Topic 24

24 Low dimensional laser diodes

24.1 Introduction: role of dimensionality in semiconductors
24.2 Basic theory for low dimensional semiconductors
Quantum Mechanics
24.3 MQWs, Qwires, QDs for laser
24.4 Growth of MQWs, QWires and QDs
24.5 Separate optical confinement
24.6 Lattice mismatch and strain
24.7 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?

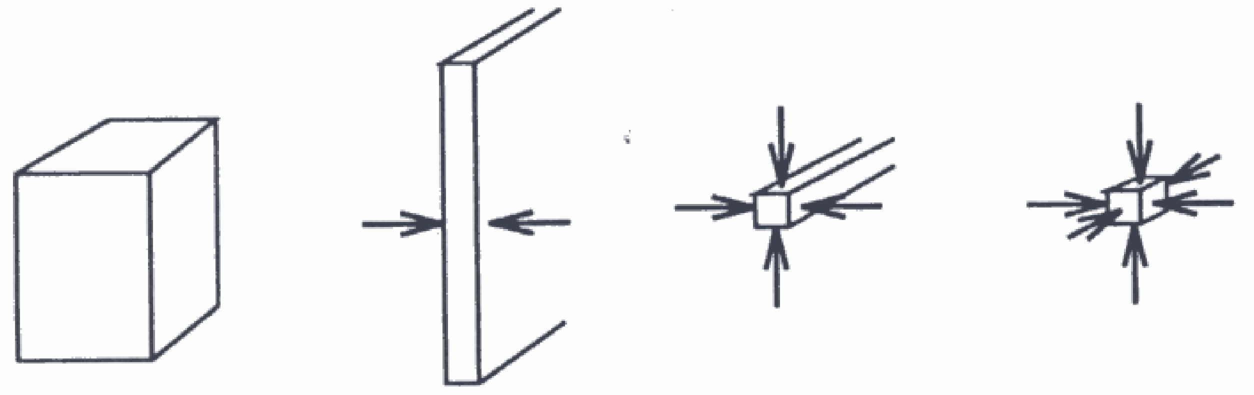
• How small should this confinement be?

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 $\qquad E = p^2/2m^* + V(r)$

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

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

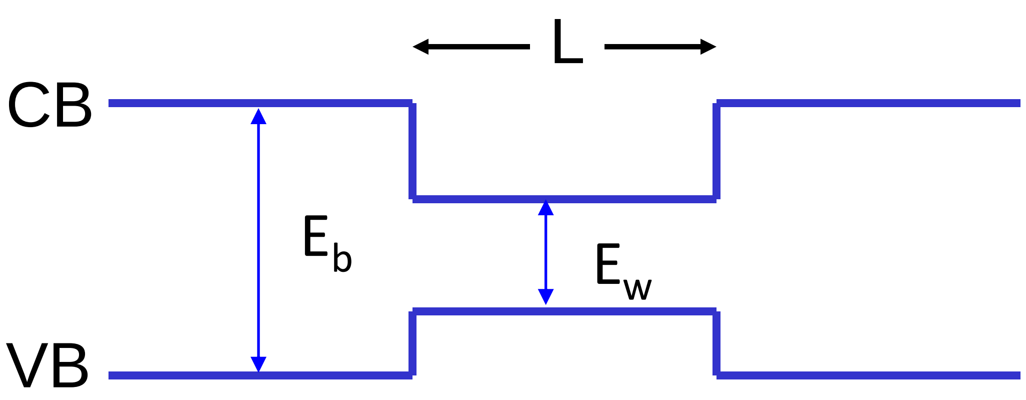
- In "new" Quantum mechanics momentum and energy replaced by operators operating on a wavefunction - "Guesswork" by Schrödinger

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

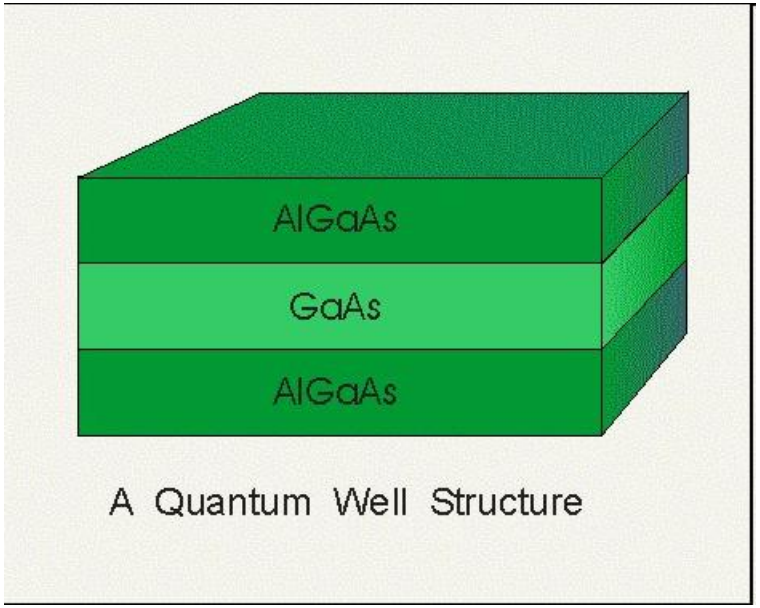
∇^2 = Laplace operator:

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

Quantum Wells & Quantum Mechanics



Quantization energy



Quantum well:

(1) Double heterostructure, **a thin layer** with a low bandgap sandwiched by two layers with **a large bandgap**

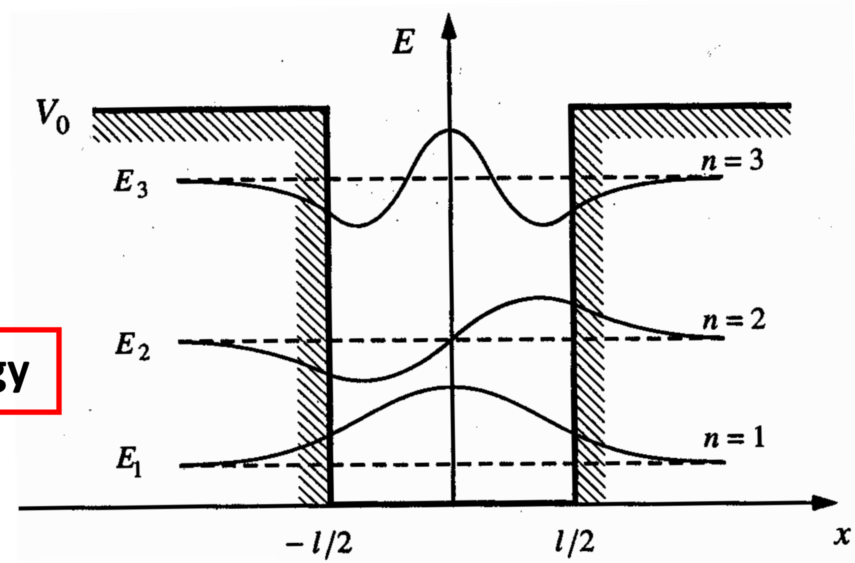
(2) The thickness of the thin layer: ~ de Broglie wavelength, (~10nm scale)

