The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR/1758-19

**"Workshop on Ion Beam Studies of Nanomaterials:
Synthesis, Modification and Characterization"**

26 June - 1 July 2006

Quantum Wells/Dots & Nanowires for Optoelectronic Device Applications

Michael Q. Gao
Dept. of Electronic Materials Engineering
The Australian National University
Canberra, Australia

Quantum Wells/Dots and Nanowires for Optoelectronic Device Applications

Michael Q. Gao, H. Hoe Tan, Chennupati Jagadish

(Michael_Gao@ieee.org)

Department of Electronic Materials Engineering

Research School of Physical Sciences and Engineering

The Australian National University, Canberra, Australia

The Group

Few people are missing
(M. Buda, Y. Kim, Q. Gao, J. Wong-Leung, H. Hattori)

Overview

- Introduction
- Growth of Quantum Dots by Metal Organic Chemical Vapour Deposition (MOCVD)
- Towards Quantum Well/Dot Photonic Integrated Circuits
  - Intermixing (QW/QD) by ion implantation
  - Quantum Well/Dot Lasers
  - Quantum Well/Dot Infrared Photodetectors (QDIPs)
- Carrier lifetime Modification by Ion Implantation for untra-fast detectors and THz emitters
- Nanowires
- Summary

Overview

- **Introduction**
- Growth of Quantum Dots by Metal Organic Chemical Vapour Deposition (MOCVD)
- Towards Quantum Well/Dot Photonic Integrated Circuits
  - Intermixing (QW/QD) by ion implantation
  - Quantum Well/Dot Lasers
  - Quantum Well/Dot Infrared Photodetectors (QDIPs)
- Carrier lifetime Modification by Ion Implantation for untra-fast detectors and THz emitters
- Nanowires
- Summary

Optoelectronics

Compound Semiconductors – GaAs, GaP, GaN, AlAs, InAs, InP, InN, AlN, ZnO

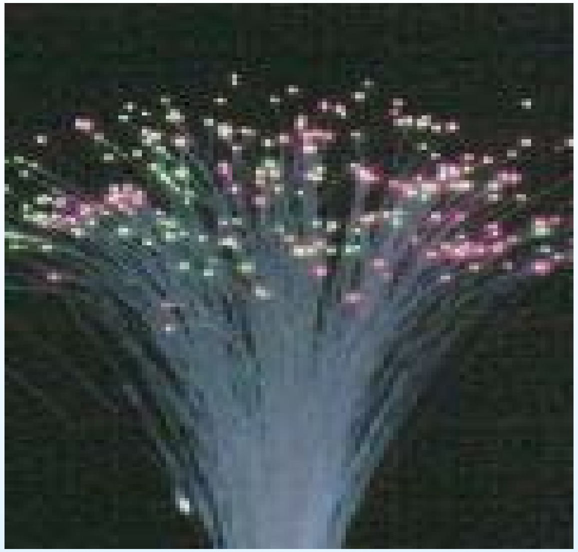
LEDs for Lighting Applications

J. Pankove
I. Akasaki
S. Nakamura

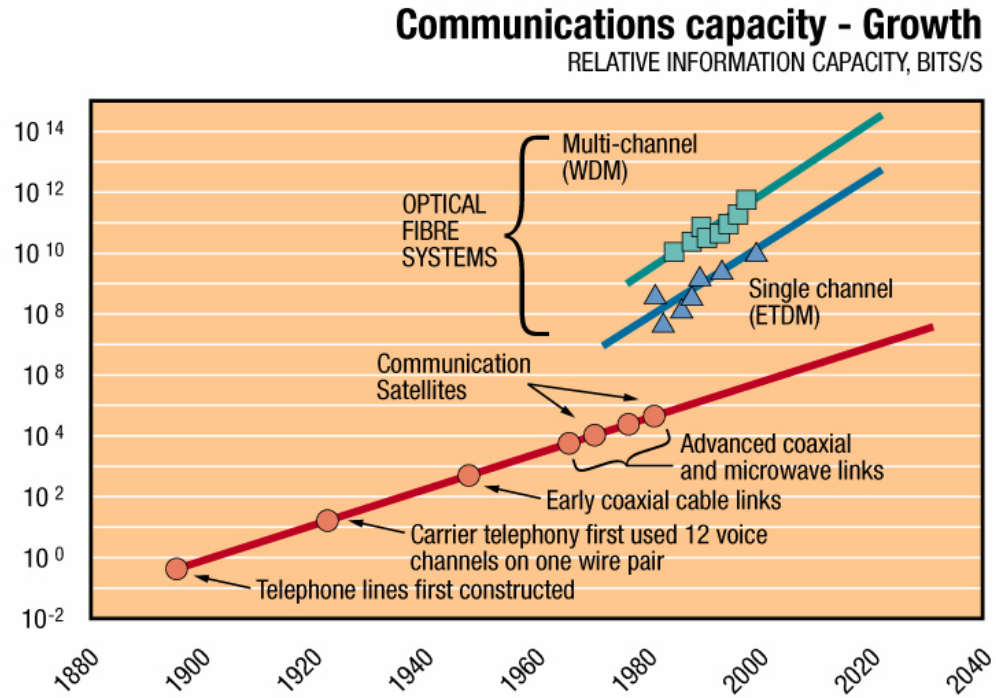
II	III	IV	V	VI
Be	B	C	**N**	O
Mg	**Al**	Si	**P**	S
Zn	**Ga**	Ge	**As**	Se
Cd	**In**	Sn	**Sb**	Te
Hg	Tl	Pb	Bi	Po

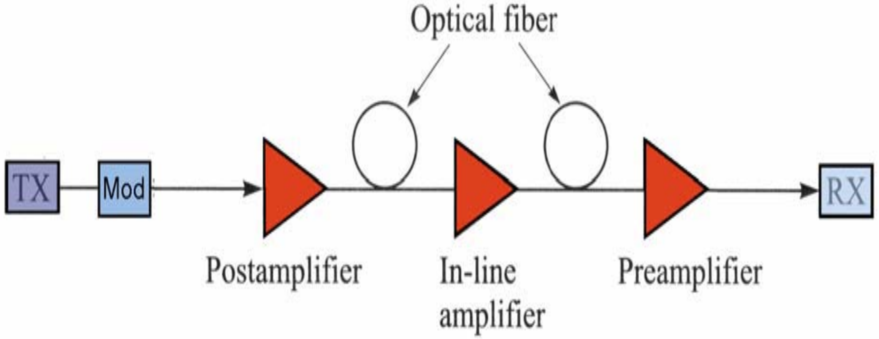
Source: Osram, Corning, Sony, Jim Harris, Joe Campbell

Optical Fiber Communications



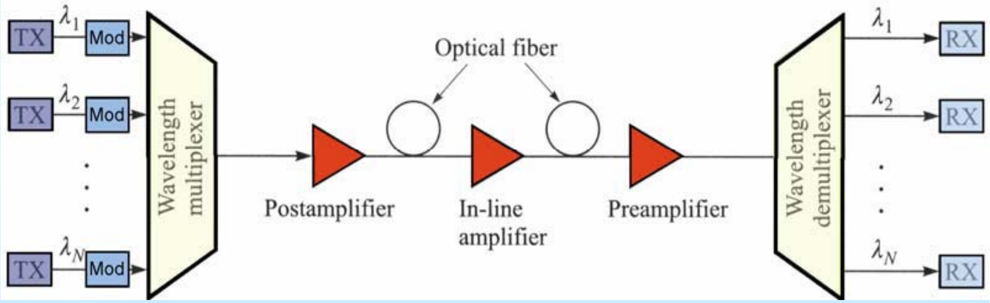
Lasers, Modulators, Photodetectors
1310 and 1550 nm





Single Channel Optical Link

Wavelength Division Multiplexing



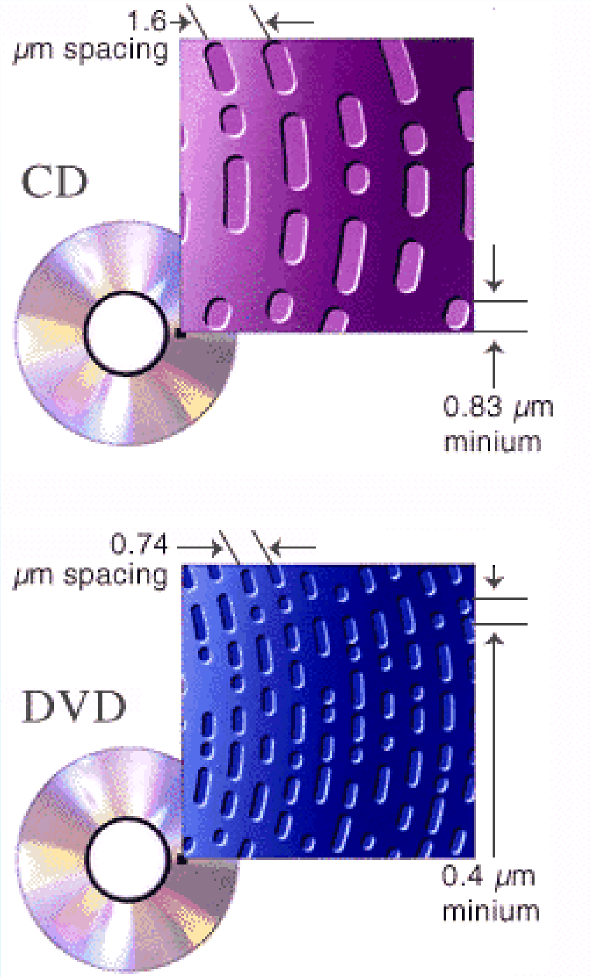
High Density

Data Storage / Entertainment

CDs (780 nm - Infrared)

DVDs (650 nm - Red)

HD-DVDs (405 nm- Violet)

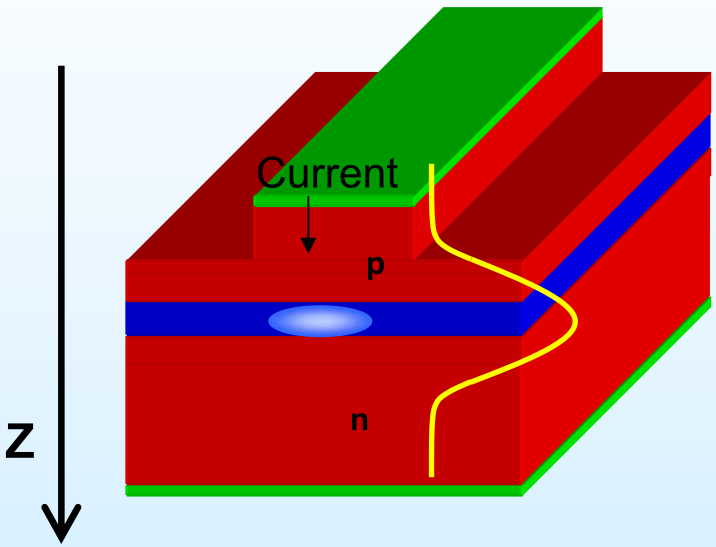


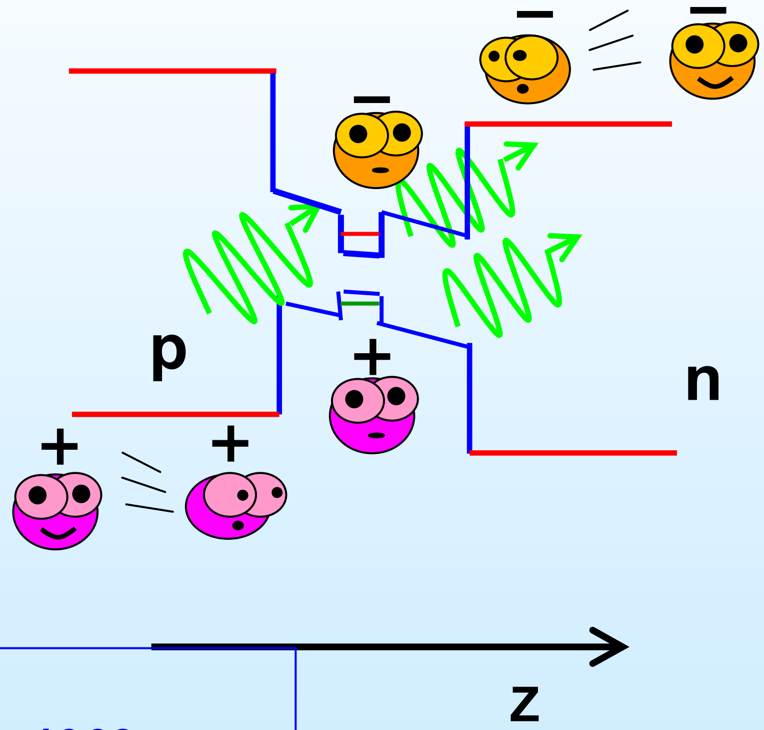
Infra-red Photodetectors

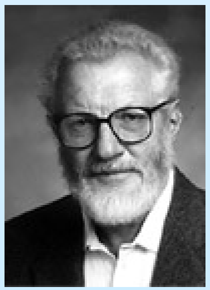
Long-wavelength infrared radiation detection (2-30μm):

- **Applications**
  - Thermal imaging, night vision, space ranging, thermal analysis, atmospheric sensing
- **Type of semiconductor detectors**
  - Intrinsic: HgCdTe, InSb, PbS, PbSe
  - Extrinsic: Si:In, Si:Ga, Si:As
  - Intersubband transition (III-V): QWIPs
- **Advantages of QWIPs (and QDIPs)**
  - Mature epitaxial and fabrication technologies
  - High degree of uniformity
  - Easy to fabricate large arrays and monolithic integration
  - Lower cost

How a Semiconductor Laser Works?

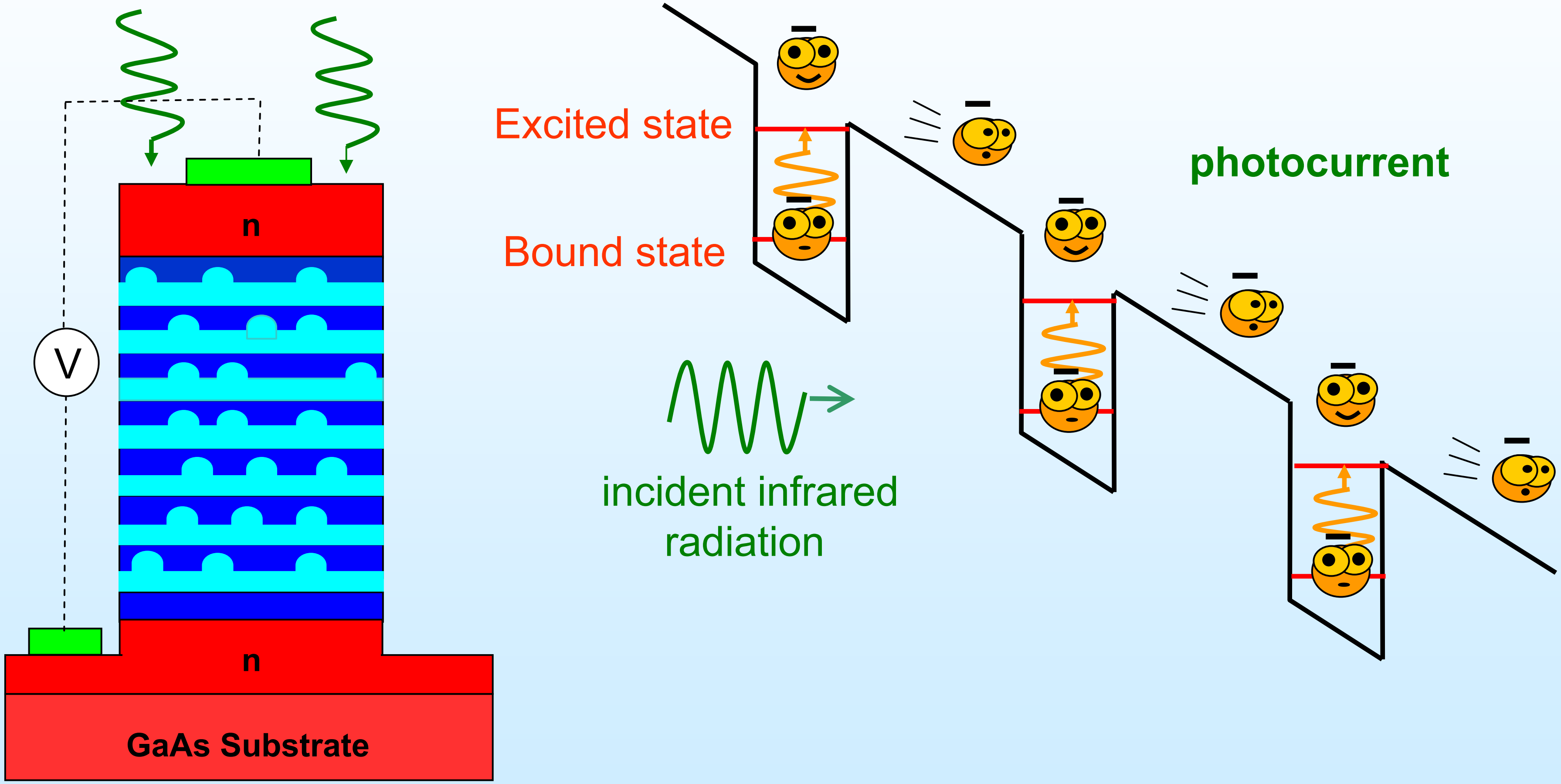




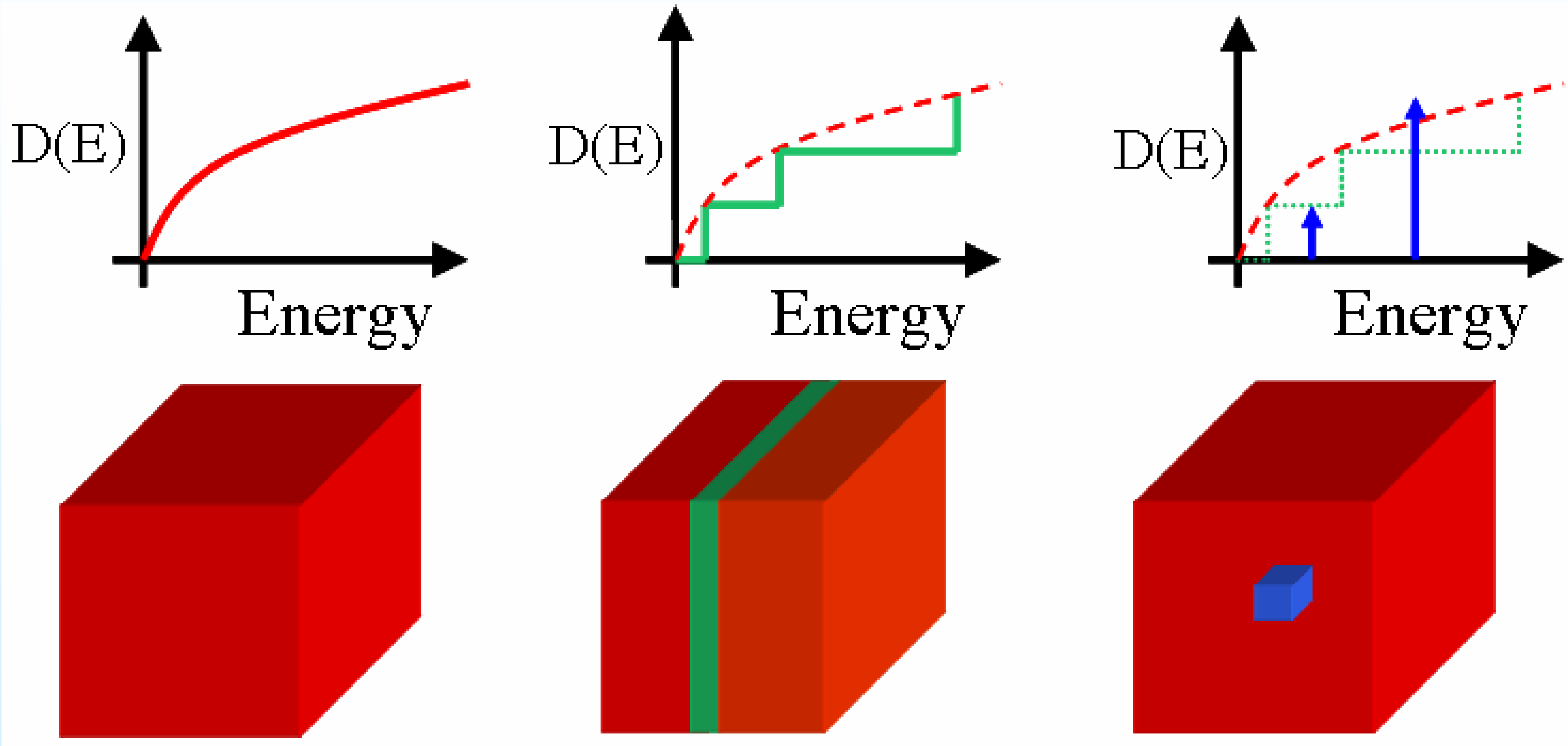


Zhores Alferov,
Herbert Kroemer, 1963
2000 Nobel Prize for Physics

How a QW/QD Infrared Detector (QDIP) Works?



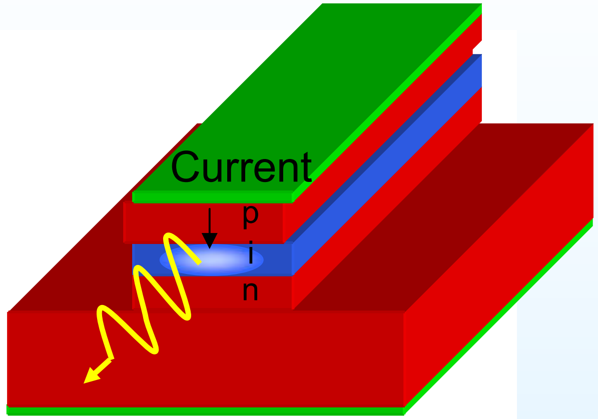
Why Quantum Dots?



