Quantum Dot Lasers for Integrated Photonics

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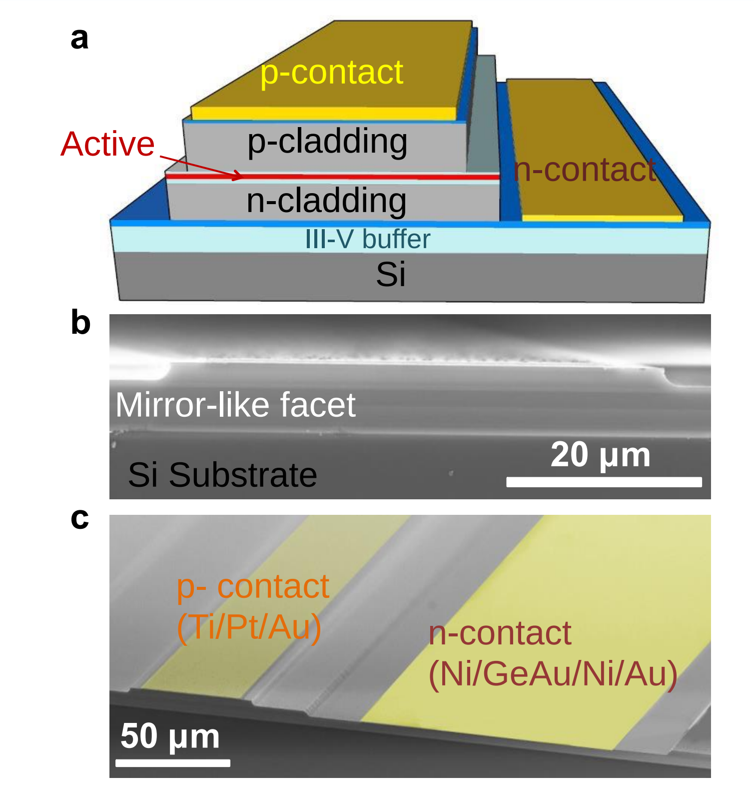
Outline

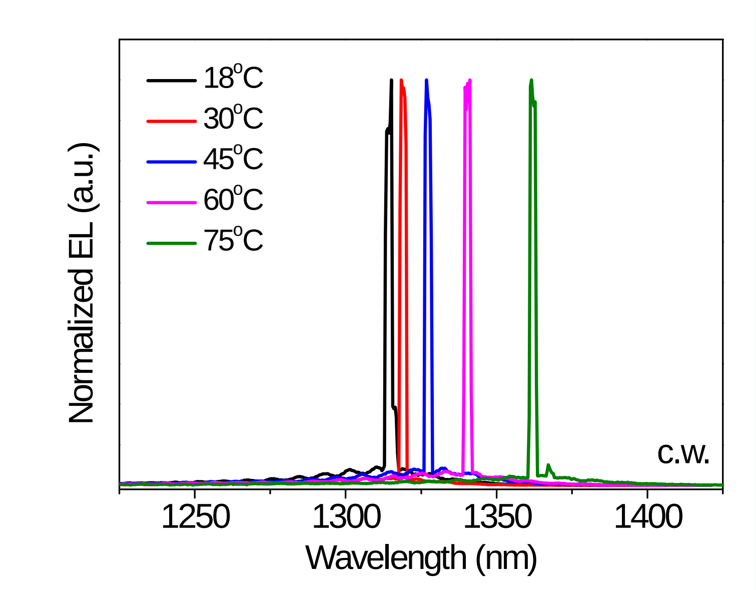
- Background, motivation and application
- Structure and optical properties
- Controlling emission wavelength
- The dot – well active medium
- Temperature insensitive wavelength
- Exploiting QD properties: Dual-wavelength lasers
- Integrated Circuits

Background

- InAs QD Lasers 1.3 – 1.6 µm (and 980-1200nm) well established – even on Silicon



CW InAs QD lasers directly grown on silicon substrates
3.2mm threshold current density of 62.5 A/cm^2
RT output power exceeding 105 mW,
Over 3,100 hours of CW operation, giving an extrapolated mean time to failure of over 100,000 hours.



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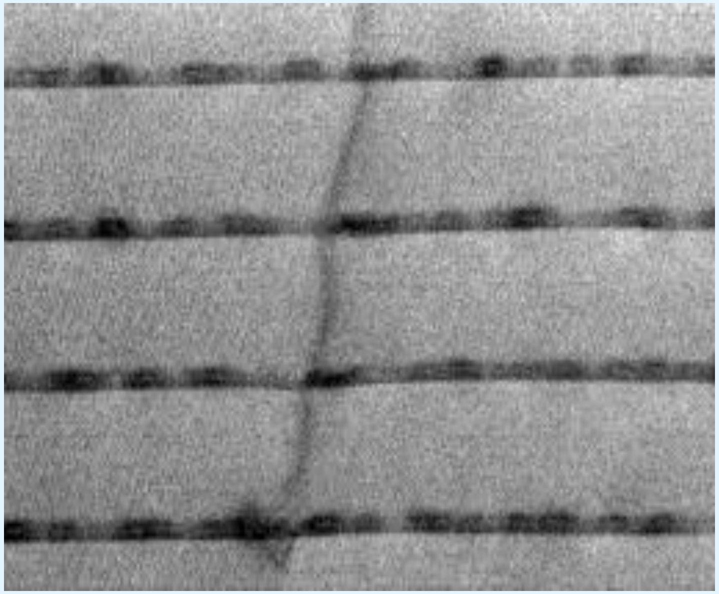

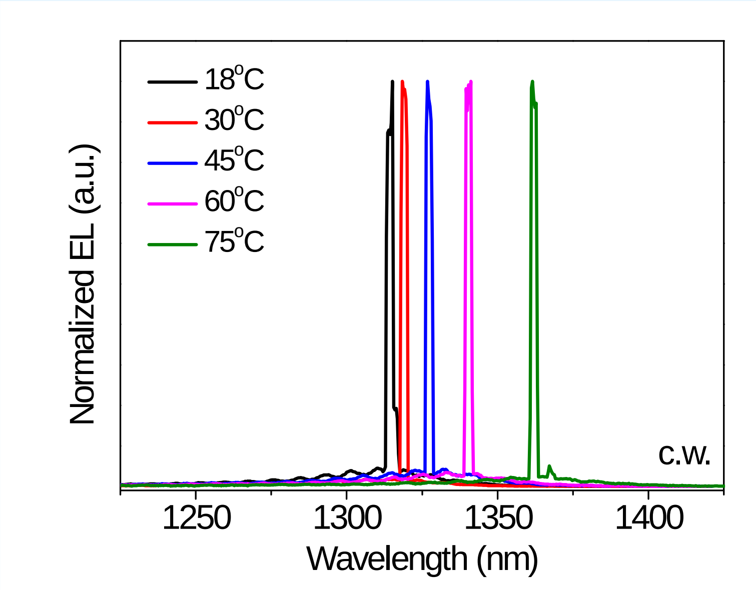

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Background

- InP-based QDs on GaAs cover 650 to 750 nm, beyond that achievable with compressively strained GaInP QWs

Early developments: (RT J_{th})

- SSMBE - 2.3 $kAcm^{-2}$ for 2 mm long cavities emitting at 728 nm (Manz Y.M 2000)
- MOVPE – 4.25 $kAcm^{-2}$ 200 µm long cavities emitting at 645 nm (Walter G. 2004)

❖ InAs QDs around that time ~ 26 Acm^{-2} (Liu G.T. et al 1999)

Progress on growth:

- Previous MOVPE carried out to maximise dot density, T_g ~ 580 to 650 °C
- Increase growth temp ~ 700 °C reduced dot density but vastly improved the material quality - 2 mm long lasers emitting at 741 nm 190 Acm^{-2} at 300 K (Lutti J. et al 2005)

❖ Further reductions in J_{th} made – adjusting core structure and optimising growth temp.

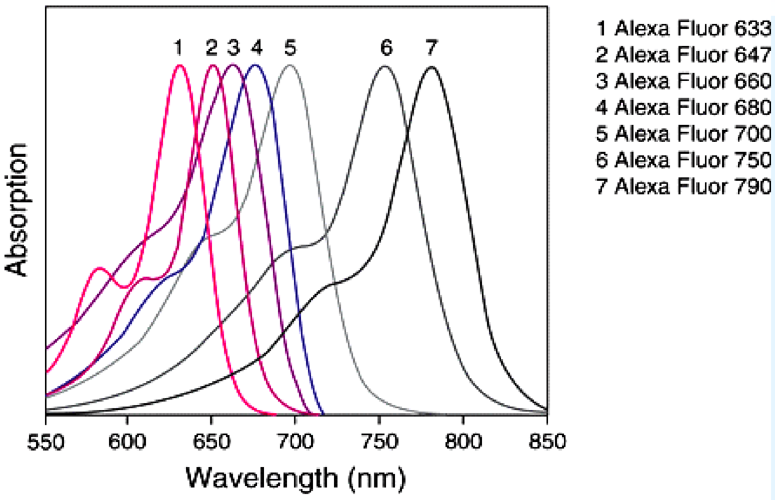
Extending to 780nm:

- Reducing the growth rate of the dots - promote the formation of larger dots extending the range of optical gain to slightly beyond 780 nm. Large number of defects!

Motivation

Applications

- Biological apps: Medical diagnostics/imaging (e.g. excitation of fluorescent dyes), blood analysis, photodynamic therapy
- Optical read/write CD/DVD compatibility
- Heterodyning, e.g. Terahertz emission via difference frequency generation (DFG)



Advantages of QDs

Inhomogeneously broadened dot sizes:

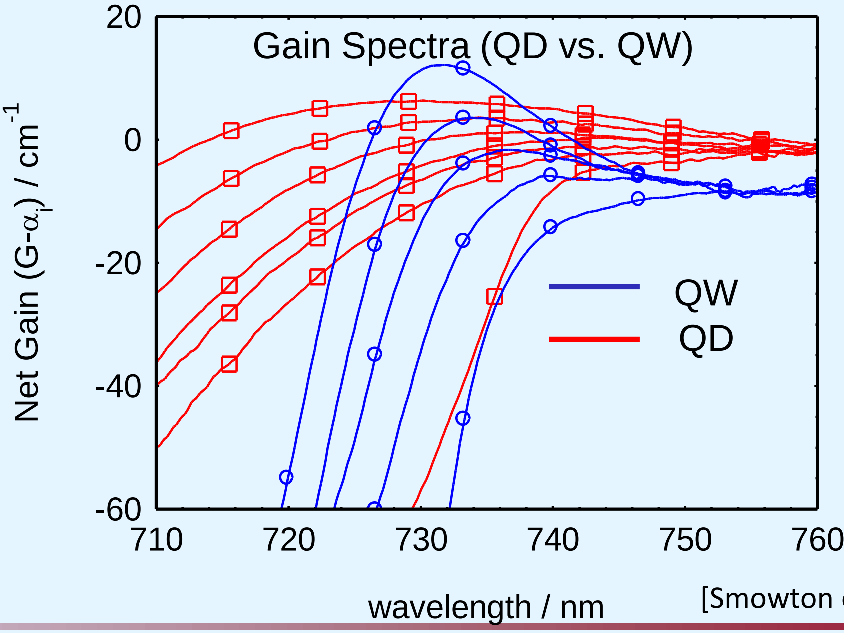
- •Wide distribution of energy states
- •Broad gain spectra compared with QWs

•Low surface recombination

•Mode locking

❖**Stable dual-wavelength laser**

❖**Reduced wavelength temperature sensitivity**



[Smowton et al. 2011]

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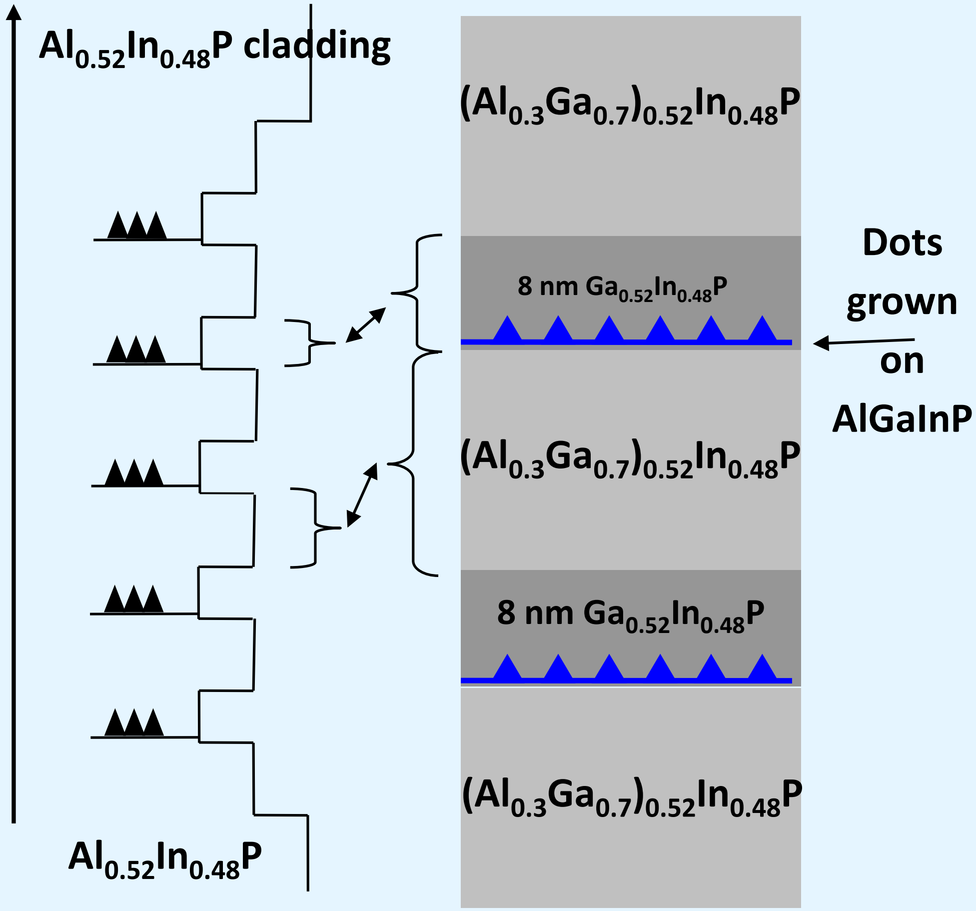
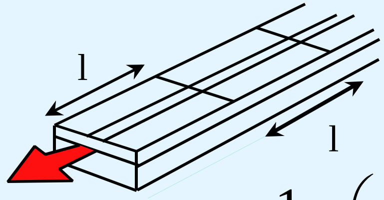
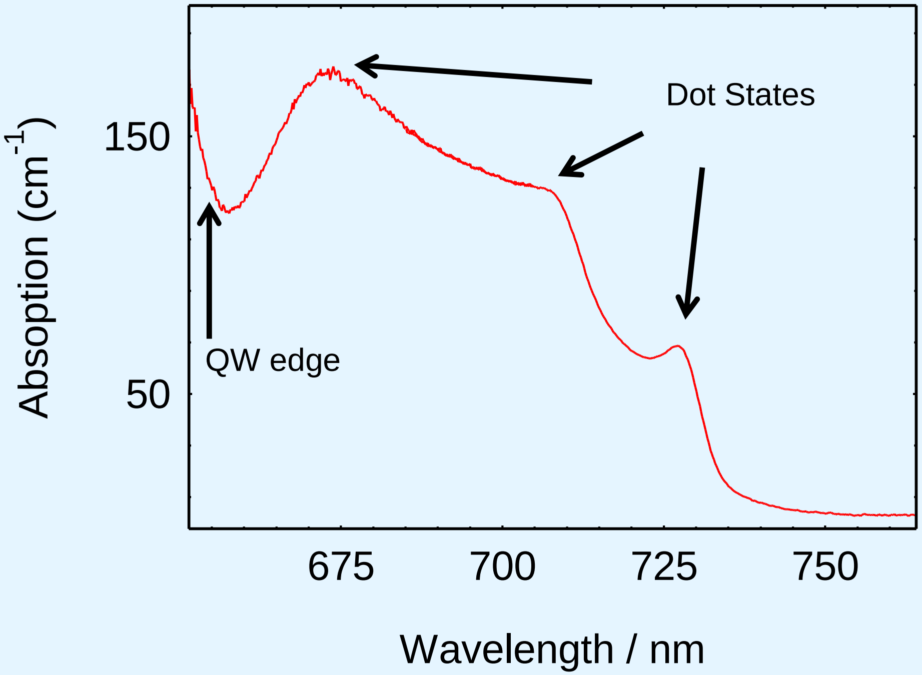
Material Structure

- Epitaxial structure deposited on *n*-GaAs substrate





$$\alpha + \alpha_i = \frac{1}{l}\ln\left(\frac{I_2}{I_1}\right)$$



InP QDs form up to three inhomogeneously broadened dot size distributions

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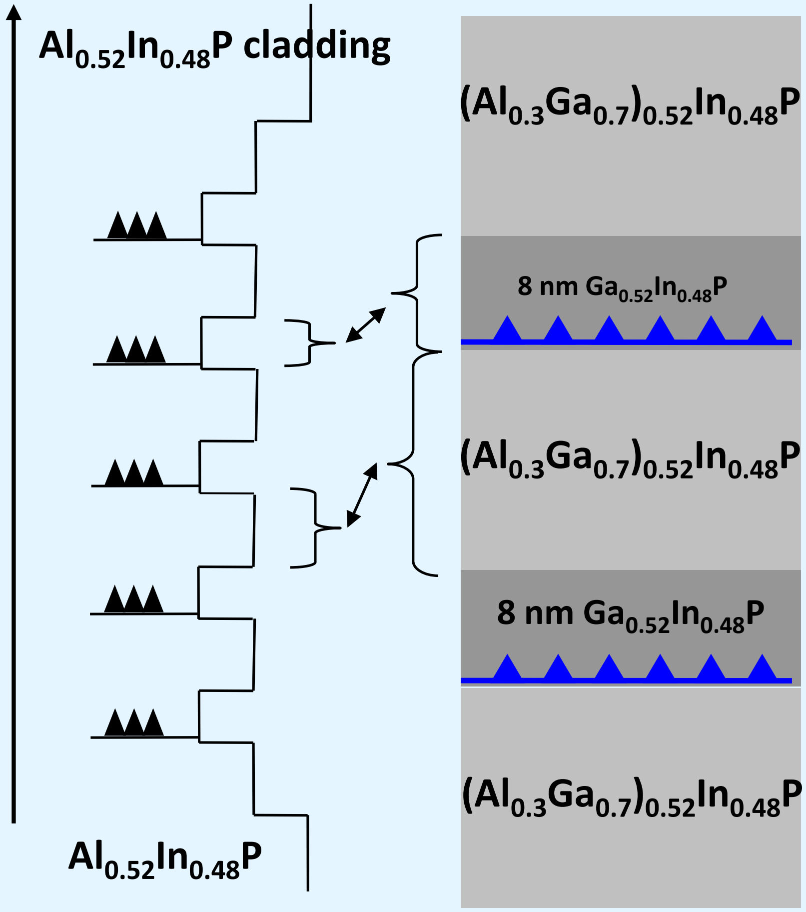

