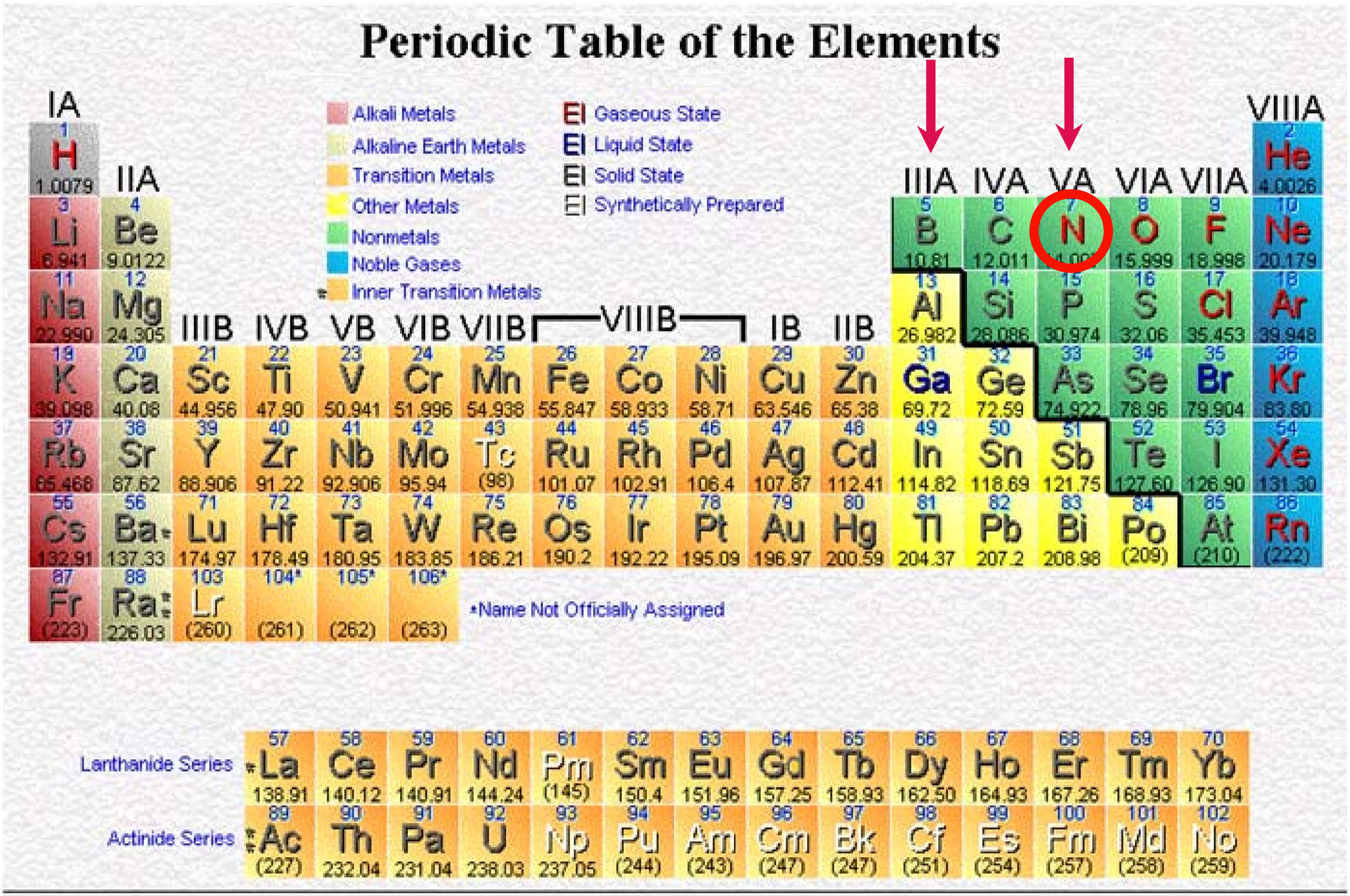
Department of Physics
Shahrood University of Technology

Optical Investigation of the Localization Effect in the Quantum Well Structures

Hamid Haratizadeh
hamid.haratizadeh@gmail.com

IPM, SCHOOL OF PHYSICS, JULY 2008


Periodic Table of the Elements
IA
IIA
IIIB IVB VB VIB VIIB VIIIB IB IIB
IIIA IVA VA VIA VIIA
VIIIA
Alkali Metals
Alkaline Earth Metals
Transition Metals
Other Metals
Nonmetals
Noble Gases
Inner Transition Metals
El Gaseous State
El Liquid State
El Solid State
El Synthetically Prepared
1 H 1.0079
2 He 4.0026
3 Li 6.941
4 Be 9.0122
5 B 10.81
6 C 12.011
7 N
8 O 15.999
9 F 18.998
10 Ne 20.179
11 Na 22.990
12 Mg 24.305
13 Al 26.982
14 Si 28.086
15 P 30.974
16 S 32.06
17 Cl 35.453
18 Ar 39.948
19 K 39.098
20 Ca 40.08
21 Sc 44.956
22 Ti 47.90
23 V 50.941
24 Cr 51.996
25 Mn 54.938
26 Fe 55.847
27 Co 58.933
28 Ni 58.71
29 Cu 63.546
30 Zn 65.38
31 Ga 69.72
32 Ge 72.59
33 As 74.922
34 Se 78.96
35 Br 79.904
36 Kr 83.80
37 Rb 85.468
38 Sr 87.62
39 Y 88.906
40 Zr 91.22
41 Nb 92.906
42 Mo 95.94
43 Tc (98)
44 Ru 101.07
45 Rh 102.91
46 Pd 106.4
47 Ag 107.87
48 Cd 112.41
49 In 114.82
50 Sn 118.69
51 Sb 121.75
52 Te 127.60
53 I 126.90
54 Xe 131.30
55 Cs 132.91
56 Ba 137.33
71 Lu 174.97
72 Hf 178.49
73 Ta 180.95
74 W 183.85
75 Re 186.21
76 Os 190.2
77 Ir 192.22
78 Pt 195.09
79 Au 196.97
80 Hg 200.59
81 Tl 204.37
82 Pb 207.2
83 Bi 208.98
84 Po (209)
85 At (210)
86 Rn (222)
87 Fr (223)
88 Ra 226.03
103 Lr (260)
104* (261)
105* (262)
106* (263)
*Name Not Officially Assigned
Lanthanide Series
57 La 138.91
58 Ce 140.12
59 Pr 140.91
60 Nd 144.24
61 Pm (145)
62 Sm 150.4
63 Eu 151.96
64 Gd 157.25
65 Tb 158.93
66 Dy 162.50
67 Ho 164.93
68 Er 167.26
69 Tm 168.93
70 Yb 173.04
Actinide Series
89 Ac (227)
90 Th 232.04
91 Pa 231.04
92 U 238.03
93 Np 237.05
94 Pu (244)
95 Am (243)
96 Cm (247)
97 Bk (247)
98 Cf (251)
99 Es (254)
100 Fm (257)
101 Md (258)
102 No (259)

Quantum Well Structures

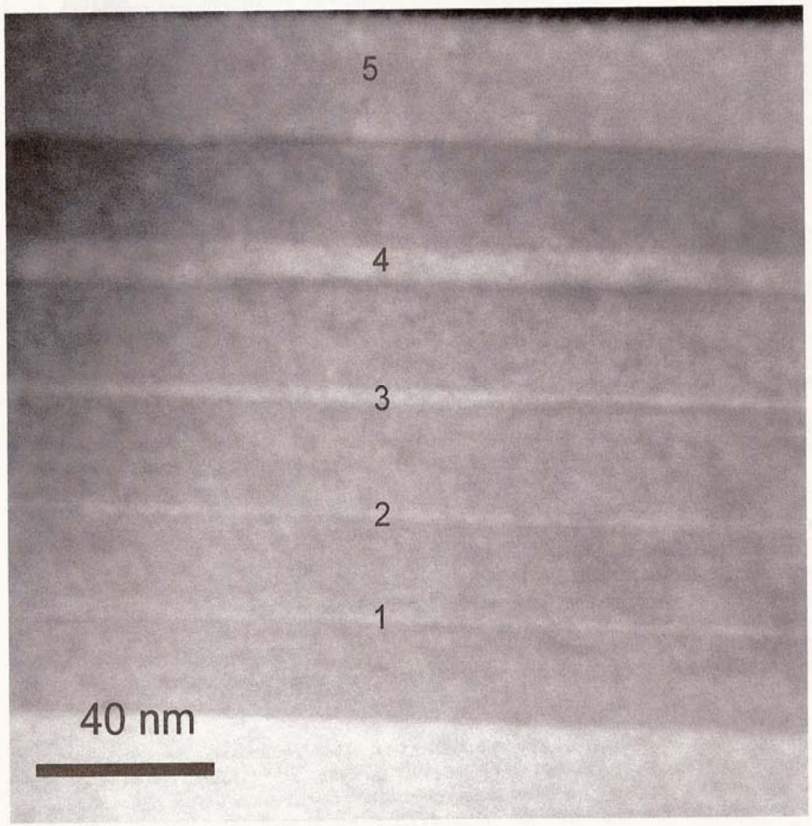
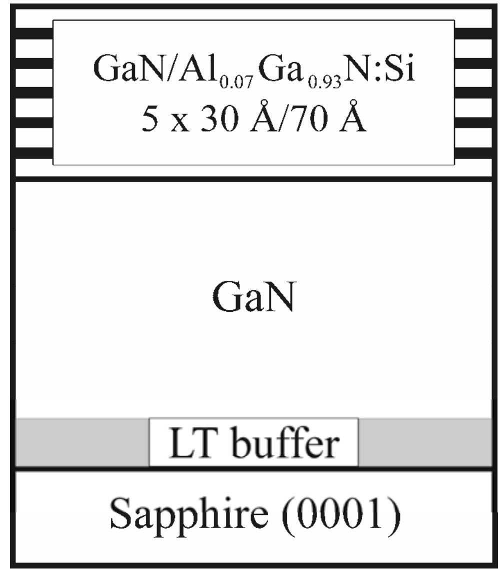
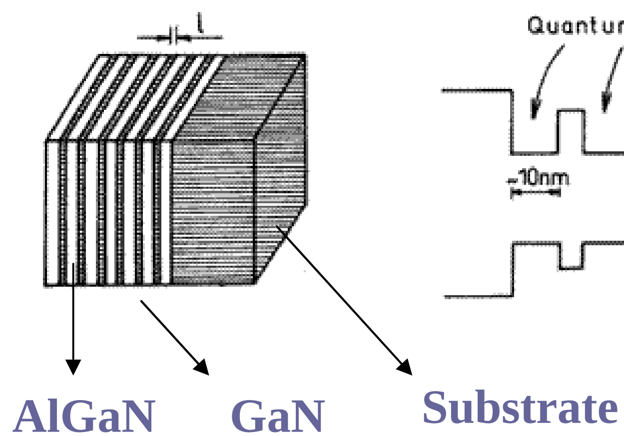
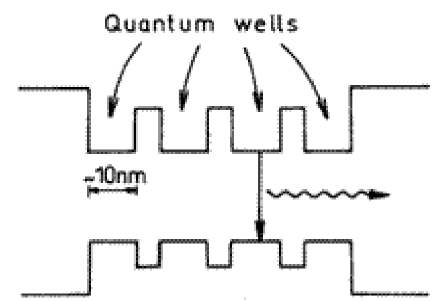


Figure 1. Transmission electron microscopy (ADF-STEM) cross sectional image of AlGaN/GaN multi quantum well structure grown by novel HVPE method at TDI, Inc. (courtes Prof. Subhash Mahajan, Arizona State University). Five GaN layers having thickness of about 2 nm, 3 4 nm, 8 nm, and 25 nm are sandwiched between AlGaN barrier layers having thickness of 20 nm.