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

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

Kinetic energy | Potential energy | Total energy



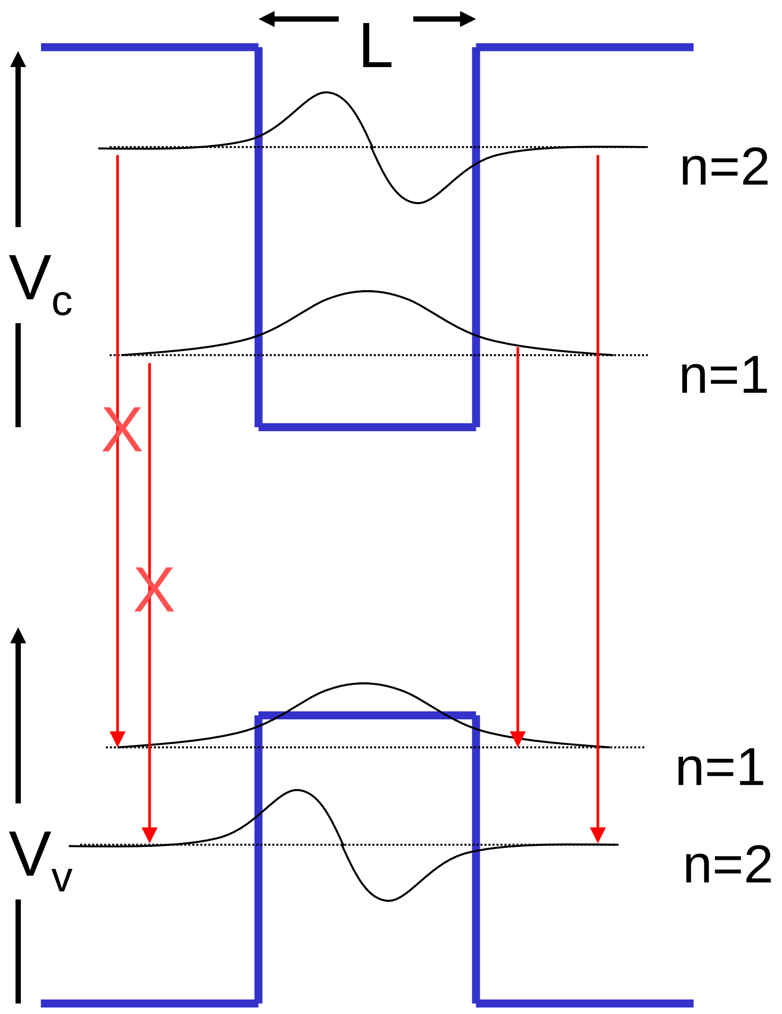
- $\hbar$: constant; *m*: mass of the particle; *V:* local potential; E: energy
- ***Ψ*: wavefunction** of the particle

- $\boxed{|\Psi(x)|^2 dx}$: 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)



