Quantum Well and Quantum Dot Intermixing for Optoelectronic Device Integration

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Overview

- Introduction
- Methods of Intermixing
- Quantum Wells
- Ion Implantation Induced Interdiffusion
  GaAs/AlGaAs, InGaAs/AlGaAs, InP/InGaAs QWs
- Lasers, Photodetectors
- Impurity Free Interdiffusion
  GaAs/AlGaAs, InGaAs/AlGaAs, InGaAsN/GaAs QWs
- Integrated Waveguide-Laser
- Quantum Dots
- Suppression of Interdiffusion
- Implantation Induced Interdiffusion
- Summary

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Photonic Integrated Circuits / Optoelectronic Integrated Circuits

- Integrated Circuits Show Superior Performance Over Discrete Devices
- Multi-functional circuits, e.g. WDM sources
- Integrated Transceivers
- Low Cost, Packaging

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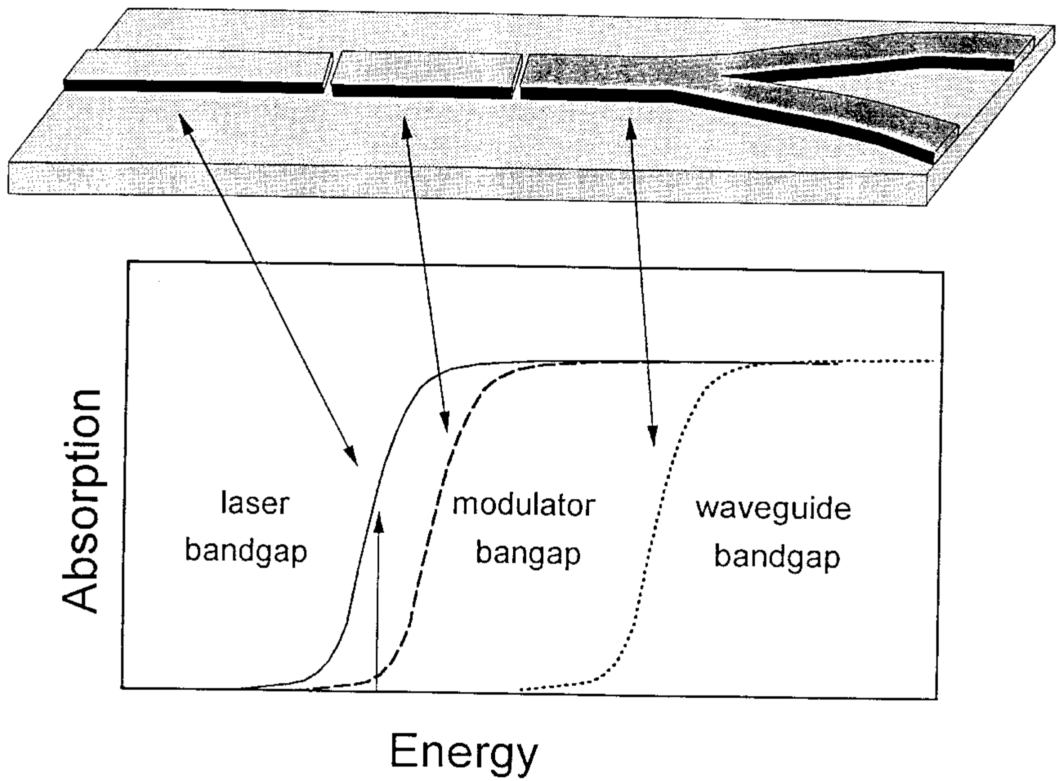
Photonic Integrated Circuits

Different Bandgaps on the same chip



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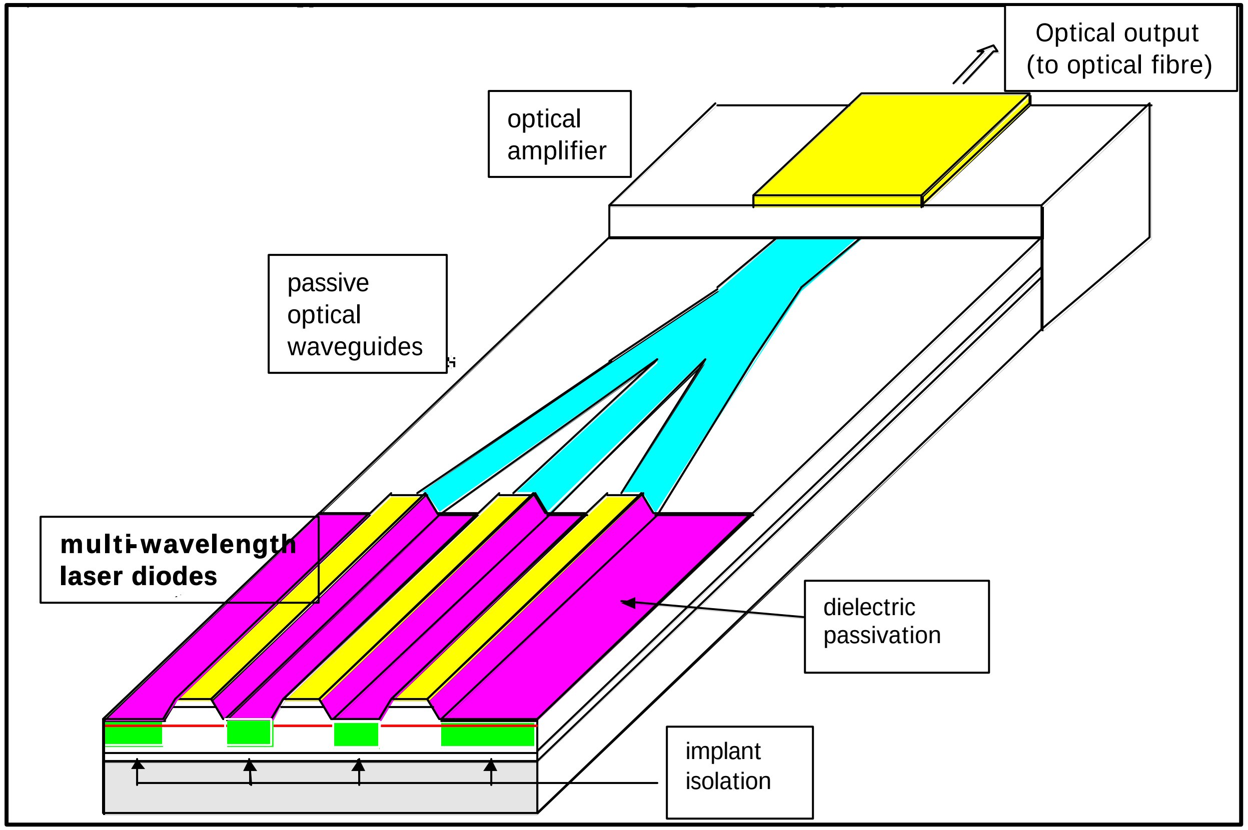
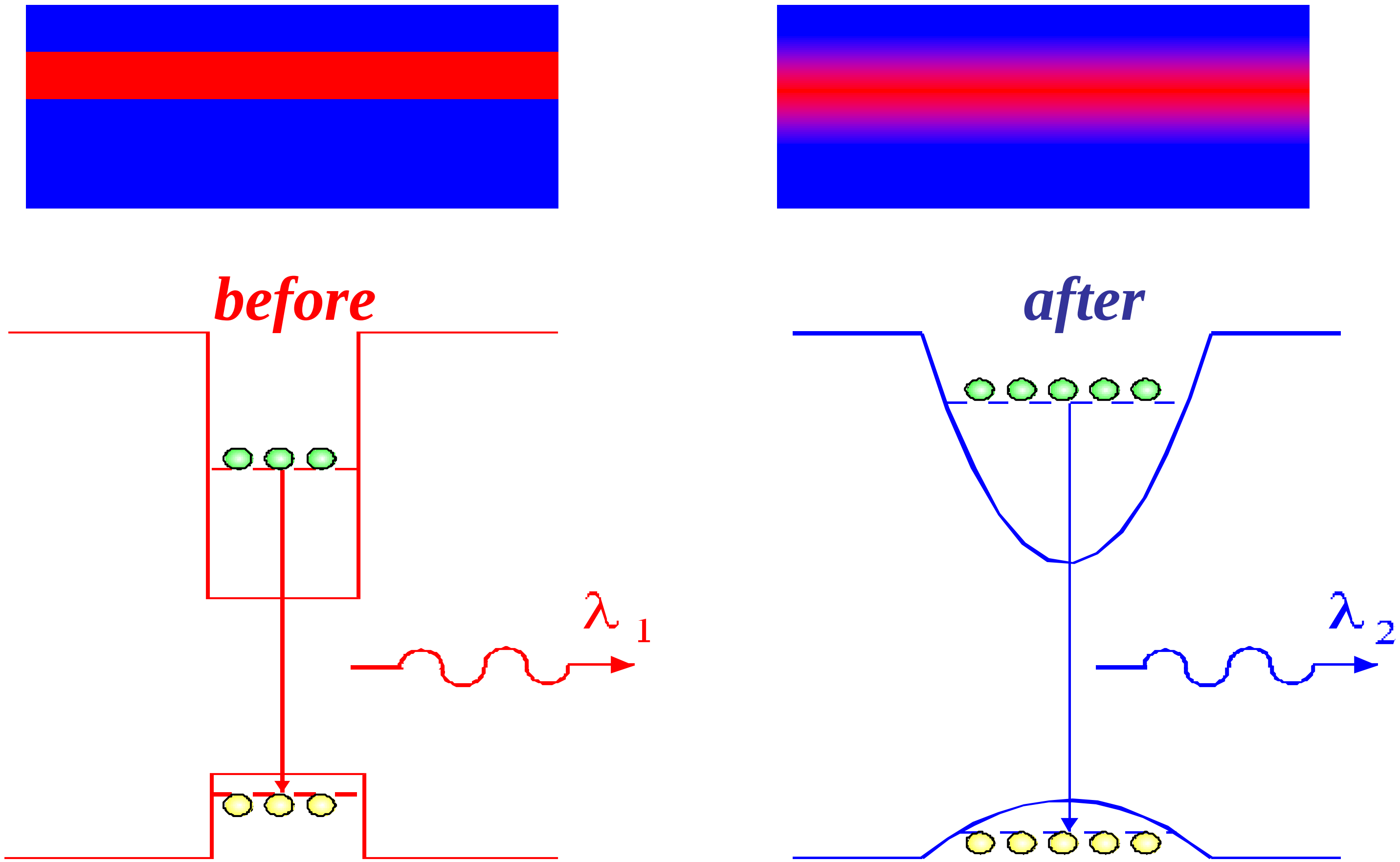
WDM Source



Optical output
(to optical fibre)
optical
amplifier
passive
optical
waveguides
multi-wavelength
laser diodes
dielectric
passivation
implant
isolation

Quantum Well Intermixing



•**Diffusion of In and Ga across interface creates graded region in the case of GaAs/InGaAs Quantum Wells**

•**Changes Bandgap, refractive index, absorption Coefficient**

Methods Widely Used for Quantum Well (Dot?) Intermixing

Impurity Induced Disordering, e.g. Zn, Si
Impurity Free Interdiffusion, e.g. SiO_2, SOG
Ion Implantation Induced Interdiffusion

Defects/Impurities introduced by these methods enhance atomic interdiffusion

Goals:
High Selectivity and Low Concentration of Residual Defects while achieving large band gap differences

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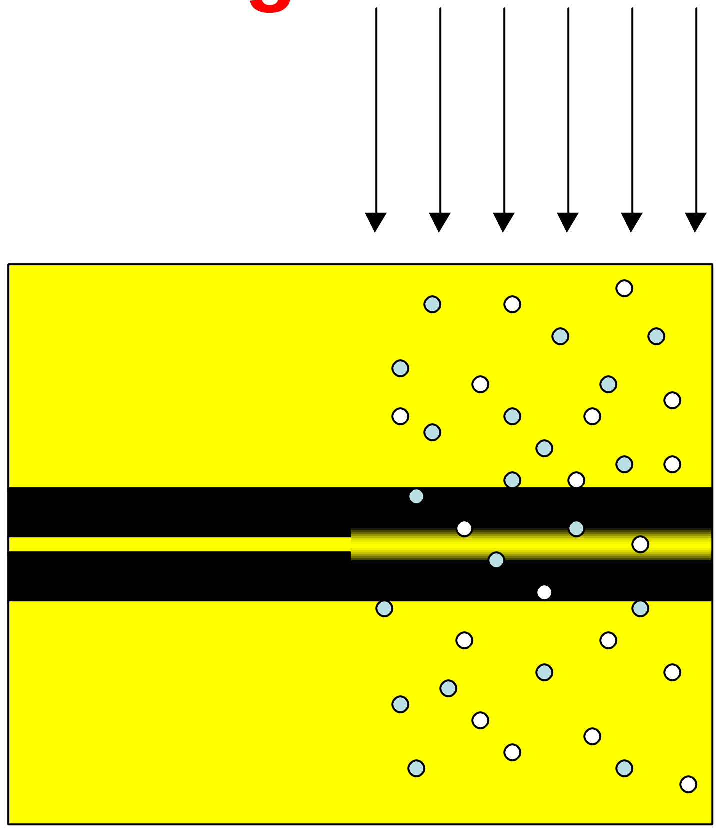
Why Ion Implantation?

Widely used in Microelectronics Industry
Defect Concentration
- Ion Dose, Ion Mass, Implant Temperature, Dose Rate

Defect Depth - Ion Energy
Selective Ion Implantation using Masks

Ion implantation induced quantum well intermixing



Ion implantation

Point defects:

- Vacancy
- Interstitial

Intermixing

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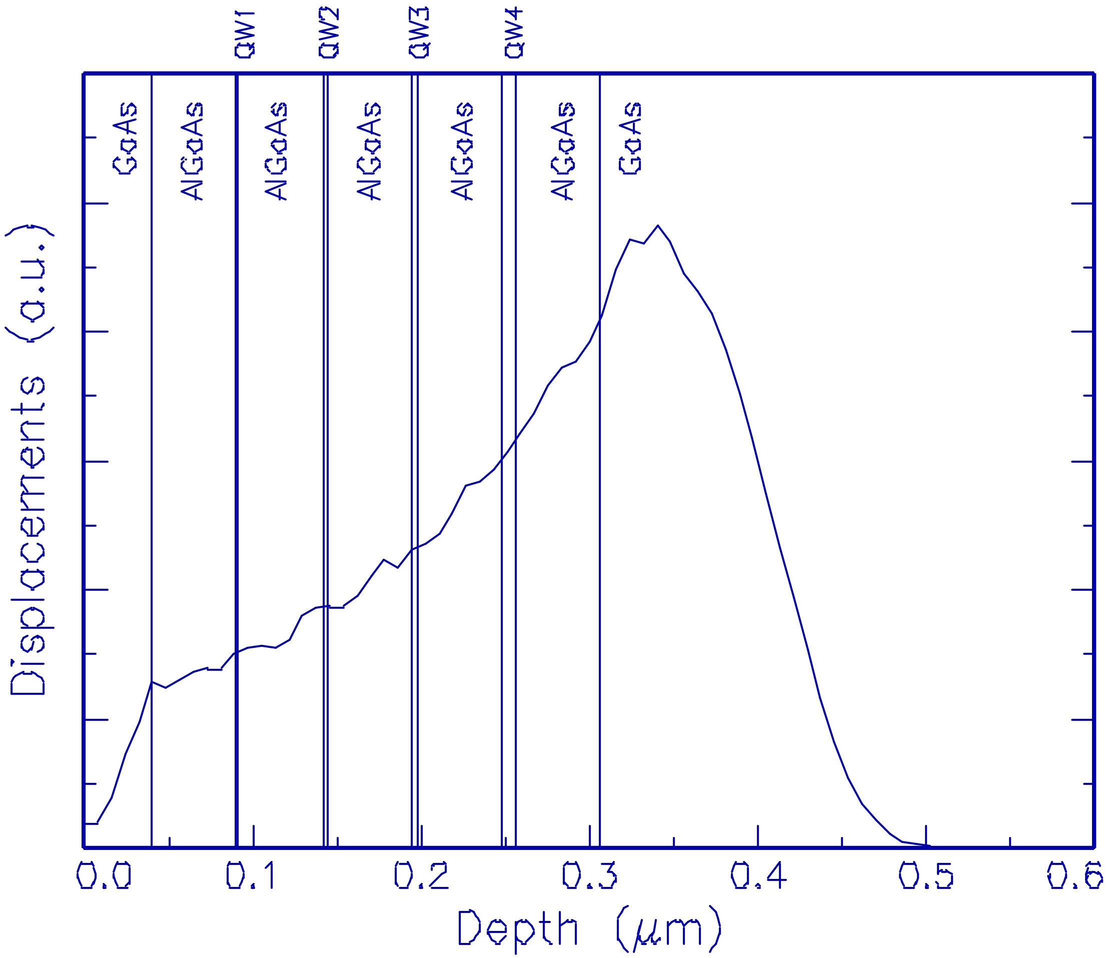
Schematic of 4 QW structure
(40 keV Proton Defect Profile)



QW1 =1.4 nm
QW2=2.3 nm
QW3=4.0 nm
QW4=8.5 nm

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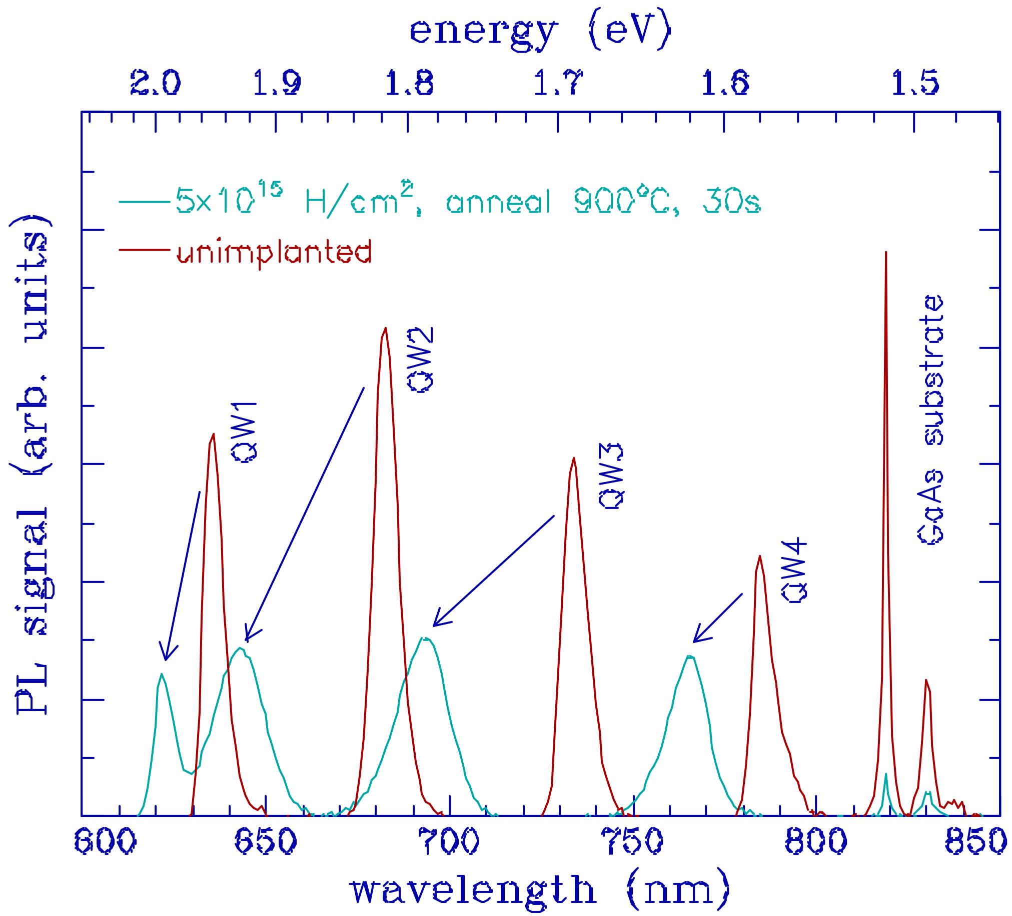
10K Photoluminescence Spectra



H.H. Tan et.al., Appl. Phys. Lett. 68, 2401 (1996).