Recombination Processes

► **Intristic:>>> no impurity**

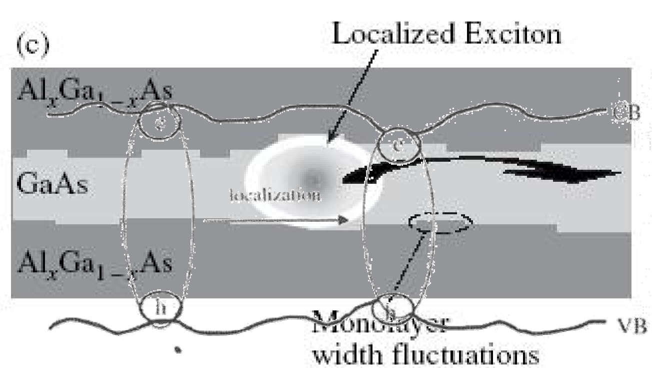
1-Band to Band Recombination

2-Free Exciton (FE) Recombination

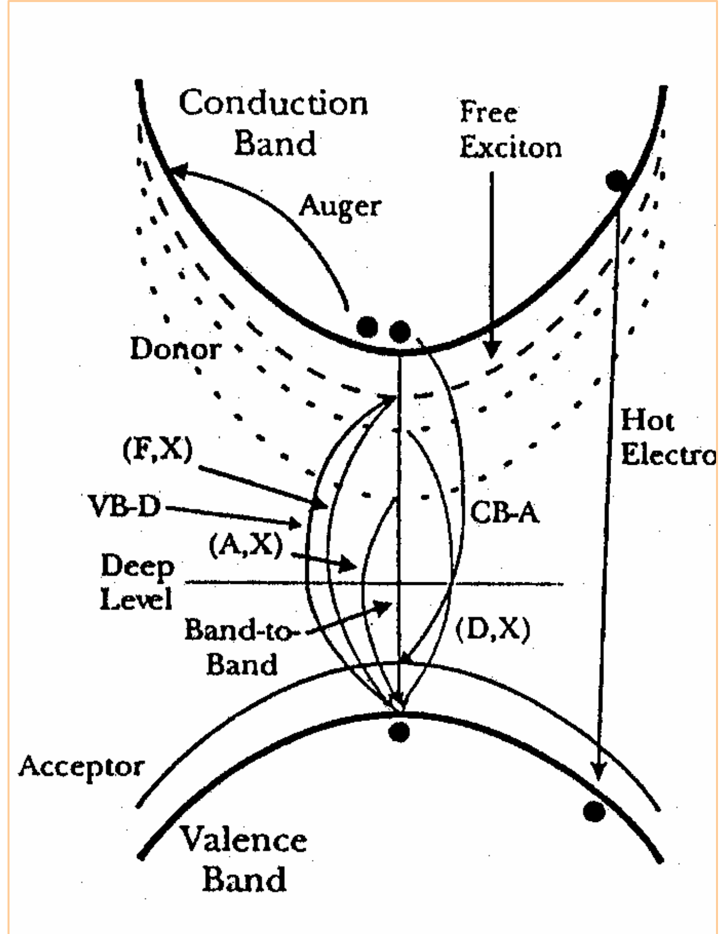
►**Extristic:>>>> with impurity**

► shallow level

► deep level

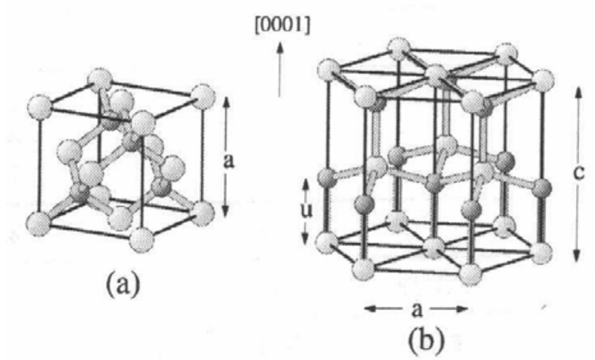


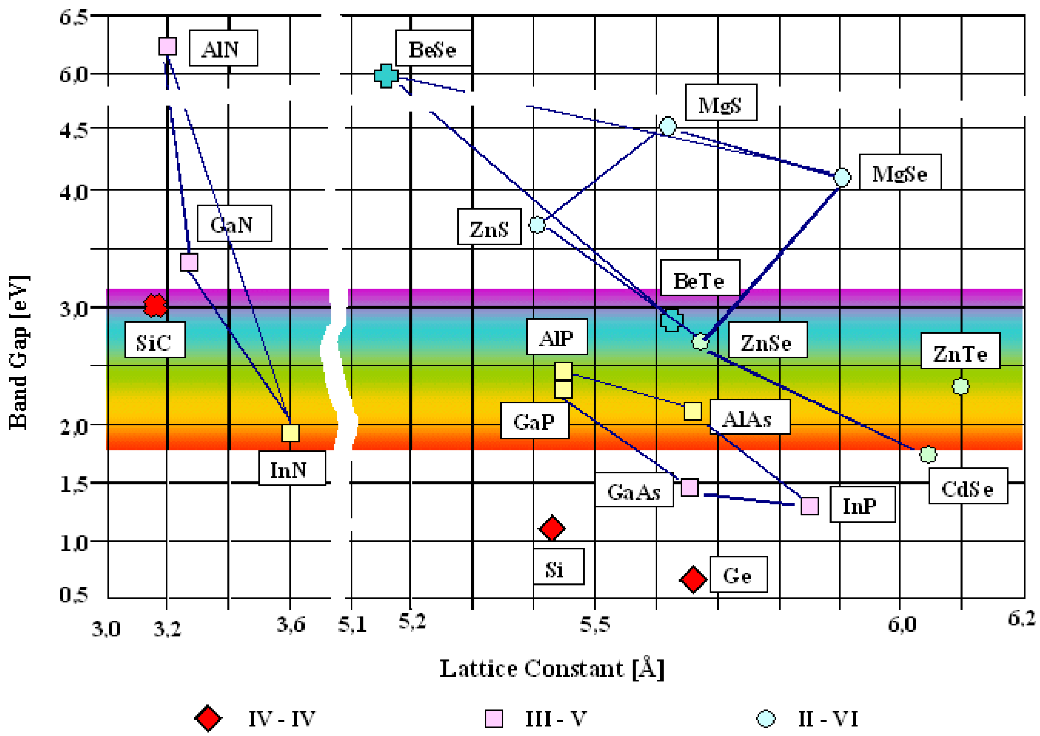
Intra Band Inter Band



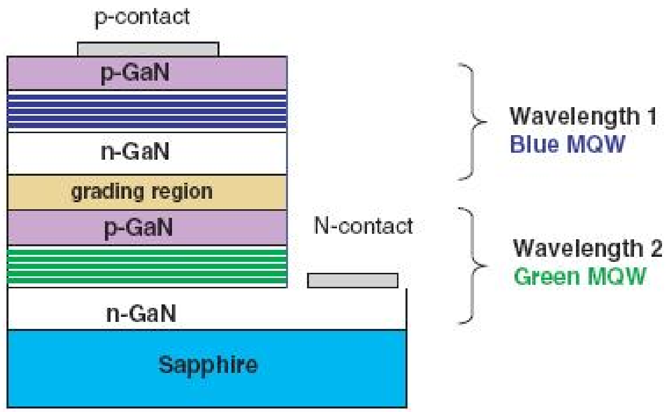
III-Nitrides Semiconductors

- (a) Cubic zincblende structure
- (b) Hexagonal wurtzite structure
- Wurtzite is thermodynamically stable for bulk AlN, GaN and InN.





- E_g(GaN)=3.43 eV (*Bo Monemar* 1974)
- E_g(AlN)=6.20 eV (*P. B. Perry et al.* 1978)
- E_g(InN)=0.7-0.8 eV (*J. Wu et al.* 2002)


p-contact
p-GaN
n-GaN
grading region
p-GaN
N-contact
n-GaN
Sapphire
Wavelength 1
Blue MQW
Wavelength 2
Green MQW

Polarization Fields

- Piezoelectric polarization appears in the presence of strain
  - Lattice mismatch strain
  - Thermal strain
  - Along the [0001] direction (Cmn is elastic tensor and εxx is in-plane strain)

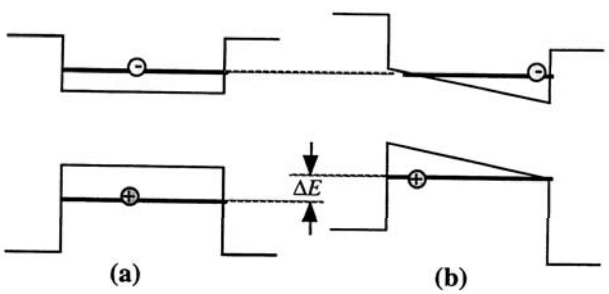
$$P_{pz} = 2\varepsilon_{xx}(e_{31} - e_{33}C_{13}/C_{33})$$

Spontaneous polarization exists in polar semiconductors with a wurtzite or lower symmetry crystal structure

⇨Fixed direction along the [0001] c-axis in the wurtzite lattice

⇨In the $Al_xIn_yGa_{1-x-y}N$ alloy systems (Vegard-like rule):

$$P_{SP}(x,y) = xP_{SP}^{AlN} + yP_{SP}^{InN} + (1-x-y)P_{SP}^{GaN}$$



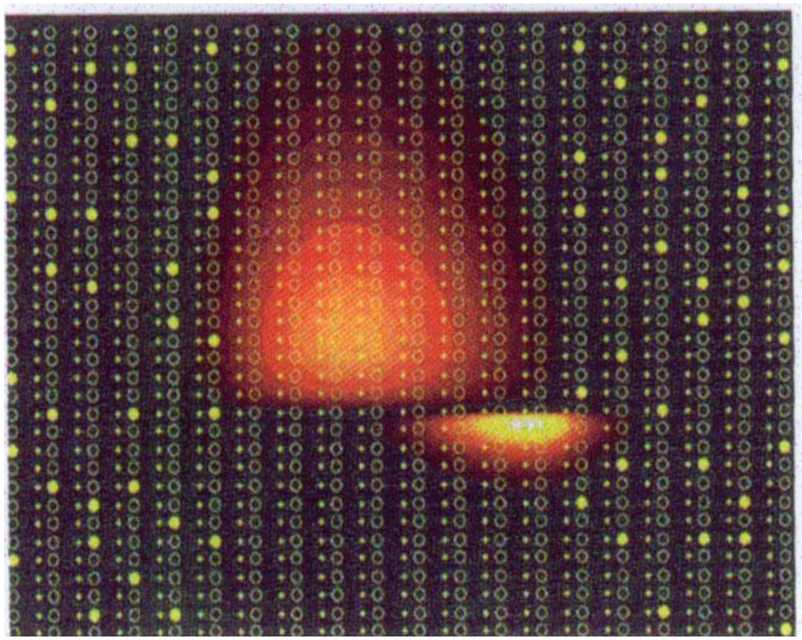
❖The energy bands are tilted and carriers are localized at the opposite interfaces

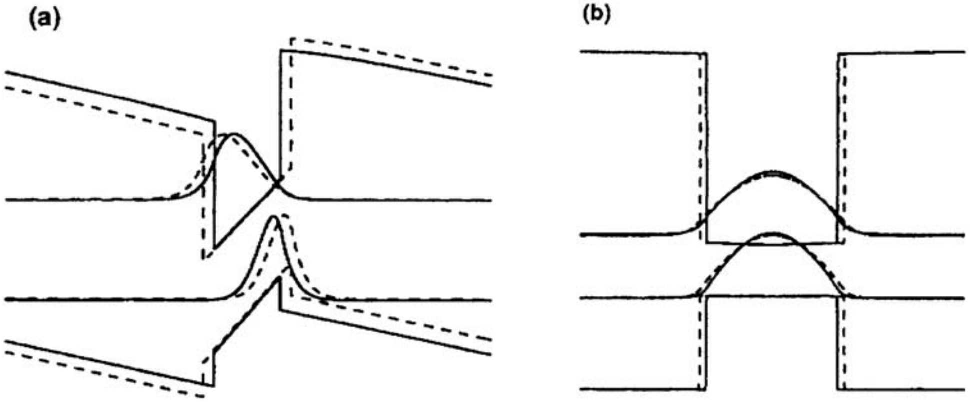
❖ The reduction ΔE of the recombination energy (QCSE)

Effect of the Polarization Fields on Carrier Localization

- The in-plane extension of the hole wave function is smaller than the average Al-Al distance in barriers.

- Moreover, both electron and hole envelope functions are pushed apart from each other by the electric field.



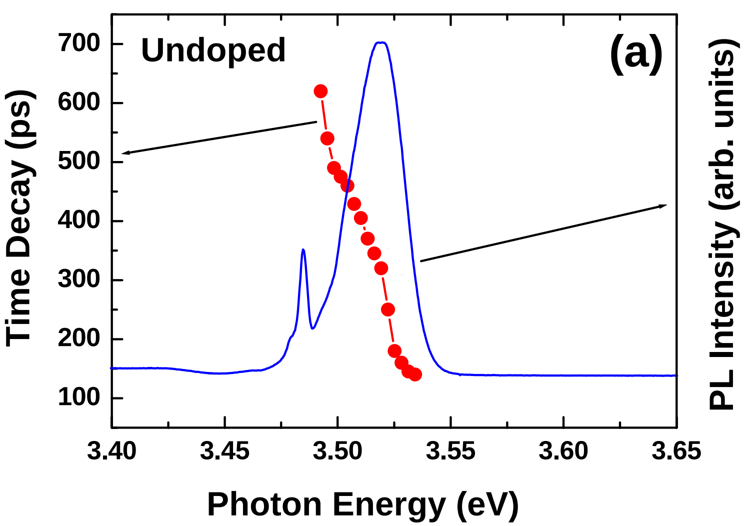


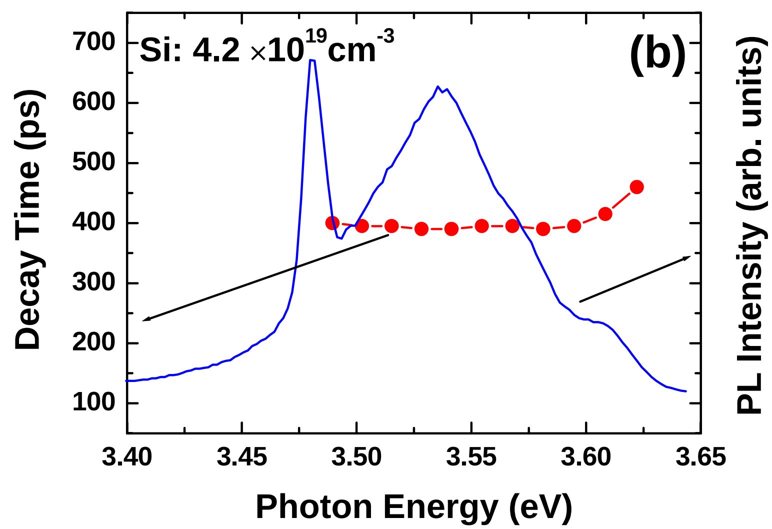
M.Gallart *et. al.*
Physica. Status Solidi A **180**, 127 (2000)

Confirmation of the Localization Effect by the Transient PL

❖ Above the Mott density, a decrease of the decay time should be expected, but an almost similar decay time was measured for all samples.

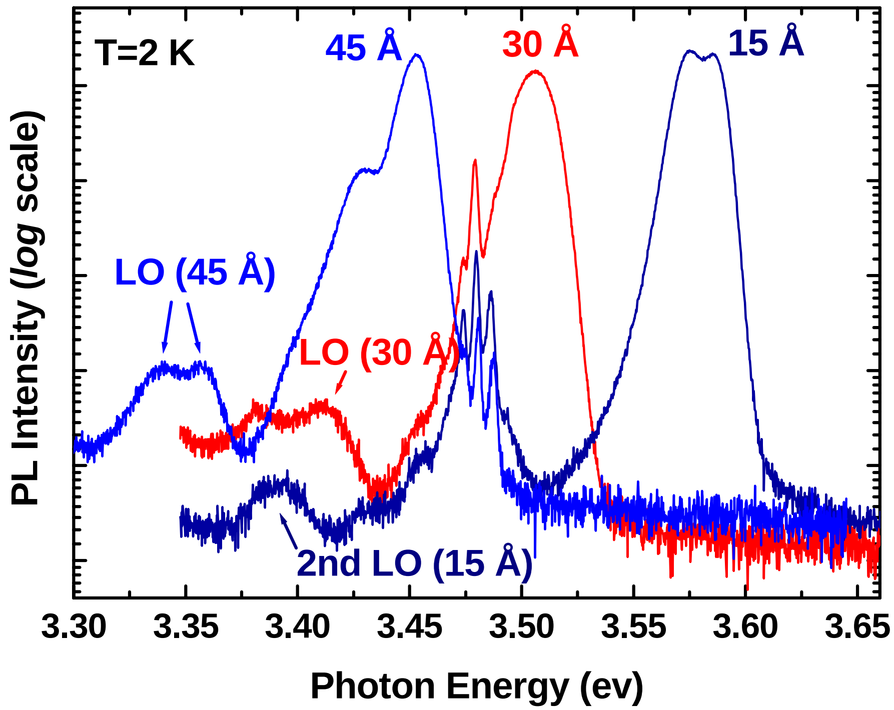
❖ In the heavily Si-doped samples: free electrons-to-localized holes and an almost constant decay time over the PL spectrum is evidence for the dominant role played by the localized holes.





