Quantum Dot Lasers

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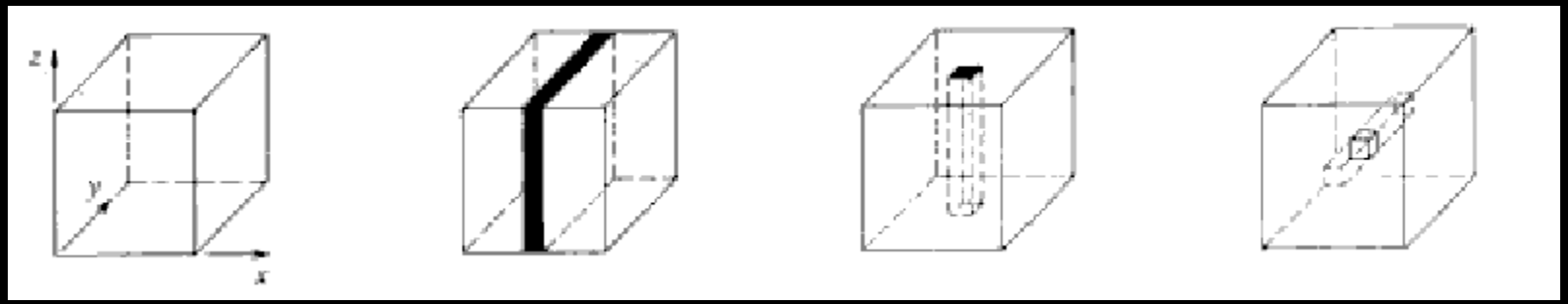
ECE 355

Overview of Presentation

- Quantum Dots
- Operation Principles
- Fabrication of Q-dot lasers
- Advantages over other lasers
- Characteristics of Q-dot laser
- Types of Q-dot lasers
- Challenges for the future

Low Dimensional Semiconductor Systems

- Low Dimensional – Reducing the dimensions of the active region of a system
- 3-D to ~ 0-D
- Bulk Q-well Q-line Q-dot



What is a Quantum Dot?

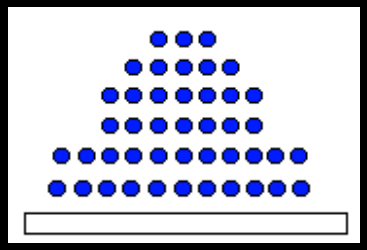
- Quantum Dots are able to confine electrons to lengths of the order of their wavelength
- ‘Artificial’ atoms that can be designed to specifications
- Allow for many quantum optical and electronic applications

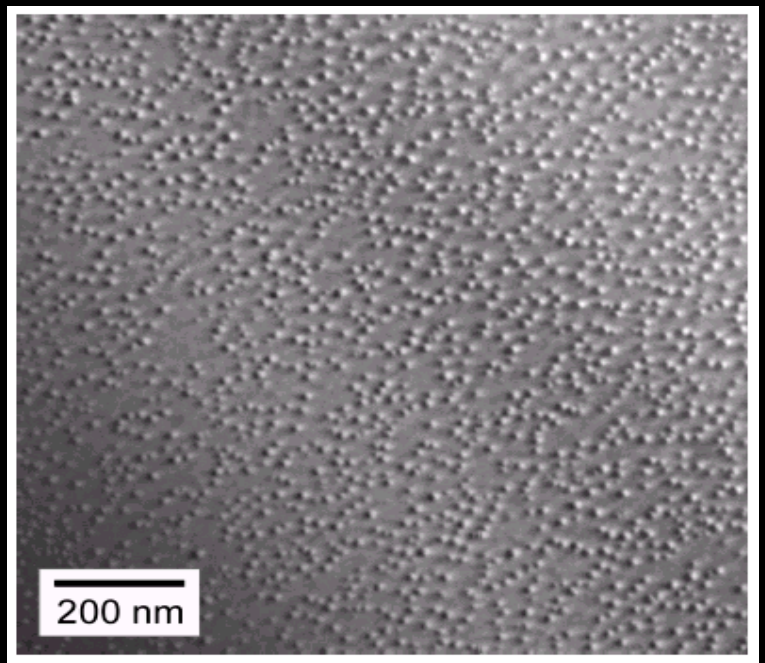
Quantum Dot Properties

- Composed of different types of semiconductors e.g. InGaAs
- 1nm-100nm across (nanostructures)
- Size, composition and shape are its most important properties for electron confinement
- Properties changed by method of fabrication:
  - Chemical
  - Lithographic Techniques
  - Molecular Beam Epitaxy

Creating Quantum Dots

- A bedding layer of a semiconductor is laid down
- A smooth layer (wetting layer) ~ 1 molecule thick of another semiconductor is laid over bedding layer.
- More wetting layer is laid down
  - Surface effects form clumps
  - Clumps are quantum dots
- Unwanted portions of semiconductor are removed