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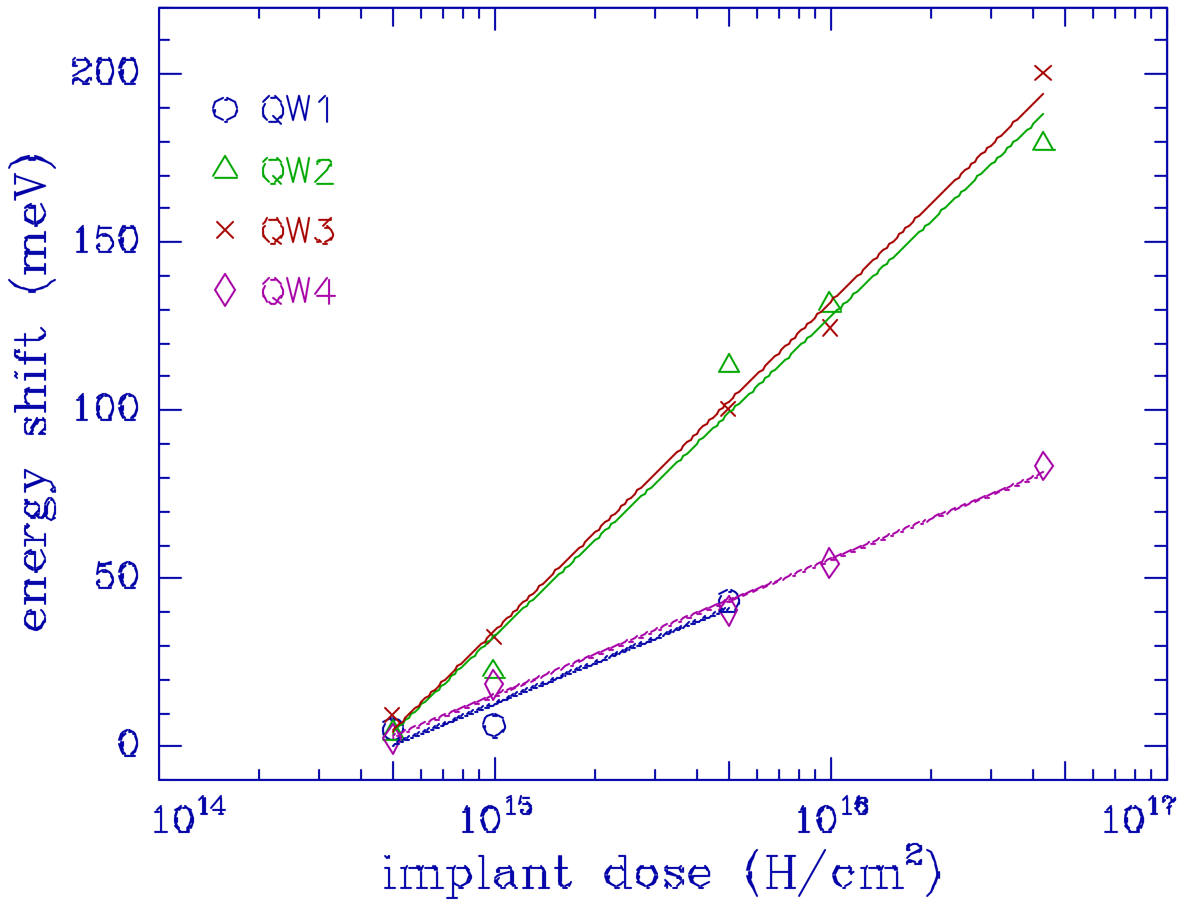
Energy Shifts vs. Proton Dose

900°C, 30 sec



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H.H. Tan et.al., Appl. Phys. Lett. 68, 2401 (1996).

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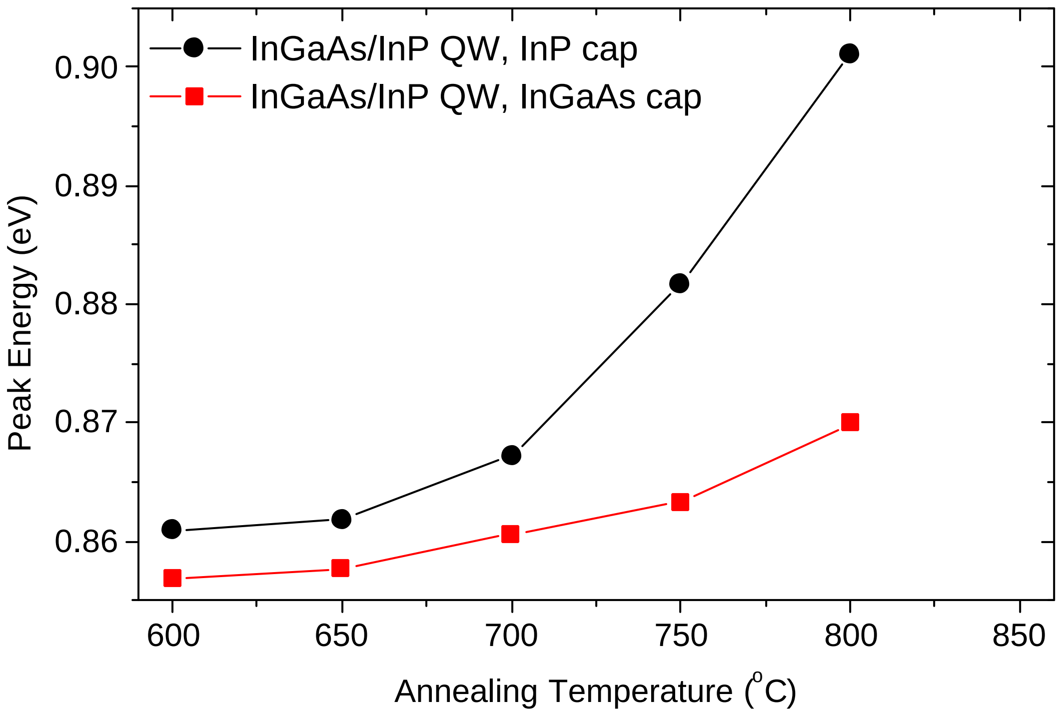
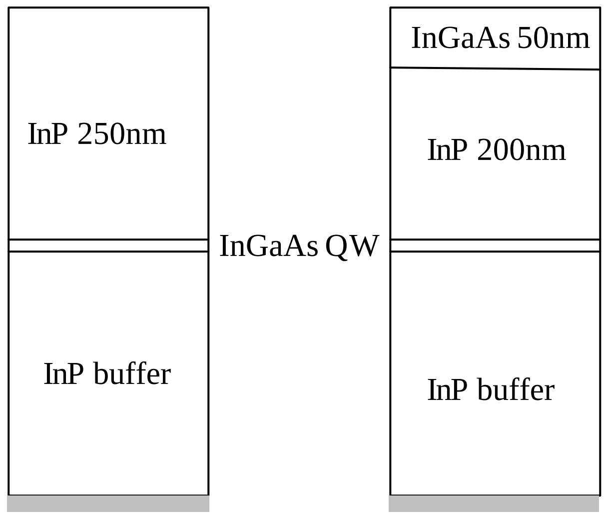
Thermal Stability of InP/InGaAs QWs with InP and InGaAs





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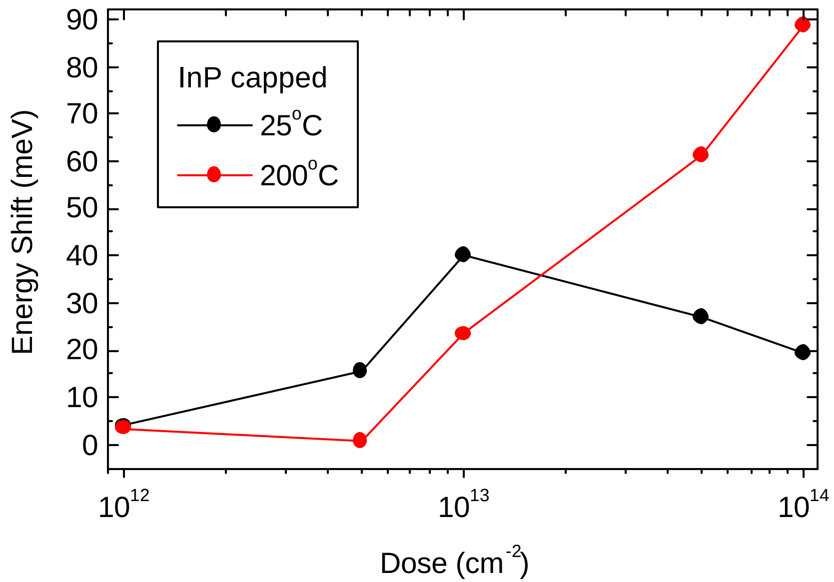
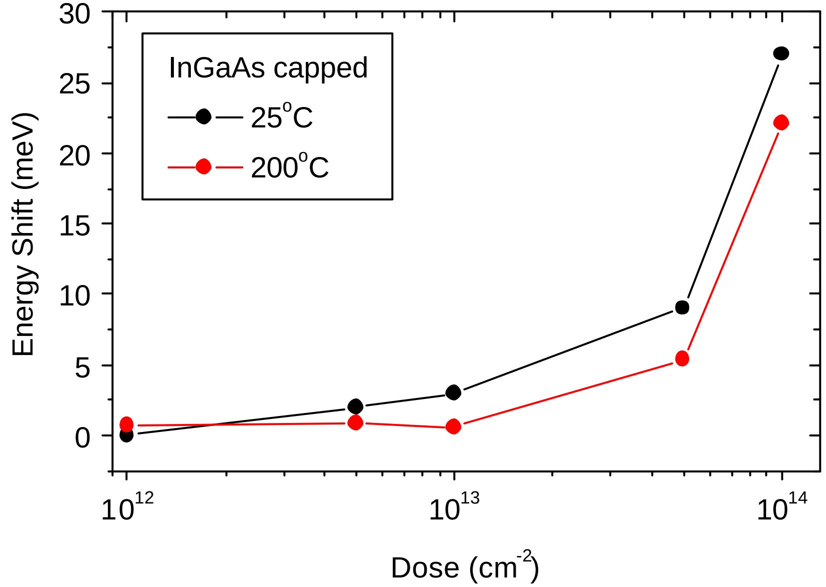
Implantation Dose (20 keV P) and Temperature Dependence of Energy Shifts in InP/InGaAs QWs

700°C, 60 sec





C. Carmody, J. Appl. Phys. 93, 4468 (2003)

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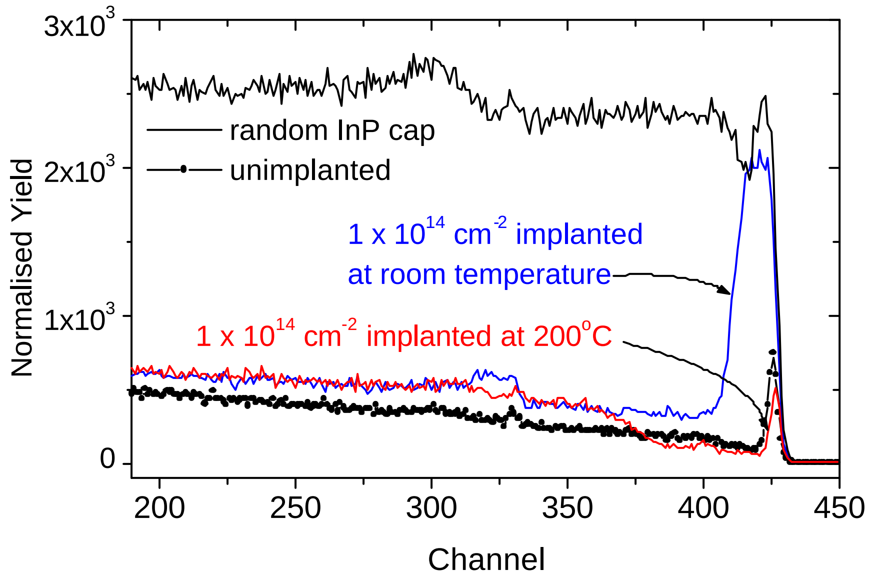
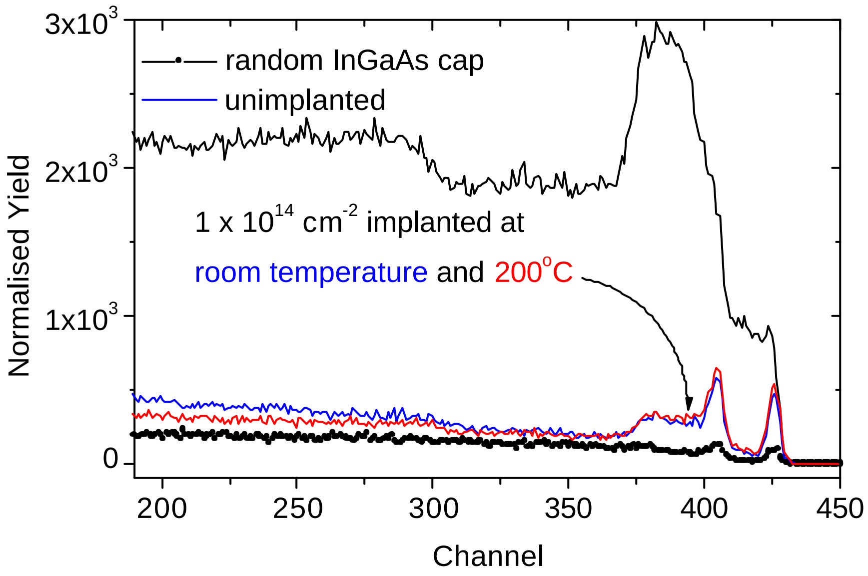
Damage Accumulation in InP and InGaAs

InP Cap



InGaAs Cap



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Tuning the Emission Wavelength of GRINSCH Quantum Well Lasers

GaAs/AlGaAs QW Lasers

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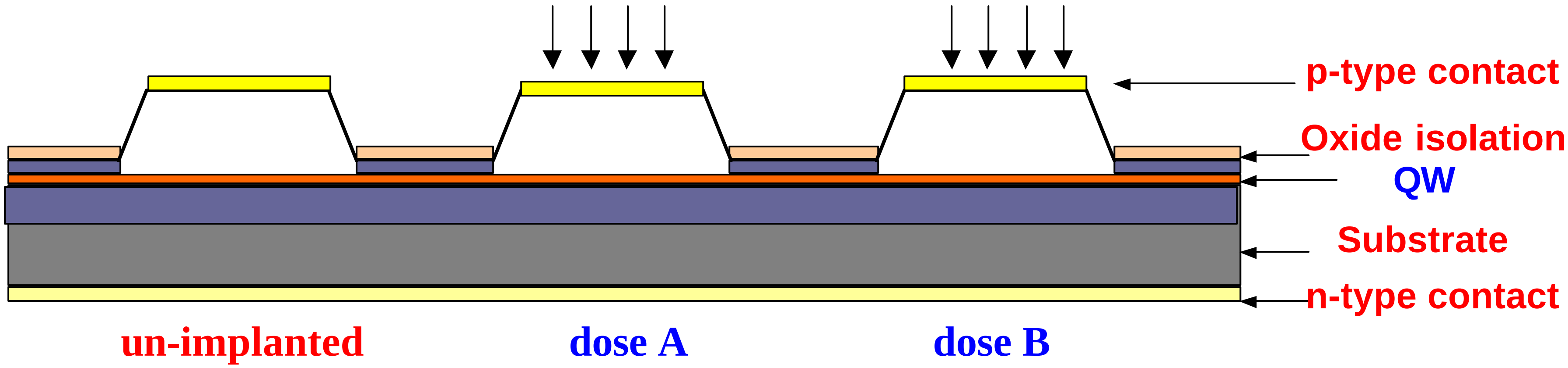
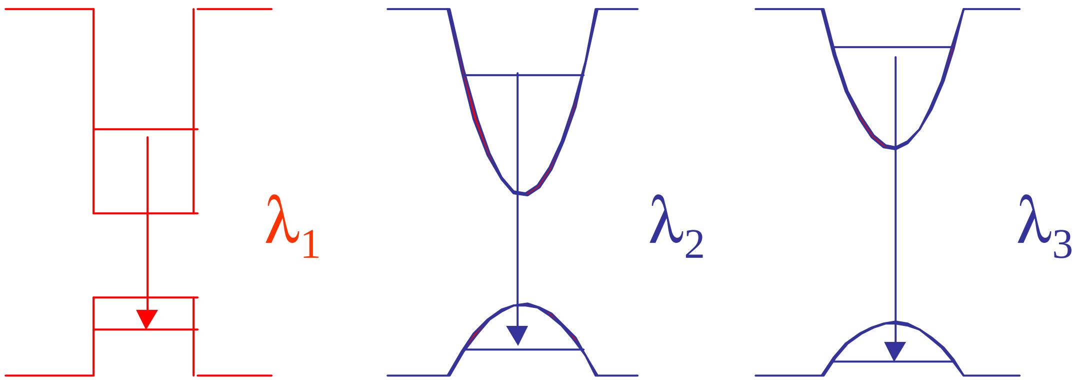
Tuning the wavelength of QW lasers