MQW samples with Different Well Width

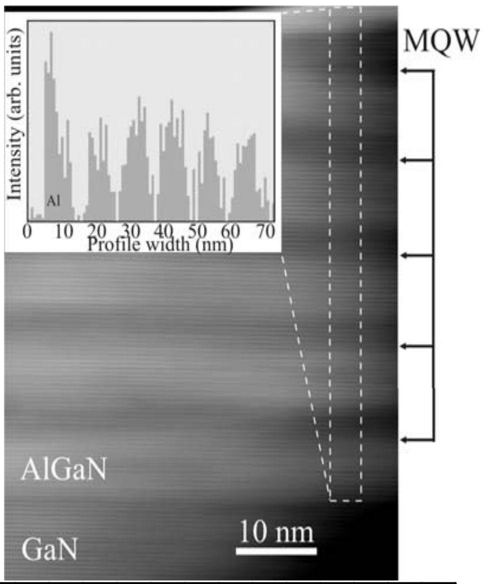
- ❖ Residual doping ~ 10^{16} cm^{-3}
- ❖15 Å → splitting 10 meV → FWHM ~ 15 meV
- ❖ 30 Å → FWHM ~ 25 meV
- ❖ 45 Å → splitting 25 meV →FWHM ~ 20 meV

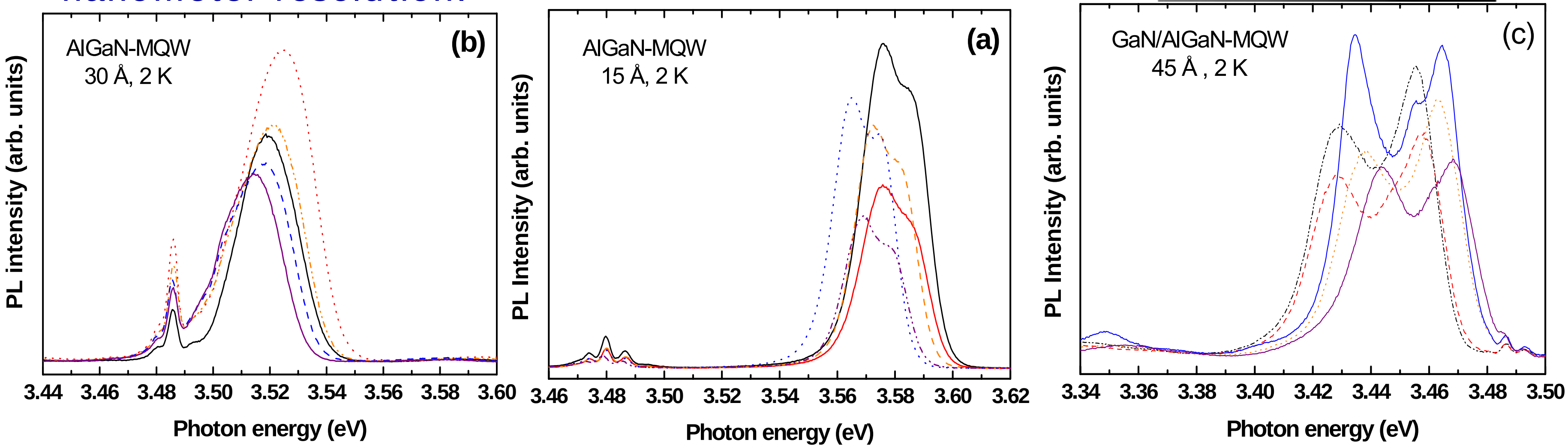


- ❖ Well width fluctuation by 2 ML.
- ❖ The main broadening mechanism is the well width fluctuation.
- ❖ The hole localization at lower interface of the QW determines the radiative process at low temperature in terms of spectral shape, line width.

PL Mapping

- A cross-section TEM image of the undoped 4.5 nm wide well sample.
- Energy-filtered TEM (EFTEM) to produce chemical distribution profiles, using inelastically scattered electrons with energy-losses characteristic of the specific Ga and Al elemental species.
- The EELS study was used to investigate the variation in the Al concentration between the wells with a near nanometer resolution.





III-V-N Structures

Diluted N-containing III-V ternary or quaternary semiconductor alloys

Ternary ⇒
- GaNAs
- InAsN
- InPN
- GaPN

Quaternary ⇒
- InGaNP
- InGaNAs

✓ ***Ultradilute*** *Nitrogen Concentration:*

$0.01 < x < 0.1$ %

✓ ***Intermediate*** *Nitrogen Concentration:*

$0.1 < x < 2$ %

✓ ***High*** *Nitrogen Concentration:*

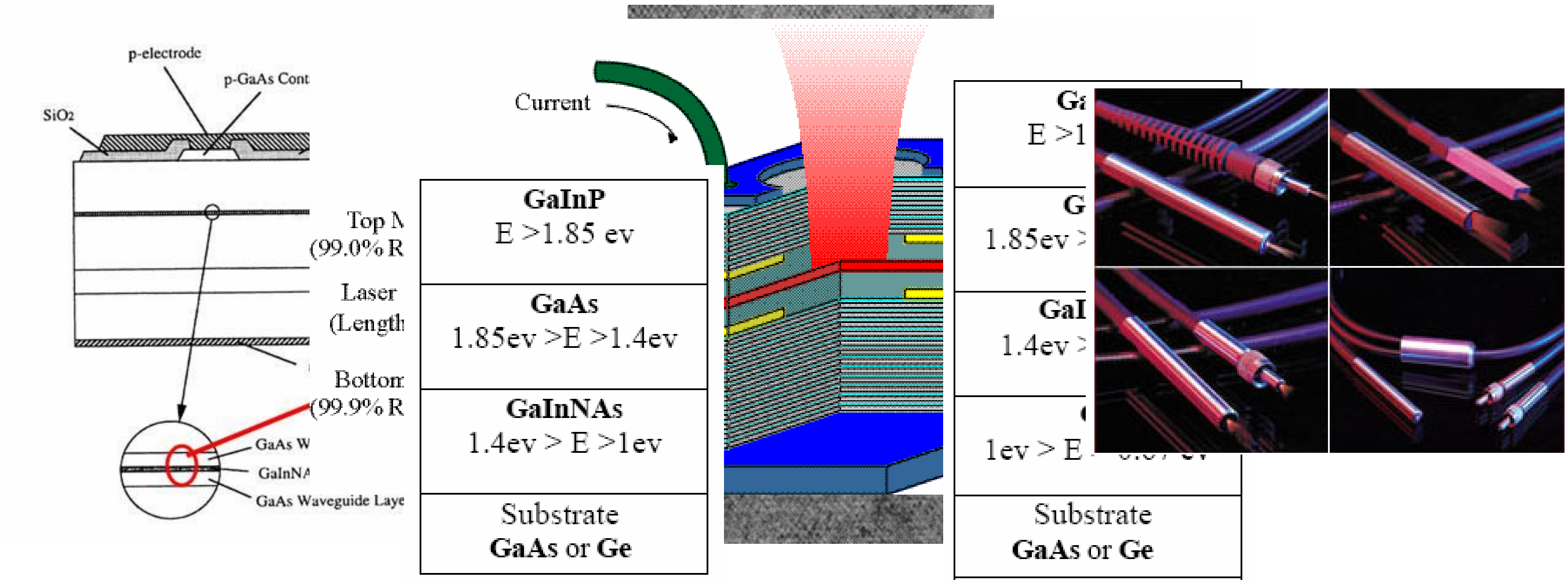
$2 < x < 5$ %

Applications

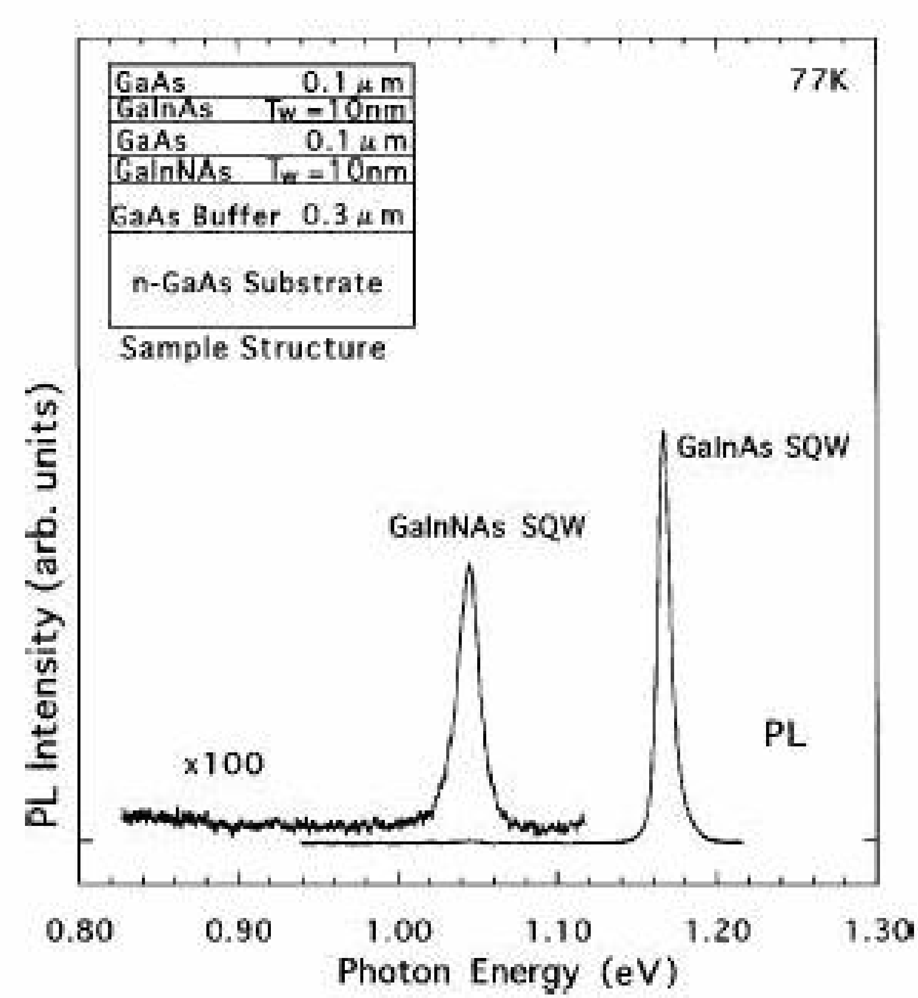
IR Diode Laser for Optical Fibers Communications

Vertical Cavity Surface Emitting Laser (VCSEL)

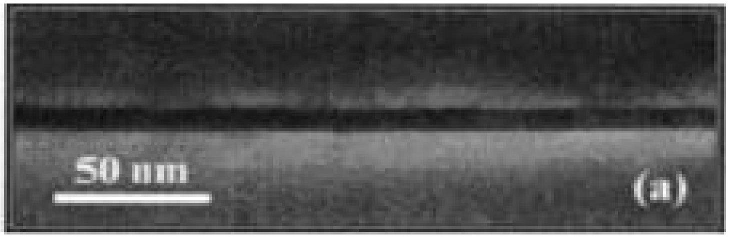
Multi-Junction Solar Cells



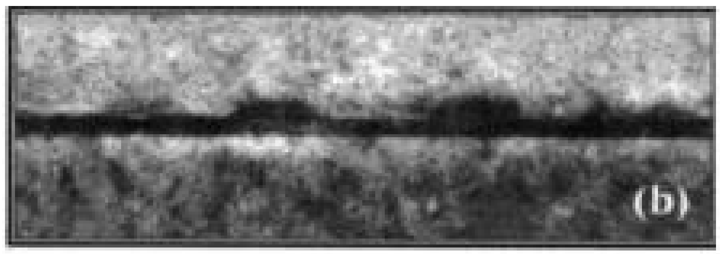
Adding N to InGaAs



- ✓Creating of fluctuations
- → localized Center
- ✓Large Band-Gap Bowing
- ✓Increasing of Effective Mass
- ✓Reduction of Band-Gap
- ✓Large Band Offset in CB



InGaAs

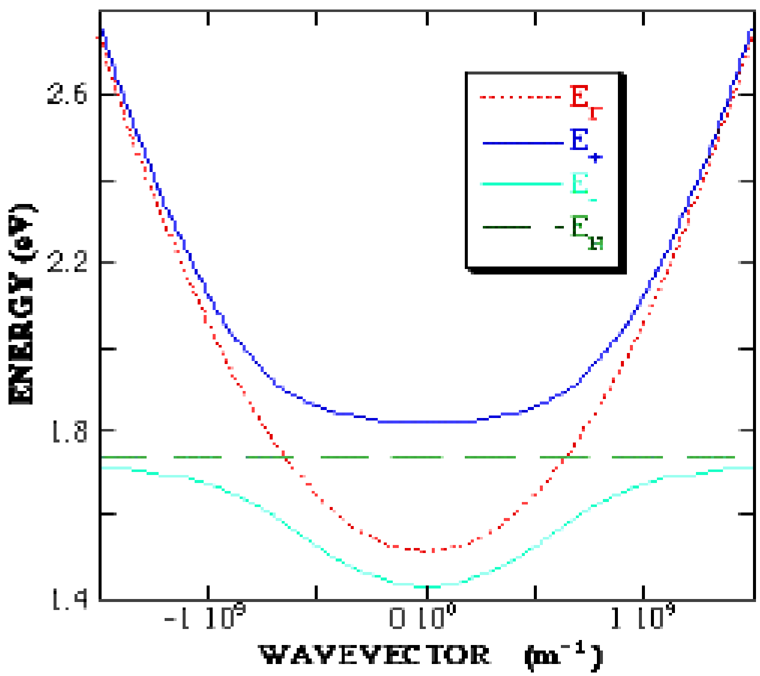


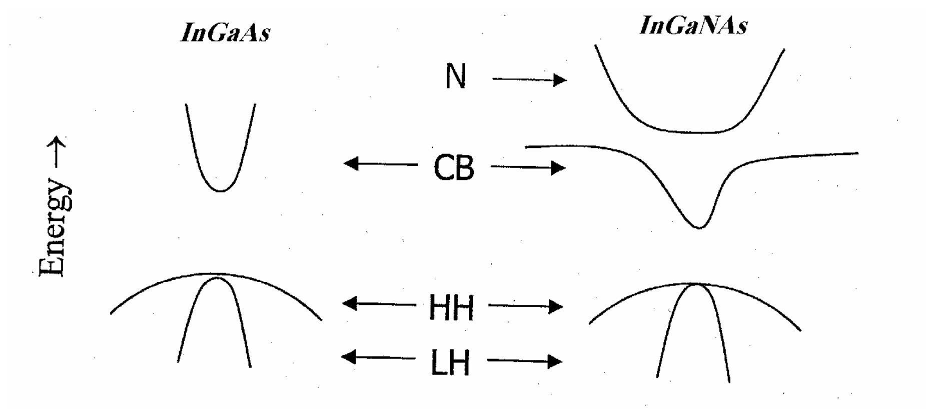
InGaNAs

Band Anticrossing model

Splitting of CB into two Subband (E_+ , E_-)