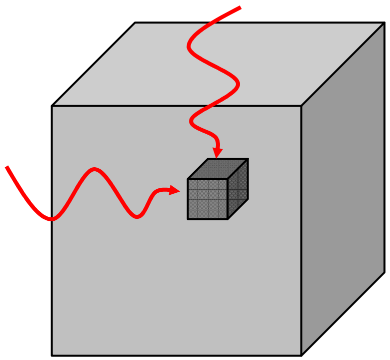
3D Carrier Confinement in QDs Leads to Atom-Like Density of States

QD Optoelectronic Devices

- **Lasers**
  - **reduced threshold current**
  - **increased differential gain (gain per injected electron)**
  - **less temperature sensitive threshold current and emission wavelength**
  - **longer wavelength VCSELs (1.3 and 1.55 um)**



- **Infrared Photodetectors (Inter sub-band)**
  - **normal incidence operation**
  - **higher detector responsivity**
  - **higher operating temperature**



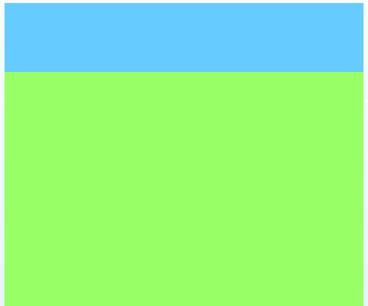
QDIPs: Normal incidence detection

Overview

- Introduction
- **Growth of Quantum Dots by MOCVD**
- Towards Quantum Well/Dot Photonic Integrated Circuits
  - Intermixing (QW/QD) by ion implantation, IFVD
    - Quantum Well/Dot Lasers
    - Quantum Well/Dot Infrared Photodetectors (QDIPs)
- Carrier lifetime Modification by Ion Implantation for untra-fast detectors and THz emitters
- Nanowires
- Summary

Self-assembled Growths of Quantum Dots

Frank-van der Merwe

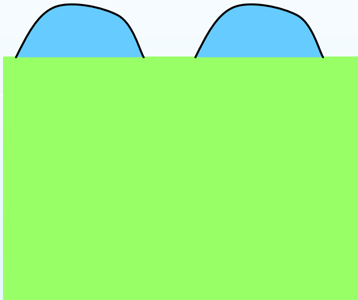


Layer by Layer

Lattice matched systems

(AlGaAs on GaAs)

Volmer-Weber

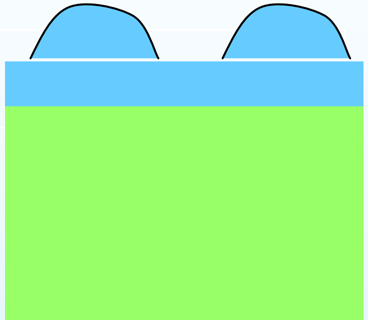


Direct Island

Large lattice mismatch
Very high interfacial energy

(GaN on Sapphire)

Stranski-Krastanow



Layer by layer, then Island nucleation

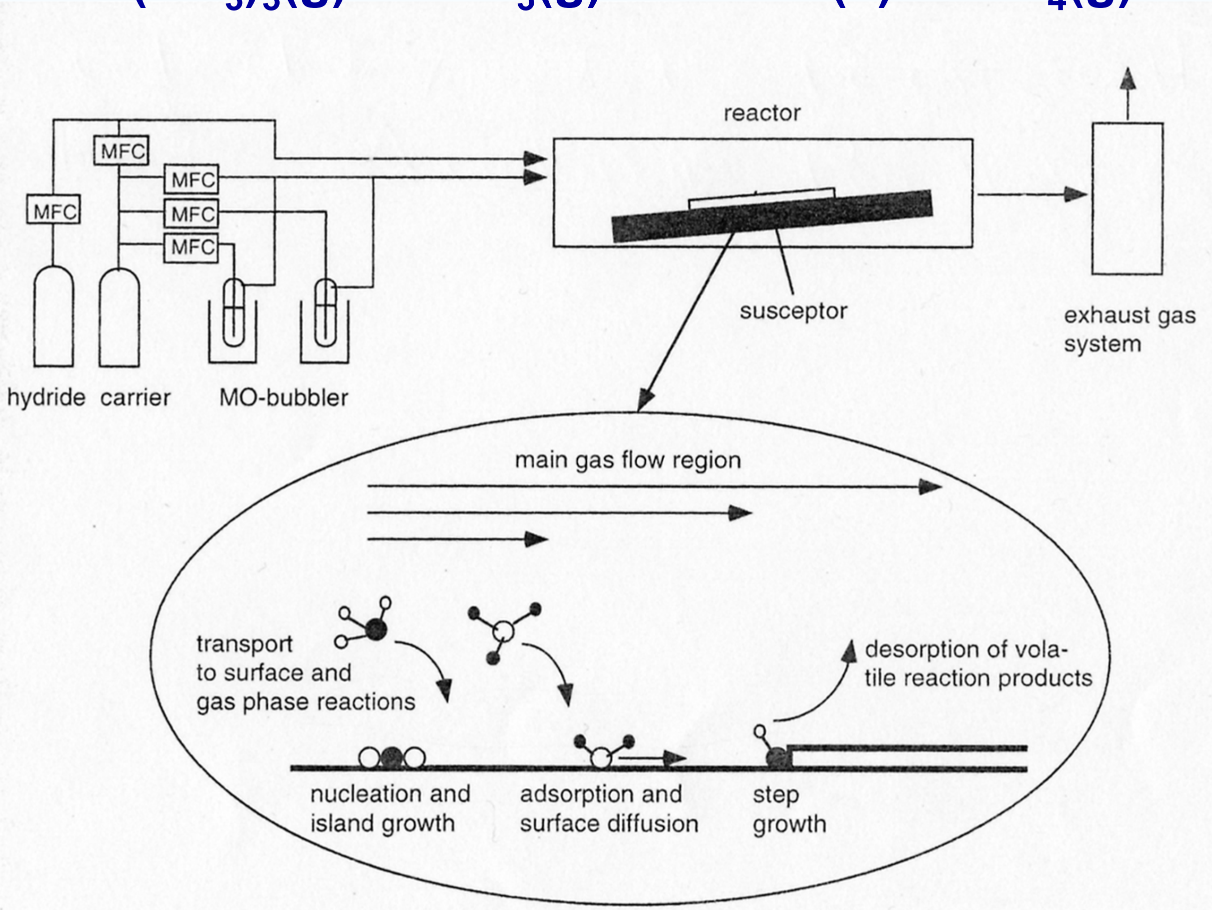
Dissimilar lattice spacing, low interfacial energy

(In(Ga)As on GaAs)

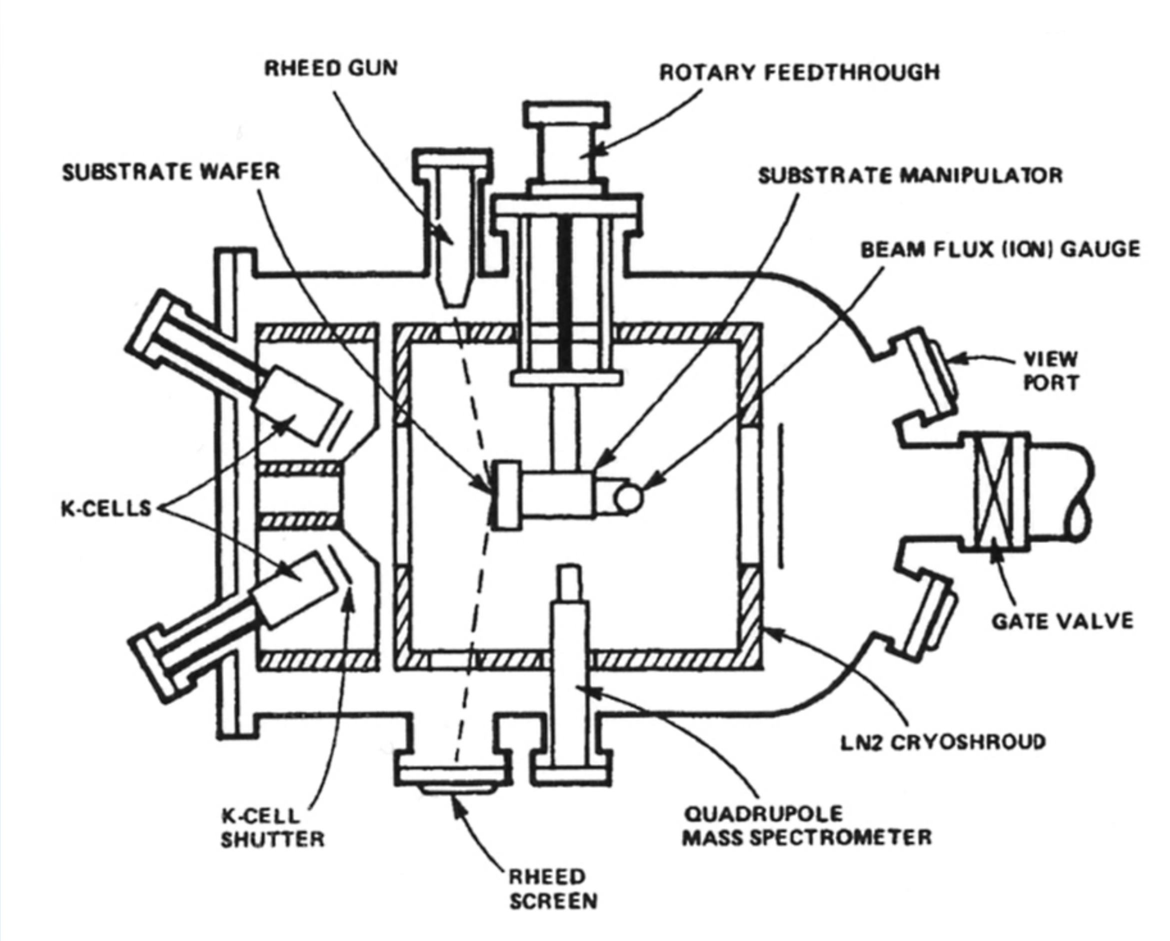
Metal Organic Chemical Vapour Deposition (MOCVD)

$$Ga(CH_3)_3(g) + AsH_3(g) \rightarrow GaAs(s) + 3CH_4(g)$$

$$In(CH_3)_3(g) + AsH_3(g) \rightarrow InAs(s) + 3CH_4(g)$$

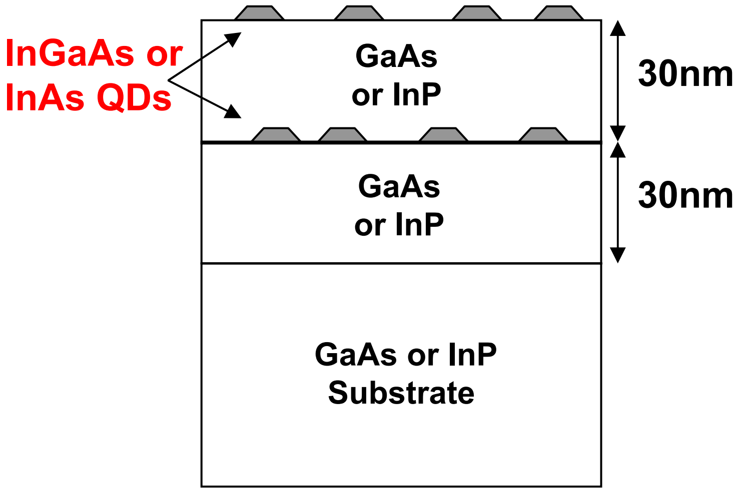


Molecular Beam Epitaxy (MBE)



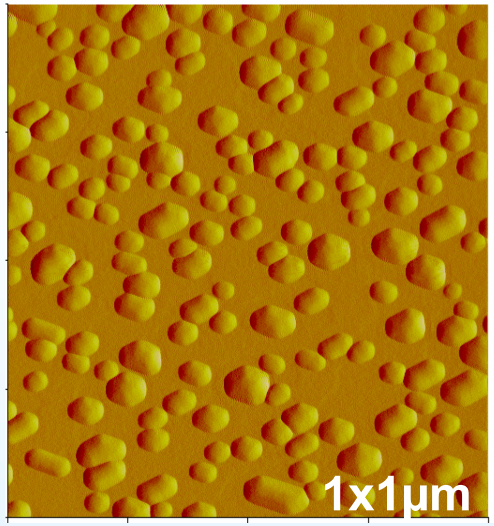
MOCVD - high T growth and lack of in-situ monitoring

- Aixtron 200/4 MOCVD reactor
- TMGa, TMAl, TMIn, AsH_3,PH_3 (Dissociation of gases)
- $In_{0.5}Ga_{0.5}As$, InAs Quantum dots
- Dot growth ~500-550°C, Other layers at 600-650°C
- AFM (surface dots) and PL (buried dots)



Growth Parameters

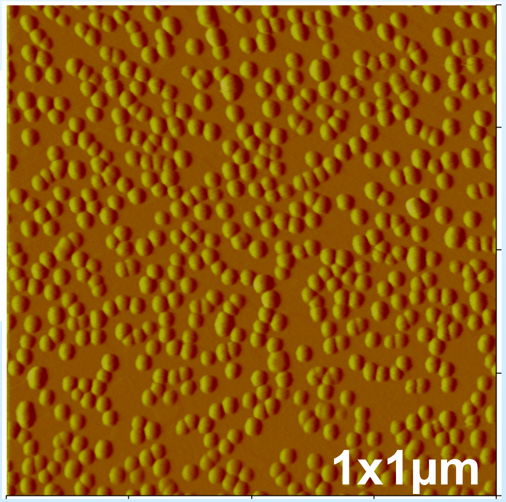
Amount of Material (Size and Density)
Growth Temperature (Adatom Mobility, Size & Density)
Growth Rate (Size and Density)
V/III Ratio (Adatom Mobility, Atomic Hydrogen)



InAs/InP QDs

Desired Properties

High density of smaller coherent islands
Good size uniformity
Minimize / avoid formation of dislocated large islands



InGaAs/GaAs QDs

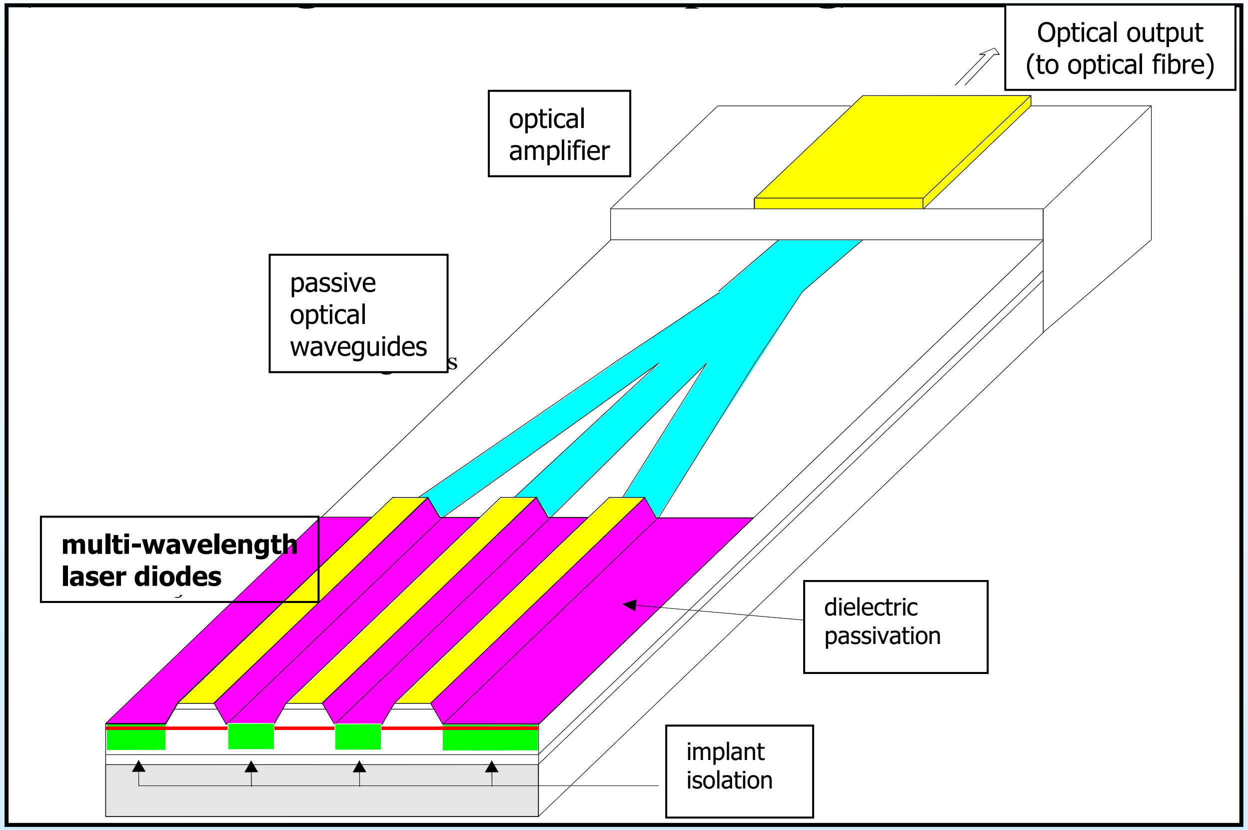
Overview

- Introduction
- Growth of Quantum Dots by MOCVD
- **Towards Quantum Well/Dot Photonic Integrated Circuits**
  - Intermixing (QW/QD) by ion implantation
  - Quantum Well/Dot Lasers
  - Quantum Well/Dot Infrared Photodetectors (QDIPs)
- Carrier lifetime Modification by Ion Implantation for untra-fast detectors and THz emitters
- Nanowires
- Summary

Photonic Integrated Circuits / Optoelectronic Integrated Circuits

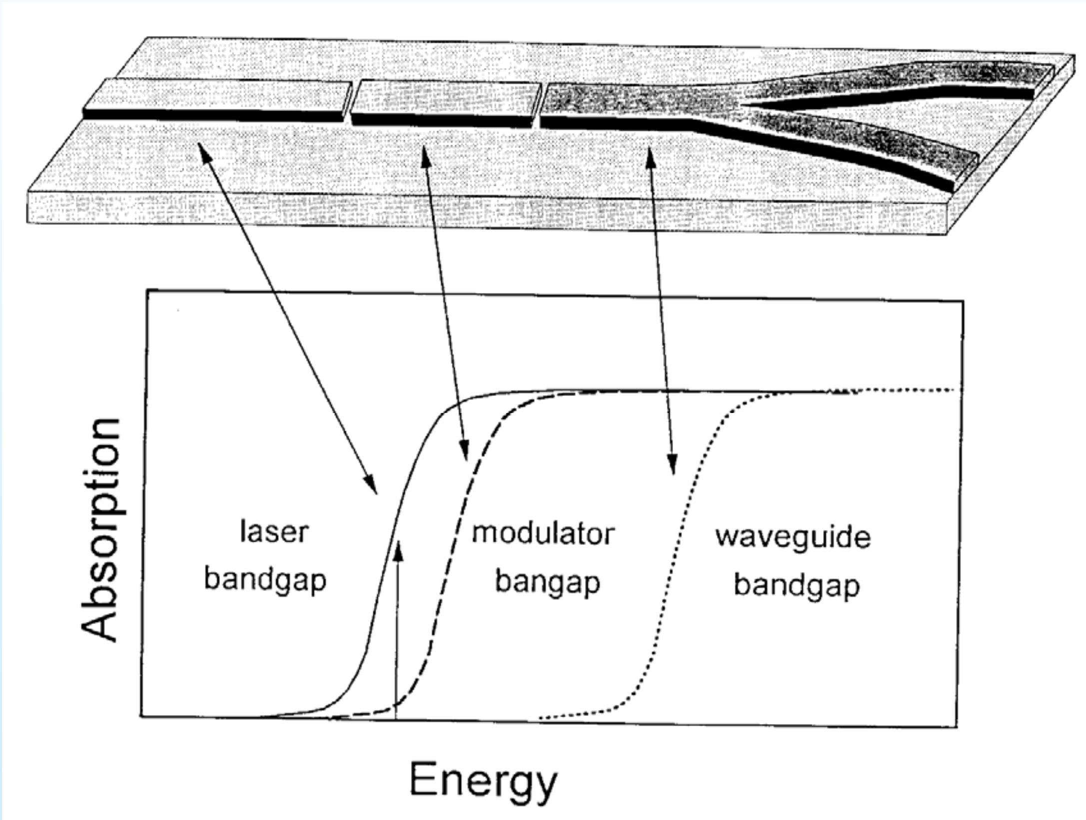
- Integrated Circuits Show Superior Performance Over Discrete Devices
- Multi-functional circuits, e.g. WDM sources
- Integrated Transceivers
- Low Cost, Packaging

WDM


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

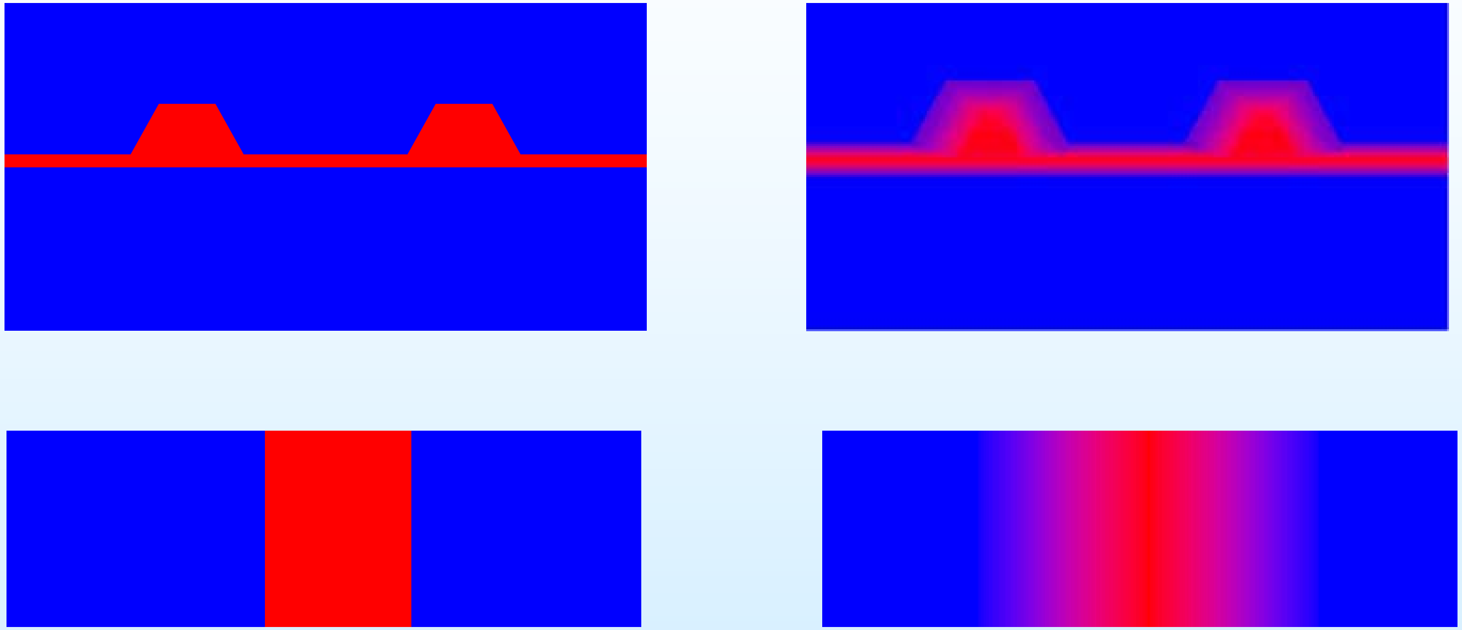
Photonic Integrated Circuits

Different Bandgaps on the same chip



Quantum Well/Dot Intermixing / Selective Area Epitaxy

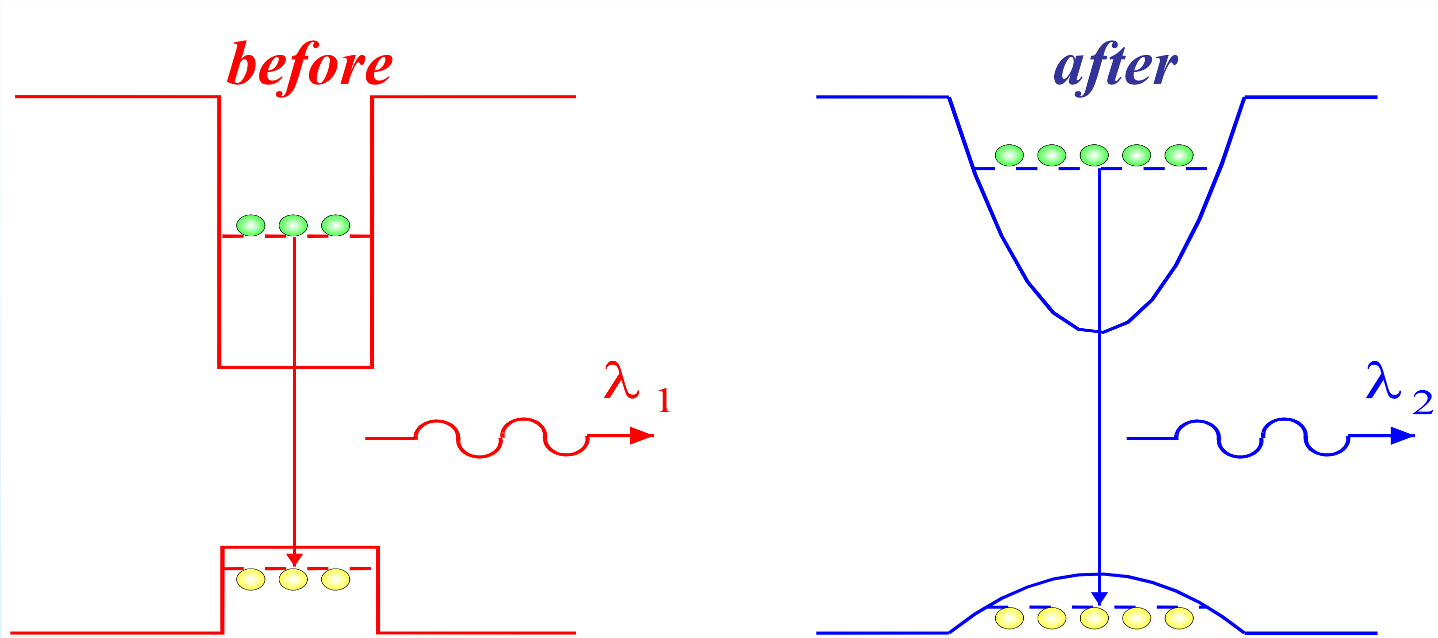
Quantum Well/Dot Intermixing



before *after*

Non-uniform composition profile

Quantum Well/Dot Intermixing



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

•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 introduced by these methods enhance atomic interdiffusion

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

Why Ion Implantation?

