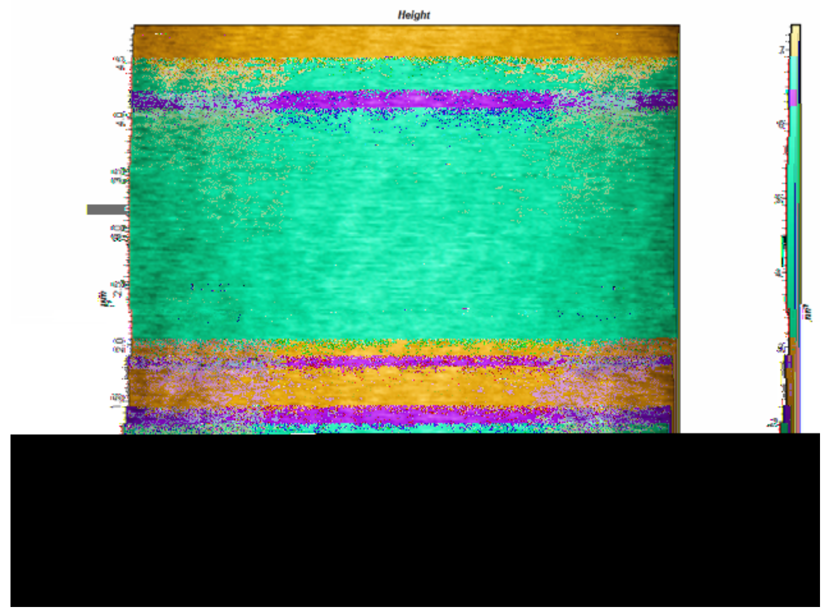
White P: 80-90 °C

P_2 pressures:0.2-2×10^{-5} Torr
P_2 /In flux ratios : 5-25

sub=460℃, V/III ratio=10



sub=490℃, V/III ratio=15-22



Optimal growth parameter:

Sub= 490°C,

P_2 /In = 20:1,

Growth rate: 0.6-0.9mm/h.

We can grow QCL materials on condition that :

Precise control:
each layer thickness,
compositions,
doping,
interfaces sharpness.

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$$\lambda = 1.24/(E_3 - E_2)$$

ΔE = (0.56 - 0.62) V_{bc},

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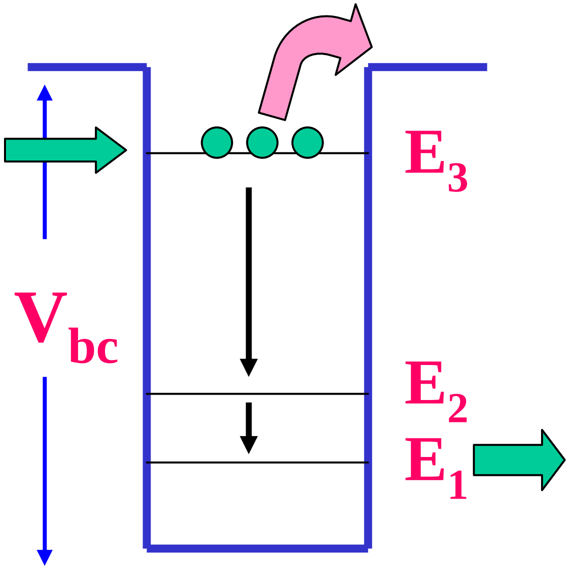
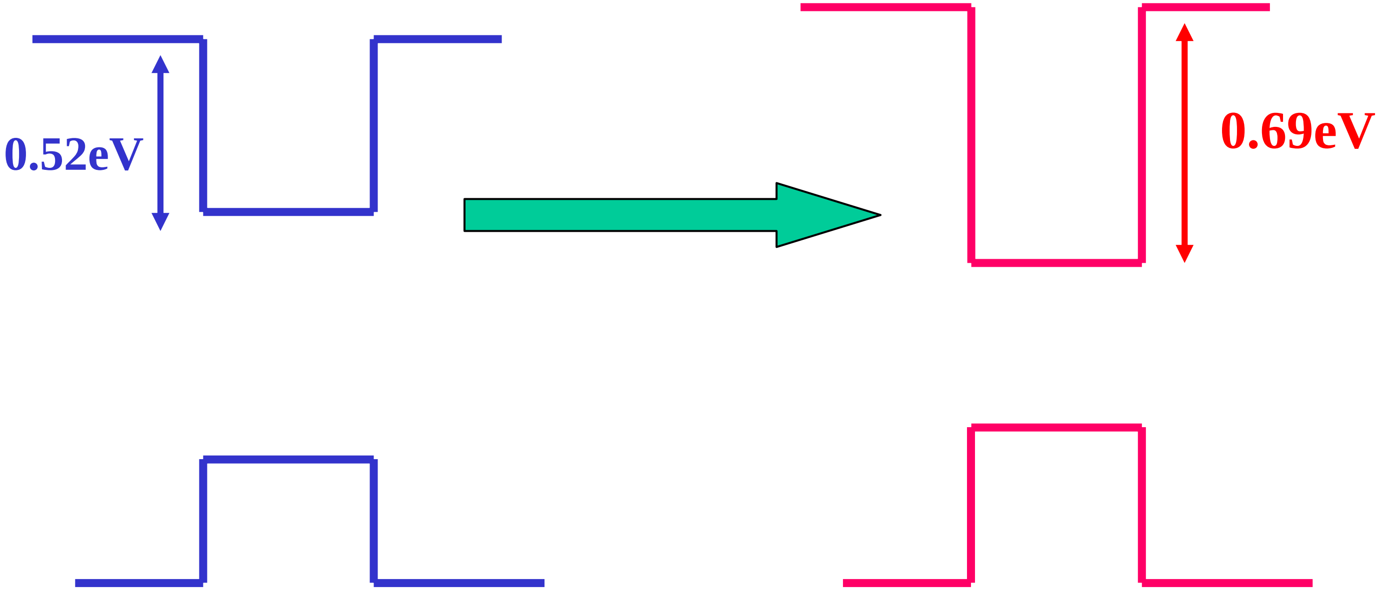


V_{bc}

: $In_xGa_{(1-x)}As$˘ x↑˘ E_g ↓

: $In_yAl_{(1-y)}As$˘ y↓˘ E_g ↑

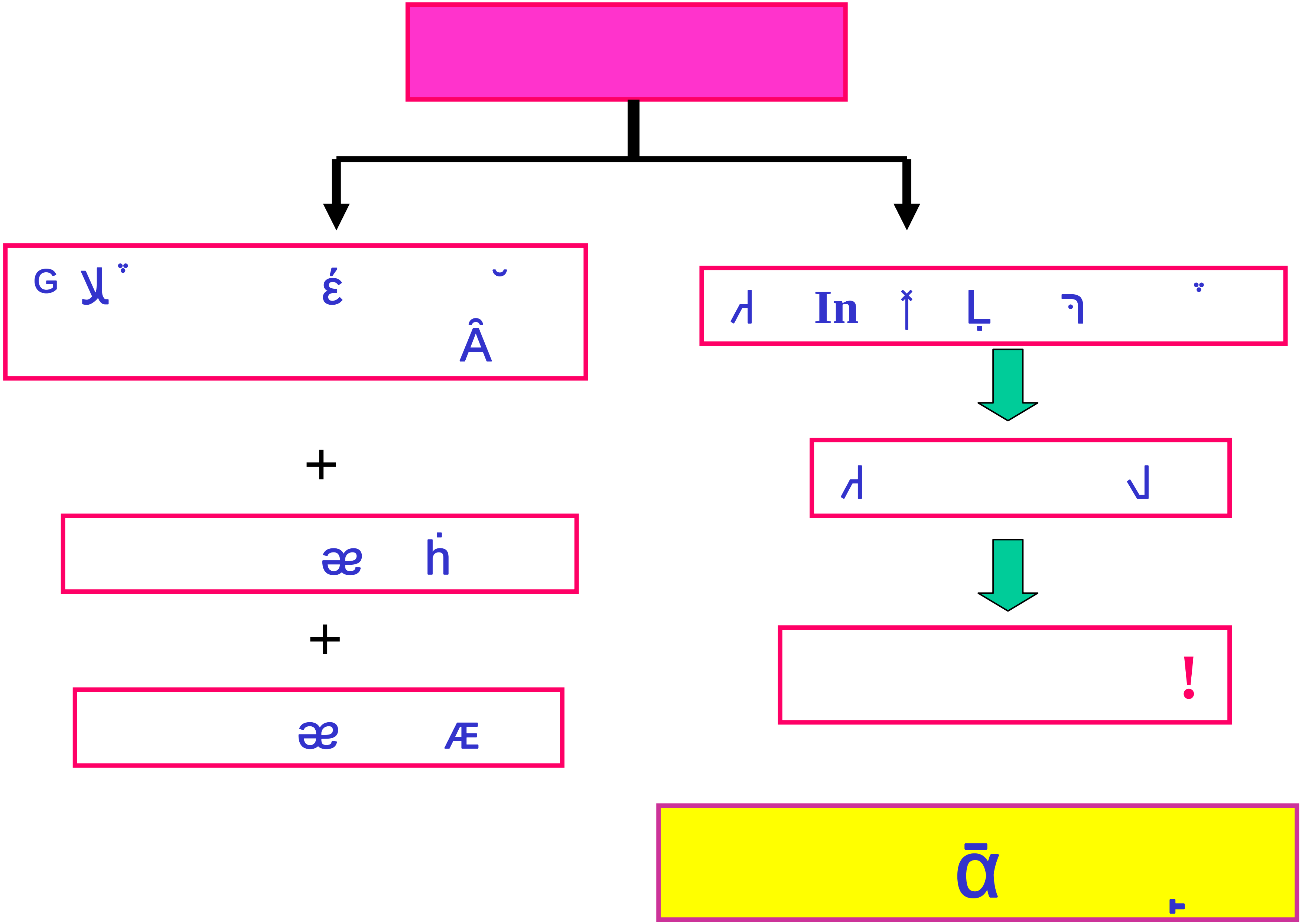


$In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$

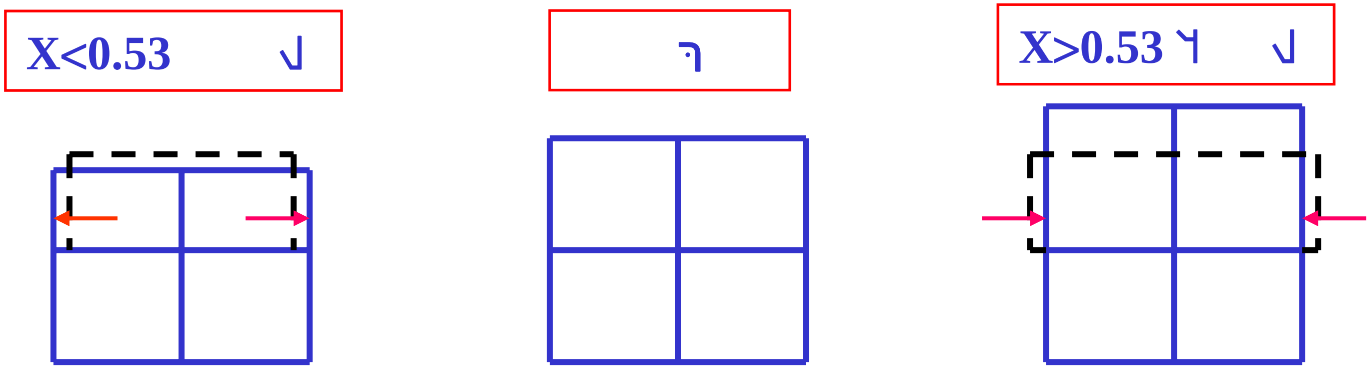
ך ¥ InP

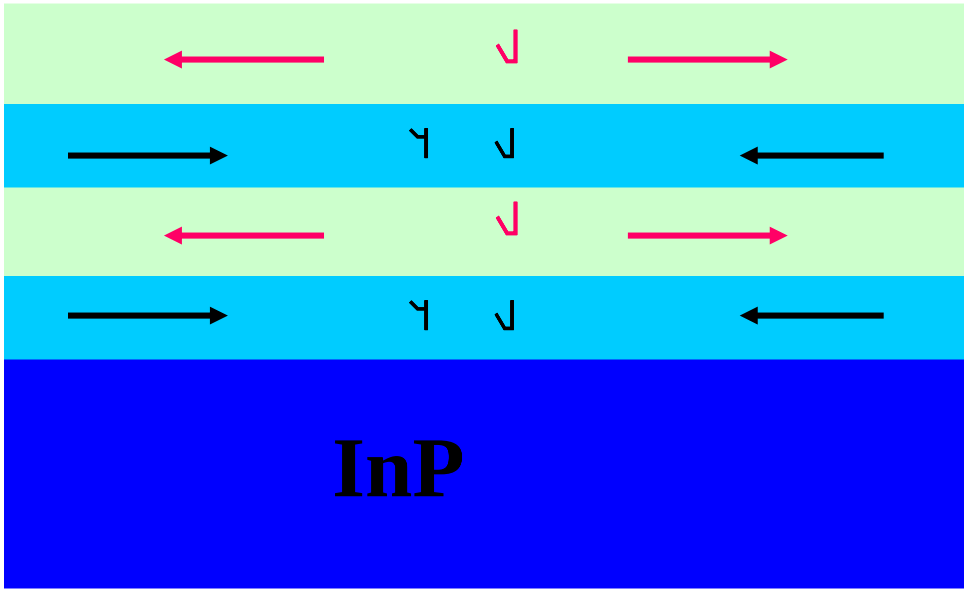
$In_xGa_{(1-x)}As/In_yAl_{(1-y)}As$

(x>53%, y<52%)



InGaAs/InP





F

$In_xGa_{(1-x)}As$ $$x = 0.532 + 7.2\,\Delta a_{\perp}/a_s$$

$In_yAl_{(1-y)}$ $$y = 0.523 + 7.4\,\Delta a_{\perp}/a_s$$

1% Ḥ 7×10^{-4} ˘ \ й
4-5μm ˘ 6 è ɖ
ɏ 1% ΰ ψ a Â

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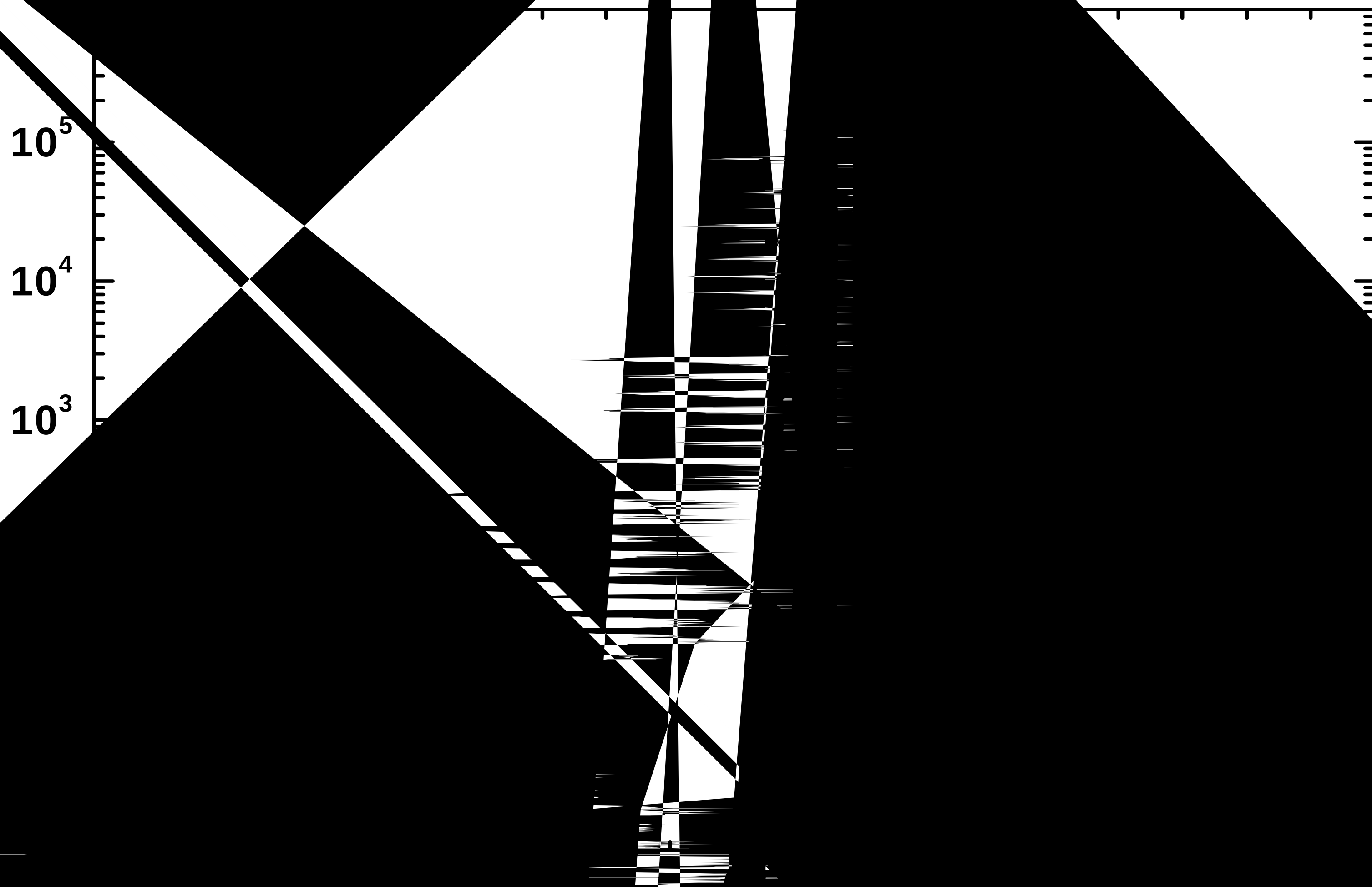
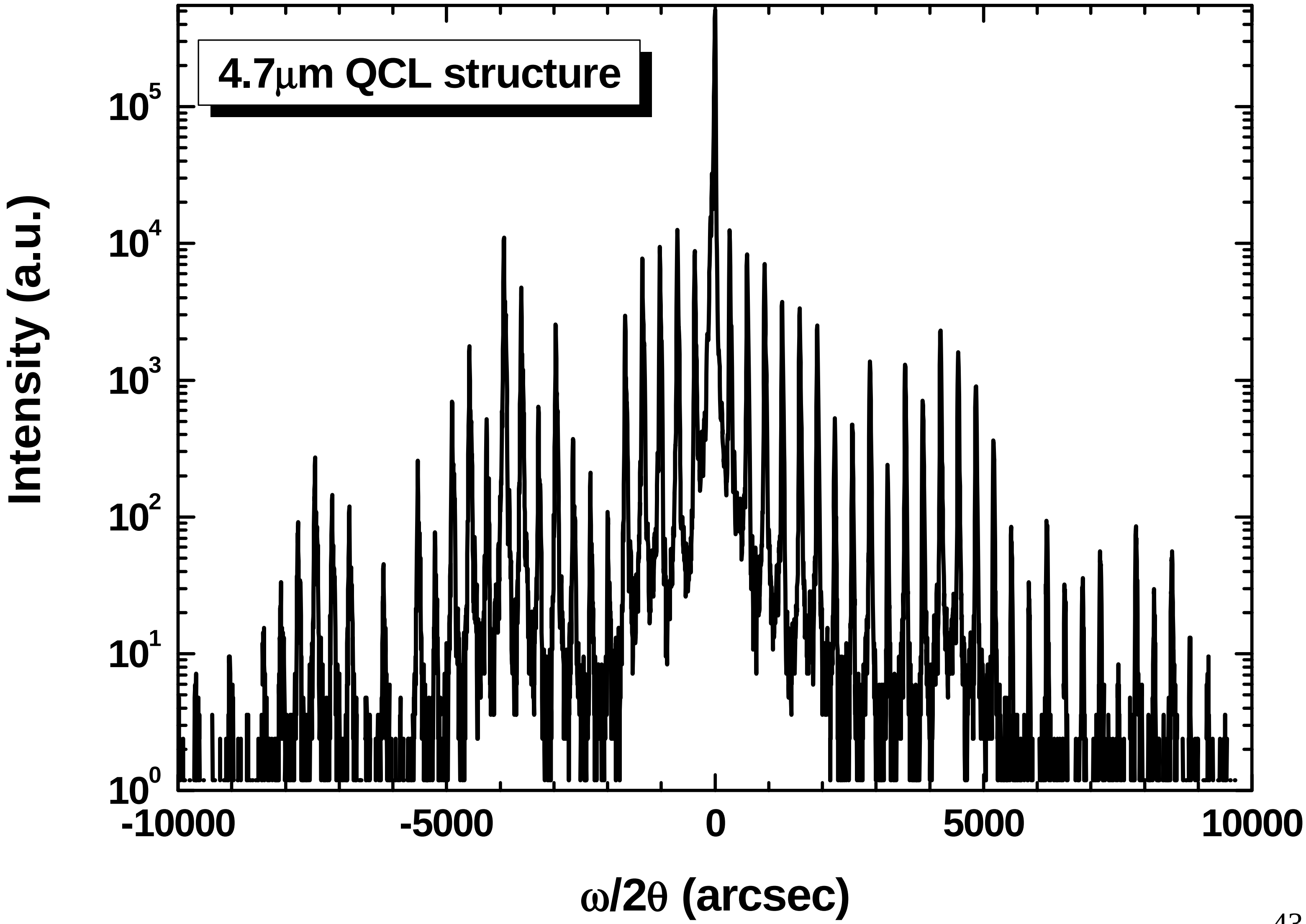
QCL structure

InGaAs	$5\times10^{18}cm^{-3}$	400nm
InP	$5\times10^{18}cm^{-3}$ ↑ $1\times10^{17}cm^{-3}$	2500nm
InGaAs	$1\times10^{17}cm^{-3}$	350nm
(Active＋Injector)	×30	
InGaAs	$1\times10^{17}cm^{-3}$	300nm
InP substrate	n-doped	