- ***Reduction of Fundamental Band-gap***

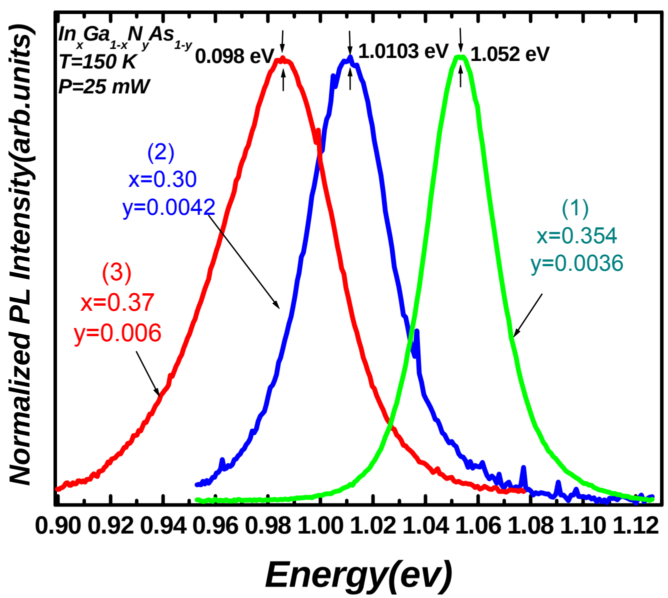


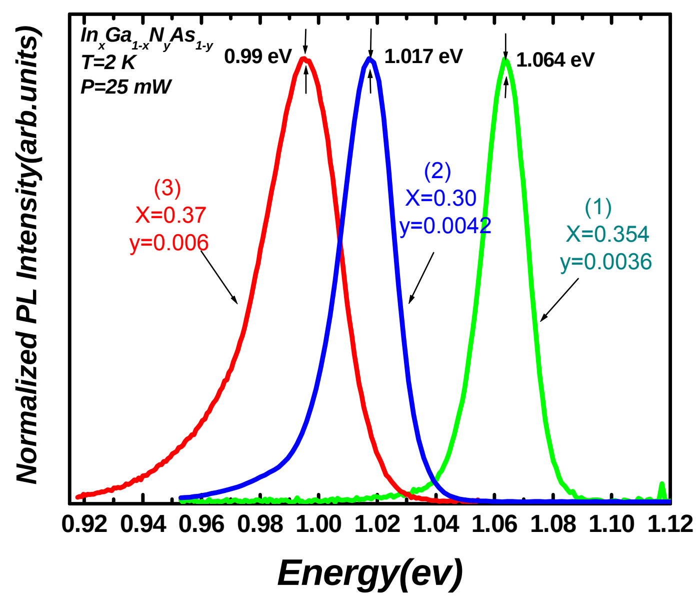


I. A. Buyanova et al, . Nitride Semiconductor. Research. (2001)

& C. Skierbiszewski et al, Appl. Phys. Lett. 76, 2409 (2000)

Effect of N on the Band Gap, FWHM and PL Intensity of $In_xGa_{1-x}N_yAs_{1-y}$ SQW



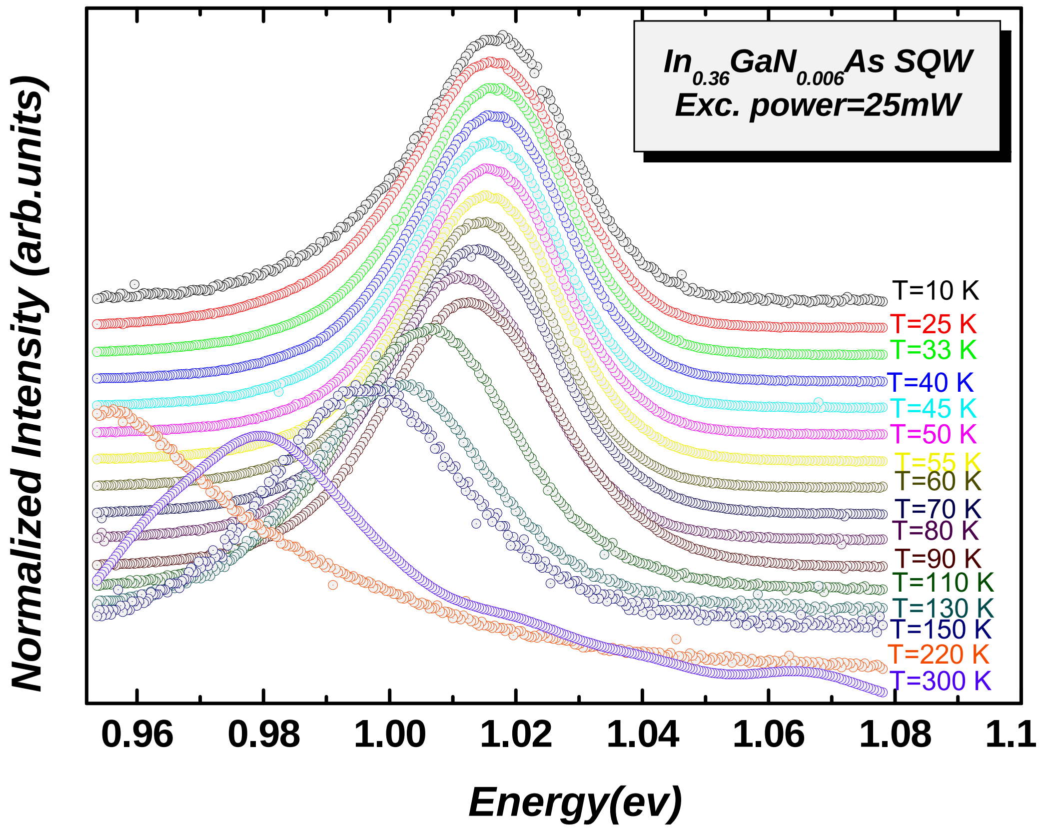


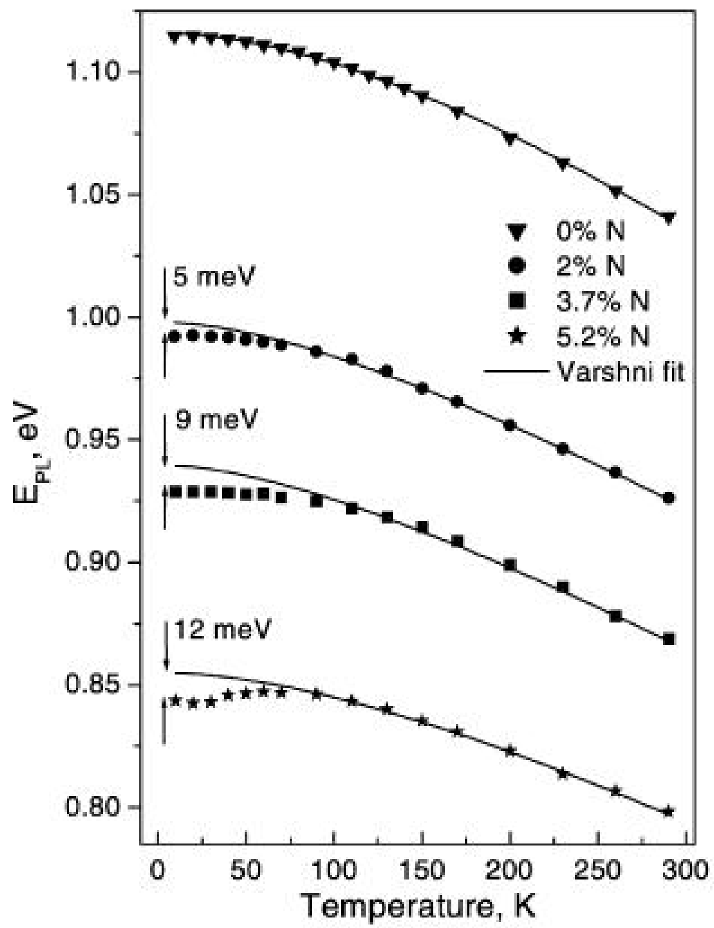
samples	1	2	3
FWHM (meV) (T=2K)	21	26	38
FWHM (meV) (T=150K)	39	48	64

240 meV decrease of band-gap per %1 N

The Role of N on the Exciton Localization

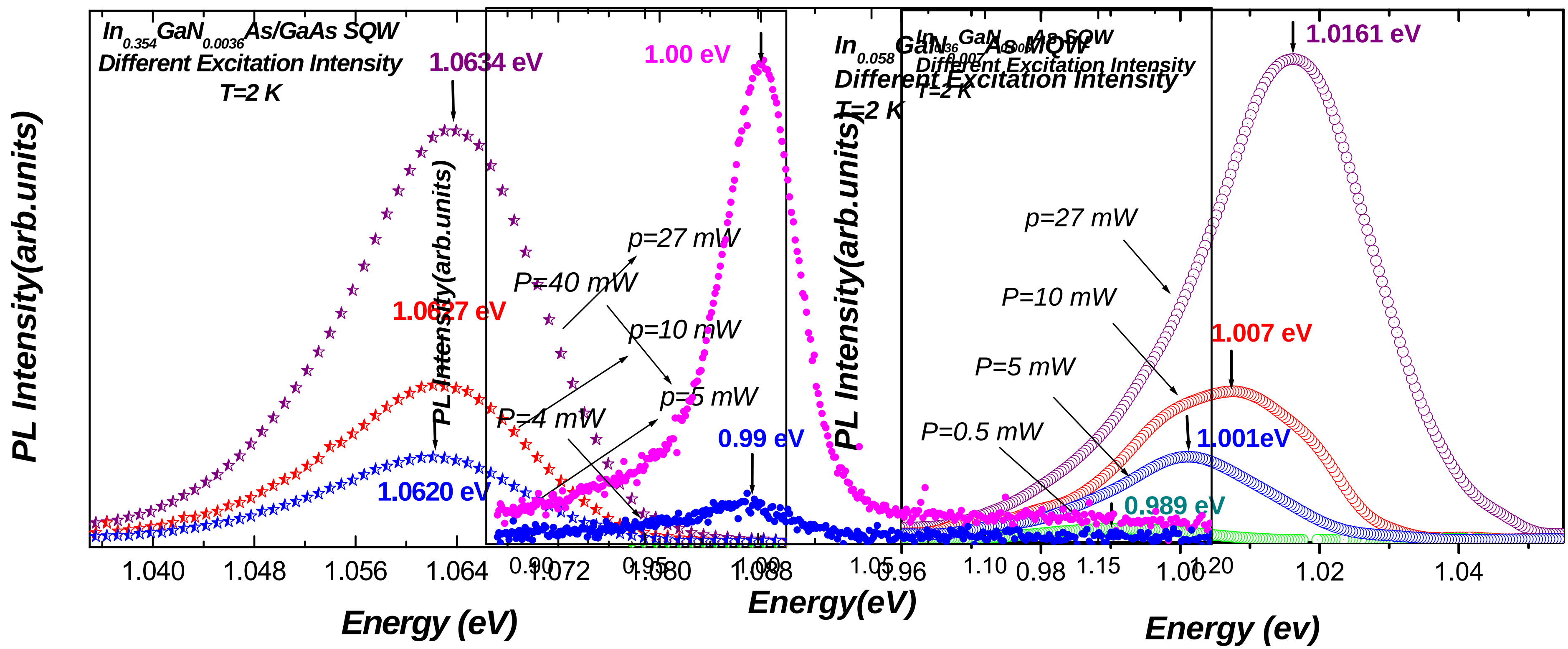
$$E(g) = E(0) - \frac{\alpha T^2}{\beta + T} \qquad \alpha = 4.5 \times 10^{-4}\ eV/K \quad \beta = 347\ K$$





The Role of N on the Exciton Localization

$In_{0.354}GaN_{0.0036}As/Ga$ $In_{0.3}GaN_{0.015}As/GaAs$ MQW $GaN_{0.006}As/GaAs$ SQW



InGaNAs

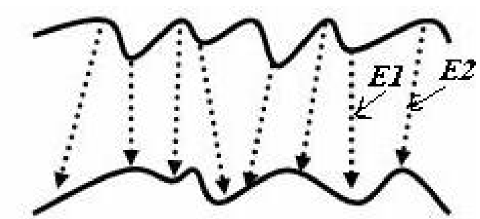
- Suitable for optoelectronic application
- Optical devices and lasers with long wavelength (1300 nm & 1550 nm)
- Quantum structures ⟹ Increase optical efficiency

Why Annealing?

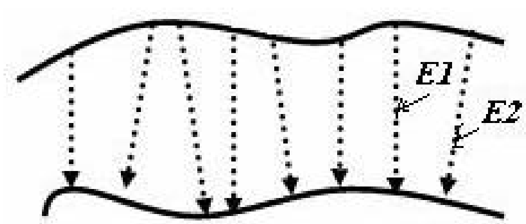
Adding N to InGaAs (less than few percent) ⟹
- Advantage: Red shift the energy emission to close to the interest wavelength
- Disadvantage: Increase nonradiative centers (Decrease the Optical Efficiency) !

