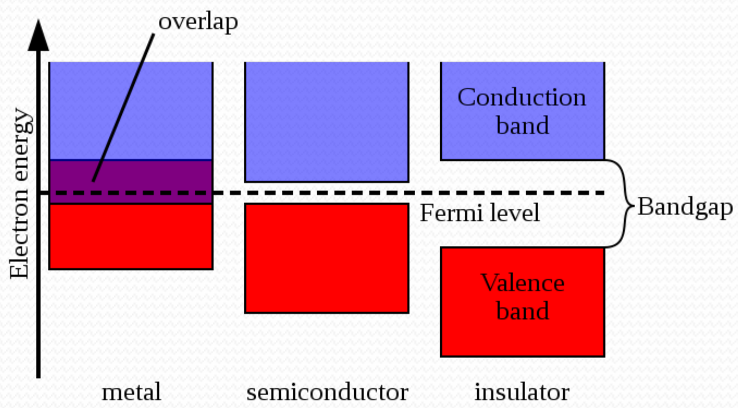
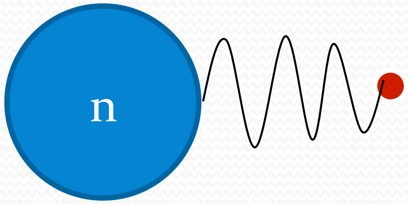
An Introduction to Quantum Dots

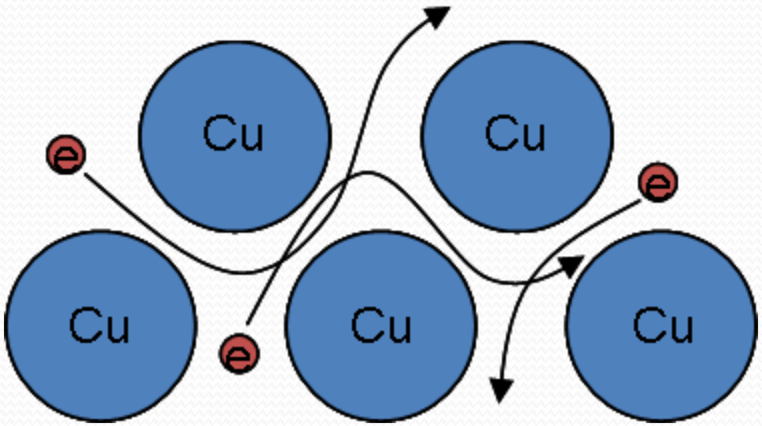
Materials

What makes a semiconductor?





Fixed Ions



Free Electrons

Some Basic Physics

- Density of states (DoS)

$$DoS = \frac{dN}{dE} = \frac{dN}{dk}\frac{dk}{dE}$$

  - e.g. in 3D:

$$N(k) = \frac{\text{k space vol}}{\text{vol per state}}$$

$$= \frac{4/3\pi k^3}{(2\pi)^3/V}$$

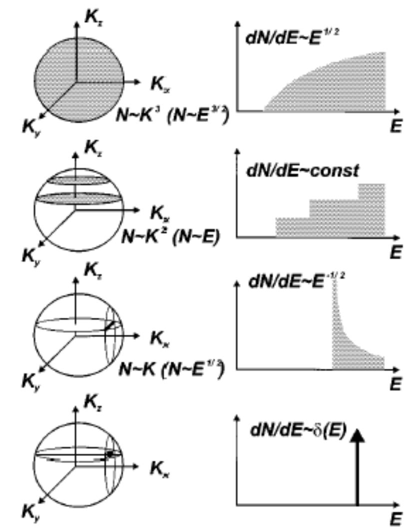
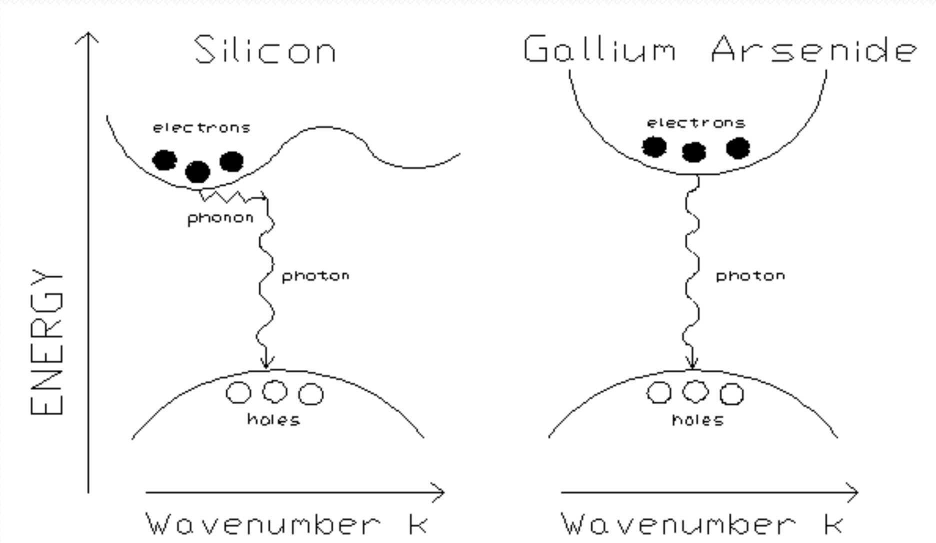


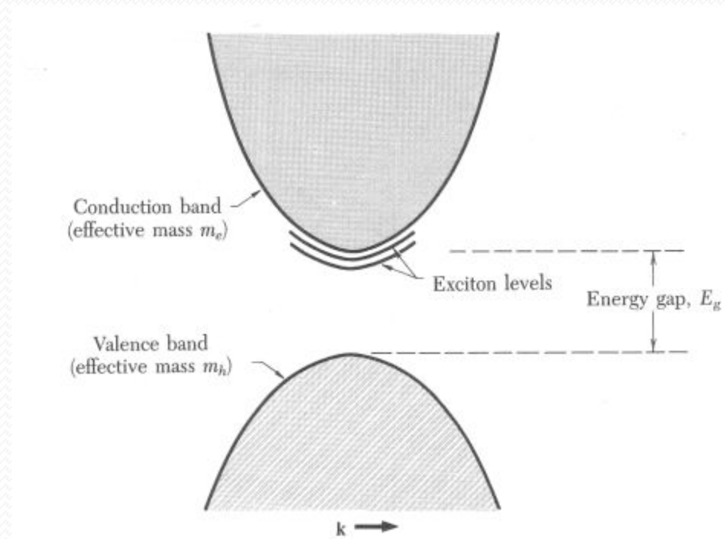
Fig. 1. Density of states for charge carriers in structures with different dimensionalities.

Structure	Degree of Confinement	$\frac{dN}{dE}$
Bulk Material	0D	$\sqrt{E}$
Quantum Well	1D	1
Quantum Wire	2D	$1/\sqrt{E}$
Quantum Dot	3D	$\delta(E)$

Optical Properties of Semi-Conductors

- Energy Band Gaps
  - Bulk Emission and Absorption
  - Coulomb attraction\Excitons



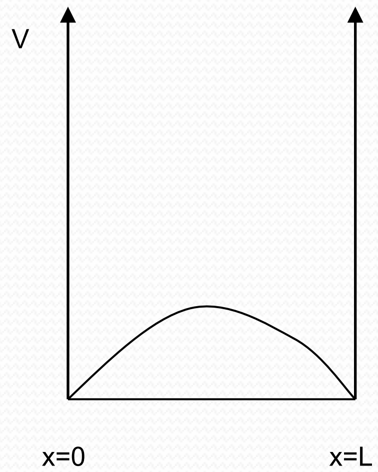


Exciton e-h pair, energy levels

Discrete States

- Quantum confinement → discrete states
- Energy levels from solutions to Schrodinger Equation
- Schrodinger equation:

$$-\frac{\hbar^2}{2m}\nabla^2\Psi + V(r)\Psi = E\Psi$$



- For 1D infinite potential well

$$\Psi(x) \sim \sin(\frac{n\pi x}{L}), \text{n = integer}$$

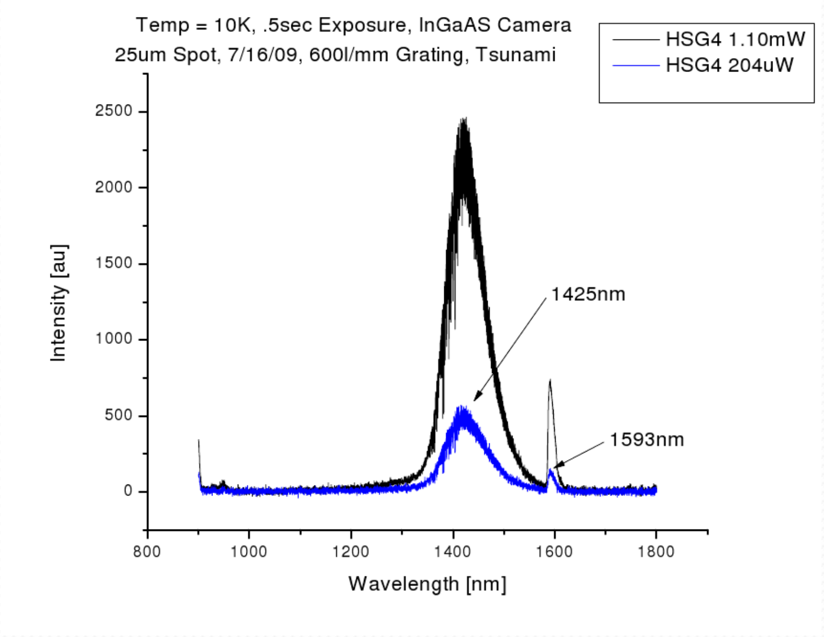
- If confinement in only 1D (x), in the other 2 directions → energy continuum

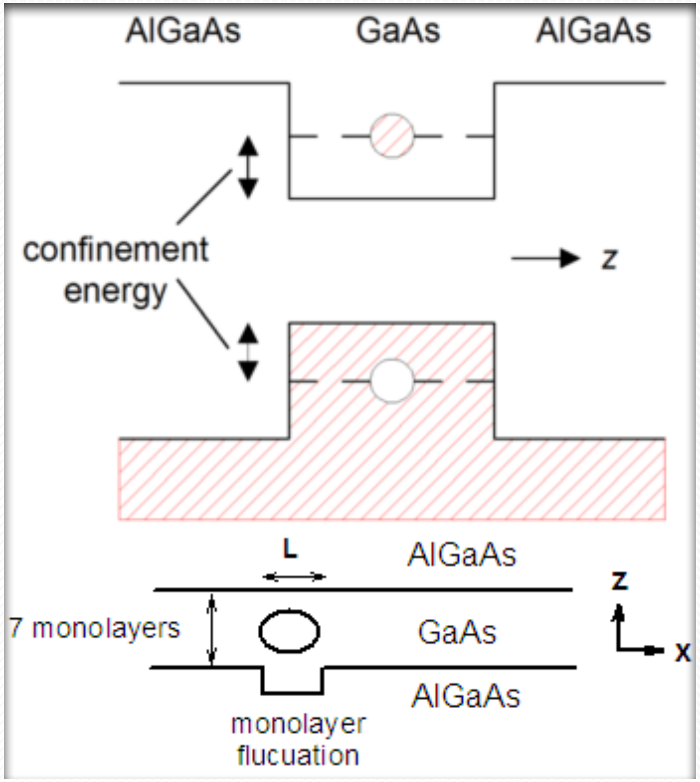
$$\text{Total Energy} = \frac{n^2h^2}{8mL^2} + \frac{p_y^2}{2m} + \frac{p_z^2}{2m}$$

