Topic 18

18 Low dimensional laser diodes

18.1 Introduction: role of dimensionality in semiconductors
18.2 Basic theory for low dimensional semiconductors
  Quantum Mechanics
18.3 MQW; QWire; QD for laser
18.4 Growth of MQW, QWire and QDs
18.5 Separate optical confinement
18.6 Lattice mismatch and strain
18.7 Strained layer lasers

Introduction

• What will happen when electrons are confined to lower dimensional semiconductor structures from bulk semiconductors?

• Influence of dimensionality on optoelectronics such as laser diodes?

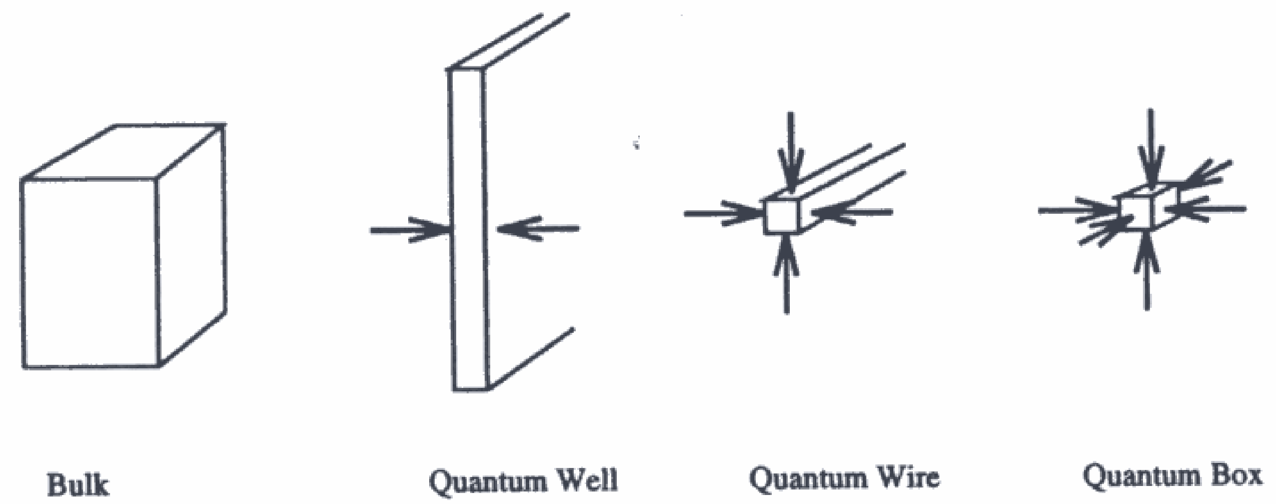
• How small should this confinement be?

The concept of the de Broglie wavelength

$$\boxed{\lambda_B = \frac{h}{p} = \frac{h}{\sqrt{2m^* E}}}$$

h: Planck's constant; p: momentum; m: effective mass; and E: energy.

Low dimensional structures



(1) Bulk (3D): electrons/holes can freely move in 3 directions
There is **no any confinement** in a range of **the de Broglie** λ

(2) Quantum well (2D): electrons/holes can freely move in 2 directions
1 dimensional confinement in a range of **the de Broglie** λ

(3) Quantum wire (1D): electrons/holes can freely move in 1 directions
2 dimensional confinement in a range of **the de Broglie** λ

(4) Quantum dot/Box (0D): electrons/holes cannot freely move in any directions
3 dimensional confinement in a range of **the de Broglie** λ

Quantum Mechanics

- Energy = KE + PE $\quad E = p^2/2m^* + V(r)$

- Electrons are wavelike $\quad \psi(x) = \exp(jkx)$

$\lambda=2\pi/k$; $p=\hbar k$; $\hbar=h/2\pi$

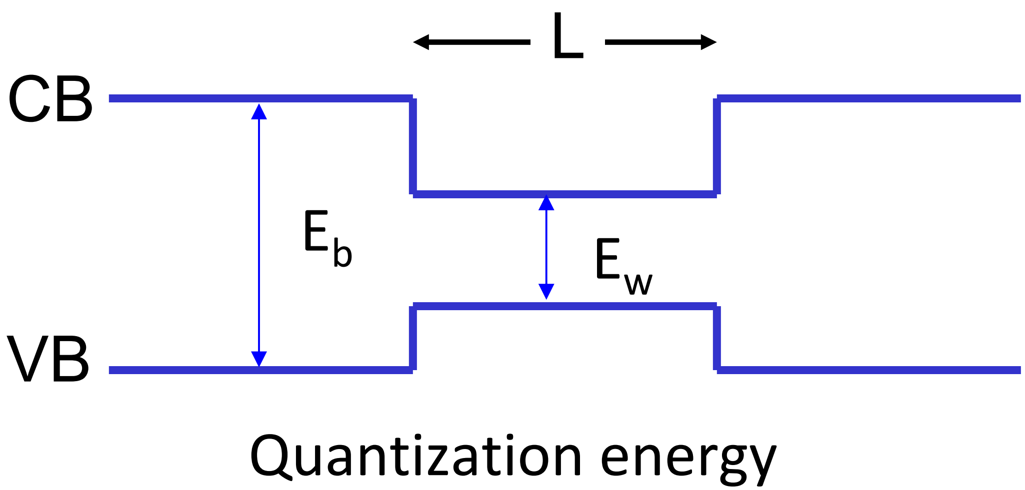
- In "new" Quantum mechanics momentum and energy replaced by operators operating on a wavefunction - "Guesswork" by Schrödinger

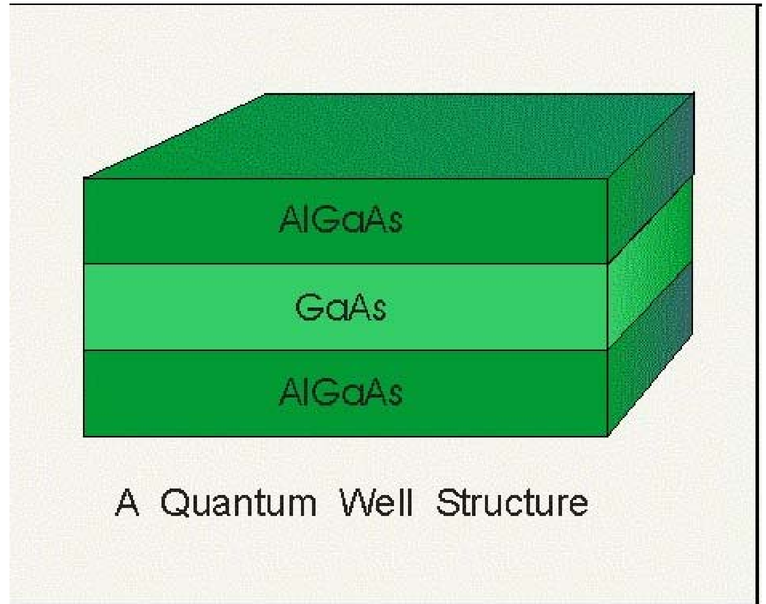
$$\mathbf{E\psi = -(\hbar^2/2m^*)\,\nabla^2\psi + V(r)\psi}$$