Low temperature growth and non-equilibrium condition ⟹ Increase defect and nonradiative centers

Thermal Annealing ⟹ Improvement the optical efficiency



⟹

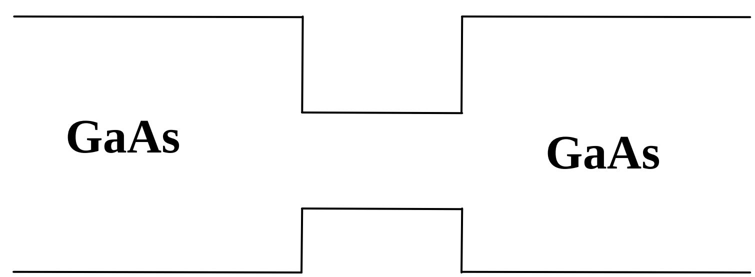


Annealing Processes

Series 1: $In_xGa_{1-x}N_yAs_{1-y}$/GaAs Single Quantum Well (SQW)

- ***Substrate:* *undoped (001) oriented GaAs***
- ***Buffer:* *300 nm undoped GaAs***
- ***Cap Layer:* *100 nm undoped GaAs***
- ***Well Thickness:* *7 nm***
- ***In Content (x) = 35.4%***
- ***N Content (y) = 0.36%***
- ***Growth Technique: HVPE***
- ***Growth Temperature: 495 c***
- ***Annealing Temperature: 900 c***
- ***Annealing Time: 0, 5, 15 and 30 seconds***

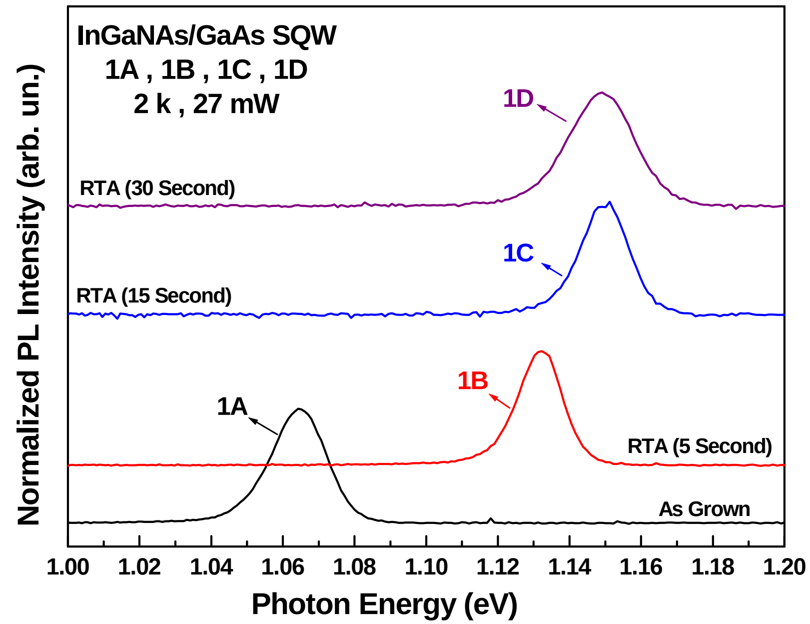
Sample	RTA Time
1A	None
1B	5 s
1C	15 s
1D	30 s

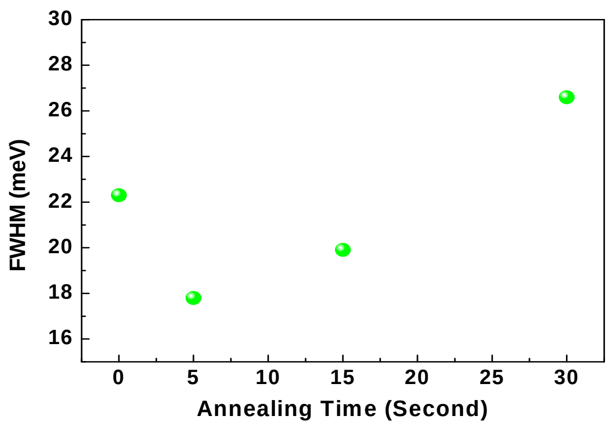


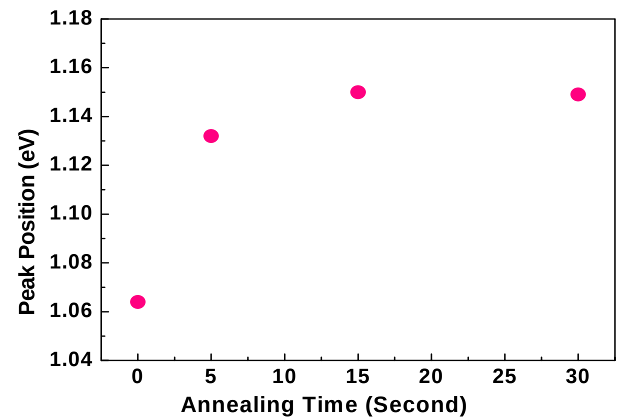
Annealing Processes

1A , 1B , 1C and 1D

Sample	RTA Time
1A	None
1B	5 s
1C	15 s
1D	30 s







Annealing Processes

Series 2: $In_xGa_{1-x}N_yAs_{1-y}$/GaAs Single Quantum Well (SQW)

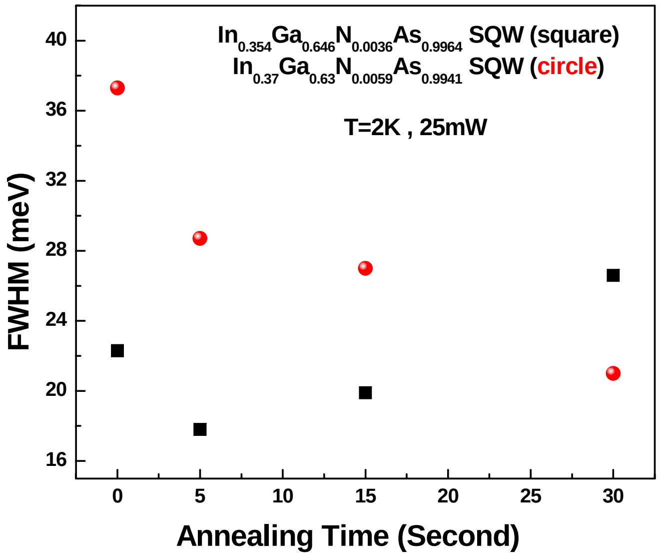
- ***Substrate:** undoped (001)Oriented GaAs*
- ***Buffer:** 300 nm undoped GaAs*
- ***Cap Layer:** 100 nm undoped GaAs*
- ***Well Thickness:** 7.2 nm*
- ***In Content (x) =** 37%*
- ***N Content (y) =** 0.59%*
- ***Growth Technique:** HVPE*
- ***Growth Temperature:** 495 c*
- ***Annealing Temperature:** 900 c*
- ***Annealing Time:** 0, 5, 15 and 30 seconds*

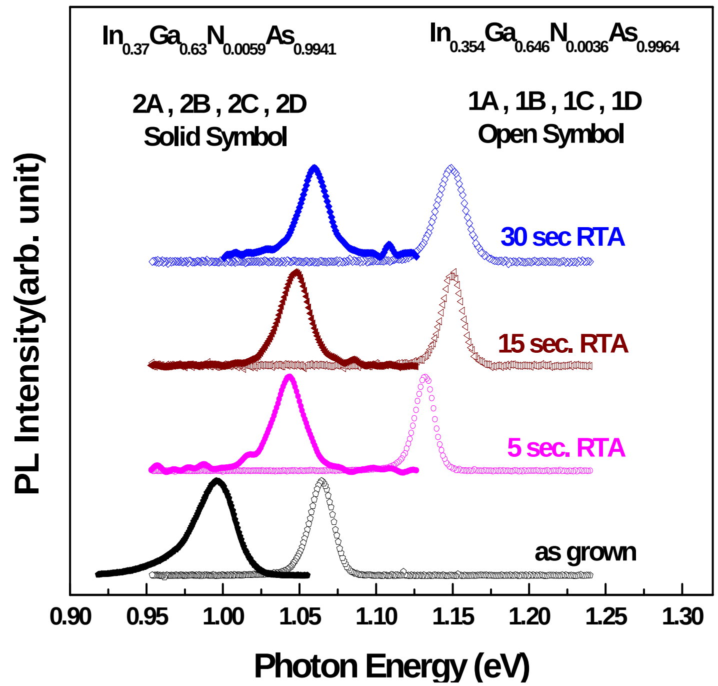
Sample	RTA Time
2A	None
2B	5 s
2C	15 s
2D	30 s

Annealing Time vs. N content

1A , 1B , 1C , 1D and

2A , 2B , 2C , 2D

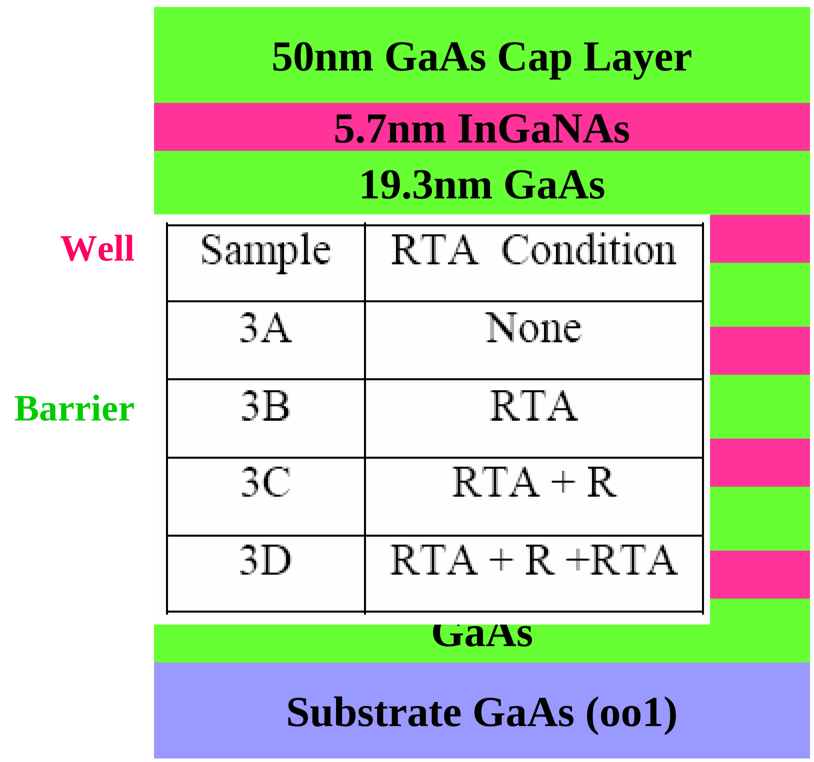




Sample	1A	1B	1C	1D	2A	2B	2C	2D
Peak position(eV)	1.064	1.122	1.151	1.149	0.995	1.043	1.047	1.059
FWHM (meV)	22	17	20	21	37	28	27	21
Normalized PL Integrated Intensity	1	0.6	0.34	0.56	1	0.5	0.03	0.02

Series 3: $In_xGa_{1-x}N_yAs_{1-y}$/GaAs Multi Quantum Well (MQW)

- ***Substrate:** undoped (001)Oriented GaAs*
- ***Buffer:** GaAs*
- ***Cap Layer:** 50 nm undoped GaAs*
- ***Well Thickness:** 5.7 nm*
- ***Barrier Thickness:** 19.3 nm*
- ***In Content (x) =** 30%*
- ***N Content (y) =** 1.5%*
- ***Growth Technique:** MOVPE (520 c)*
- ***Thermal Annealing Processes:***
  - *Rapid Thermal Annealing (RTA) at N_2 atmosphere and 650 c for 15 seconds.*
  - *Reactor Annealing (R) at $H_2 + AsH_3$ and 650 c for 30 minuets.*

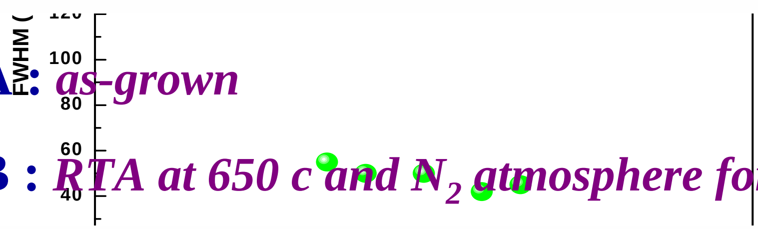


Sample	RTA Condition
3A	None
3B	RTA
3C	RTA + R
3D	RTA + R +RTA

1A , 1C , and 3A , 3B

1A : ***as-grown*** **1C :** ***RTA at 900 c for 15 s***

Sample	1A	1C
Peak Position (eV)	1.064	1.151
N. PL Intensity	1	0.3
N. PL Integrated Intensity	1	0.32
FWHM(meV)	22	20



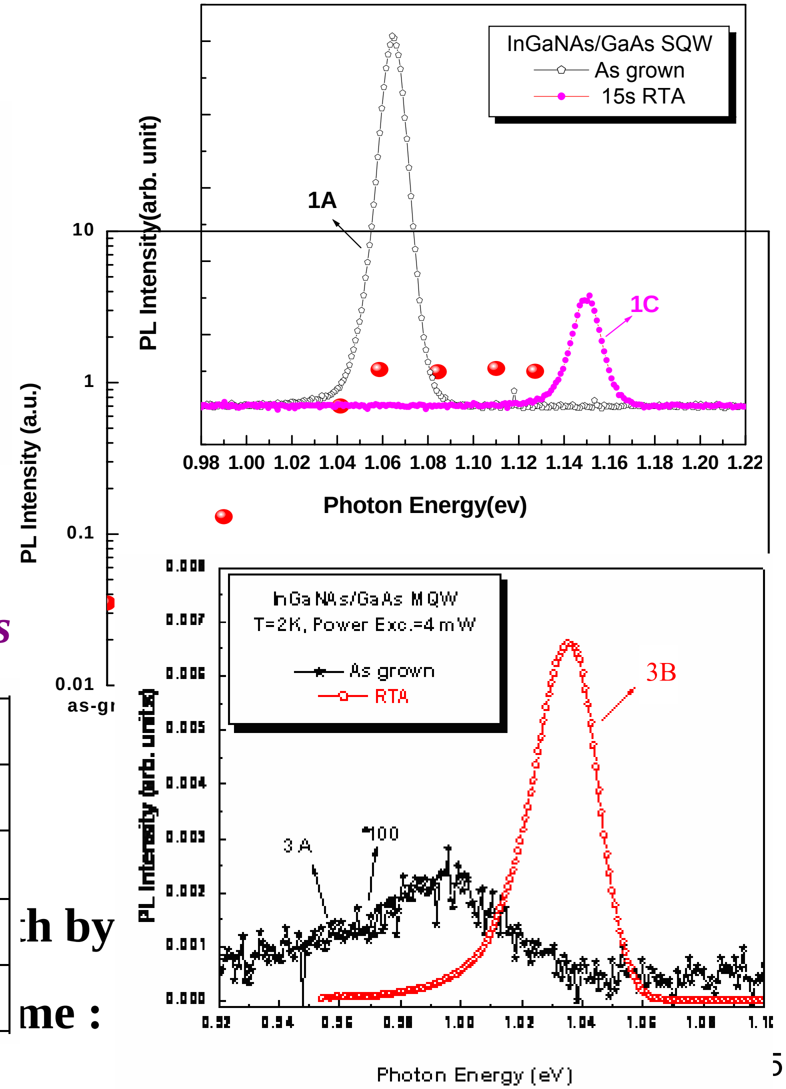
3A: ***as-grown***

3B : ***RTA at 650 c and N_2 atmosphere for 15 s***

Sample	3A	3B
Peak Position (eV)	0.995	1.034
N. PL Intensity	1	236
N. PL Integrated Intensity	1	68
FWHM(meV)	58	32