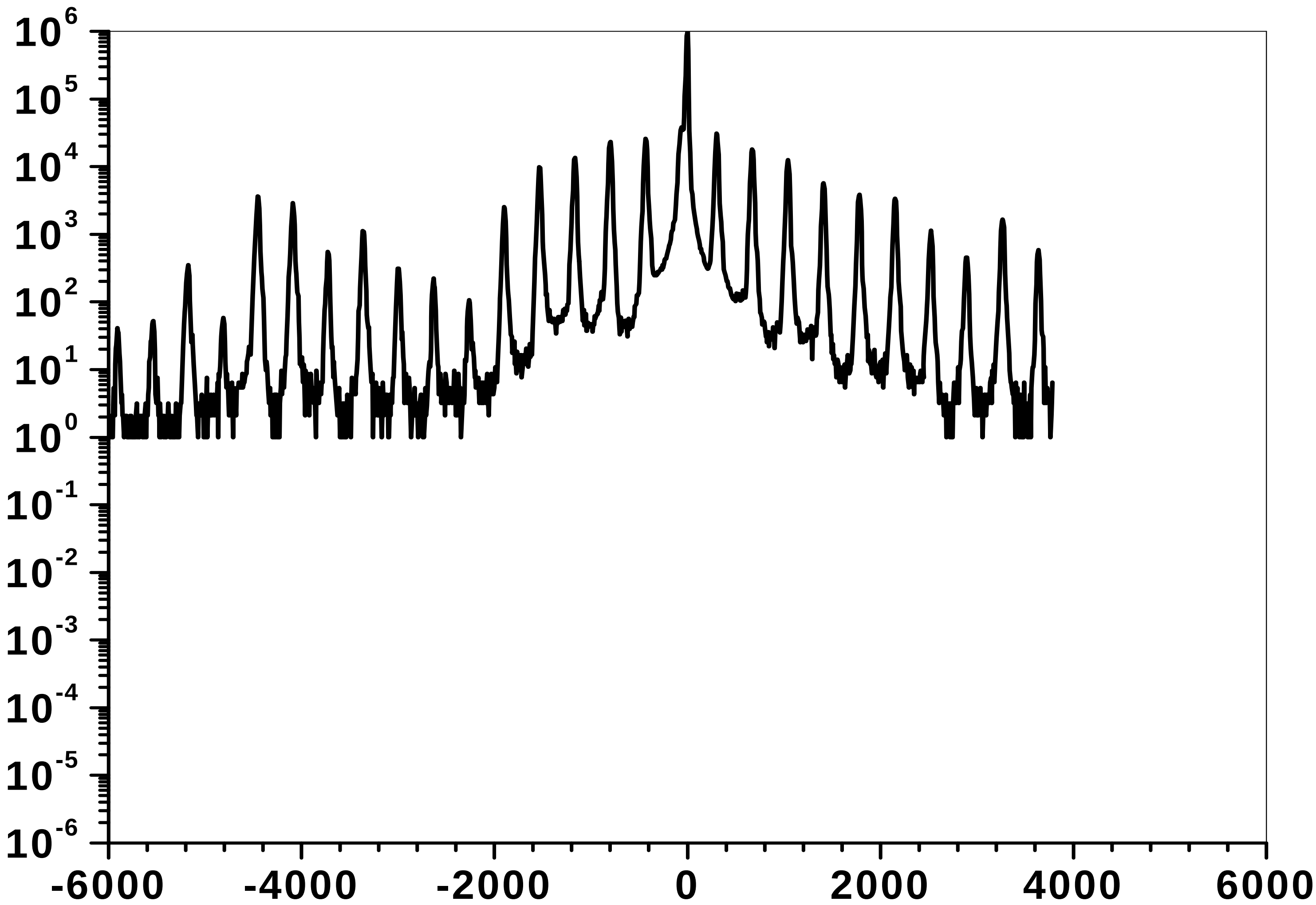


10^5
10^4
10^3

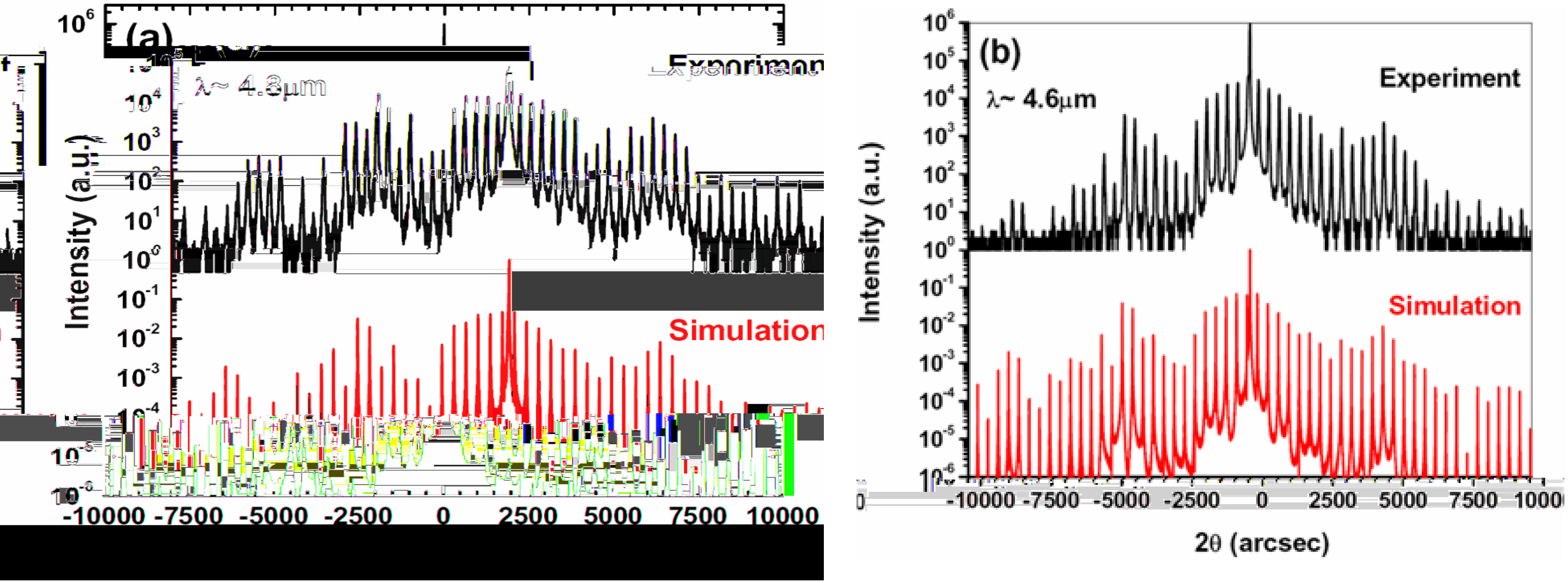
$In_{0.669}Ga_{0.331}As/In_{0.362}Al_{0.638}As$ ώ QCL



DXRD results



10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
-6000
-4000
-2000
0
2000
4000
6000

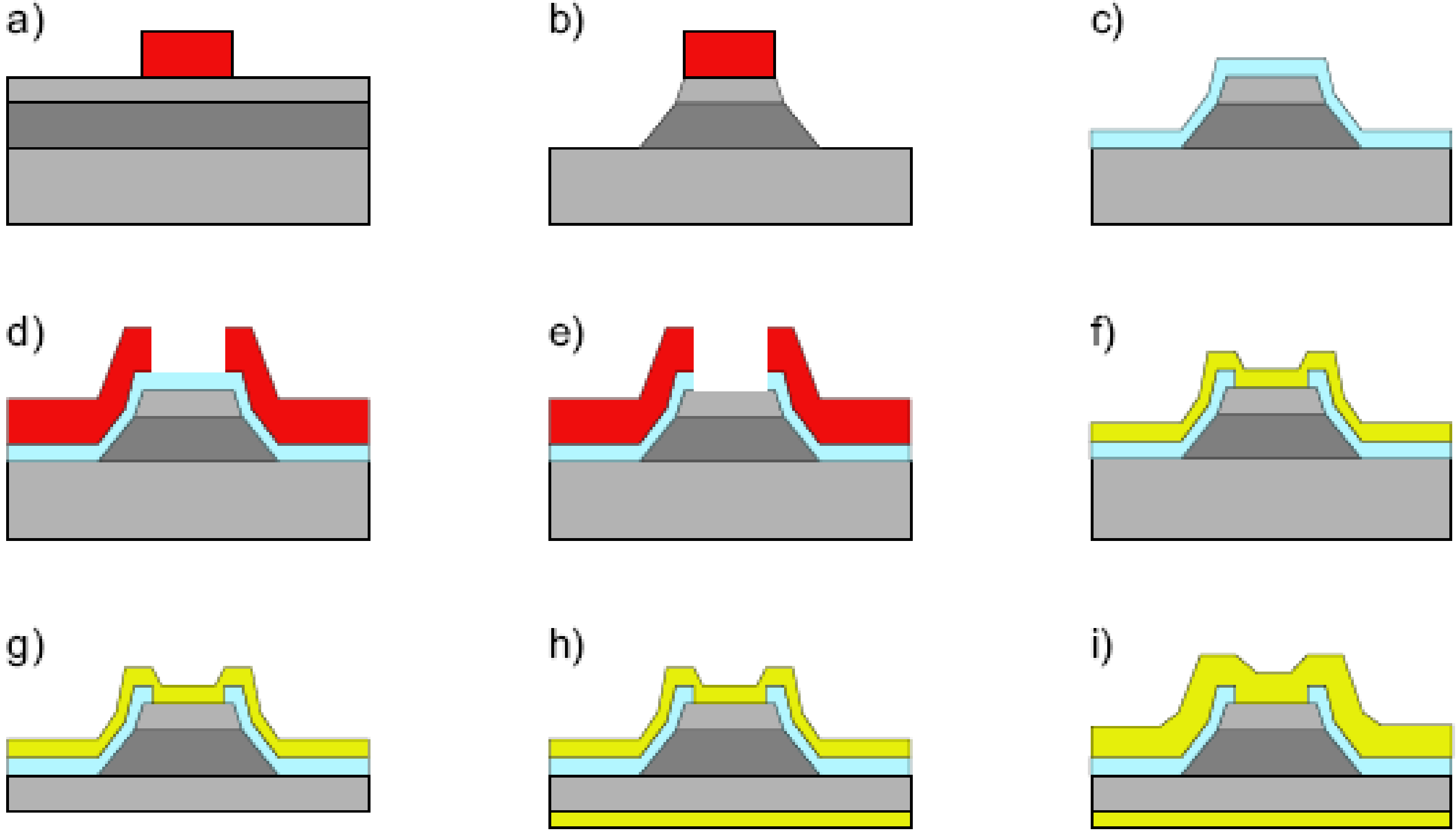


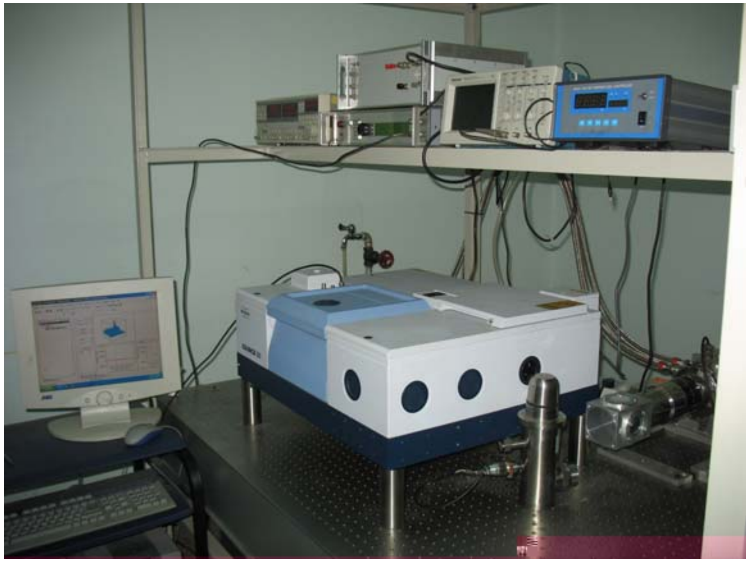
4.8μm ằ 4.6μm ˩ Ŝ QCL ẅ Ⅱ

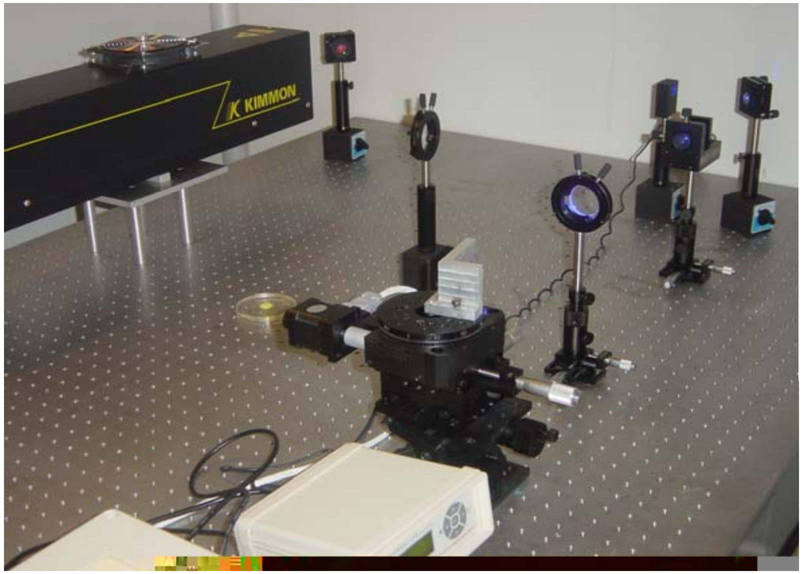
ṅ ˧ X ˧ ˘ ˧ X

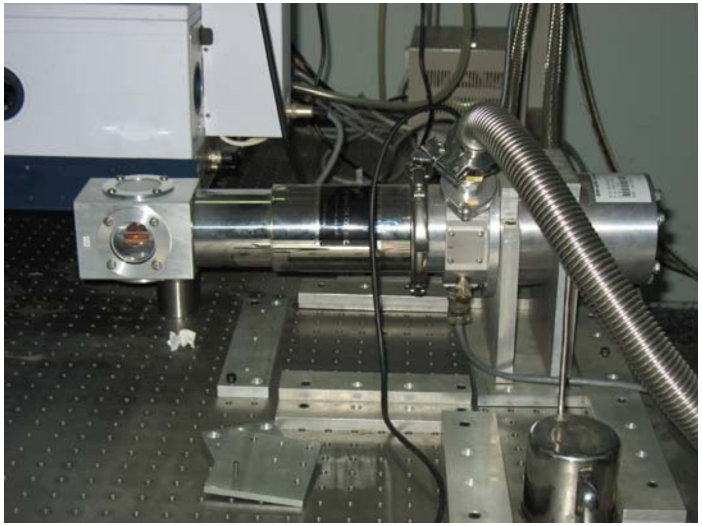
˜ 60 Â

$$\Lambda = \frac{(i-j)\lambda}{2(\sin\theta_i - \sin\theta_j)}$$


a)
b)
c)
d)
e)
f)
g)
h)
i)