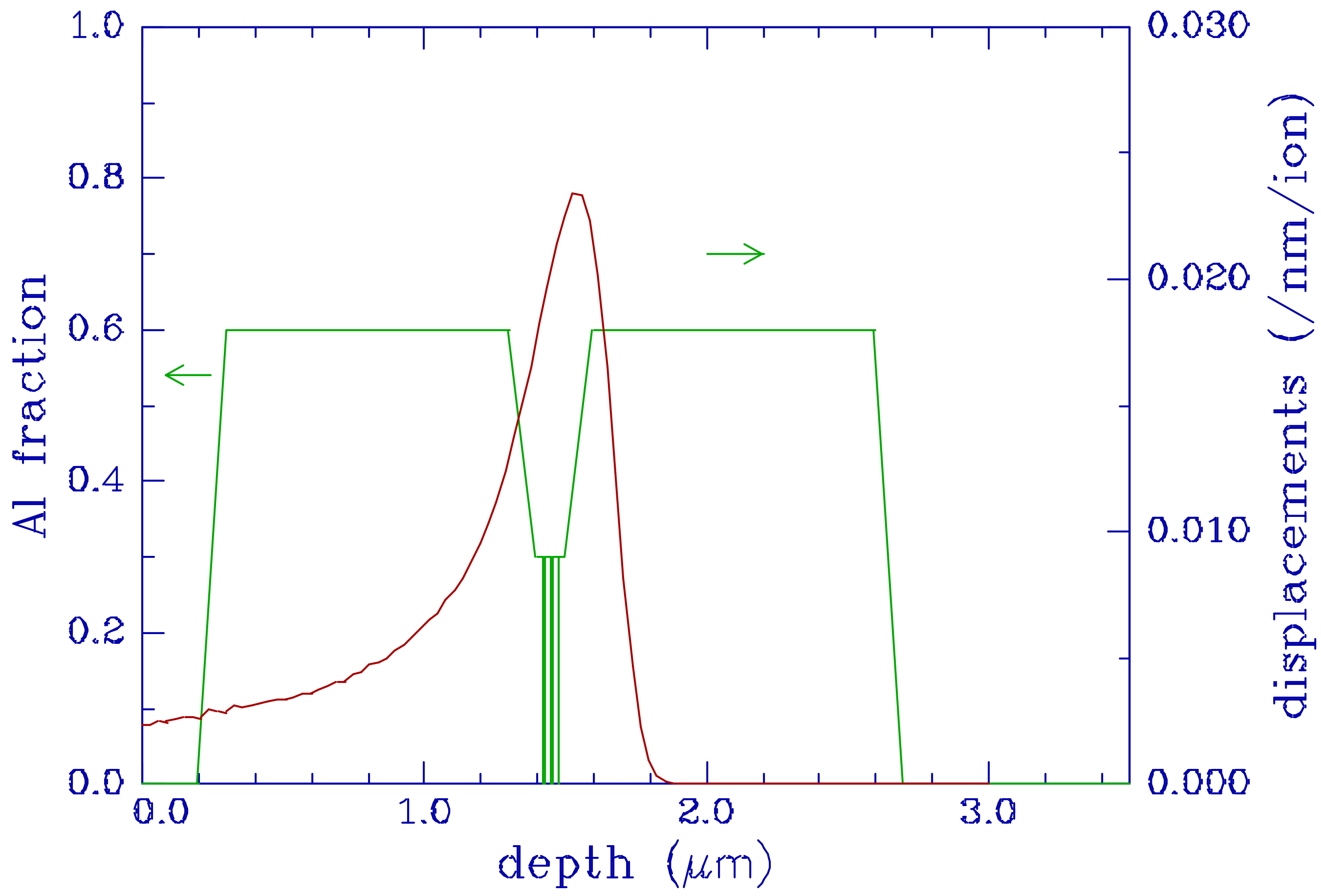




dose A < dose B

l1 > l2 > l3

GRINSCH QW Laser and 220 keV Proton Defect Profile



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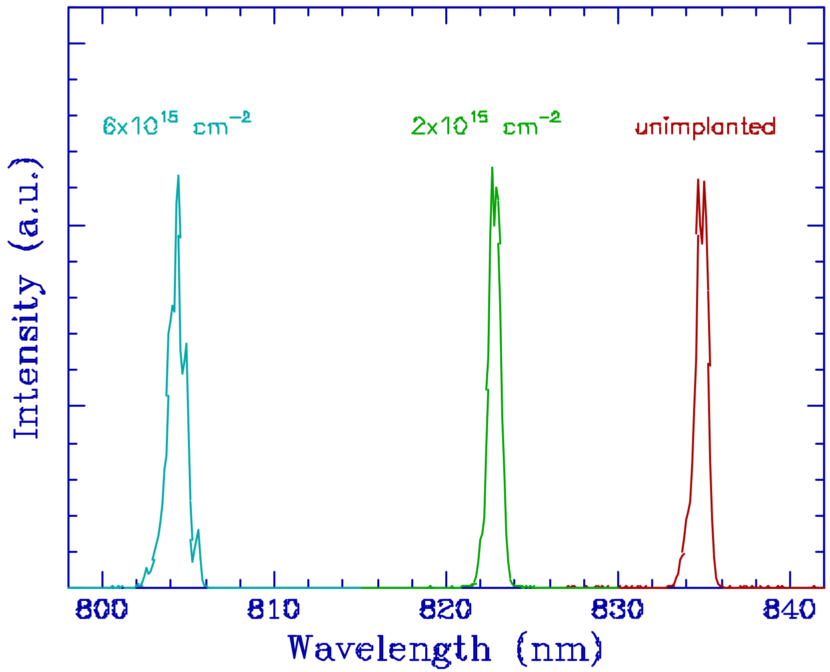
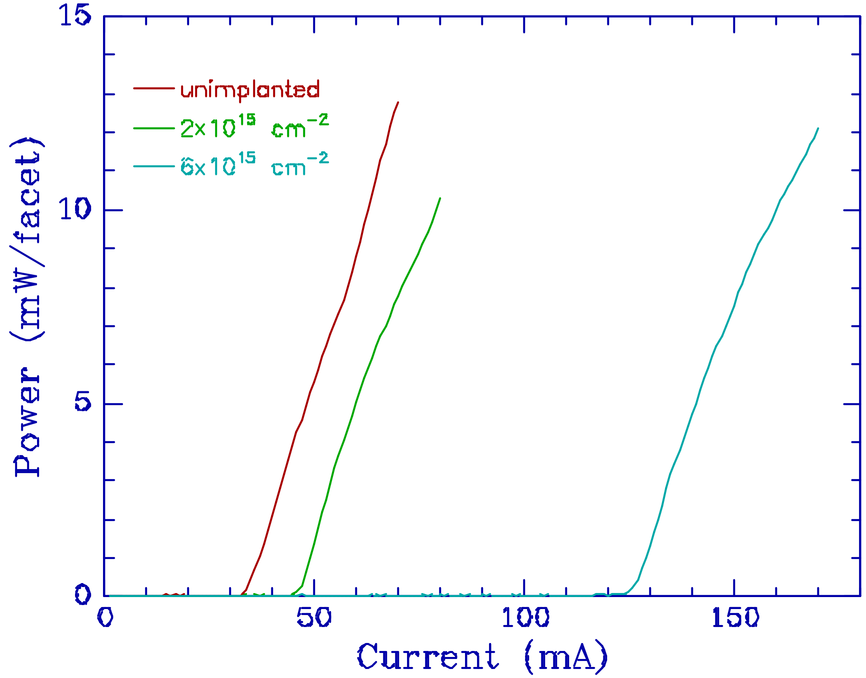
Lasing Spectra and L-I Characteristics of GaAs/AlGaAs QW Lasers

(900°C, 60 sec)





H.H. Tan and C. Jagadish, Appl. Phys. Lett. 71, 2680 (1997).

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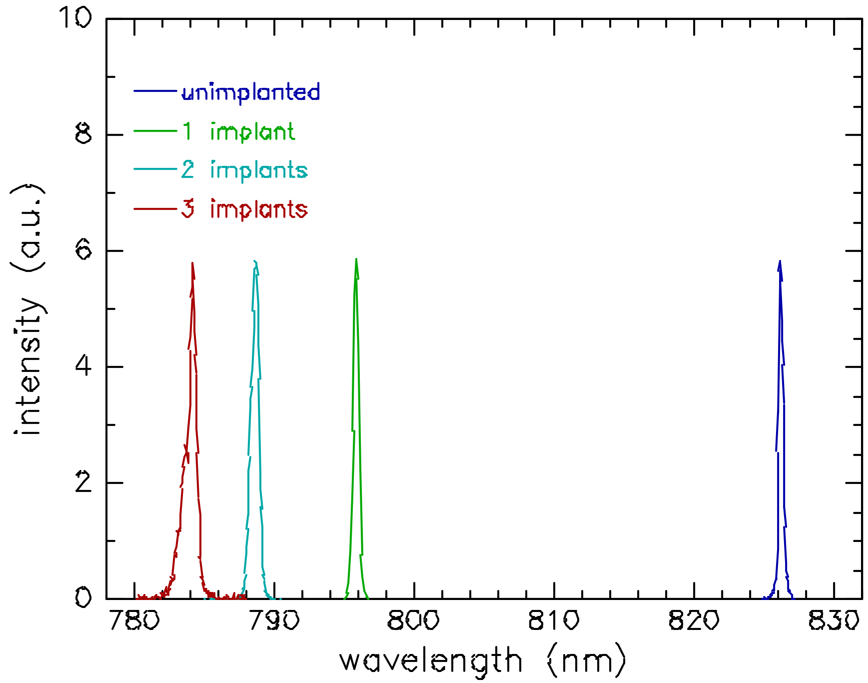
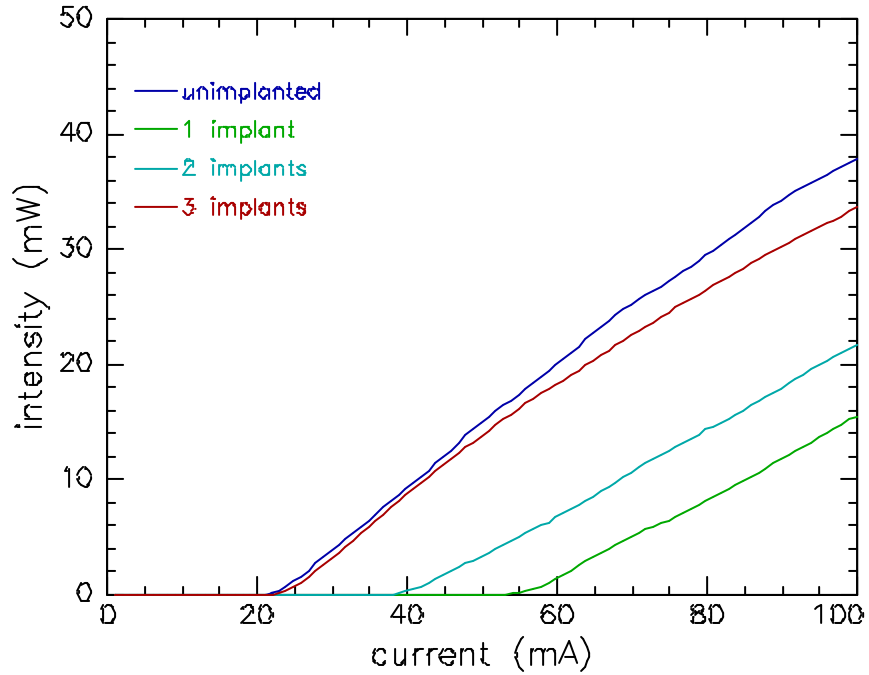
Multi-Step Implantation Scheme for Improved GaAs/AlGaAs QW Laser Performance





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Tuning the Detection Wavelength of Quantum Well Infrared Photodetectors (QWIPs)

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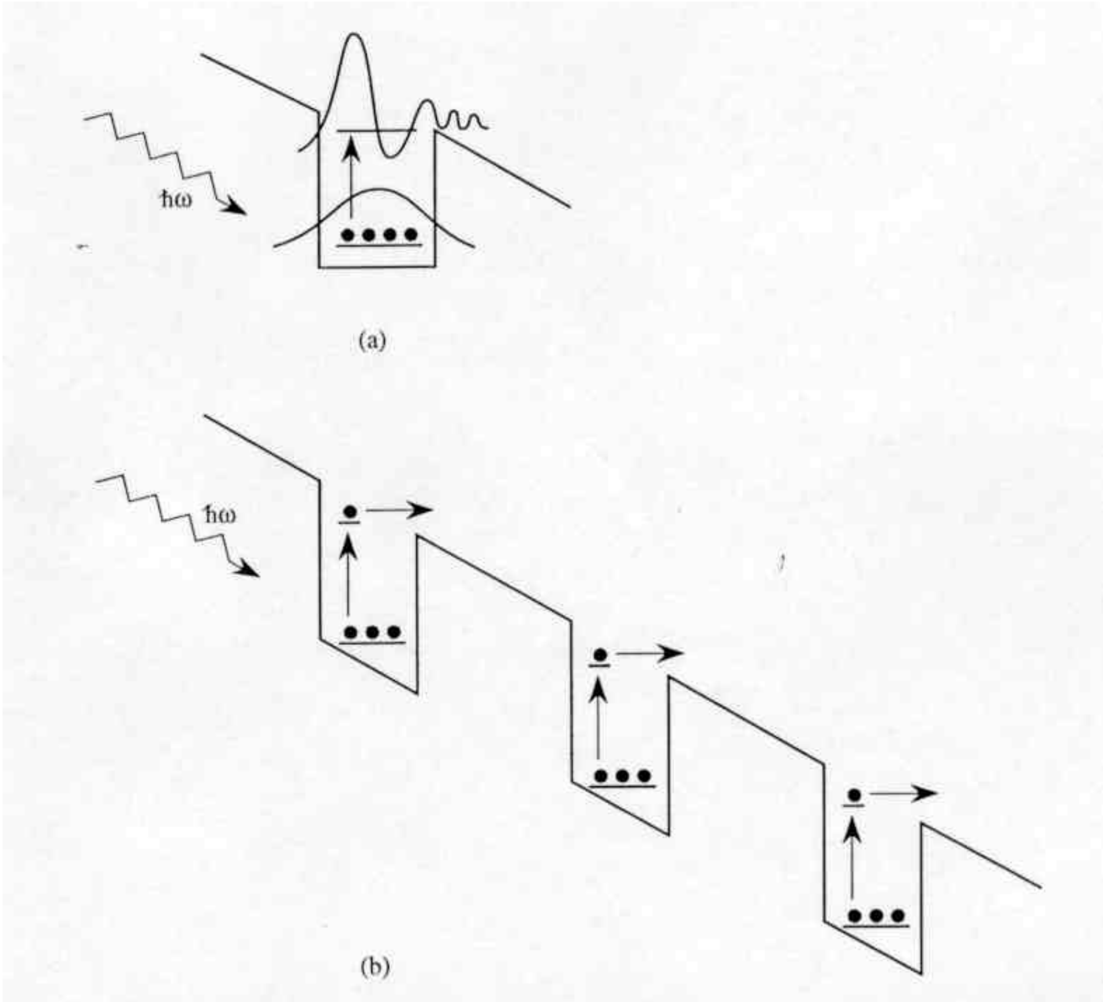
Quantum Well Infrared Photodetectors



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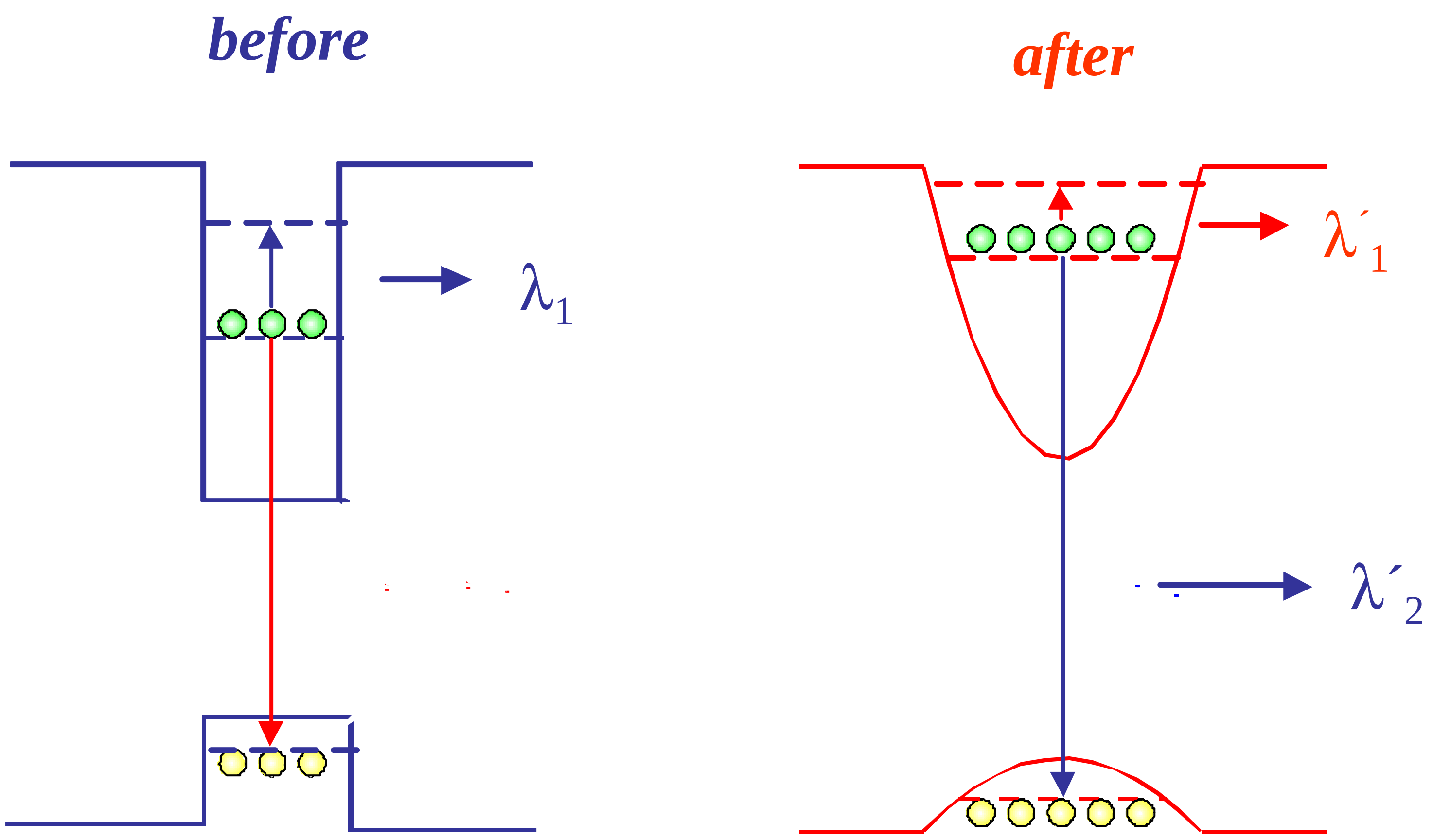
Quantum well intermixing