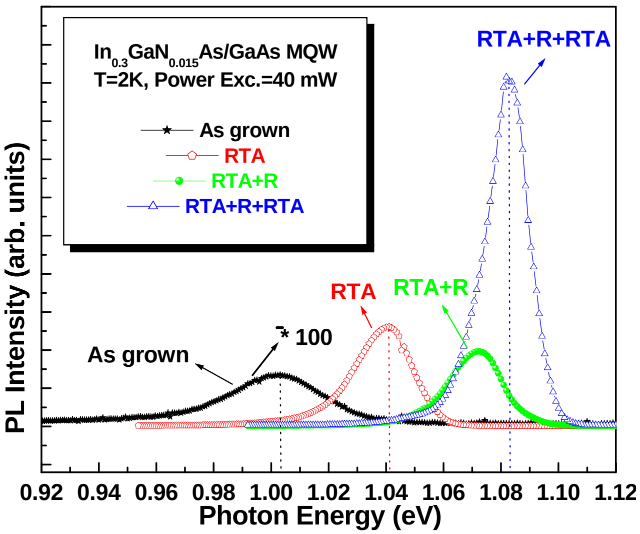
h by

me :



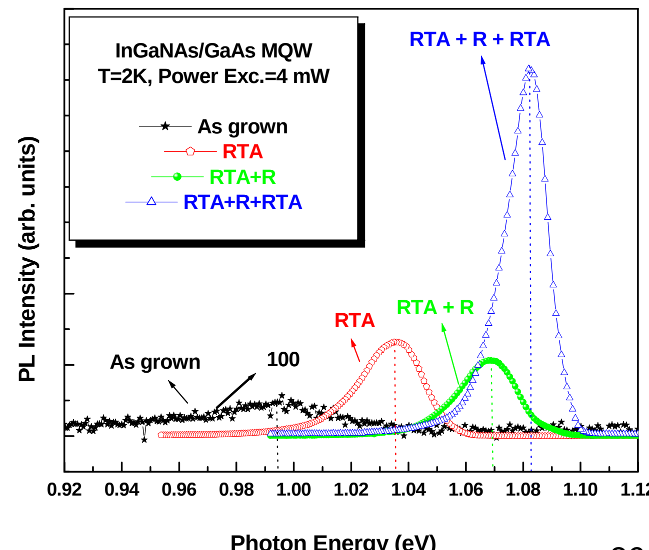
Multi Thermal Annealing Processes

3A, 3B, 3C and 3D



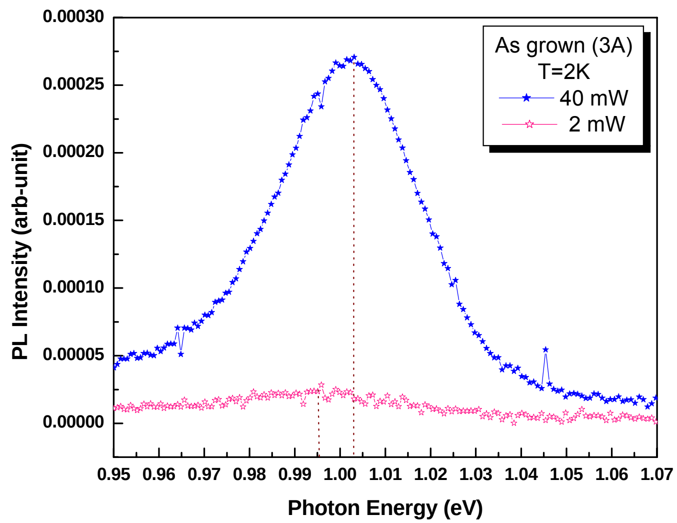
Excitation power = 40mw	3A	3B	3C	3D
N. Integrated PL Intensity	1	83	61	217
Peak position (eV)	1.003	1.041	1.072	1.0819
N. PL Intensity	1	192	145	676
FWHM (meV)	49	32	27	22

Excitation power = 4mw	3A	3B	3C	3D
N. Integrated PL Intensity	1	66	52	187
Peak position (eV)	0.995	1.035	1.068	1.0819
N. PL Intensity	1	236	189	920
FWHM (meV)	58	32	28	21