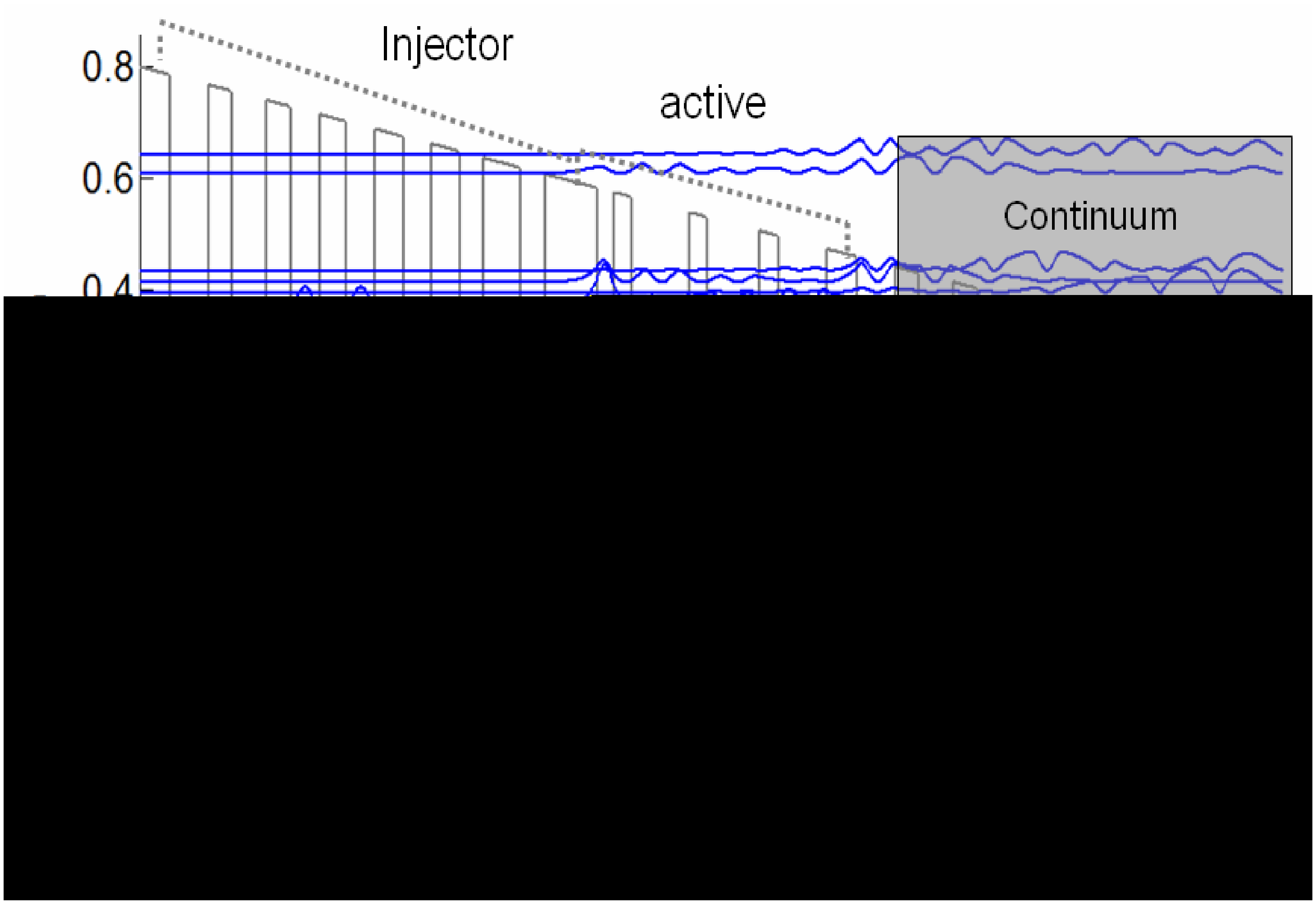


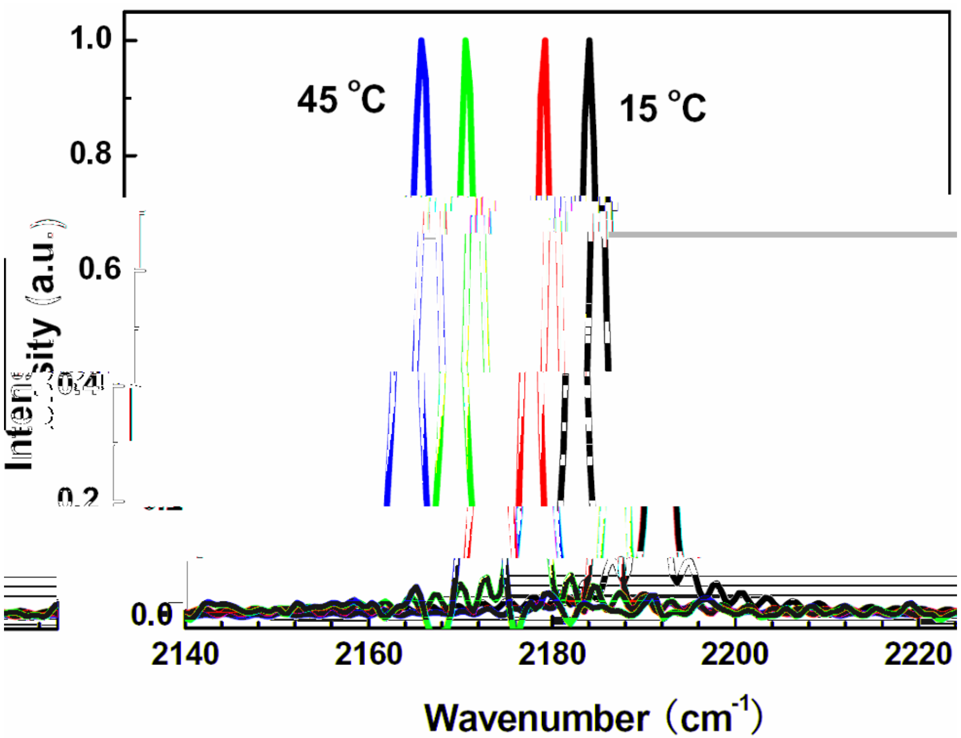

KIMMON

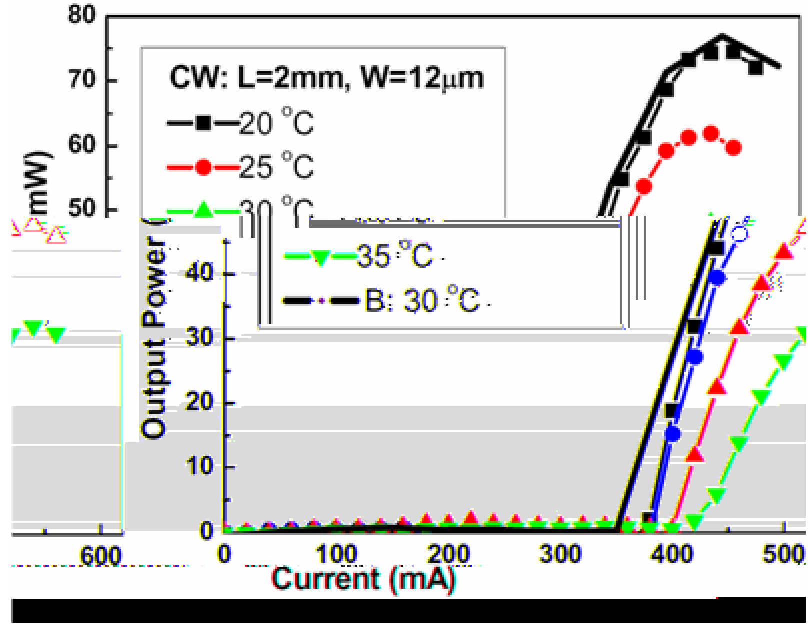


ɔ QCLs

λ~4.6µm





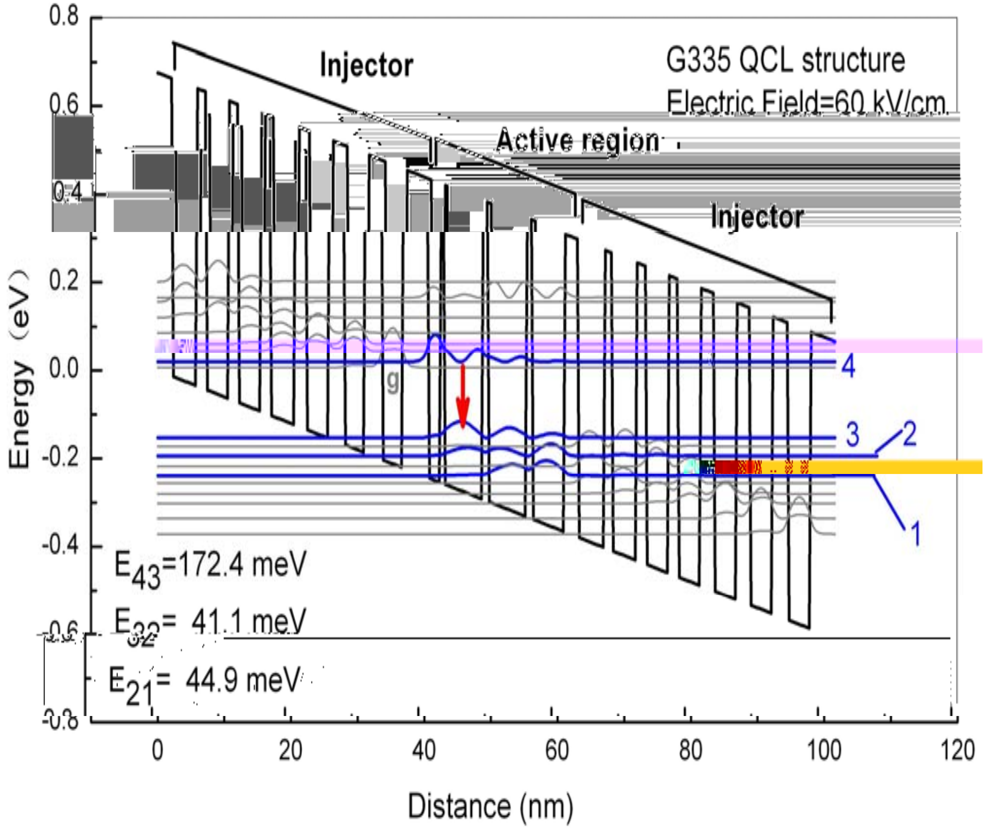


λ~4.6 QCL ( )

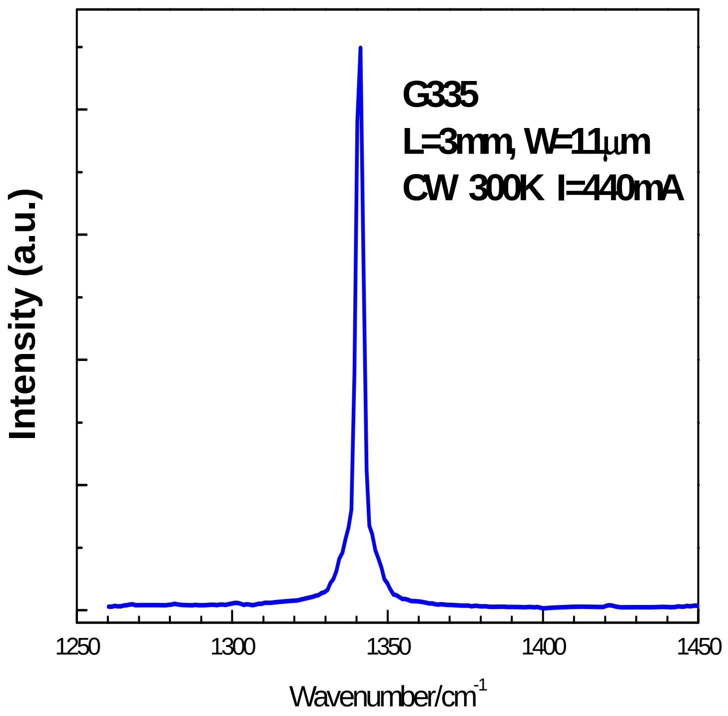
( ) 2mm×12μm

Appl.Phys.A 97, 527 (2009)

ɔ λ~7.4μm



Injector
G335 QCL structure
Electric Field=60 kV/cm
Active region
Injector
4
3
2
1
g
E43=172.4 meV
E32= 41.1 meV
E21= 44.9 meV
Energy (eV)
Distance (nm)
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
20
40
60
80
100
120



G335
L=3mm, W=11μm
CW 300K I=440mA
Intensity (a.u.)
Wavenumber/cm-1
1250
1300
1350
1400
1450

Fabry-Pérot ‟l ʯ

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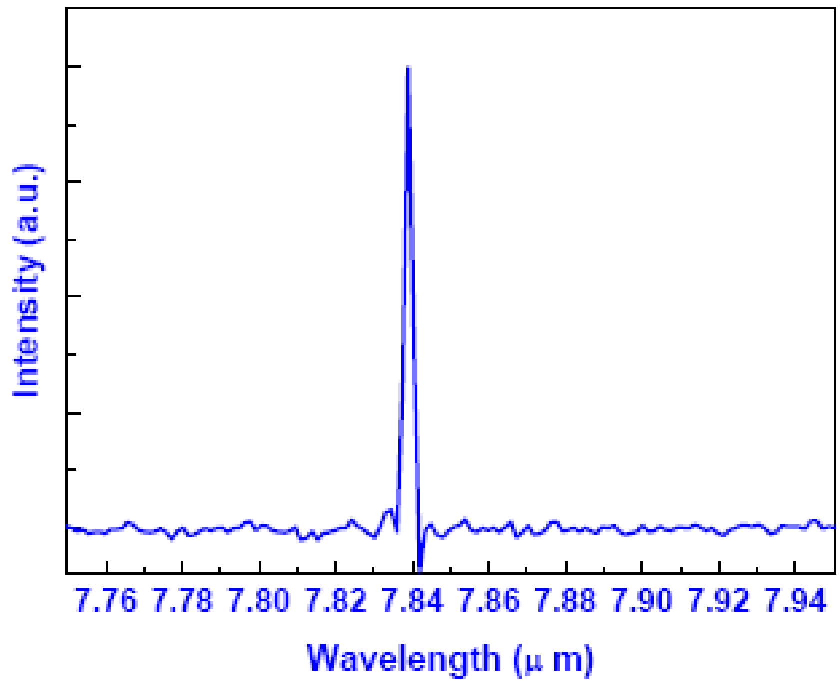
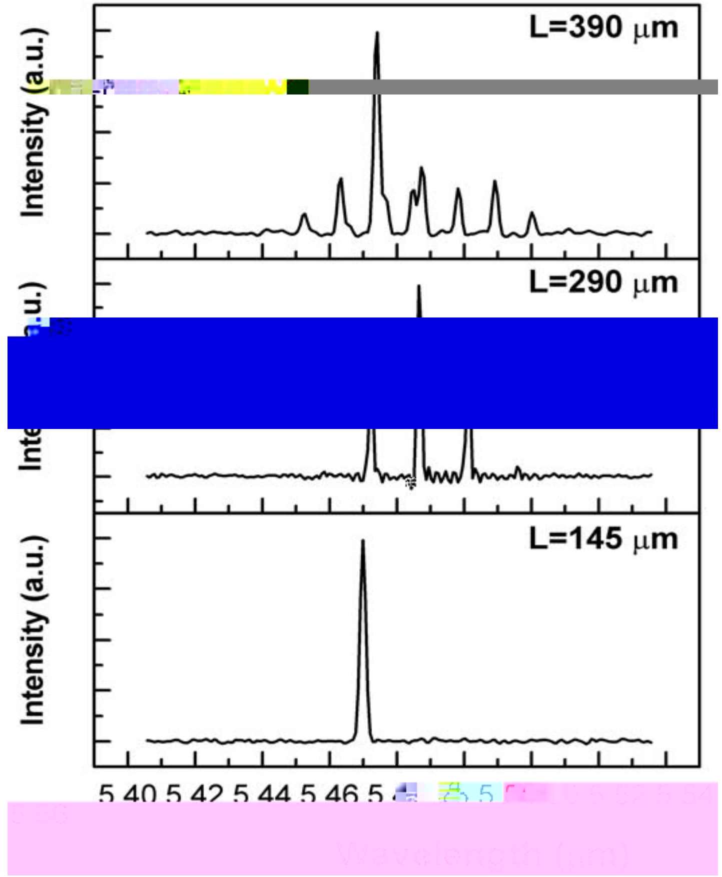
! ´ ɔ ˫