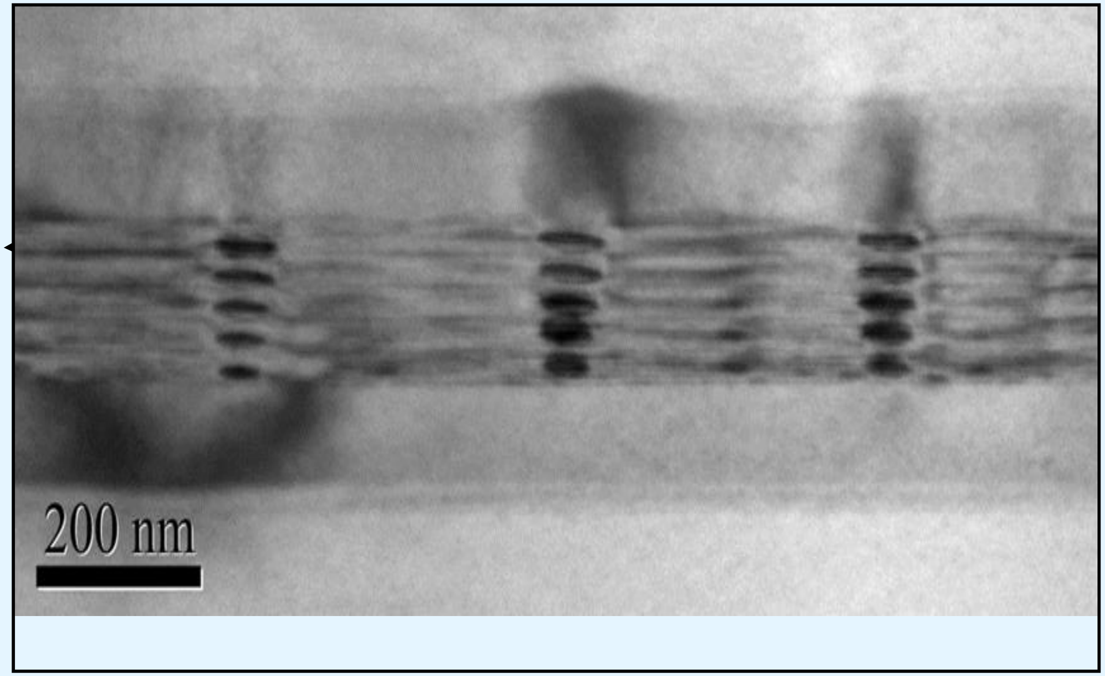

Richard Beanland, Warwick University

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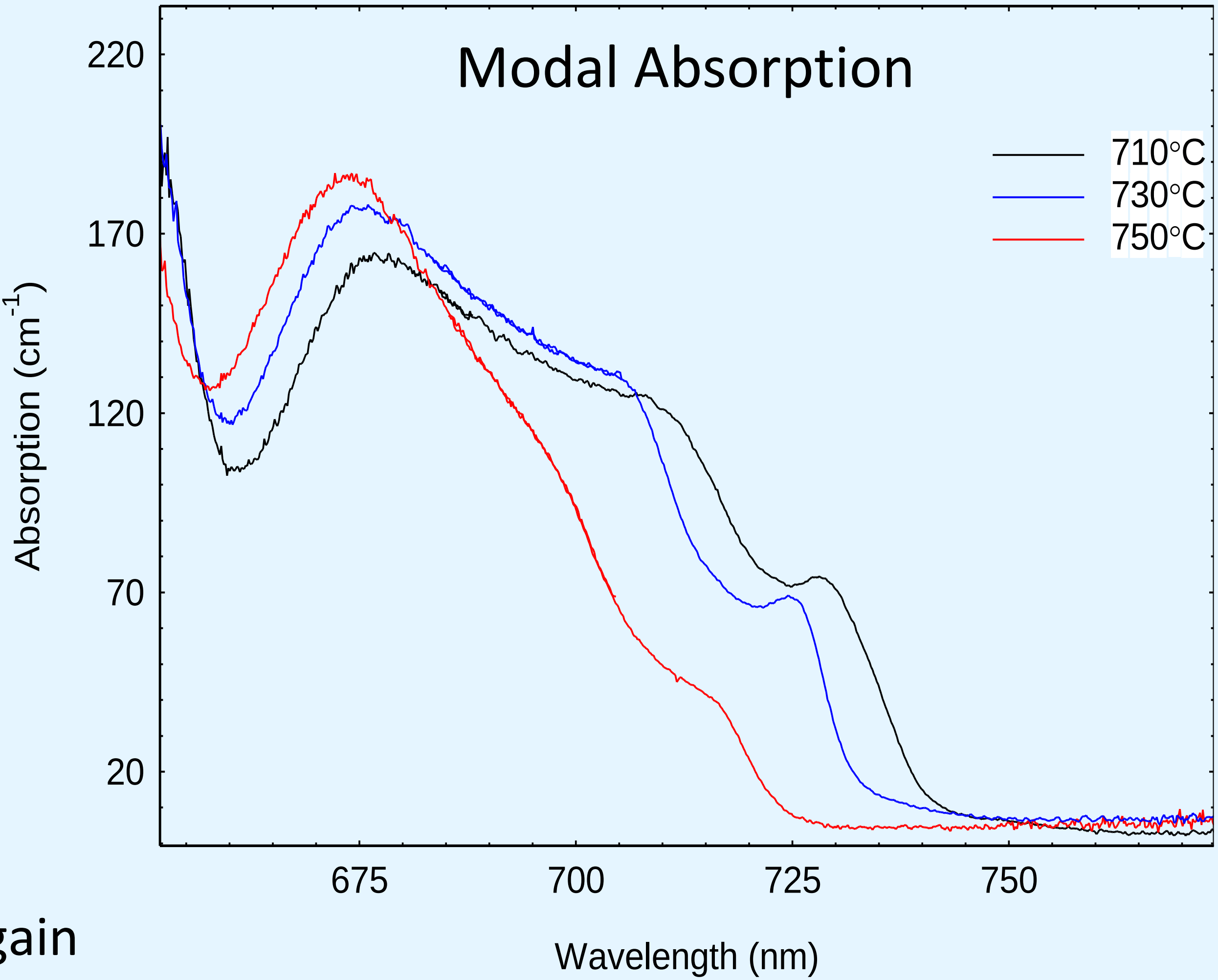
Influencing emission wavelength

Growth temperature (T_g):

Increase T_g

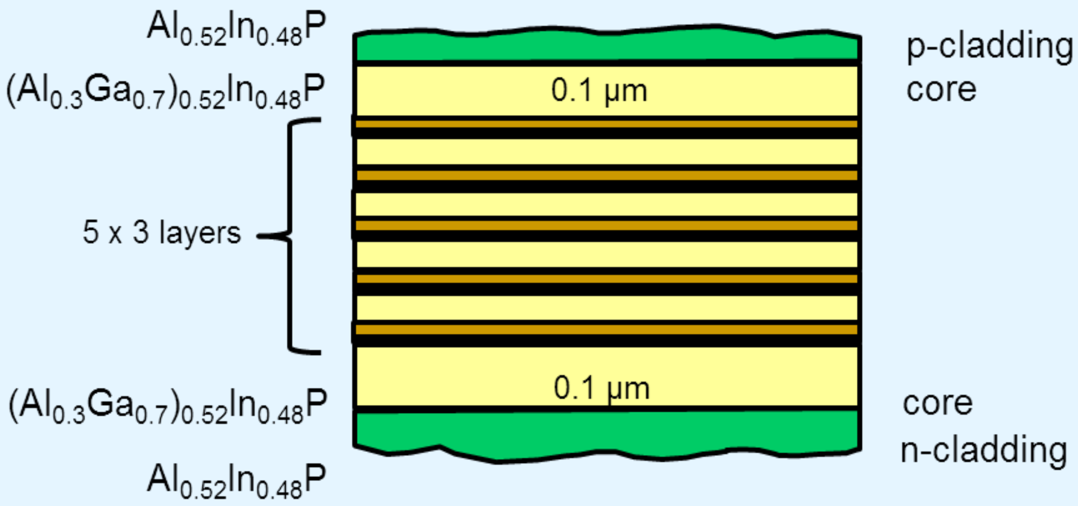
- Blue-shifts dot states
- Reduces magnitude of GS absorption
- Fewer 'large dots'
- Penalty is lower maximum gain



Influencing emission wavelength

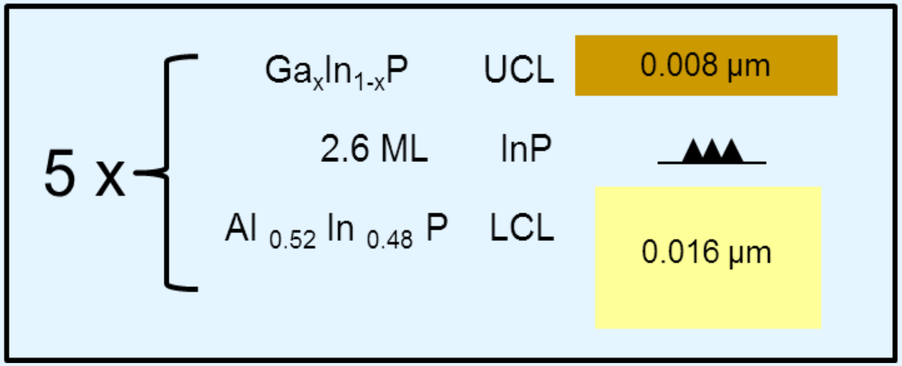
Strain

• Upper confining layer (UCL) of dots comprises GaInP effective QW



Adjust Ga fraction in UCL:

•Ga % = 51.6, GaInP lattice matched to GaAs – unstrained

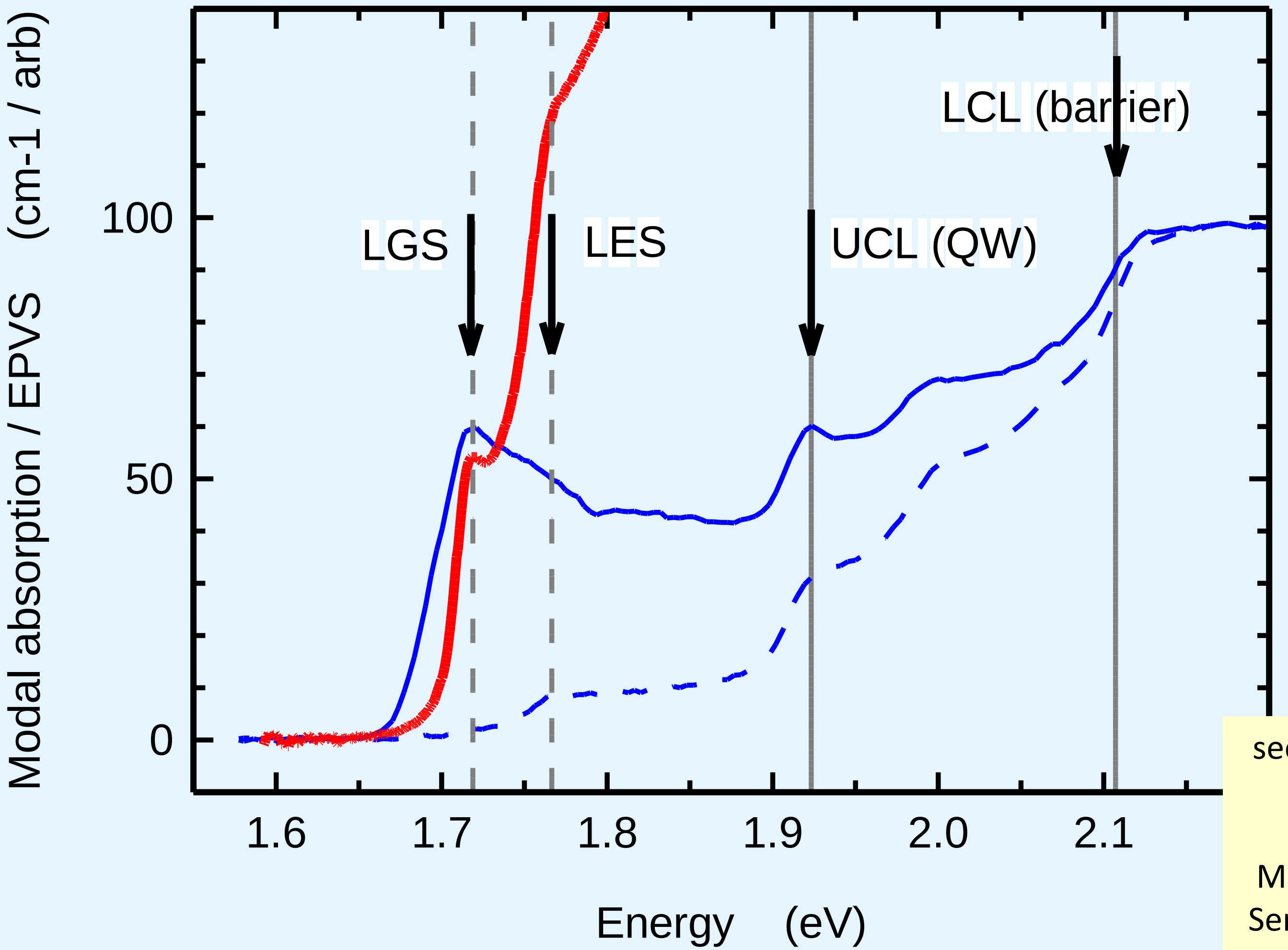


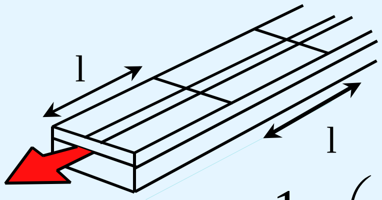
•Ga % > 51.6 tensile strained

•Ga % < 51.6 compressively strained

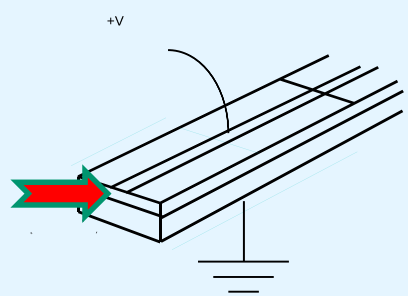
❖Causes deleterious effects on material quality, no lasing at room temperature.

Measuring state energies



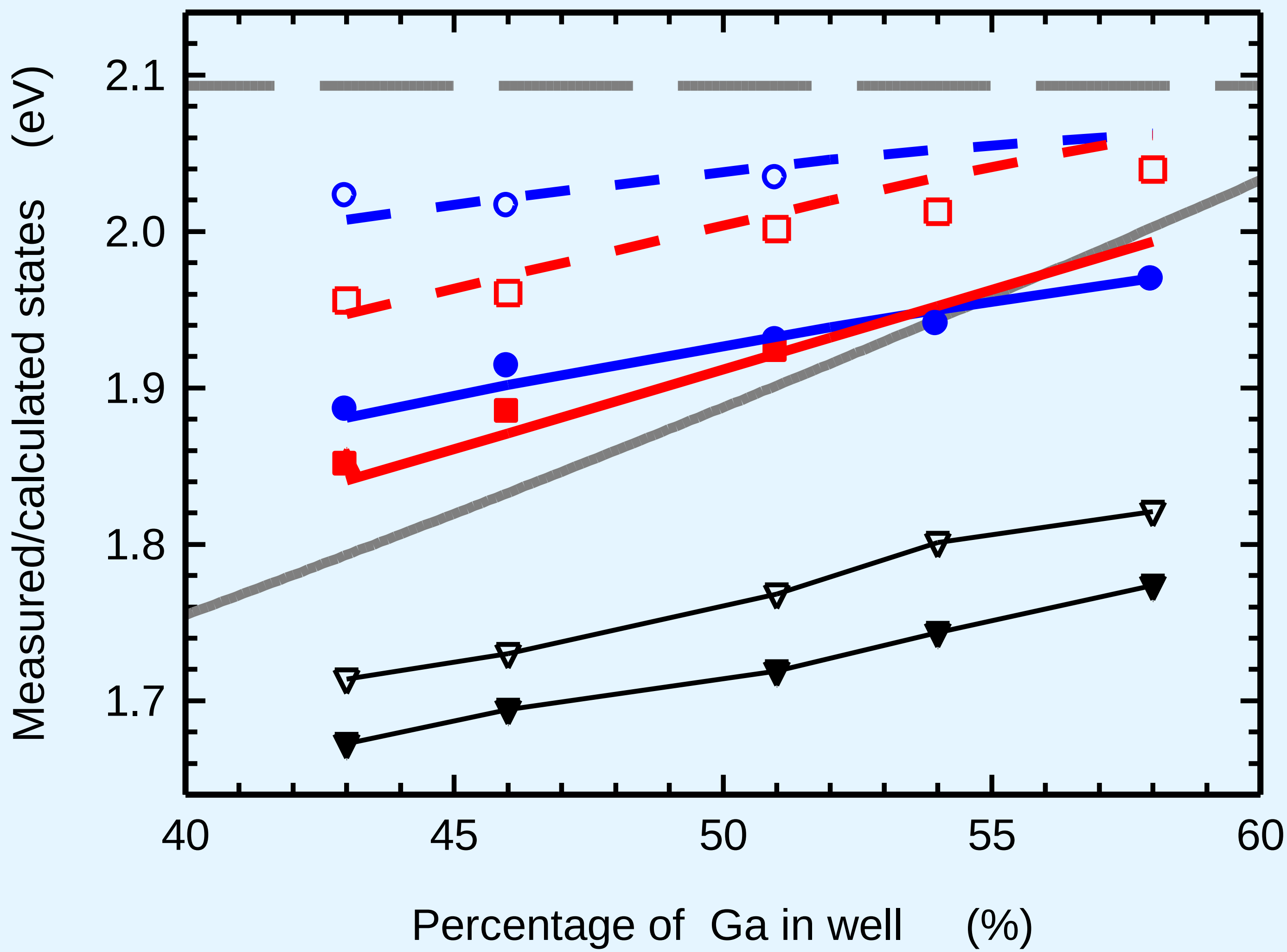


$$\alpha + \alpha_i = \frac{1}{l} \ln\left(\frac{I_2}{I_1}\right)$$



see “Polarization response of quantum confined structures using edge-photovoltage spectroscopy”, M. Mexis, P. Blood and P.M. Smowton, Semiconductor Science and Technology 22, pp. 1298-1301 (2007)

Well and dot state energies



Influencing emission wavelength

Strain

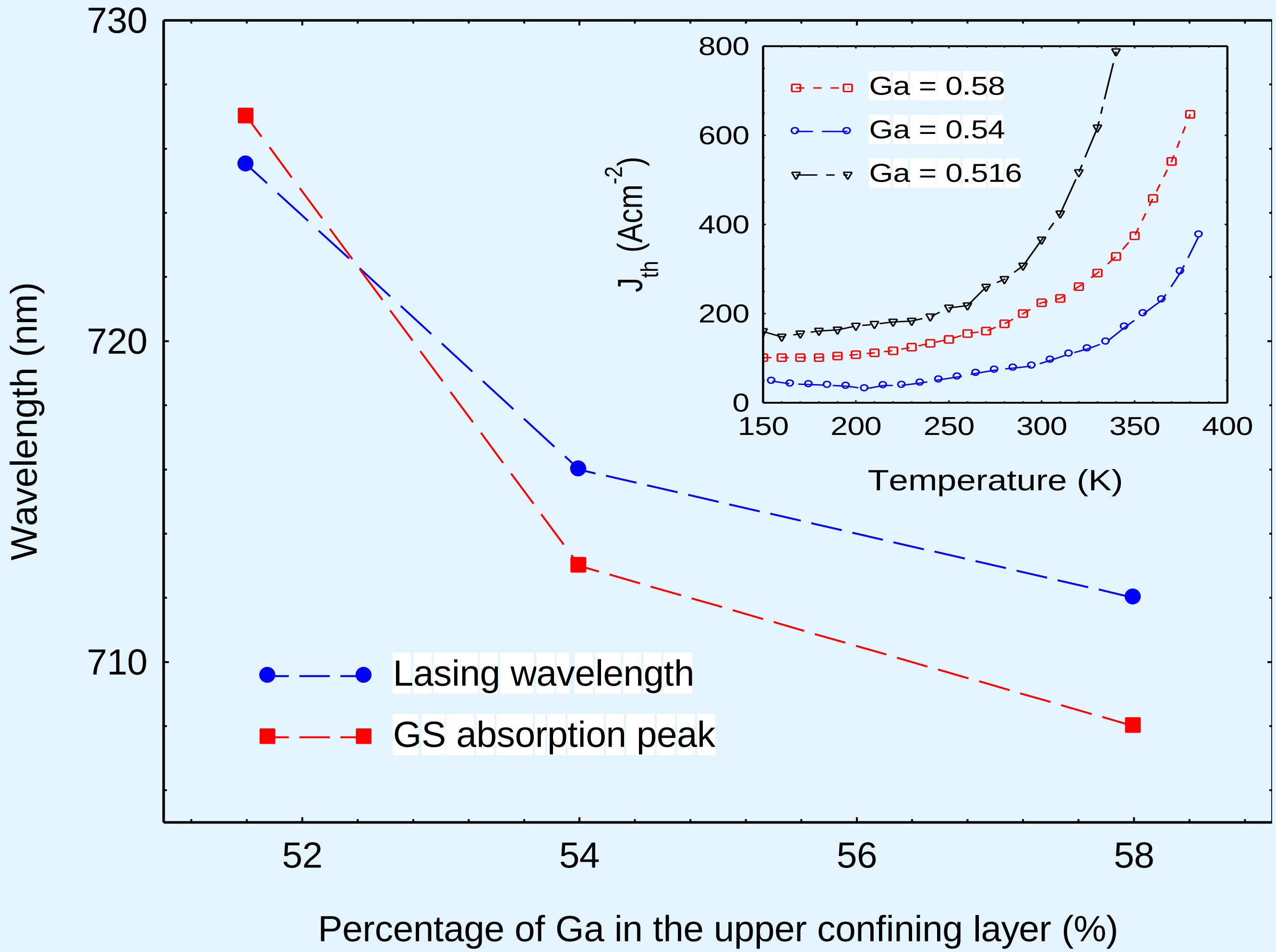
•Tensile strain – leads to blue shift dot transition wavelength