∇^2 = Laplace operator:

$$\boxed{\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}}$$

Quantum Wells & Quantum Mechanics





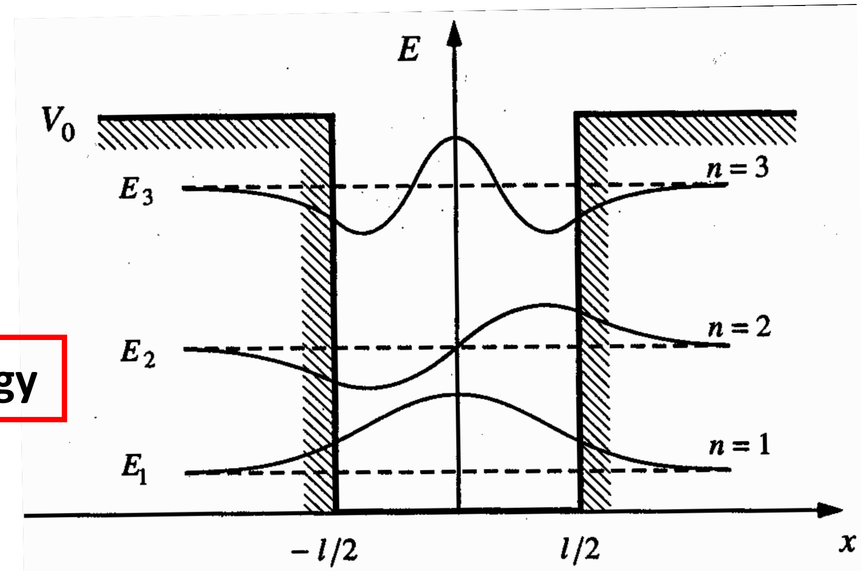
Quantum well:
(1) Double heterostructure, **a thin layer** with a low bandgap sandwiched by two layers with **a large bandgap**
(2) The thickness of the thin layer: ~ de Broglie wavelength, (~10nm scale)

As the thin layer is on ~ de Broglie wavelength scale, the system has to be described by **quantum mechanics.**

Schrödinger Equation for an potential well

$$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi(x)+V(x)\psi(x)=E\psi(x)$$

Kinetic energy **Potential energy** **Total energy**



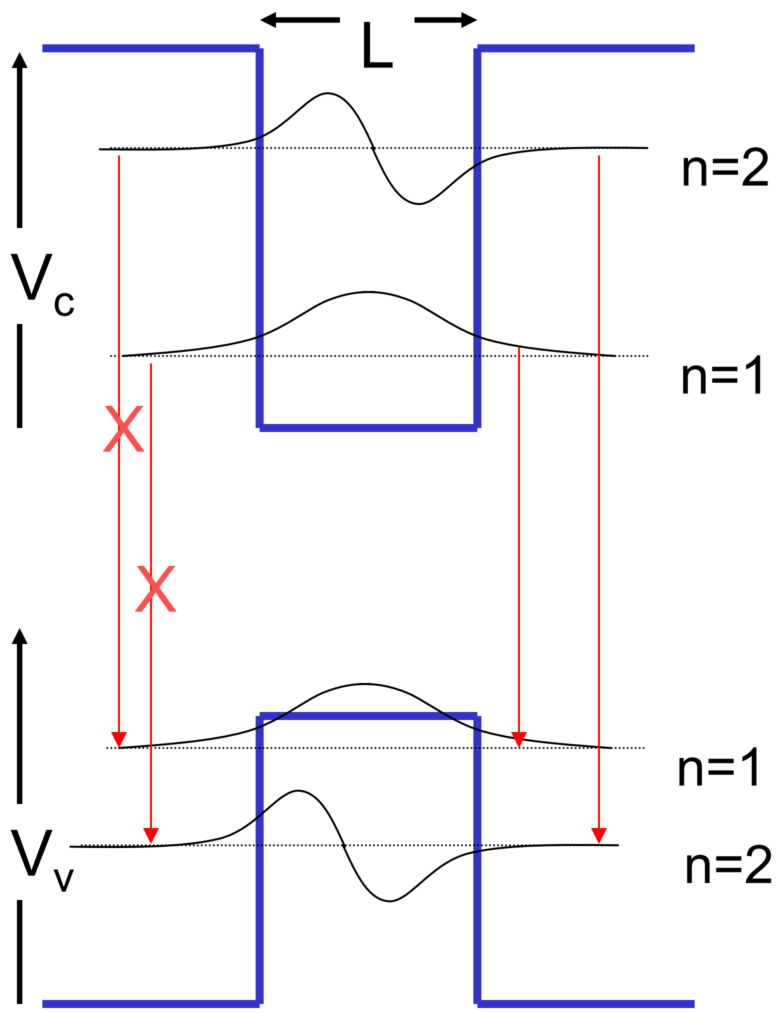
- $\hbar$: constant; *m*: mass of the particle; *V:* local potential; E: energy
- ***Ψ**:* **wavefunction** of the particle

- $|\Psi(x)|^2 dx$: probability that a particle can be found in *dx* around the point (*x*)

  part of wavefunction can be extended into **barrier**
- Allowed particle energies are **quantized** (i.e., quantization energy)
- Allowed particle energies depends on **well thickness**

  A thin well leads to a high energy
- Allowed particle energies depends on **energy potential** (i.e., confinement)

2D Confinement – Quantum Well (QW)