´ QCLs



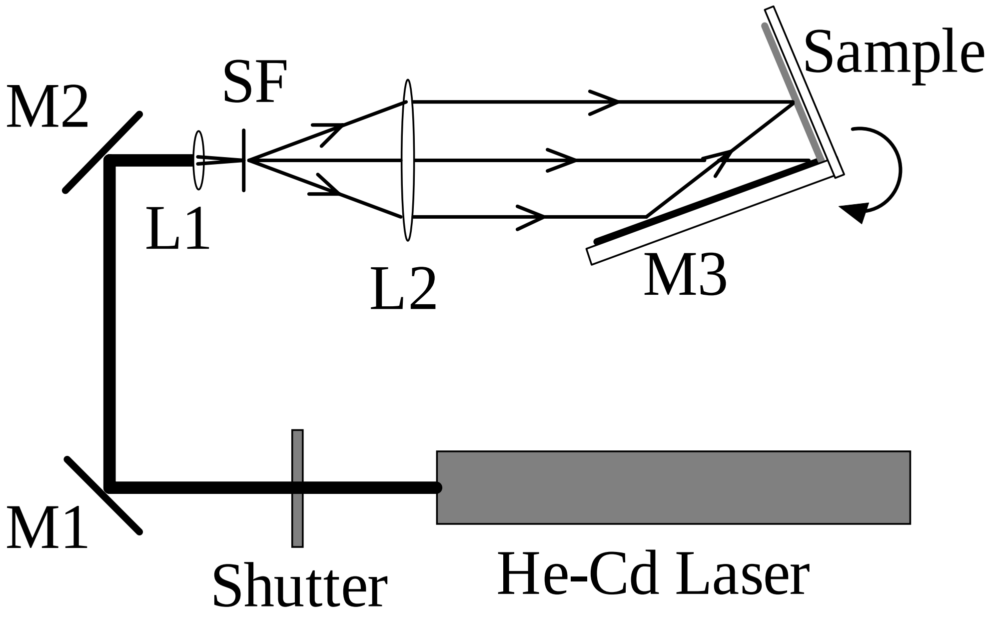


¥ ש ˘ a Â ᾱ

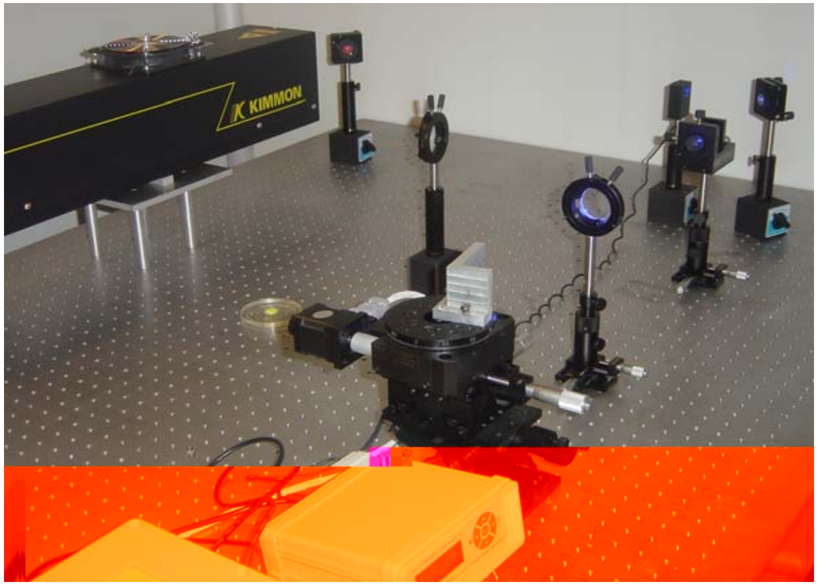
ɷ↑ ˧ QCL ằ QCL ʺl ˩ Ꮑ ⁸ Â

' $$d\lambda_0 = \frac{\lambda_0^2}{2nL}$$

DFB-QCLs ầ ˝l E DFB-QCLs



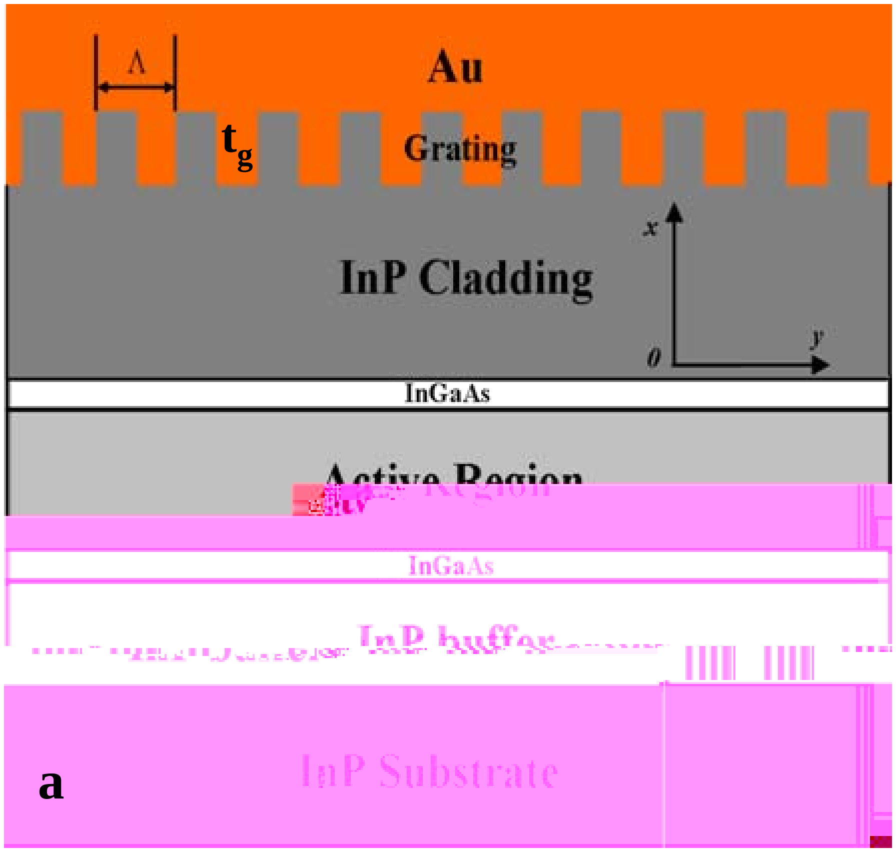
ώ ˝l

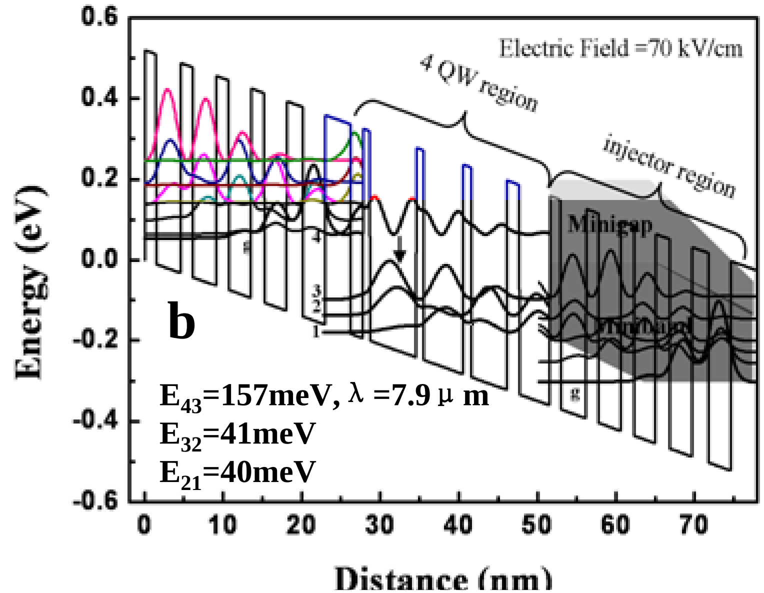


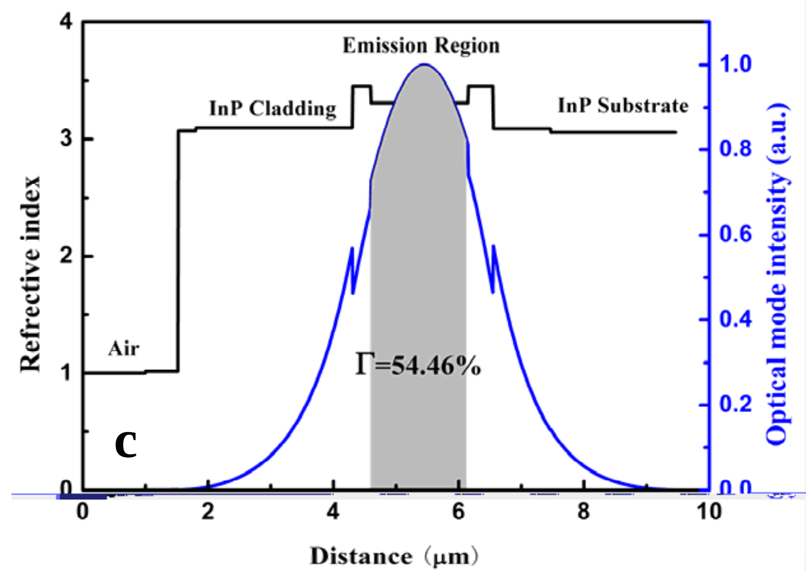
ώ ˝l ˝l

˝l ﻻ ‘ 441.6 nm

DFB-QCL有源区及波导结构





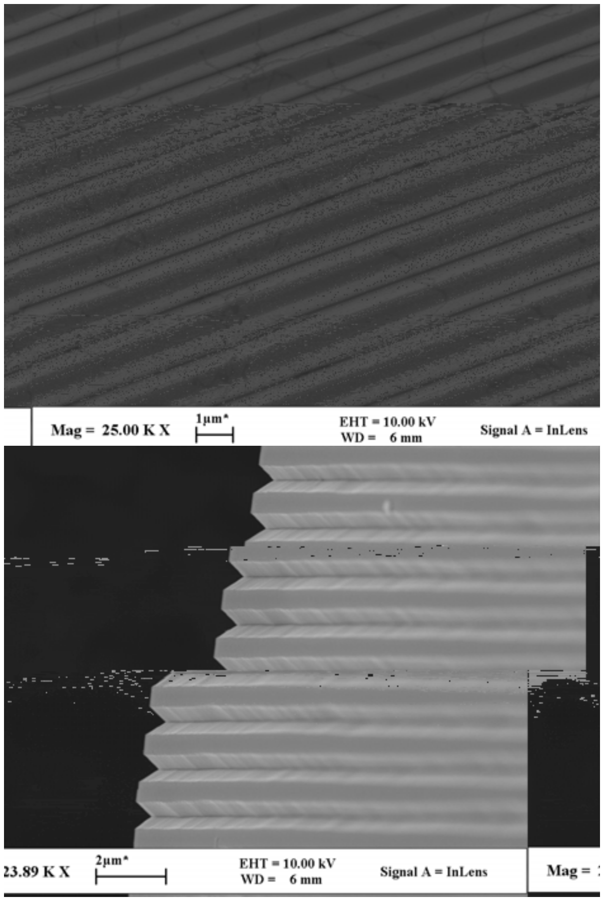


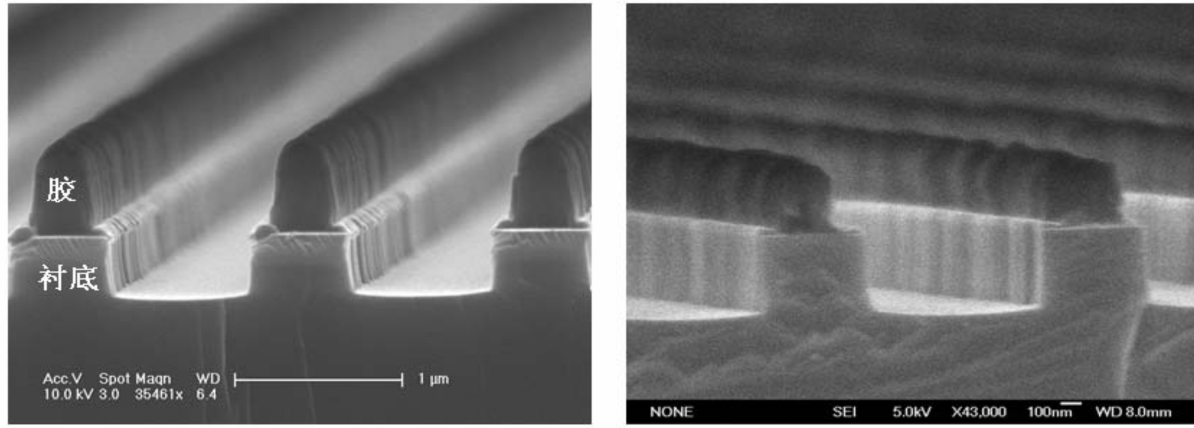
a：波导结构示意图

b：双声子共振结构能带图

c：一维模式分布

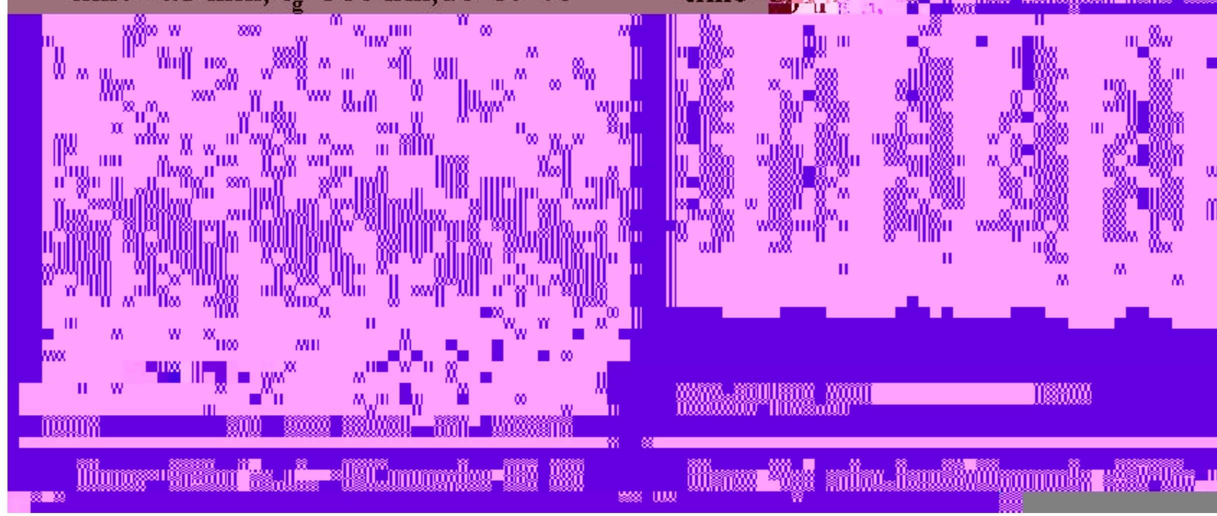
光栅刻蚀





time=4.5 min, t_g=380 nm,dc=39 %

time=5.0 min, t_g=410 nm,dc=



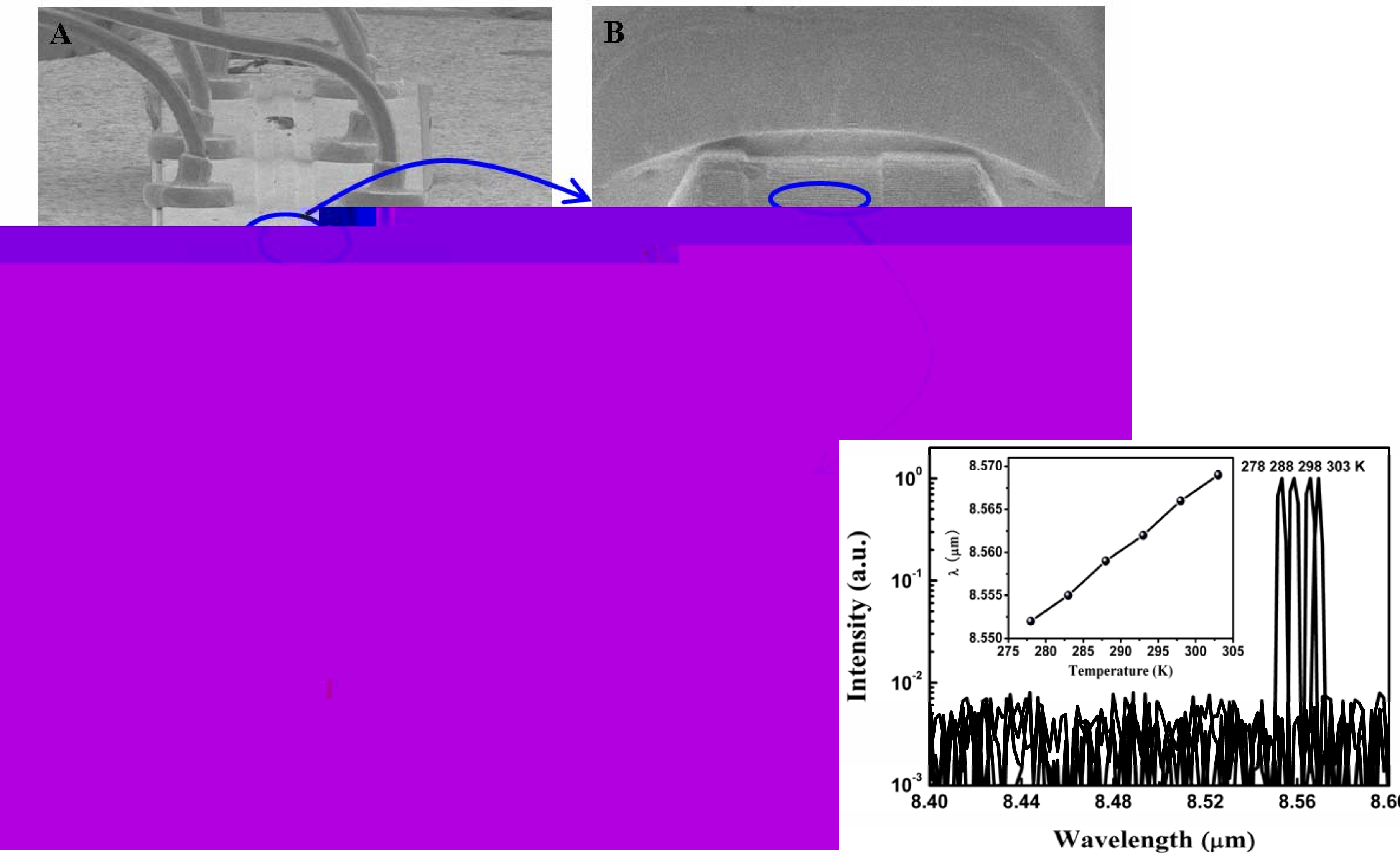
Wet Etch

RIE Dry Etch

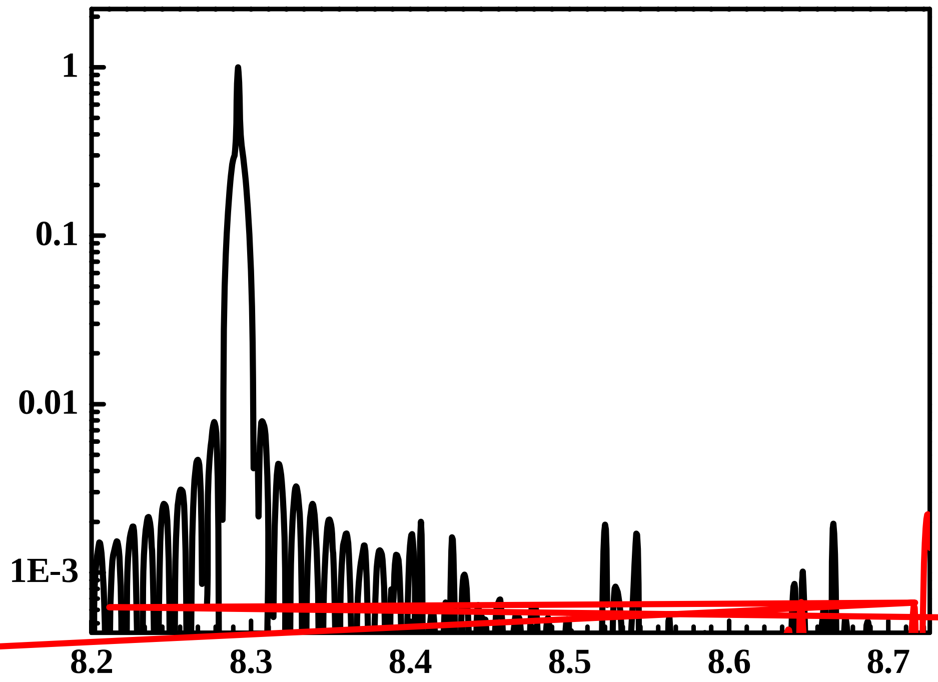
HBr：HNO_3：H_2O=1：1：20

Ar_2：CH_4：H_2=5：18：45

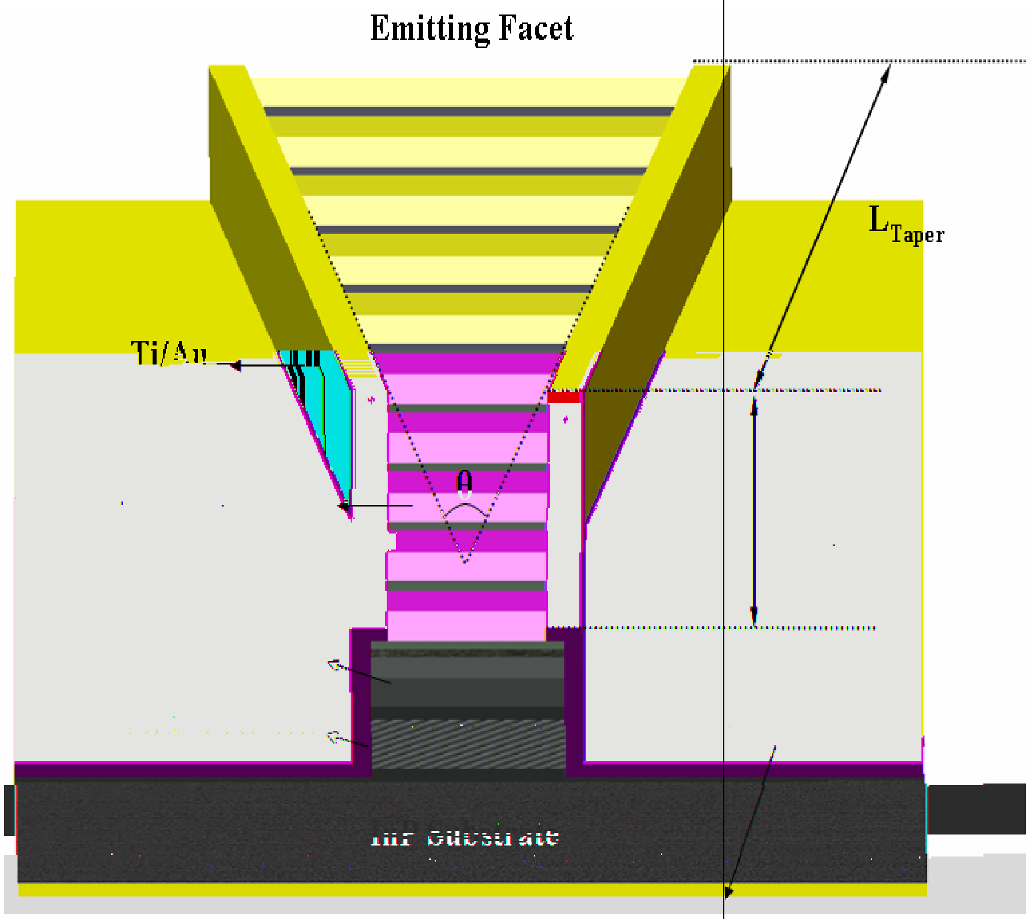
室温工作表面金属光栅DFB-QCL



掩埋光栅DFB-QCLs的连续工作

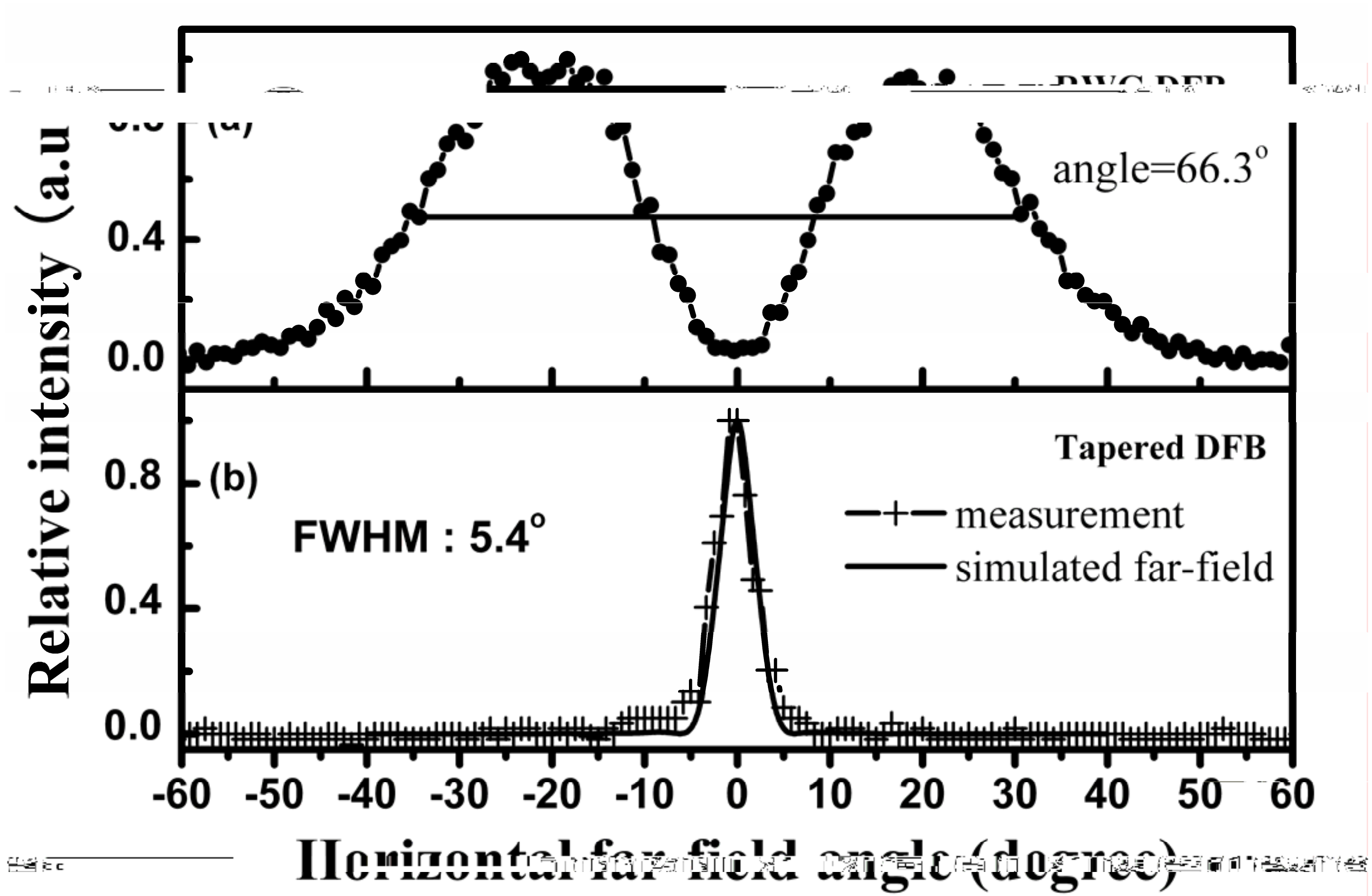


锥形DFB结构的优点



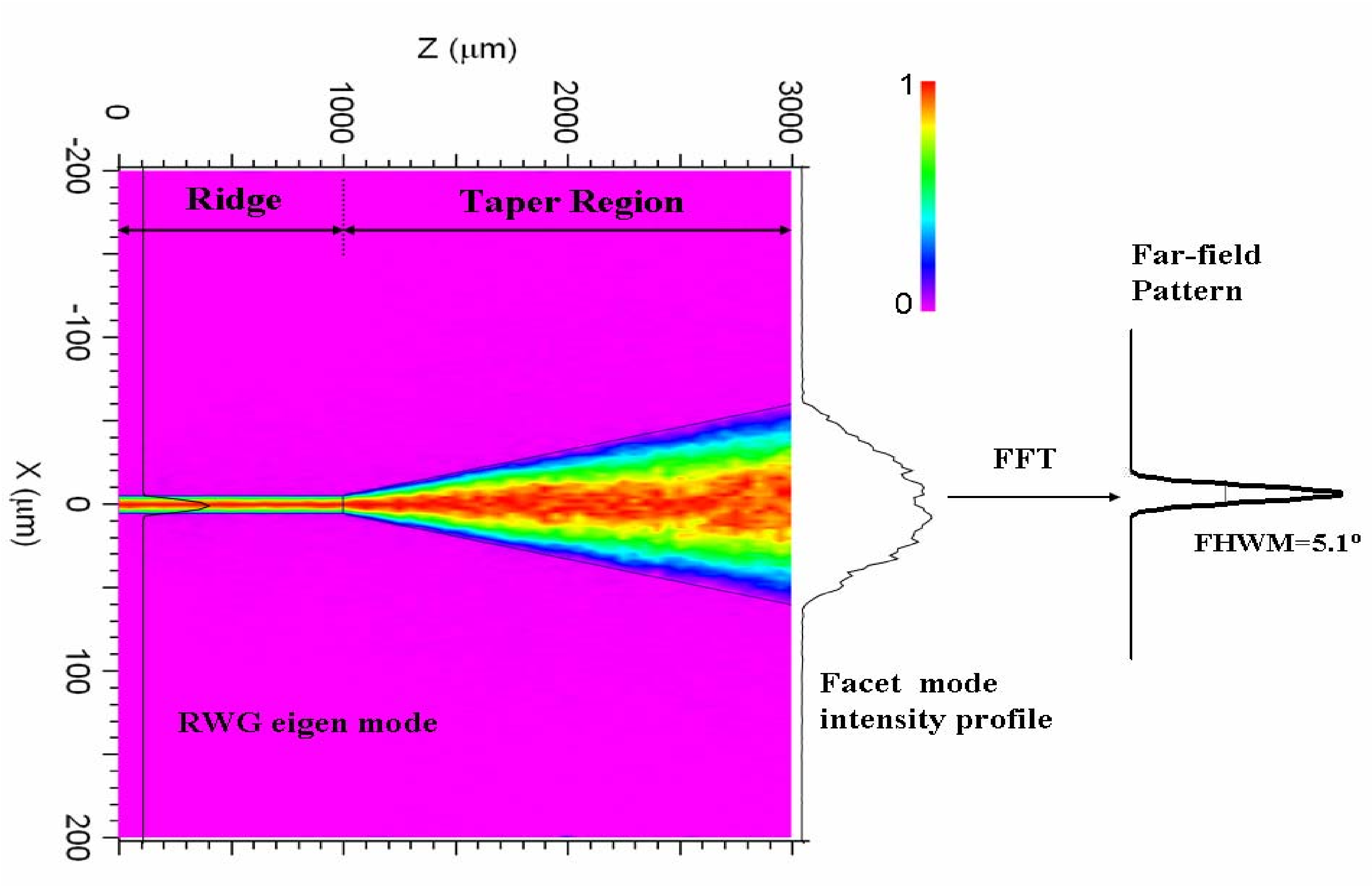
DFB光栅

锥形DFB远场特性

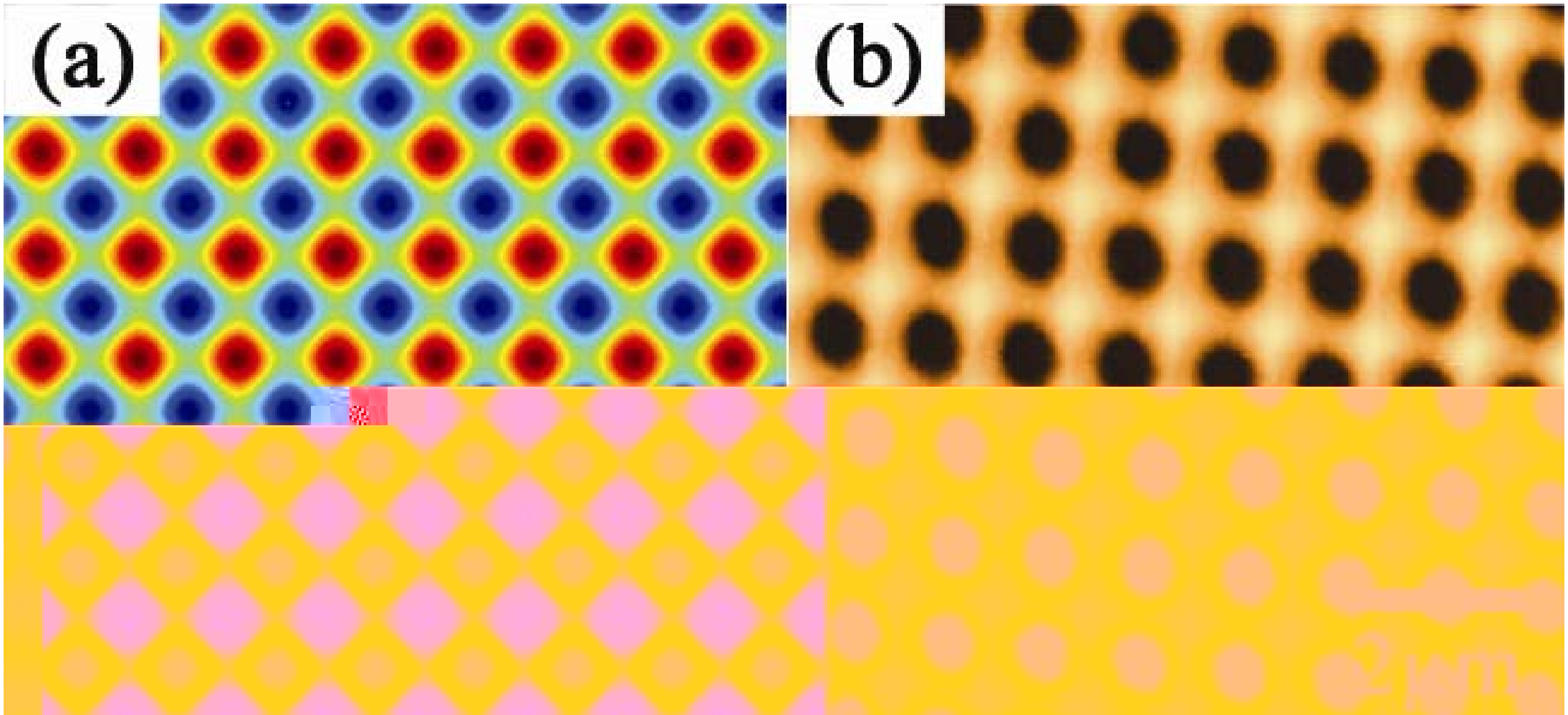


Relative intensity（a.u
(b)
Tapered DFB
FWHM : 5.4°
measurement
simulated far-field
angle=66.3°
0.0
0.4
0.8
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60