•Shorter lasing wavelength

• Compared 3 Ga compositions

0.516 (unstrained), 0.54, 0,58

•0.54 Ga fraction produced lasers with lowest threshold current, e.g. **89 Acm^{-2}** at **300 K** and **186 Acm^{-2}** at **350 K** (3 mm laser with uncoated facet)

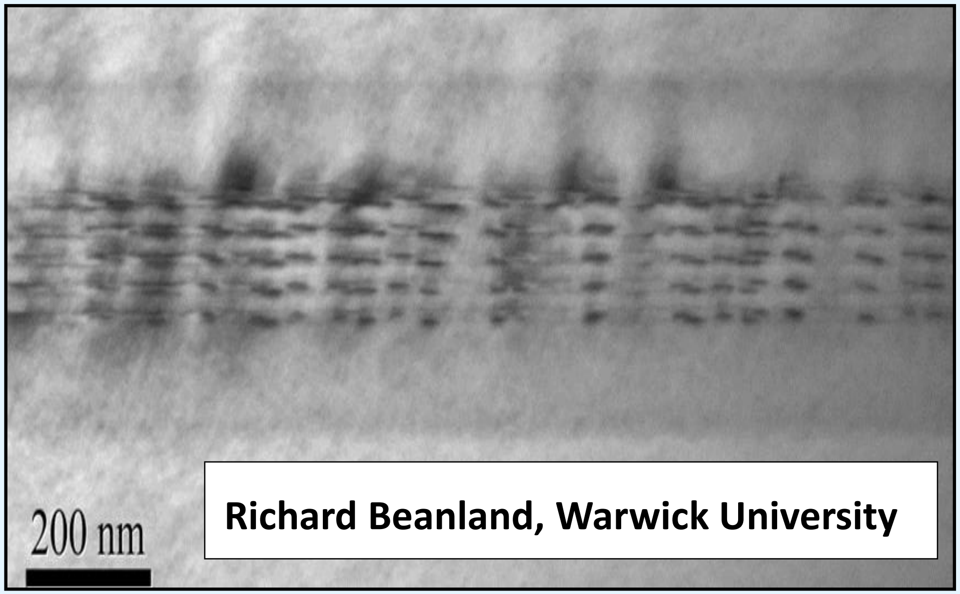


Emission Wavelength: InPAs dots

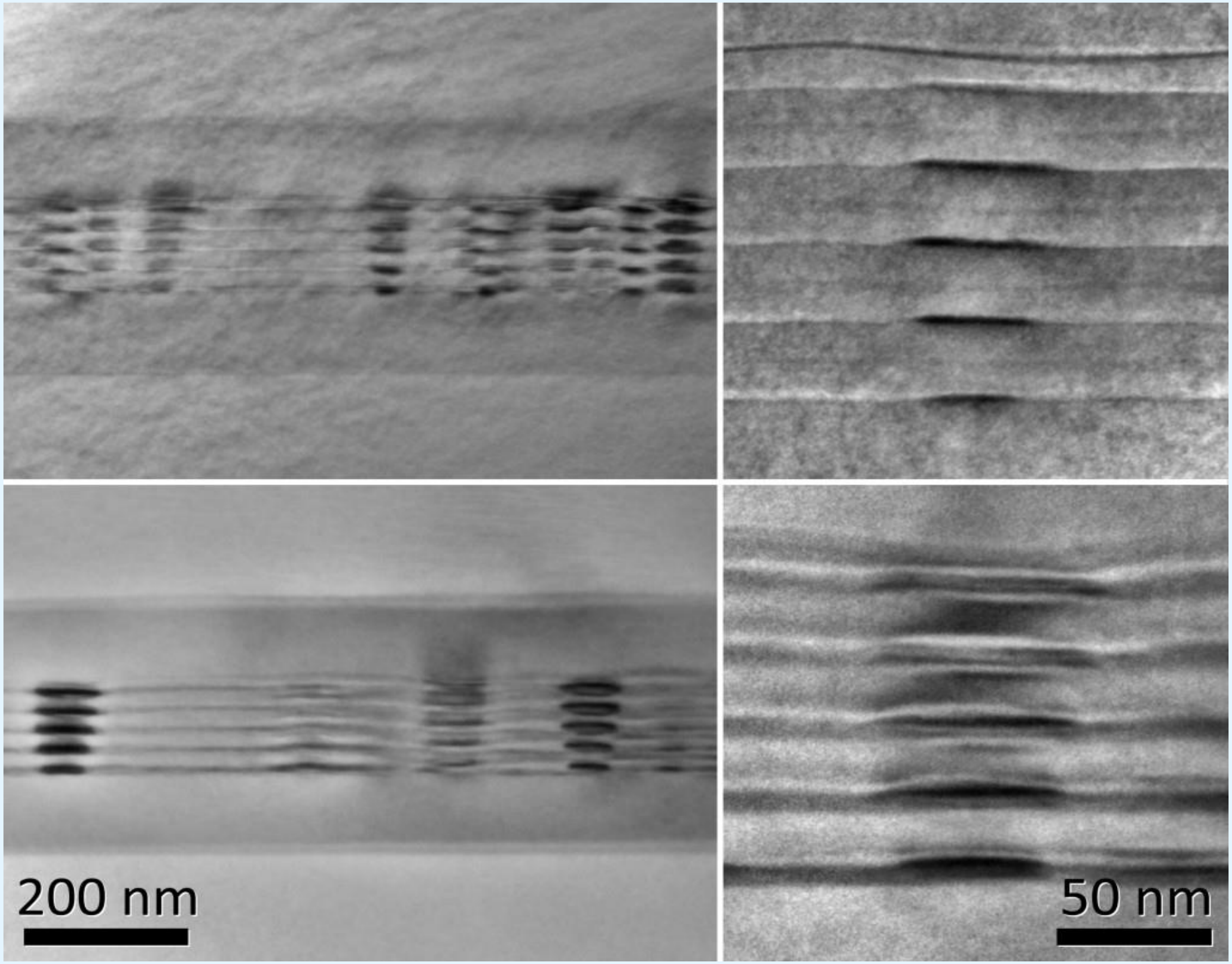
- Emission at longer wavelengths – towards 780nm possible for dots grown at lower temperatures
- penalty of much higher recombination current density (defect density / order-disorder)

See Smowton et al JSTQE 2005

- Alternative – add As to create ternary dots – proof of principle!



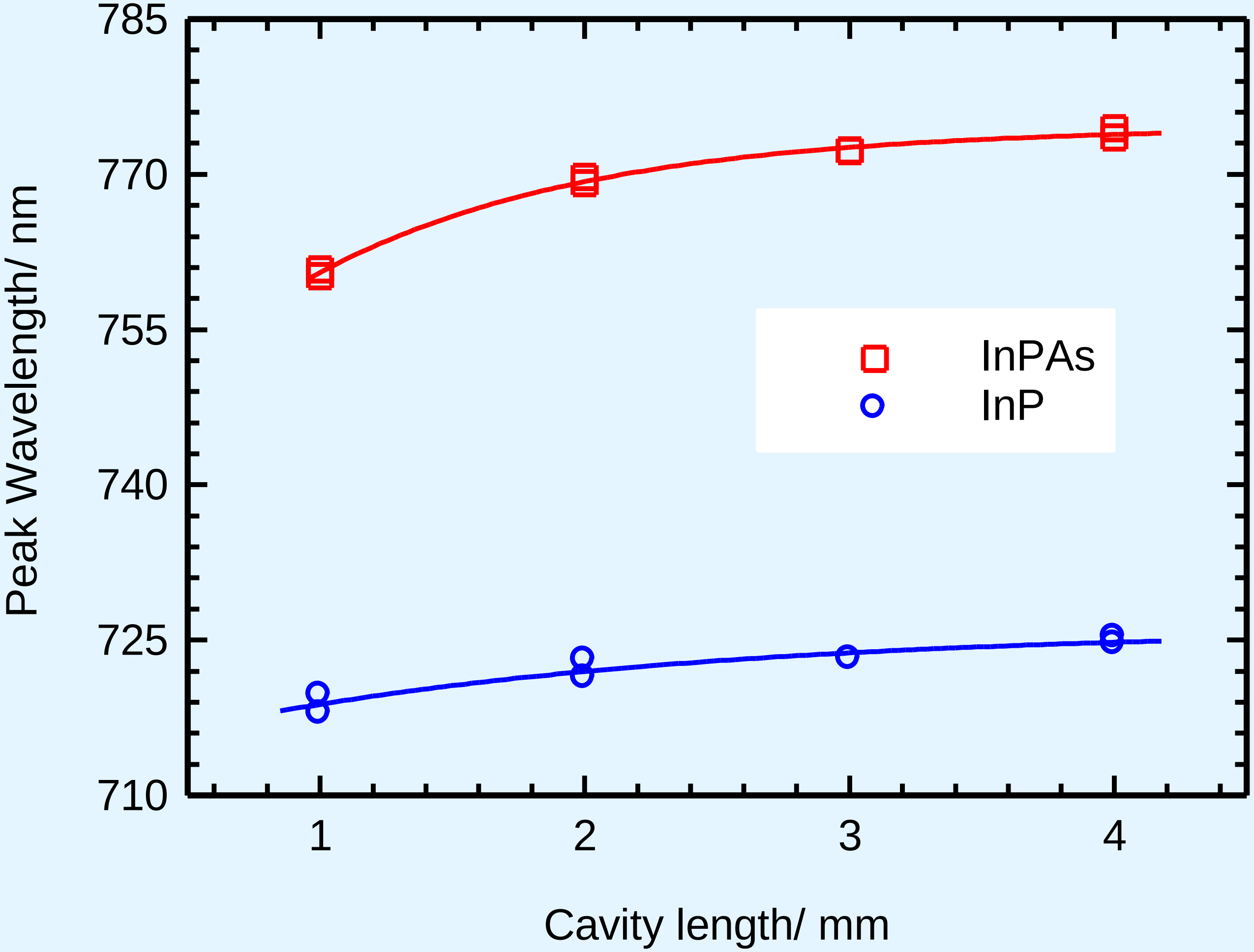
Samples Structure



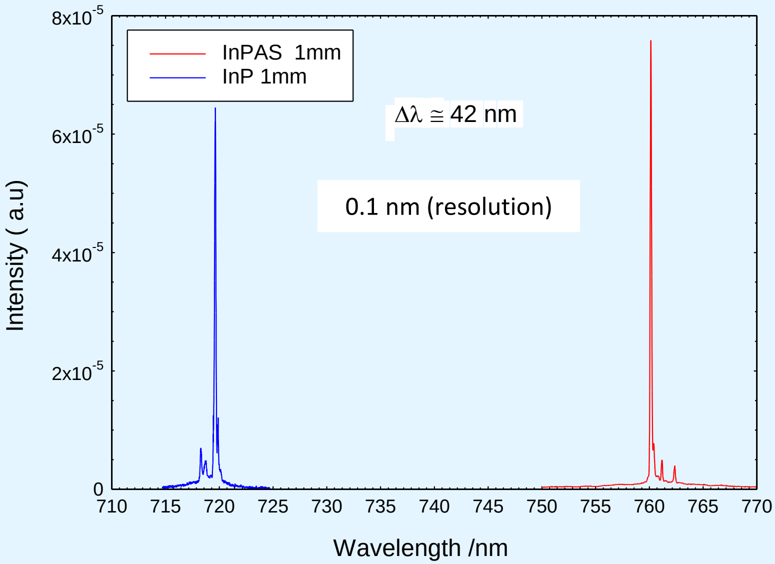
TEM (InPAs)

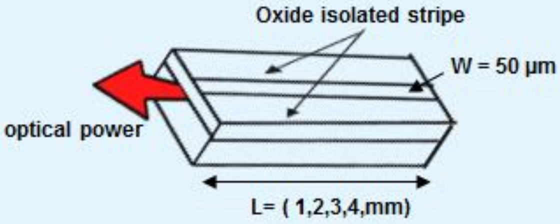
TEM (InP)