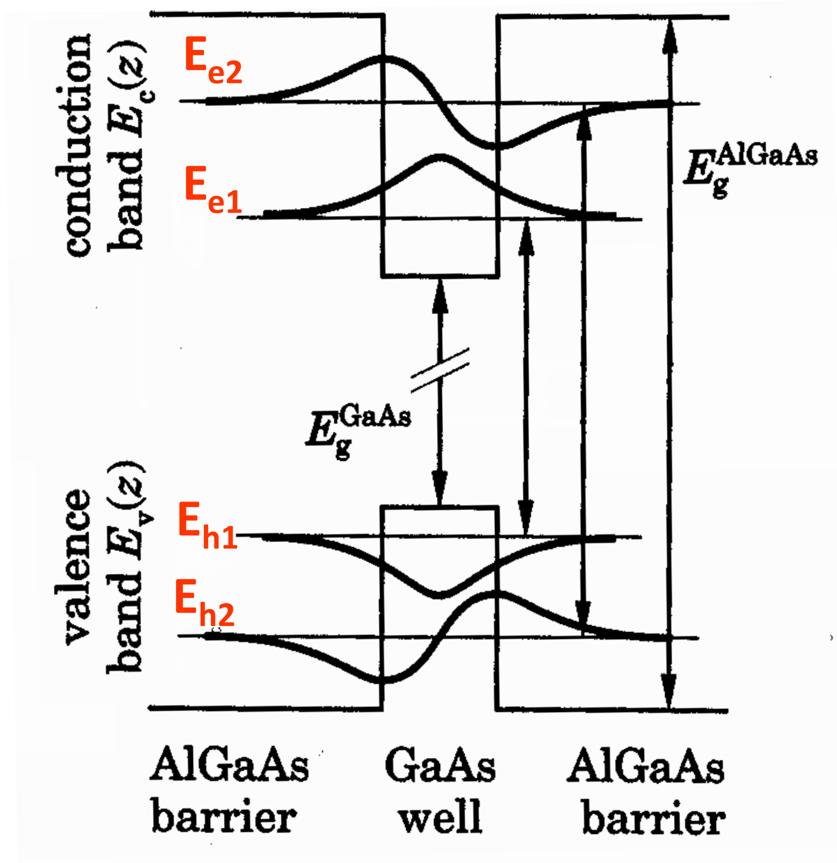
$E_n = (\hbar^2/2m^*)\,(n\pi/L)^2$

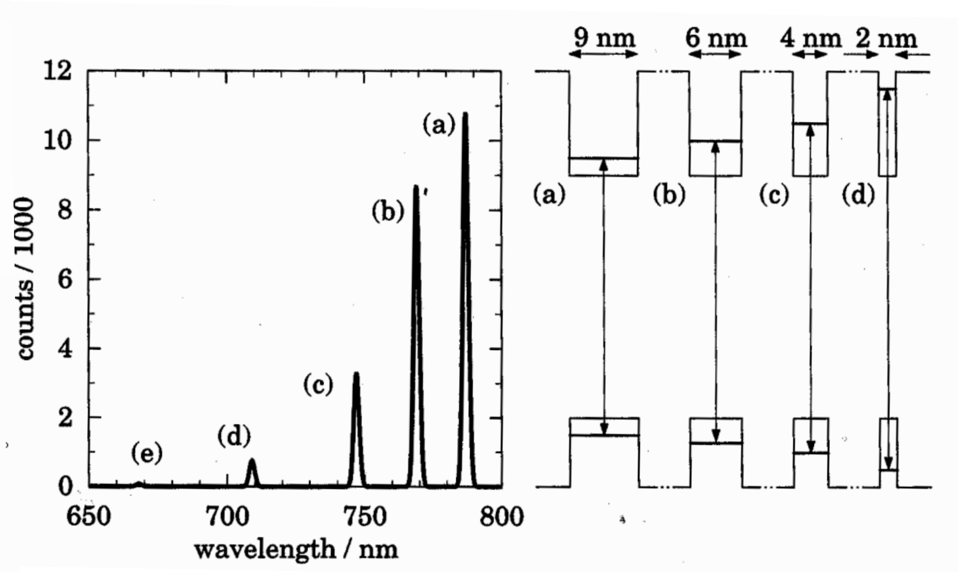
Due to Symmetry transitions

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

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

GaAs/AlGaAs quantum well



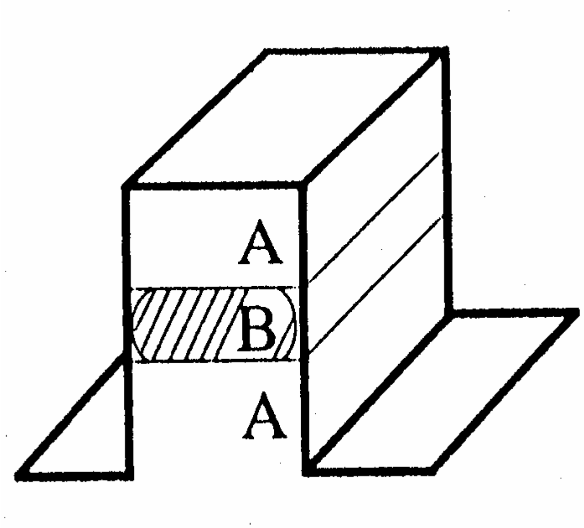


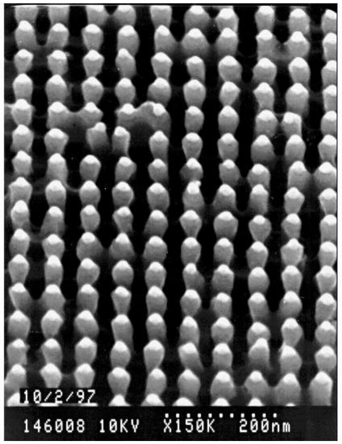
Transition Energy (ignore exciton binding energy):

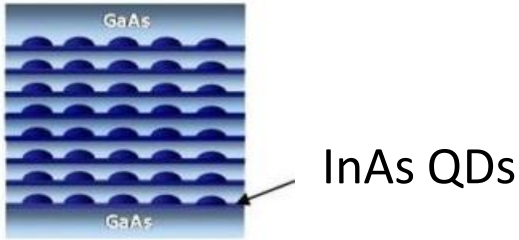
E (ground state)=E_g(GaAs)**+E_{e1}+E_{h1}**

- 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

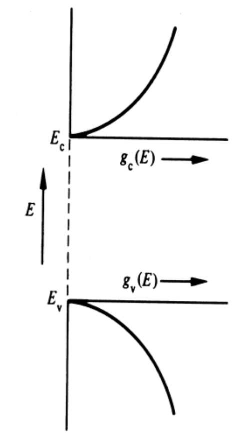
We need to introduce an important concept:

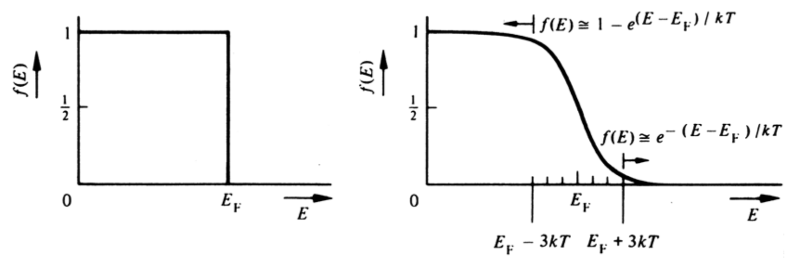
Density Of States *g(E)*: how many states exist at a given energy *E*.

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

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

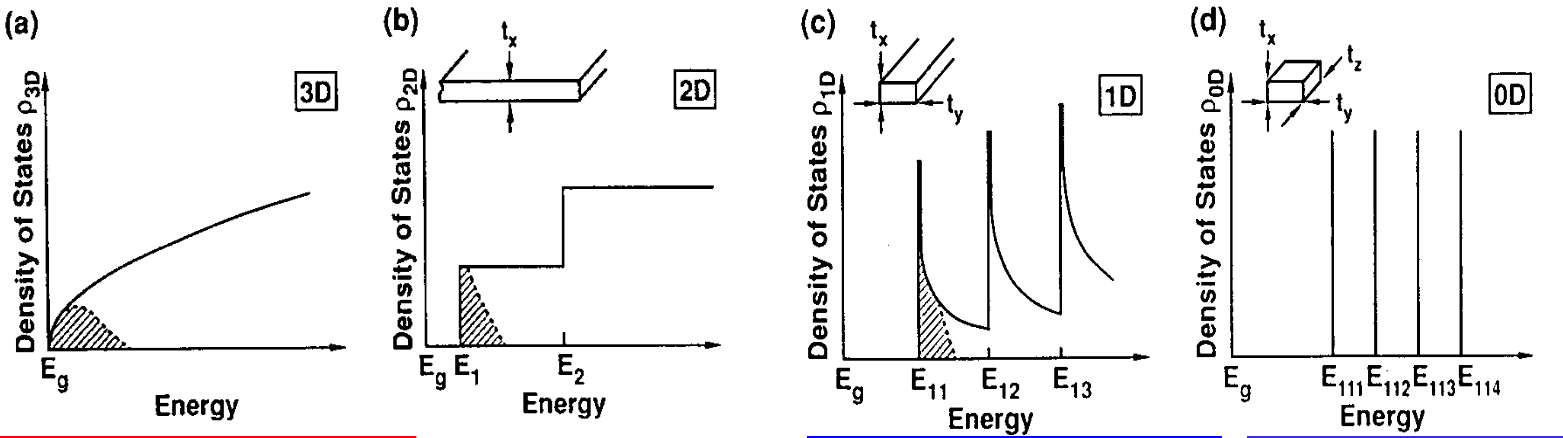
The distribution of carriers will depend on the density of states, and also on the probability of occupancy (**Fermi-Dirac statistics, not discussed**)