锥形DFB-QCL水平远场模拟

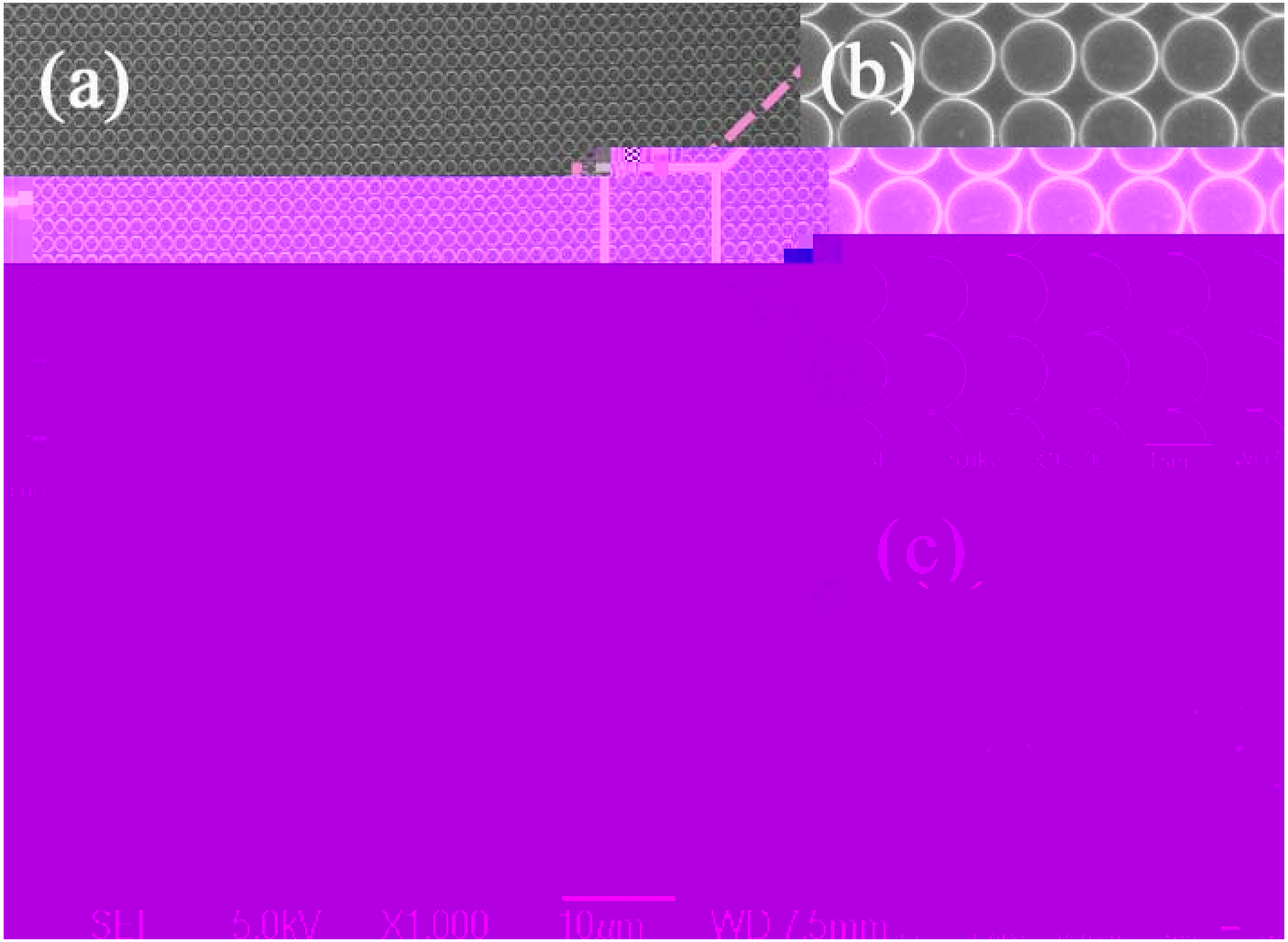


γ ˮl E DFB-QCL



ώ ⁸ 2D ˮl E

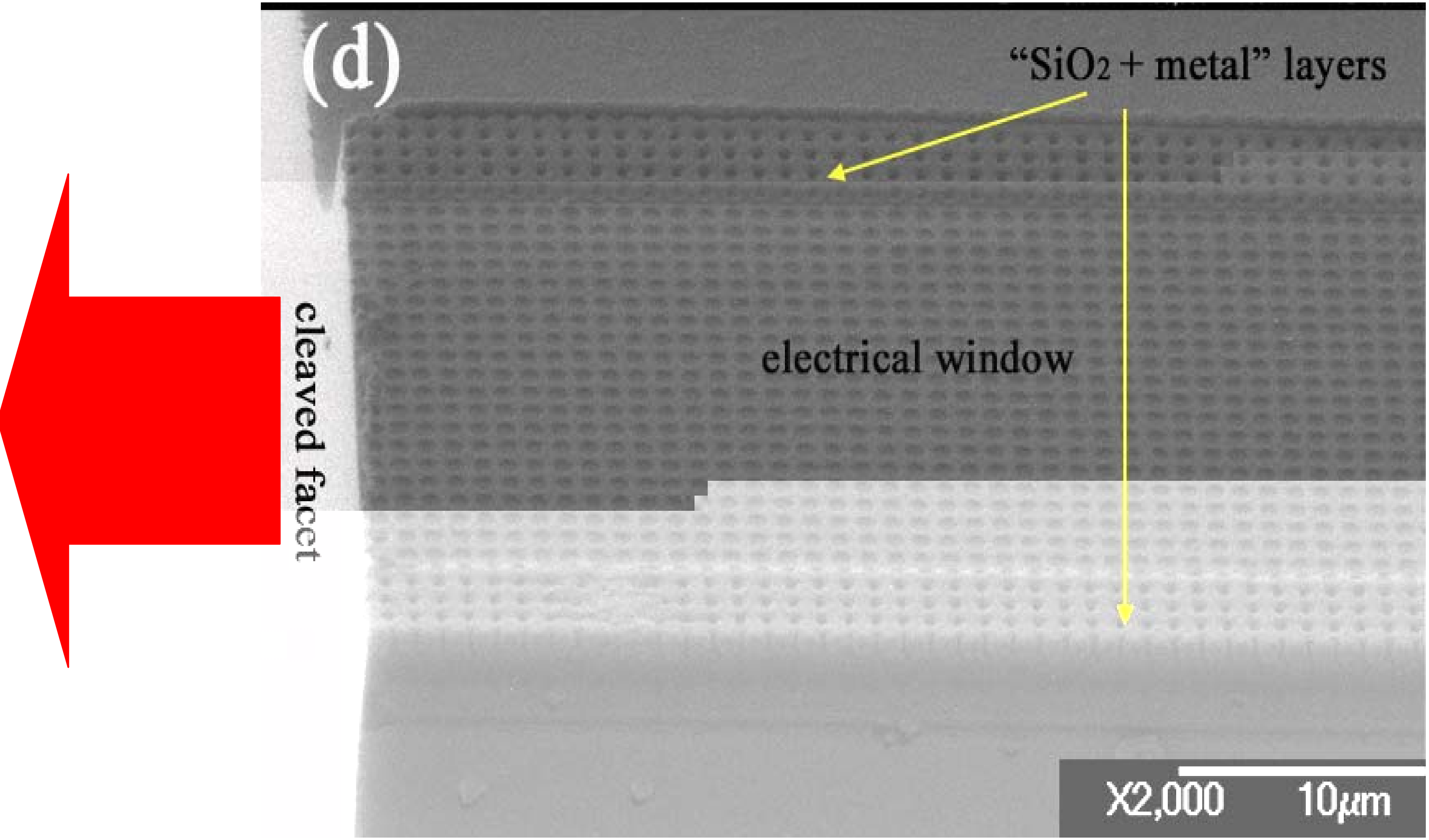
γ "l E DFB-QCL



Λ˘ Э γ "l E

Electronics Letters 45, 53(2009)

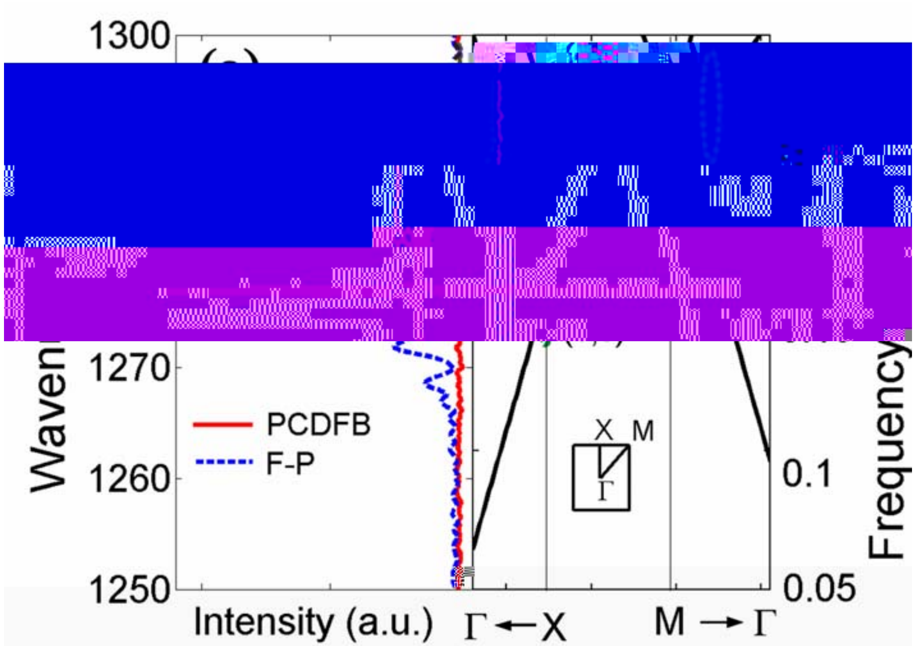
γ ˮl E DFB-QCL

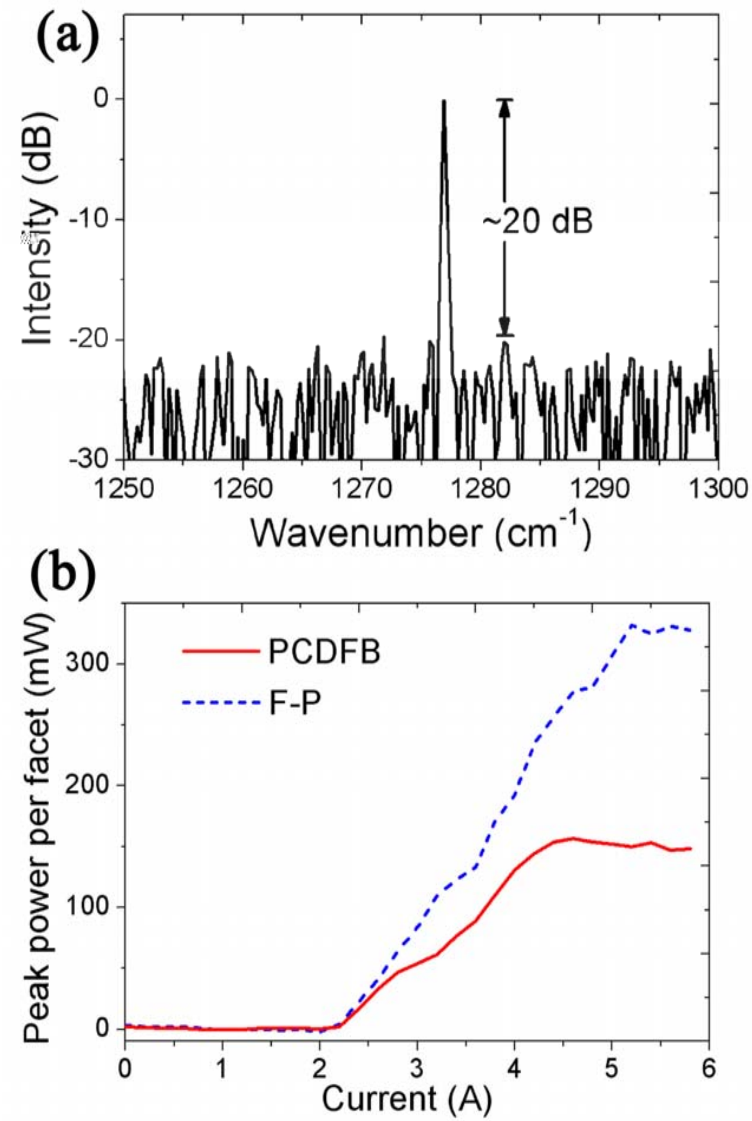


γ ˮl E DFB-QCL Ӽ̈

Electronics Letters 45, 53(2009)

γ ˝l ᴇ DFB-QCL



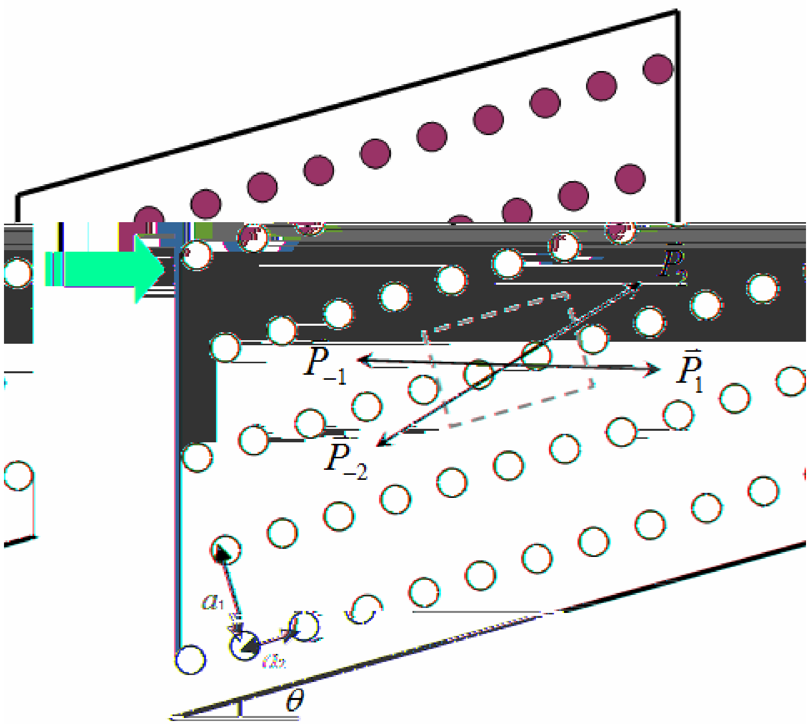


Э (a)PCDFB-QCL б FP-QCL ˝l ; (b) γ ˝l ᴇ Â

ɺ (a) ᛘ PCDFB-QCL ˝l ’ (b)PCDFB-QCL б FP-QCL ╖ ὡ ɺ ӯ Â

Electronics Letters 45, 53(2009)

γ ‶l ᴇ DFB-QCL



γ 2 Э˘ ‾

(1,2) ⅄ 8˘ γ

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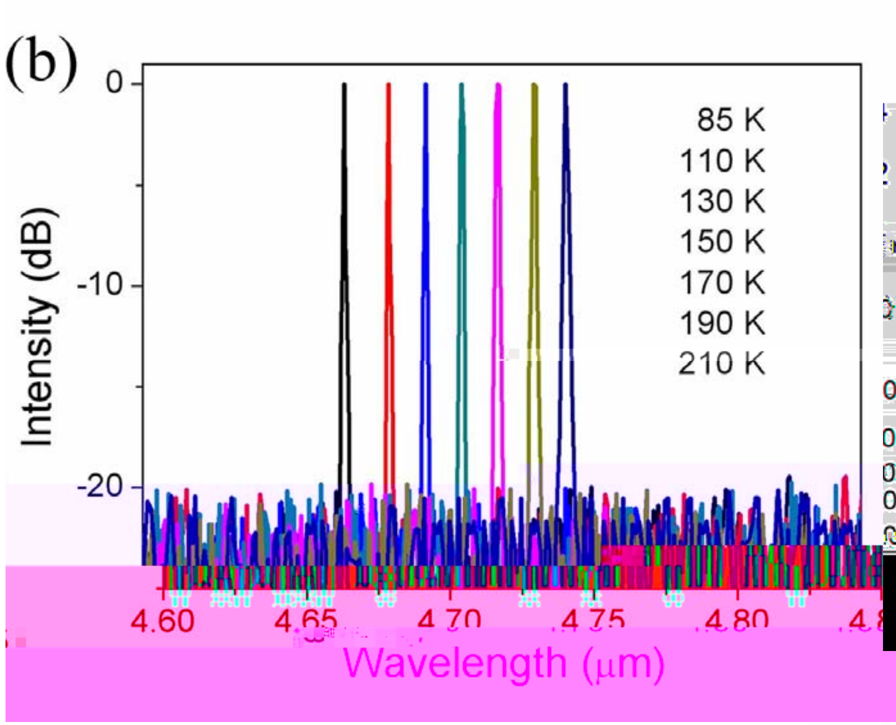
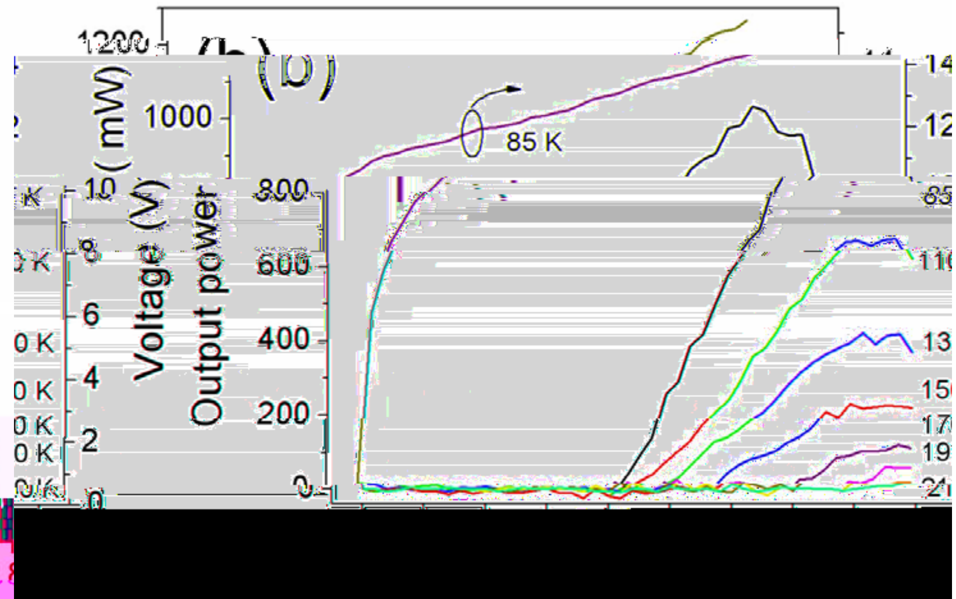
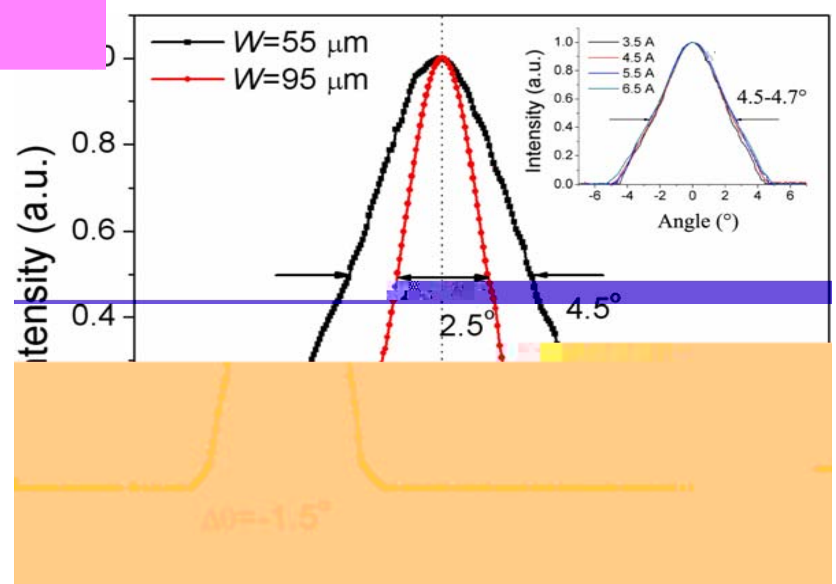
γ ˝l ε DFB-QCL