Widely used in Microelectronics Industry

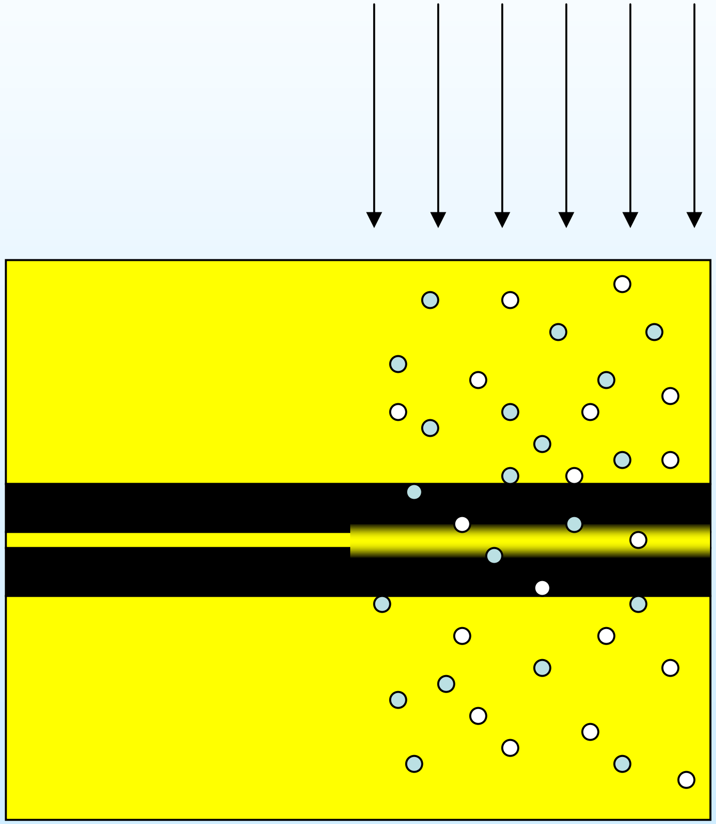
Defect Concentration

- Ion Dose, Ion Mass, Implant Temperature, Dose Rate

Defect Depth - Ion Energy

Selective Ion Implantation using Masks

Ion implantation induced quantum well/dot intermixing



Ion implantation

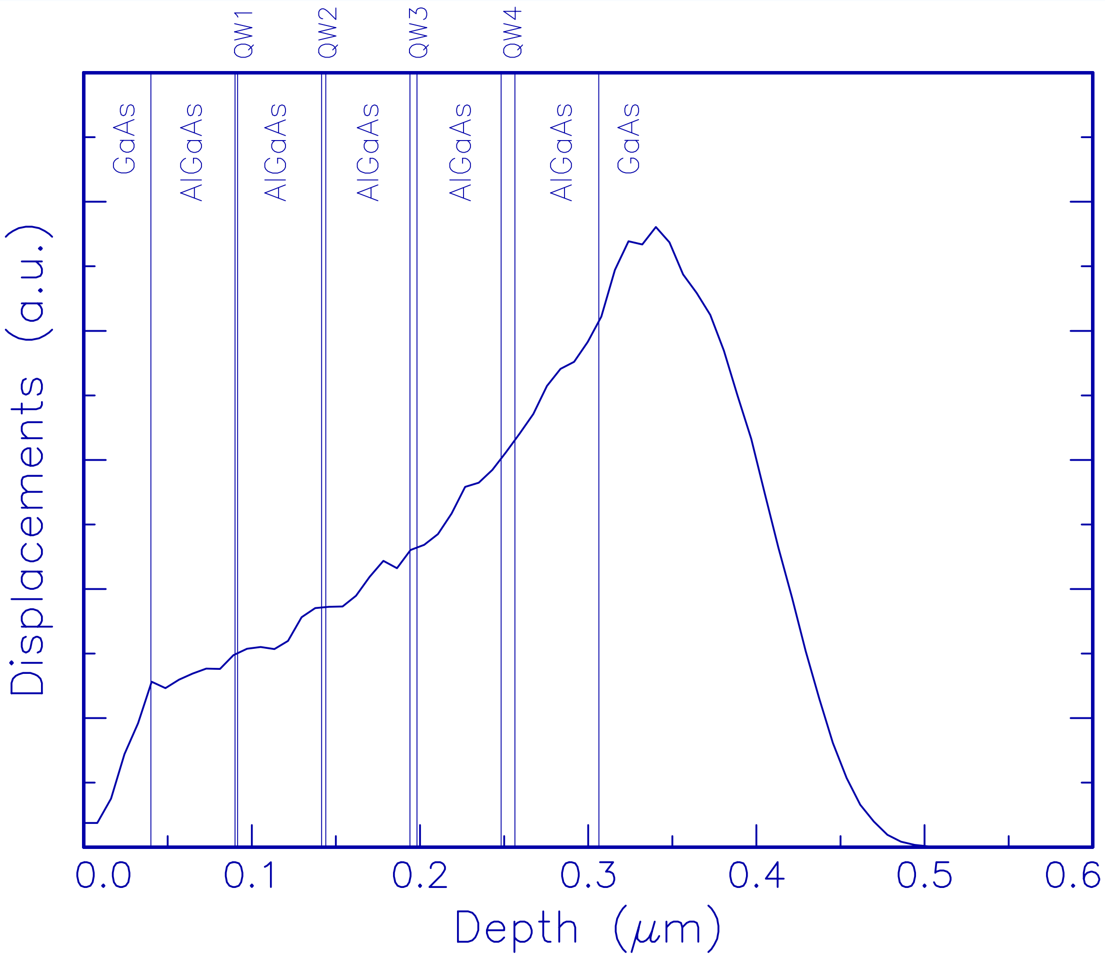
↓

Point defects:
- Vacancy
- Interstitial

↓

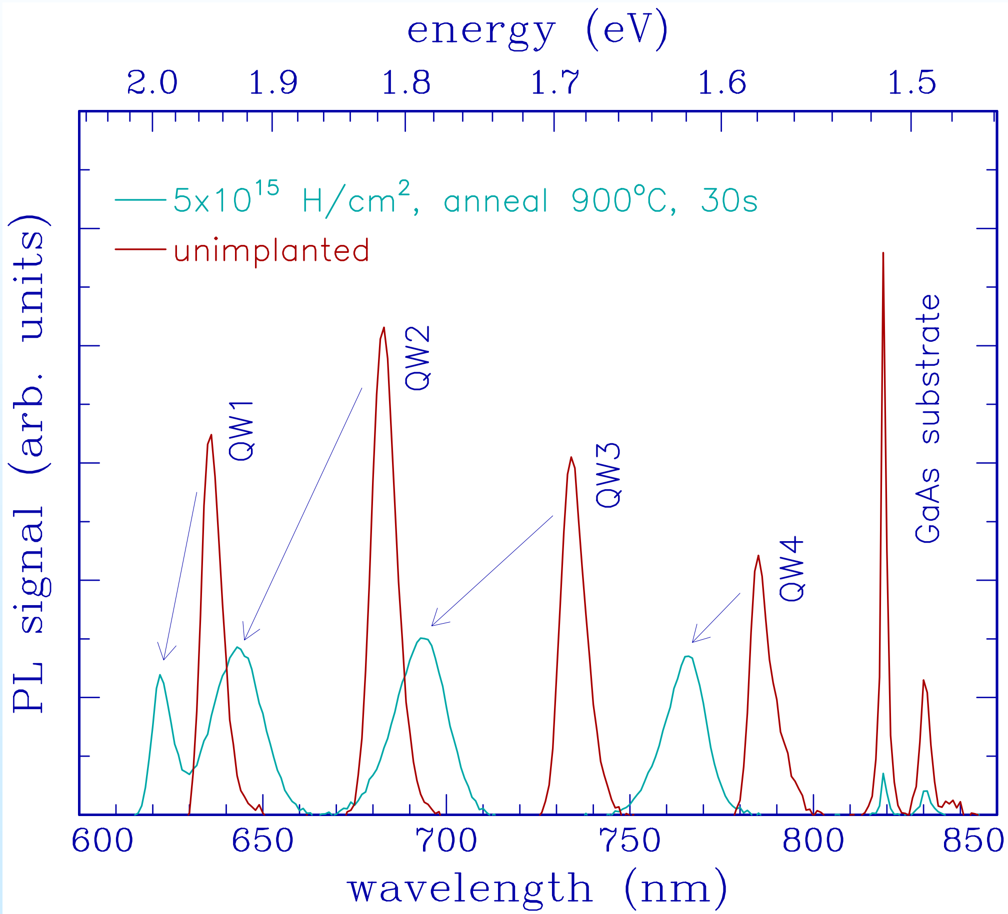
Intermixing

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

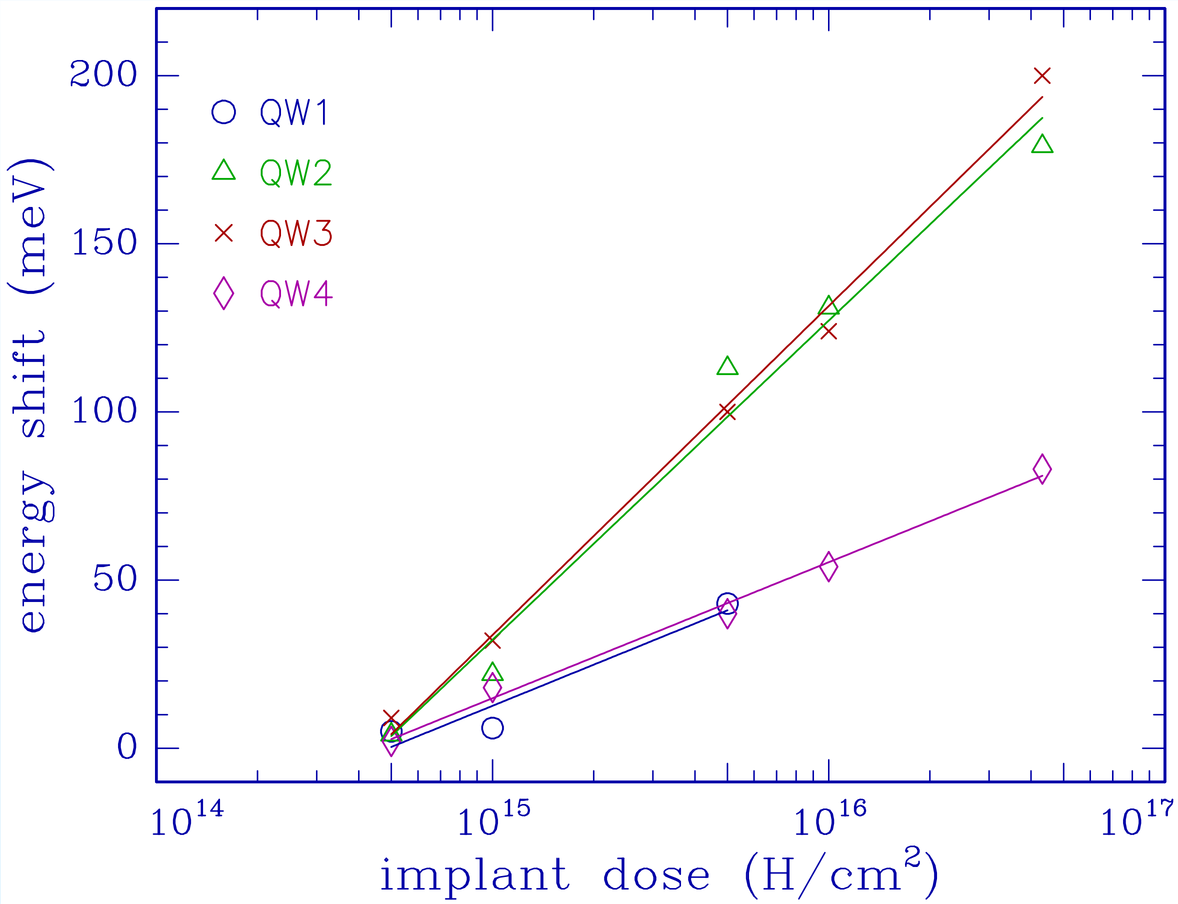
10K Photoluminescence Spectra



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

Energy Shifts vs. Proton Dose

900°C, 30 sec

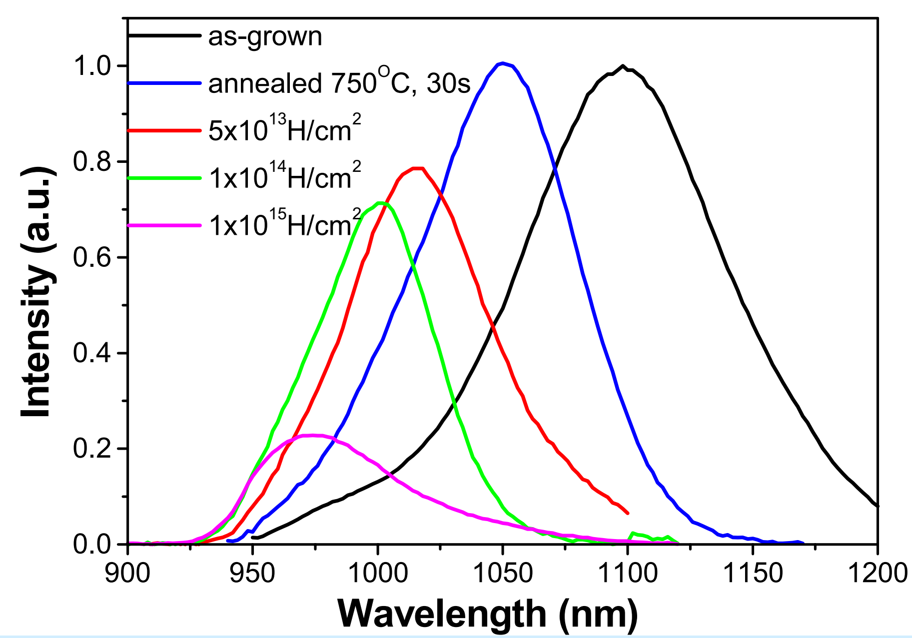


QW1 =1.4 nm
QW2=2.3 nm
QW3=4.0 nm
QW4=8.5 nm

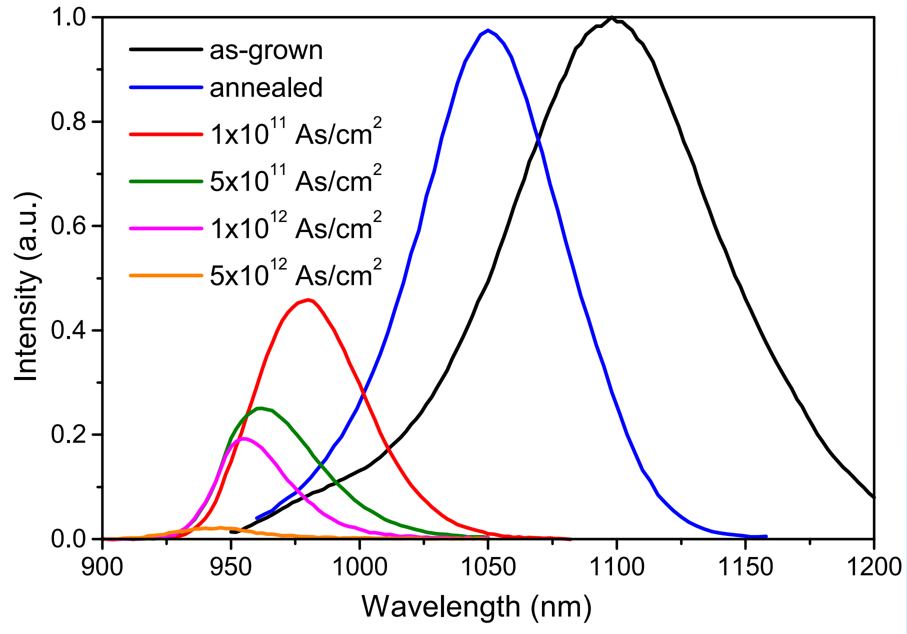
H.H. Tan et.al., Appl. Phys. Lett. 68, 2401 (1996).

Implantation Induced InGaAs QD Interdiffusion

Protons



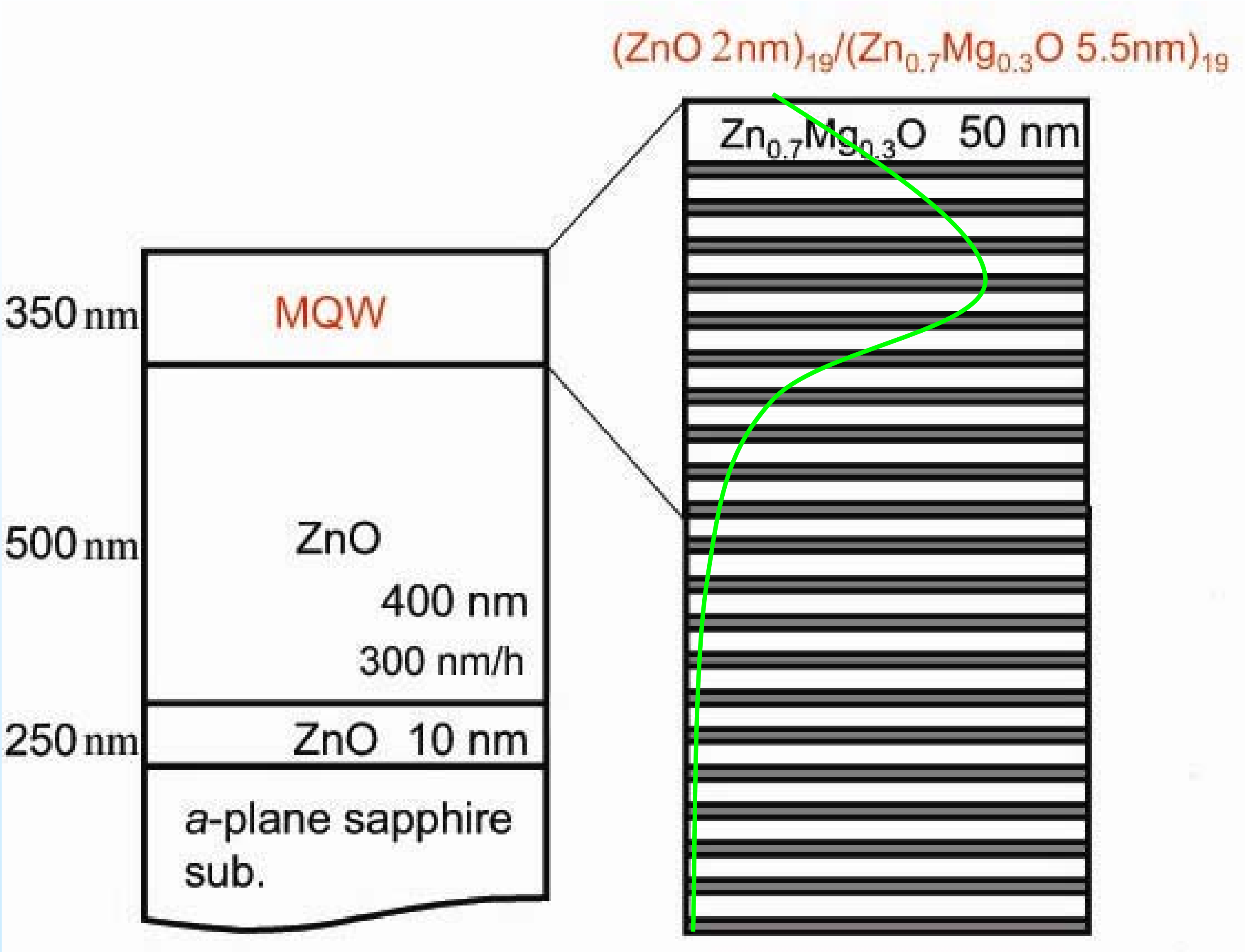
Arsenic Ions



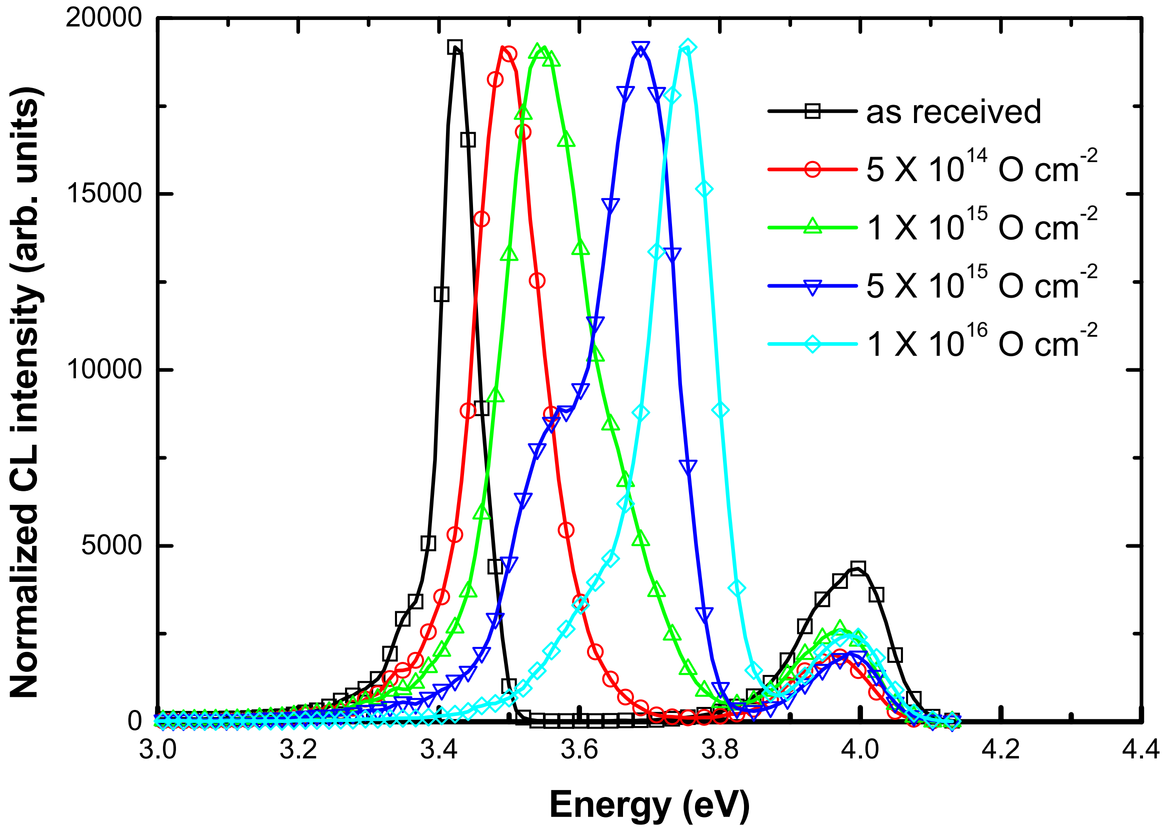
P. Lever et al, Appl. Phys. Lett. 82, 2053 (2003)