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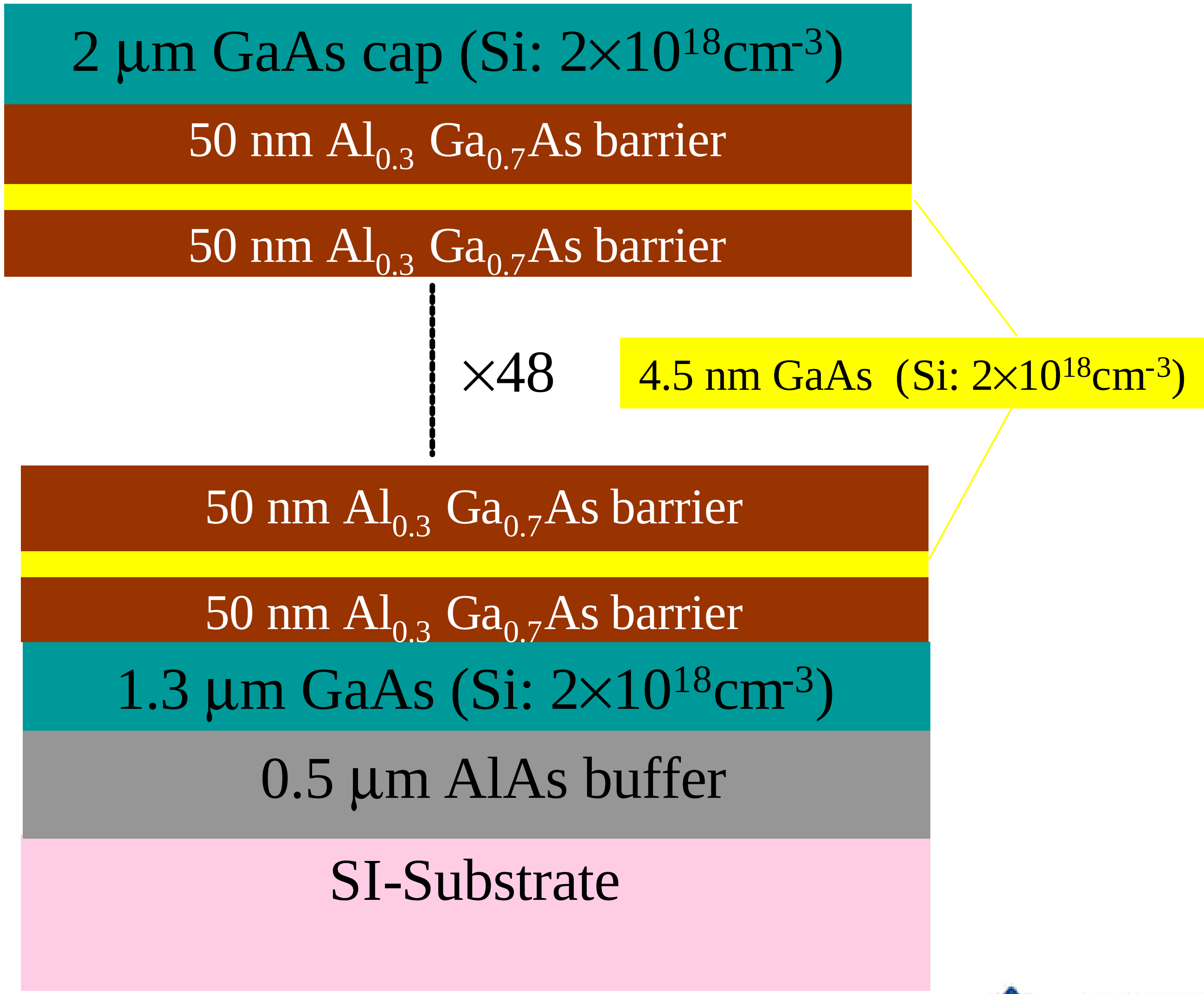
QWIP structure Grown by MBE



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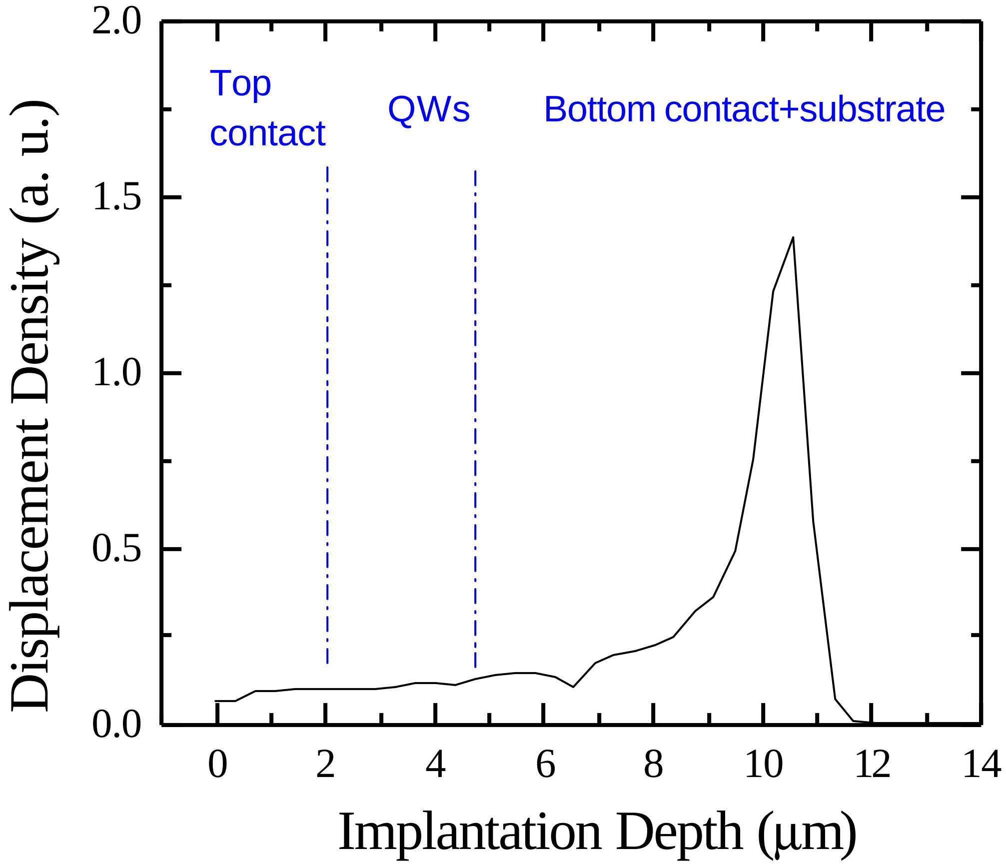
Defect distribution profile of 0.9 MeV Protons



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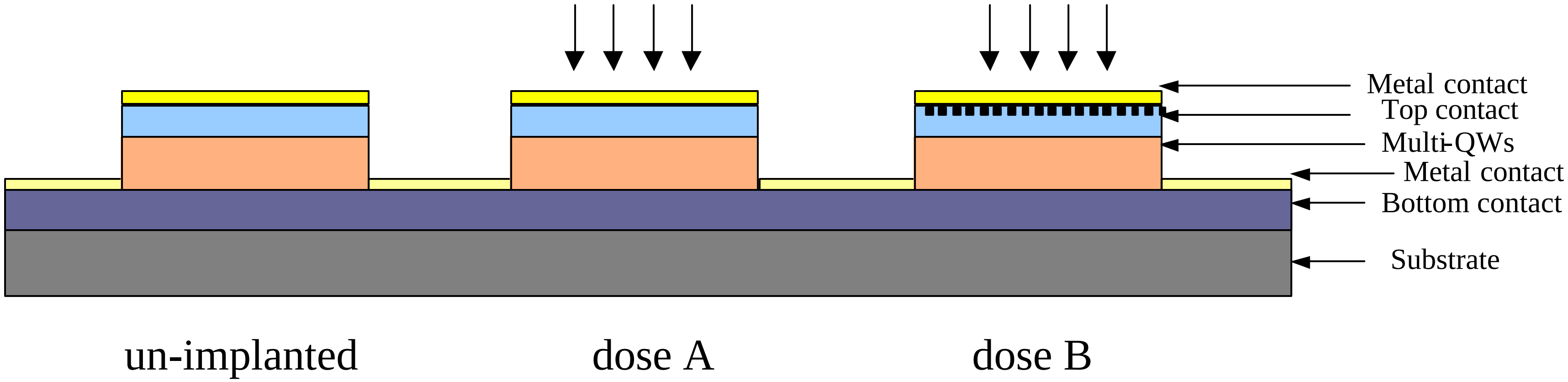
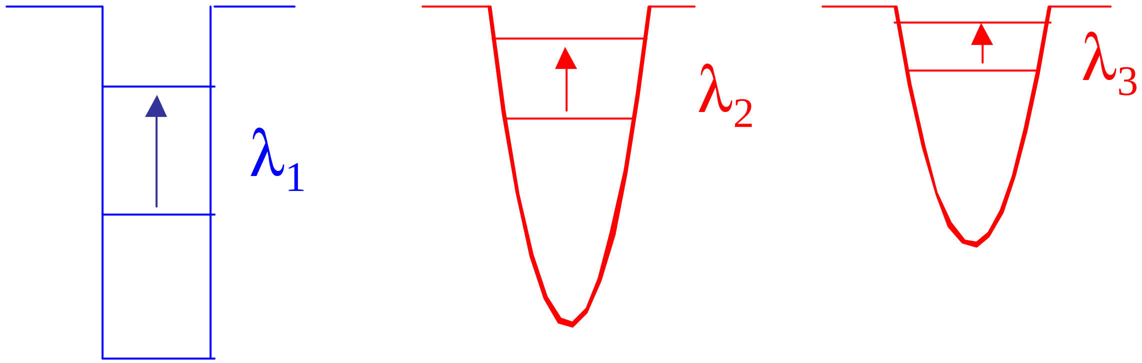
Tuning the wavelength of QWIP





dose A < dose B

$\lambda_1 < \lambda_2 < \lambda_3$

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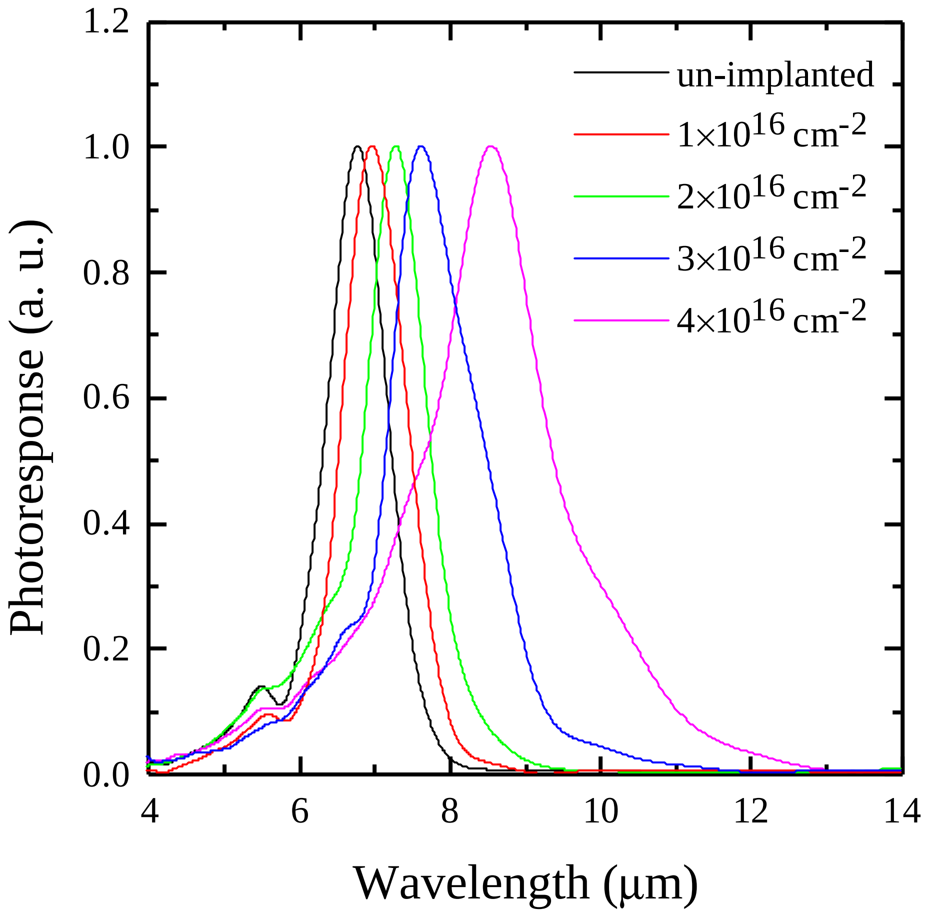
QWIP spectral response



950°C, 30 sec

M.B. Johnston et.al, Appl. Phys. Lett. 75, 923 (1999).

***L. Fu et al*, Appl. Phys. Lett. 78, 10 (2001).**

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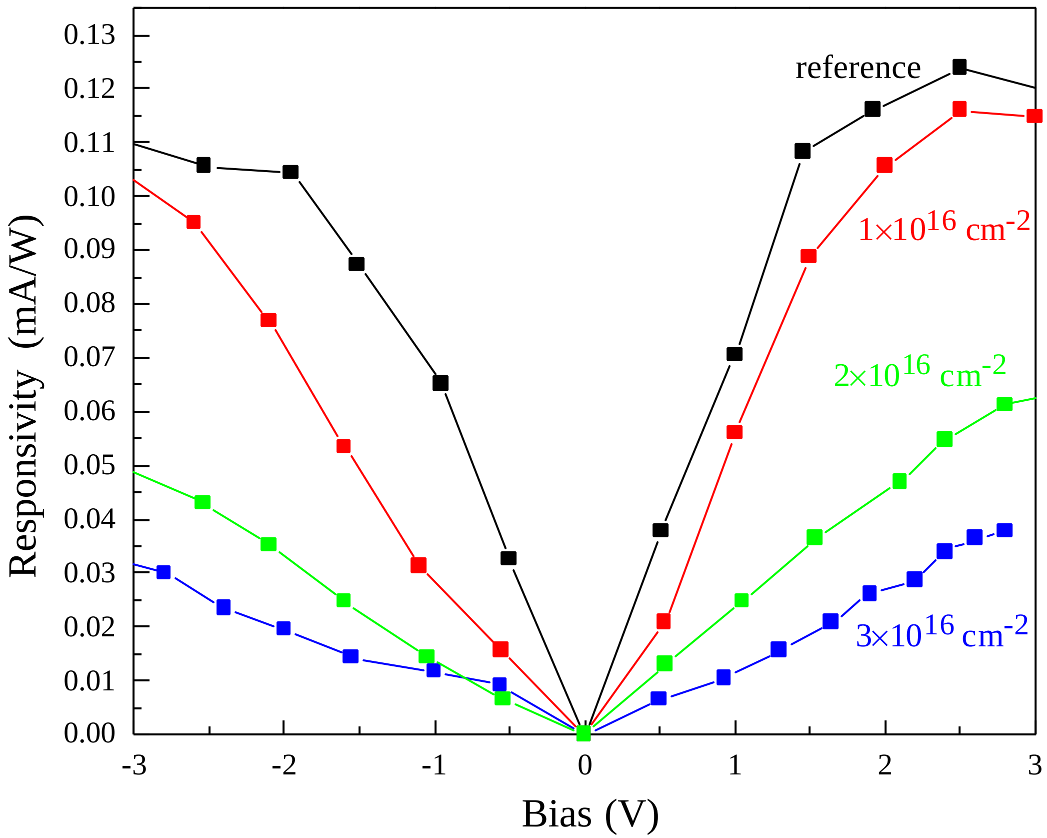
Responsivity