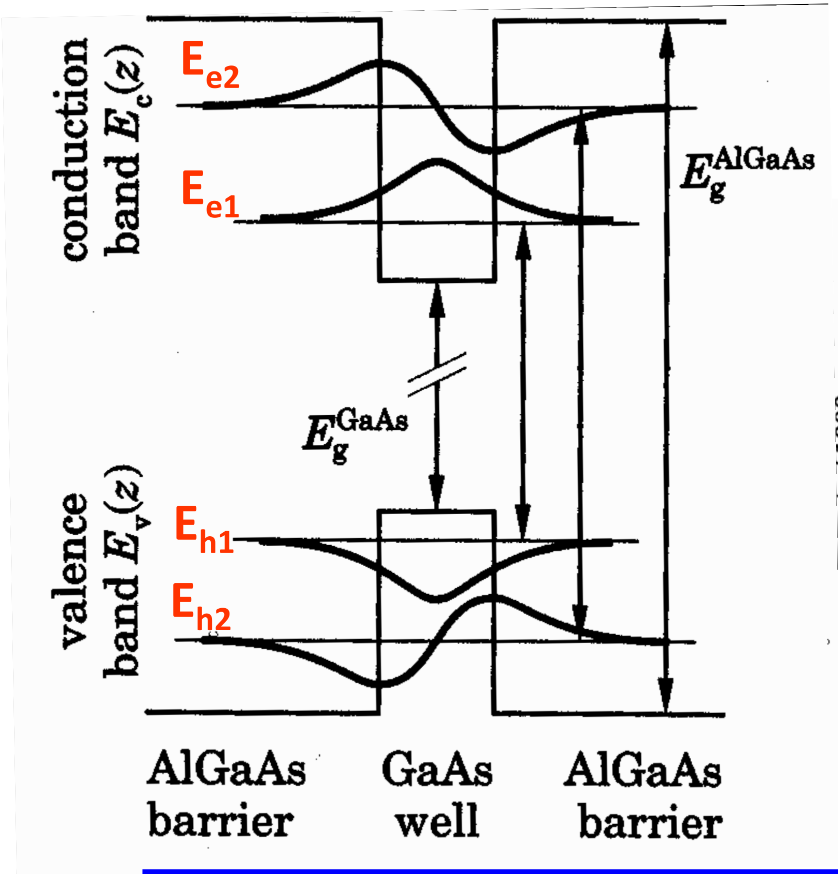
$E_n = (\hbar^2/2m^*)\,(n\pi/L)^2$

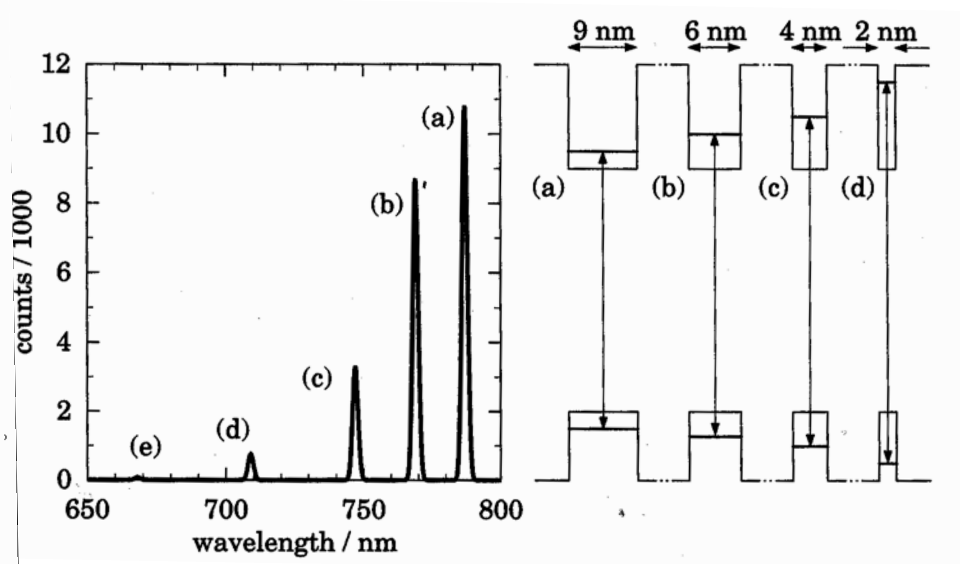
Due to Symmetry transitions

- n =1 $\rightarrow$ n =1 allowed
- n =2 $\rightarrow$ n =2 allowed

- n =1,2 $\rightarrow$ n =2,1 forbidden

GaAs/AlGaAs quantum well





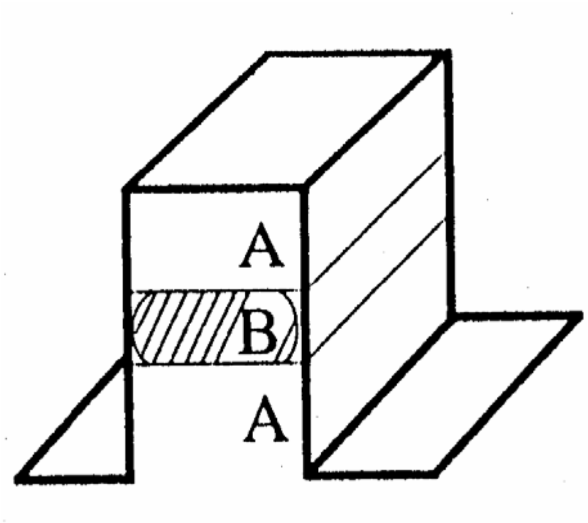
Transition Energy (ignore exciton binding energy):

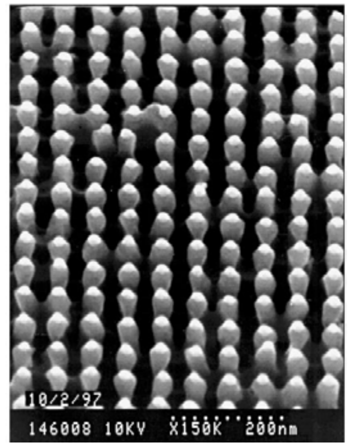
E (ground state)=E_g(GaAs)**+E_{e1}+E_{h1}**

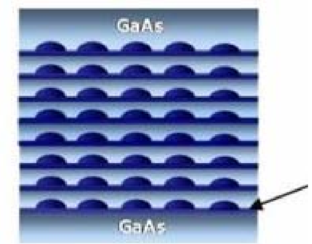
•Thin well: high quantization energy (i.e, high E_{e1} and E_{h1})

• Transition energy can be tuned through changing quantum well thickness

Quantum wire and Quantum dots







Compared with quantum well (confinement in one direction)

- Quantum wires: Confinement in two directions, leading to two extra quantization energies in both directions
- Quantum dots: Confinement in all 3 directions, leading to three extra quantization energies in all three directions

Density of States

- Determine the carrier distribution as a function of energy in different bands.
- Determine the total number of carriers

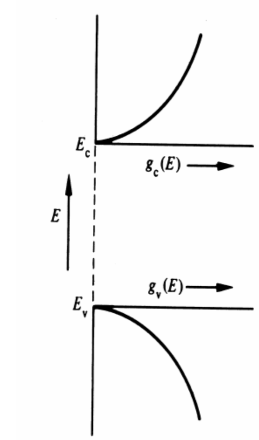
We need to introduce an important concept:

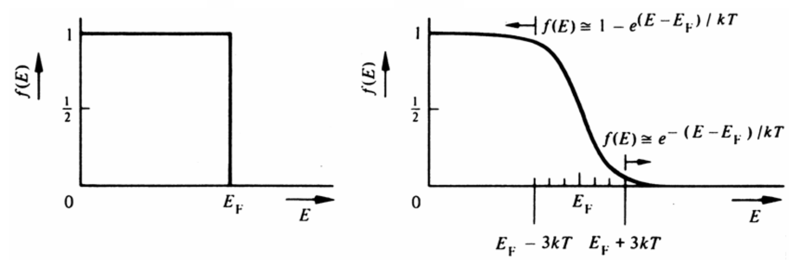
Density Of States *g(E)*: how many states exist at a given energy *E*.

g(E) dE : number of quantum states per unit volume of the crystal between E and E + dE

$$g(E)dE = \left[N(E+dE) - N(E)\right]/V$$

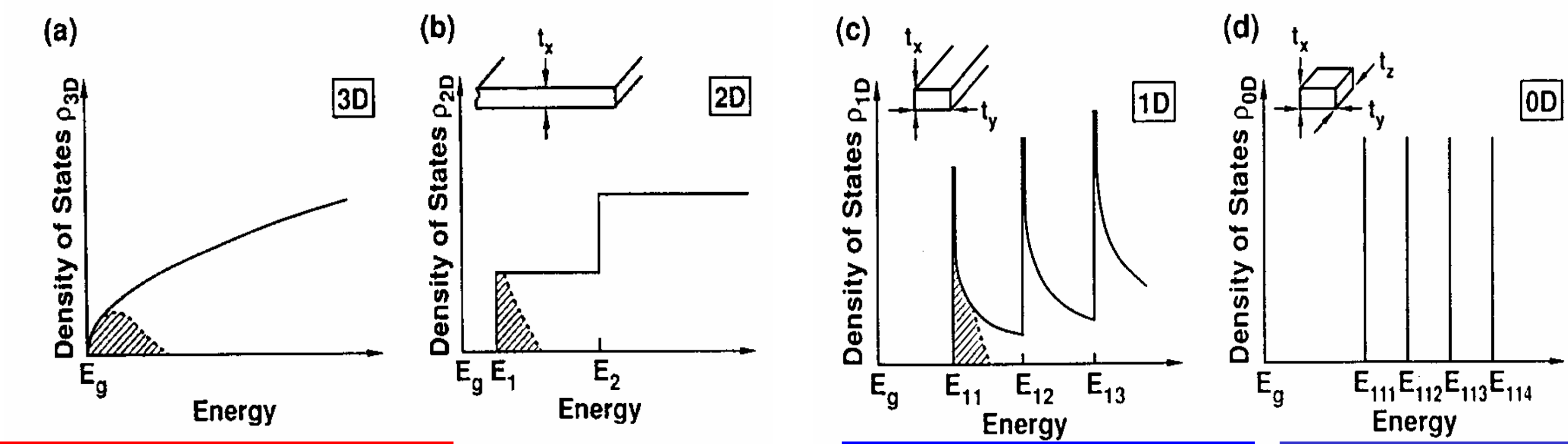
The distribution of carriers will depend on the density of states, and also on the probability of occupancy (**Fermi-Dirac statistics, not discussed**)