Wavelength vs Device length



Laser spectrum

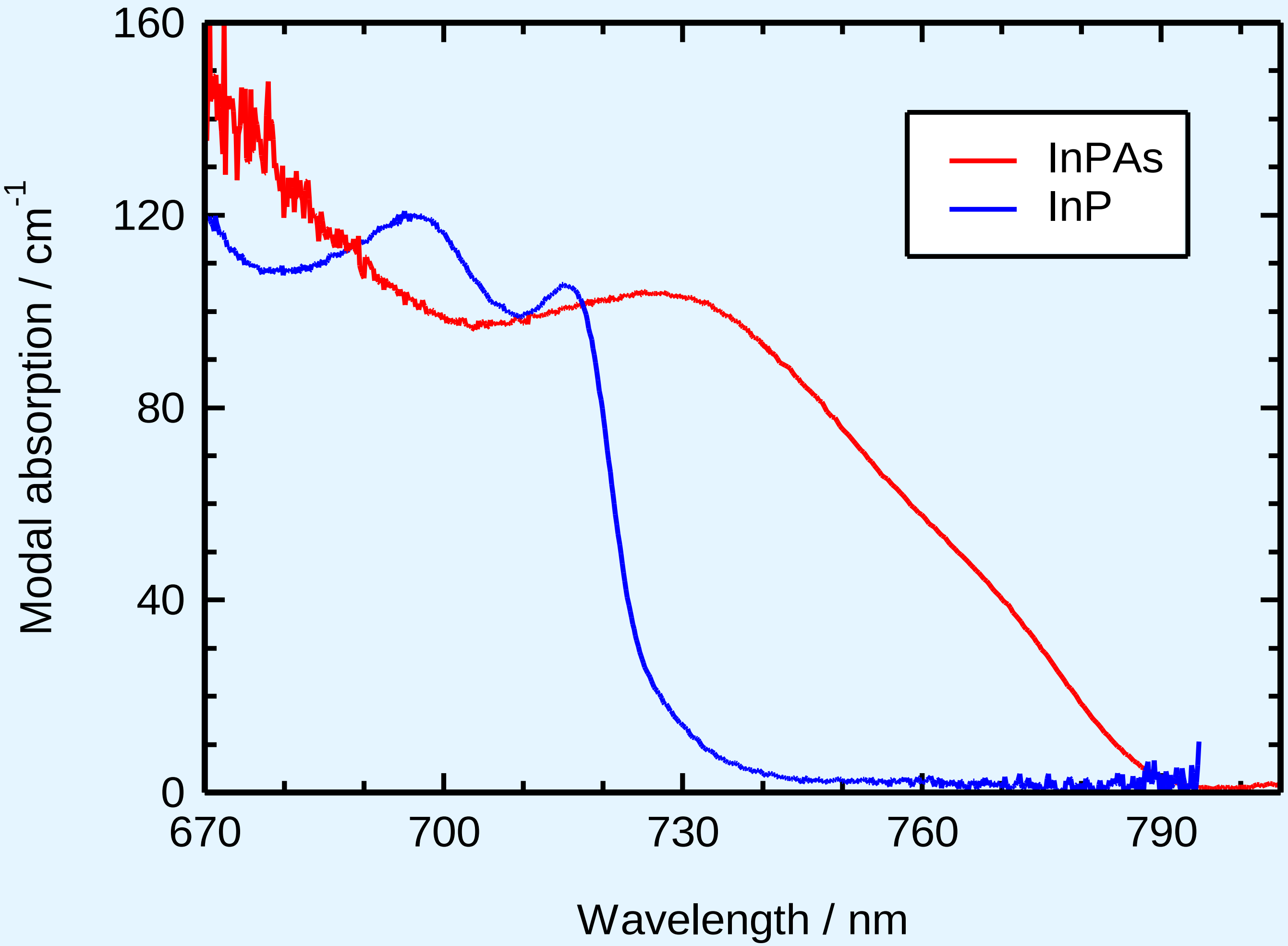


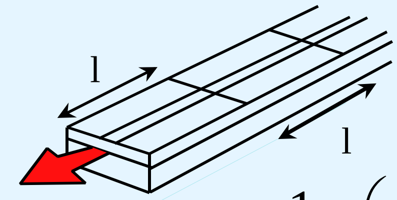


- **InP (715-725nm)**
- **InPAs (760-775nm)**

I. Karomi, P.M. Smowton, S. Shutts, A.B. Krysa, R. Beanland, Optics Express 23 (21) , DOI 10.1364/OE.23.027282 2015

Modal Absorption Spectrum

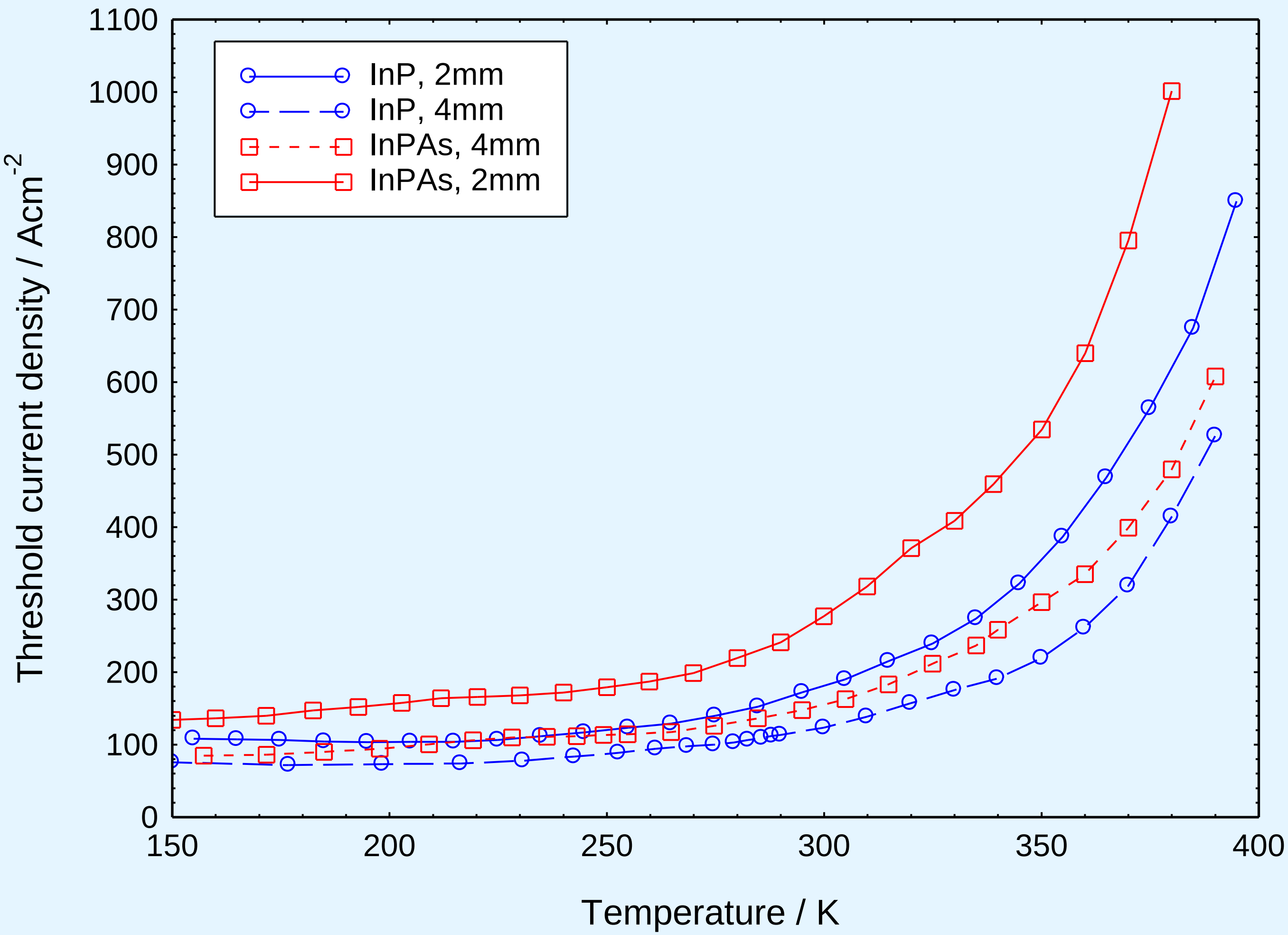


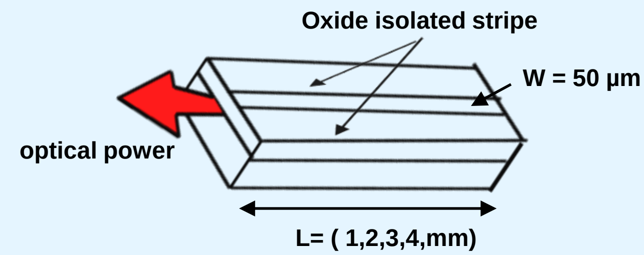


$$\alpha + \alpha_i = \frac{1}{l}\ln\left(\frac{I_2}{I_1}\right)$$

- **InPAs Absorption shifted to longer wavelengths.**
- **InPAs ground state feature is less well pronounced.**
- **InPAs larger inhomogeneous broadening**

Threshold current density vs Temperature





*InPAs lasers work up to 380 K with 260 A/cm^2 @ 300 K for 2mm.

*InPAs lasers have higher temperature dependence of Jth.

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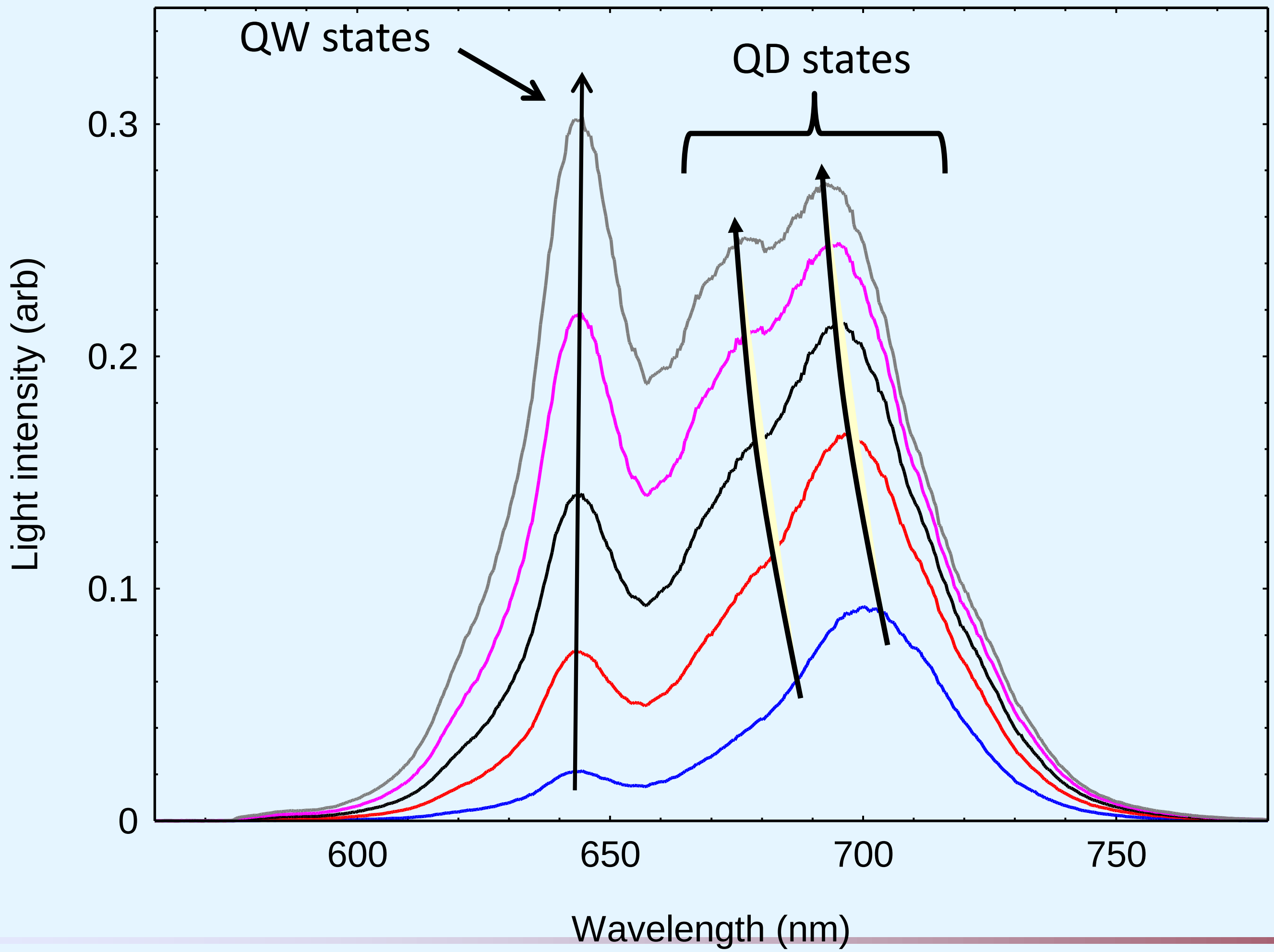
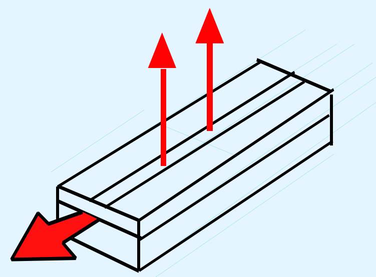
Spontaneous Emission – where are the carriers

- Emission from dots covers 660 – 750 nm, peaks blue shift with injection
- QW emission peaks at 645 nm, relatively fixed due to large number of states



Spontaneous Emission

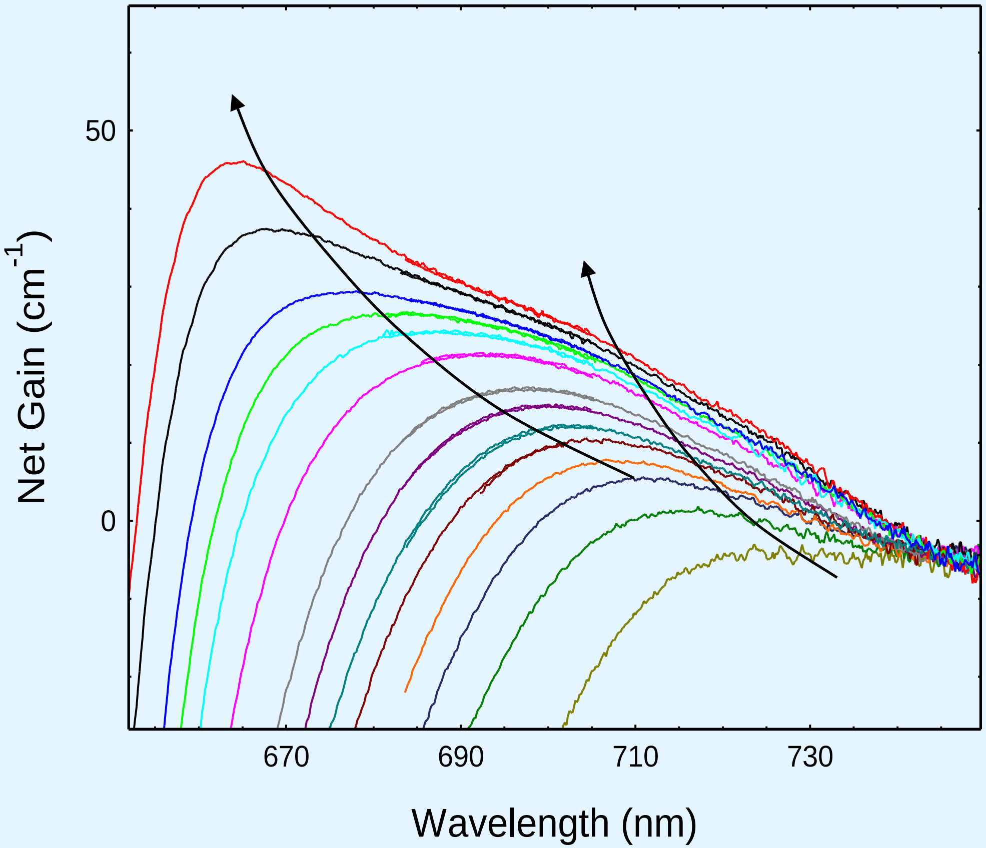


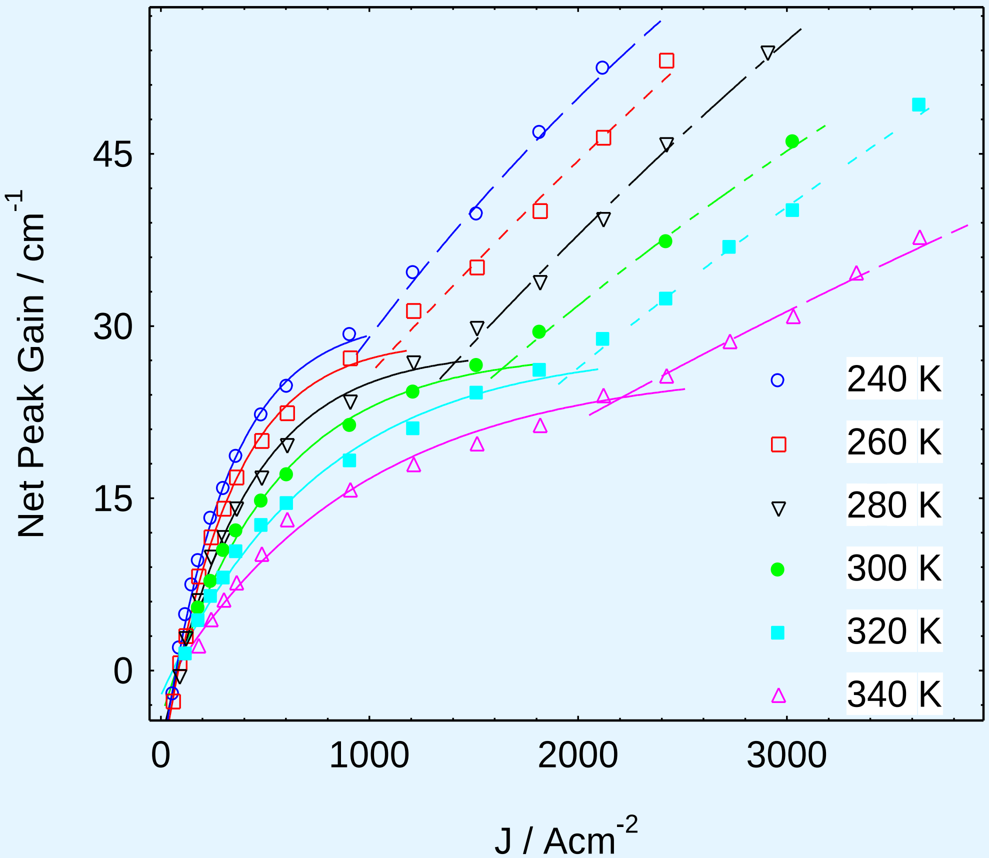
Optical gain-current relations

•Gain peak wavelength blue-shifts with increased carrier injection due to state-filling.

•Gain saturation of the ground state transition occurs between 20 – 30 cm^{-1} and gain from higher density of states takes over.

•At 300 K gain values over 45 cm^{-1} measured for current density ~ 3000 Acm^{-2}





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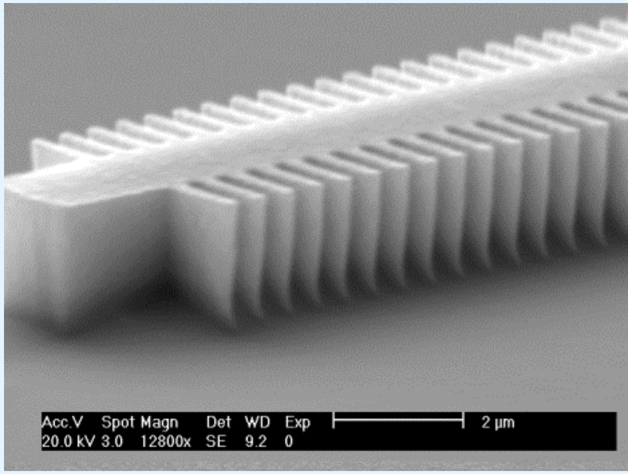
Wavelength-Temperature Dependence

Problem: Gain Peak of light emitting semiconductors have temperature sensitive λ.

Applications where Gain Peak λ stability is important:

- Emission λ of Fabry Perot cavities
- 'Lab on a Chip', monolithic multilaser devices
- Threshold current of VCSELs and DFB/DBR laser devices
- Laser pump sources



Question: Can we achieve a temperature insensitive λ ?

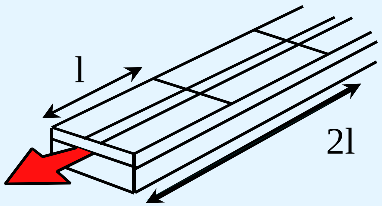
- Δλ influenced by temperature coefficient of band gap.
- Inhomogeneously broadened QD ensembles – λ strongly dependent on state filling.

Wavelength temperature dependence has been studied in InAs QDs:

J.D. Thomson, H.D. Summers, P.M. Smowton, E. Herrmann, P. Blood, M. Hopkinson, Journal of Applied Physics 90(9) 4859-4861 (2001)