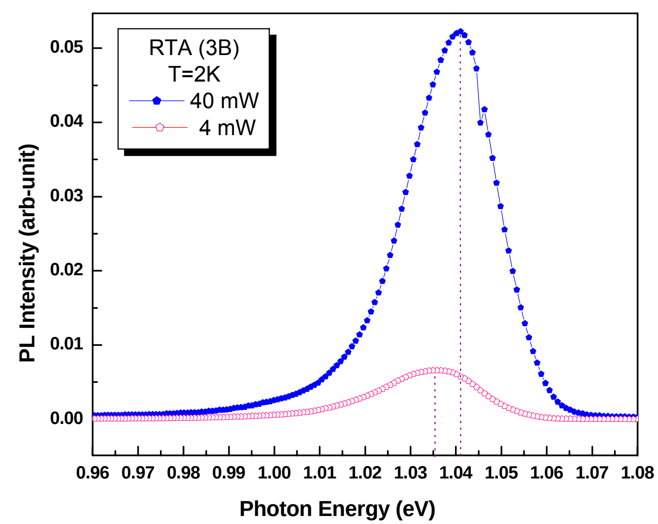


Multiple Thermal Annealing Processes

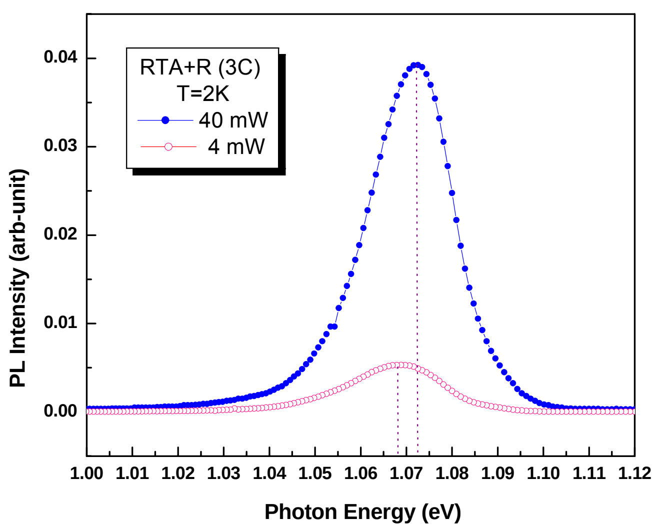
3A



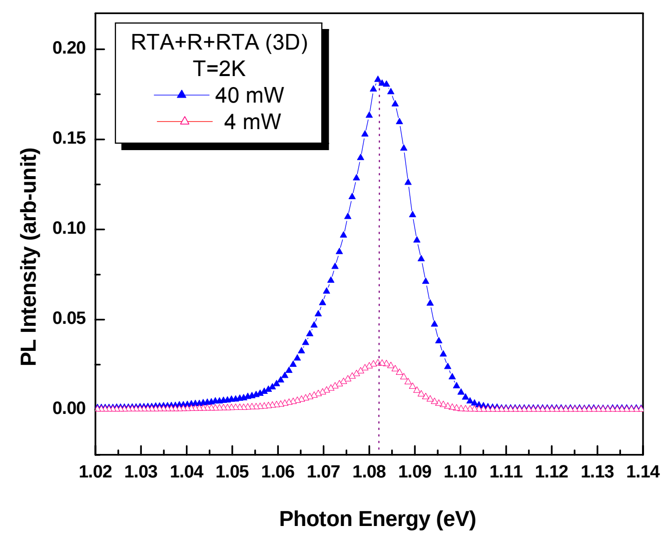
3B



3C



3D

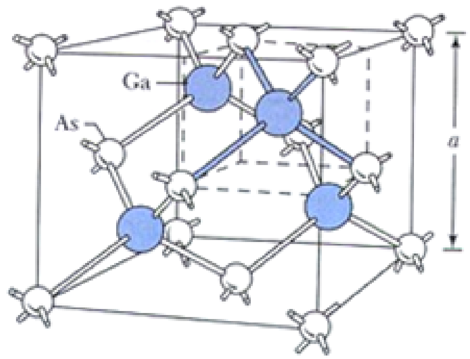


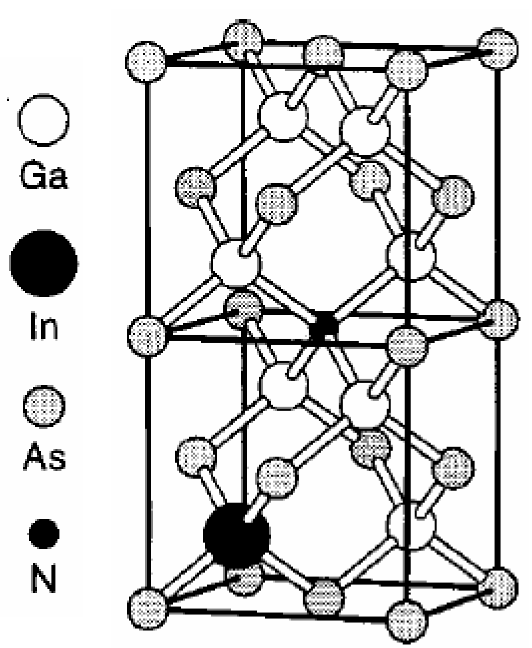
Structural Changes

Ga-As : 2.45 Å

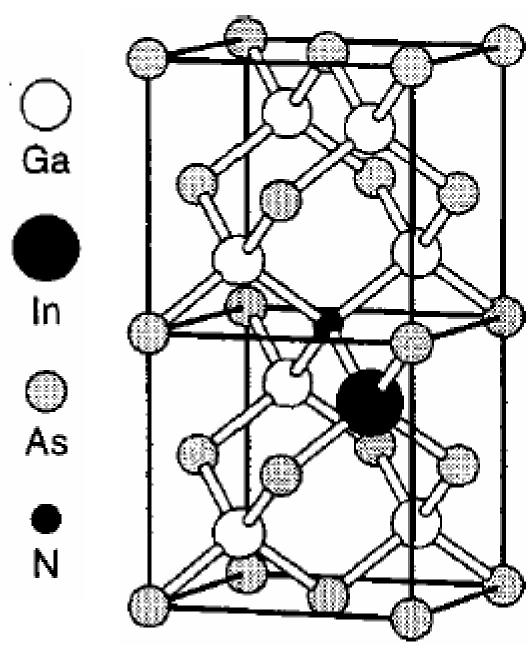
In-N : 2.14 Å

Ga-N : 1.95 Å





As grown

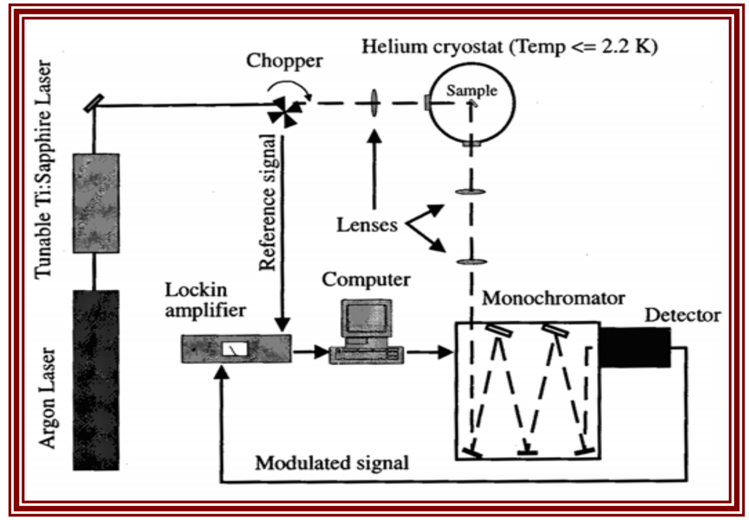


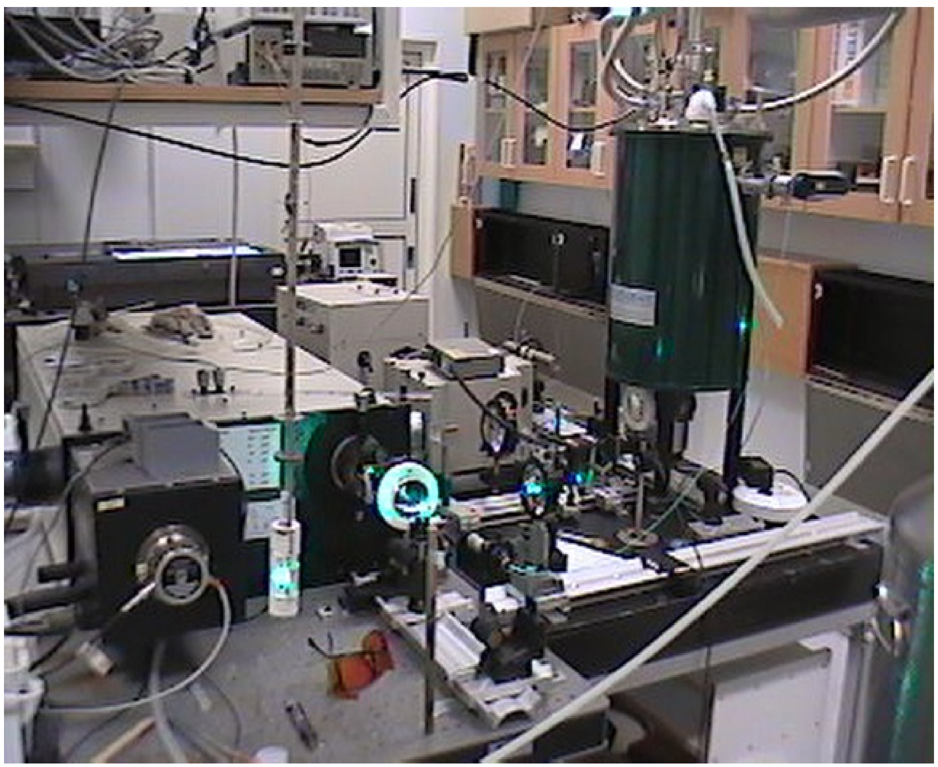
Annealed

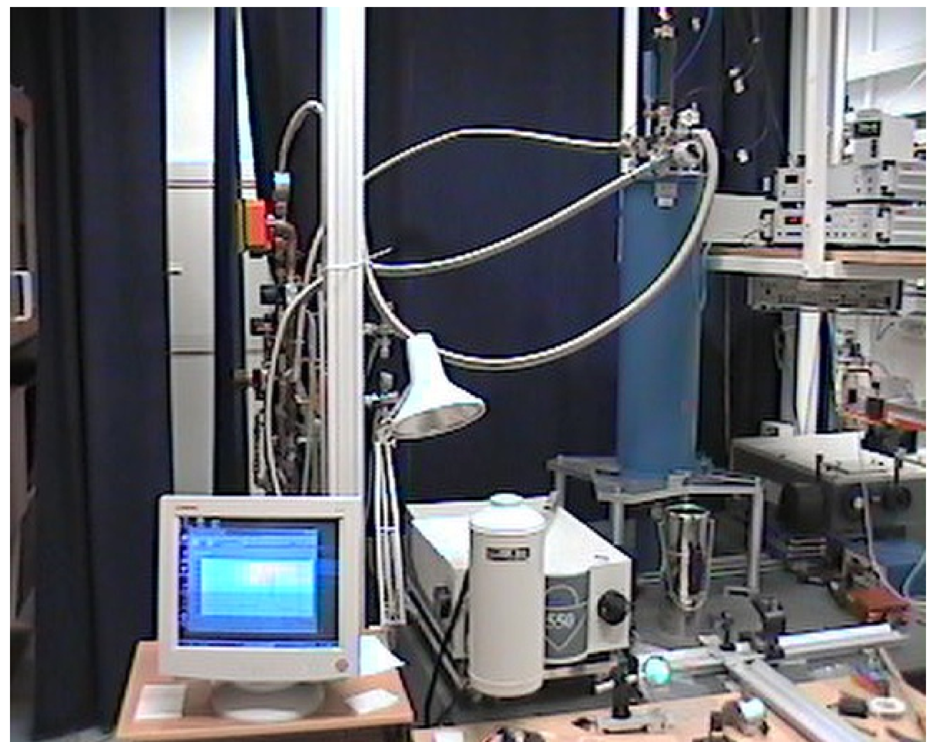
Conclusions:

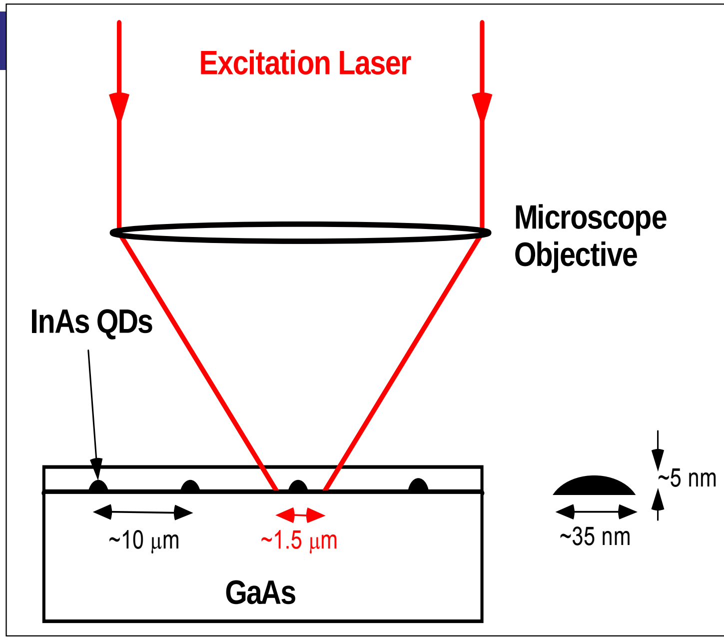
- *Adding Nitrogen to InGaAs*
  - *Reduction of band-gap (Long Wavelength (IR region)) .*
  - *Increasing Localized Center due to Potential fluctuations*
  - *Asymmetry of PL spectra*
  - *S-shape behavior of peak position of PL spectra*
  - *Decrease Optical Efficiency by Increase in non-radiative Centers.*
- *Thermal annealing.*
  - *Improvement the Optical Efficiency by Suitable Thermal annealing*
  - *Changes in N Surrounding from Ga4 -N to Ga3In-N Causes Reduction of Strain and Potential Fluctuation.*
  - *Increases Optical Efficiency*
- *Thermal annealing temperature optimum is around 600-700c*
- *To avoid escaping of nitrogen from compound during annealing, the samples should be annealed in presence of N_2 gas.*

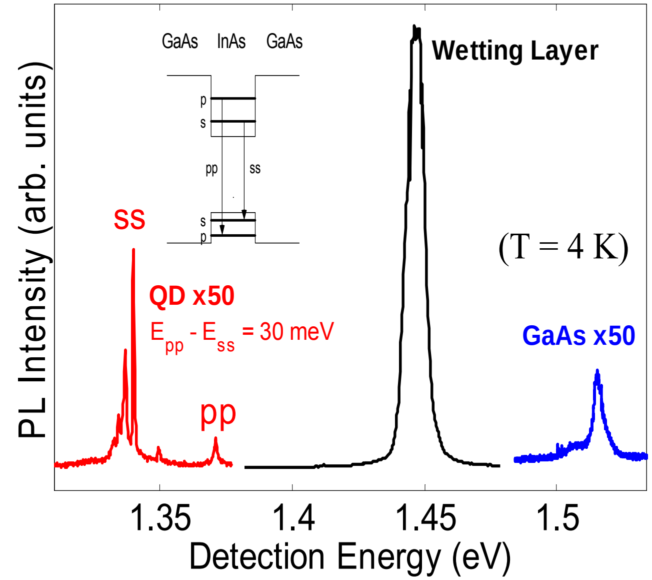
Photoluminescence (PL) Setup

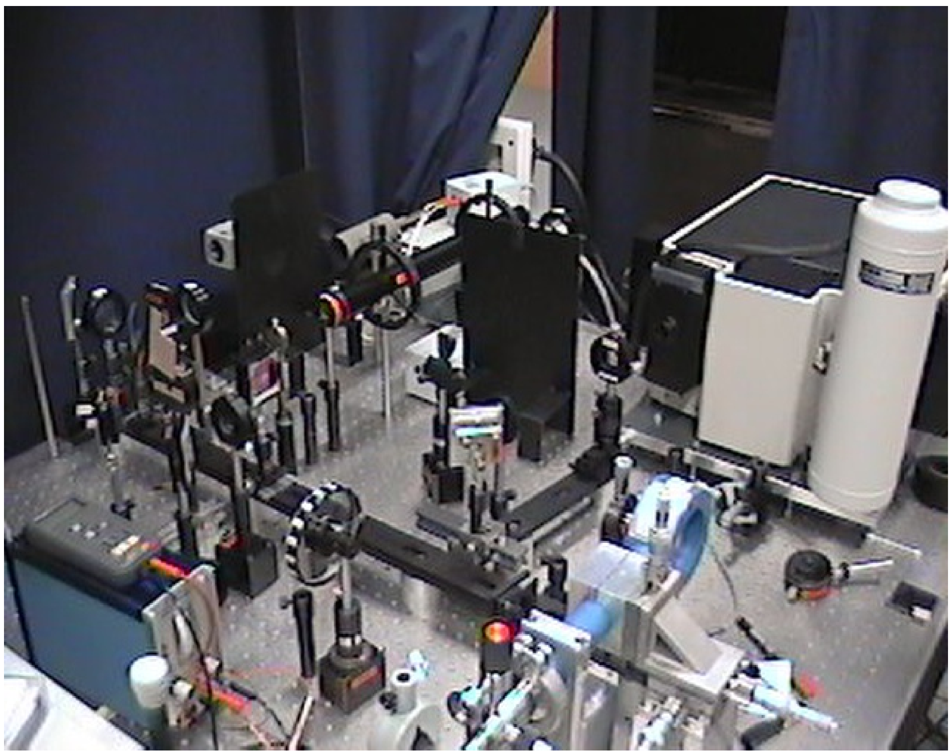


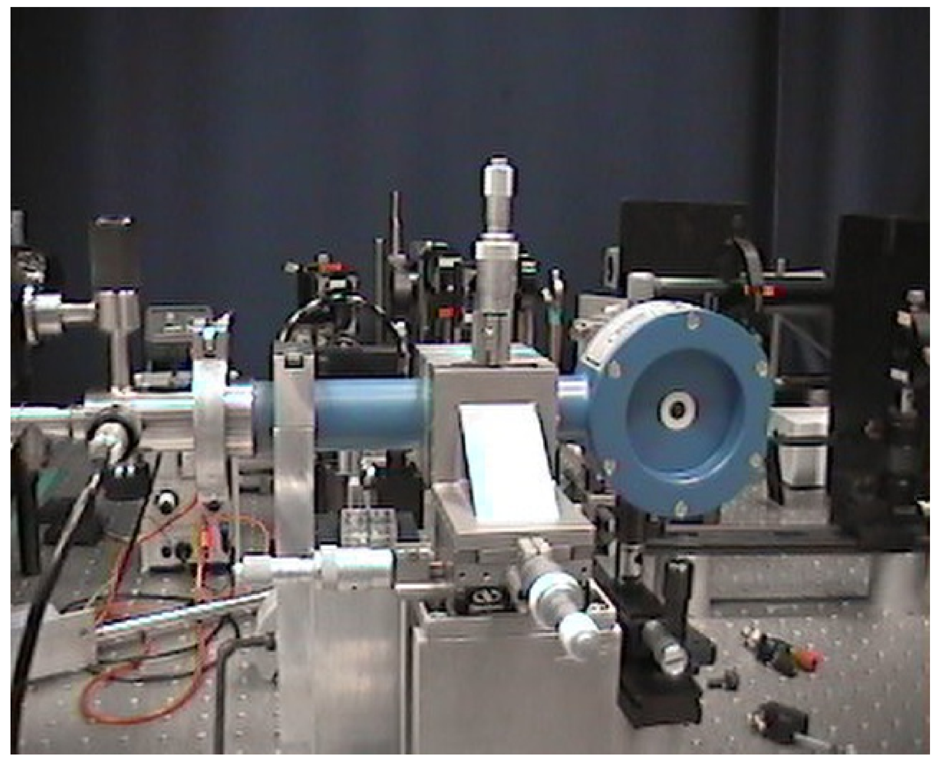




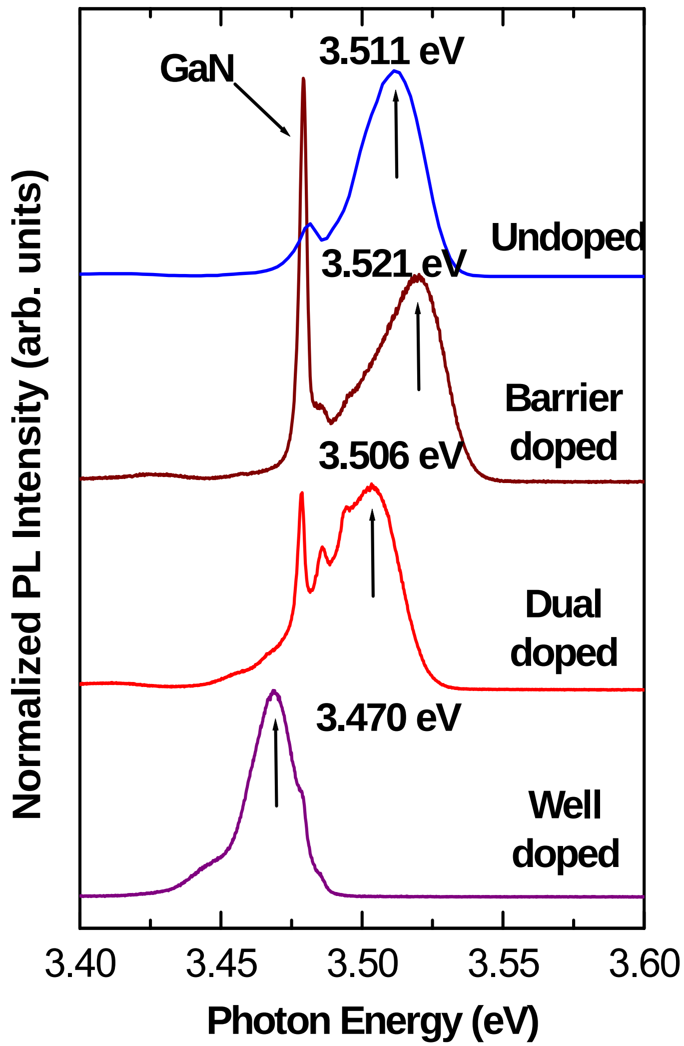

Excitation Laser
Microscope Objective
InAs QDs
~10 µm
~1.5 µm
GaAs
~5 nm
~35 nm


GaAs InAs GaAs
p
s
pp
ss
s
p
SS
QD x50
$E_{pp} - E_{ss}$ = 30 meV
pp
Wetting Layer
(T = 4 K)
GaAs x50
PL Intensity (arb. units)
1.35
1.4
1.45
1.5
Detection Energy (eV)