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

Density of States – 3D, 2D, 1D, 0D



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

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

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

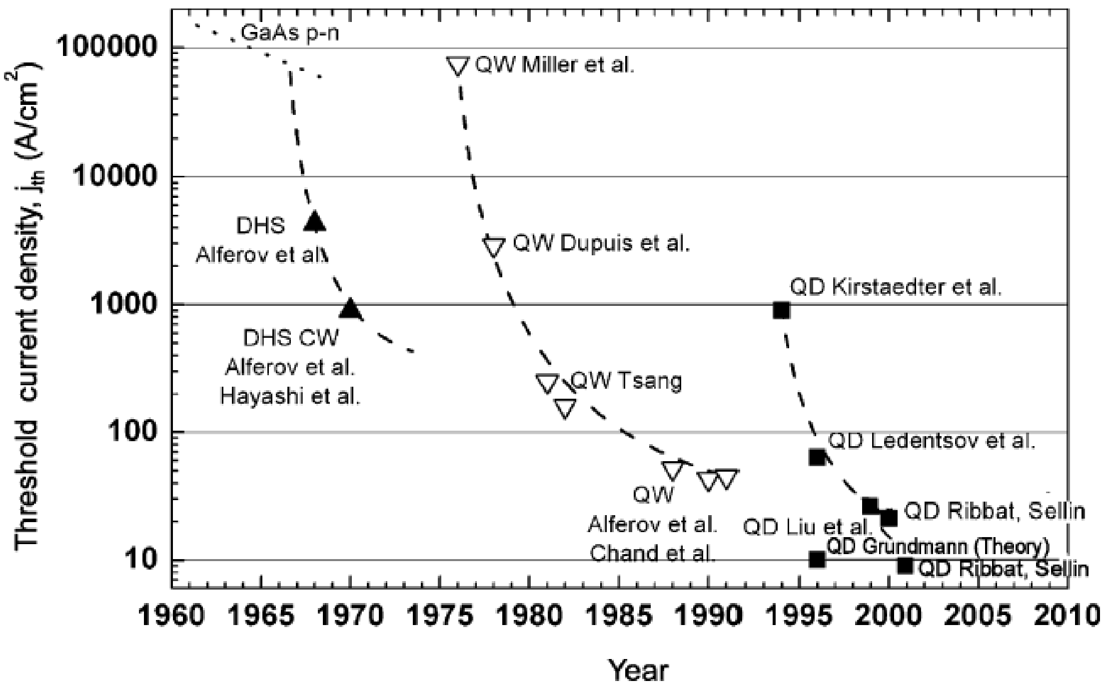
$$g_{1D} = 2\,\delta(E - E_0)$$

- 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.

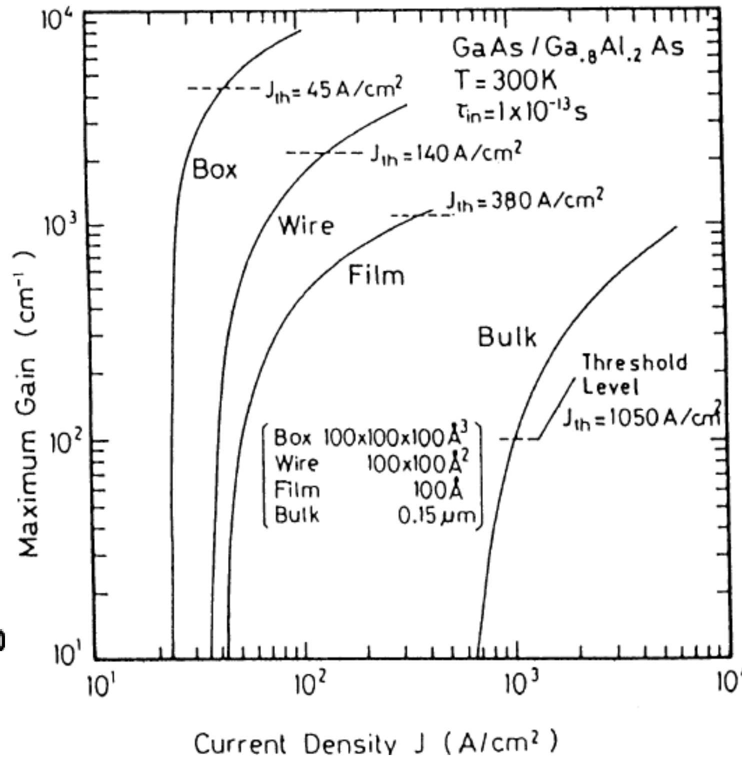
- The greater density of states near the band edge for low dimensional structures leads to a **higher material and differential gain** compared with quantum well or bulk material

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

Reduction in J_{th} – Records As Fn Time



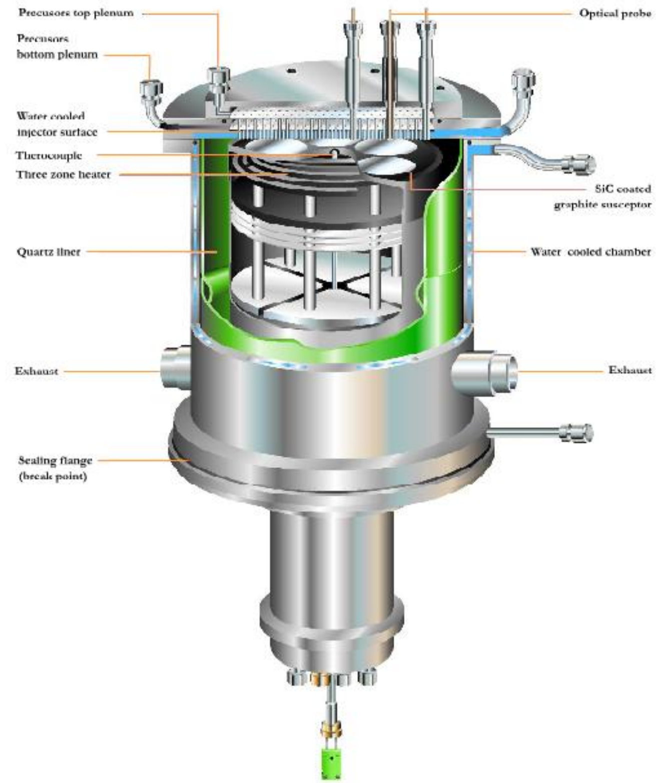
M. Henini, M. Bugajski / Microelectronics Journal 36 (2005) 950–956



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

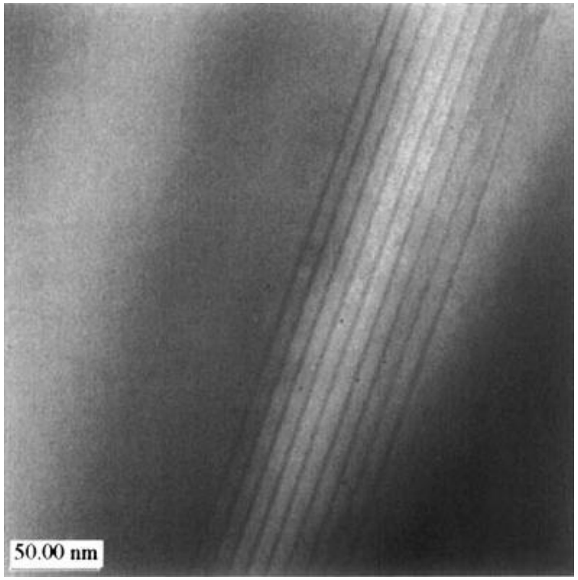
- QDs: highest Gain
- QDs: lowest threshold for lasing