F. Klopf, S. Deubert, J-P. Reithmaier, A. Forchel, Applied Physics Letters, 81(2), 217-219 (2002)

Rationale

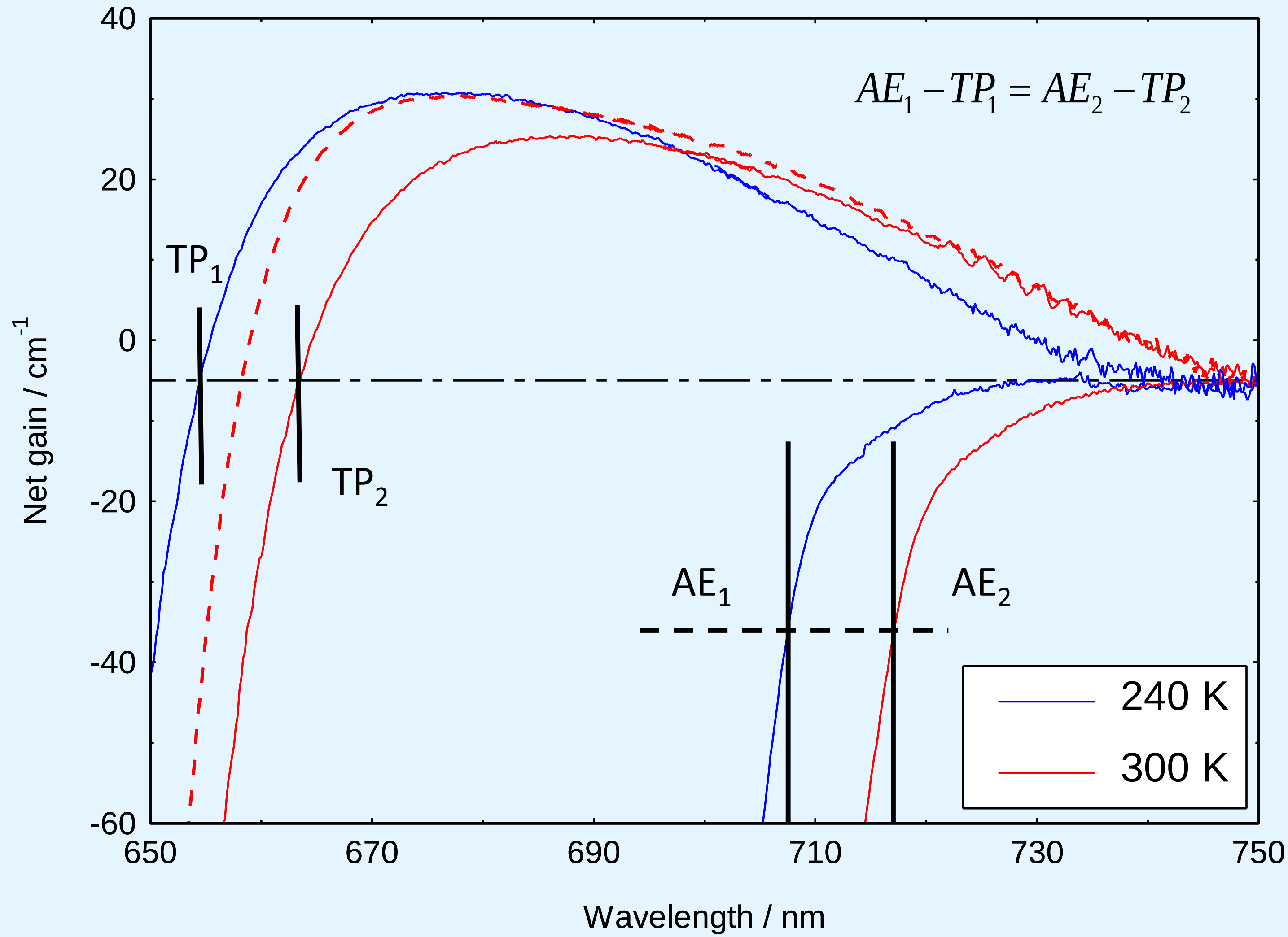


$$G-\alpha_i=\frac{1}{l}ln\left[\frac{I_{1,2}}{I_1}-1\right]$$

1) Absorption edge moves with temperature dependence of band gap

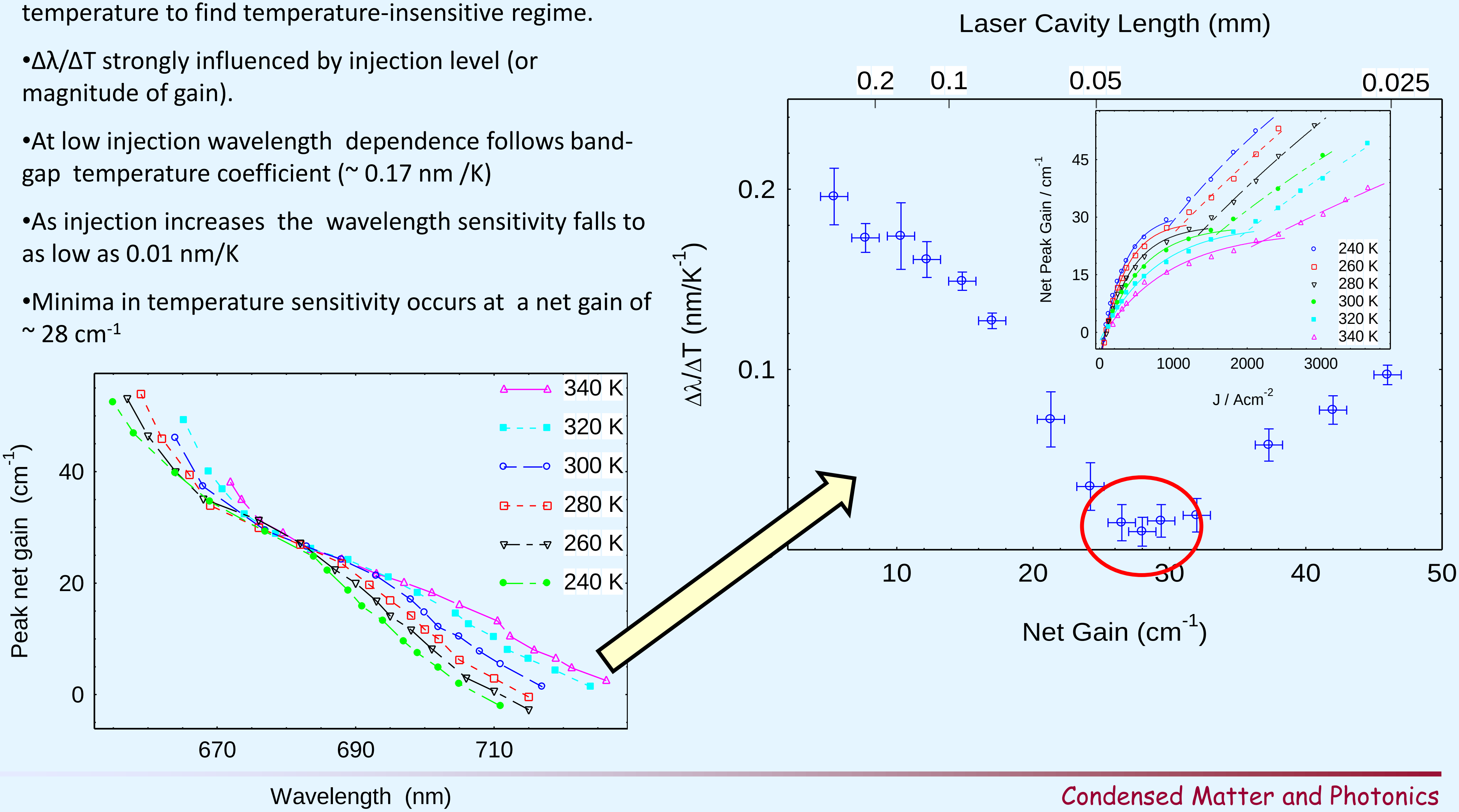
2) Gain peak amplitude is very temperature dependent

3) Can we use state filling to compensate band gap temperature dependence?



Wavelength insensitivity

- Measured change in gain-peak wavelength with temperature to find temperature-insensitive regime.
- Δλ/ΔT strongly influenced by injection level (or magnitude of gain).
- At low injection wavelength dependence follows band-gap temperature coefficient (~ 0.17 nm /K)
- As injection increases the wavelength sensitivity falls to as low as 0.01 nm/K
- Minima in temperature sensitivity occurs at a net gain of ~ 28 cm^{-1}



Temperature insensitive lasing wavelength

Laser design:

Find net-gain *(G-α_i)* at which Δλ/ΔT falls to a minimum and calculate corresponding laser cavity length *(L_c)* :

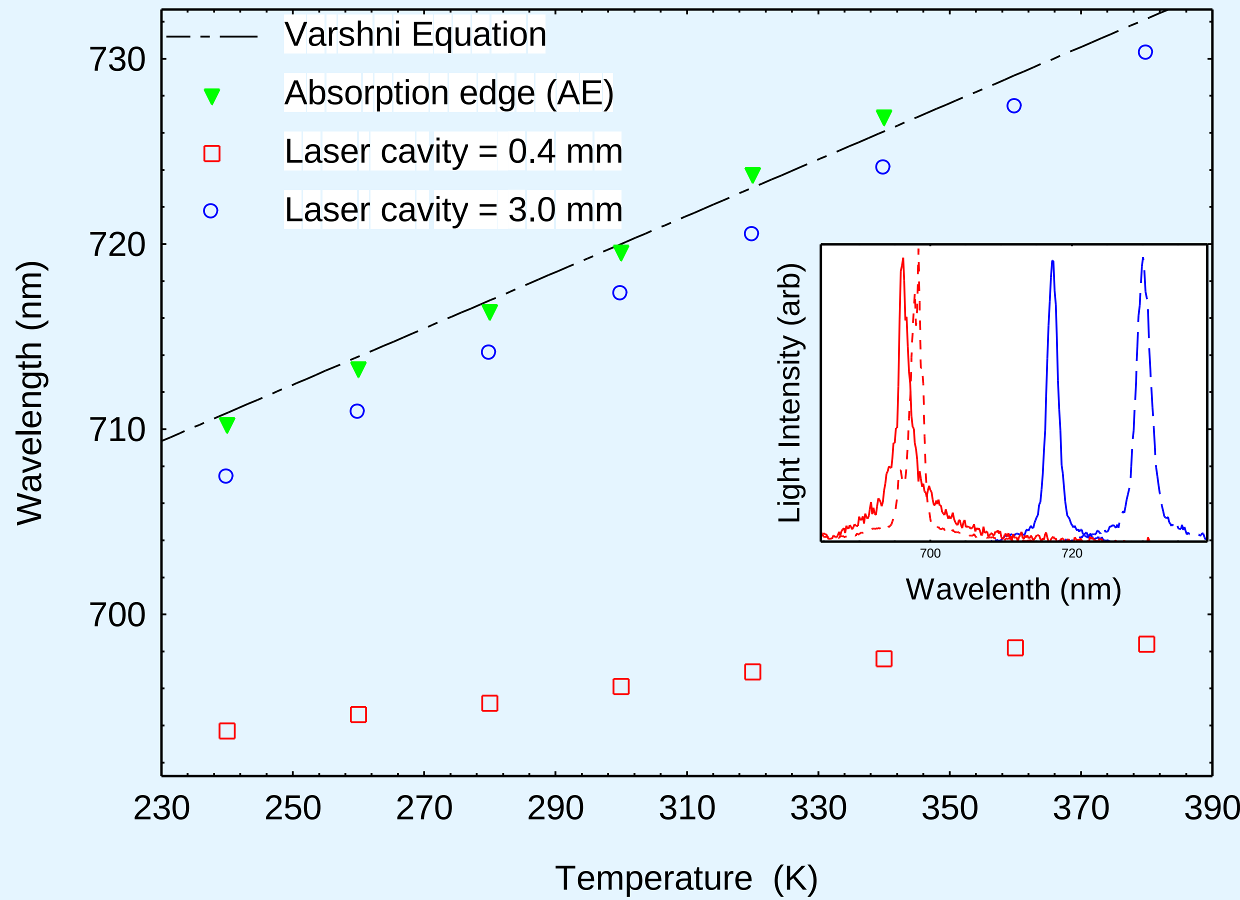
$$(G-\alpha_i)=\alpha_m$$
$$=\frac{1}{L_c}\ln\left[\frac{1}{R}\right]$$

For minimum wavelength sensitivity:

$$0.3 \le L_c \le 0.5mm$$

3 mm laser *(G-α_i = 4 cm^{-1})* dependence is nominally the same as the band-gap.

This is lowered to 0.03 nm/K using a 0.4 mm long cavity *(G-α_i = 30 cm^{-1})*.



S. Shutts, P.M. Smowton, A.B. Krysa, Appl. Phys. Lett. 103, 061106 (2013)

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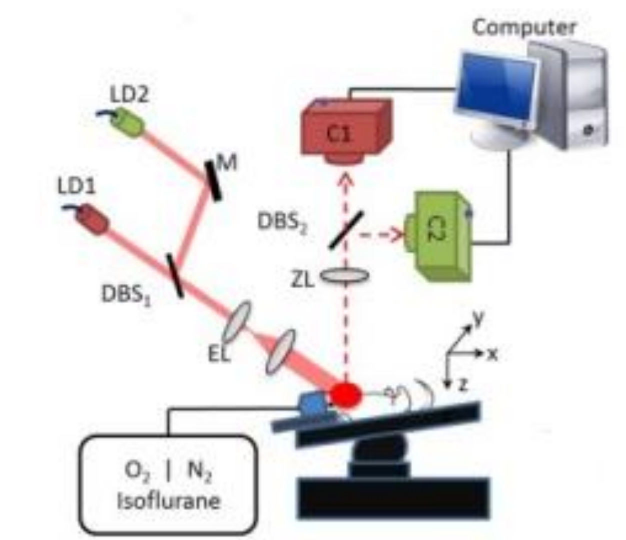
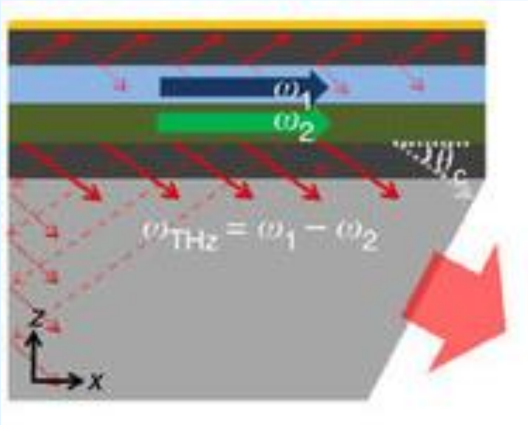
Dual-wavelength Laser

Applications

- Medical – imaging/diagnostics
  - ➢ Laser speckle contrast imaging (LSI)
  - ➢ 2D photo-acoustic imaging
- Optical storage – single chip CD/DVD
- Heterodyning – THz by difference frequency generation
- Interferometric measurements
- Probing carrier dynamics of QD ensembles



LSI (Qin J. et al *Biomedical Optics Express, 2012*



THz - Cherenkov radiation (Karun Vijayraghavan et al, *Nature Communicationsl* 2013)

Wavelength selection

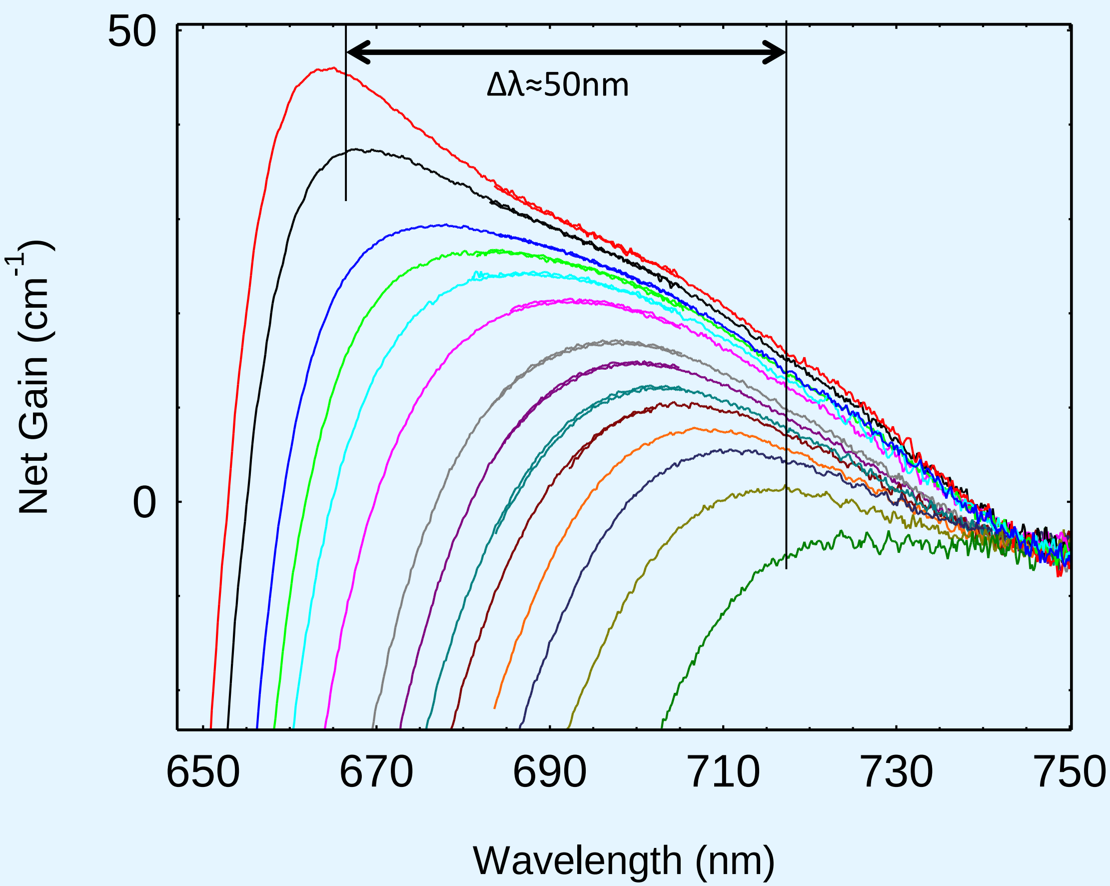
State-filling:

- Inhomogeneously broadened QD ensembles – λ strongly dependent on state-filling
- Injection level controls the degree of state-filling
- Increasing injection level causes gain-peak λ to blue-shift
- Level of injection depends on the gain requirement of the laser

λ is influenced by the loss of the laser cavity (α_m):

$$G_{th} = \alpha_i + \alpha_m \qquad \alpha_m = \frac{1}{2L_c}\ln\left(\frac{1}{R_1 R_2}\right)$$