(a) $T \to 0$ K (b) $T > 0$ K

Density of States – 3D, 2D, 1D, 0D



$$g_{3D} = \frac{dN_{3D}}{dE} = \frac{8\pi}{h^3}\sqrt{2}m^{3/2}E^{1/2}$$

$$g_{2D} = \frac{dN_{2D}}{dE} = \frac{4\pi}{h^3} m E^{0}$$

$$g_{1D} = \frac{dN_{1D}}{dE} = \frac{\sqrt{2\pi}}{h} m^{1/2}E^{-1/2}$$

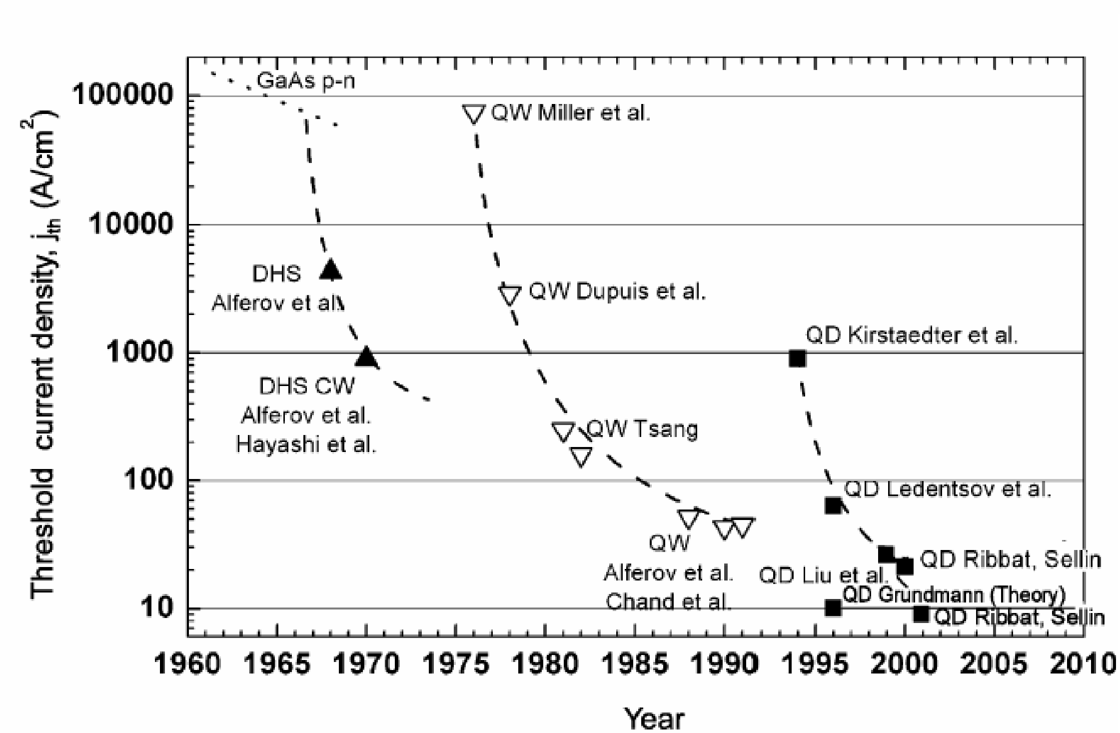
$$g_{1D} = 2\,\delta(E - E_0)$$

- For a reduction in dimensionality, DOS tends to **concentrate at the energy minimum of a sub-band**, meaning that a greater proportion of the electrons will be close to this energy minimum.

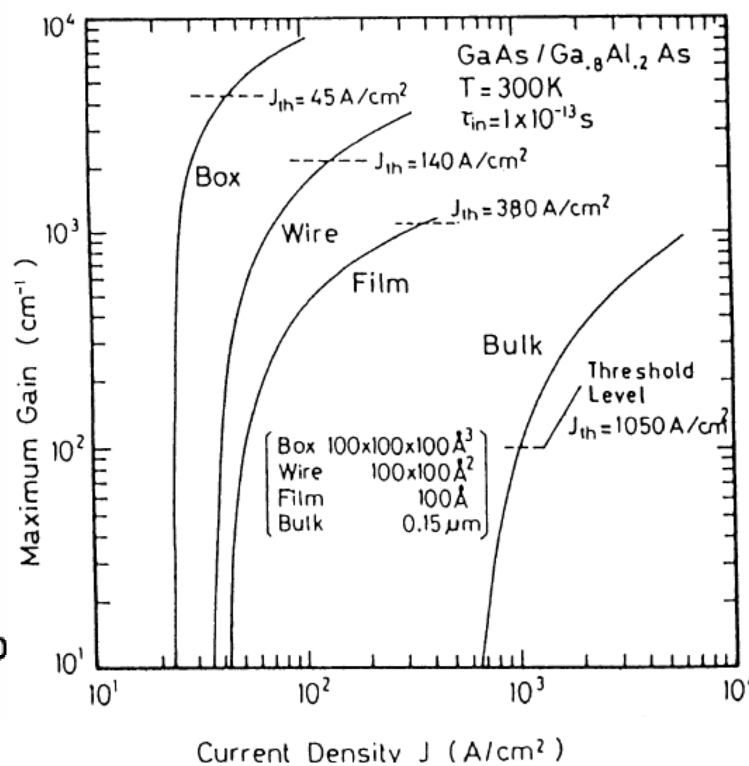
- The greater density of states near the band edge for low dimensional structures leads to a **higher material and differential gain** compared with quantum well or bulk material

- **This becomes significantly enhanced for QDs, potentially leading to a very low threshold for lasing.**

Reduction in J_{th} – Records As Fn Time



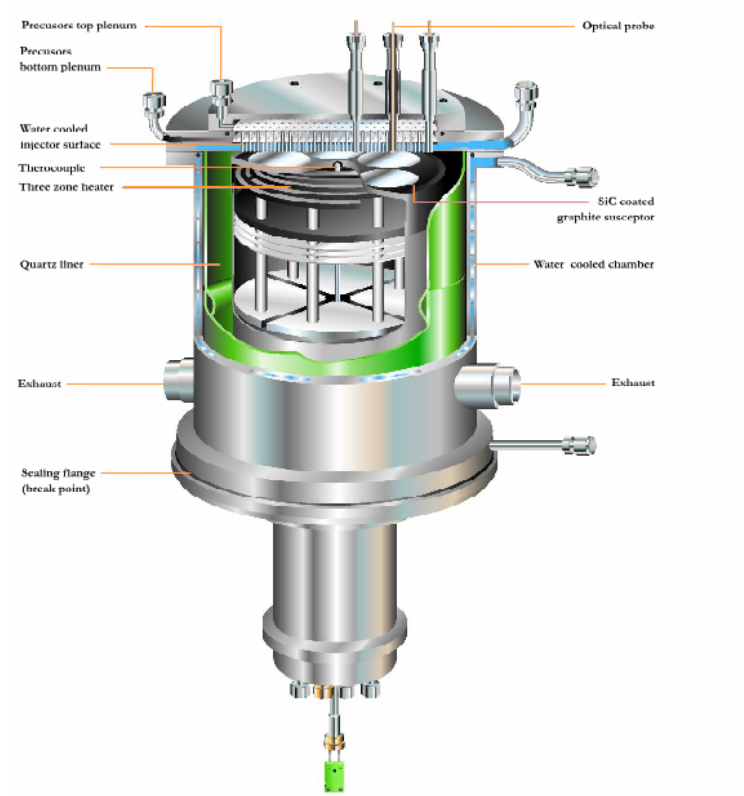
M. Henini, M. Bugajski / Microelectronics Journal 36 (2005) 950–956