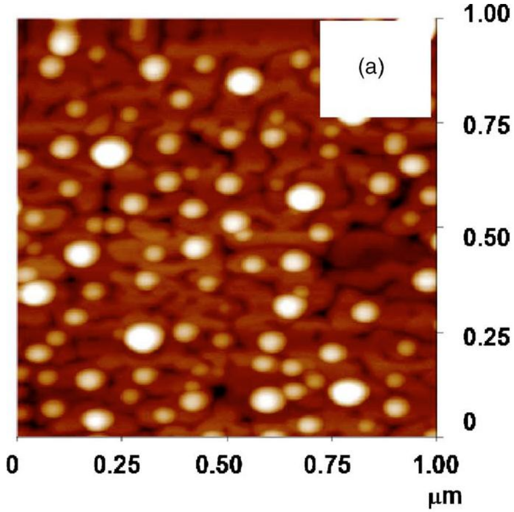
Advanced growth facility (i)

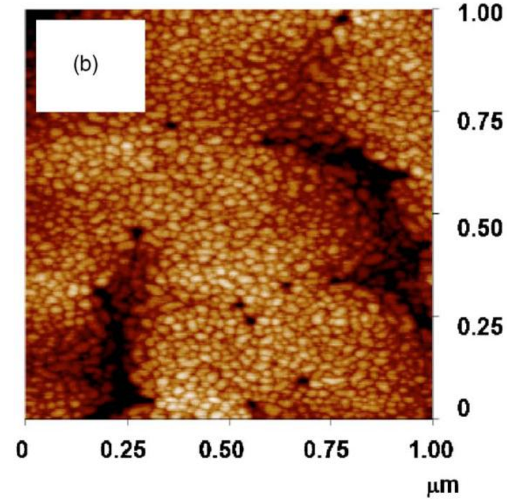


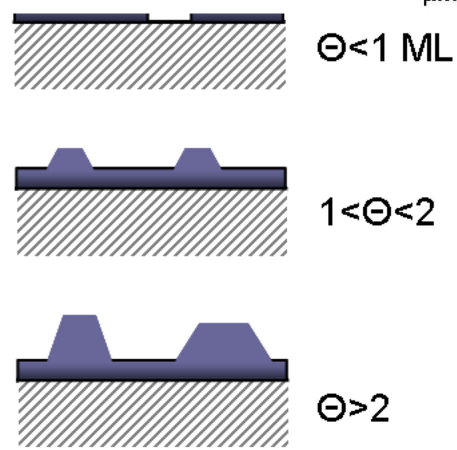
Metal Organic Chemical Vapour Deposition (MOCVD)