Low Dose – 80 keV O → $ZnO/Zn_{0.7}Mg_{0.3}O$

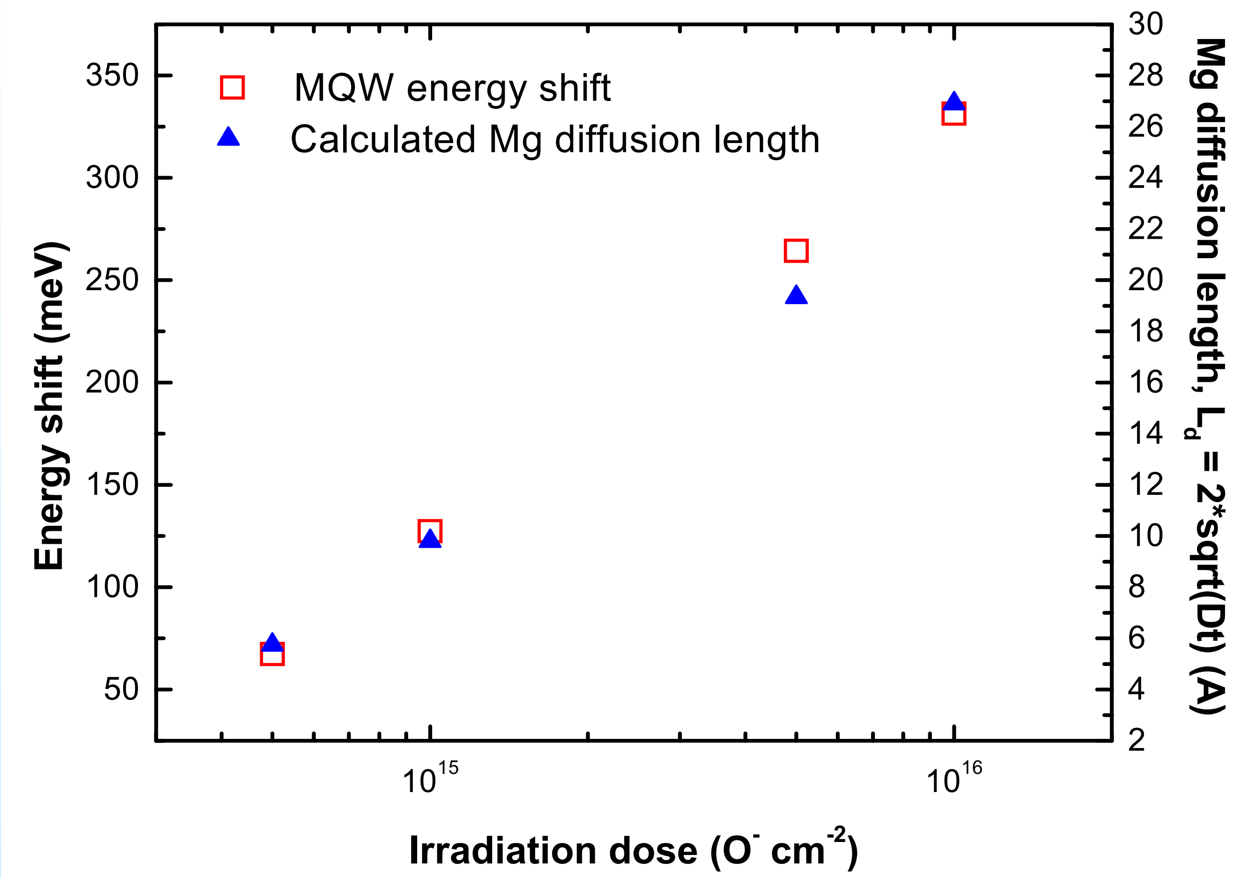
- Implanted a-axis epitaxial MQW ZnO(2 nm)/$Zn_{0.7}Mg_{0.3}O$(5.5 nm) sample with low energy oxygen ions. Low doses in the range 5 x 10^{14} $O^{-}cm^{-2}$ – 1 x 10^{16} $O^{-}cm^{-2}$
- Following implantation, MQW samples were annealed for 60 s at 800 ^{o}C under Ar ambient. Energy shifts, caused by interdiffusion of Mg and Zn species between the well and barrier were observed with CL spectroscopy
- Study on unimplanted MQW samples showed them to be thermally stable under this annealing regime, meaning that all observed changes arose as a result of defects introduced during implantation


(ZnO 2nm)19/(Zn0.7Mg0.3O 5.5nm)19
Zn0.7Mg0.3O 50 nm
350 nm
MQW
500 nm
ZnO
400 nm
300 nm/h
250 nm
ZnO 10 nm
a-plane sapphire
sub.

CL spectra of O implanted ZnO/ZnMgO MQW sample implanted with varying doses of O ions and RTA at 800 °C for 60s under Ar Ambient



Diffusion length, L_d and peak energy shift as a function of implantation dose

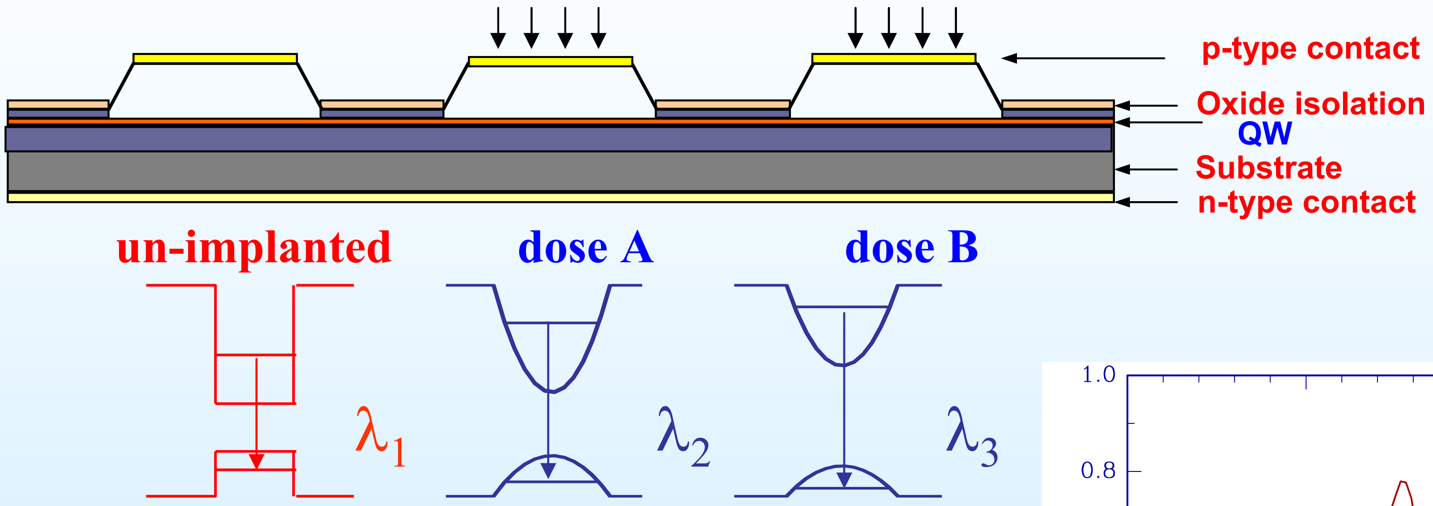


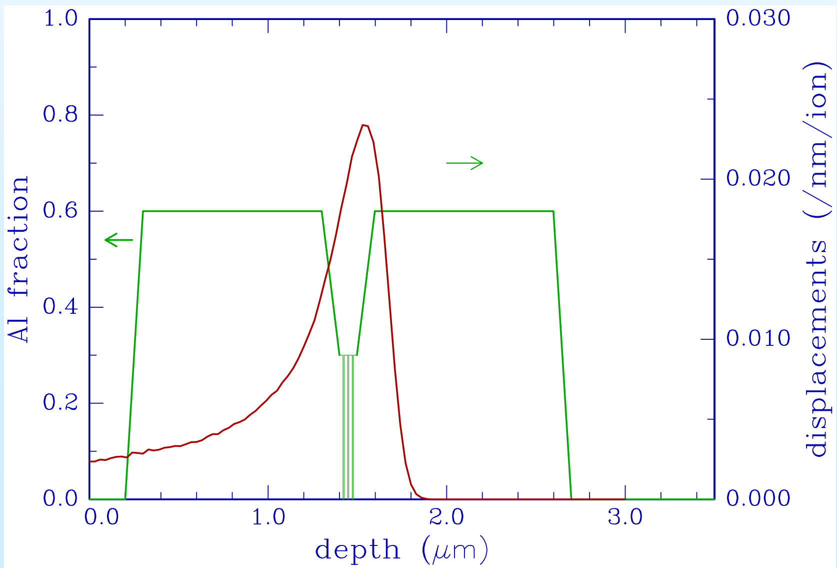
V. Coleman et al, Semicond. Sci. Technol. 21, L25 (2006)

Tuning the Emission Wavelength of GRINSCH Quantum Well Lasers

GaAs/AlGaAs QW Lasers

Multi Wavelength Lasers



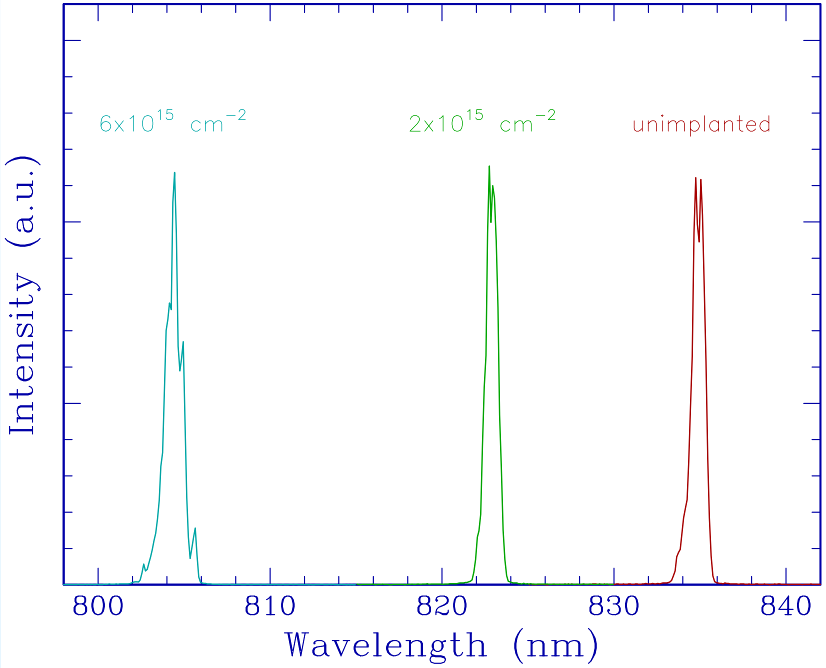


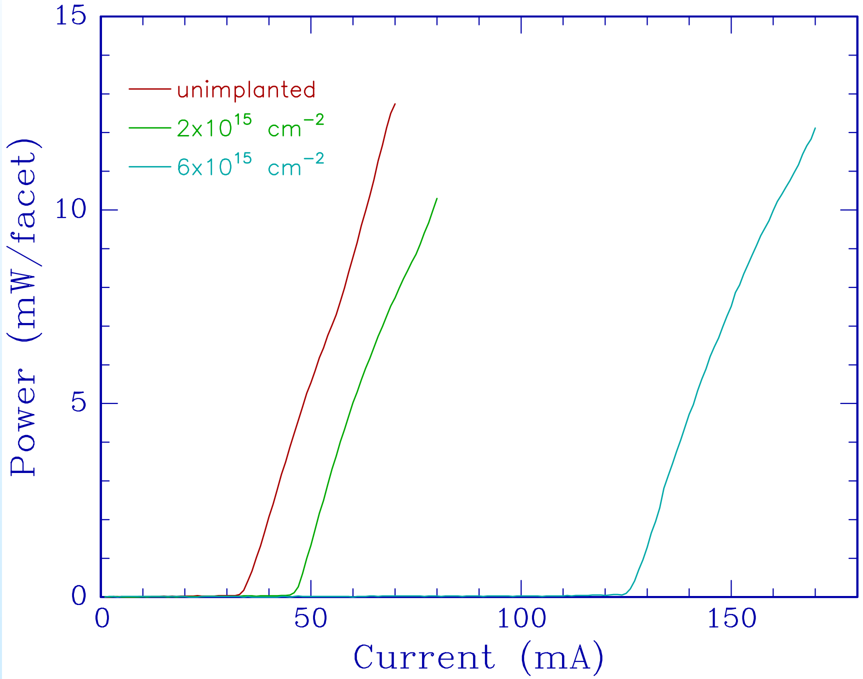
dose A < dose B

$\lambda 1 > \lambda 2 > \lambda 3$

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

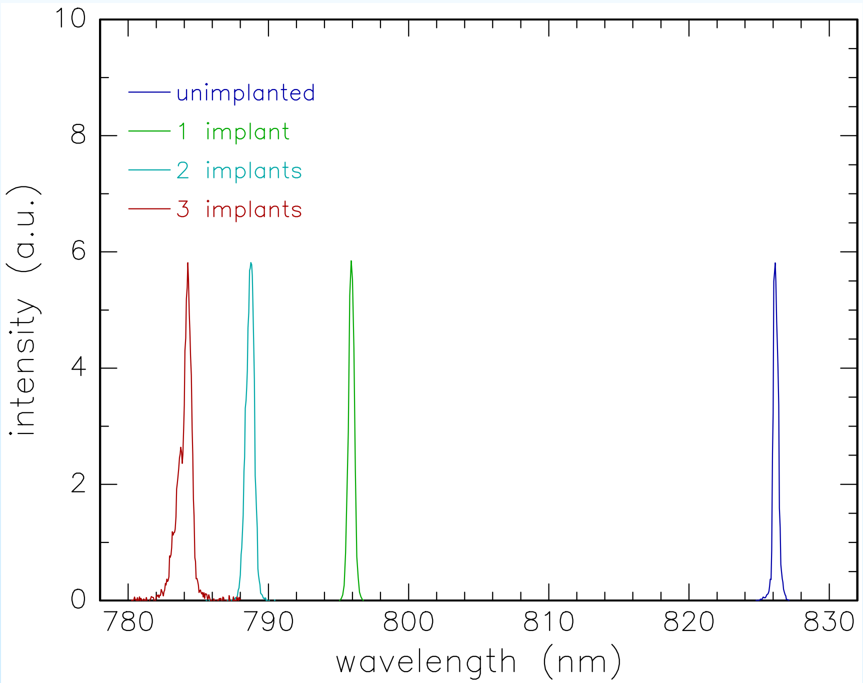
(900°C, 60 sec)

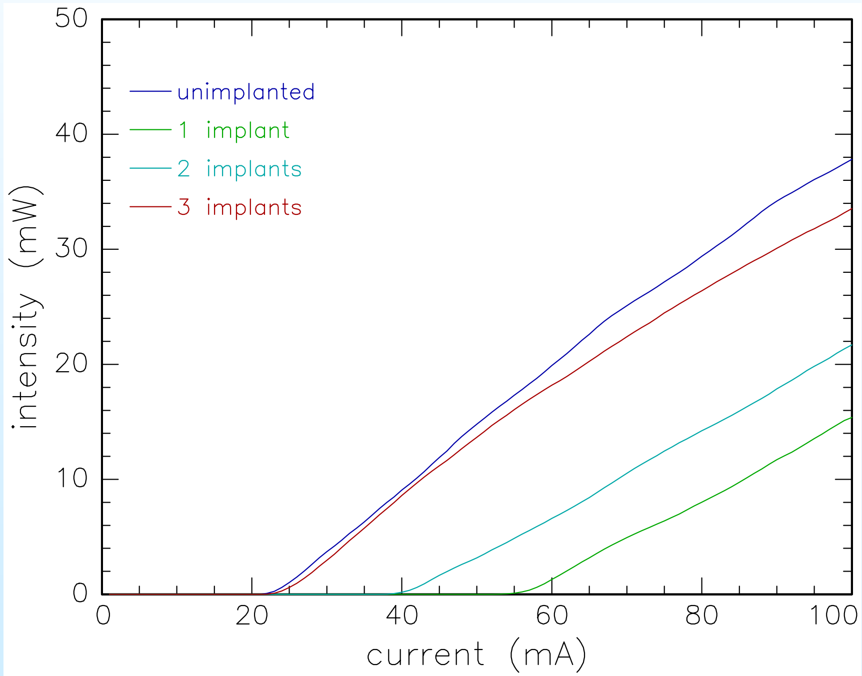




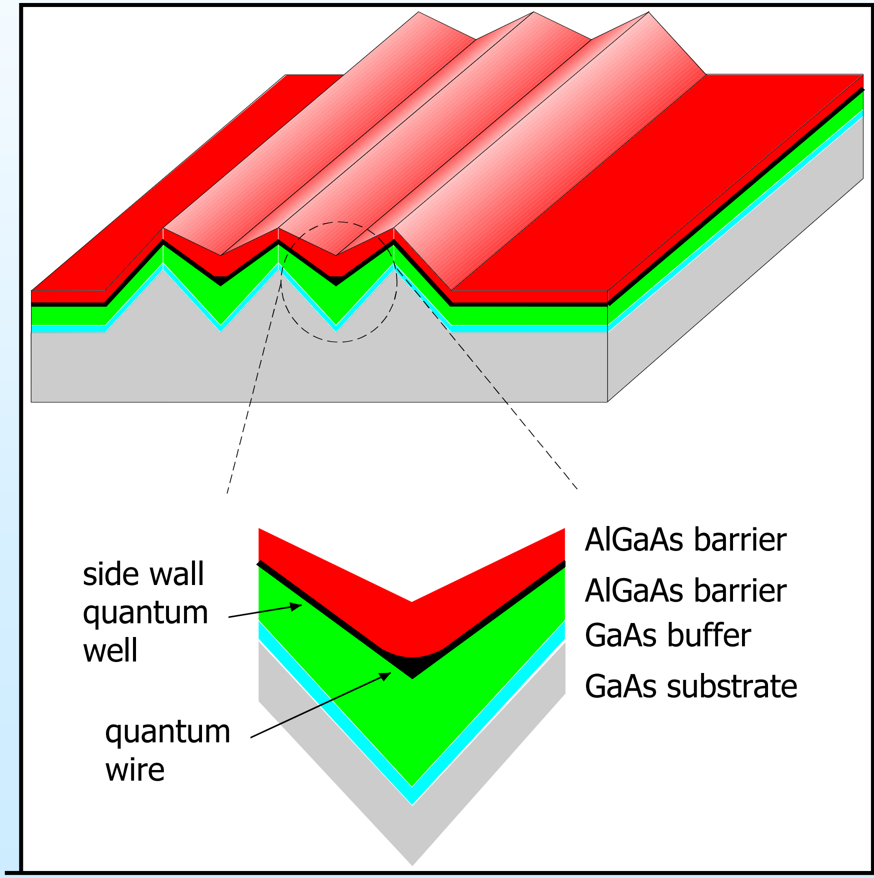
H.H. Tan and C. Jagadish, Appl. Phys. Lett. 71, 2680 (1997).