Gain Spectra at various injection levels



➢Vary the cavity length, L_c

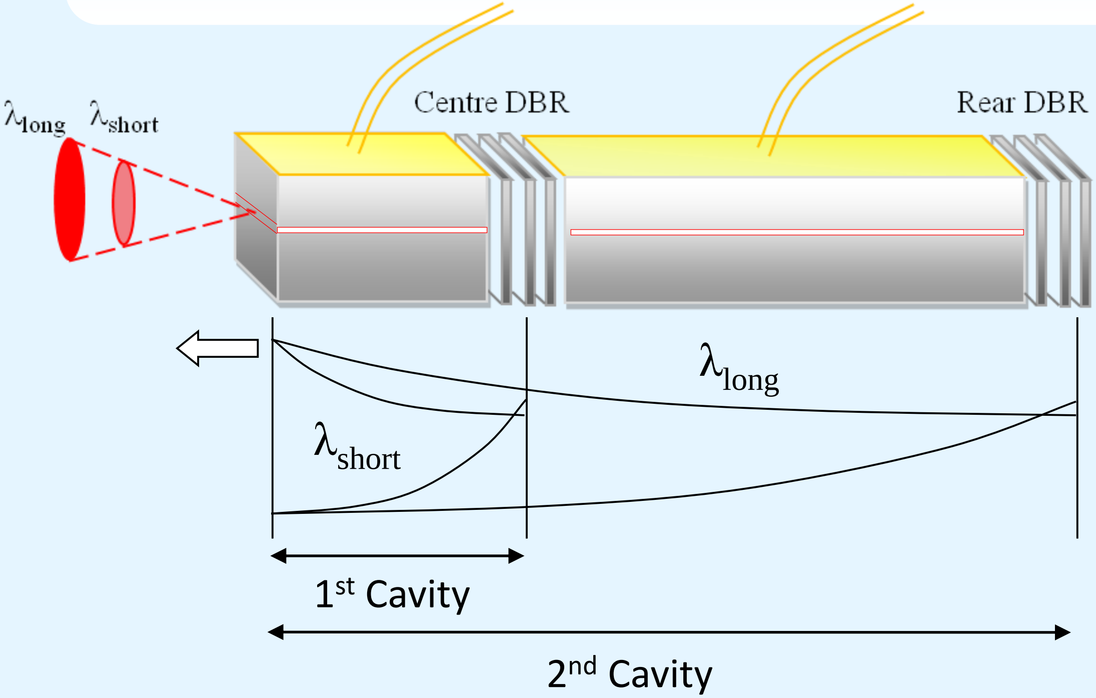
a_m - *mirror loss*

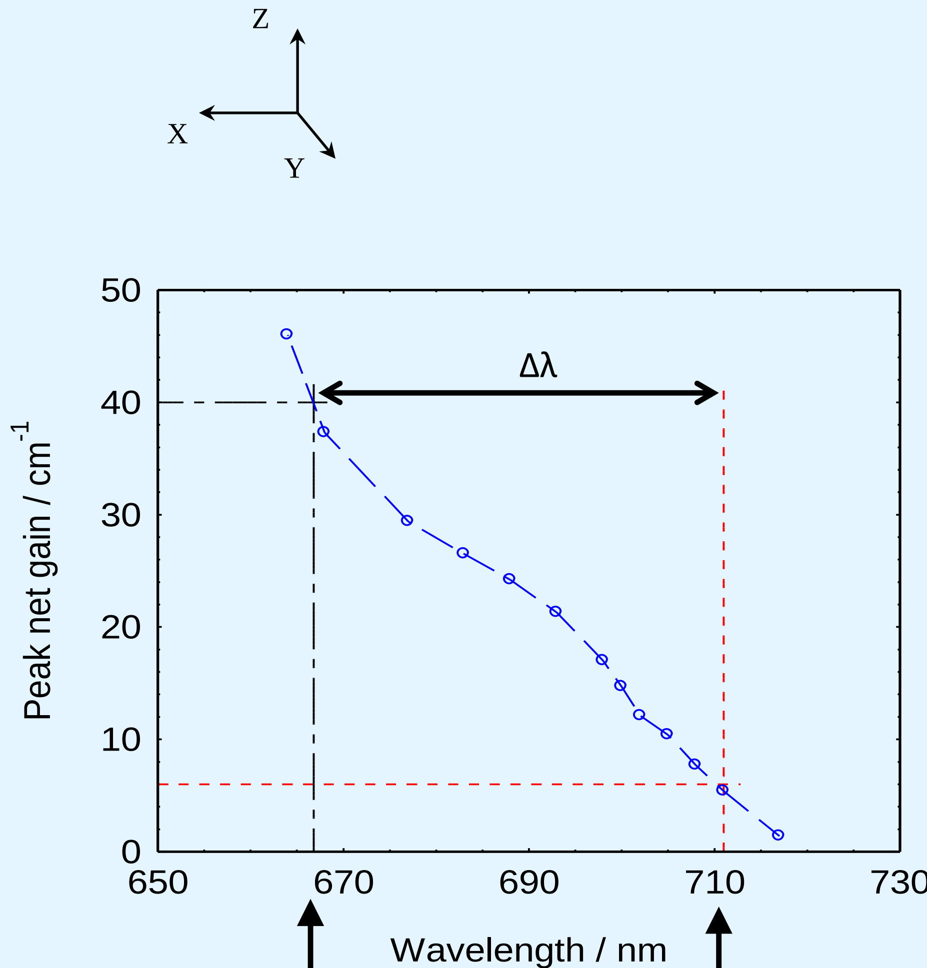
R_1,R_2 = *reflectivities*

a_i = *internal optical loss*

L_c – *Cavity Length*

Dual-wavelength laser: Device Architecture

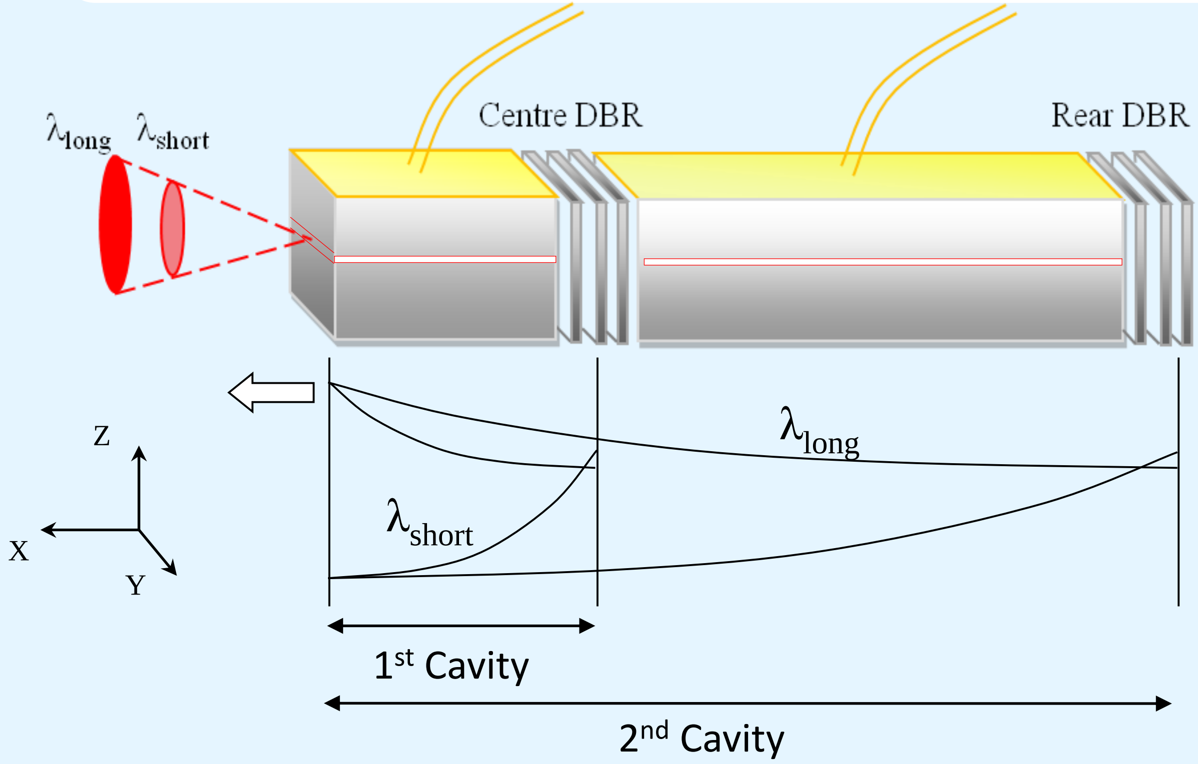


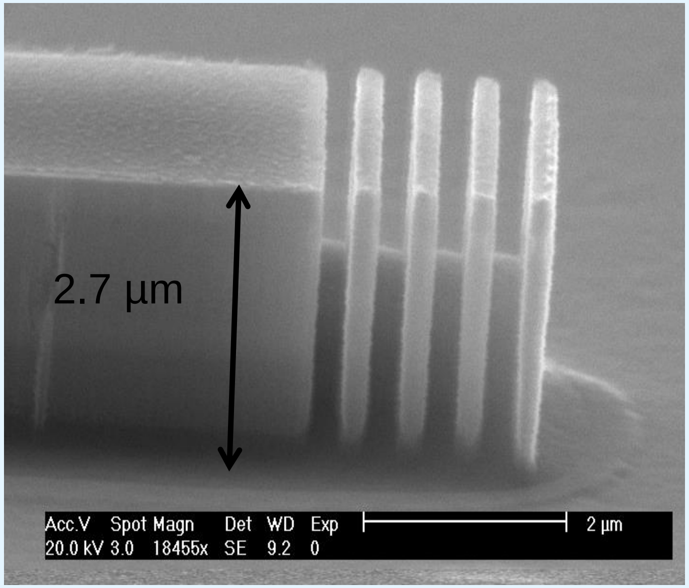


Principle of operation:

- Two unequal RWGs separated by DBR
- Common optical axis
- Independent pumping of each section
- Short cavity – high loss utilising high energy dot states
- Long cavity utilises low energy dot states

Device Architecture: Fabrication





Deep-etch gratings penetrate to the substrate:

- Provides electrical isolation of two sections
- Allows for asymmetric pumping
- Fewer periods required
- No transverse guiding by grating section

Grating Fabrication: Developed InP/AlGaInP etch recipe

- ICP reactor using Ar/Cl gas chemistry
- 200/500 W RIE/ICP powers
- High temperature (200 °C) – enhances removal of etch product $InCl_3$

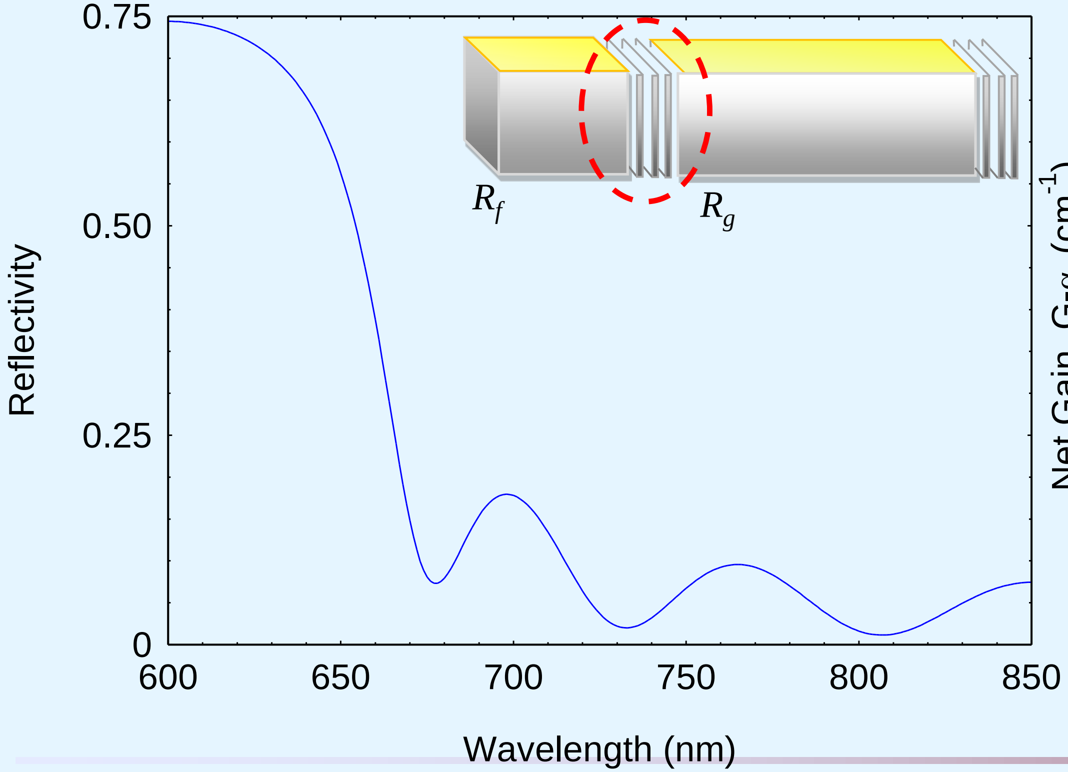
Achieving Dual-mode: Principle of operation

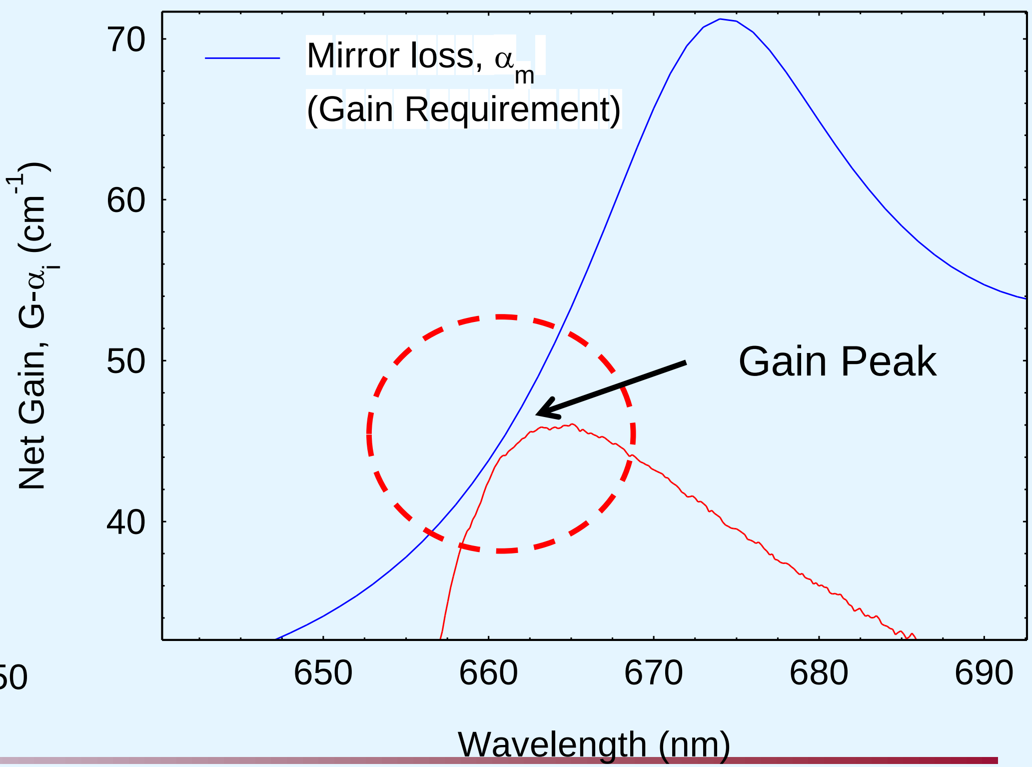
Preferential feedback: Spectrally dependent mirror loss

Centre DBR grating:

- High reflectivity at short wavelengths – promotes lasing at short wavelength
- Low reflectivity at long wavelengths – increases transmission of long wavelength

$$\alpha_m(\lambda) = \frac{1}{2L_c}\ln\left(\frac{1}{R_f R_g(\lambda)}\right)$$

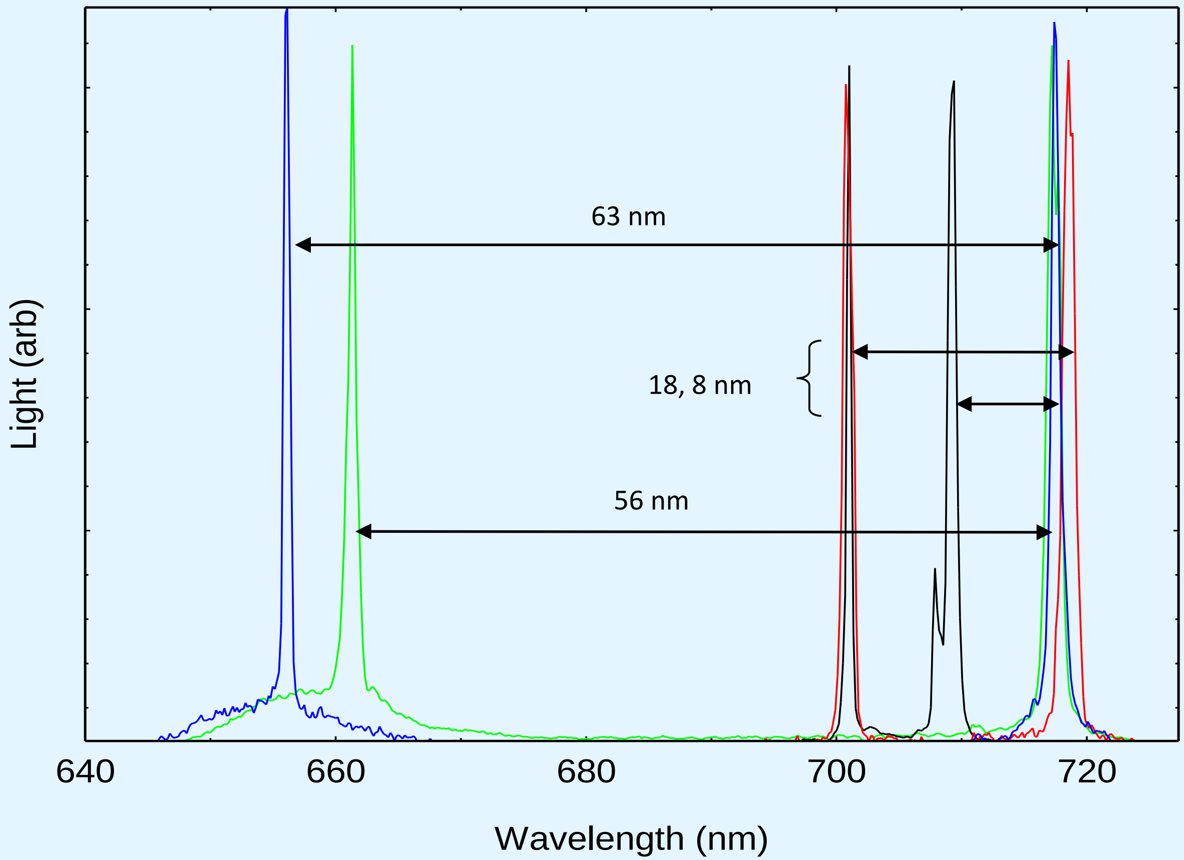


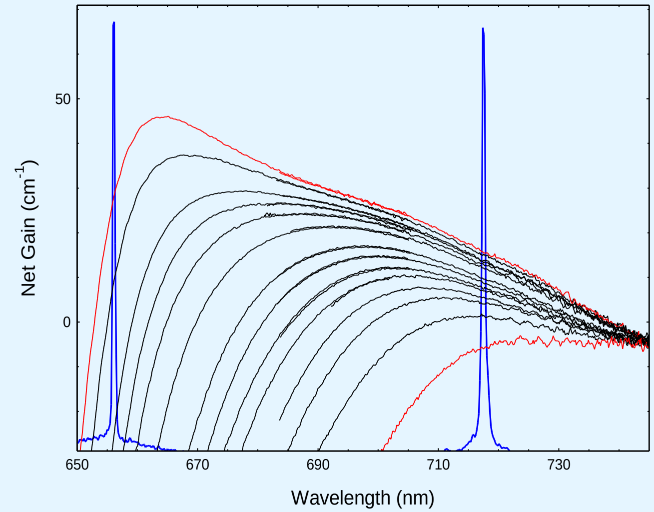


Dual-Mode operation

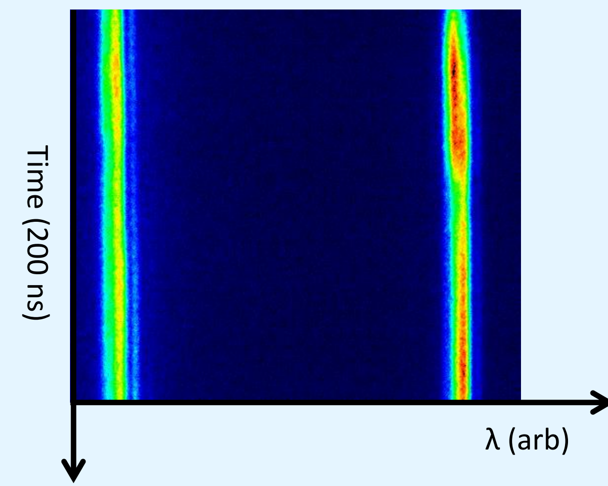
Device characteristics:

- Single or dual mode operation with up to 63 nm wavelength separation





Time resolved



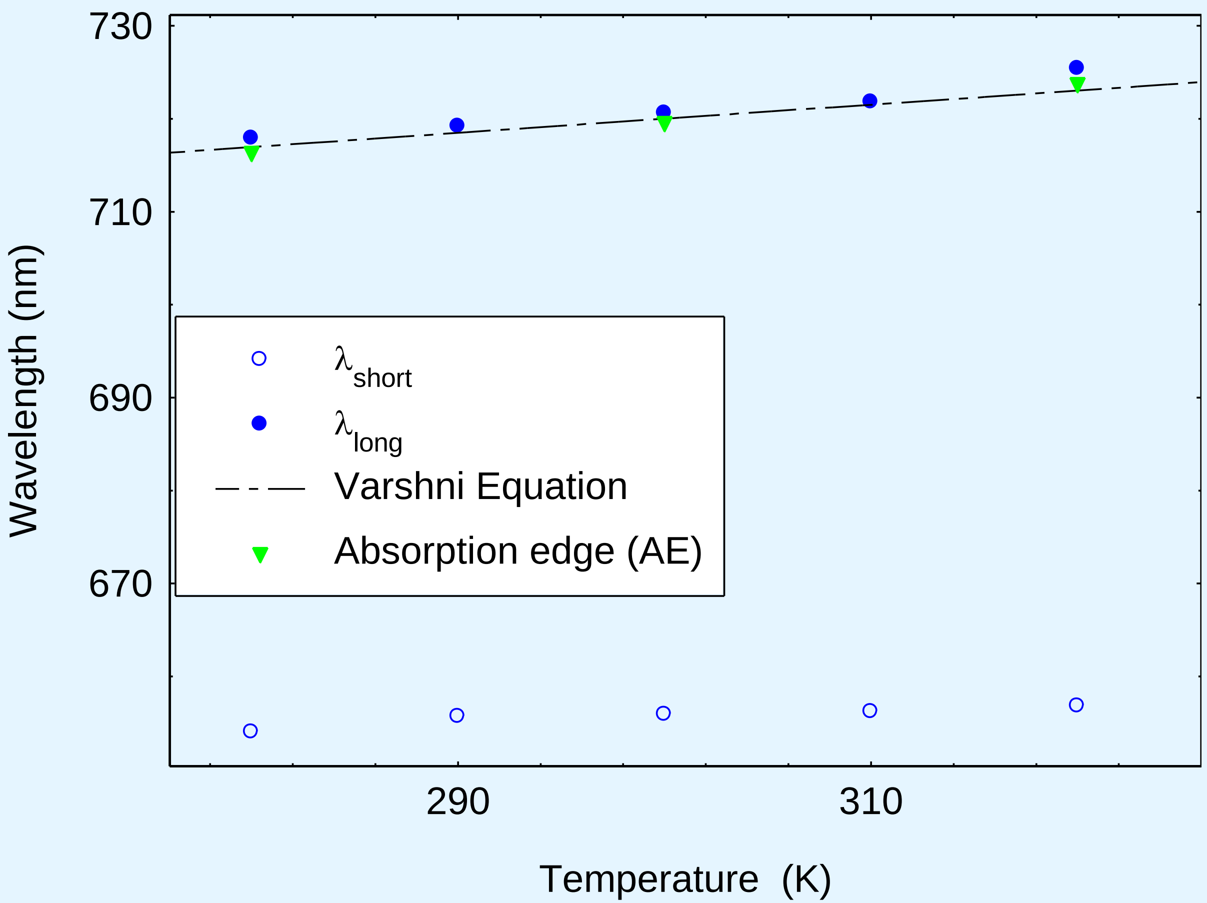
S. Shutts, P.M. Smowton, A.B. Krysa, Applied Physics Letters, 104, 241106; (2014)