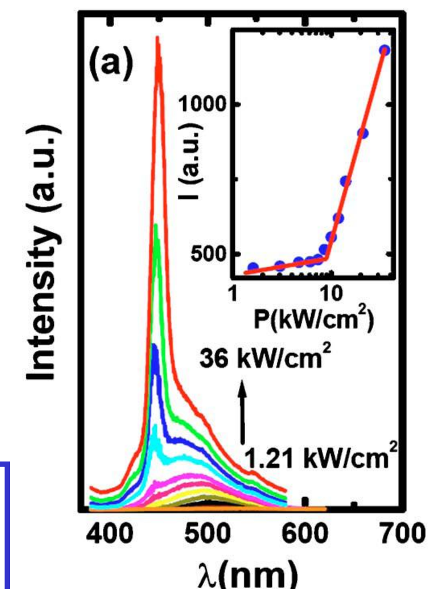
MOCVD grown III-nitride MQWs and QDs







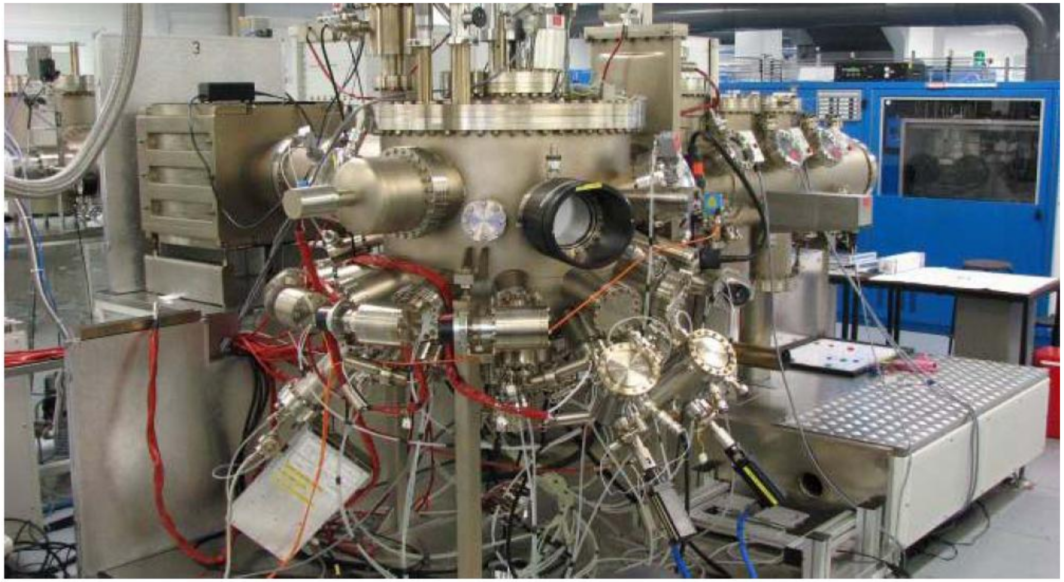


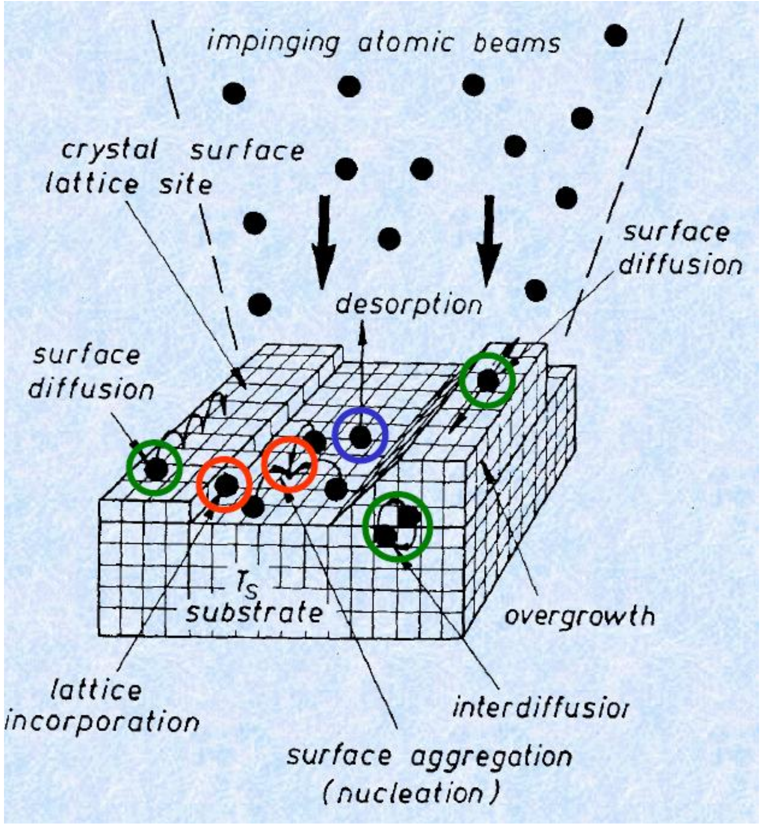


•InGaN/GaN MQWs for solid state lighting

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

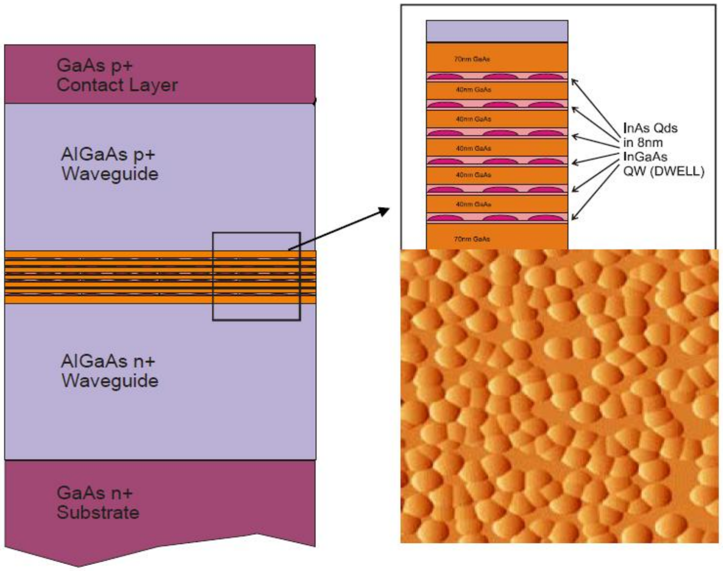
Advanced growth facility (ii)