M. Asada et al., IEEE JQE 22, 1915 (1986)

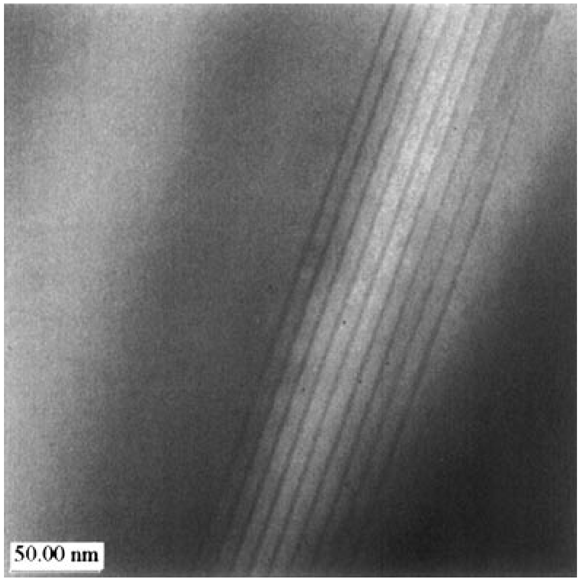
- QDs: highest Gain
- QDs: lowest threshold for lasing

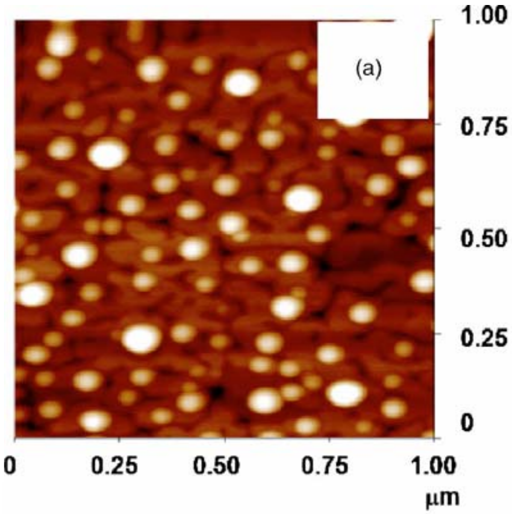
Advanced growth facility (i)

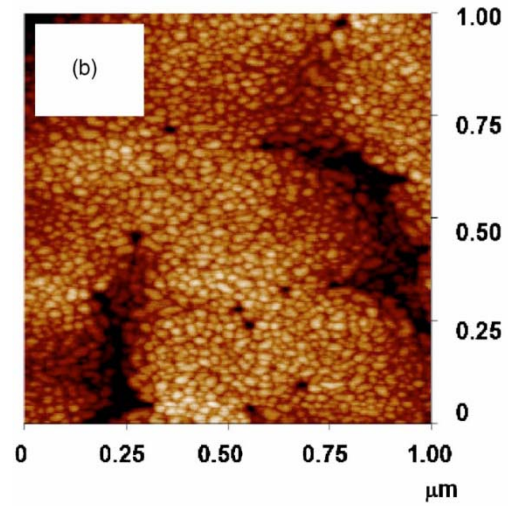


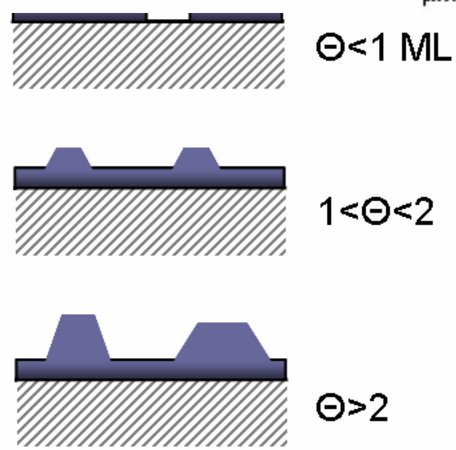
Metal Organic Chemical Vapour Deposition (MOCVD)