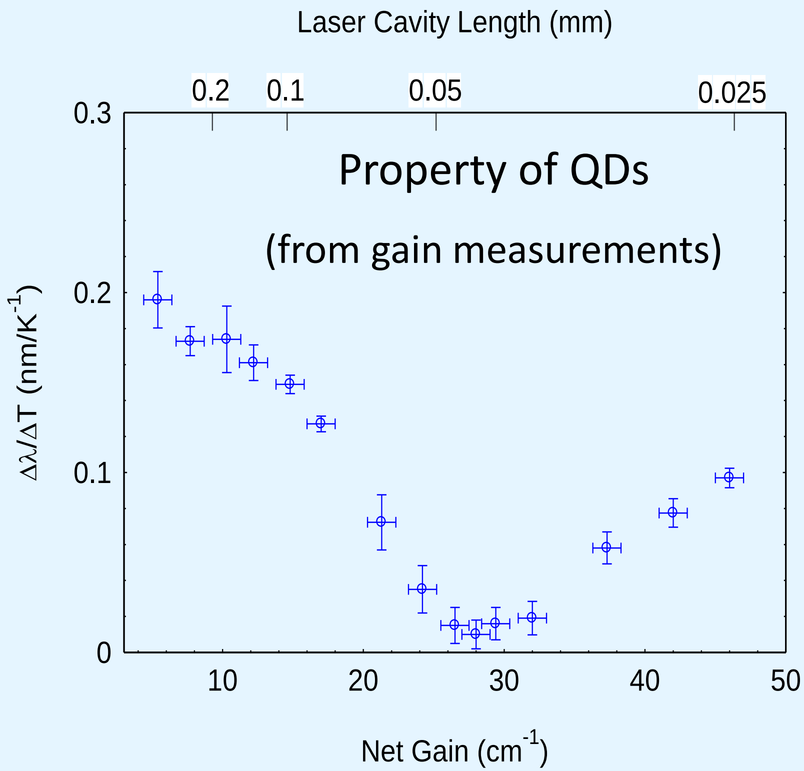
Temperature tuning

63 nm wavelength separation @ 300 K:

- Short wavelength: 0.06 nm/K
- Long wavelength: 0.17 nm/K

Tune the difference wavelength (0.11 nm/K)





Operation and Stability of Lasing modes

Varying current to section two (λ_{long}):

- Increases light output at long wavelength
- Short wavelength output relatively unaffected
- Carrier competition not significant to suppress dual-λ emission

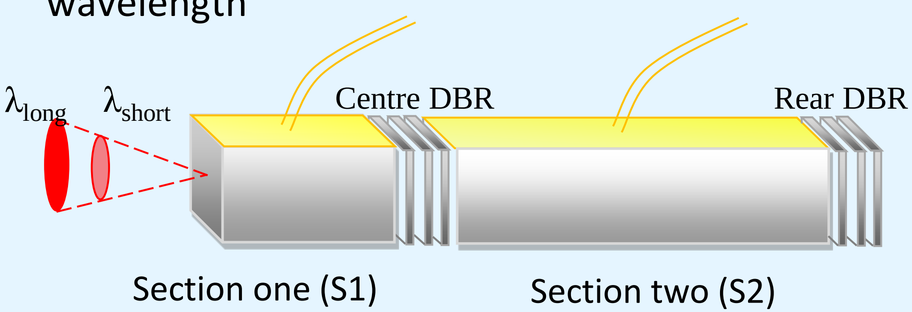
λ_{short} - circles

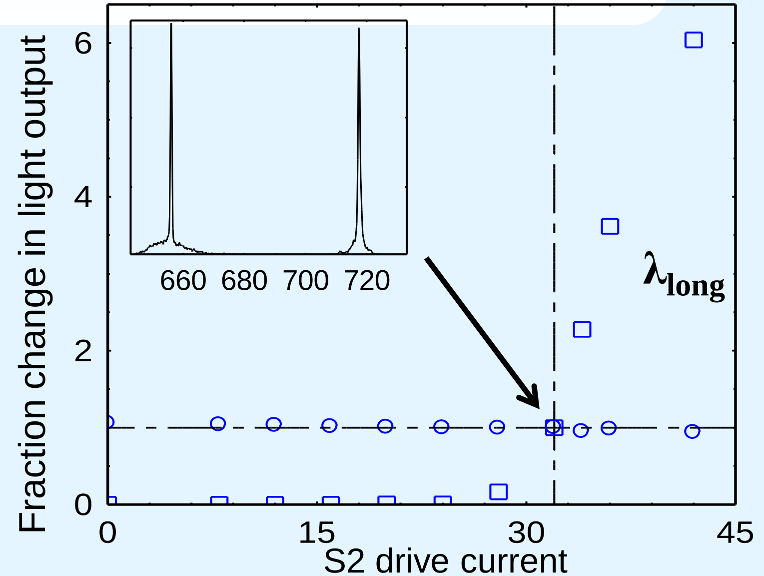
63 nm wavelength separation @ 300 K

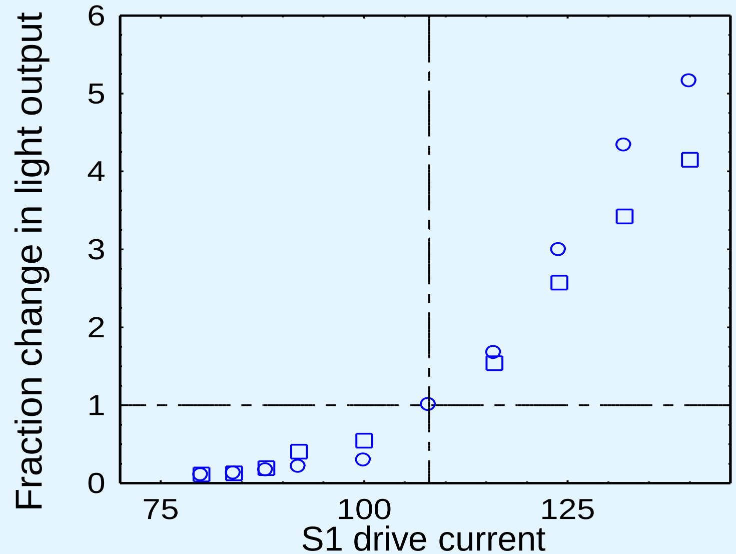
λ_{long} - squares

Varying current to section one (λ_{short}):

- Increases light level of short and long wavelength
- Photons generated in section one actively pump section two
- Carriers in section one stimulated to recombine at long wavelength





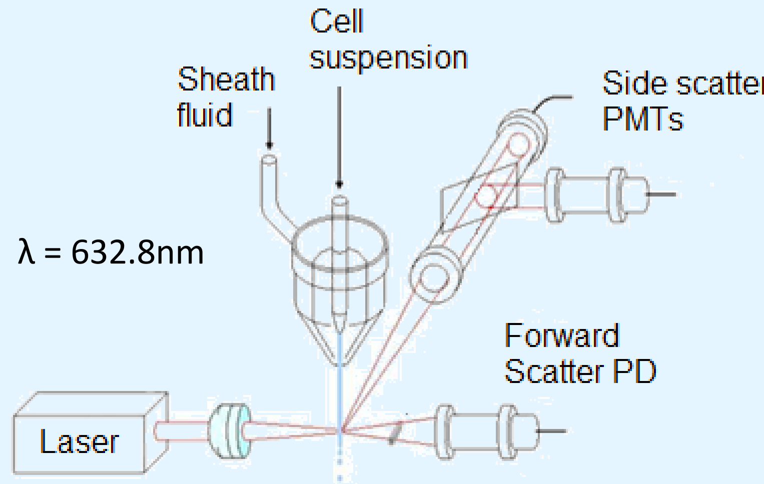


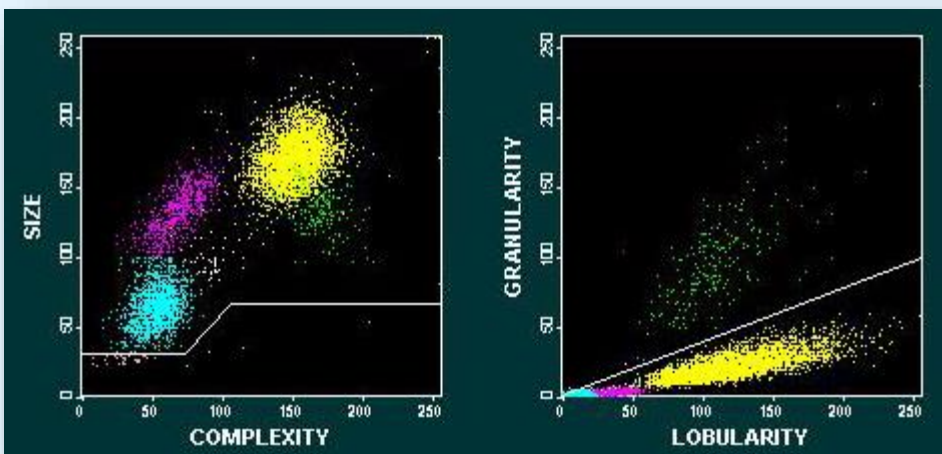
Outline

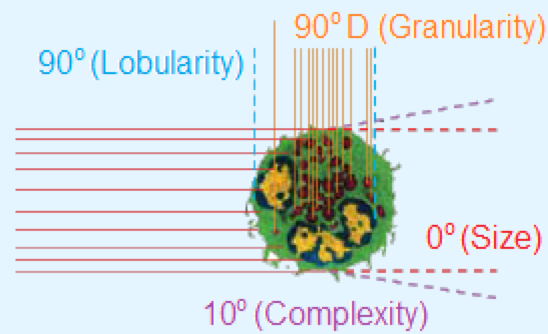
- Background, motivation and application
- Structure and optical properties
- Controlling emission wavelength
- The dot – well active medium
- Temperature insensitive wavelength
- Exploiting QD properties: Dual-wavelength lasers
- Integrated Circuits

Bench top flow cytometry

benchmark hemocytometer: Abbott Cell Dyn Ruby







- Single pass light scatter measurement
  - 10,000 cells per sample

Chip-based flow cytometry

Pros

- portability
- low power consumption
- low cost (disposability)
- reduced sample volumes

Cons

Typically requires external:

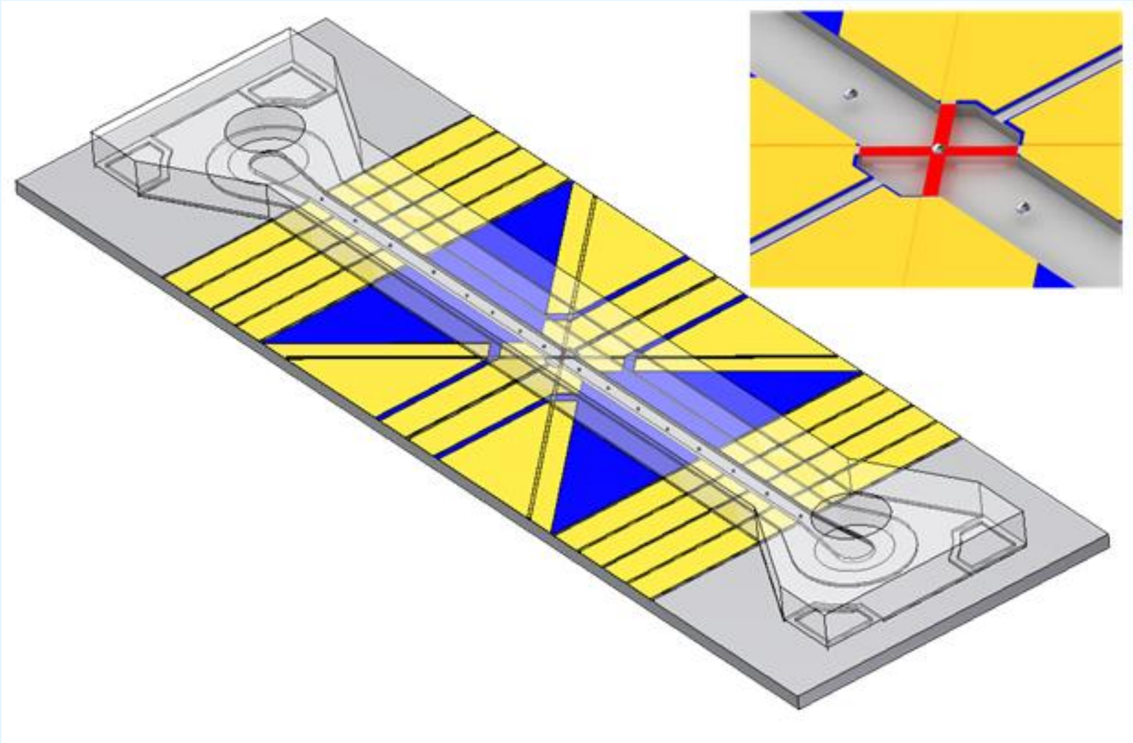
- light sources
- detectors
- fluid pumping equipment

adds cost and limits portability

- low throughput < 1000 cells/s

What are the advantages of a monolithically integrated III-V substrate?

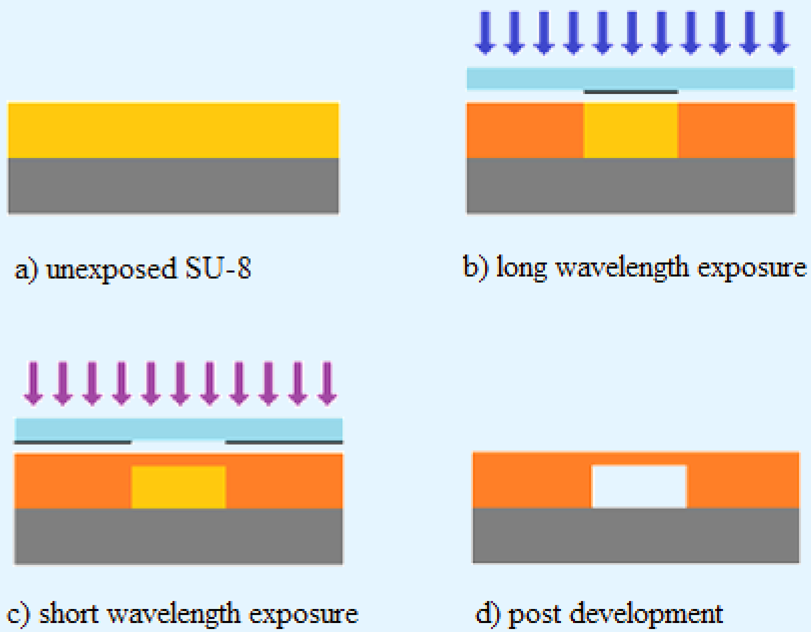
- Lasers and detectors can be defined anywhere in the plane of the substrate
- arrayed lasers/detectors: multiple measurements per cell
- fast switching (ns): re-configurability and time resolved measurement
- cell is part of the lasing cavity: multi-pass interrogation

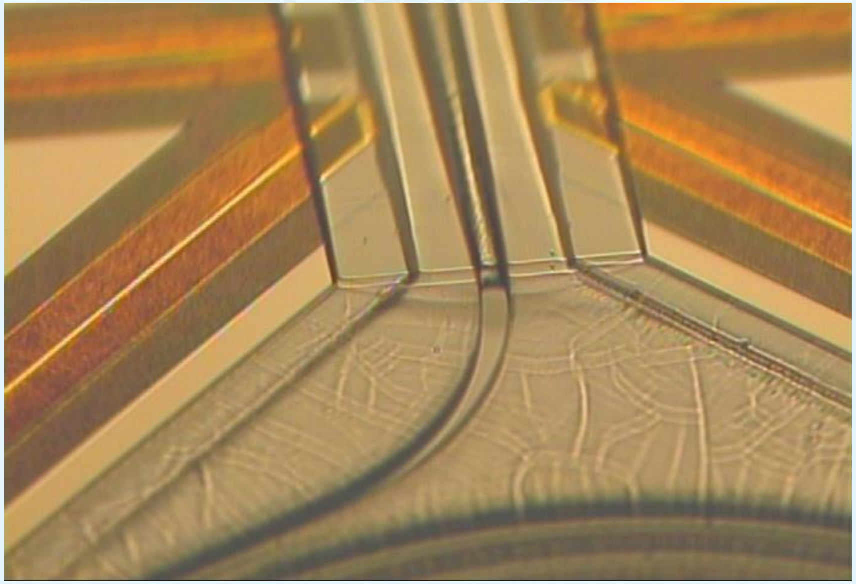


Goal: Integration of capillary fill micro-fluidics and optoelectronics on III-V substrate

Integrated micro-fluidics

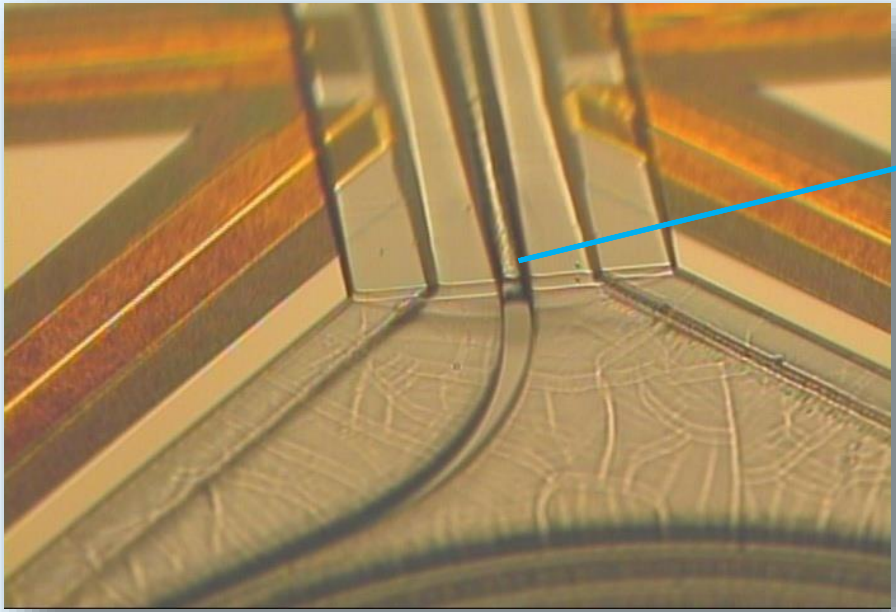
3-D micro-channels made using SU-8 photo-epoxy: transparent, chemically stable and can be patterned into deep, near vertical structures