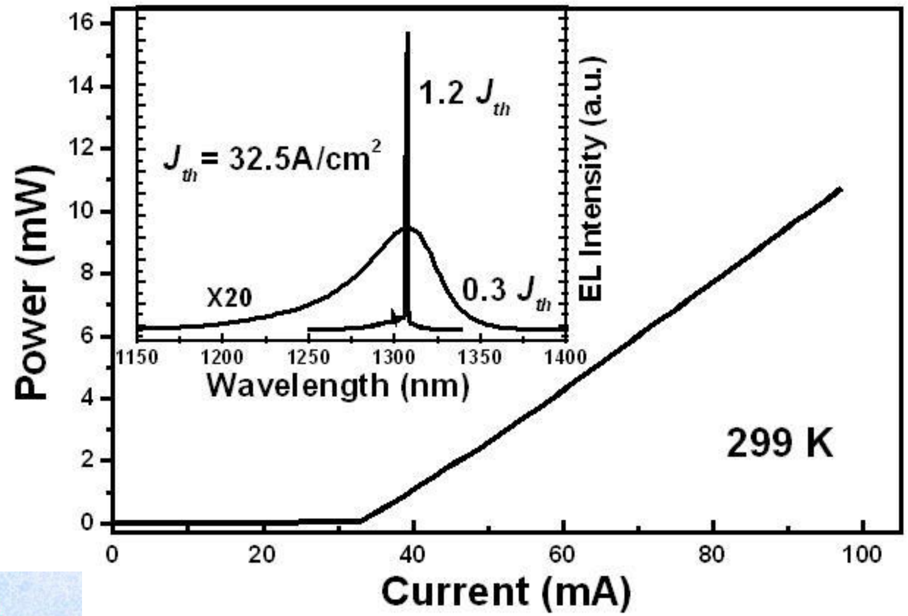


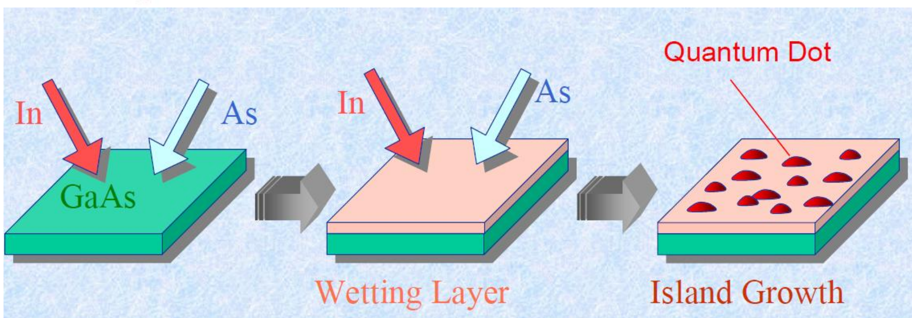


Molecular Beam Epitaxy

MBE growth quantum dot laser diode



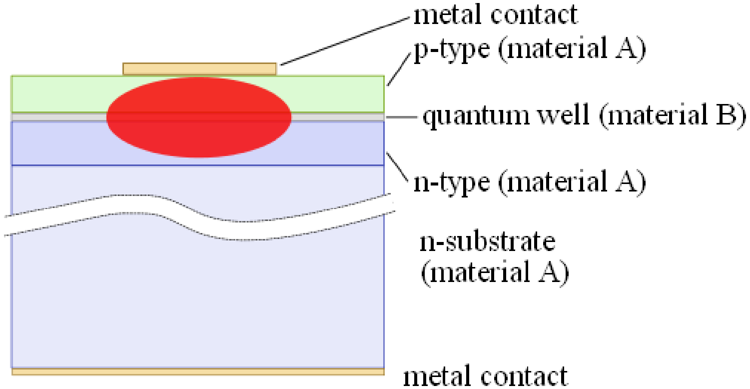


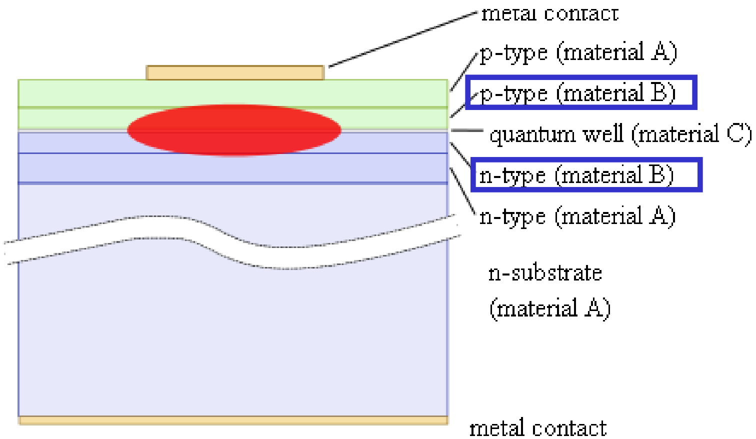


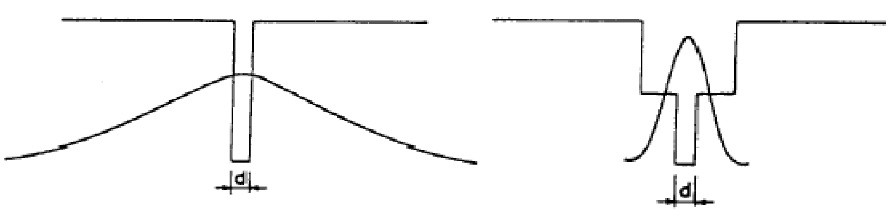
AFM image – energy of surface is minimised by the formation of "bumps" instead of a 2D layer

Quantum dot lasers can now be realised with world beating performance

Separate Confinement Heterostructure (SCH)







- Previous slide:

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

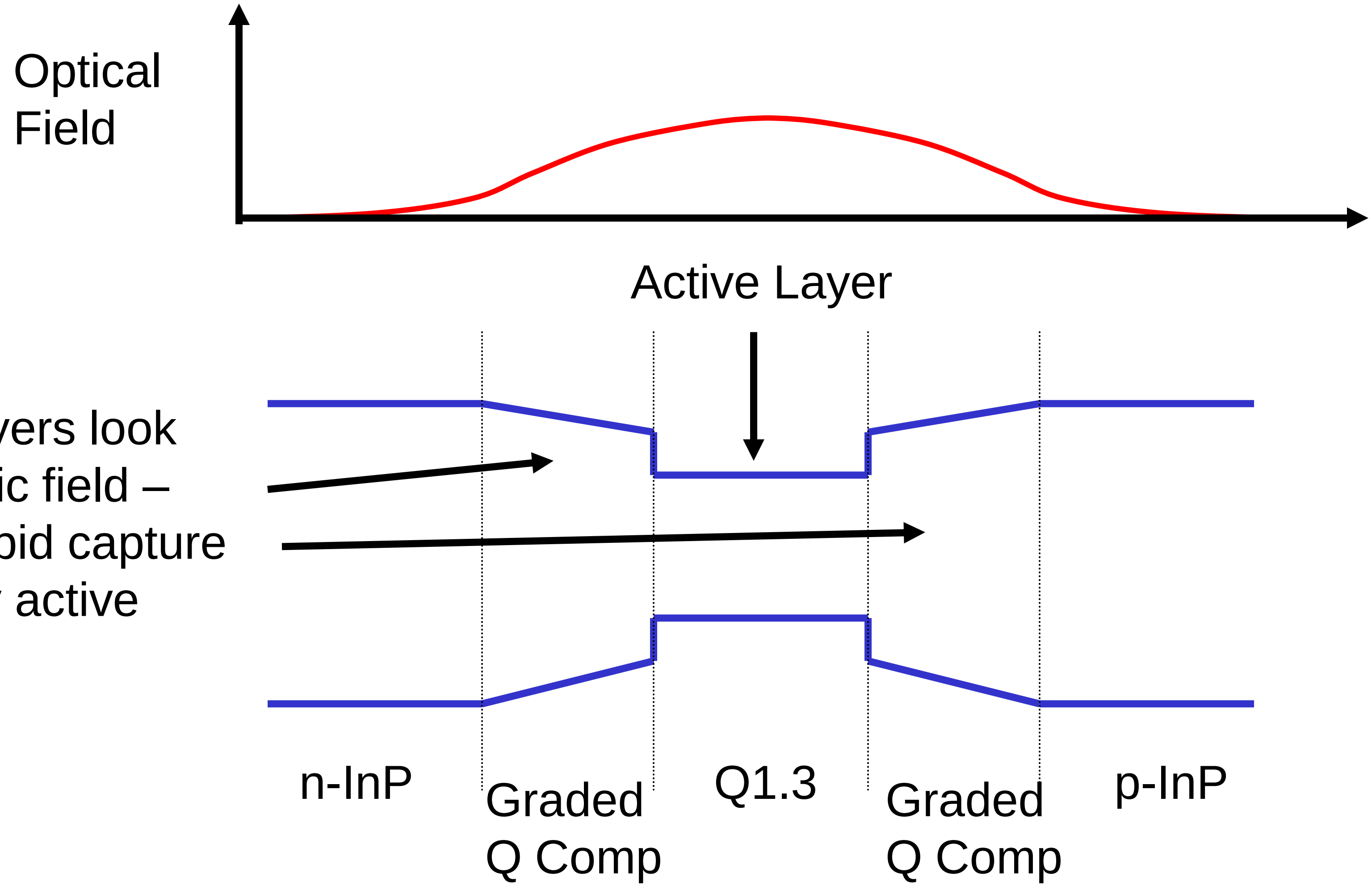
Large optical confinement is necessary for a low threshold laser

- 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).**

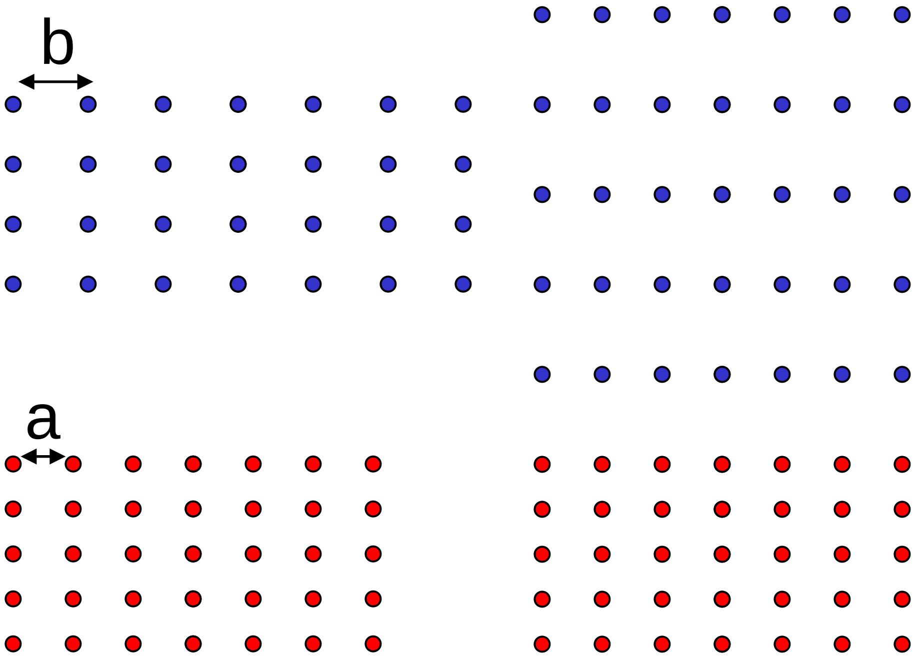
Graded Index Separate Confinement Heterostructure (GRINSCH)