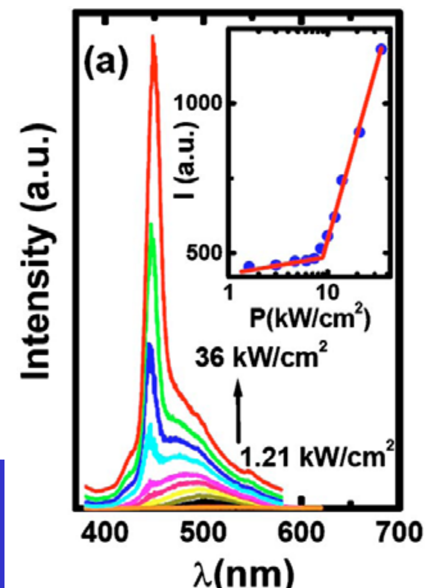
MOCVD grown III-nitride MQWs and QDs







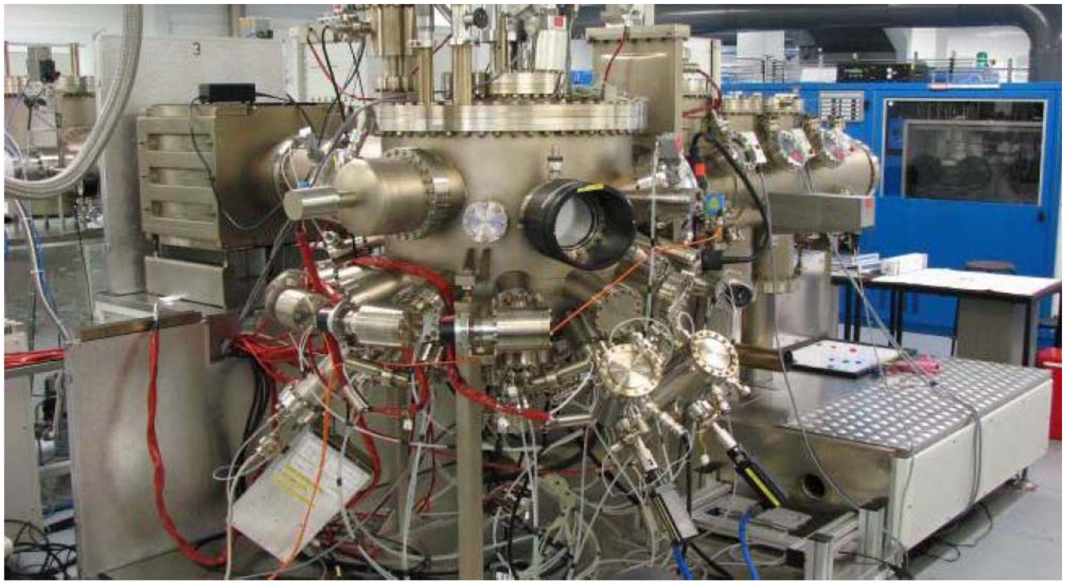


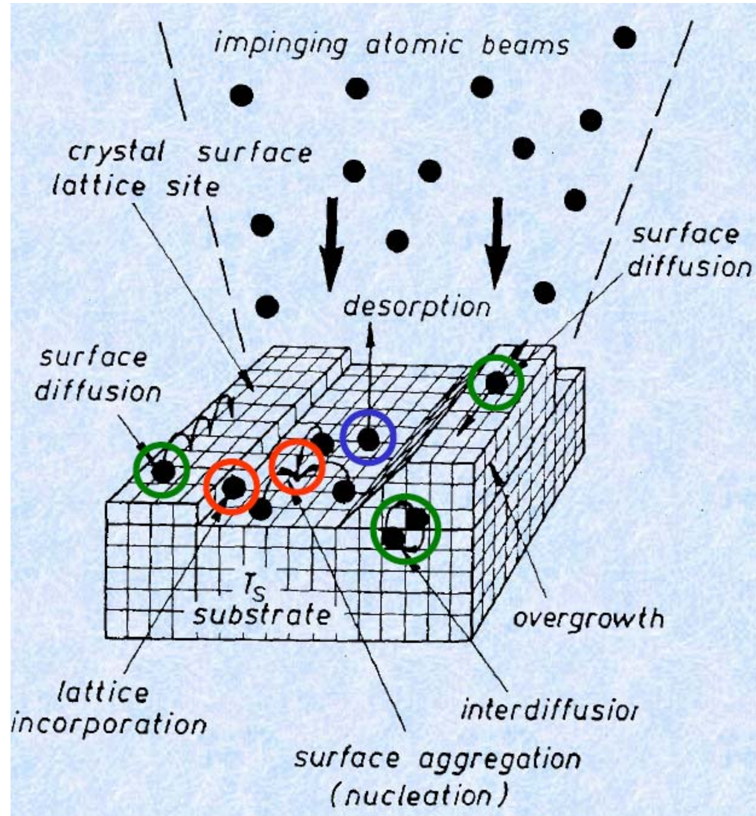


•InGaN/GaN MQWs for solid state lighting

•InGaN QDs on GaN surface for blue laser (S-K growth mode for formation of self-organised QDs

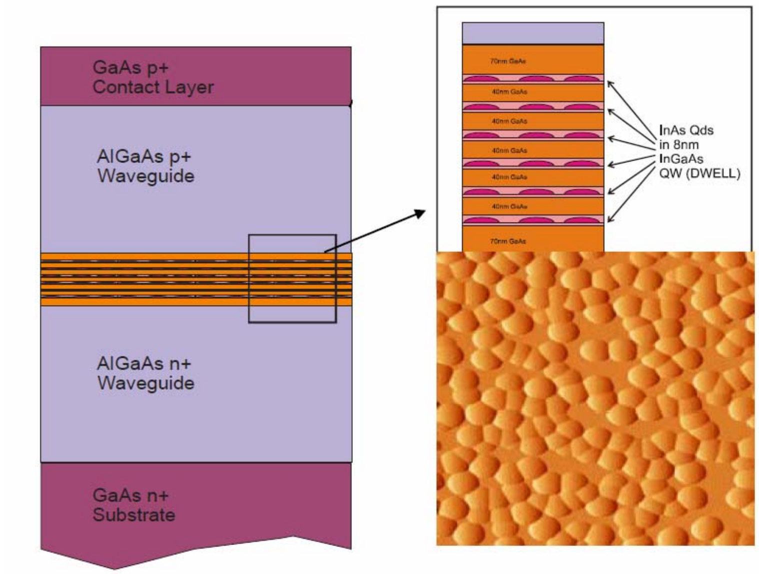
Advanced growth facility (ii)