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

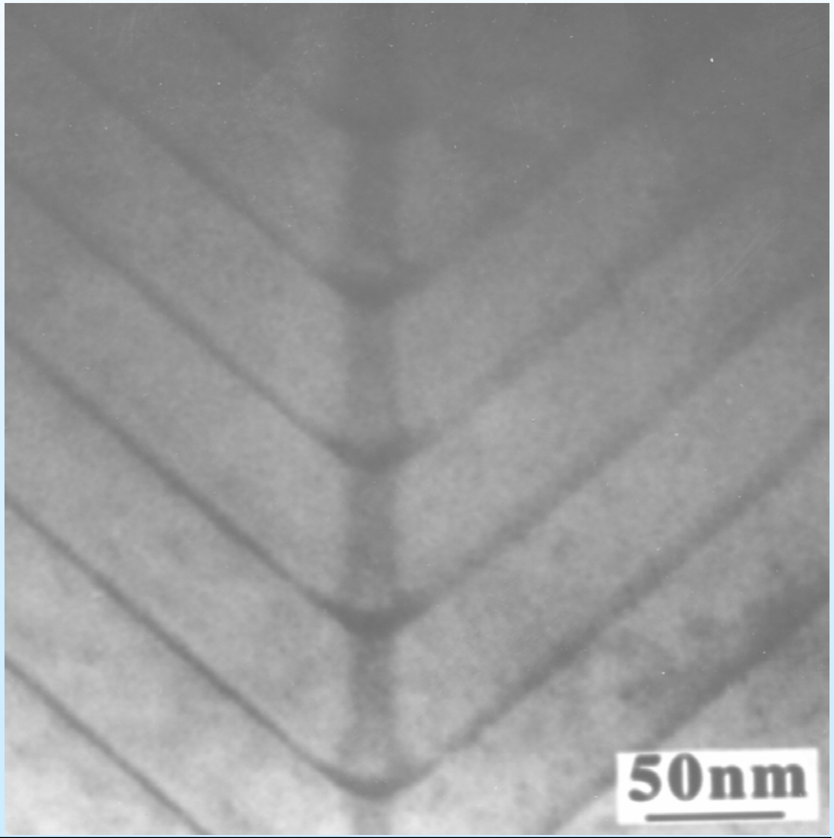




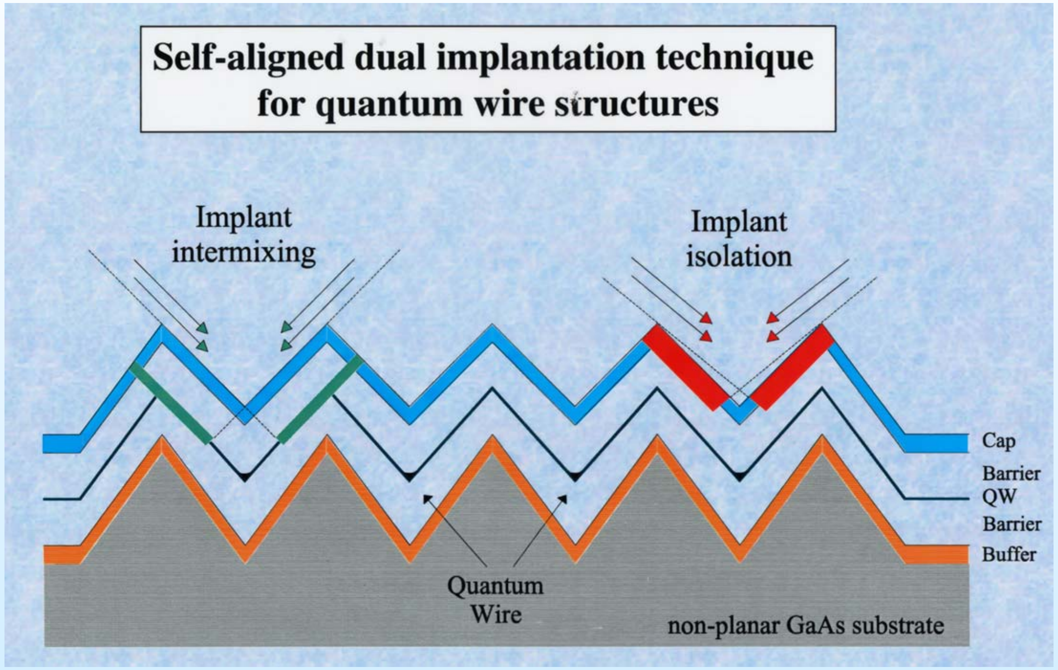
Quantum Wire Lasers

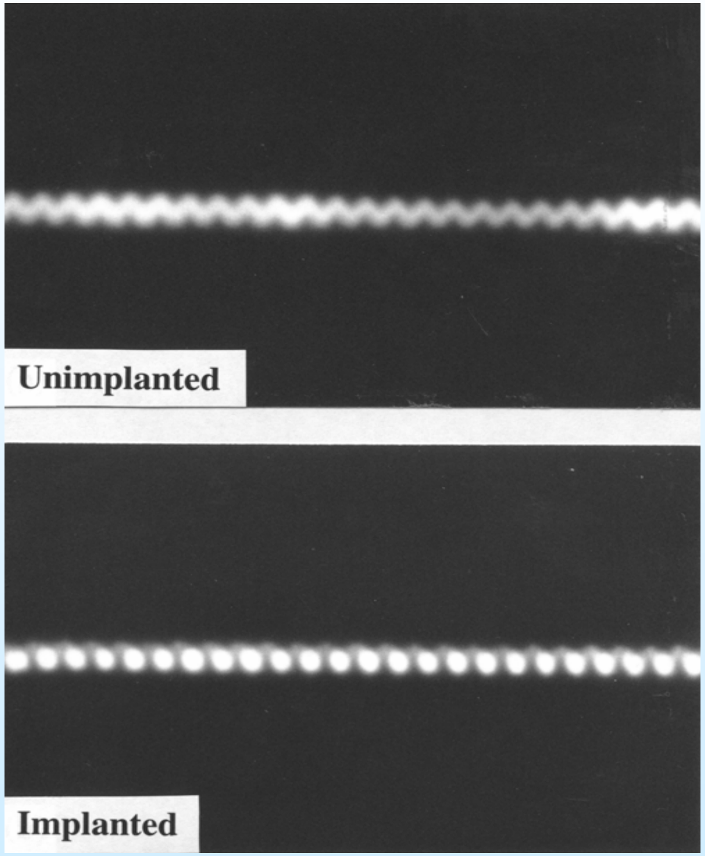


Cross-sectional TEM of GaAs-AlGaAs quantum wire structure



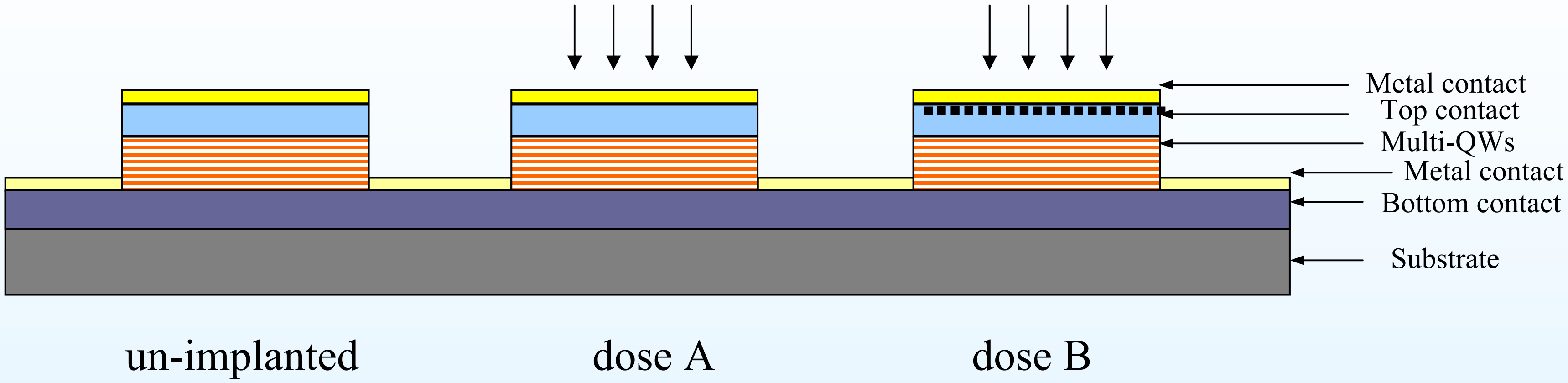
Light emission from quantum wire laser array

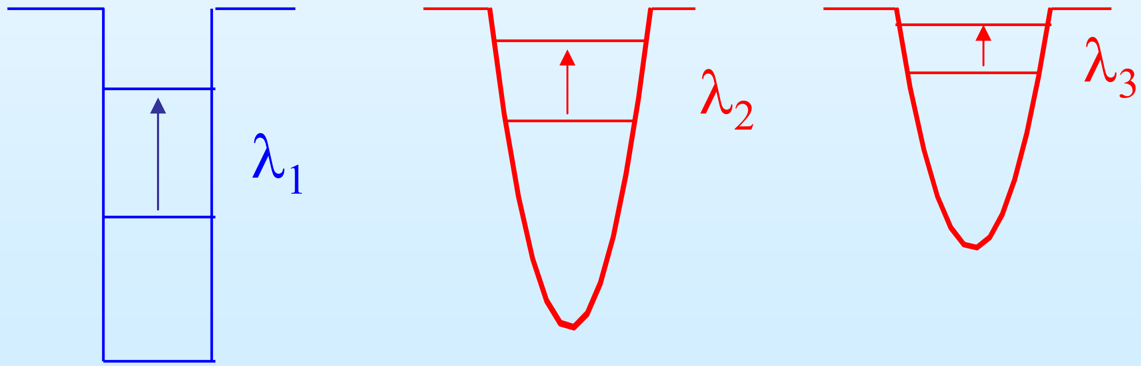




Tuning the Detection Wavelength of Quantum Well Infrared Photodetectors (QWIPs)

Tuning the wavelength of QWIP

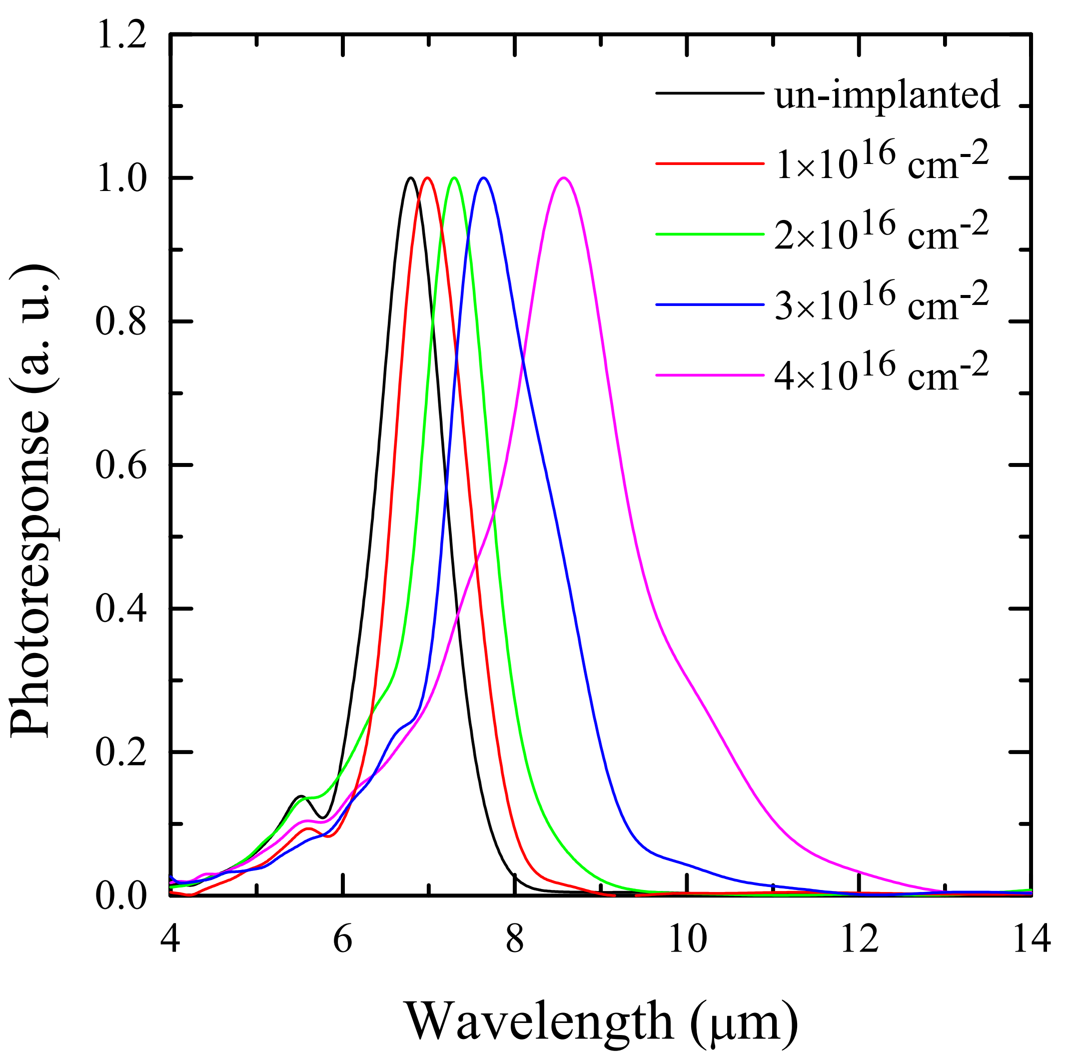




dose A < dose B

$\lambda_1 < \lambda_2 < \lambda_3$

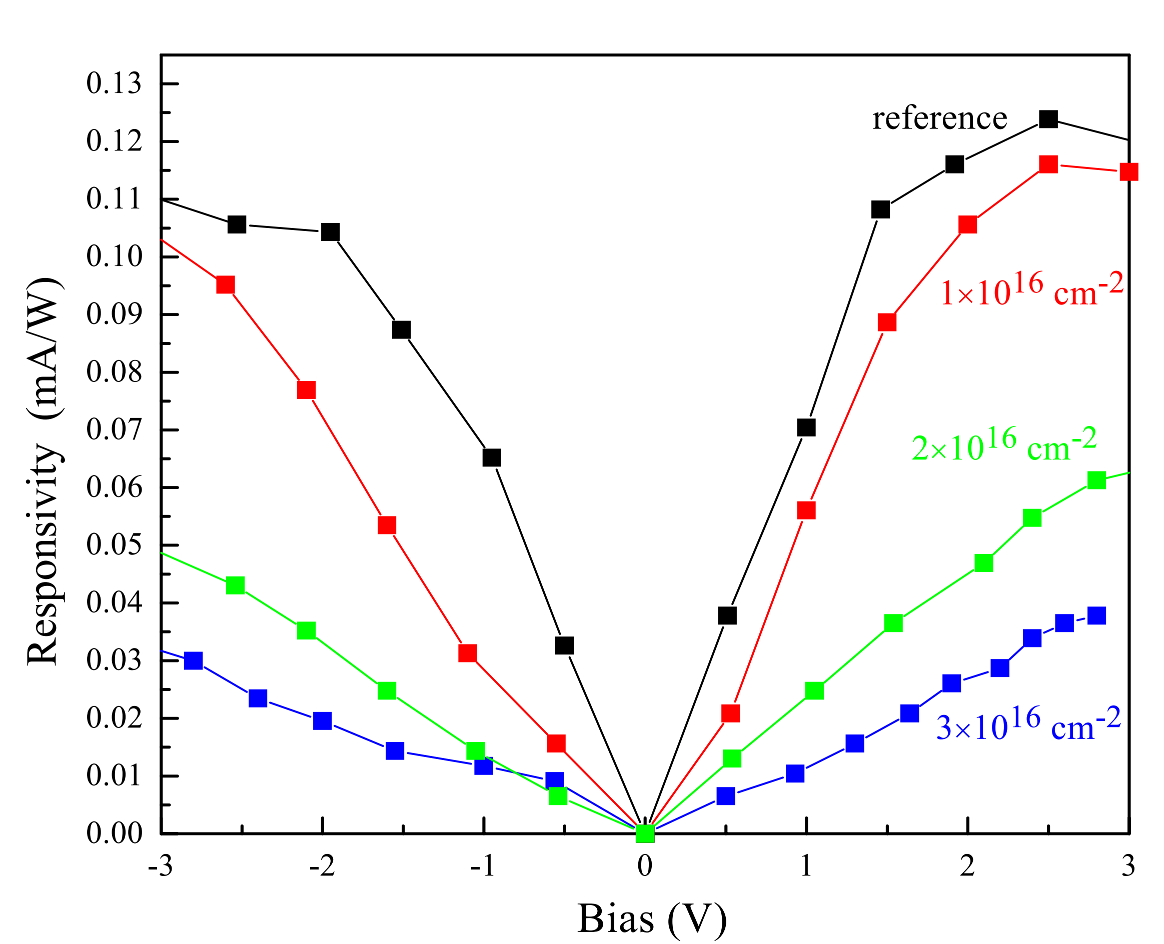
QWIP spectral response



950°C, 30 sec

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

Responsivity



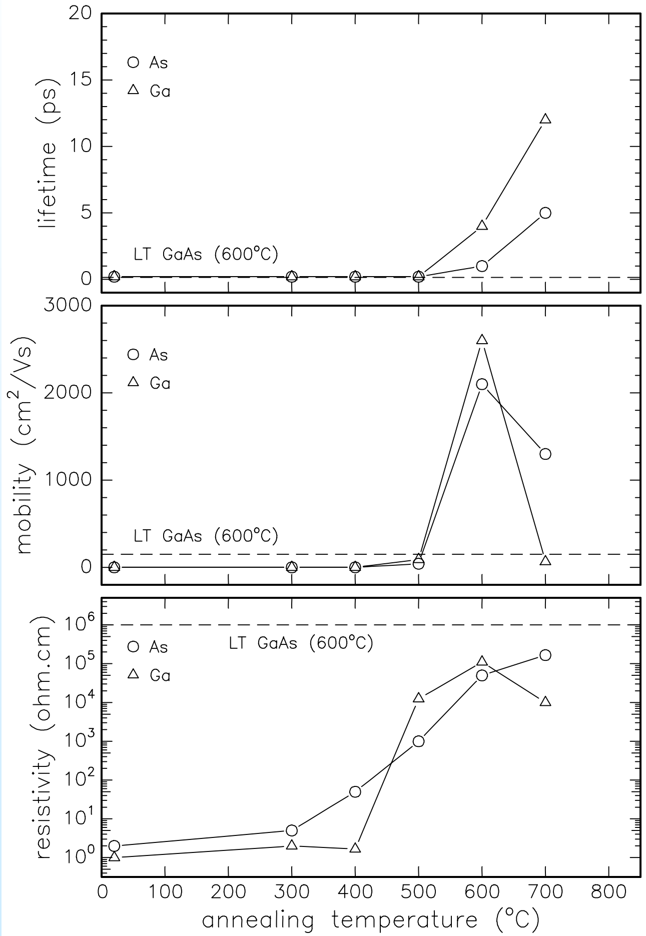
***L. Fu et al*, Appl. Phys. Lett. 78, 10 (2001).**

Overview

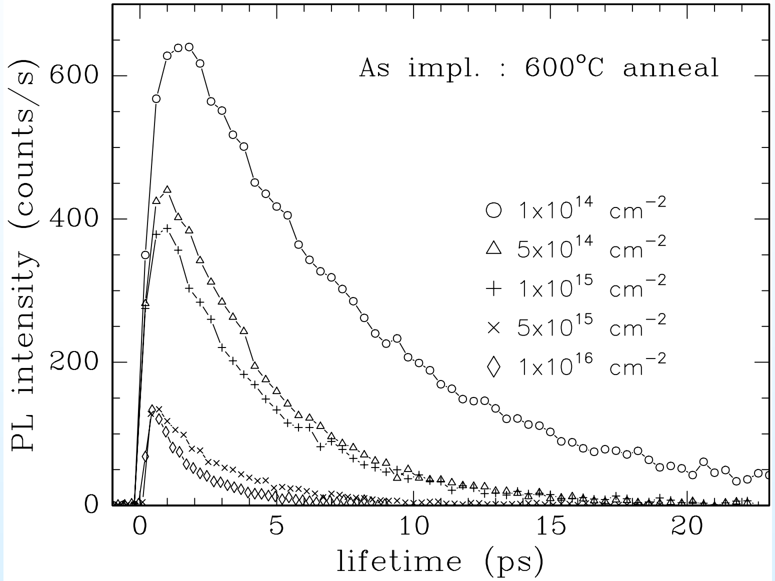
- Introduction
- Growth of Quantum Dots by MOCVD
- Towards Quantum Well/Dot Photonic Integrated Circuits
  - Intermixing (QW/QD) by ion implantation, IFVD
    - Quantum Well/Dot Lasers
    - Quantum Well/Dot Infrared Photodetectors (QDIPs)
- **Carrier lifetime Modification by Ion Implantation for untra-fast detectors and THz emitters**
- Nanowires
- Summary

Implantation for Ultrafast photodetector materials

Ultrafast photodetector materials - GaAs



2 MeV Ga/As into SI GaAs, dose = $1x10^{16}$ cm^{-2}

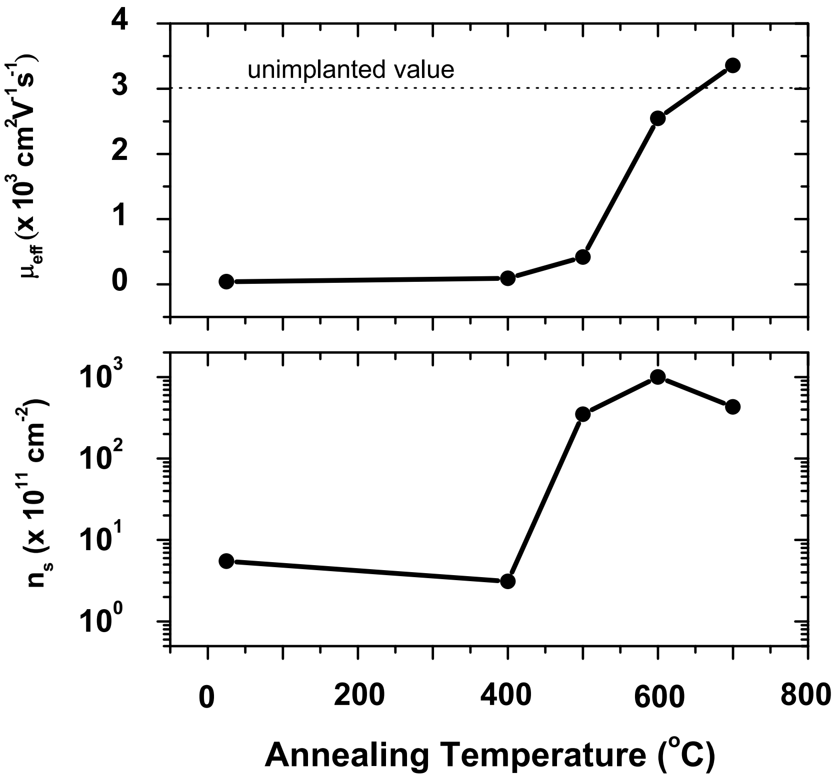


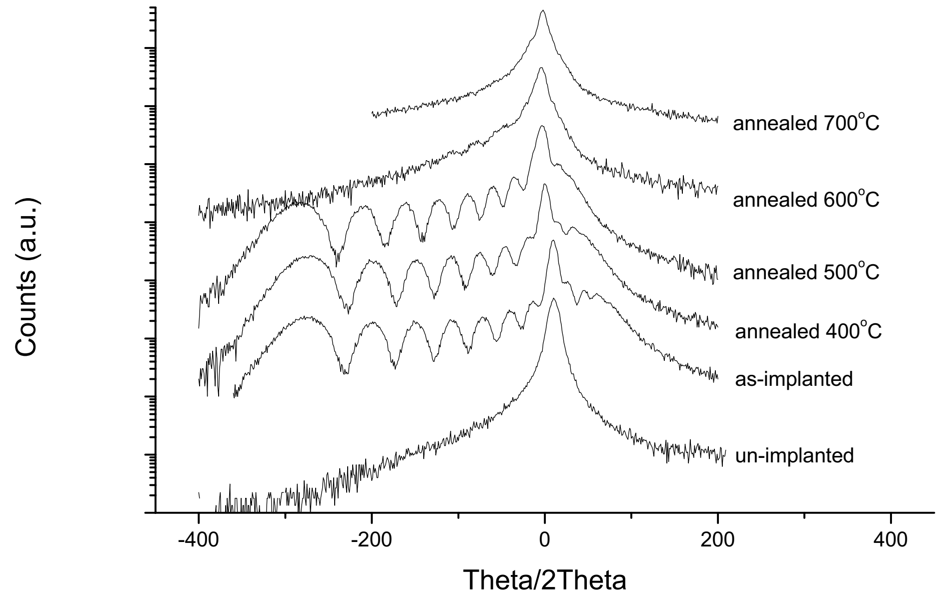
At low annealing temperature:
- **very short carrier lifetimes,**
- **low mobility and low resistivity**

At 600°C annealing:
- **short carrier lifetimes - ps range,**
- **high mobility and high resistivity**

H.H. Tan et al., IEEE Sel. Topics Quan. Electron. 2, 636 (1996)