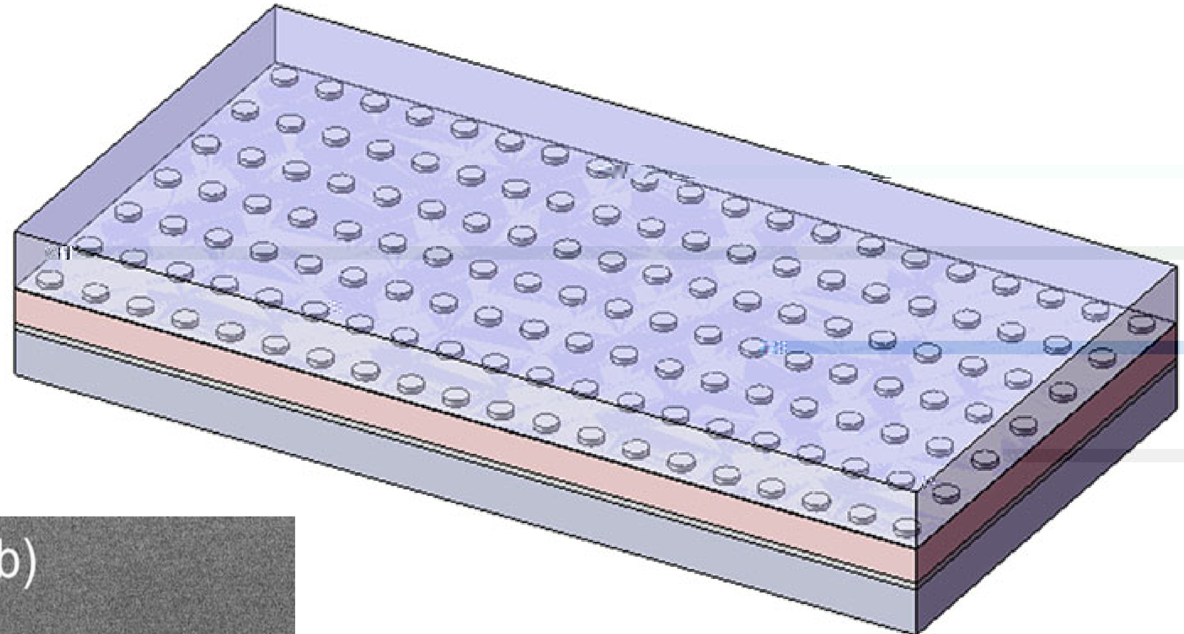
´ à

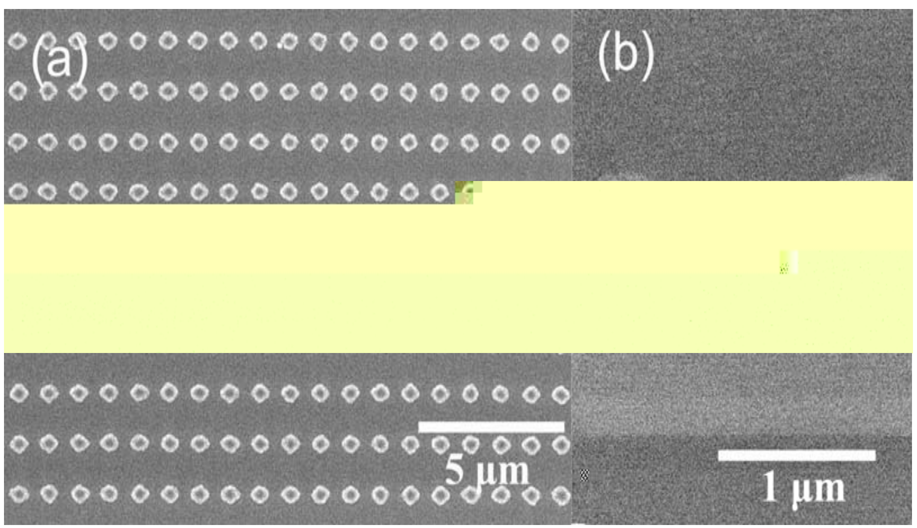
$$\phi \geq \sin^{-1}\left(\lambda/(2n_{eff}W)\right)$$



Optics Express 17, 18900 (2009).

γ ‴l ᴇ DFB-QCL

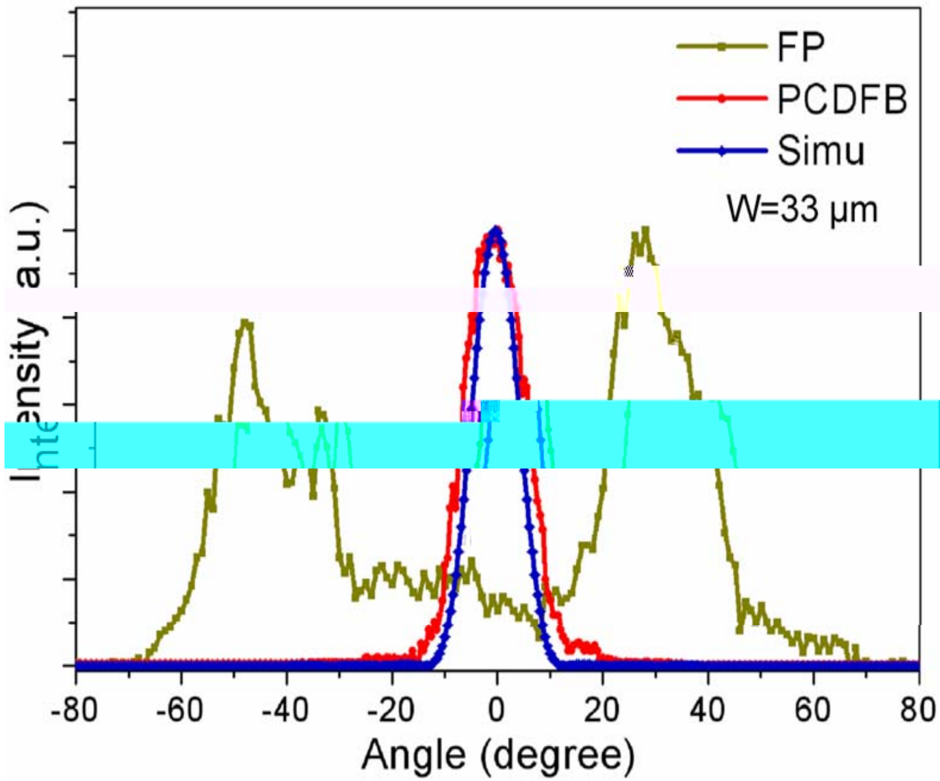




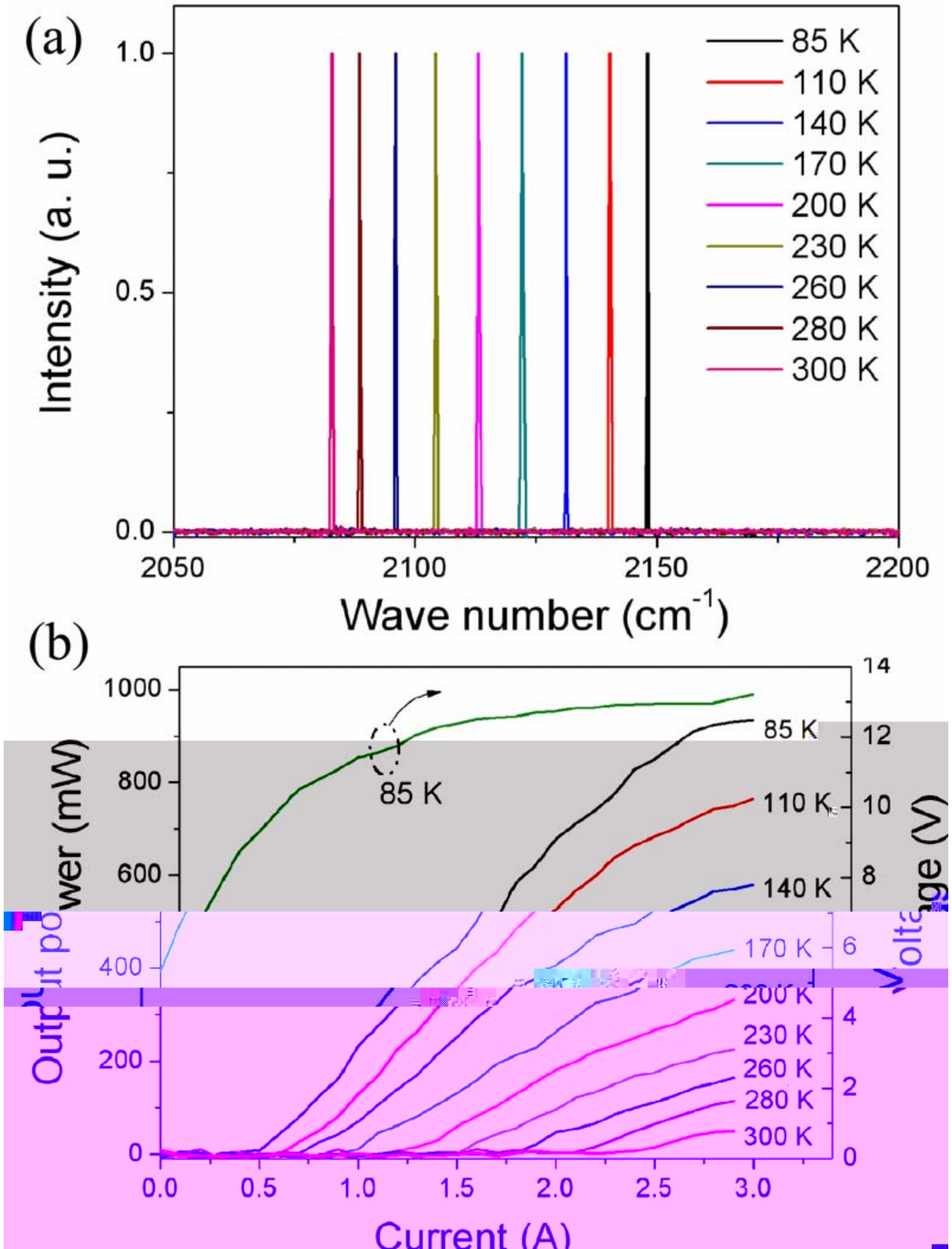
PC ¥

Appl. Phys. Lett. 96, 1(2010)

γ ʺl ᴇ DFB-QCL



ɣ γ DFB ᵴ˘ ɮ˚ ʺl й ɪ˘ ѐ ɹ й 12º ɣ FP 93º ɹ ˘ б ɹ 10.5º ˘ ɹ й PCDFB QCLs ᛏ ҩ ʺl Â



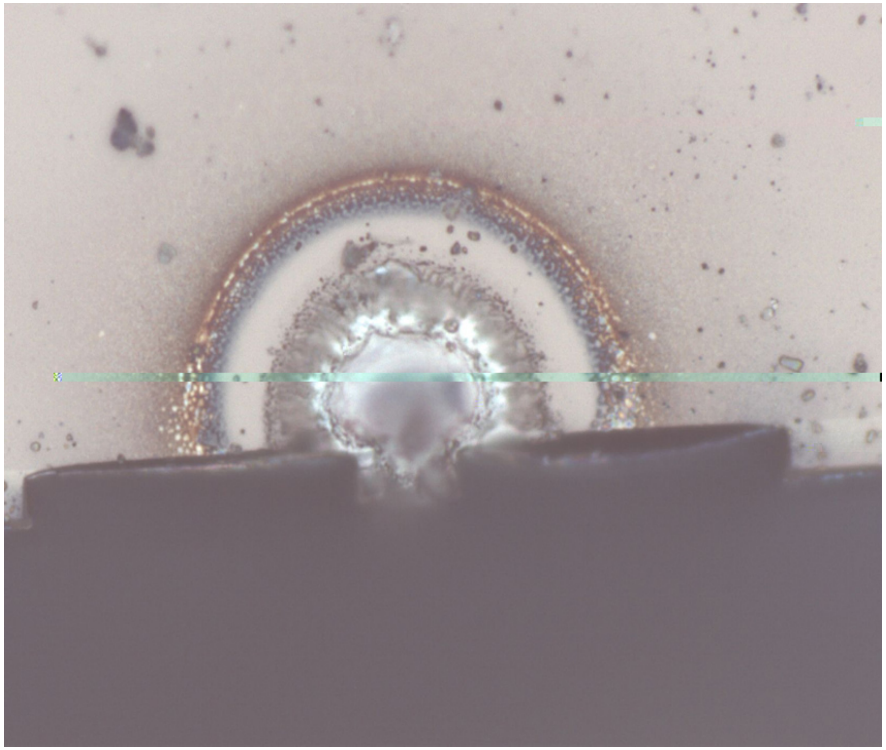
(a)
Intensity (a. u.)
1.0
0.5
0.0
2050
2100
2150
2200
Wave number (cm^{-1})
85 K
110 K
140 K
170 K
200 K
230 K
260 K
280 K
300 K
(b)
Output power (mW)
Voltage (V)
1000
800
600
400
200
0
14
12
10
8
6
4
2
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Current (A)
85 K
110 K
140 K
170 K
200 K
230 K
260 K
280 K
300 K

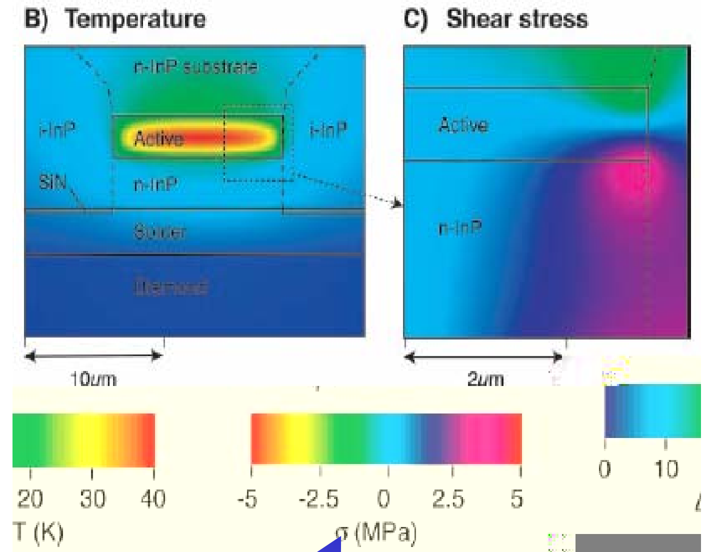
4.7

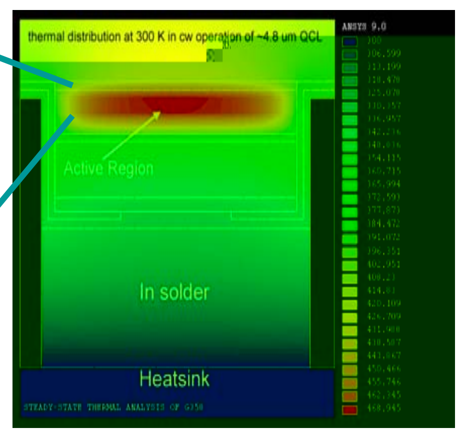
E

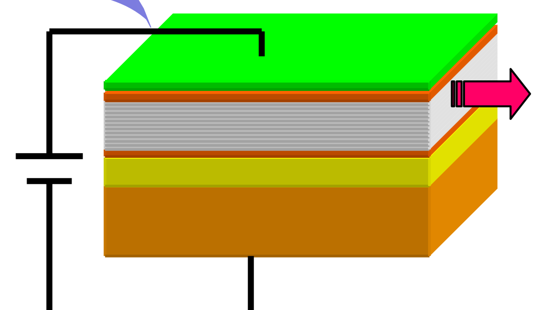
QCL

QCL

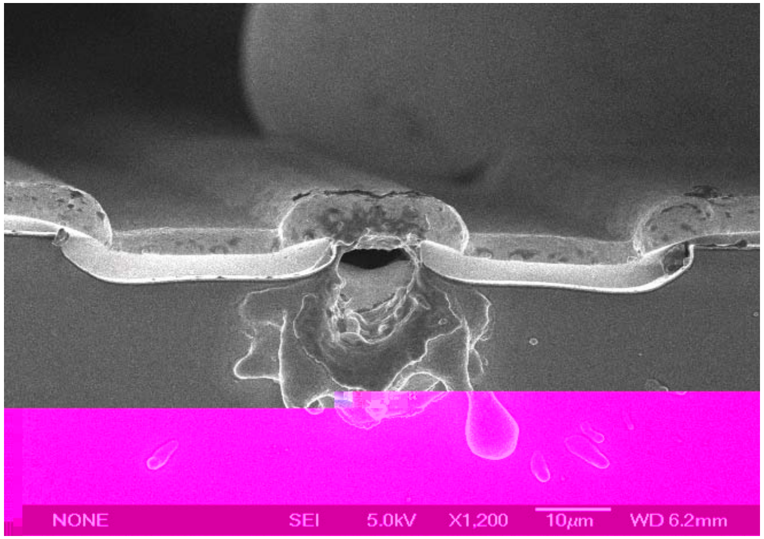


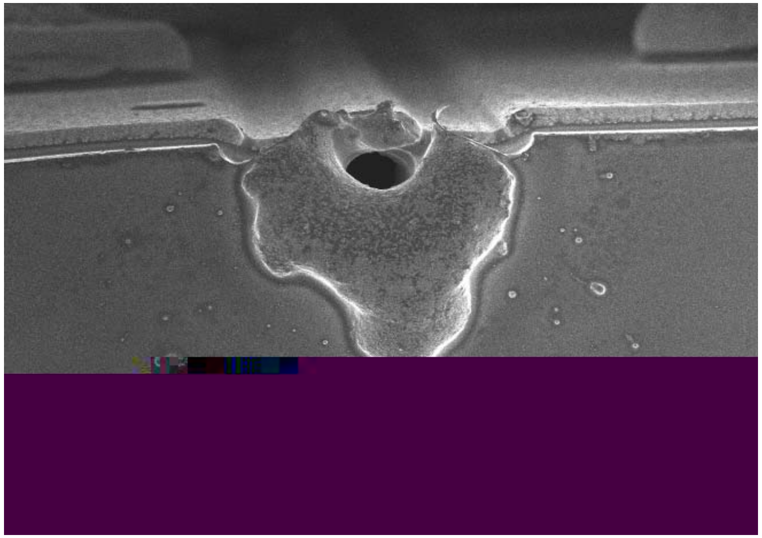

B) Temperature
C) Shear stress
n-InP substrate
i-InP
Active
i-InP
SiN
n-InP
Solder
Diamond
Active
n-InP
10um
2um
20
30
40
T (K)
-5
-2.5
0
2.5
5
σ (MPa)
0
10

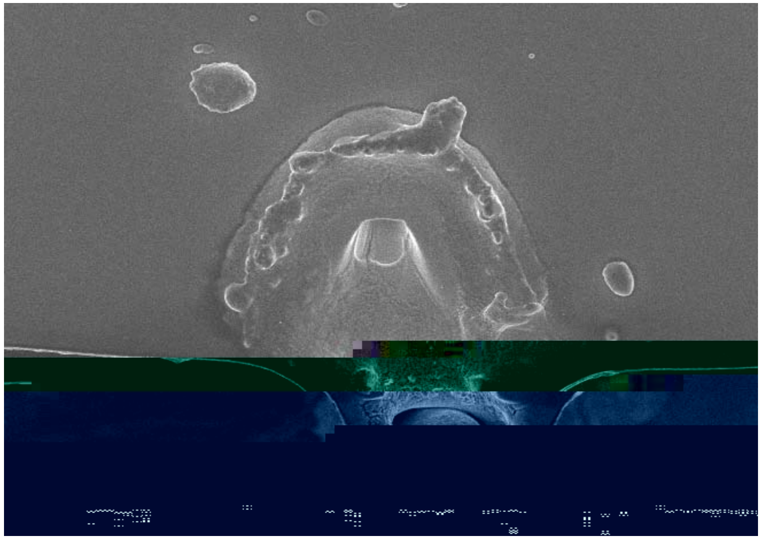

thermal distribution at 300 K in cw operation of ~4.8 um QCL
ANSYS 9.0
Active Region
In solder
Heatsink
STEADY-STATE THERMAL ANALYSIS OF G358