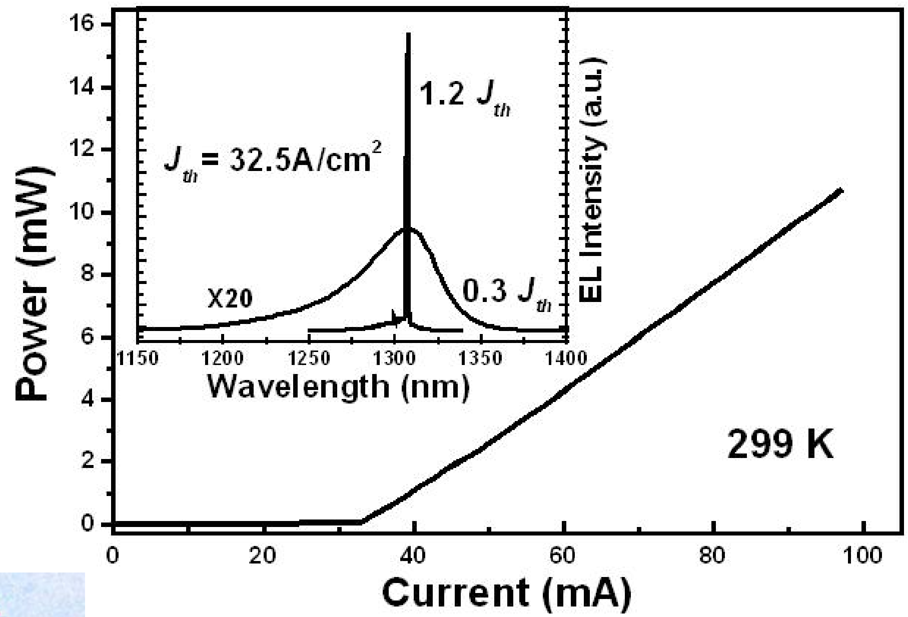


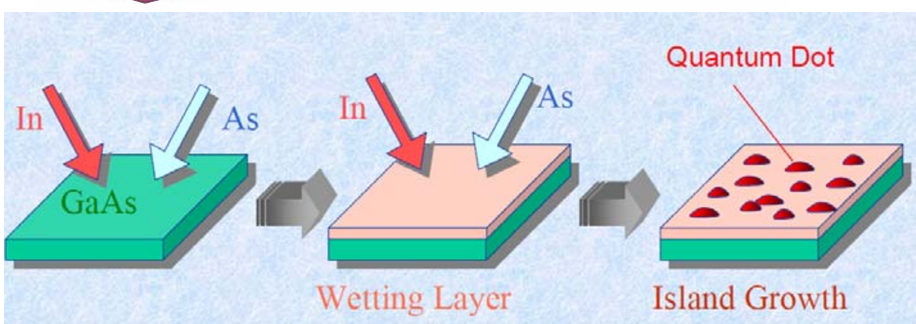


Molecular Beam Epitaxy

MBE growth quantum dot laser diode



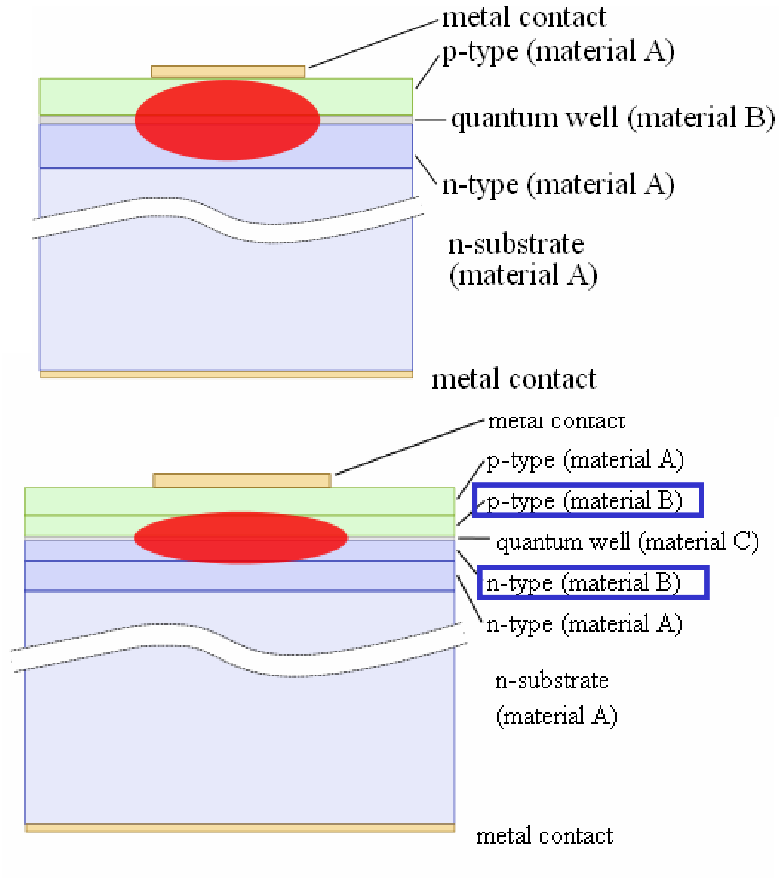


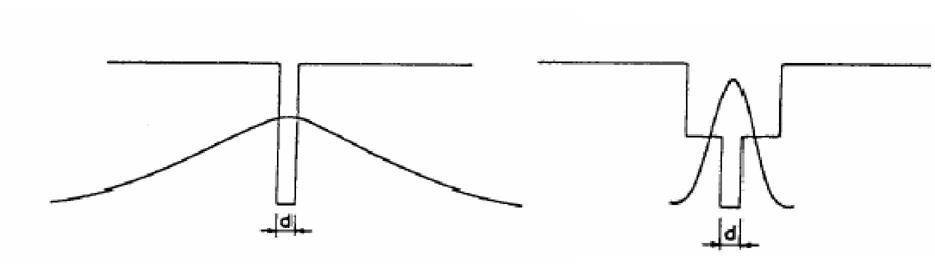


AFM image – energy of surface is minimised by the formation of "bumps" instead of a 2D layer

Quantum dot lasers can now be realised with world beating performance

Separate Confinement Heterostructure (SCH)





- Previous slide:

$$g_{th} = \frac{1}{\Gamma}[\alpha_i + \frac{1}{2L}\ln(\frac{1}{R_1 \cdot R_2})]$$

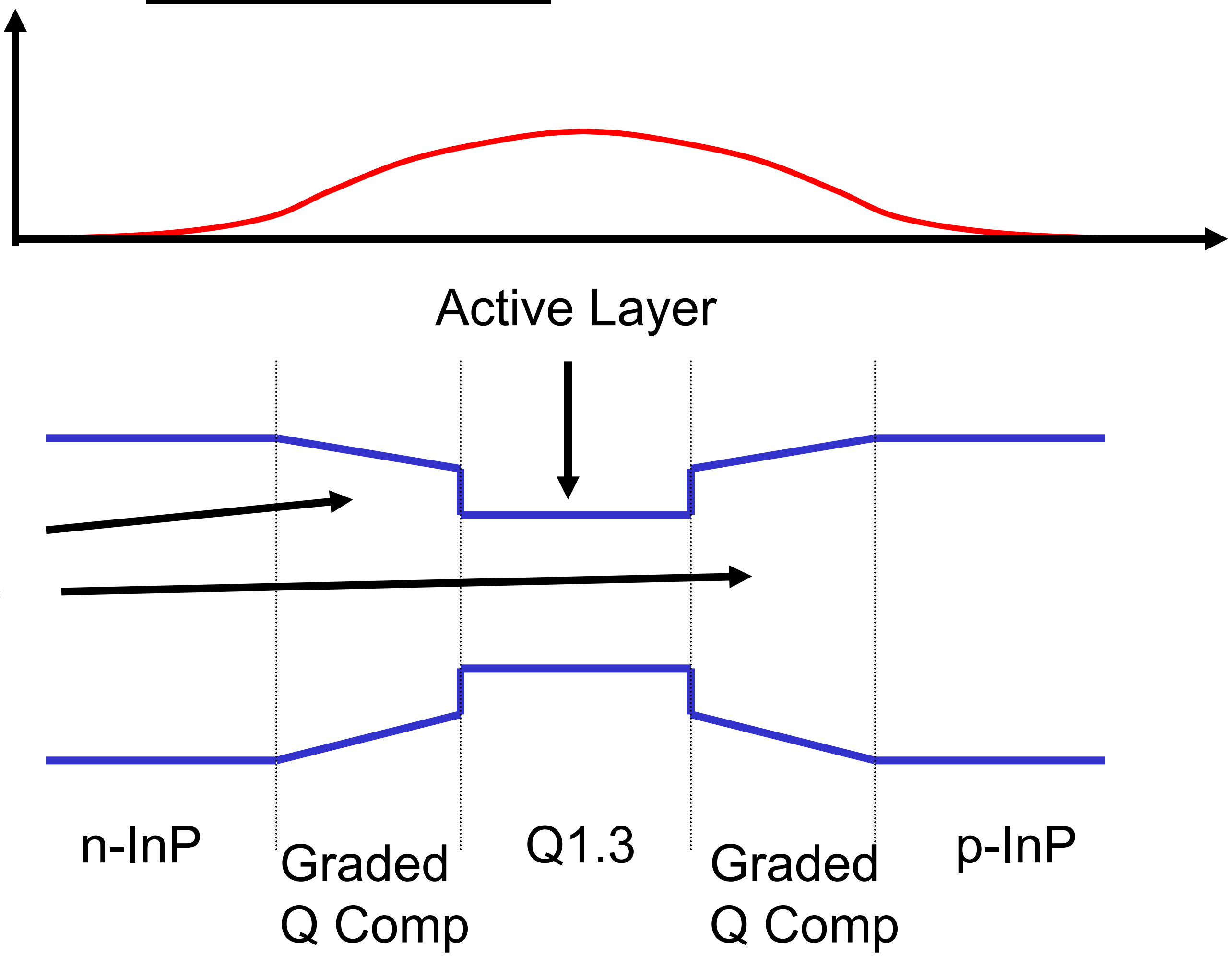
Large optical confinement is necessary for a low threshold laser

- The left figure: **a thin quantum well** based LD is not enough to effectively confine the light.

- Another two layers added outside the thin quantum well. These layers have a **lower refractive index** than the quantum well centre layers, hence confining the light effectively. **Electrons can be well confined as well**

Such a design is called a **separate confinement heterostructure (SCH).**

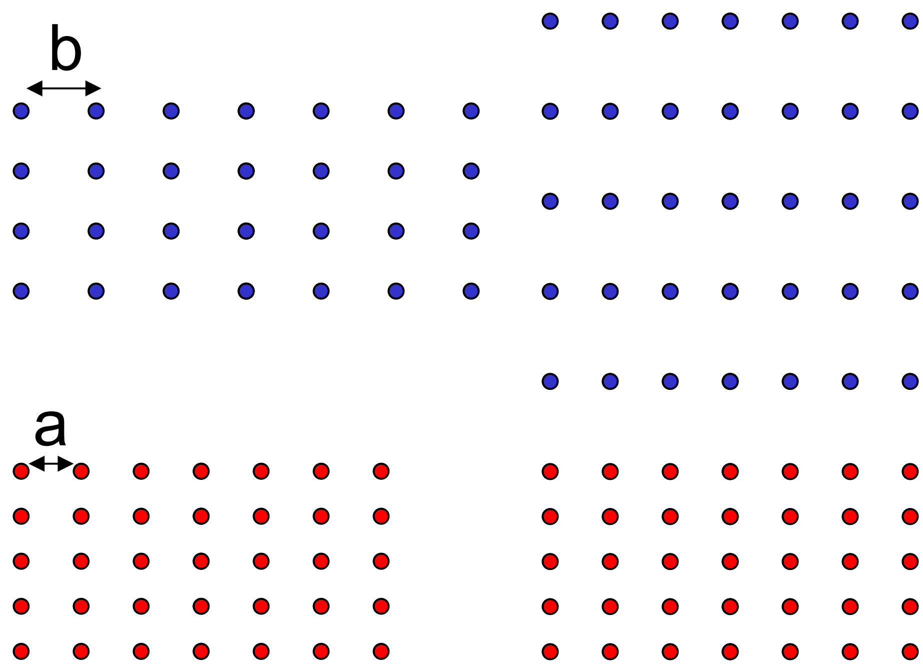
Graded Index Separate Confinement Heterostructure (GRINSCH)