Ultrafast photodetector materials - InP



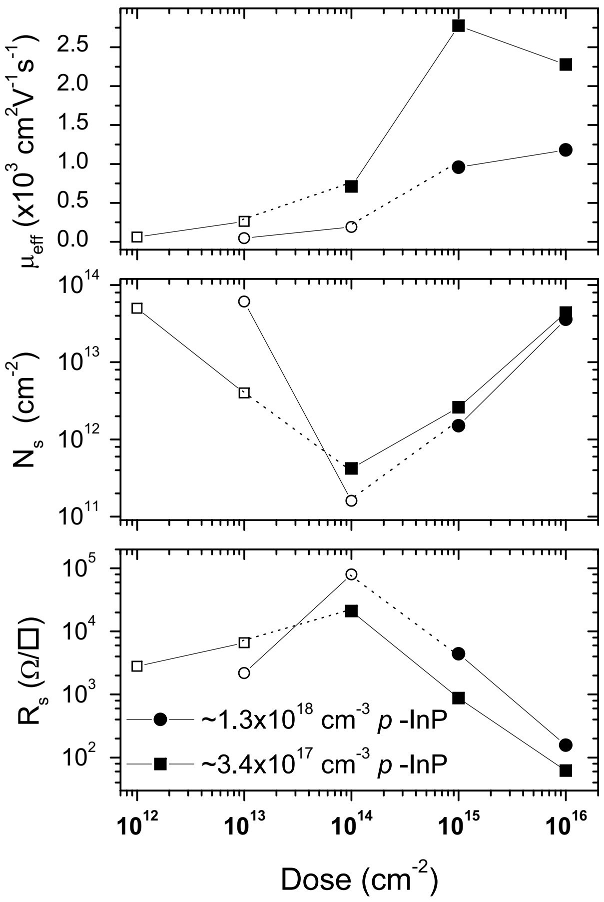


1 MeV P into SI InP, dose = 1×10^{16} cm^{-2}

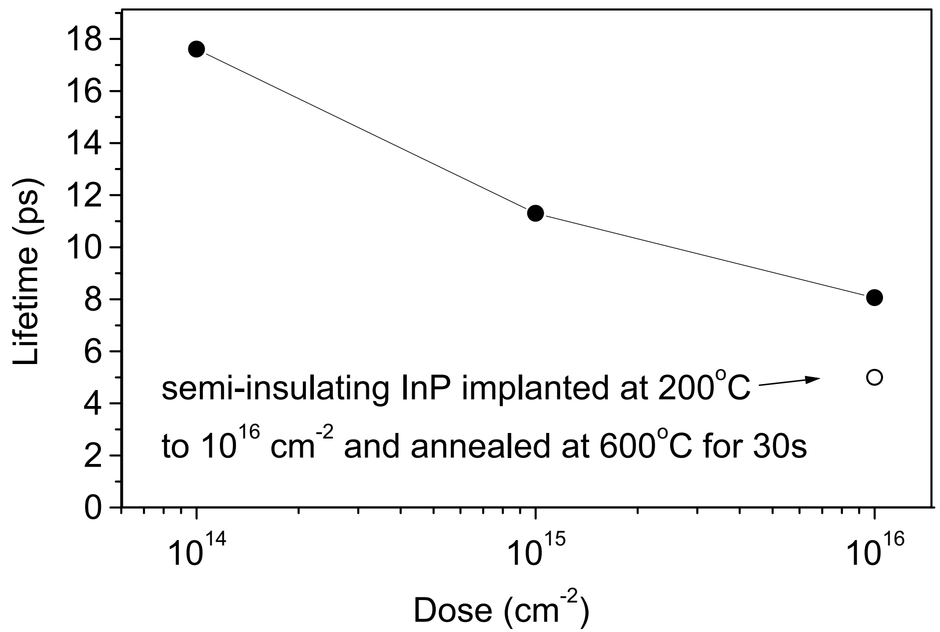
- **At 600-700°C, recovered most crystalline damage and original mobility**
- **Increased carrier concentration with annealing temperature (due to shallow donors)**

C. Carmody et al., J. Appl. Phys. 94, 1074 (2003)

Ultrafast photodetector materials - InP



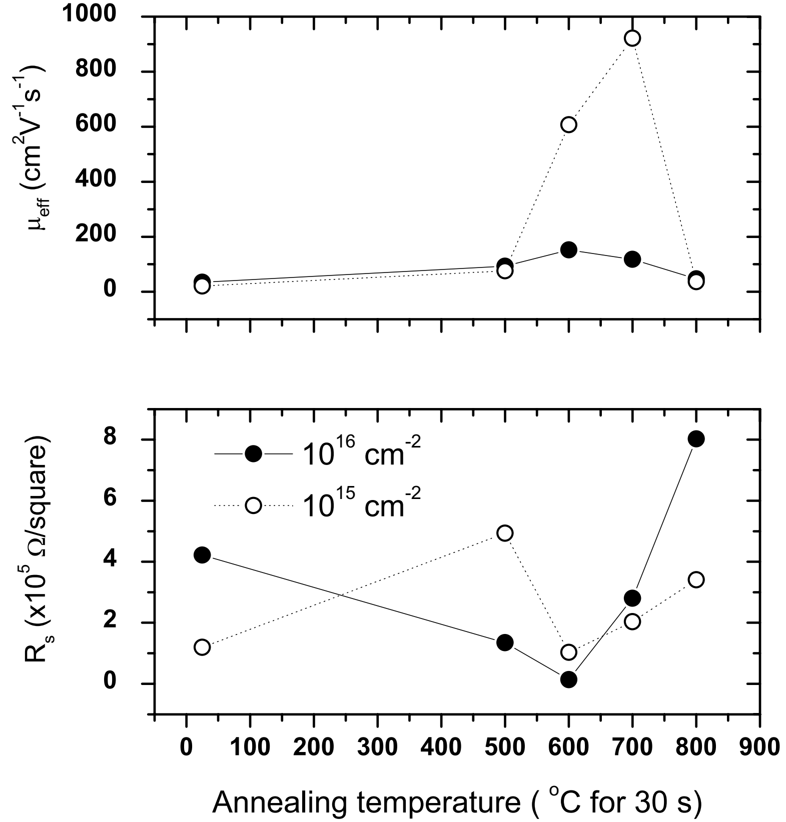
1 MeV P into p-type InP, annealed 600°C, 30s

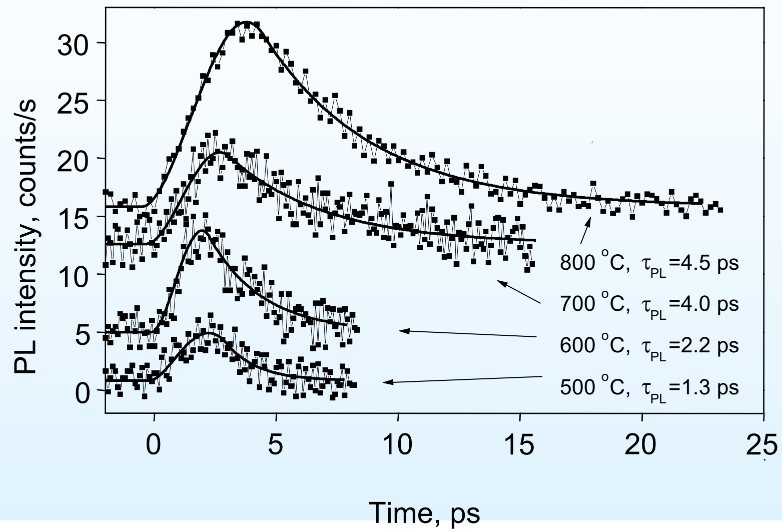


- **By implanting into p-type, the shallow donors can compensate the acceptors**
- **Short lifetimes with high mobility and high resistivity could be achieved**

C. Carmody et al., J. Appl. Phys. 94, 1074 (2003)

Ultrafast photodetector materials - InGaAs





2 MeV Fe into InGaAs

- **Implantation creates shallow donors, as in InP**
- **Higher dose required to achieve high resistivity, hence no luminescence observed due to highly defected material**
- **Use Fe instead as it creates a deep level**
- **ps lifetimes and with reasonable resistivity, mobility maybe achieved**

C. Carmody et al., Appl. Phys. Lett. 94, 1074 (2003)

Summary of ultrafast photodetector materials by implantation

GaAs

- **Relatively easy - ps lifetimes, high resistivity, high mobility**
- **Compromise btw carrier lifetimes and resistivity/mobility**

InP

- **Implantation creates shallow donor**
- **Hence, need p-type material and careful control of impl. dose**
- **ps lifetimes, high resistivity, high mobility achievable**

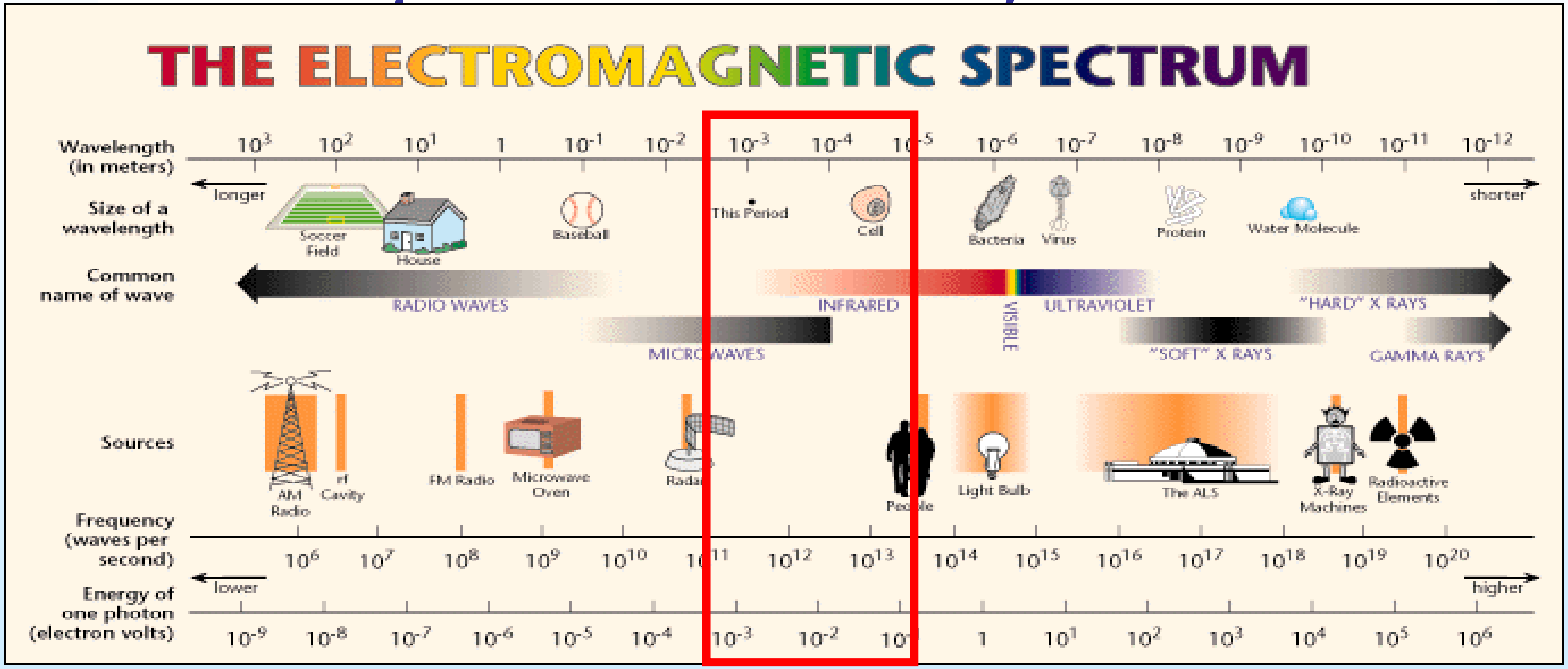
•InGaAs

- **Implantation creates shallow donor**
- **Higher implantation dose required, compared to InP (highly defective material)**
- **By using Fe (deep trap), ps lifetimes with reasonable resistivity, high mobility achievable**

Implanted III-V Materials for THz Emitters

How do we define "THz Radiation"?

Terahertz / sub millimetre wave / far infrared

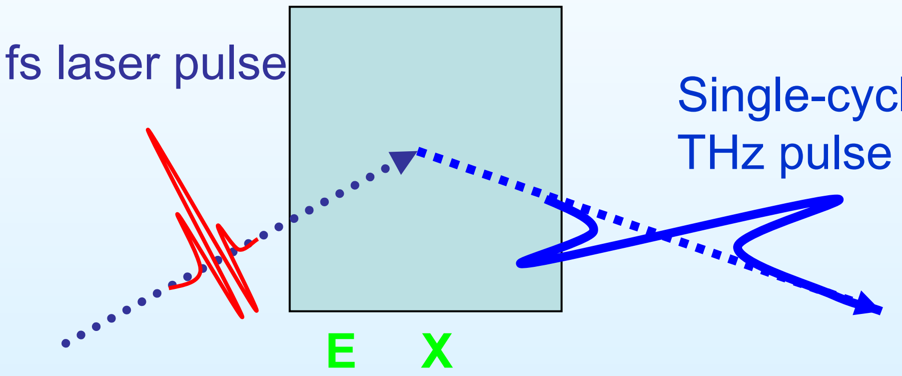


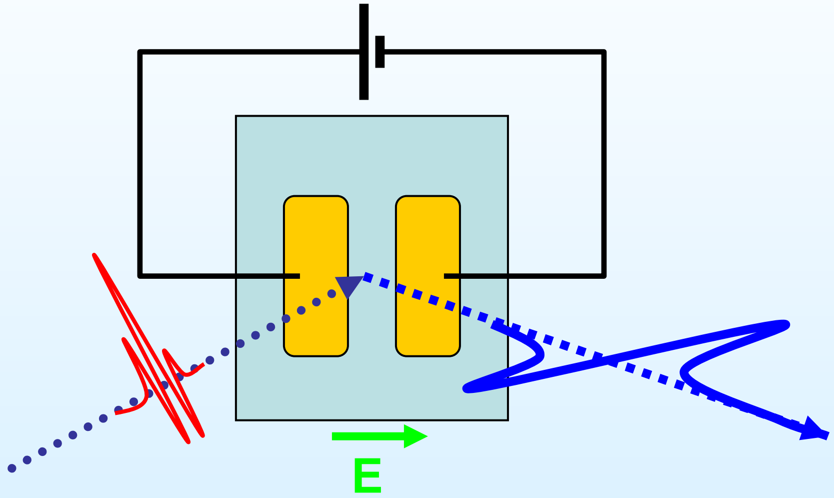
UNITS: 1THz / 1ps / 300μm / 4.1meV / 47.6K

Why are we interested in THz photonics?

- THz spectroscopy covers energy range of correlated systems (excitons, Cooper Pairs, phonons, plasmons…)
- Also energy range for molecular rotations and vibrations (plastic explosive detection)
- Non-contact probe of conductivity
- High resolution electric field detection in devices (chip diagnostics)
- Time resolved probe of dielectric properties of materials & devices
- Non ionising (medical/dental imaging)
- Non destructive testing (imaging faults)
- MANY MORE USES ACROSS DIVERSE FIELDS!!

Single-cycle terahertz emitters





What optimization is required?

Improve spectral intensity

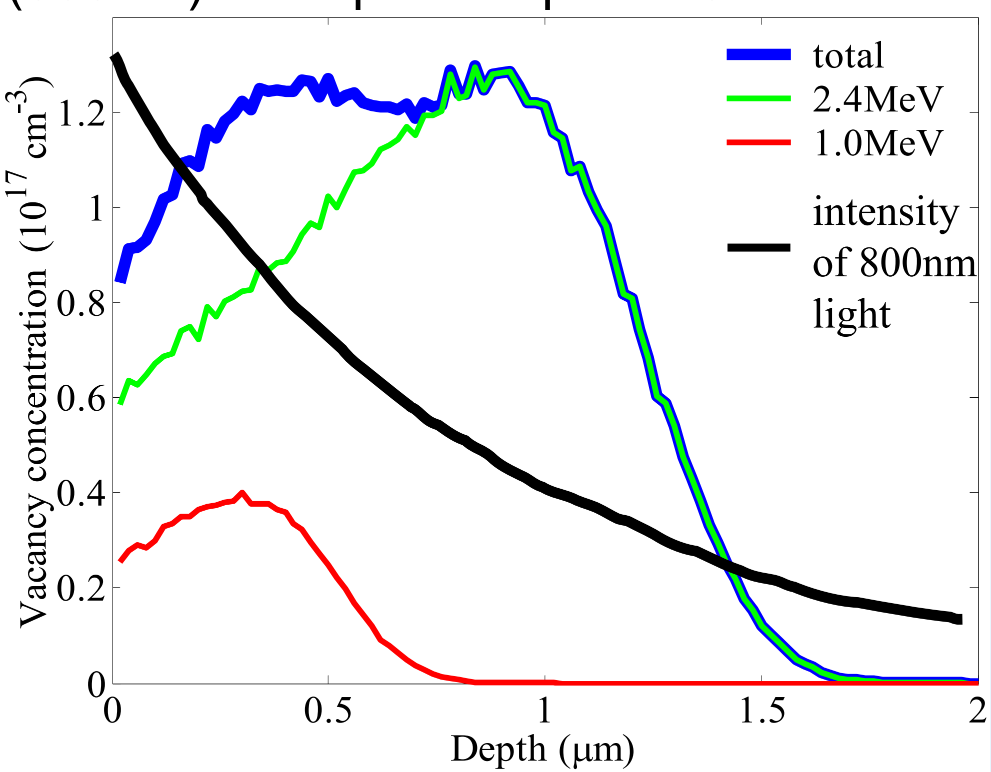
Increase bandwidth

Ion implanted GaAs

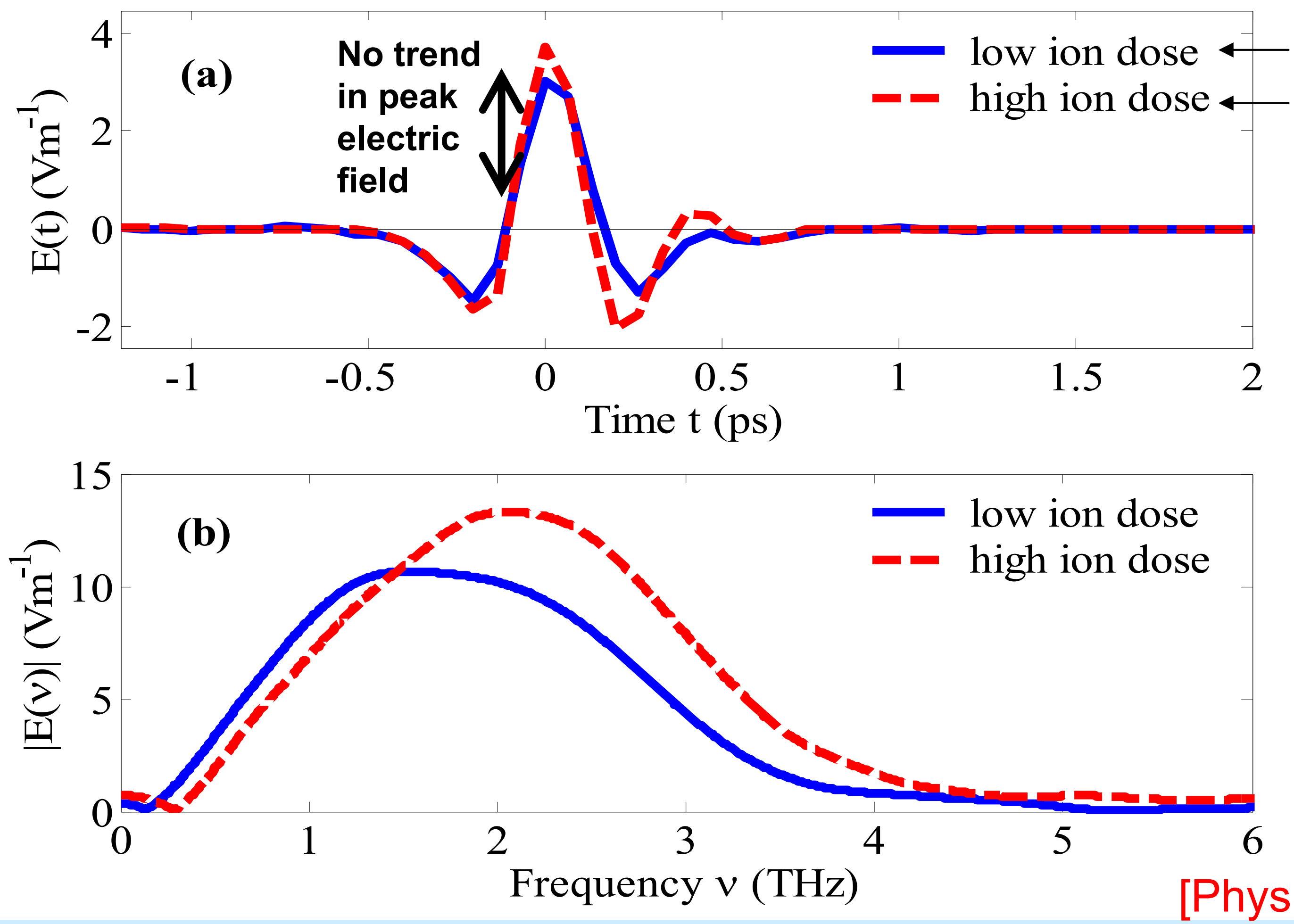
[Phys. Rev. B **70** 235330; Appl. Phys. Lett. 86:254102 (2005)]

- GaAs was implanted with dual, high energy doses of As^+ at 1MeV and 2.4MeV, creating:
  - An approximately uniform vacancy damage profile
  - Extending over the infrared (800nm) absorption depth of GaAs

- Past work used low energy (~200keV) As ions [Appl. Phys. B: Lasers Opt. **72**, 151; J. Appl. Phys. **93**, 2996]
- Annealed at 500˚C for 30 min to allow mobility to recover, while retaining ultrashort carrier lifetimes (~0.1ps) [Appl. Phys. Lett. **66** 3304; **76** 1306]
- Also $In_{0.53}Ga_{0.47}As:Fe^+$ and $InP:Fe^+$



Terahertz emission from GaAs:As⁺ surfaces

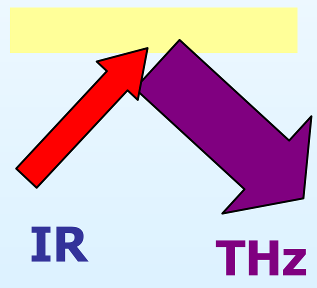


1MeV, 2.4MeV

0.25, 1x10^{13} cm^{-2}

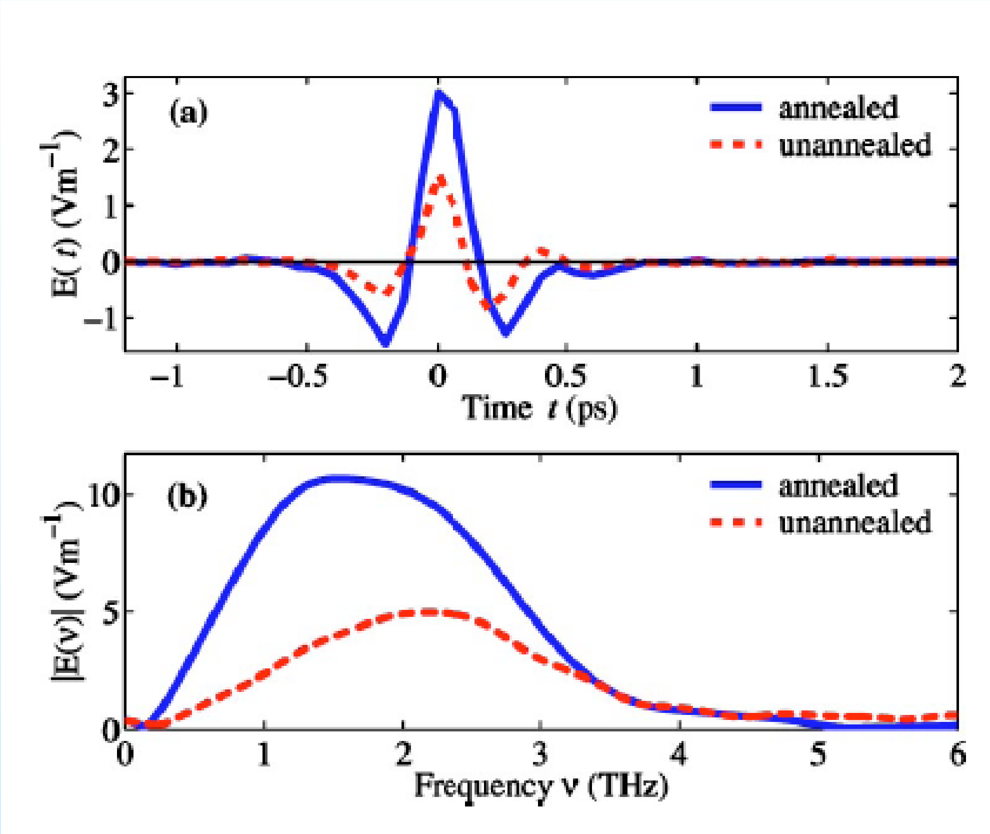
1.25, 5x10^{15} cm^{-2}

geometry



[Phys. Rev. B **70** 235330]