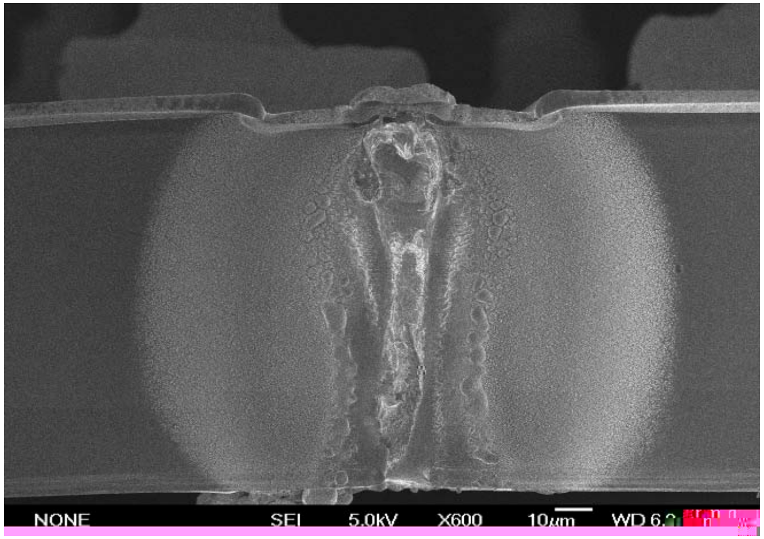


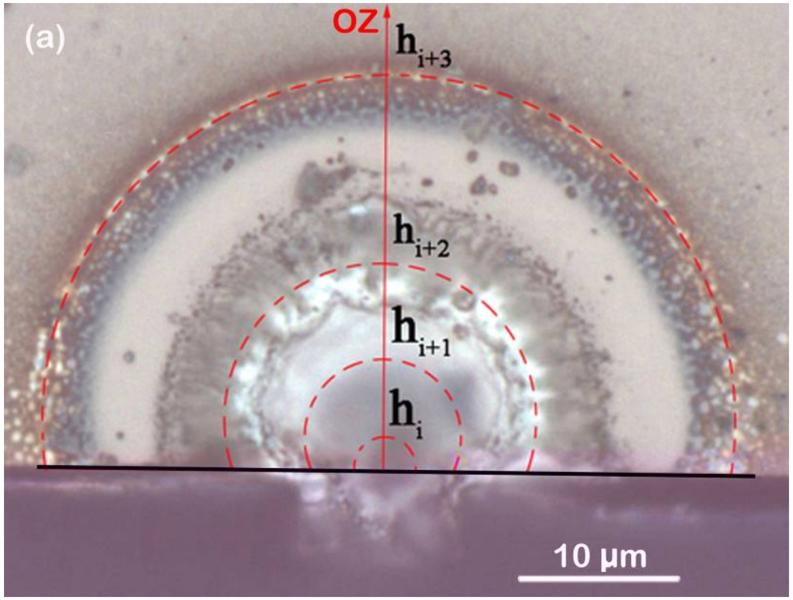
QCL



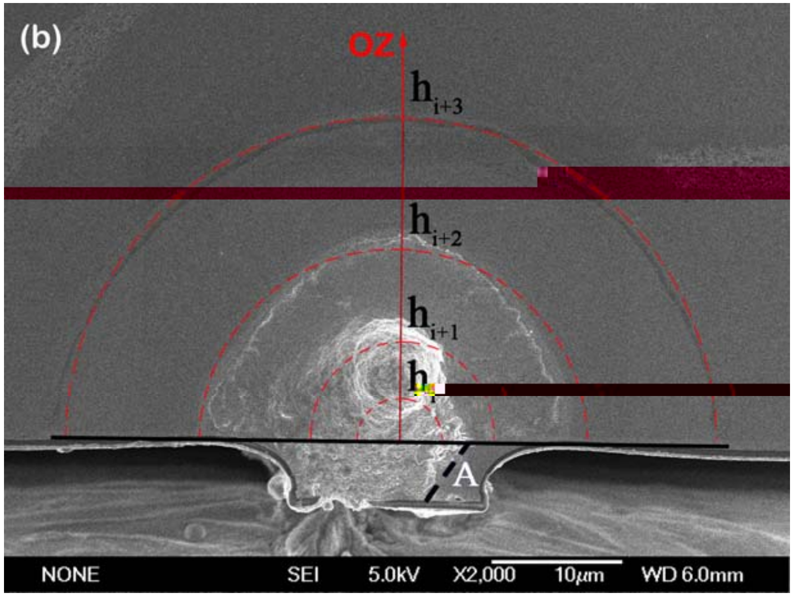








（a）G358



（b）G085

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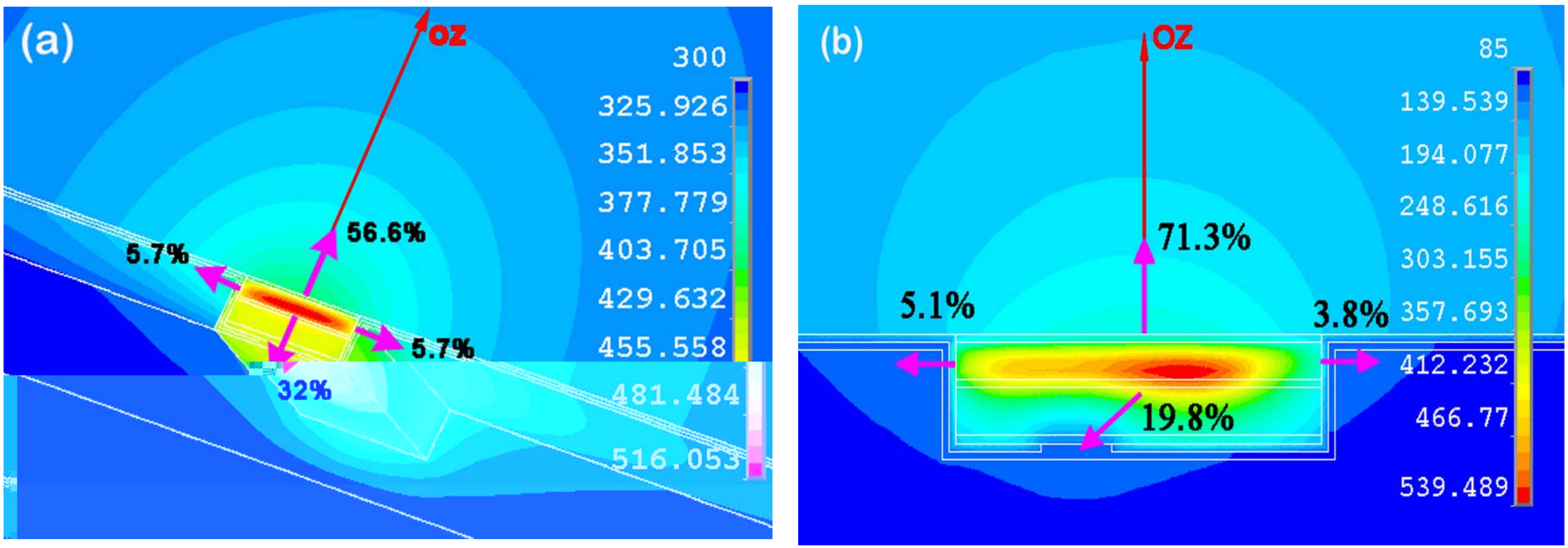


ɺ ' ˆ a˜ G358˘ ˆ b˜ G085

力学平衡模型：

$$F_H = G\frac{1+v}{1-v}bhf$$

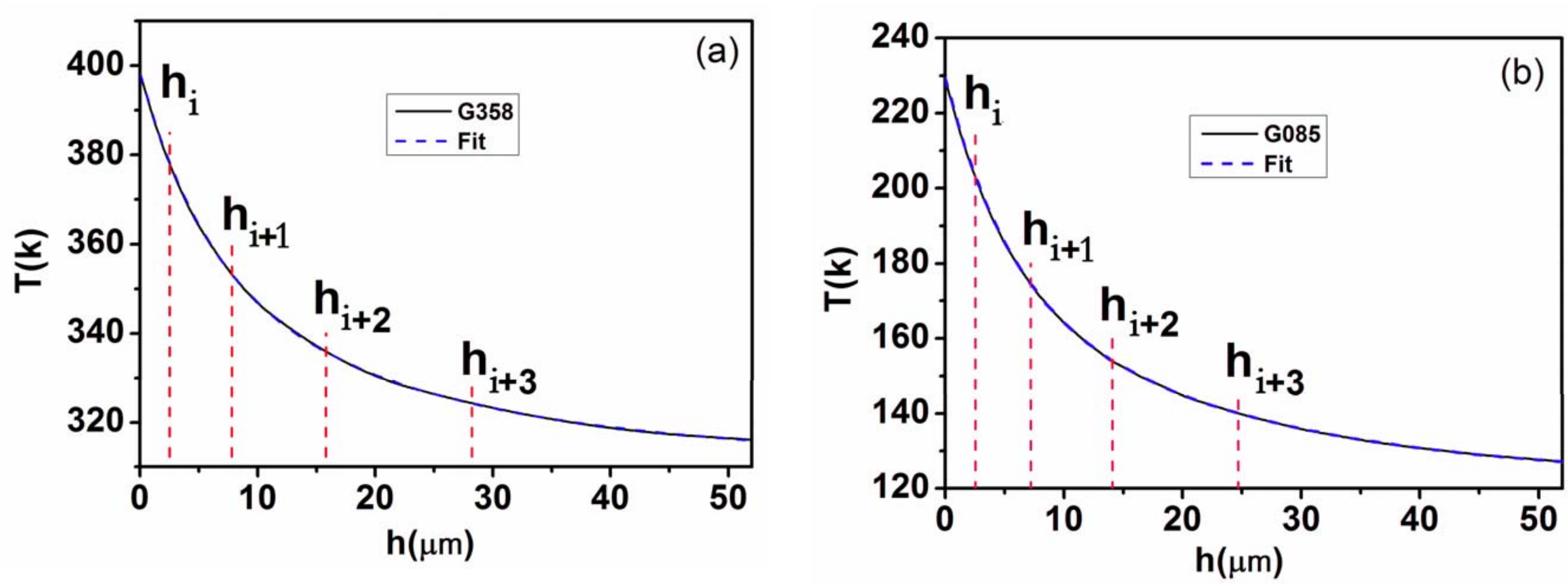
$$F_D = \frac{Gb^2}{4\pi(1-v)}[\ln\frac{h}{b}+1]$$

热晶格失配模型：

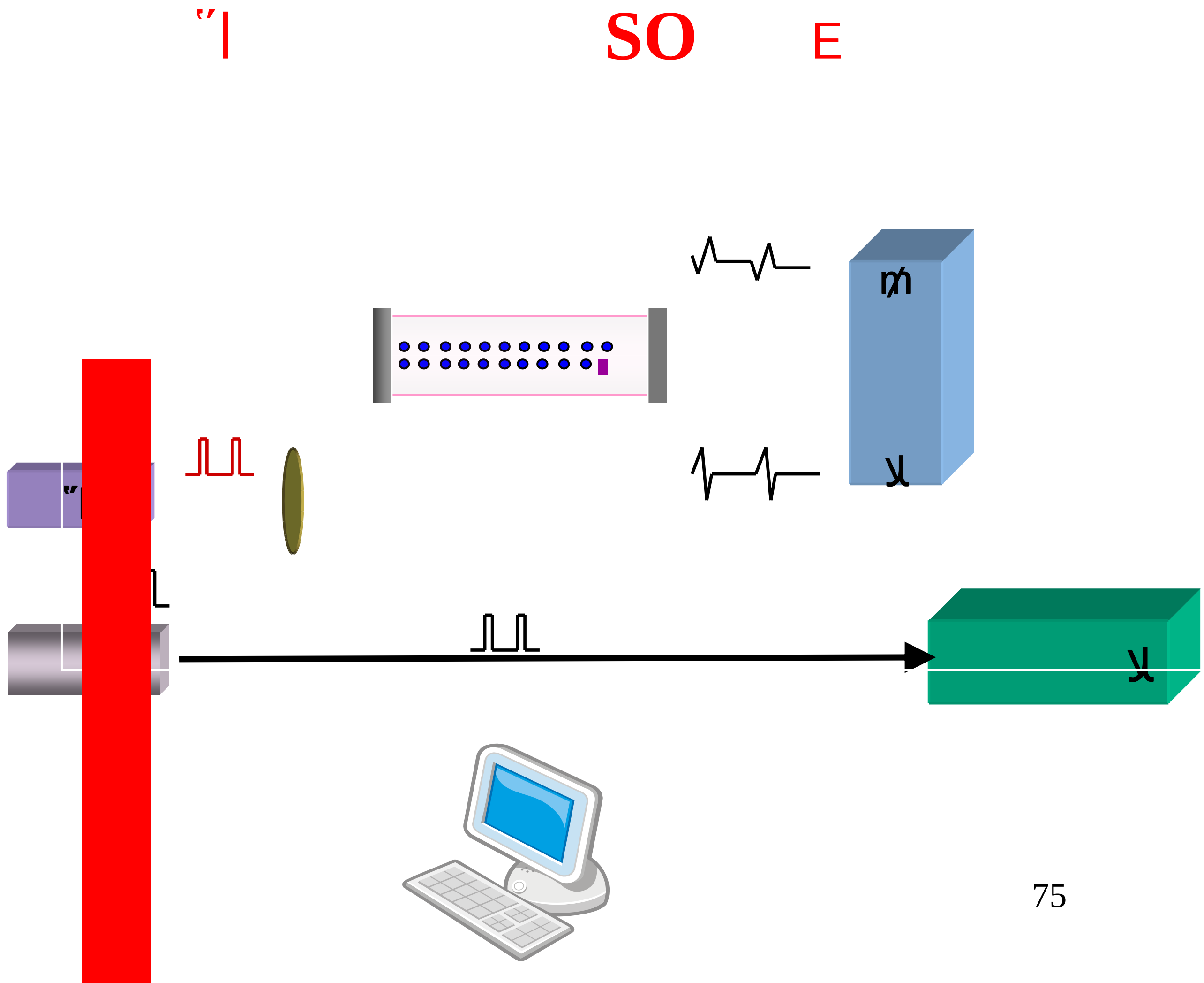
$$F_H = G\frac{1+v}{1-v}b\int_{h_i}^{h_{i+1}} f\ dh$$

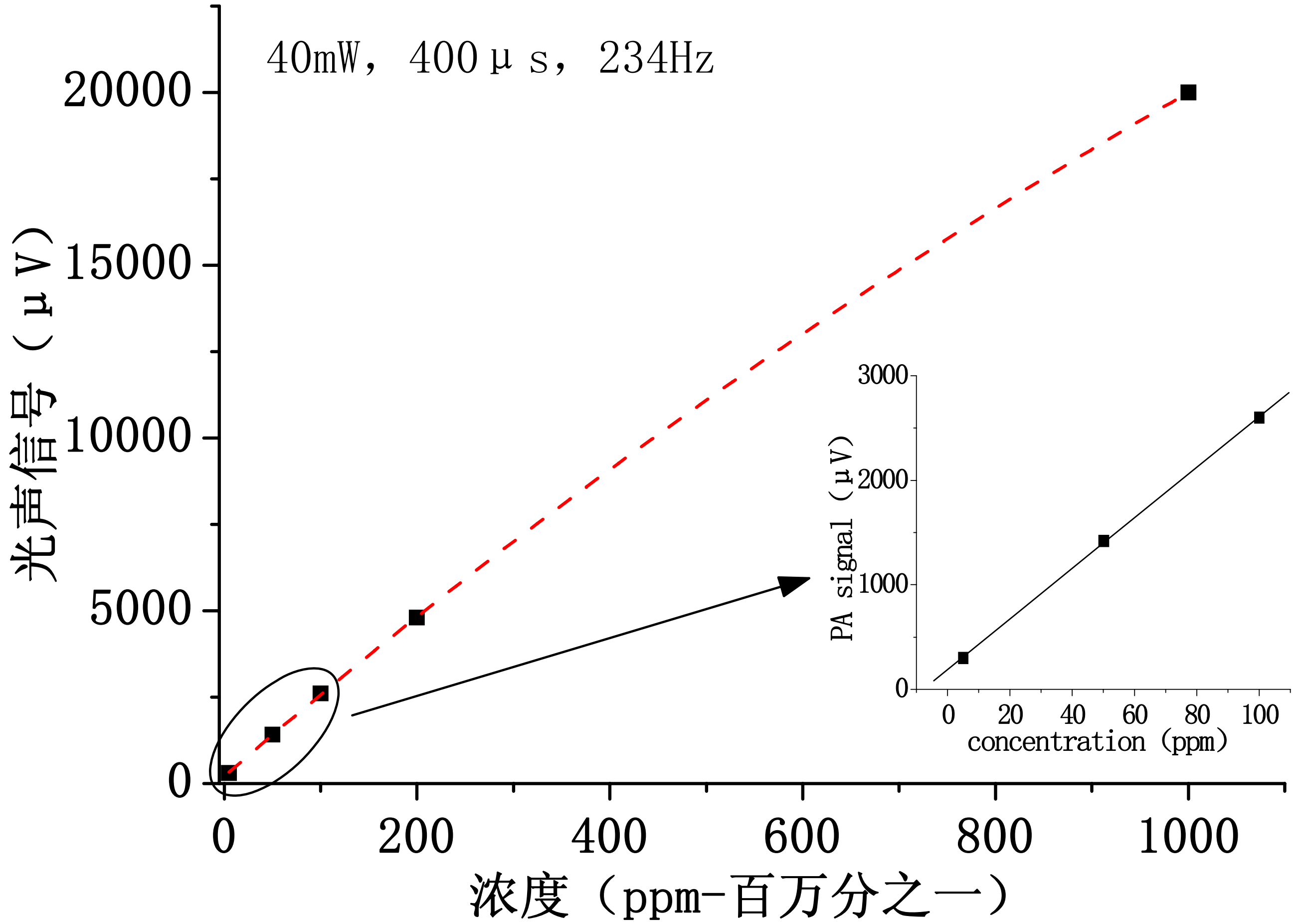
$$F_D = \frac{Gb^2}{4\pi(1-v)}[\ln\frac{h_{i+1}-h_i}{b}+1]$$

给定 $\mathbf{h_i}$
获得 $\mathbf{h_{i\pm 1}}$



OZ Э ↑ ' ^ a˜ G358˘ ^ b˜ G085


SO
E



γ у й 167ppbˆ ˊ Йↅ ǯ У˜

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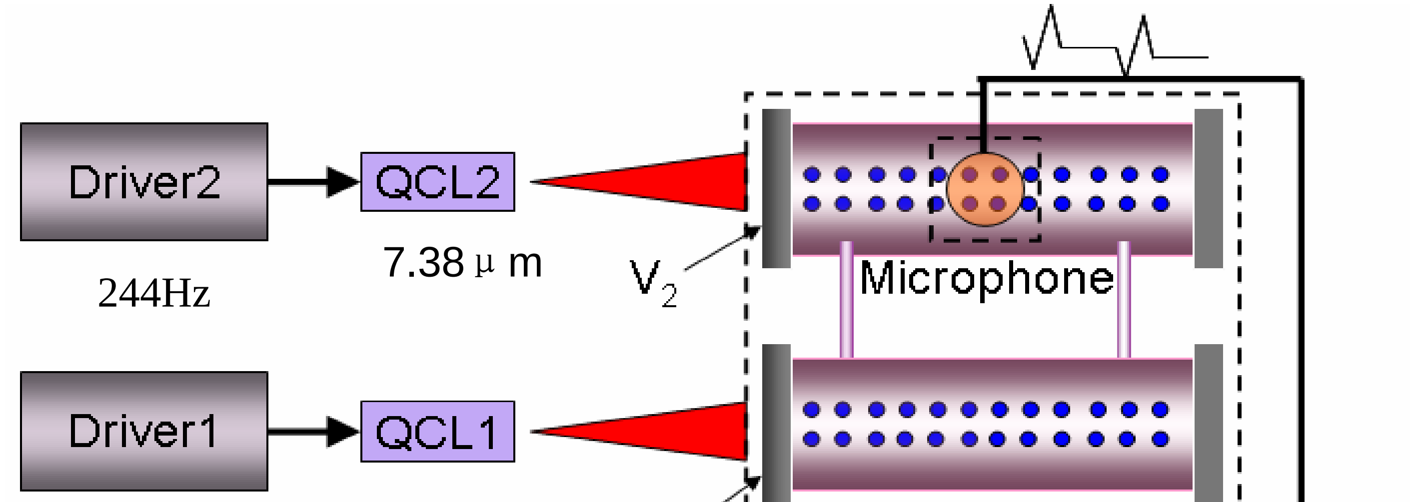
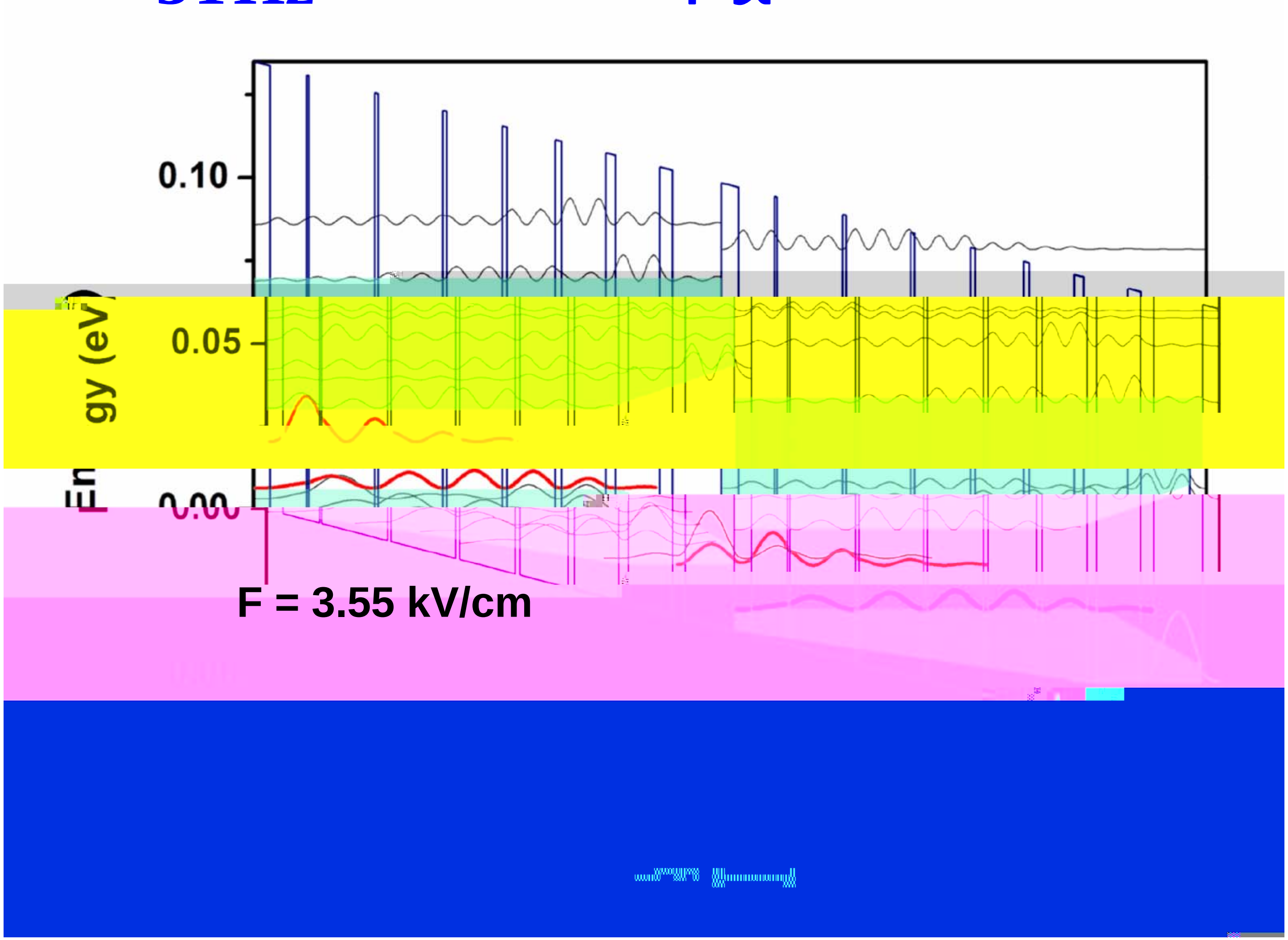