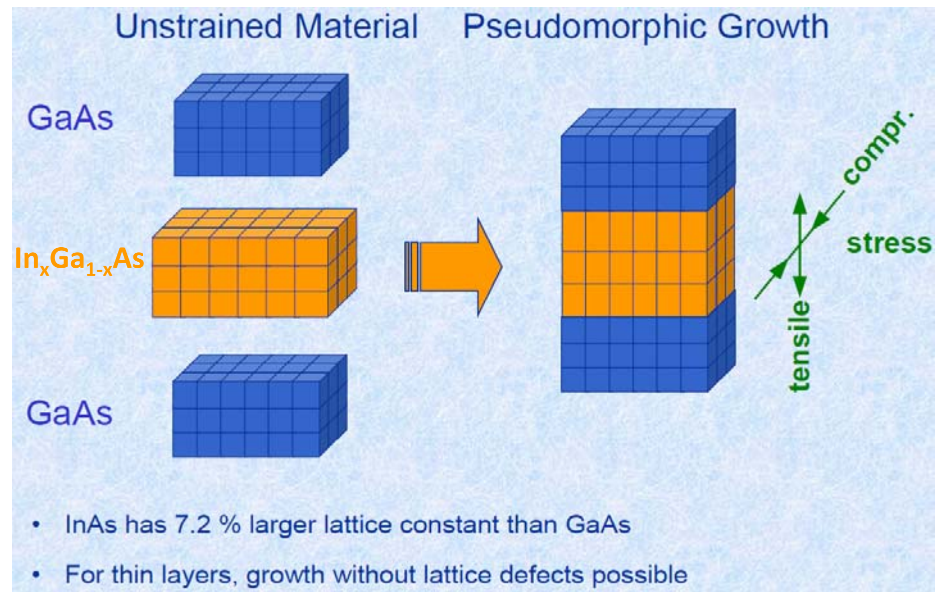


Graded Q layers look like an electric field – efficient & rapid capture of carriers by active layer

GRINSCH structures are produced by altering the alloy concentration during the growth process.

Lattice mismatch and strain

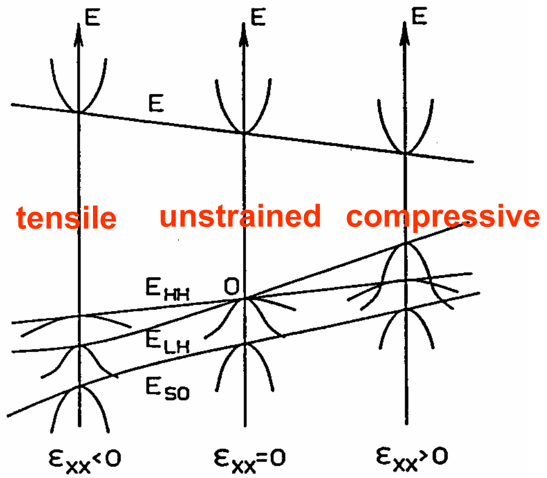




•In-plane compressive and tensile strain – example above is compressive stress

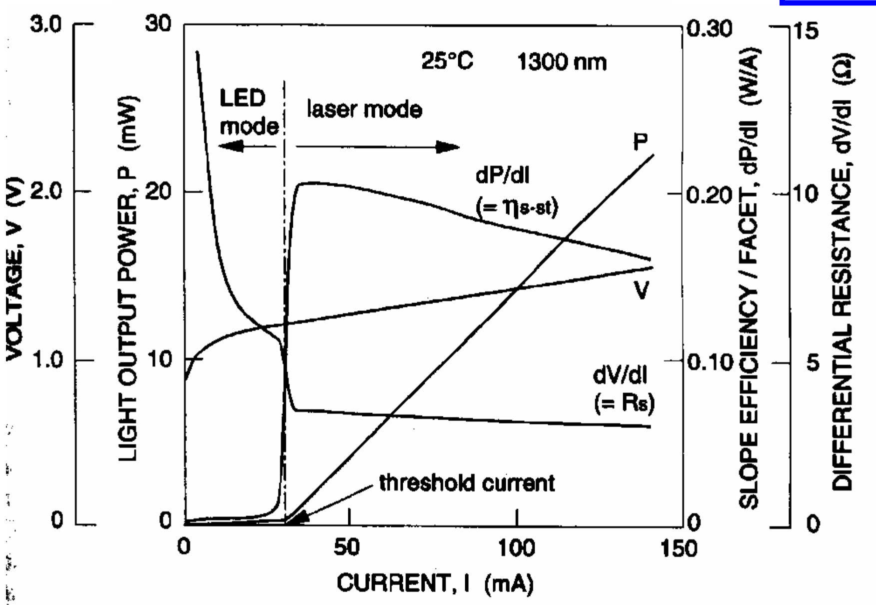
•Find experimentally that the product of % strain and thickness is a constant – above which the material is not coherent – defects and/or 3D growth

Effect of Strain on Laser Performance

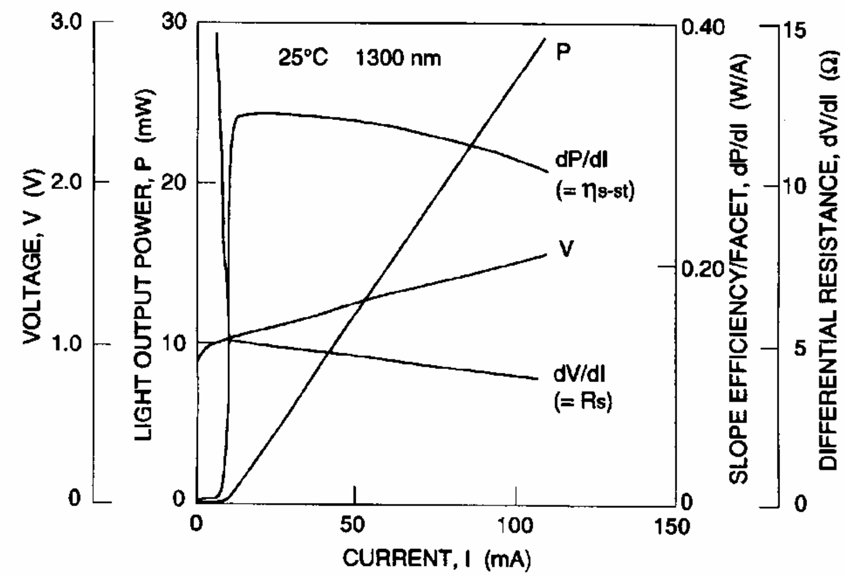


Effect of Strain on Band-structure

- Can tune band-gap – access wavelengths lower than lattice mismatched material
- Split heavy and light-hole bands
- Match effective masses more closely – more gain per carrier…..lower I_{th}



Bulk InGaAsP



Strained MQW Buried Het

Strained MQW Buried Het has – lower J_{th}, higher efficiency, higher dg/dn so higher modulation rate, as lower J_{th}, probably

Summary

- Threshold current is proportional to the active volume – active also provides wave-guiding in laser structure
- If we reduce the waveguide thickness too much we get poor waveguiding - light is not confined
- A solution is to have separate optical confinement and carrier confinement layers – get well confined light and reduction of active volume (with the reduction of photon: active overlap)
- Strained Quantum wells lift degeneracy of valence band – reduced threshold current
- Quantum wells, wire, dots allow reduction in active volume and quantum mechanical effects (quantum confinement – increased dg/dn)

Tutorial Questions

T18.1 Describe strategies to reduce the threshold current of a semiconductor laser

T18.2 What is the effect of reducing the density of states (at the lasing wavelength) for a semiconductor laser?

T18.3 What is the effect of strain on the operation of a quantum well laser?