Effects of Annealing on THz Emission

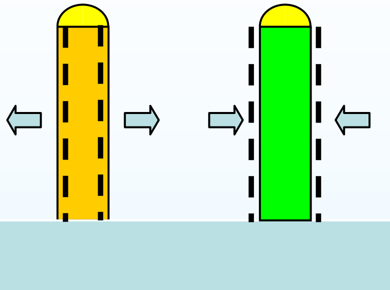


- ***For low implant dose, annealing causes an increase in maximum THz field from 1.6 V m^{-1} to 3.0 V m^{-1}, but a decrease in the frequency of peak power from 2.1 THz to 1.6 Thz.***

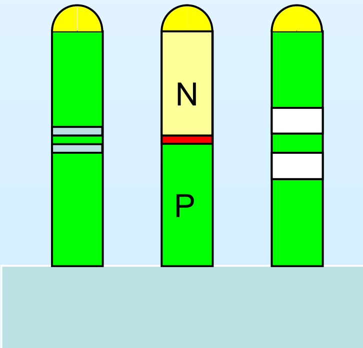
Overview

- Introduction
- Growth of Quantum Dots by Metal Organic Chemical Vapour Deposition (MOCVD)
  - InGaAs/GaAs, InAs/GaAs
  - InAs/InP, InAs/InGaAsP/InP
- Towards Quantum Well/Dot Photonic Integrated Circuits
  - Intermixing (QW/QD) by ion implantation, IFVD
  - ➢ Quantum Well/Dot Lasers
  - ➢ Quantum Well/Dot Infrared Photodetectors (QDIPs)
- **Nanowires**
  Single Photon Sources / Detectors
  Photonic Crystals
- Summary

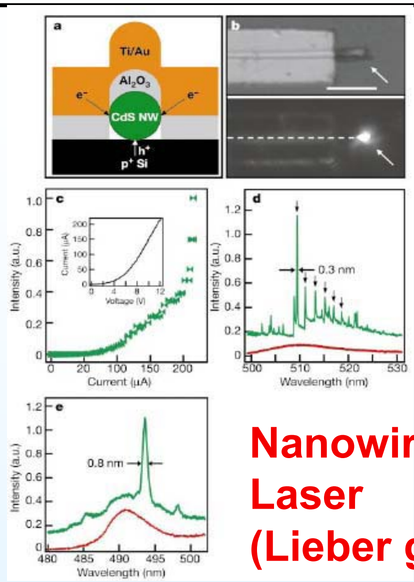
Nanowires



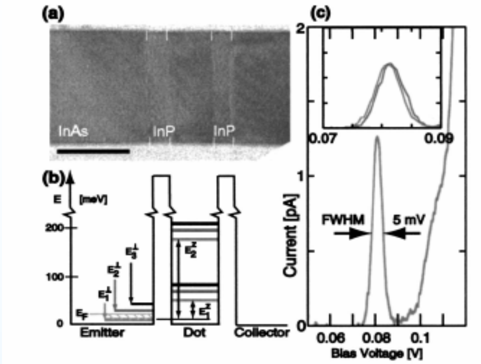
GaAs: 5.653 A
InAs : 6.058 A
Si : 5. 431 A



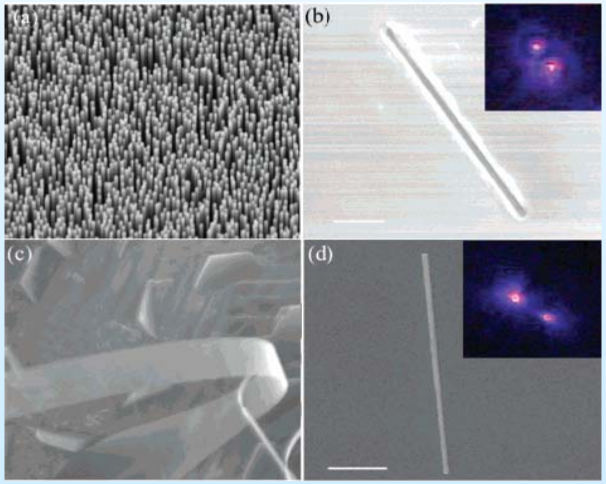
Exploration of truly one-dimensional Heterostructure semiconductor devices



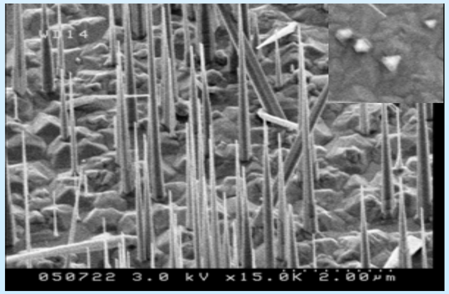
Nanowire Laser (Lieber group)



RTD (Samuelson group)

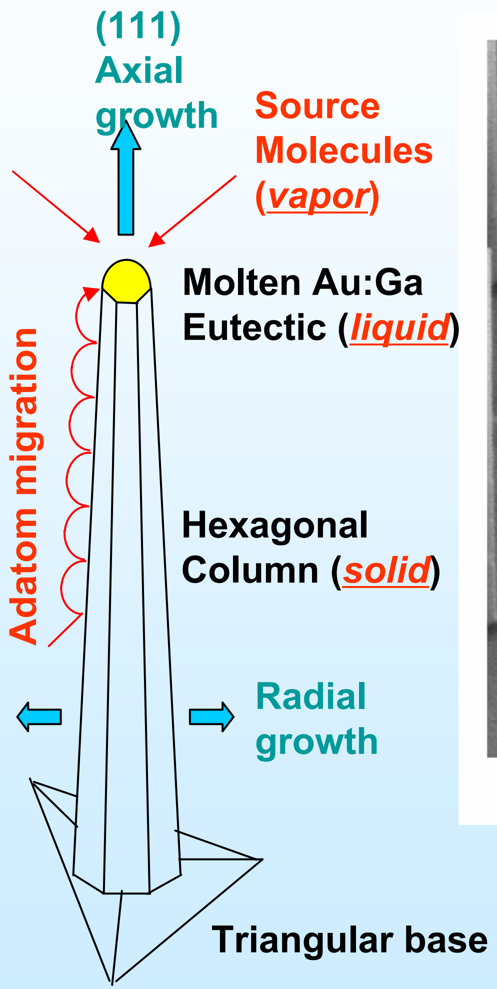


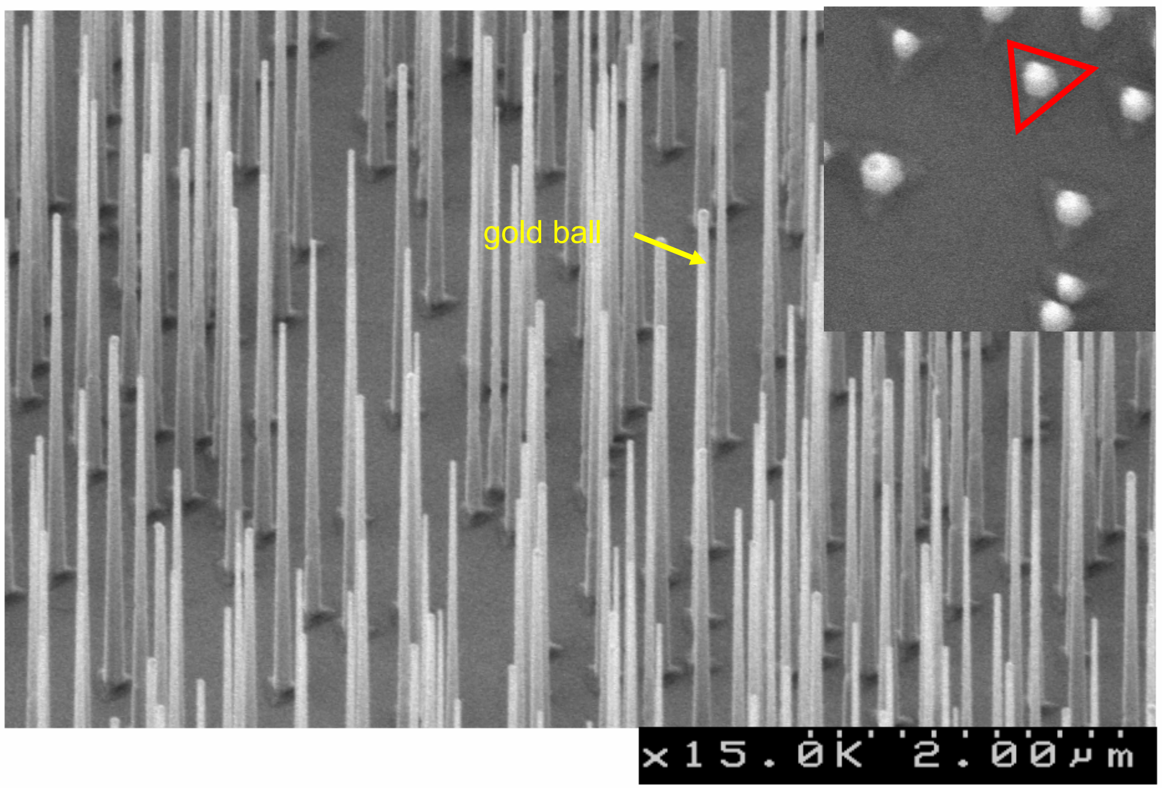
ZnO Nanowire laser (Peidong Yang, UCB)



InAs on GaAs (ANU)

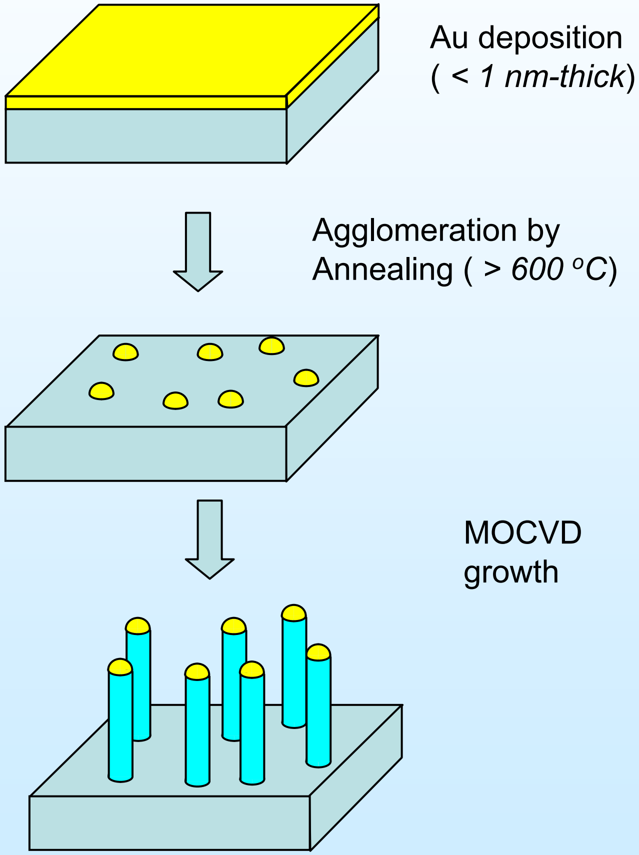
Vapor-Liquid-Solid Growth of GaAs (111)B nanowires

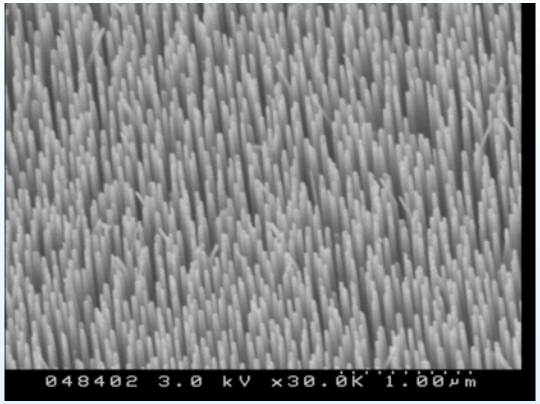




GaAs Nanowires grown using Gold Nanoparticles

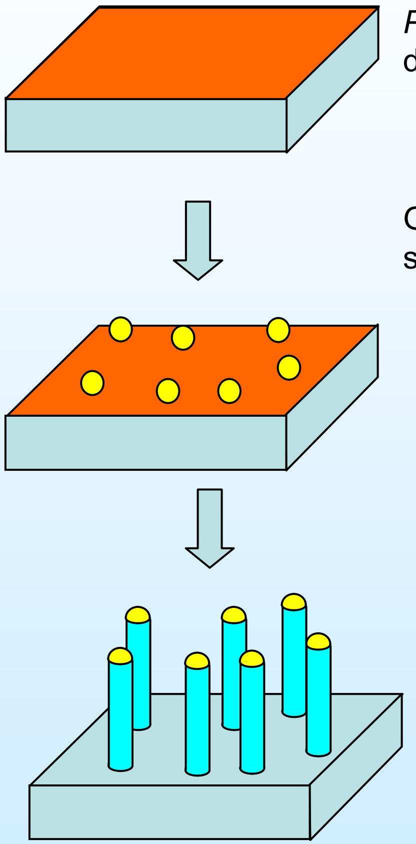
Nanowires Growth Methods

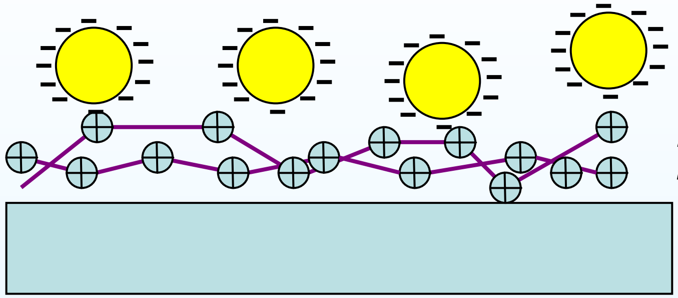




- Significant diameter dispersion of nanowires due to random agglomeration
- Poor reproducibility due to the difficulty in Au film thickness control
- Possible high optical/structural quality

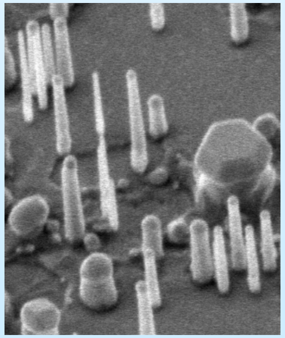
Nanowires Growth Methods



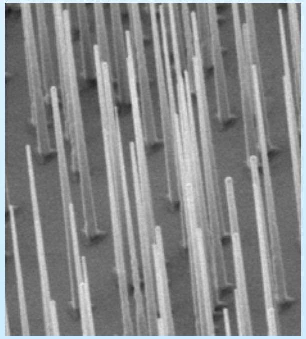


Poly-L-lysine (*PLL*, one of polymer electrolytes)
- attracts negatively charged gold nanoparticles
- prevents the agglomeration of gold nanoparticles

See the difference !