***L. Fu et al*, Appl. Phys. Lett. 78, 10 (2001).**

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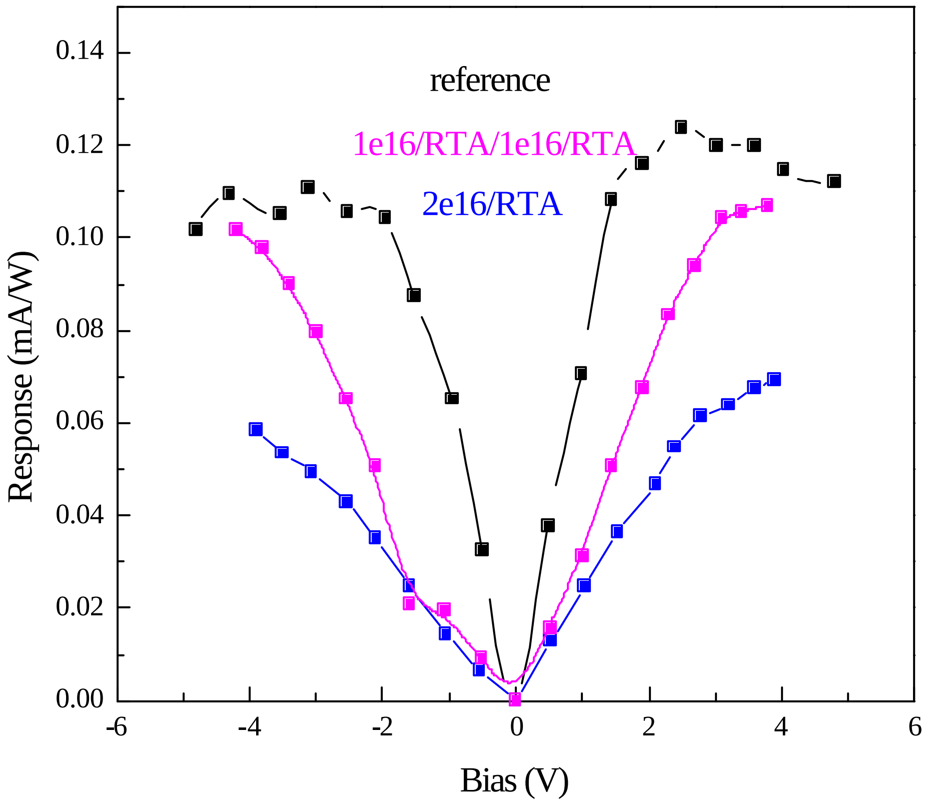
Responsivity



One-step implant-anneal sequence:

0.9 MeV 2´10^{16} cm^{-2} / 950ºC 30 s

Two-step implant-anneal sequence:

0.9 MeV 1´10^{16} cm^{-2} / 950ºC 30 s /0.9 MeV 1´10^{16} cm^{-2} / 950ºC 30 s

***L. Fu et al*, Infrared Phys. & Technol. 42, 171 (2001).**

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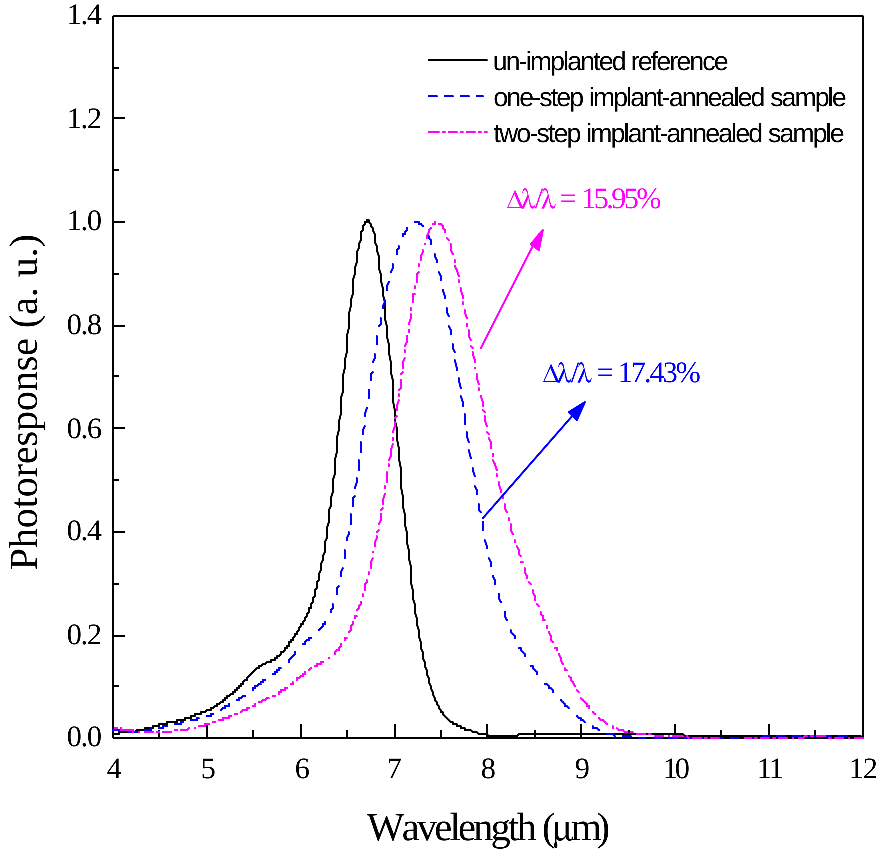
Relative spectral response



***L. Fu et al*, Infrared Phys. & Technol. 42, 171 (2001).**

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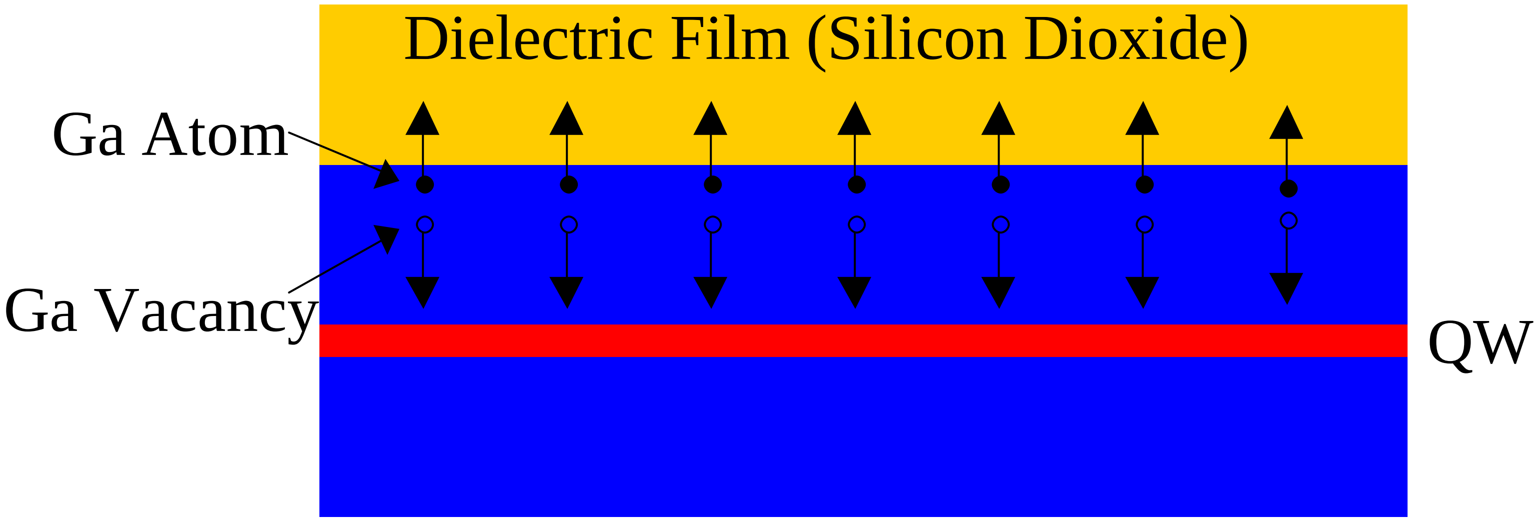
Impurity Free Vacancy Disordering



Silicon dioxide acts as a sink for Ga out-diffusion

(i) Creation of Ga vacancies, (ii) Diffusion of Ga Vacancies

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Why Impurity Free Vacancy Disordering?

Maintains Good Crystal Quality
Low Concentration of Residual Defects
Low Concentration of Electrically Active Defects

Relatively Simple Technique and No Residual Impurities in the Active Regions

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Experimental conditions

- Spin-on glass (un-doped and Ga-doped): 3000 rpm for 30 s, baking at 400°C for 15 min
- SiO_2: Plasma enhanced chemical vapour deposition (PECVD)
- TiO_2: E-beam evaporation
- RTA: 700 ºC to 900ºC for 30 s
- Low temperature photoluminescence

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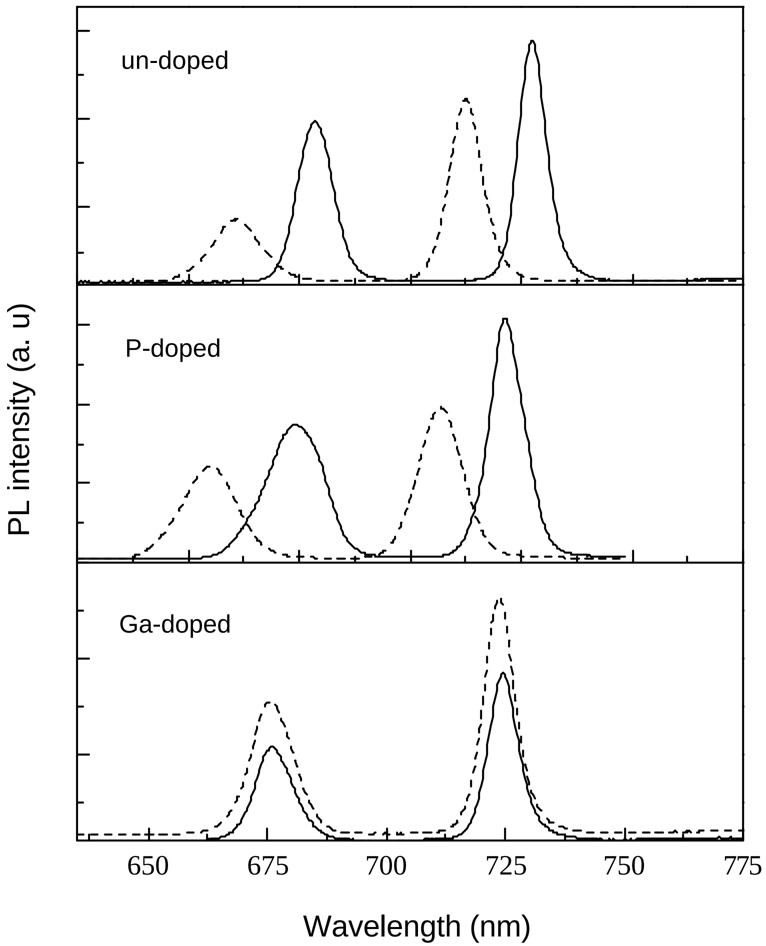
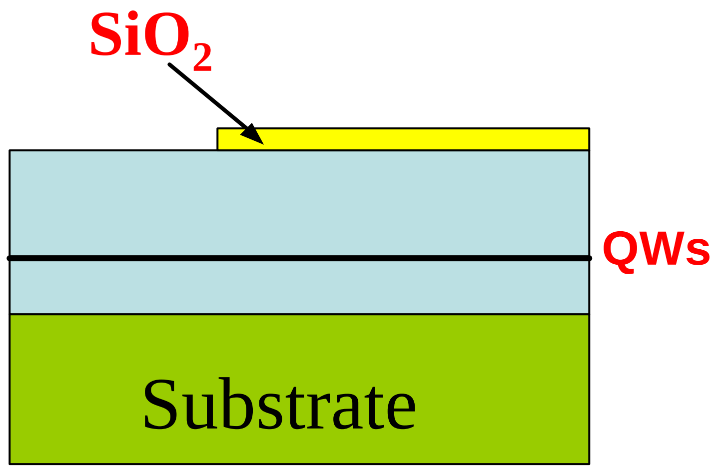
IFVD using doped spin-on layers
GaAs/AlGaAs 2 QW structure





L. Fu et al., Appl. Phys. Lett. 7, 1171 (2002).

L. Fu et. Al., Appl. Phys. Lett. 76, 837-839 (2000).

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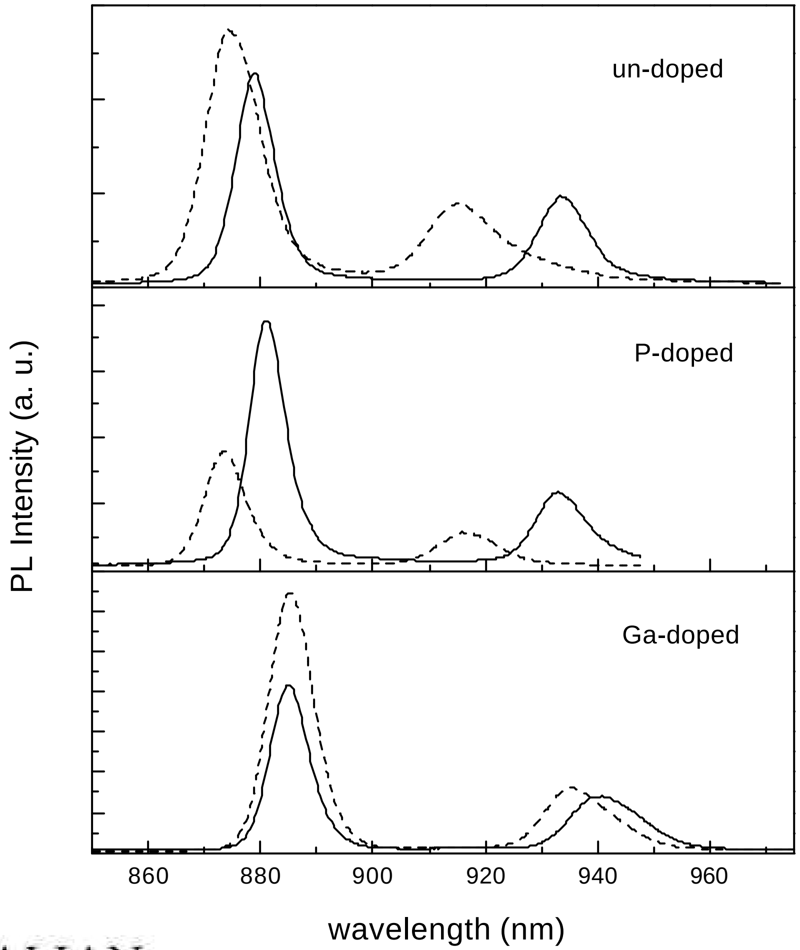
IFVD using doped spin-on layers InGaAs/AlGaAs structure



L. Fu et. al., J. Appl. Phys. 92, 3579 (2002)

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Integration of a Waveguide and a Laser Diode Using IFVD

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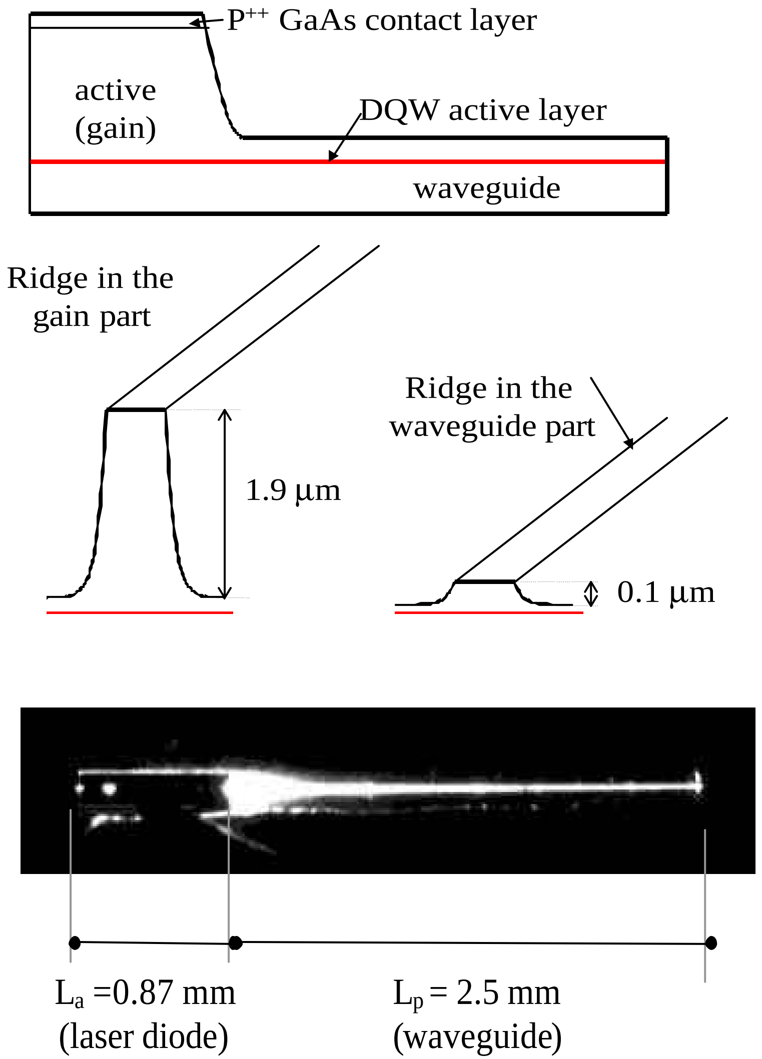
Lateral waveguiding



M. Buda et.al.,
J. Electrochem. Soc.
150, G481 (2003).

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Quantum Dot Photonic Integrated Circuits

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Why Quantum Dots?