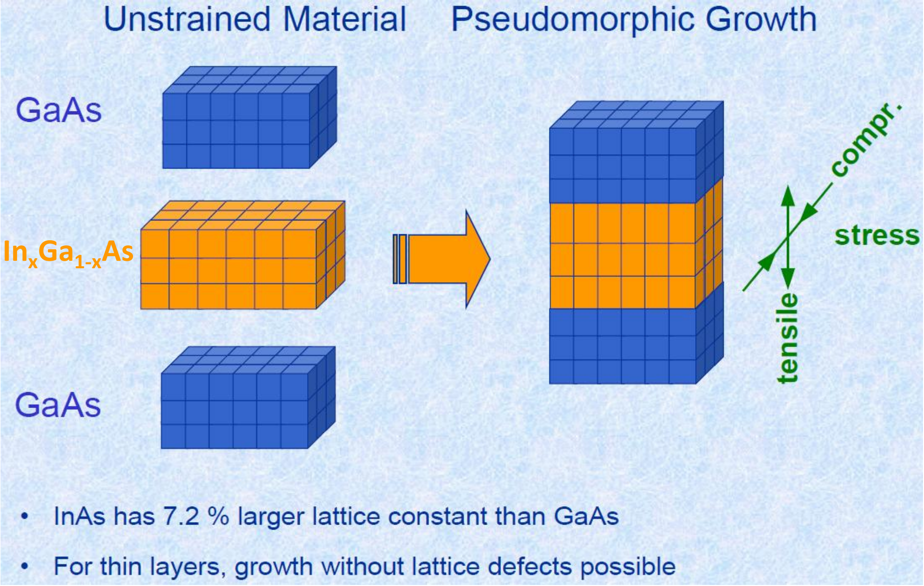


Graded Q layers look like an electric field – efficient & rapid capture of carriers by active layer

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

Lattice mismatch and strain

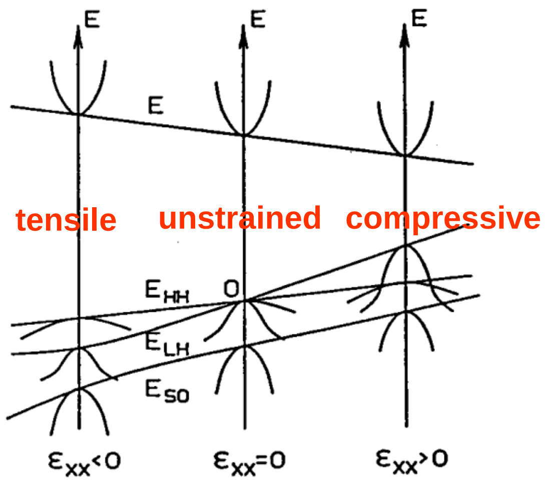




•In-plane compressive and tensile strain – example above is compressive stress

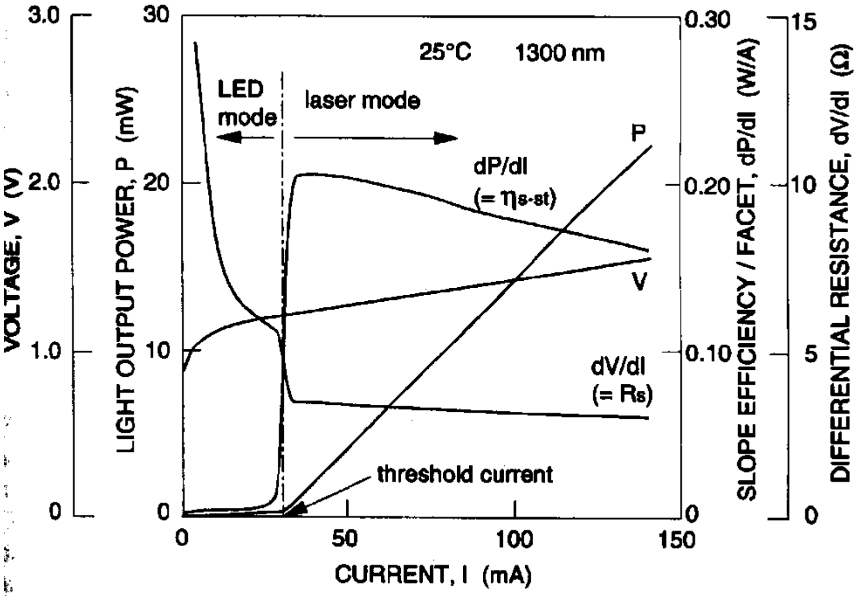
•Find experimentally that the product of % strain and thickness is a constant – above which the material is not coherent – defects and/or 3D growth

Effect of Strain on Laser Performance

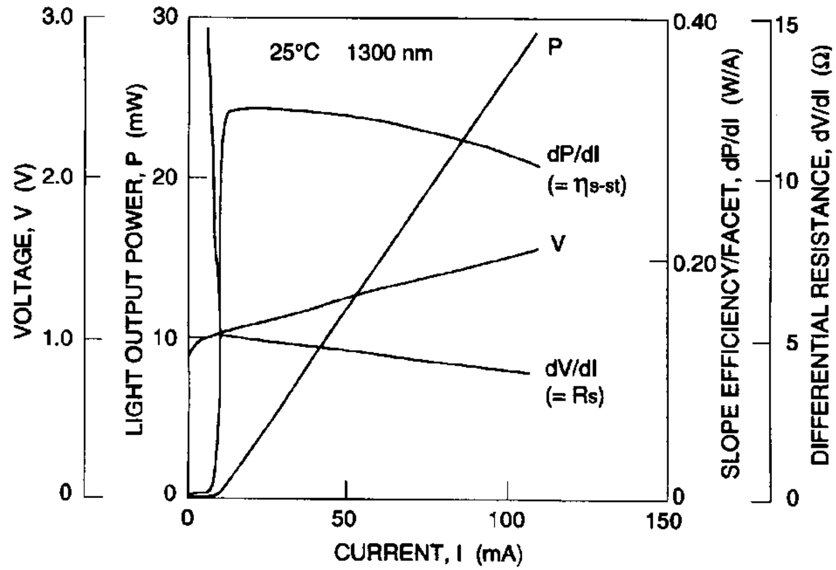


Effect of Strain on Band-structure

- 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

T24.1 Describe strategies to reduce the threshold current of a semiconductor laser

T24.2 What is the effect of reducing the density of states (at the lasing wavelength) for a semiconductor laser?

T24.3 What is the effect of strain on the operation of a quantum well laser?