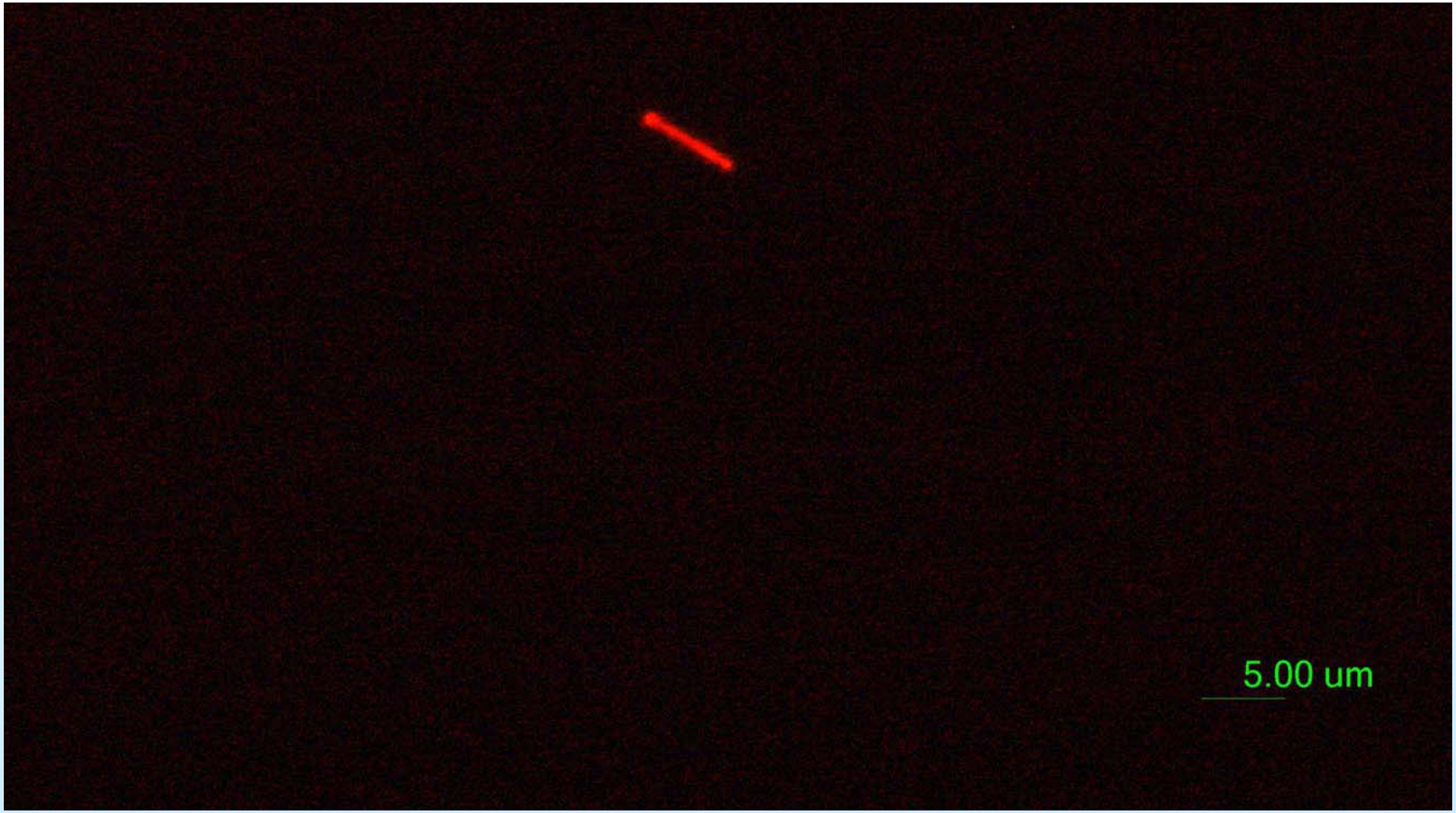


without *PLL* treatment

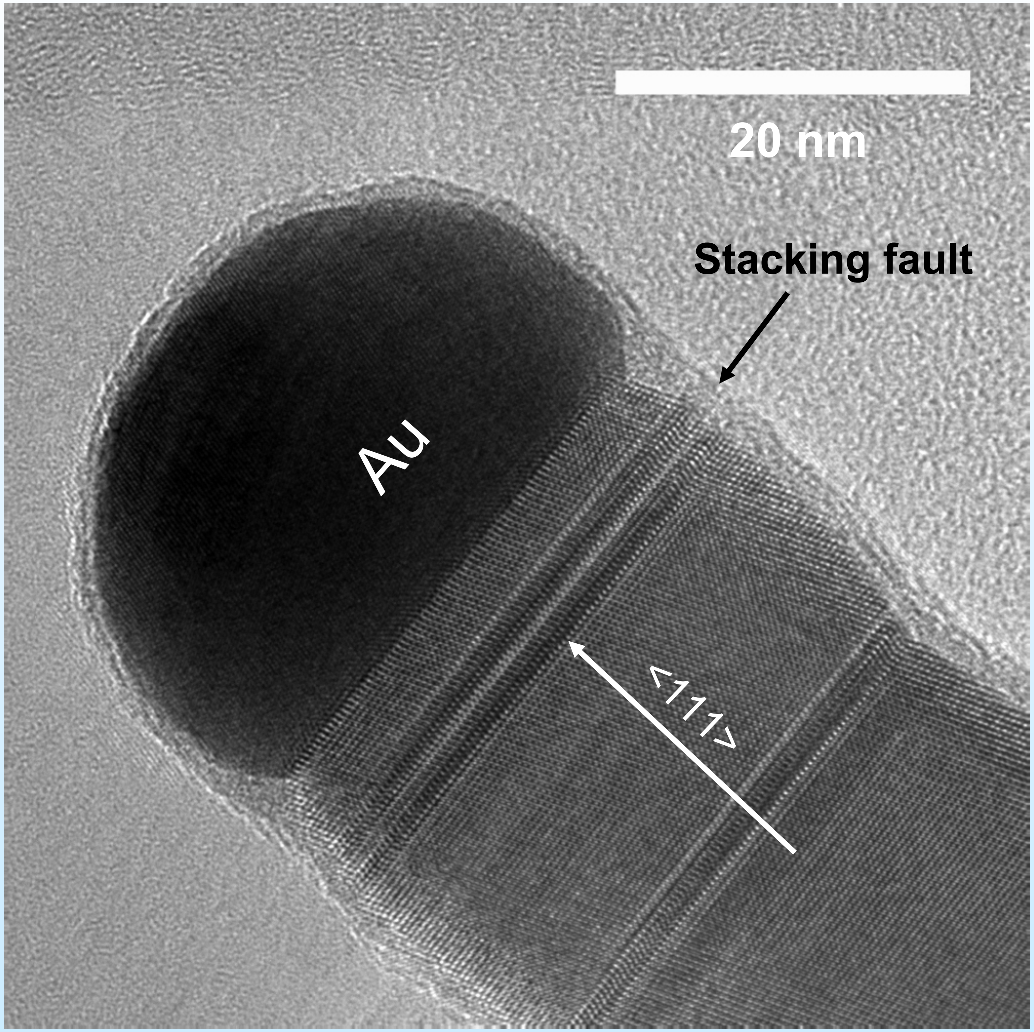


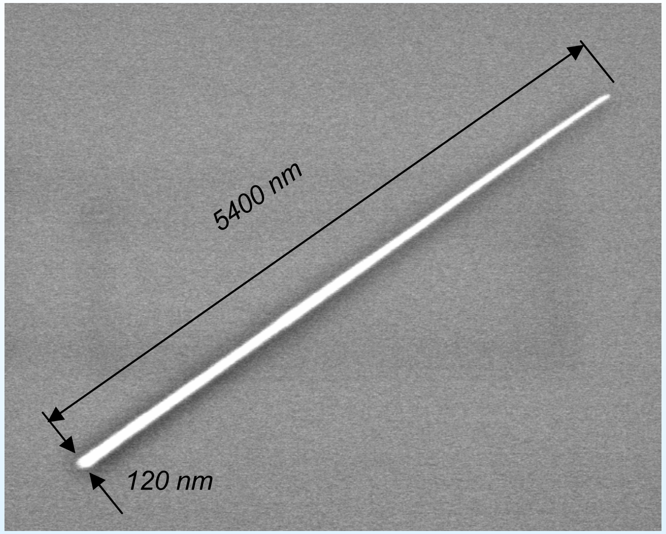
with *PLL* treatment

Image of a single GaAs NW PL



TEM of GaAs nanowire

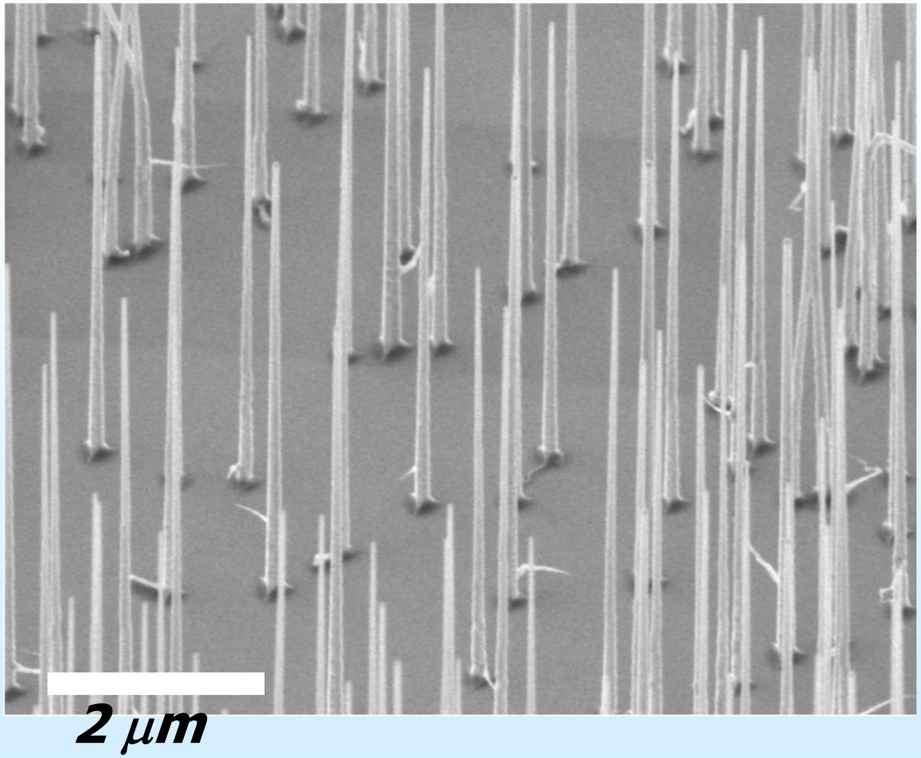


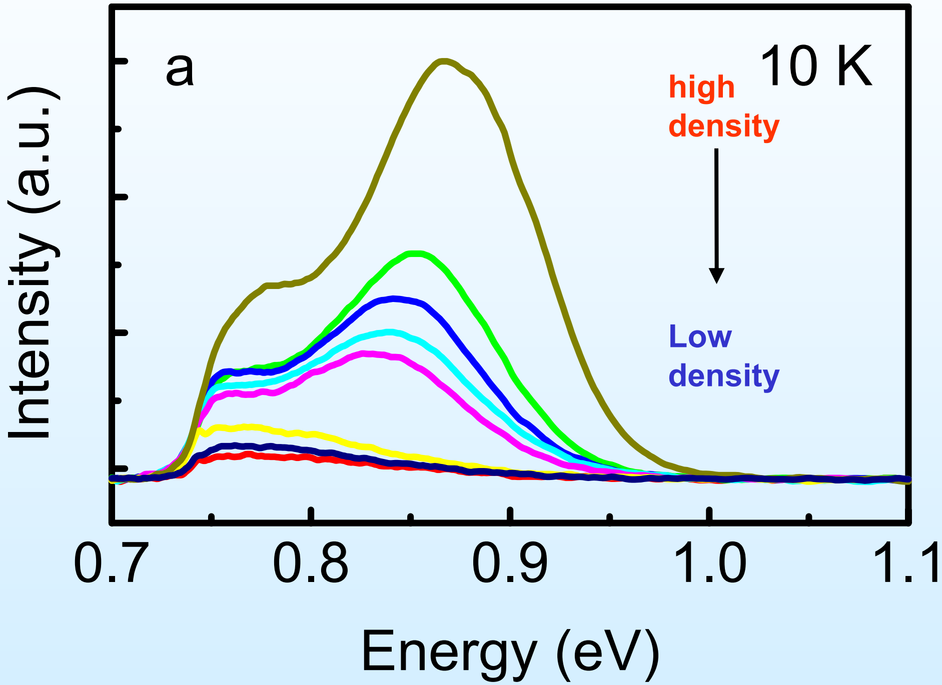


Sonicated GaAs nanowire grown @ 450 ^{o}C

- Perfect crystalline property except stacking faults

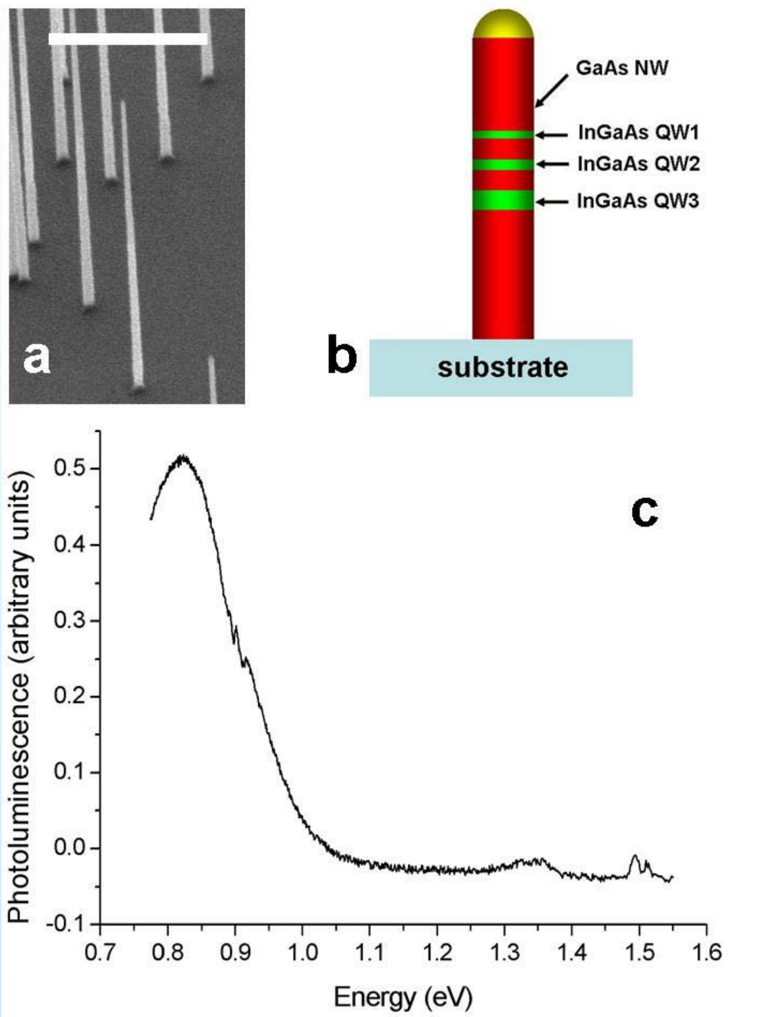
InGaAs nanowires on GaAs (111)

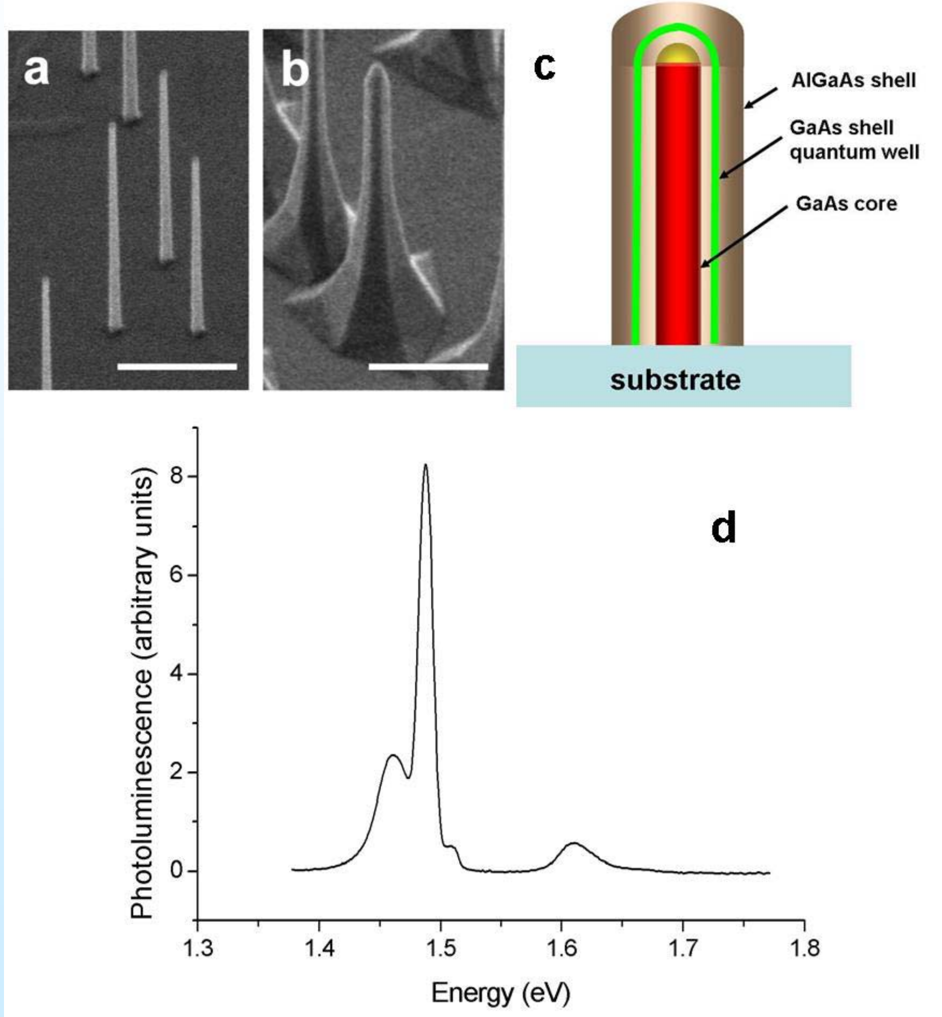


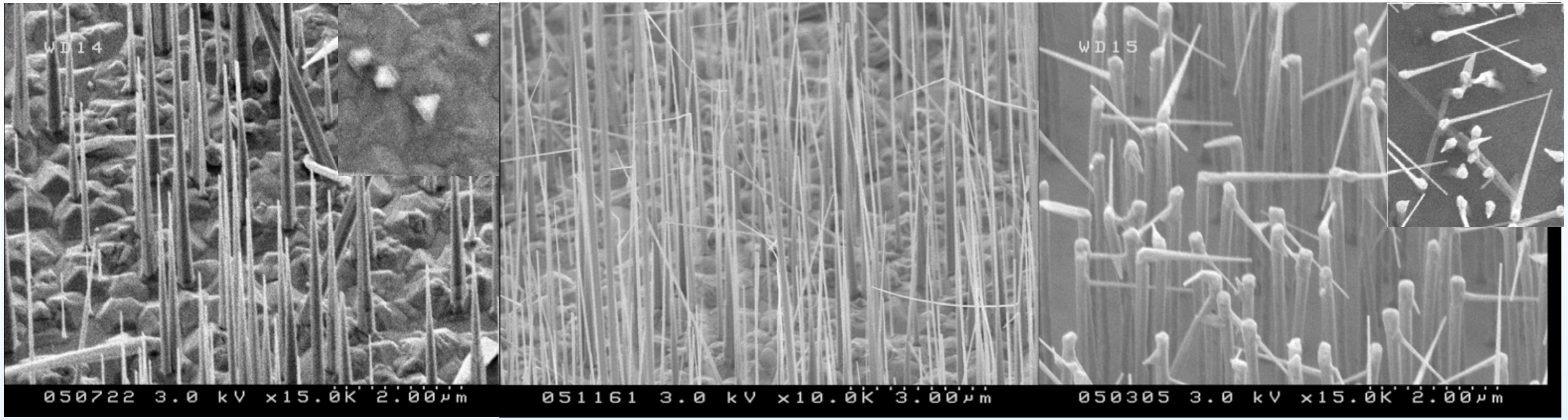


Y. Kim, H. Joyce. Q. Gao, H.H. Tan, C. Jagadish, M. Paladugu, J. Zou, A. Suvorova, Nano Lett. 6, 599-604 (2006)

*Heterostructural N*anowires on GaAs (111)

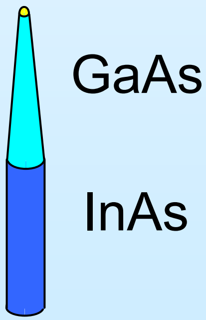




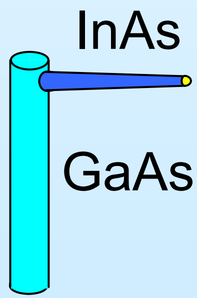


InAs NWs on GaAs sub

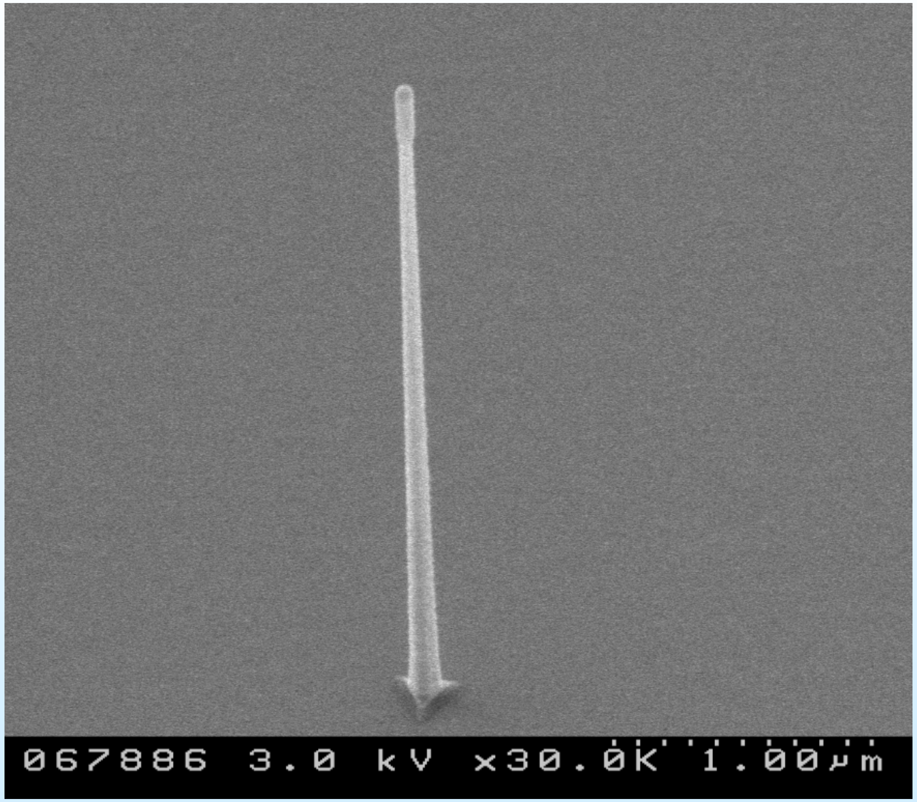
GaAs/InAs NW

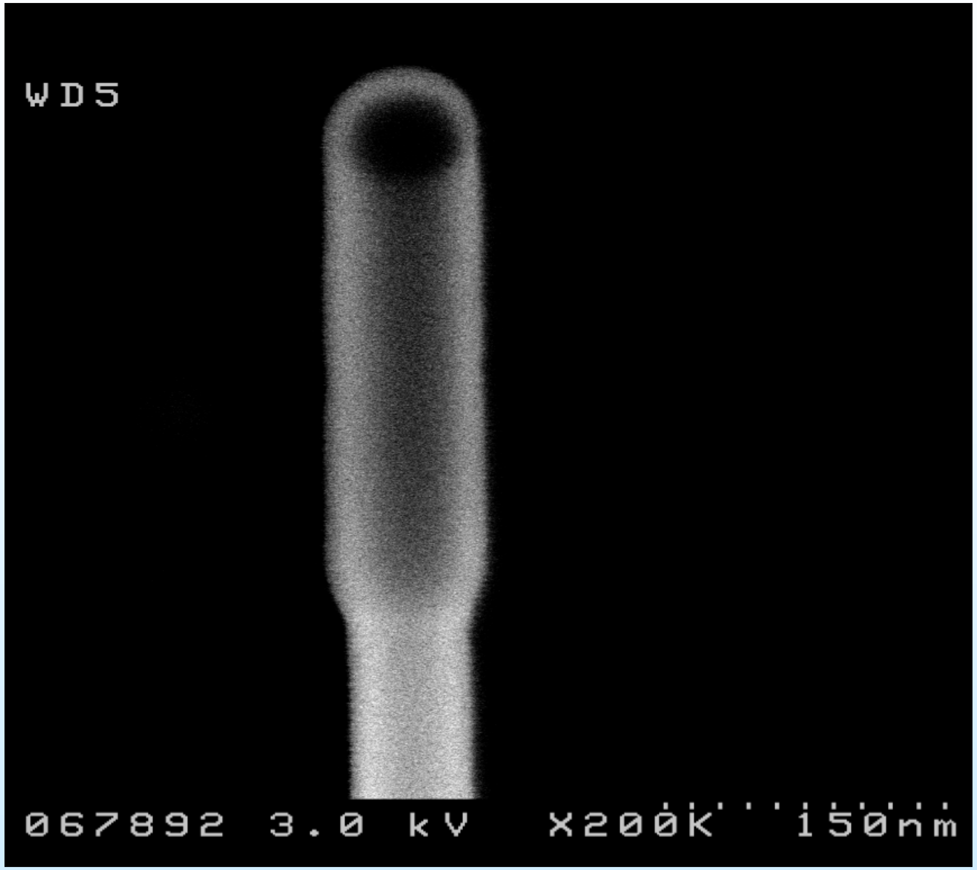


InAs/GaAs NW



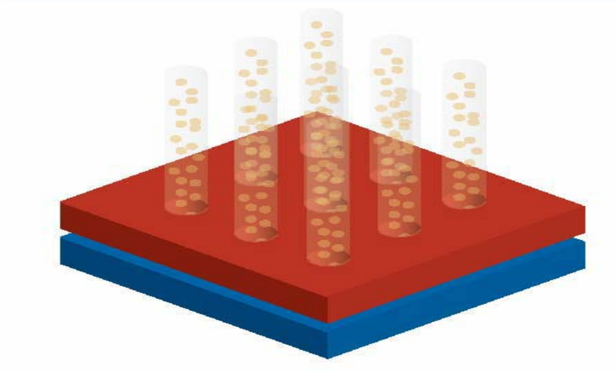
GaSb nanowires on GaAs (111)

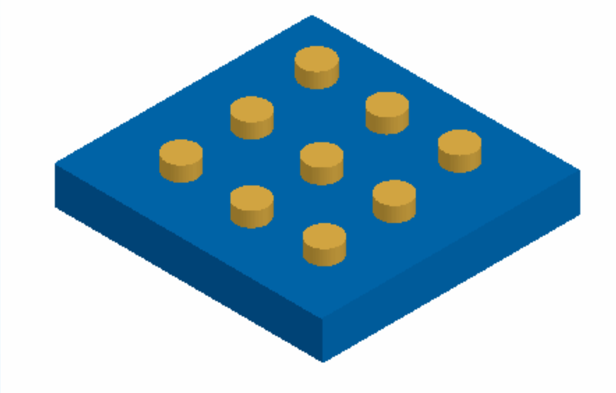


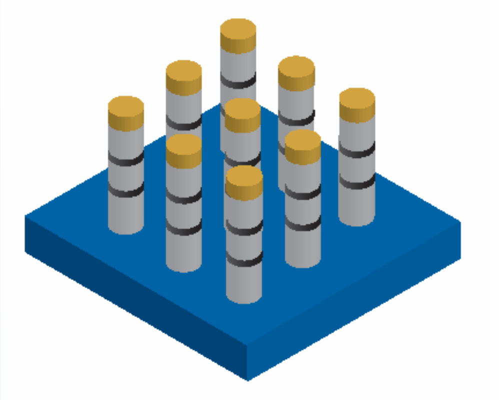


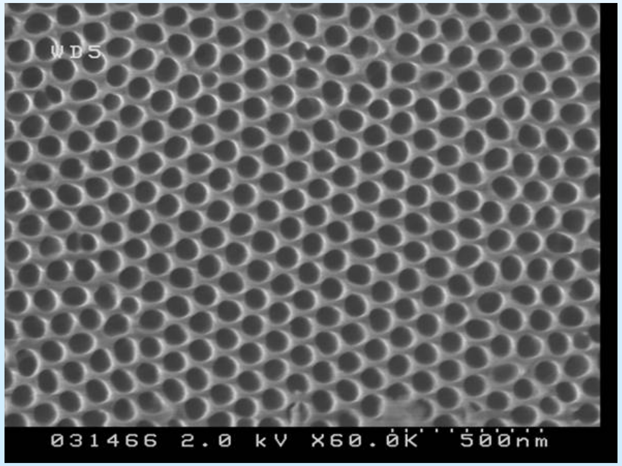
HRTEM of GaSb/GaAs NWs

Future: Ordered Nanowires









Porous Alumina Template

Summary

- Quantum Dots - strongly affected by growth conditions
- MOCVD growth of Quantum Dots is challenging and promising for optoelectronic device applications
- 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
- Carrier lifetime
- Nanowires offer opportunities to develop novel nano-photonic devices, e.g. single photon sources, QD lattices, photonic crystals

Acknowledgment

- **Kallista Stewart, Sudha Mokkapati, Satya Barik, Greg Jolley, Victoria Coleman, Michael Fraser, Paulus Gareso, Mykhaylo Lysevytch, Ian McKerracher, Hannah Joyce, Mohan Paladugu (UQ)**
- **Fu Lan, Jenny Wong-Leung, Yong Kim, Michael Aggett**

- **Mike Gal, University of New South Wales**
- **Matthew Phillips, University of Technology, Sydney**
- **Zou Jin, University of Queensland**
- **A. Suvorova, University of Western Australia**

Australian Research Council

Michael_Gao@ieee.org

Thank you for your attention