Three Dimensional carrier confinement Leads to Atom Like Density of States

Low Threshold Current Lasers
High Quantum Efficiency
High Thermal Stability (To) Lasers
Lasers operating at 1.3 & 1.55 um on GaAs (VCSELs)
Normal Incidence Operation of QDIPs

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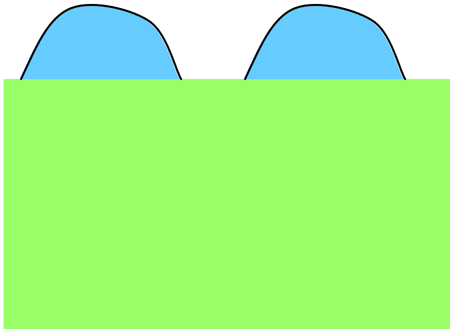
Self Assembled Growth of Quantum Dots

Frank- van der Merwe Growth Mode

Layer by Layer Growth

Lattice matched Systems, e.g. AlGaAs on GaAs

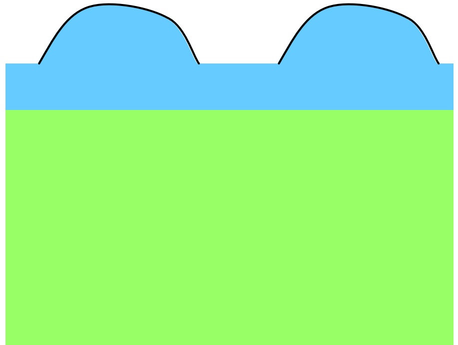
Volmer-Weber Growth Mode



Direct Island Growth

Large lattice mismatch Very High Interfacial Energy, e.g GaN on Saphire

Stranski-Krastanow Growth Mode



Layer by Layer followed by Island Nucleation

Dissimilar Lattice Spacing, Low Interfacial Energy e.g. InAs on GaAs

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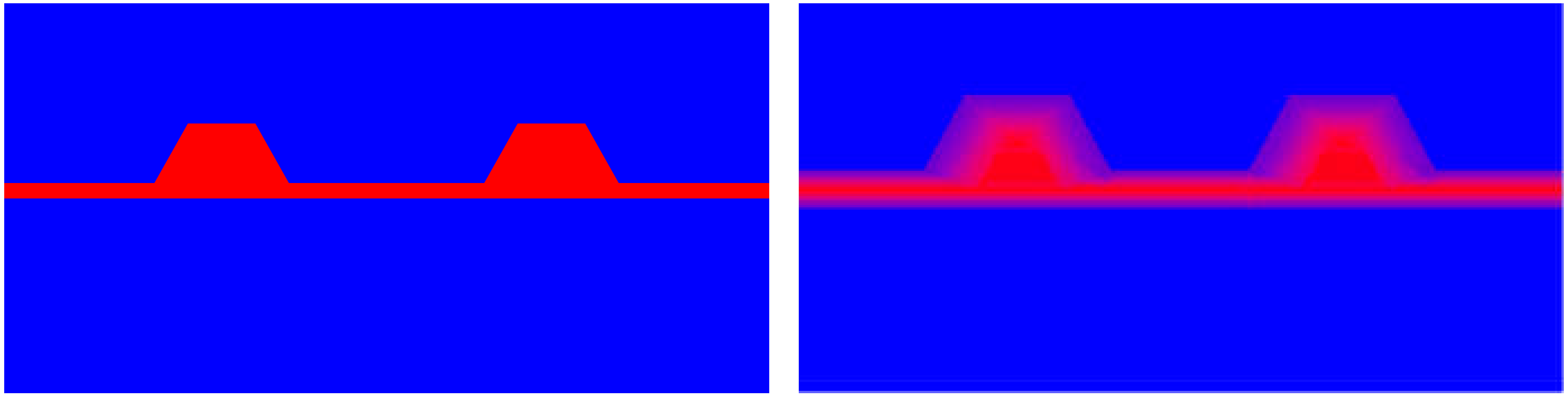
Quantum Dot Intermixing



- Large surface area to volume ratio
- Non-uniform composition profile
- Large strain field around the dots

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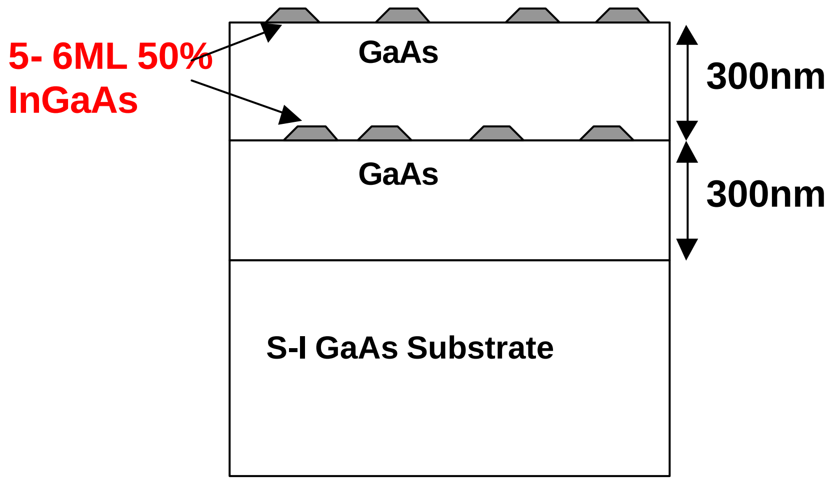
Growth details

- Aixtron 200/4 MOCVD reactor
  - rotation
  - IR lamps
- TMGa, TMIn, AsH_3 & PH_3
- Single layer $In_{0.5}Ga_{0.5}As$ dots
- Dot growth ~500-550°C
- GaAs cap at 650°C

Characterization

- AFM and PL



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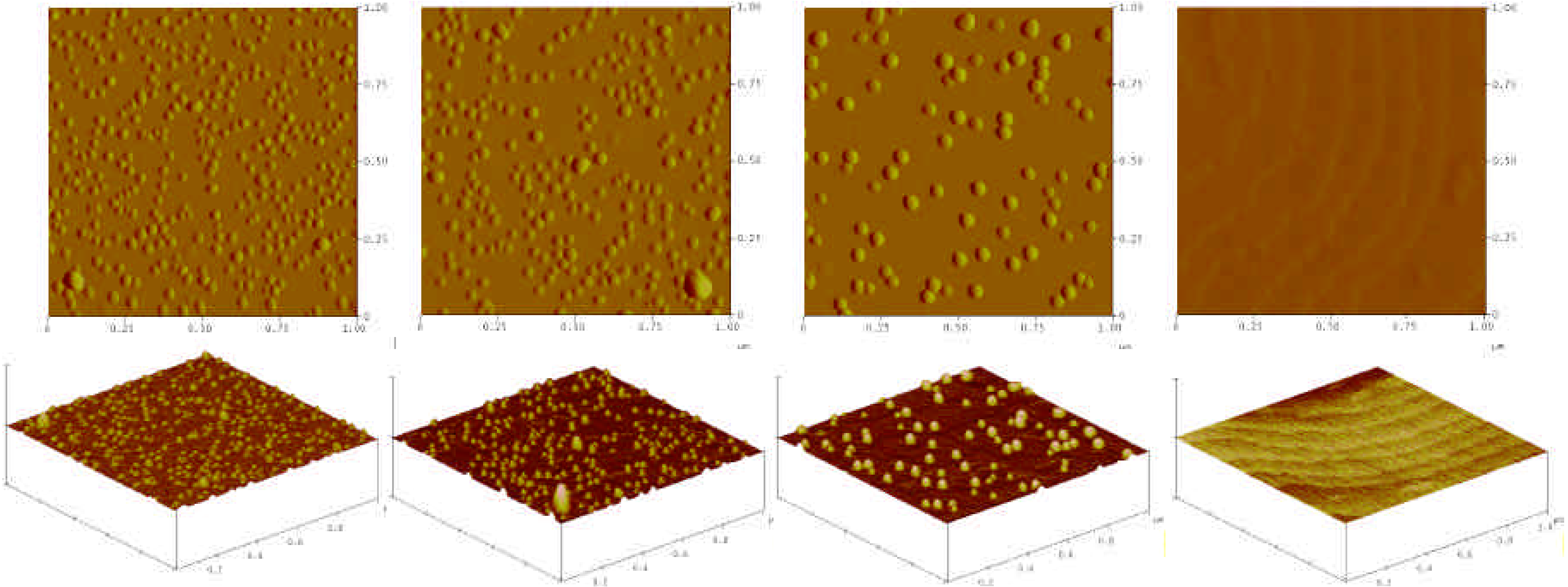
Amount of Material



6.5ML 5.8ML 5ML 4ML

- Increase material:
  - Density increases until saturation
  - Size decreases

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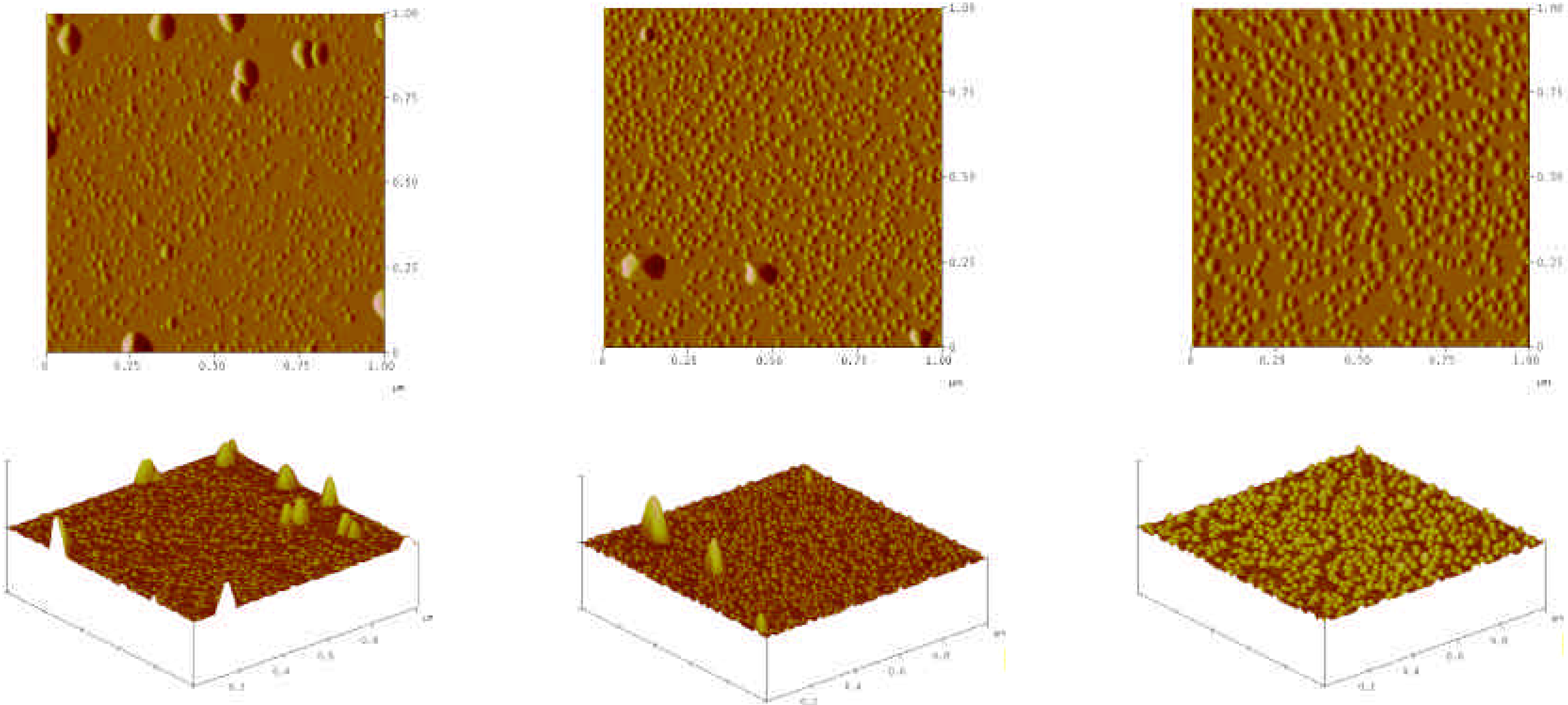
Temperature - AFM



500°C　　520°C　　550°C

Height increases with increasing temperature

Less incoherent dots with increasing temperature

Experimental Details

- Samples annealed for 30sec
  - Proximity capped RTA
  - Anneals at 700, 800, 850 and 900°C

Spin on Glass, PECVD SiO_2, E-Beam TiO_2

- Photoluminescence
  - 10K
  - Cooled Ge detector
  - Argon-ion laser at 514.5nm

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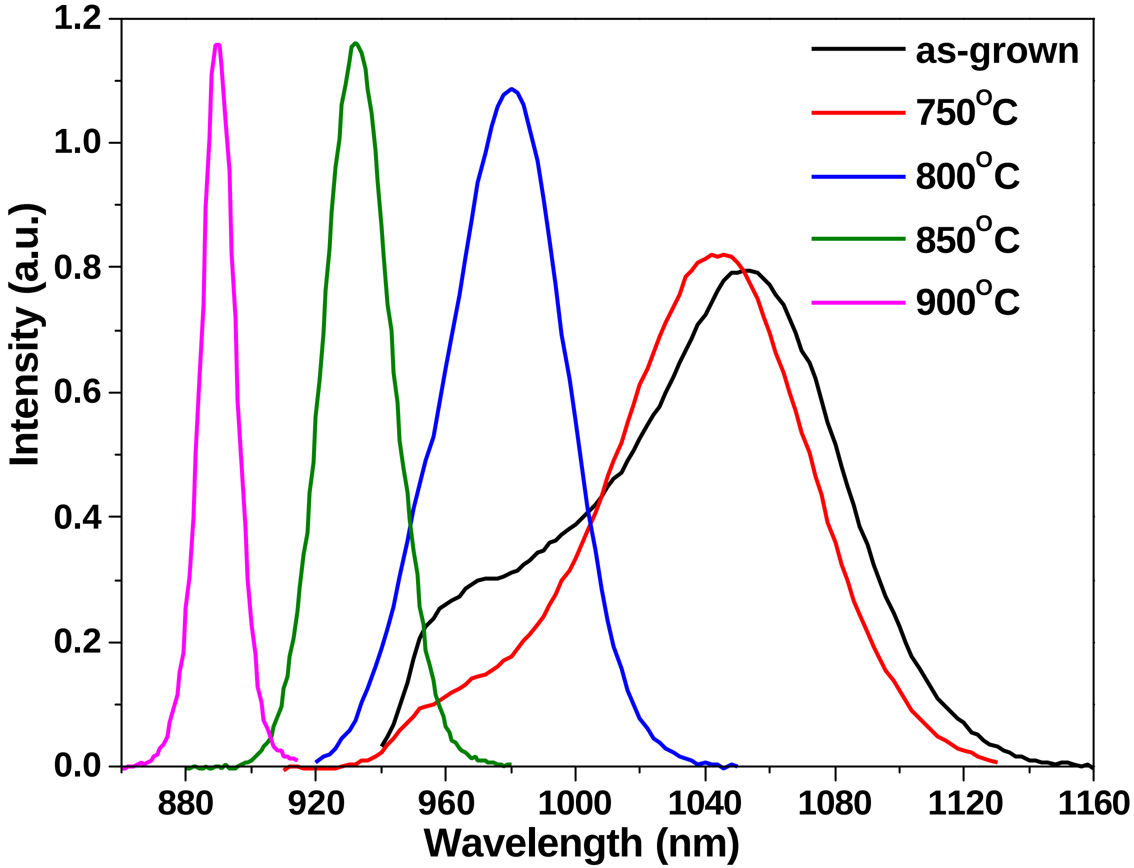
Thermal stability of single layer QDs



12K Photoluminescence Spectra

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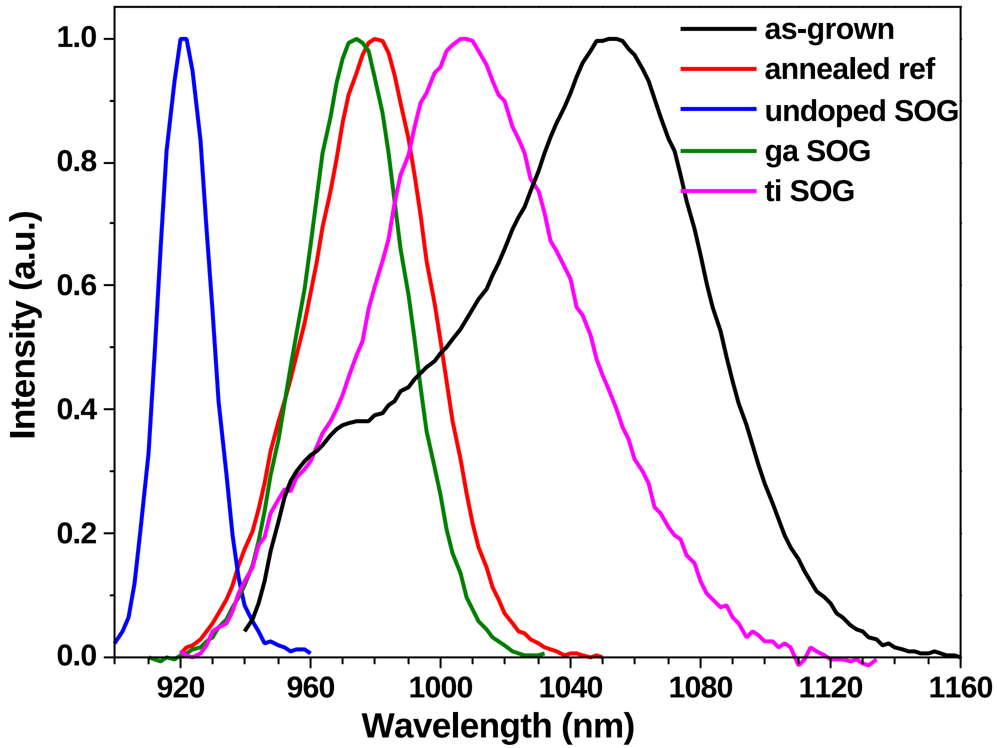
IVFD of single layer QDs Spin on Glass (SOG)