Quantum confinement

- Quantum Wells

Quantum Wells create confinement in one dimension





In 3D…

- For 3D infinite potential boxes

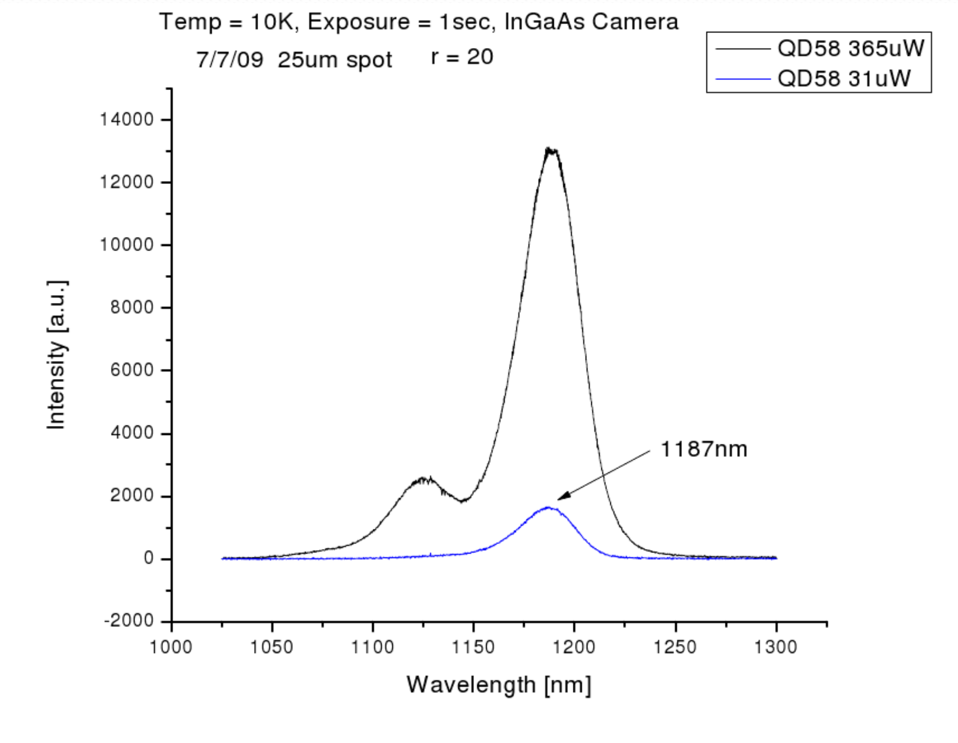
$$\Psi(x, y, z) \sim \sin(\frac{n\pi x}{L_x})\sin(\frac{m\pi y}{L_y})\sin(\frac{q\pi z}{L_z}), \text{n, m, q} = \text{integer}$$

$$\text{Energy levels} = \frac{n^2 h^2}{8mL_x{}^2} + \frac{m^2 h^2}{8mL_y{}^2} + \frac{q^2 h^2}{8mL_z{}^2}$$

- Simple treatment considered here
  - Potential barrier is not an infinite box
    - Spherical confinement, harmonic oscillator (quadratic) potential
  - Only a single electron
    - Multi-particle treatment
    - Electrons and holes
  - Effective mass mismatch at boundary (boundary conditions?)