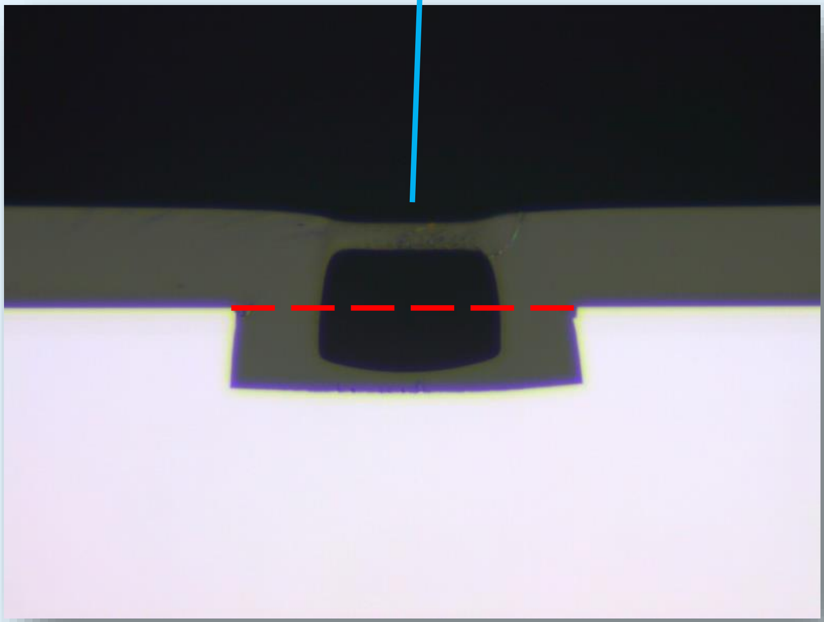


Channel cross section (wxh) : (50x30) μm

Buried capillary fill micro-fluidics



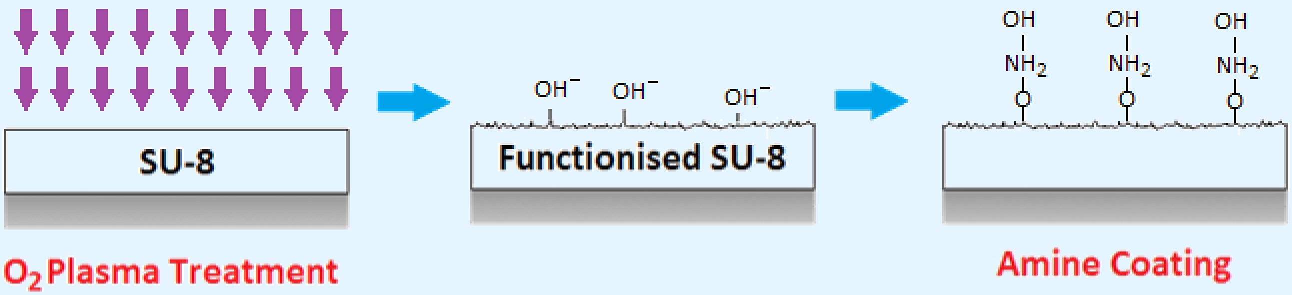
SU-8 flow cell



- eliminates meniscus
- encourages laminar flow

Hydrophilic surface treatment

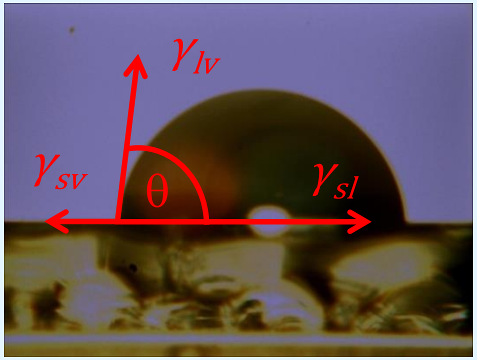
Two stage surface treatment for long term (3 months) hydrophilicity of SU-8 micro-fluidics

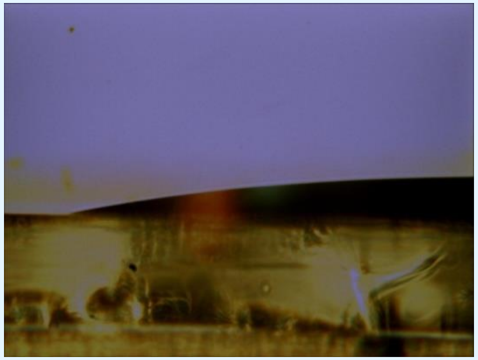


contact angle measurement

Before:

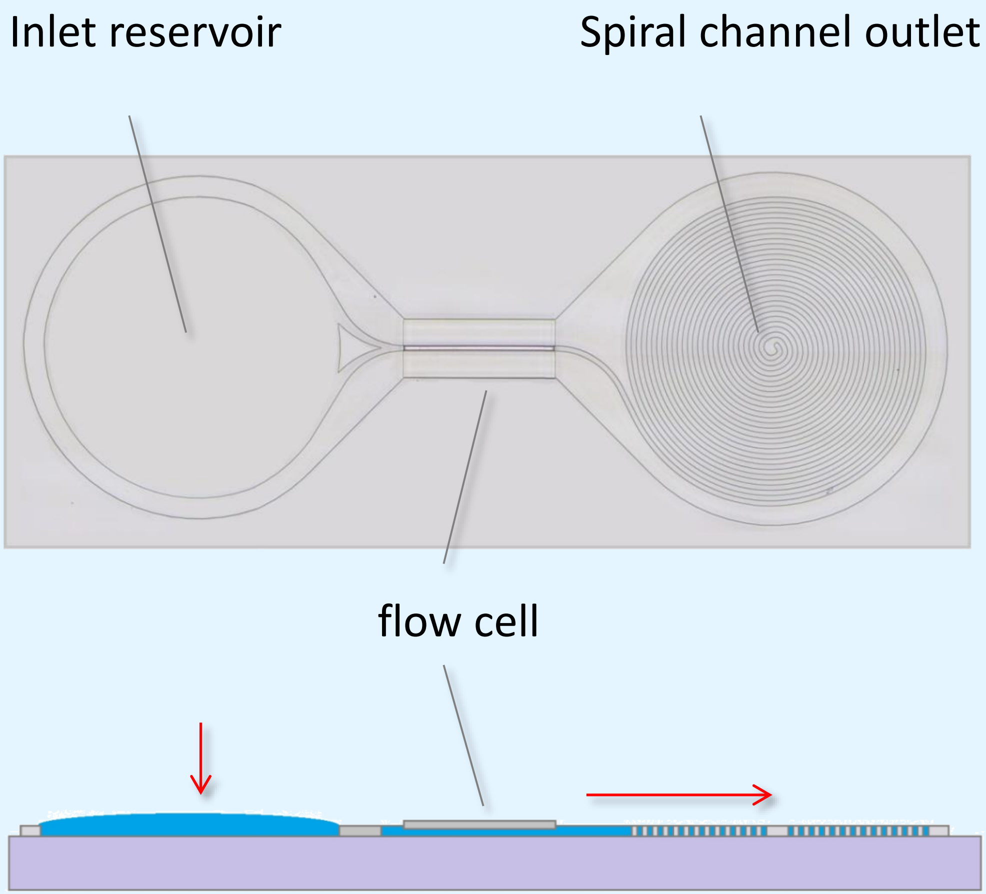
after:

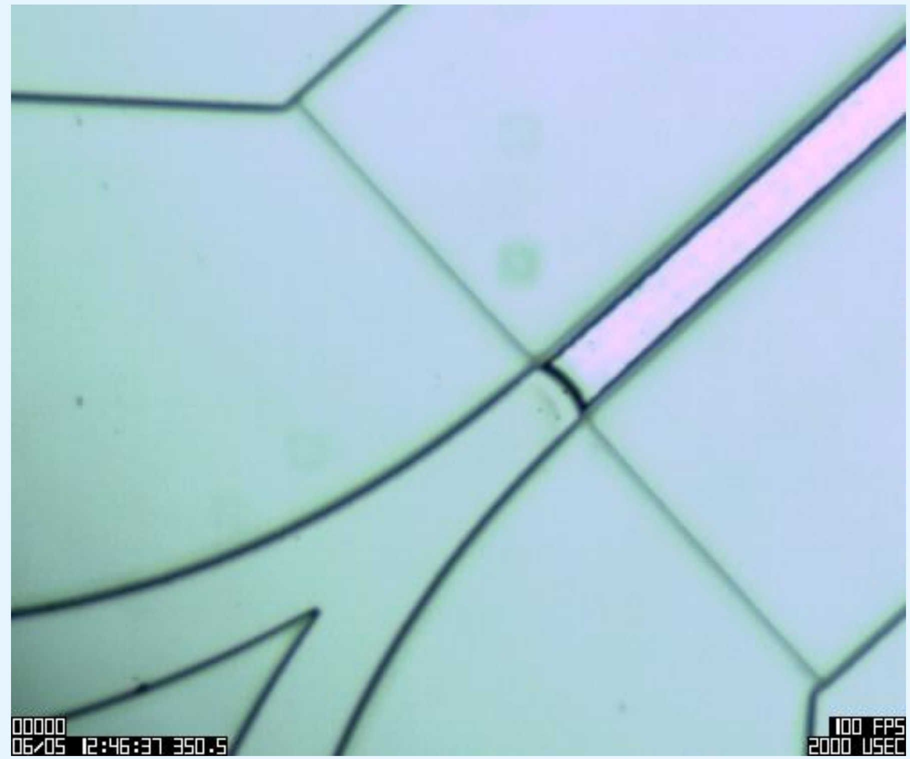




A. Sobiesierski, R. Thomas, P. Buckle. D. Barrow and P.M. Smowton, “Surface and Interface Analysis” 47 (13) , pp. 1174-1179, 2015

Capillary fill micro-fluidics



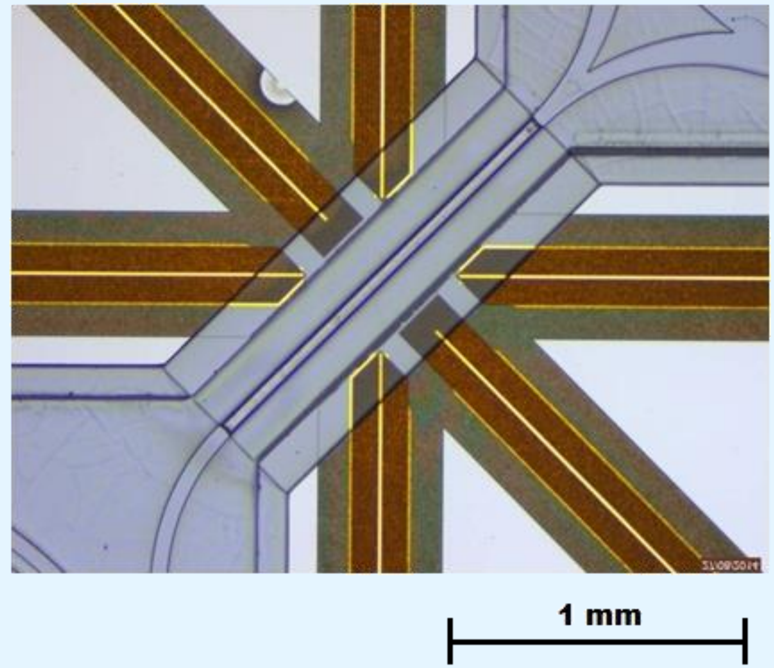


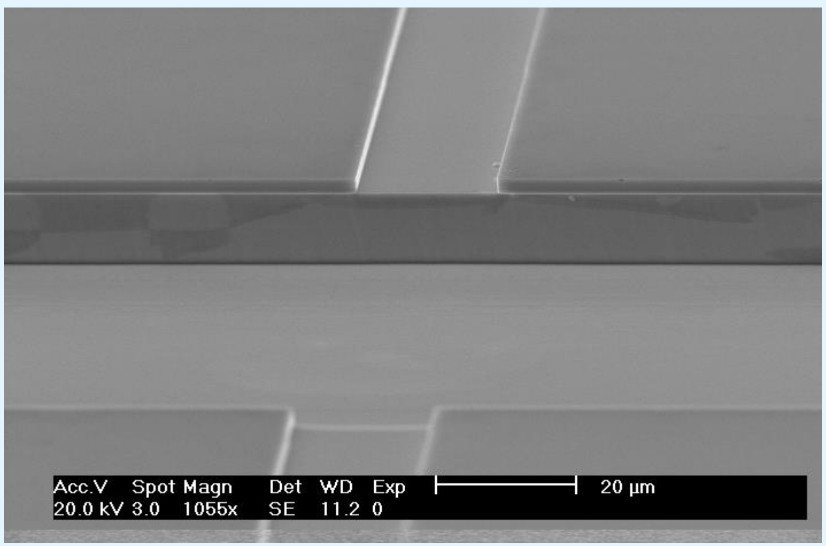
- throughput ~ 200 cells/s
- approximately 6000 cells/ sample

Integration with a monolithic III-V substrate

Fabrication steps:

1. plasma etch 2.5 µm deep lasers/detectors
2. Deposit contacts
3. Wet etch 15 µm deep trench for fluidics
4. Apply capillary fill micro-fluidics

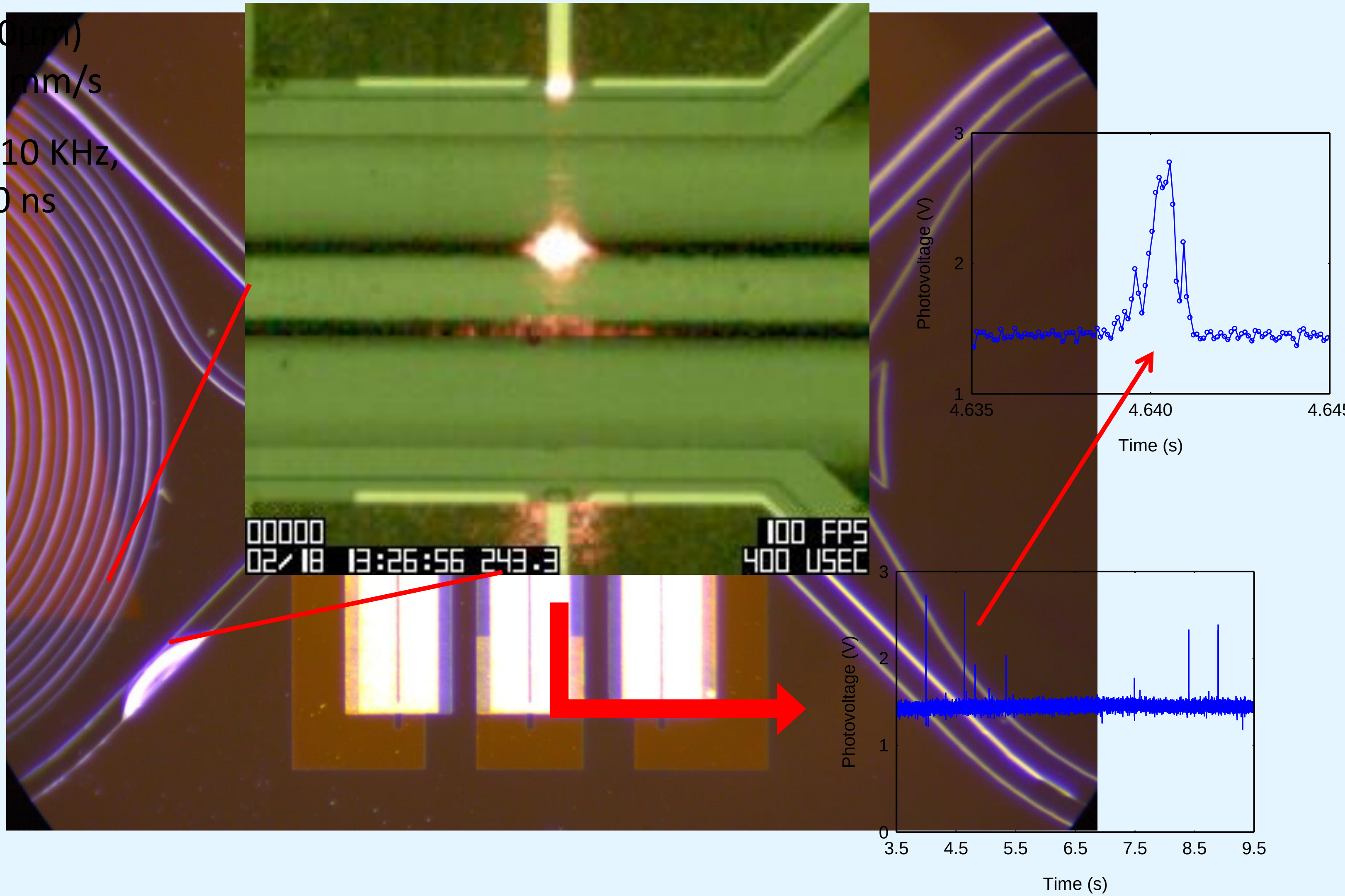




Micro-bead detection results

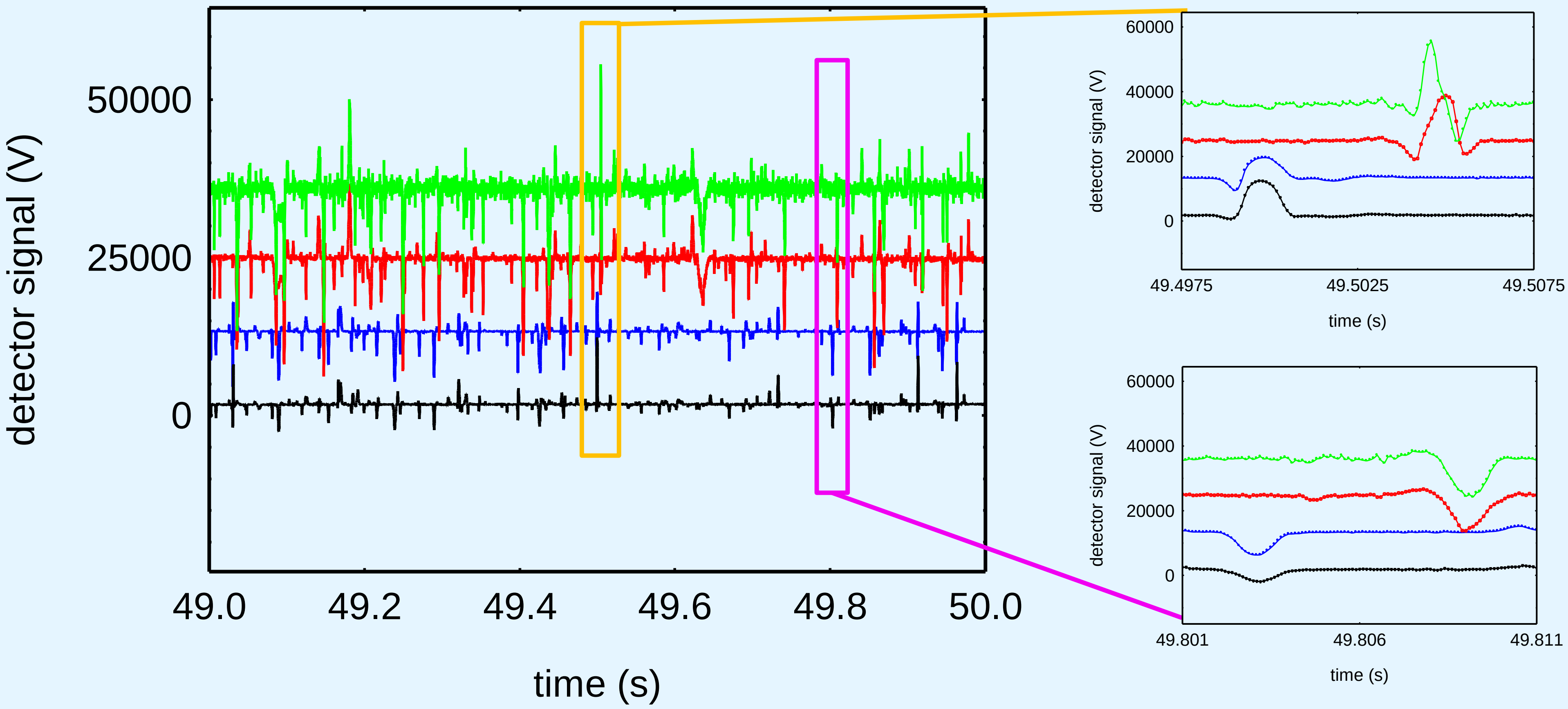
Micro-beads (10µm) travelling ~ 4.3 mm/s

Laser pulsed @10 KHz, pulse width 300 ns



White blood cell measurement

data from a white blood cell preparation of Monocytes and lymphocytes



Summary

- Progress made on InP QD lasers emitting 650 – 780 nm
- Shown that a regime exists where wavelength is insensitive to operating temperature
- Use effect of state-filling and preferential feedback to produce dual-wavelength emission
- Each wavelength operated simultaneously or independently
  - ➢ Emission from a common aperture
  - ➢ Temperature dependence – tune wavelength separation
- Monolithically integrated microfluidics and optoelectronics
  - ➢ e.g. Closely spaced laser arrays enable measurement of local velocity at the point of interrogation and toggling provides position
  - ➢ With knowledge of velocity and position, size can be found from time based laser beam transit measurement