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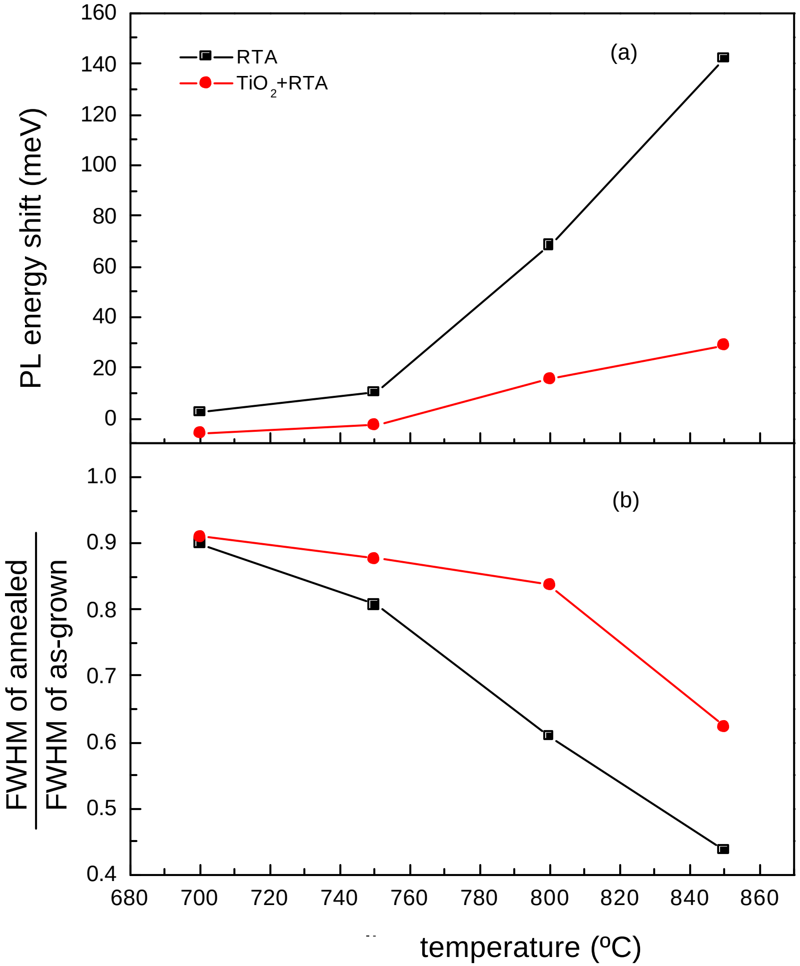
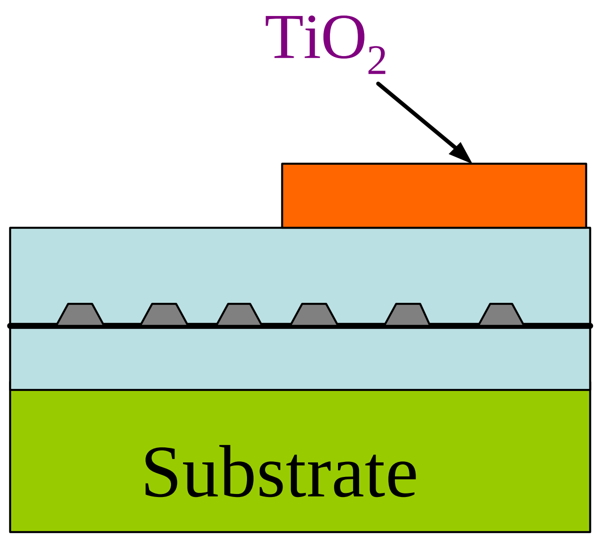
Suppression of thermal interdiffusion by TiO_2 as function of RTA temperature





L. Fu et.al., Appl. Phys. Lett. 82, 2613 (2003)

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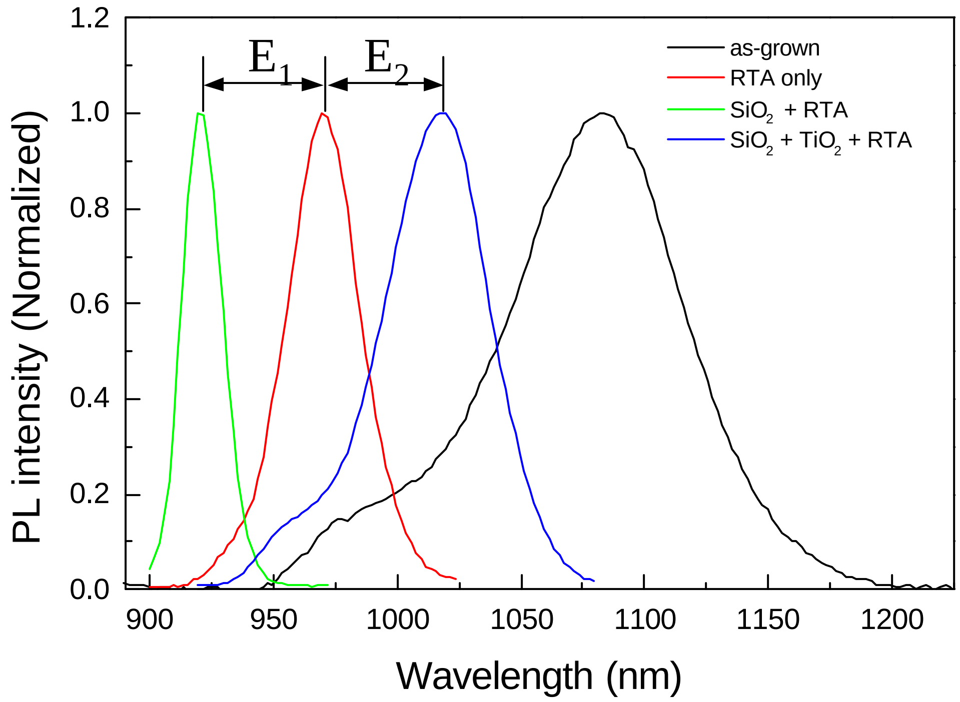
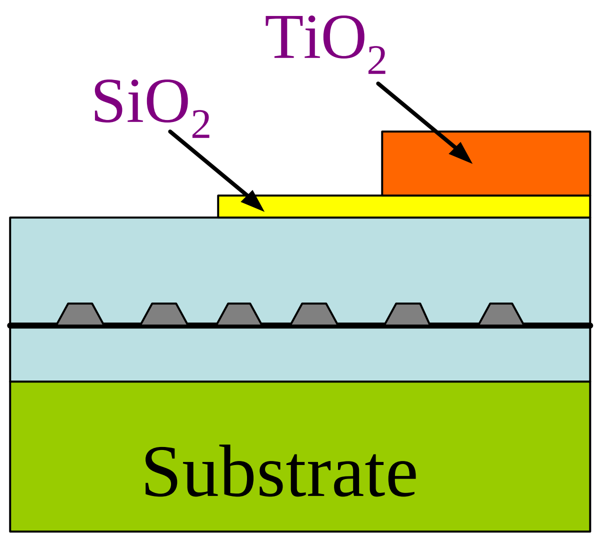
Suppression of interdiffusion using bi-layer SiO_2 + TiO_2

RTA: 850ºC 30 s





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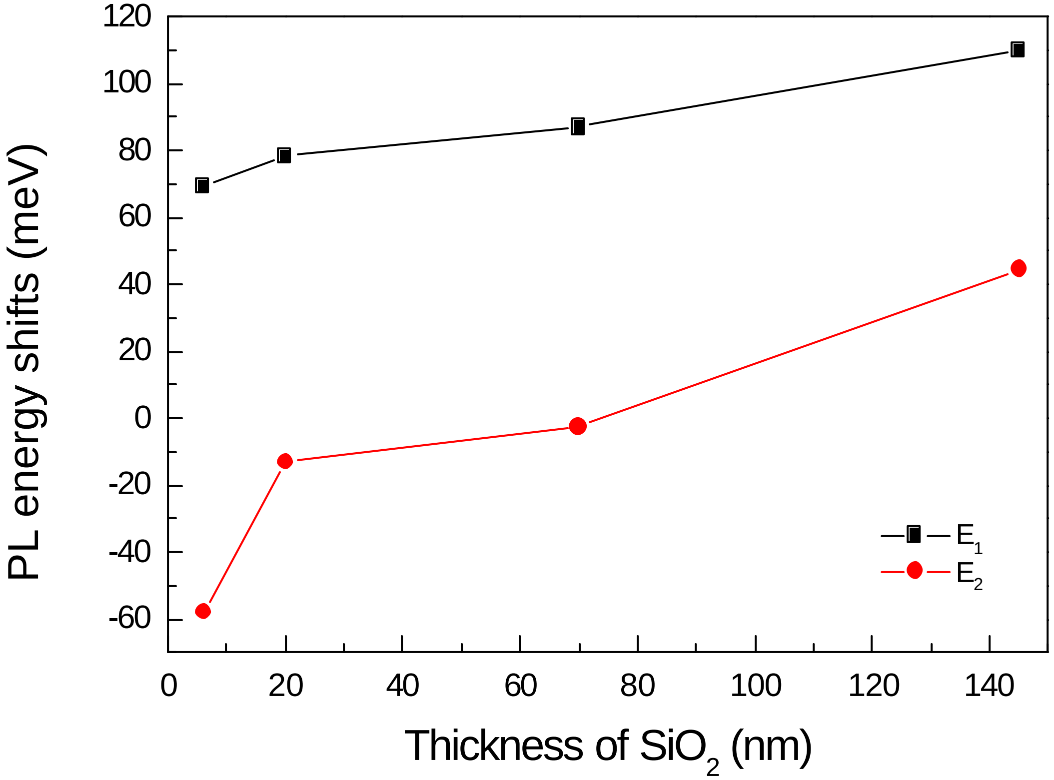
Suppression of interdiffusion using bi-layer SiO_2 + TiO_2 as a function of SiO_2 thickness



L. Fu et al, **Appl. Phys. Lett. 82, 2613 (2003).**

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Thermal expansion coefficient

Material	α ($^oC^{-1}$)
GaAs	6.86×10^{-6}
SiO_2	0.52×10^{-6}
TiO_2	8.19×10^{-6}

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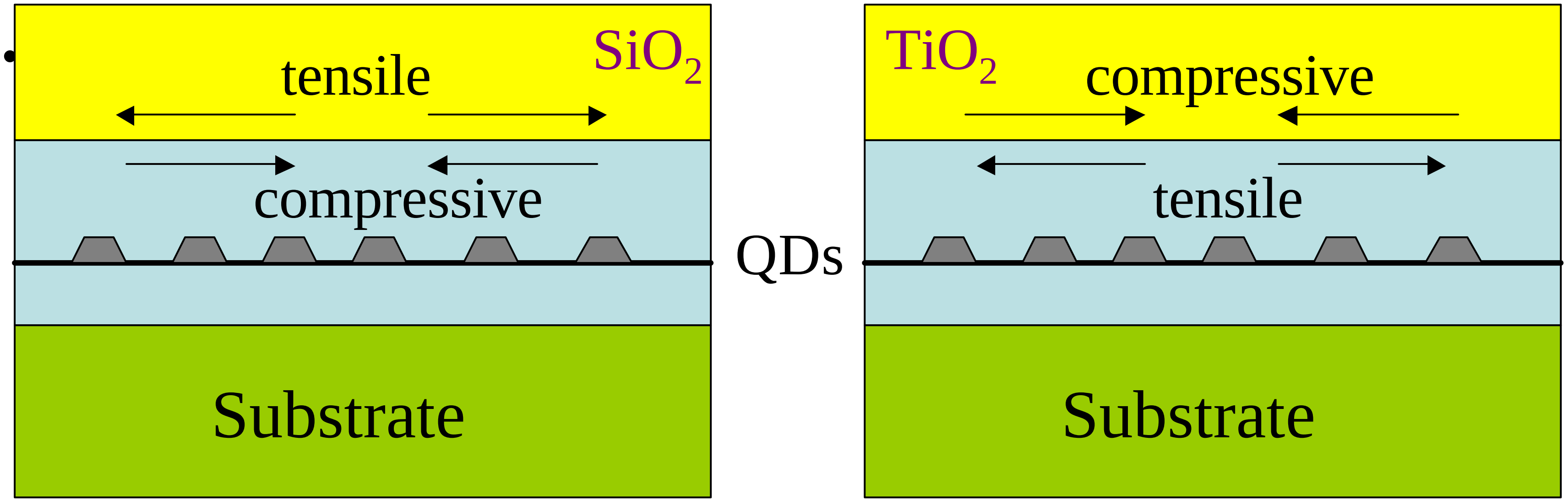
Thermal stress effect



Compressive stress on GaAs surface Þ favourable for V_{Ga} diffusion Þ enhanced interdiffusion

Tensile stress on GaAs surface Þ unfavourable for V_{Ga} diffusion Þ inhibited interdiffusion

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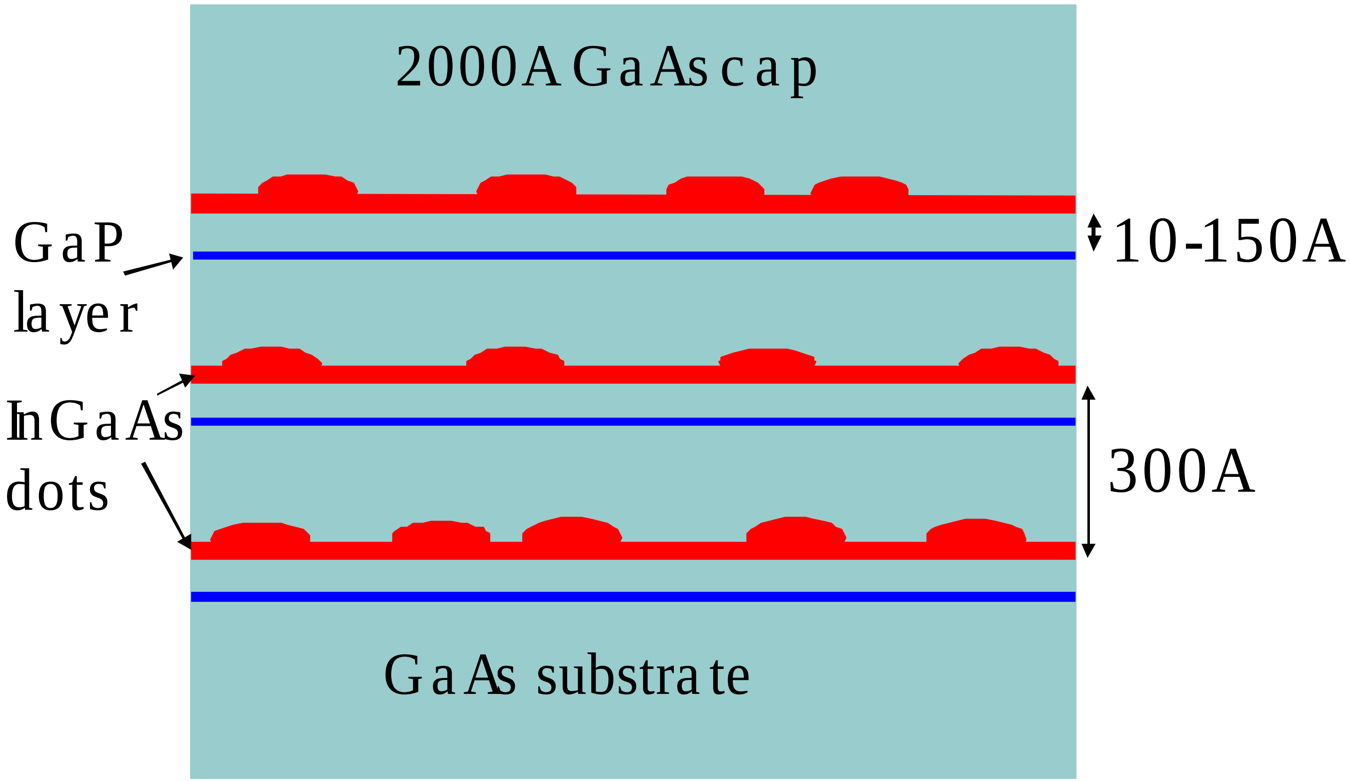
Stacked Dots



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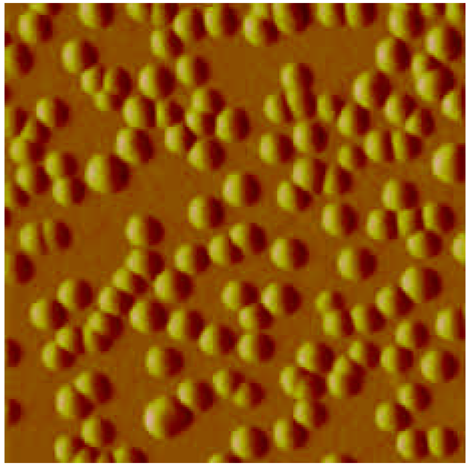
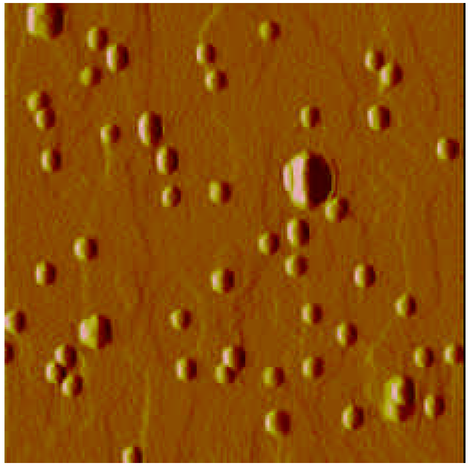
Growth of stacked layers



Single Layer

Density
~$4x10^{10}/cm^2$

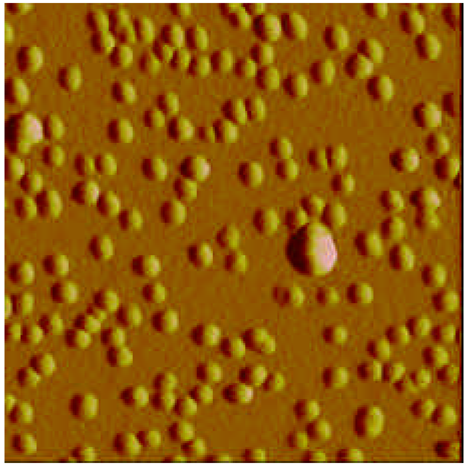


Top layer of 3-layer stack.

Original conditions

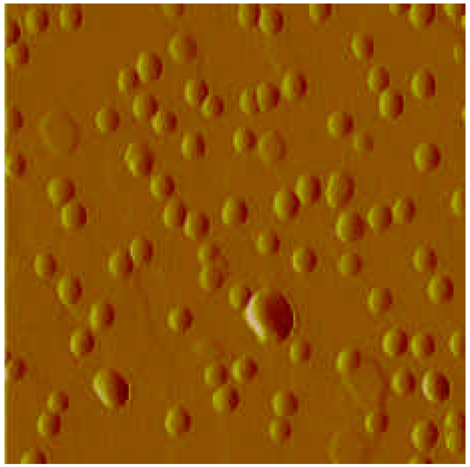
Dots smaller than for single layer.

Density
~$2x10^{10}/cm^2$



Top layer of 3-layer stack.
With smoothing

Density
~$4x10^{10}/cm^2$



Top layer of 3-layer stack.
Low V/III, with GaP layers.
Dots slightly flatter.