[redacted]

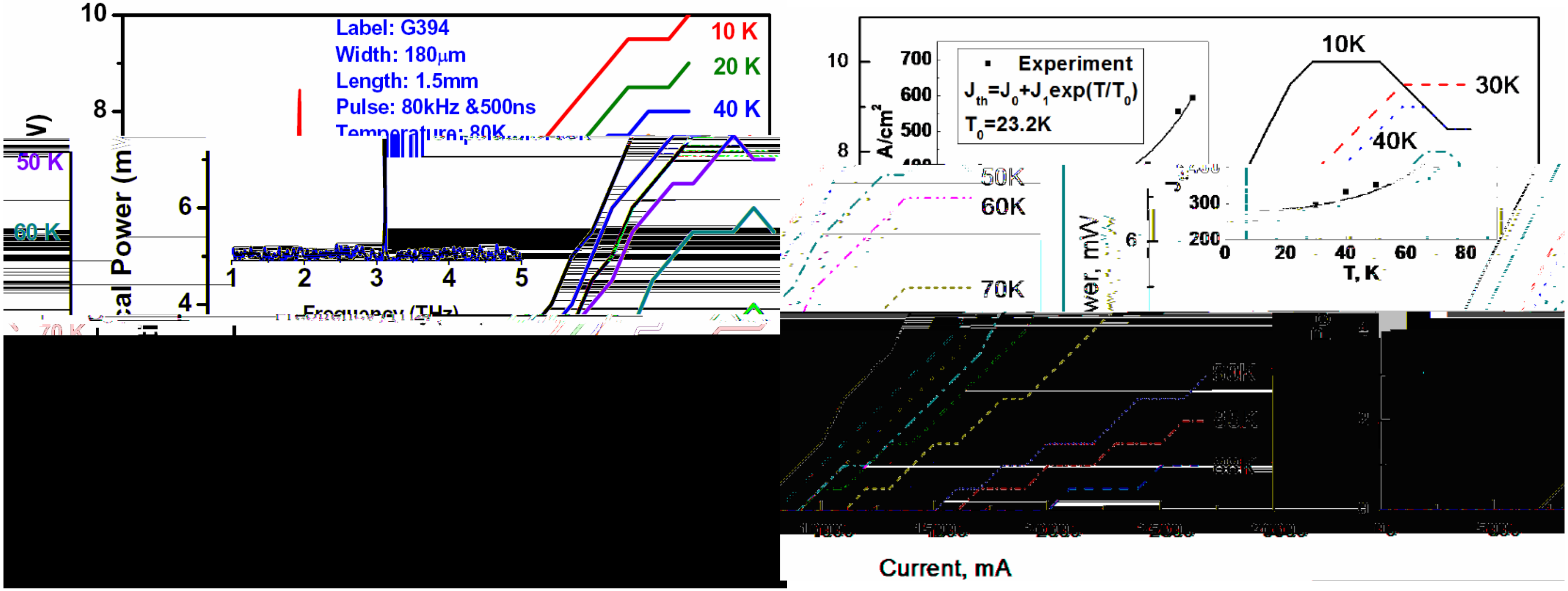
THz-QCL 8

3THz ״ו ג— - ש



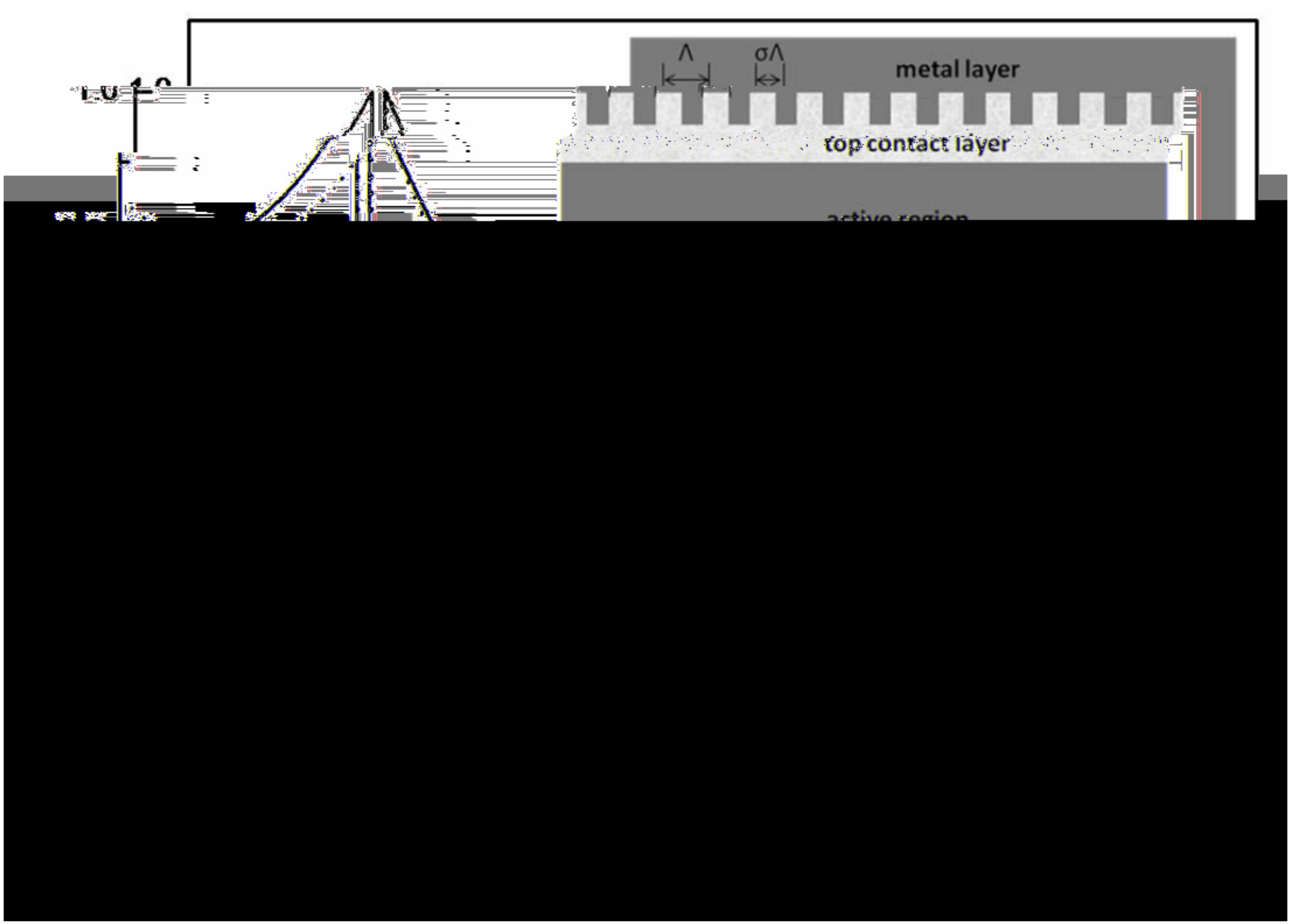
– 2006 8 3THz

˝l ɣ˘ ɔ ᶦ 88K



' ɔ ɣ 90K ằ æ ╖ 14mW Â

√ THz-QCL 8



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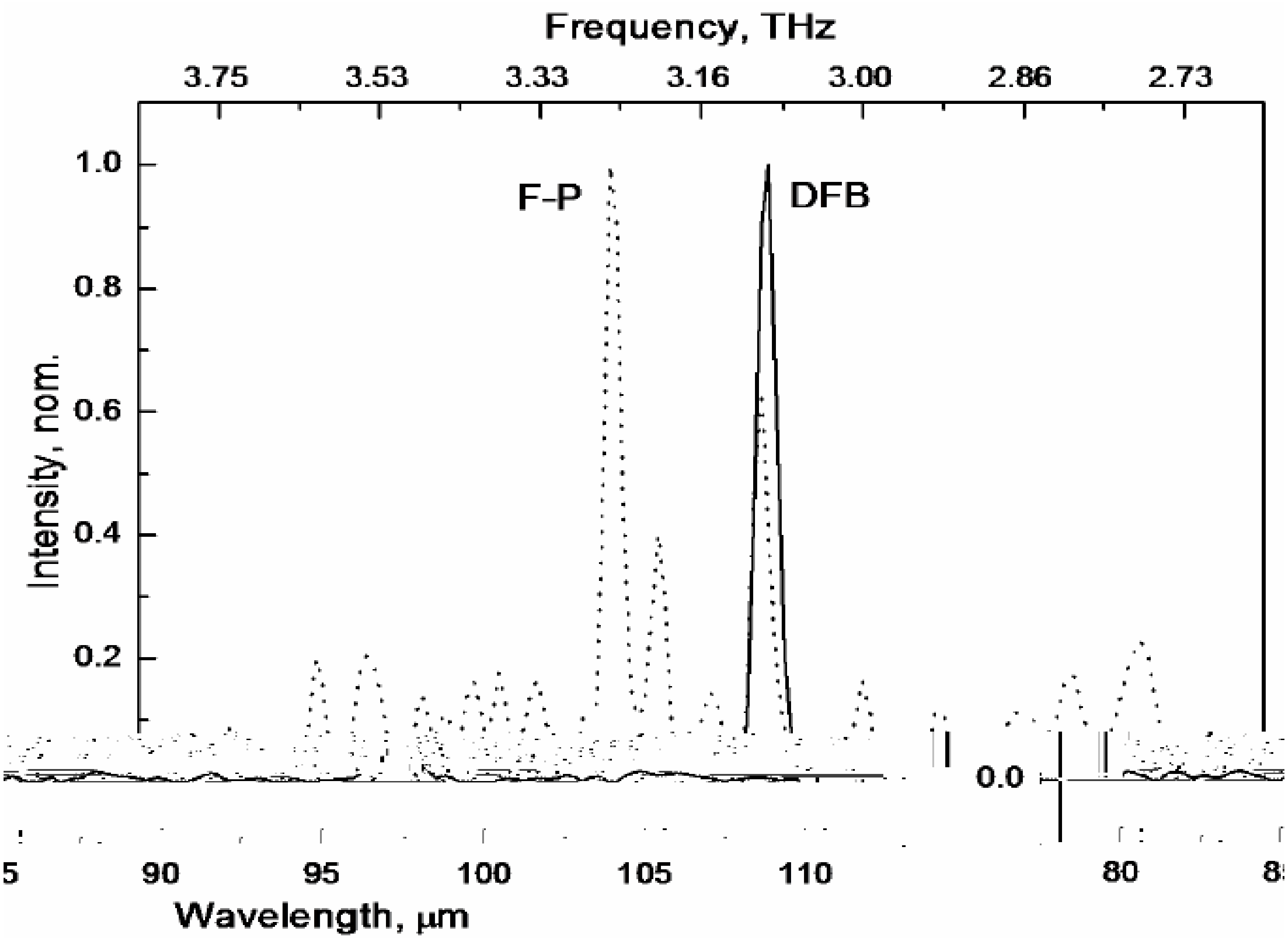

DFB THz-QCL˘ 97 Â (2006) Â

Electron. Lett. 46(19)_ 1340(2010)

‶l ɻ (QCL) ‿ ΰ

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QCLs έ ầ ╖ ầ ꜝ ầ

˩ ˘ ầ ភ ầ ˨

ầ ⁸ ầ έ

ɱ Â

` E 8 У ‟ $In_xGa_{1-x}As/In_yAl_{1-y}As$ QCLs:

ɔ : 3.5μm, 4.6μm, 4.7μm, 4.8μm, 5.2μm, 5.5μm, 5.7μm, 7.4μm, 7.8μm, 8.9μm.

4.6μm, 7.4μm .

ɔ ´ QCLs

´ QCLs;

‟l ầ ˧ ầ DFB-QCLs;

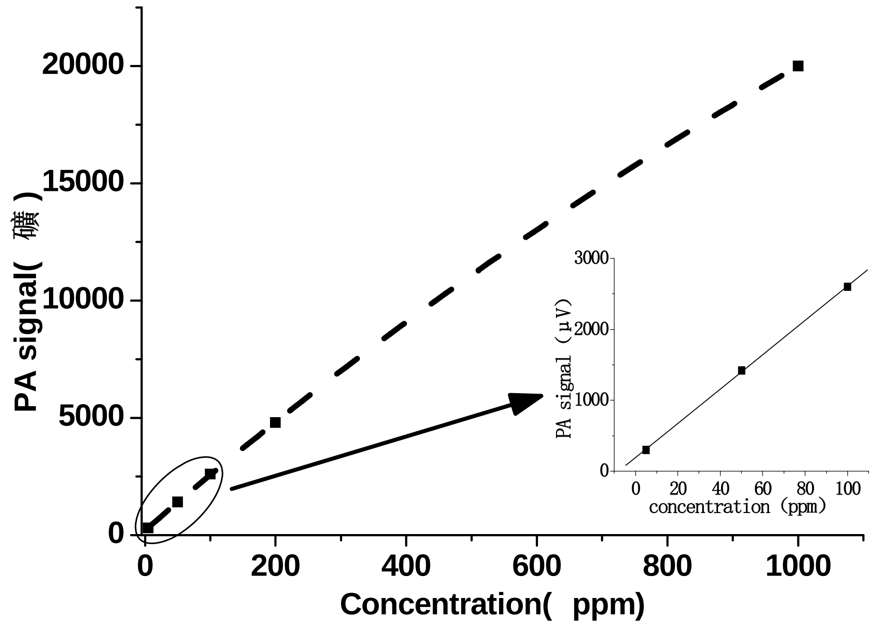
‟l E⍏ √ QCL;

GaAs/AlGaAs QCLs: У ‟ 9.1--11.4 μm

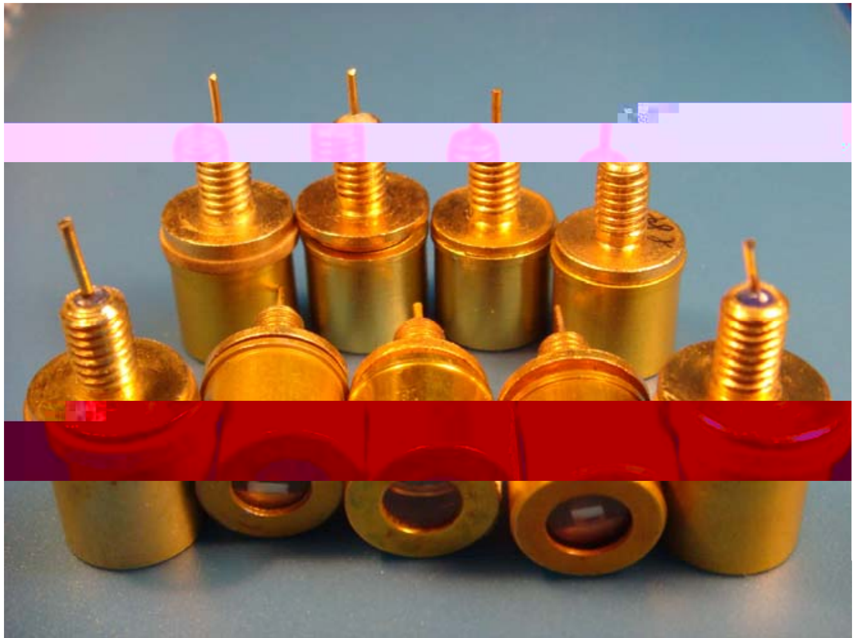
THz-QCLs ầ ╖ 14mW Â

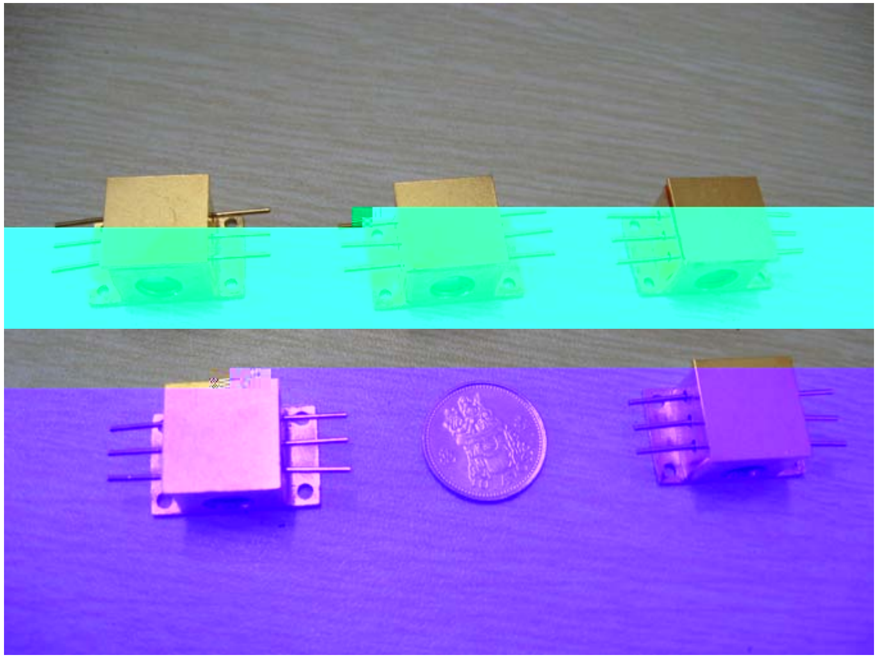
E

k QCL

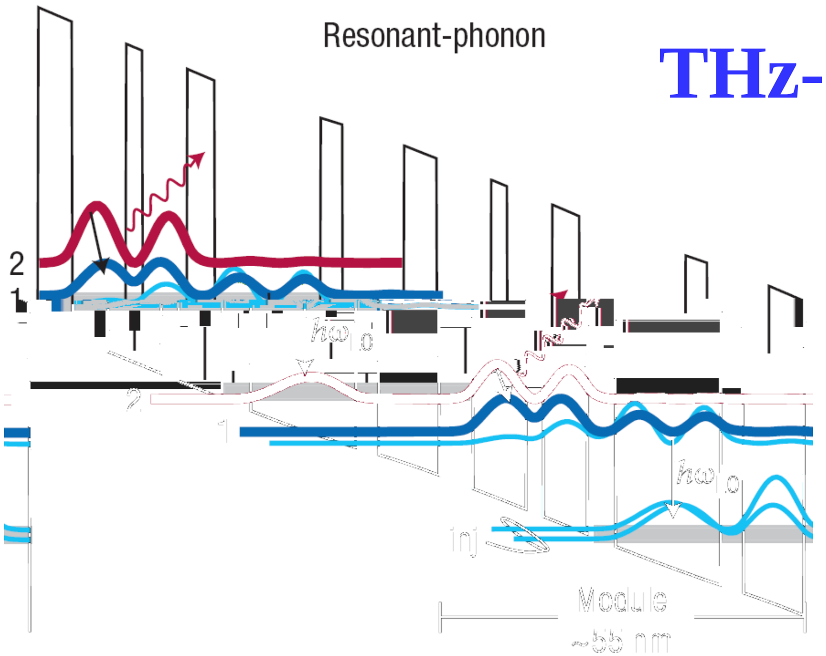


20000
15000
10000
5000
0
PA signal(
)
0
200
400
600
800
1000
Concentration(ppm)
3000
2000
1000
0
PA signal (μV)
0
20
40
60
80
100
concentration (ppm)

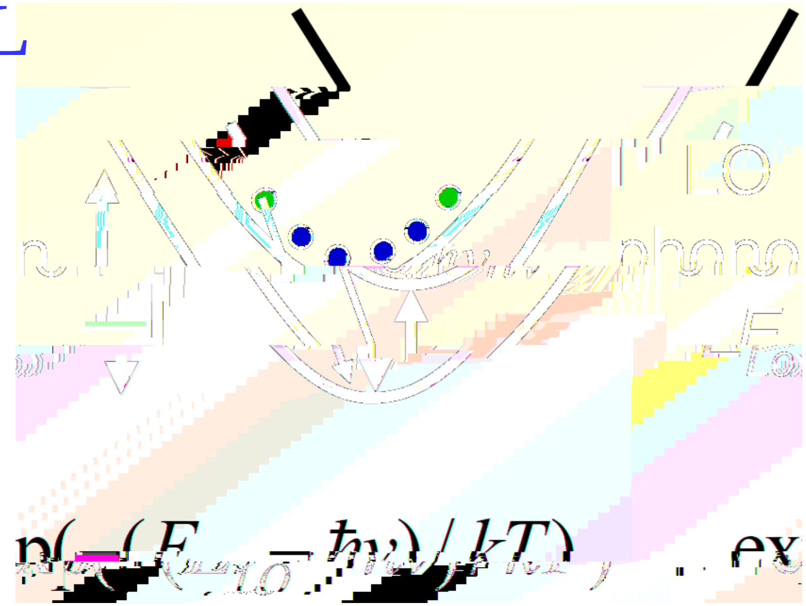




• , Superlatt.Microstruct. 37, 107–113 (2005)



THz-QCL



Challenges and Frontier

(1). GaN E QCLs à THz-QCL

(2). Surface plasmonic structures

(3).