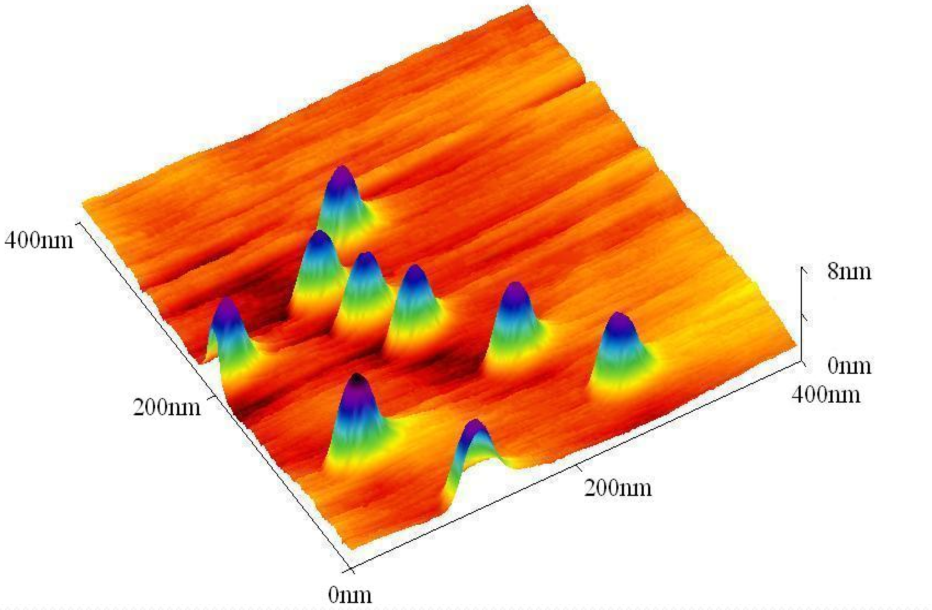
Quantum Dots

Confinement in three dimensions, more confinement yields higher energy photons

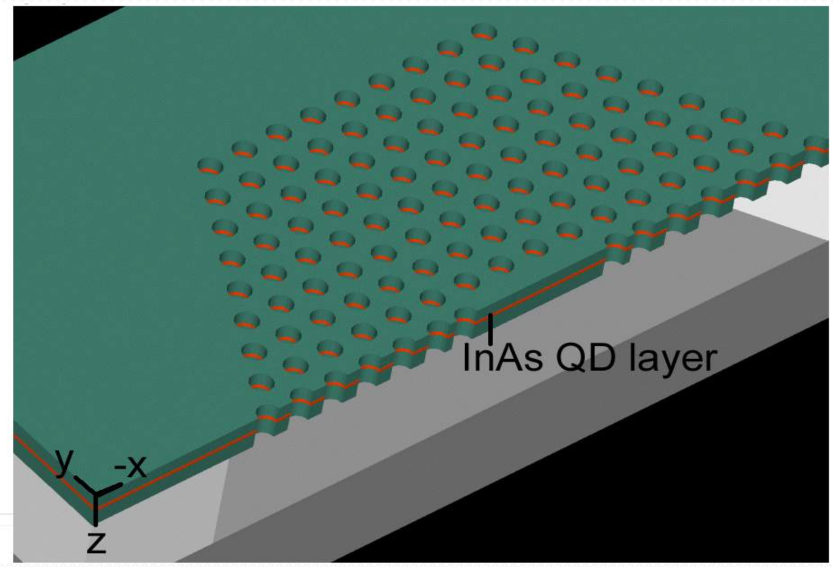


Photoluminescence of an InAs QD ensemble. InAs bulk band gap would appear around 1.61 um at this temperature

Applications of QD's



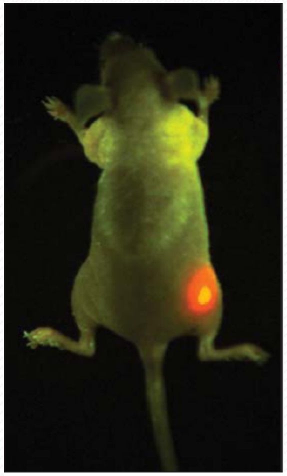
Atomic Force Microscope image of Surface quantum dots



Photonic Crystal Nano-Cavity

Future Outlook

- Gain and stimulated emission from QDs in polymers
  - Polymeric optoelectronic devices?
- Probe fundamental physics
- Quantum computing schemes (exciton states as qubits)
  - Basis for solid-state quantum computing?
- Biological applications
- Material engineering
  - How to make QDs cheaply and easily with good control?
- Let's not forget the electronic applications too!
- Lots to do!



Bull's-eye. Red quantum dots injected into a live mouse mark the location of a tumor.

C. Seydel. Quantum dots get wet. Science, 300, p. 80-81, Apr 2003.