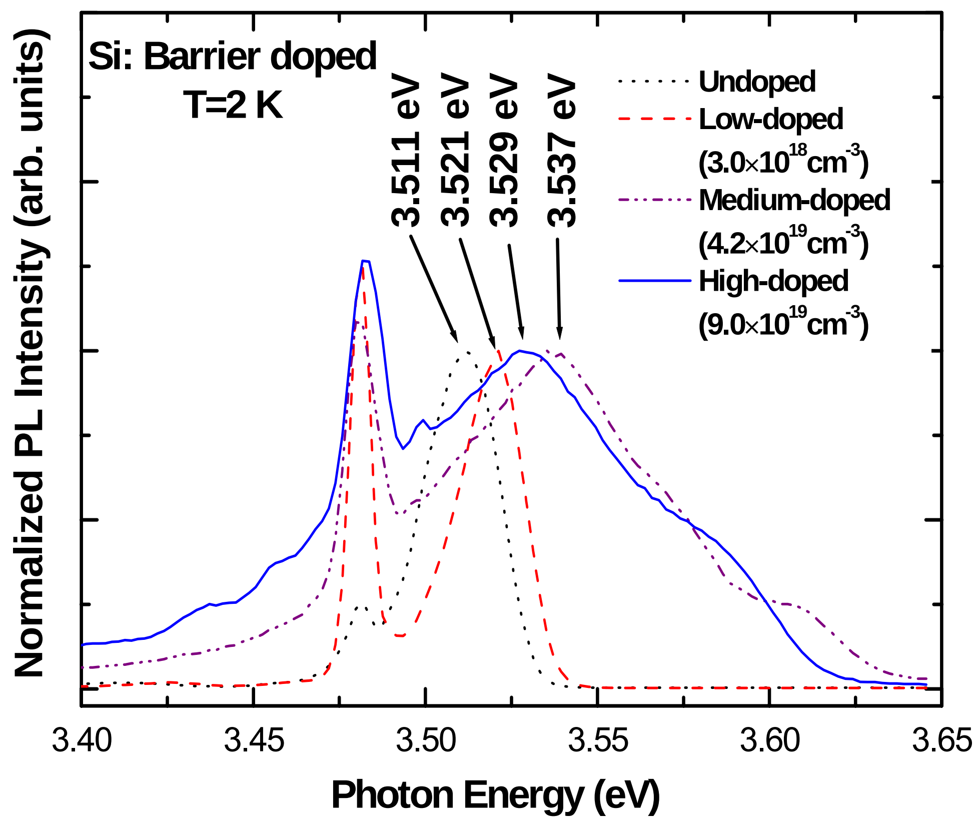




PL spectra

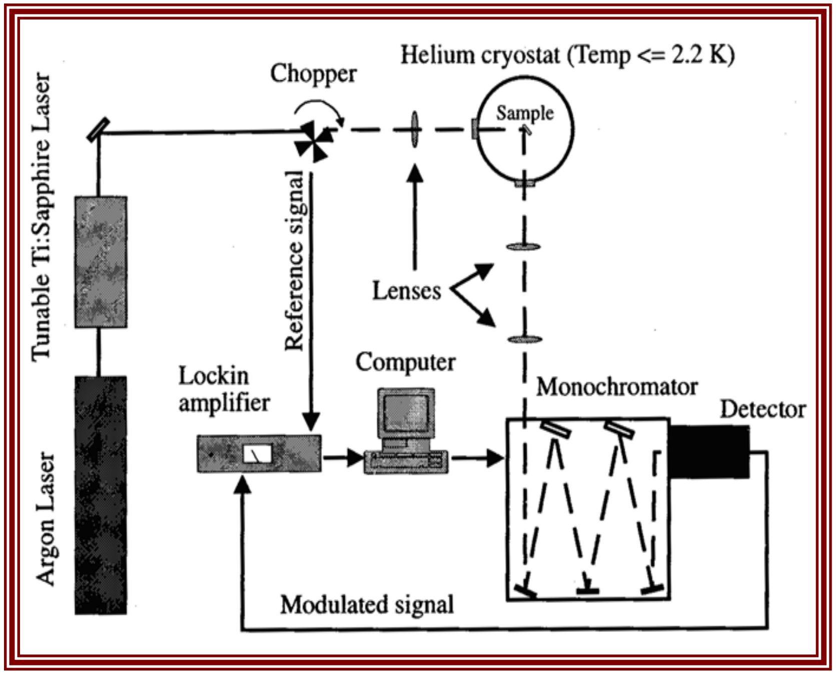


GaN
3.511 eV
Undoped
3.521 eV
Barrier
doped
3.506 eV
Dual
doped
3.470 eV
Well
doped
Normalized PL Intensity (arb. units)
3.40
3.45
3.50
3.55
3.60
Photon Energy (eV)

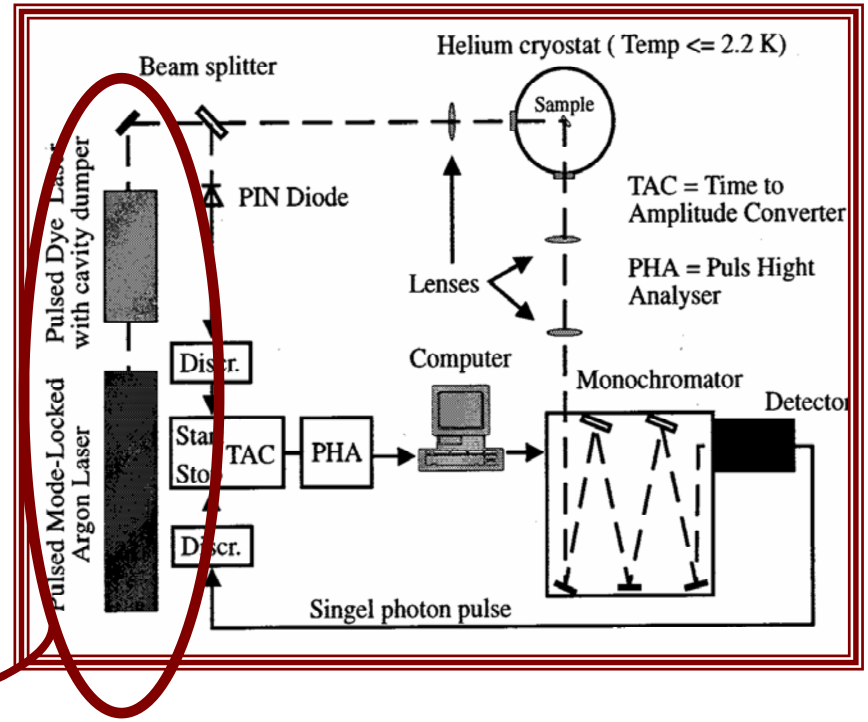


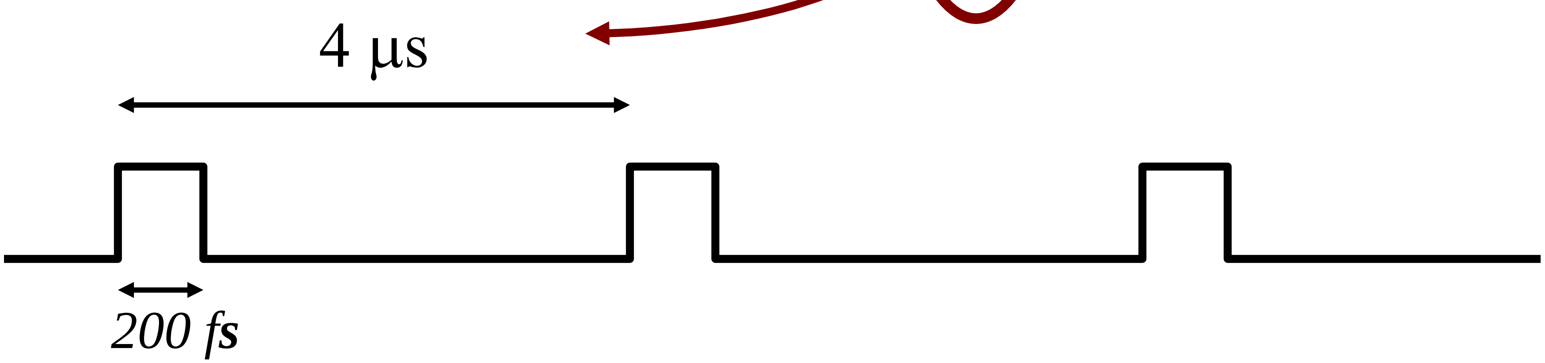
Si: Barrier doped
T=2 K
3.511 eV
3.521 eV
3.529 eV
3.537 eV
Undoped
Low-doped
(3.0×10^18 cm^-3)
Medium-doped
(4.2×10^19 cm^-3)
High-doped
(9.0×10^19 cm^-3)
Normalized PL Intensity (arb. units)
3.40
3.45
3.50
3.55
3.60
3.65
Photon Energy (eV)

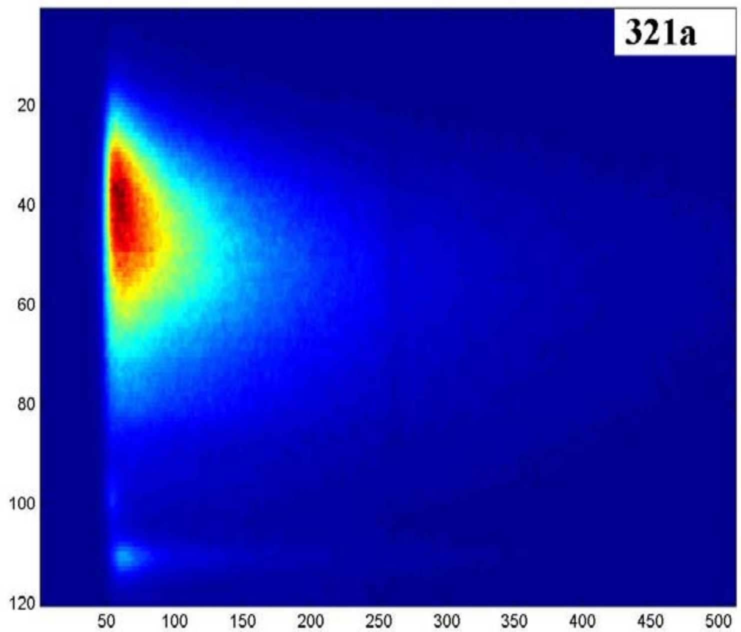
PhotoLuminescence Setup

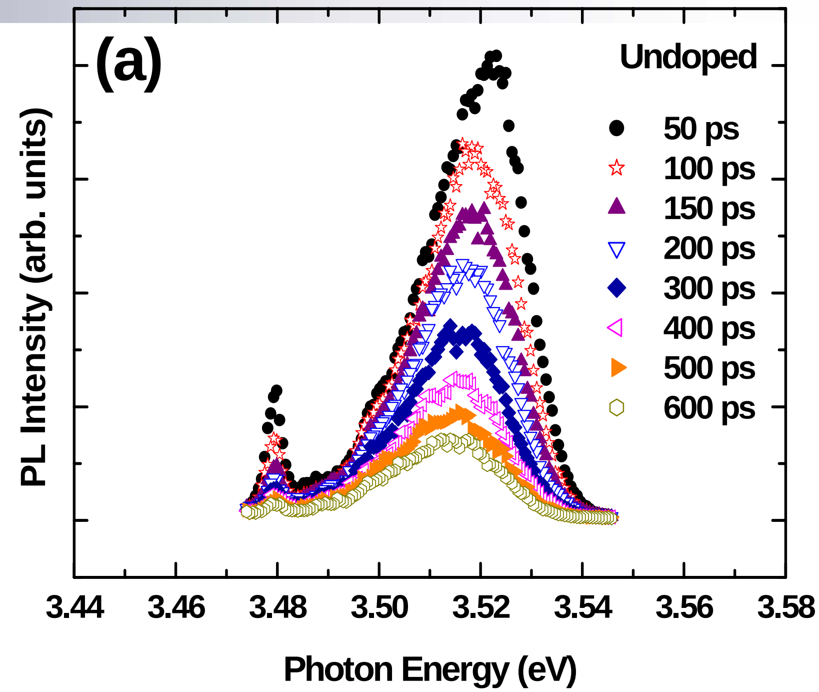


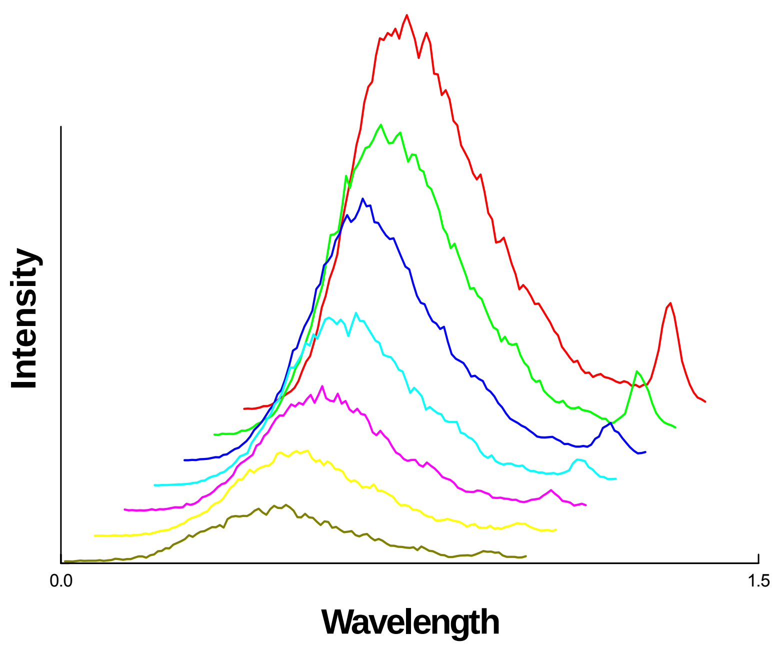
Time-Resolved PL Setup

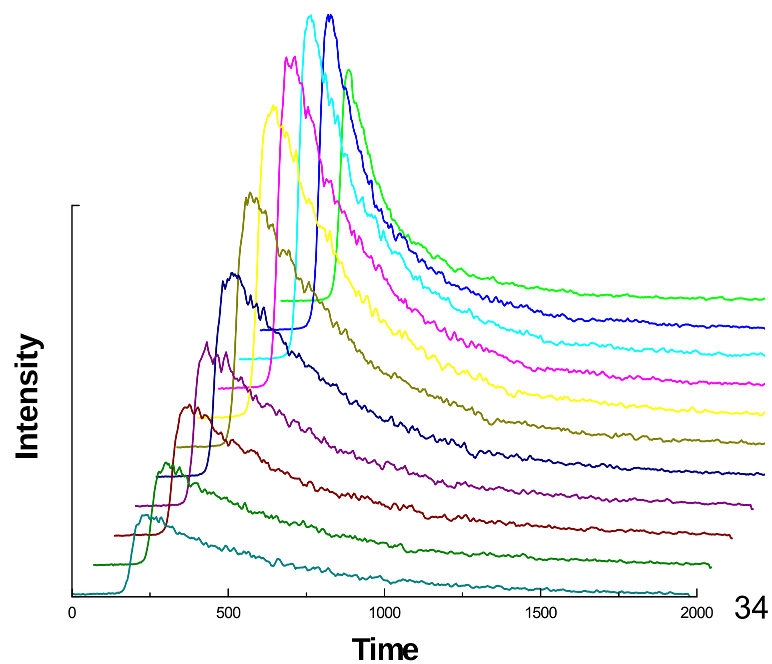





321a
20
40
60
80
100
120
50
100
150
200
250
300
350
400
450
500


(a)
Undoped
50 ps
100 ps
150 ps
200 ps
300 ps
400 ps
500 ps
600 ps
PL Intensity (arb. units)
3.44
3.46
3.48
3.50
3.52
3.54
3.56
3.58
Photon Energy (eV)


Intensity
0.0
1.5
Wavelength


Intensity
0
500
1000
1500
2000
Time