Density
~$3x10^{10}/cm^2$

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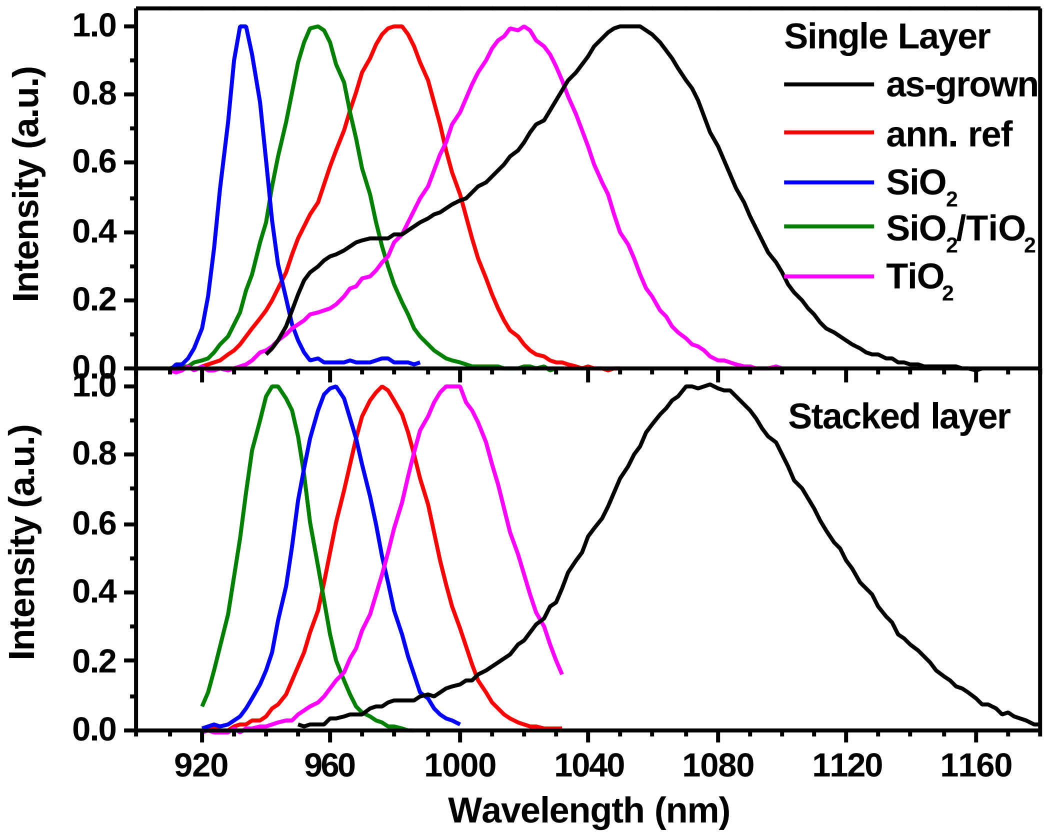
IFVD of stacked QDs



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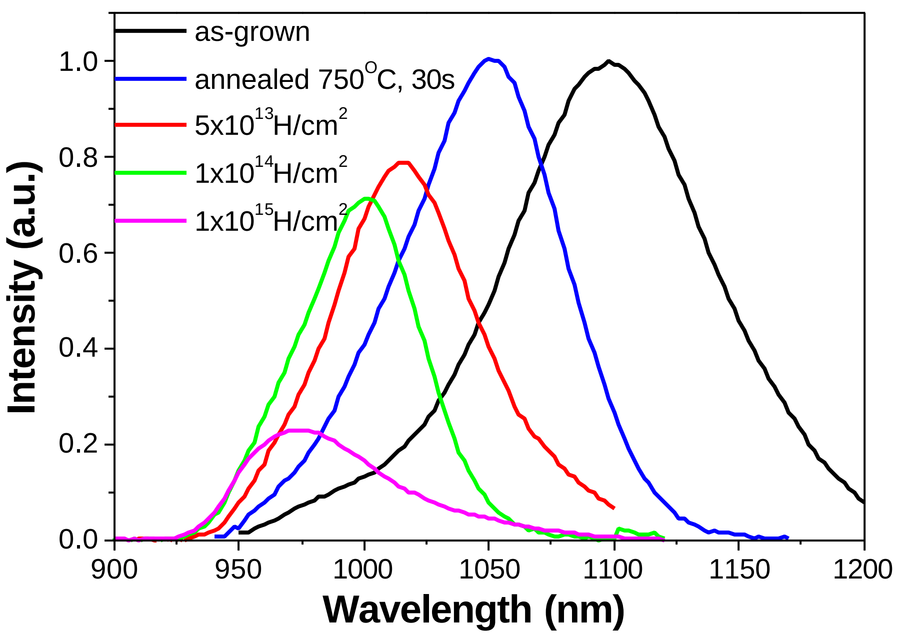
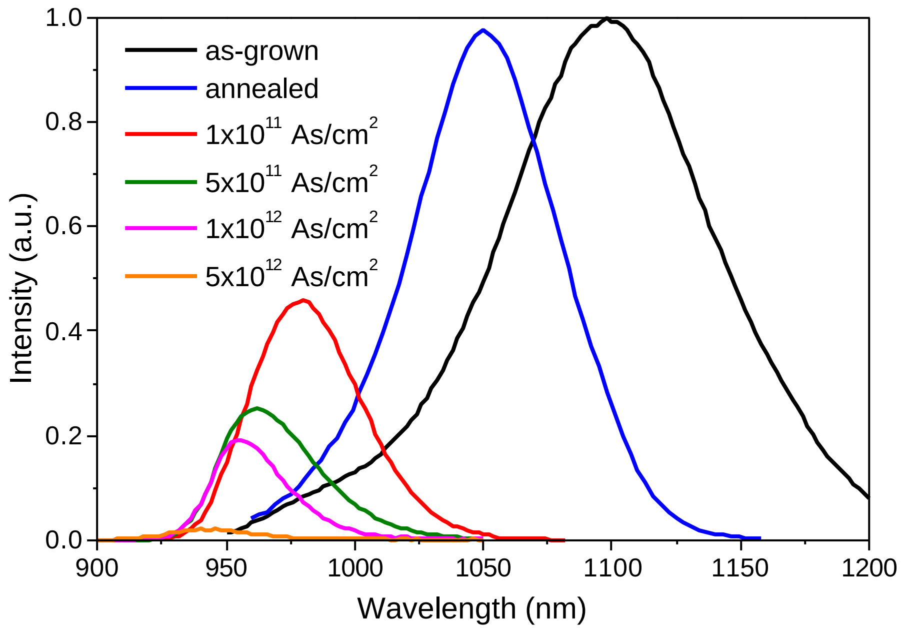
Implantation
(Single QD Layers)

Protons



Arsenic Ions



P. Lever, Appl. Phys. Lett. 82, 2053 (2003)

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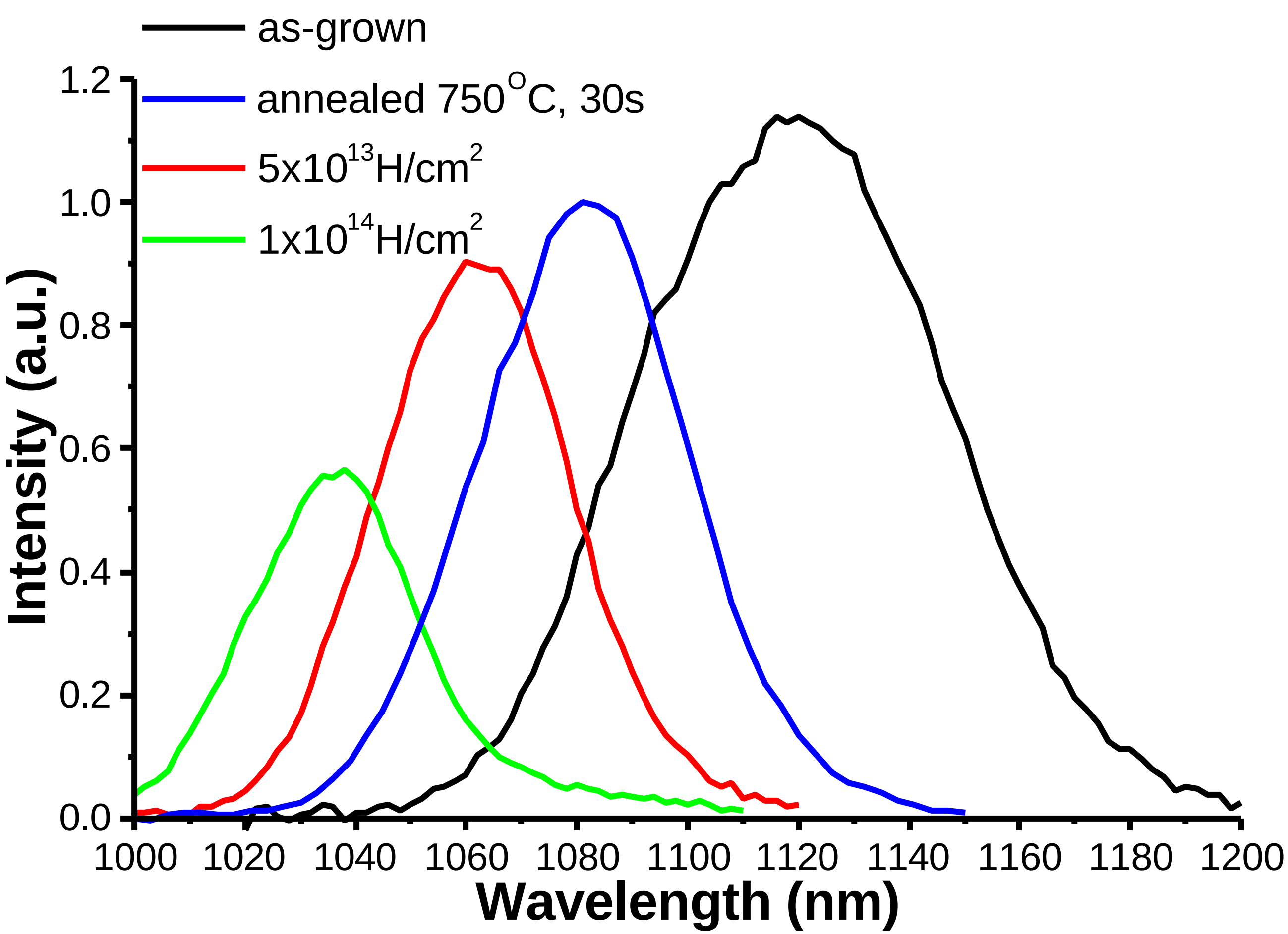
Stacked QDs -H implant



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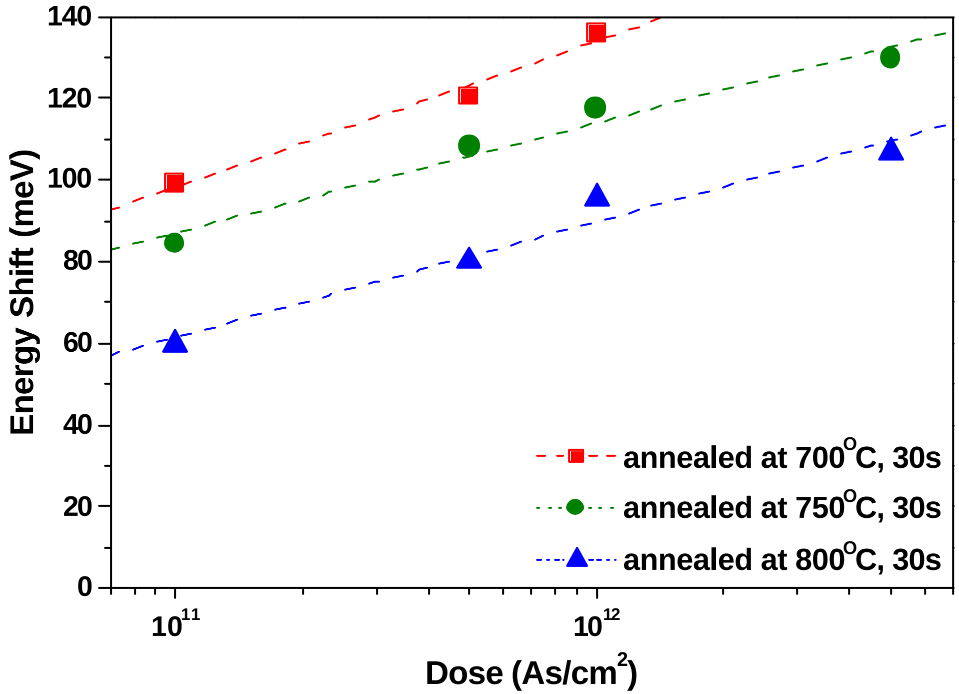
Energy Shifts – As Ion Dose, Annealing Temperature (Single Layer of QDs)



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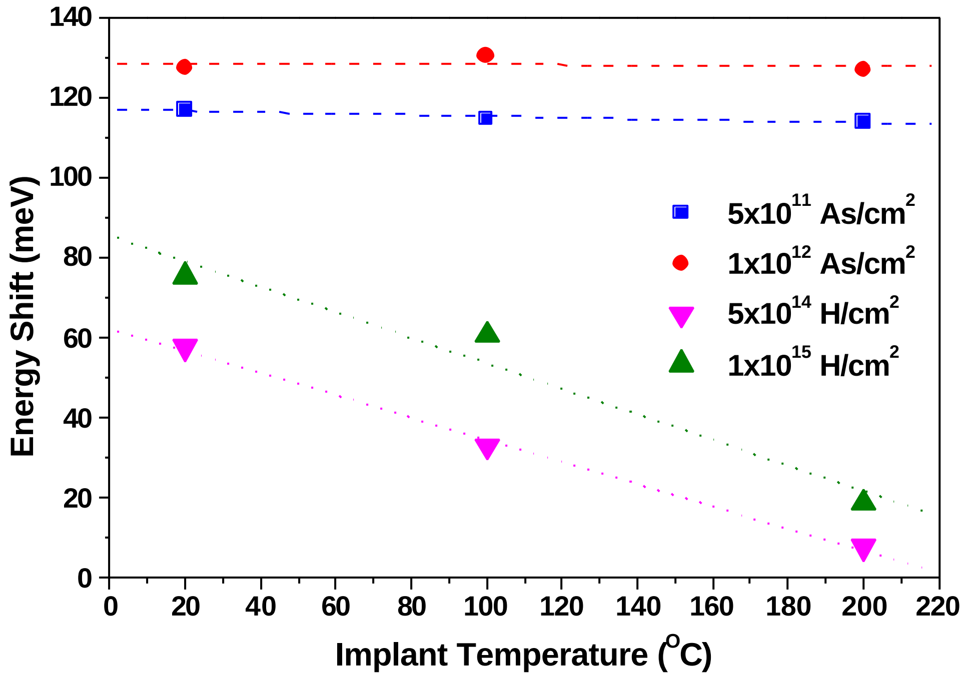
Energy Shifts vs Implant Temperature
(Protons and Arsenic Ions)



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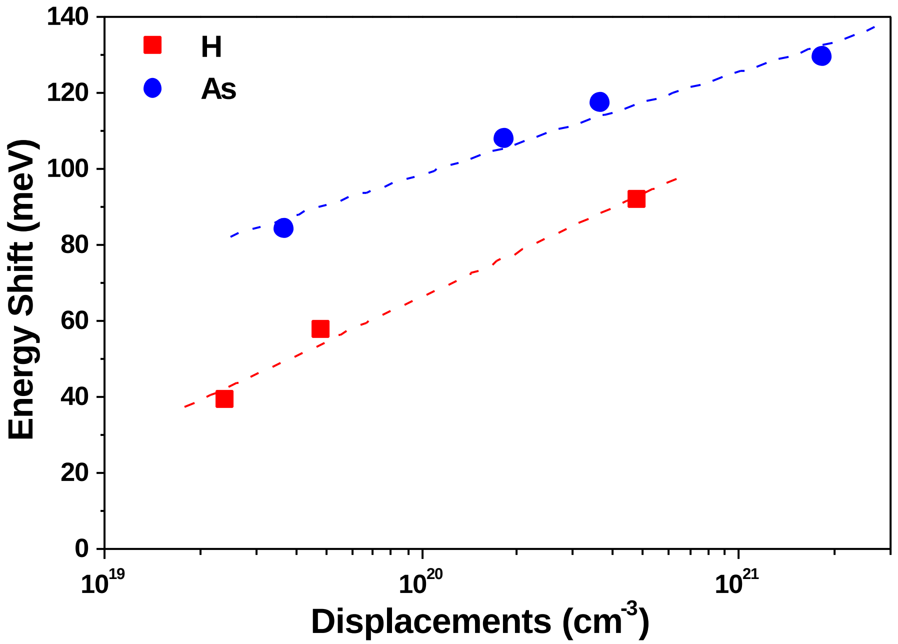
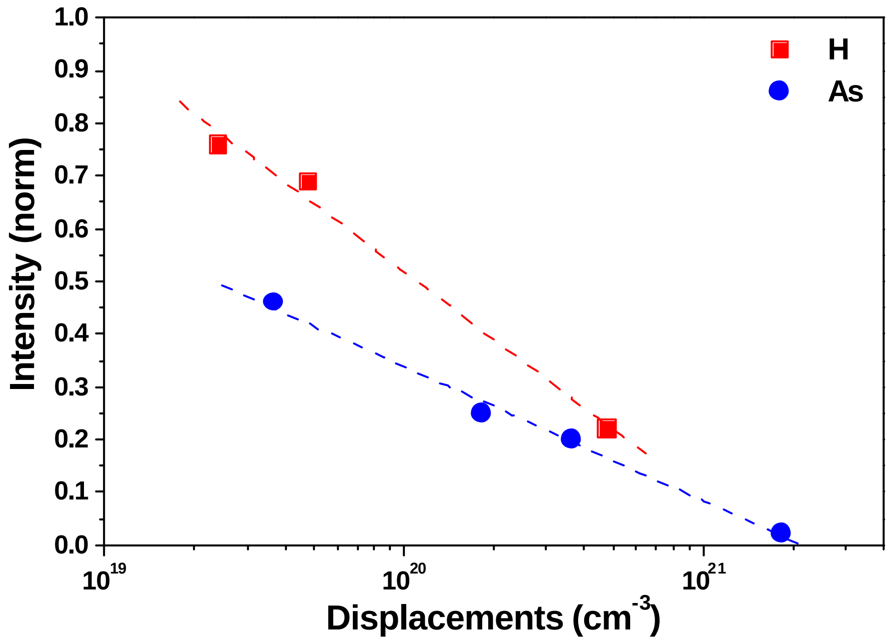
Energy Shift and PL Intensity Vs. Displacement Density





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Summary

Quantum Well and Quantum Dot Intermixing Techniques are promising for Optoelectronic Device Integration

Understanding defect generation, diffusion and annihilation processes are important for achieving QWI and QDI

Dopant diffusion issues need to be taken into consideration for Device Structures such as Lasers and Photodetectors

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