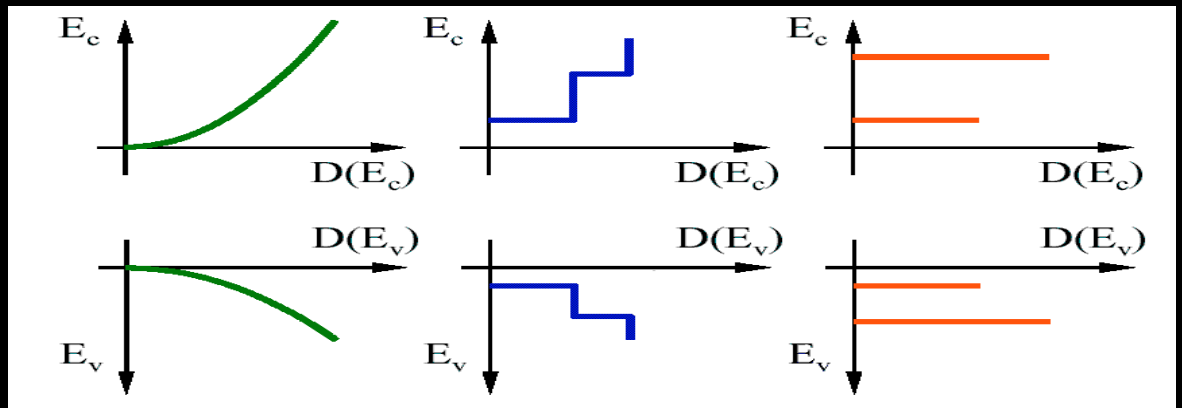


Characteristics and Applications of Quantum Dots

- Discrete emission spectrum
- Sharp emission peak allow for better resolution between peaks of different Q-dots
- Frequency of emitted light changed by altering properties of Q-dot
- Useful in laser systems
  - Quantum Dot Lasers
    - Very new area
    - Started exploring in the 1990's

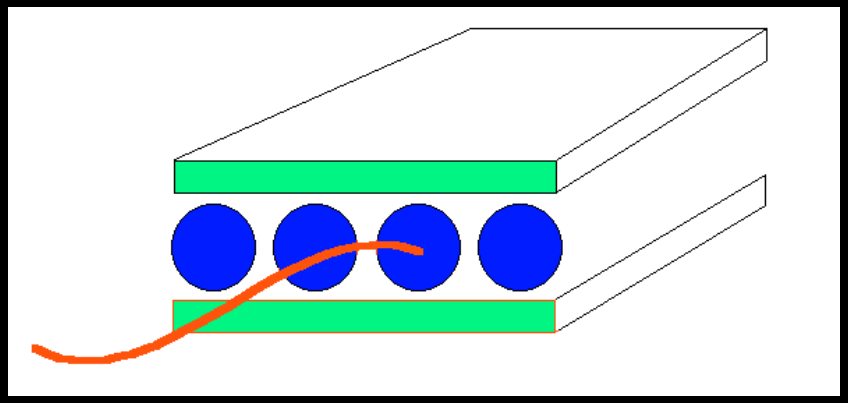
Operation Principle of Quantum Dot Lasers

- Electrons confined to three dimensions in a Q-dot.
- Solving a 3-D Schrodinger eq. yields a density of states function~delta function
- Since the Q-dot has some dimensions the density of states function has a finite linewidth
- Energy pumped into system goes to excite carriers between levels and not random motion leads to more efficiency
- Comparing to other quantum systems:



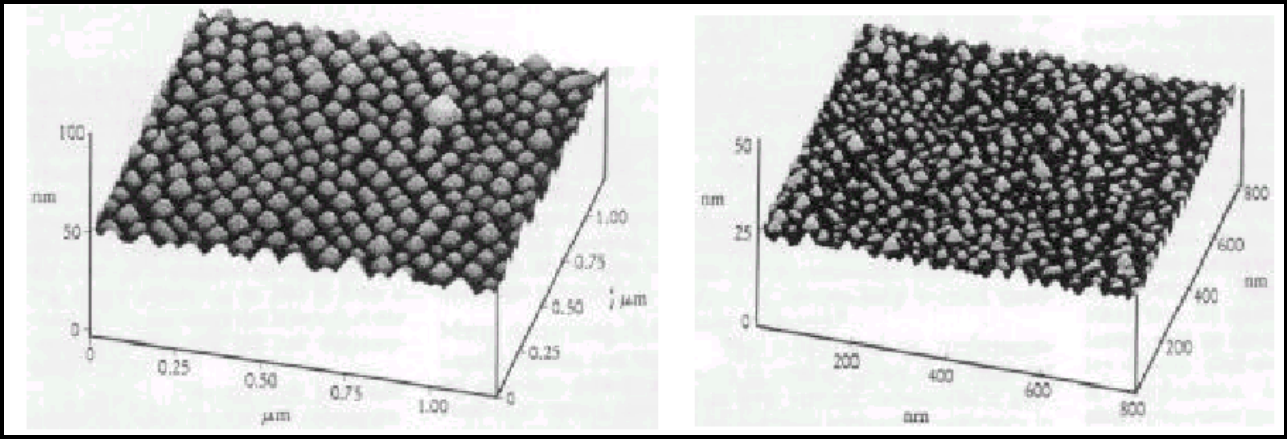
Quantum Dot Laser Fabrication

- Most common arrangement consists of layers of vertically stacked quantum dots.
- To achieve optical confinement, dots are placed in between a separate structure called the confinement heterostructure.



Why stack the dots?

- Although stacking the layers increases the amount of active material in the device
  - Stacked dots have been shown to display a narrower linewidth since they form more uniform, equally sized Q-dots



•20 layers

1 layer

- Setup leads to many advantages

Ideal Quantum Dot Laser

- Emit light at wavelengths corresponding to the energy levels of the dots
- Maximum material and differential gain
- Small active volume leads to many advantages over other systems

Advantages Over Other Quantum Systems

- Quantum Well vs. Quantum Dot
  - 2-D vs. 0-D
- Quantum Well lasers
  - Change the output wavelength by changing the dimensions of the well
  - Larger population inversion needed to lase
- Q-dot lasers
  - Broad range of light emission by changing dot size
  - Small active volume means smaller population inversion necessary for lasing. Leads to:
    - Less temperature dependence of threshold current density
    - Increase in gain (2-3 times larger than Q-well)
    - High frequency operation
    - More efficient laser

Quantum Dot Characteristics

- Threshold Current Density
- Gain
- Lasing Spectrum
- Chirp

Threshold Current Density (Jth)

- A single layer of Q-dots is enough to have lasing
- Typical values

Q-dot Material	Threshold Current	Temperature
InAs/InGaAs	12.7 A/cm^2	100 K
InGaAs	210 A/cm^2	293 K
InAs	11 A/cm^2	77 K

Temperature Stability of Threshold Current Density

- Great temperature stability
  - Characteristic T can increase up to a certain level and keep threshold current steady
  - InP Q-dot laser:
    - T=180 K J th=80 A/cm^2
  - InP Q-well laser:
    - T=60 K J th=80 A/cm^2

- Problem: Above this T, J th increases exponentially
  - Due to:
    - Inhomogeneous linewidth broadening
    - Carrier escape from wetting layer to waveguide region

Gain

- Material Gain strongly influences Jth and Modulation Bandwidth
- Exact value depends on Q-dot density and oscillator strength
- Typical values for max gain ~10^5 1/cm
- Q-well one order of magnitude less
- Problem: Maximum gain has operating temperature dependence which can cause level switching and hinder performance

Lasing Spectrum

- Single mode operation is possible
- Usually there is inhomogeneous broadening of the Q-dot gain spectrum
  - Allows for different sub sets of quantum dots to reach threshold independently
  - Multimode oscillation
- High power operation broadens spectrum as well since individual modes saturate in intensity
  - Leads to increase in output power carried by additional modes

Chirp

- Frequency chirp of lasers leads to broadening of the mode spectrum
  - Limits modulation rate
- Caused by refractive index change induced by carrier density
- Ideal Q-dot lasers would have no chirp, but realistically due to inhomogeneous broadening they do
- Good news is that small values of the linewidth enhancement factor (alpha) have been reported
  - Linewidth enhancement factor is an important characteristic in describing dynamics laser
  - Found to be much smaller than bulk lasers and comparable to Q-well lasers

Range of Light Emission

- Using different Q-dot structures scientists have achieved emission of light in the ranges of:
  - .9-1.1 um
  - 1.27-1.3 um
  - 1.9 um

Existing Quantum Dot Lasers

- 1300 nm lasers on InP substrate
  - Used in fiber optics
- 1300 Q-dot laser on GaAs substrate
  - Better eye safety
  - Large transmission distance
  - Smaller attenuation
- High power QD lasers
  - Recently explored
  - Its high T stability and low threshold lead to
    - Low temperature sensitivity of laser
    - Slightly larger wall plug efficiency than some Q-well lasers

Future Development of Q-dot Lasers

- Single Q-dot laser
  - Fabrication of Q-dot VCSEL with one dot
  - Threshold Current of about ~ 22 pA calculated
- Distributed Feedback Q-dot laser
  - Contain array of periodic Q-dots along cavity
  - Promise single mode emission
  - Low threshold and high power operation

Challenges for the future

- Advantages depend on dot characteristics
- Challenge is in forming high quality dots
  - Uniform size
  - Higher density

- Better understanding of:
  - Carrier confinement
  - Loss mechanisms
- Lead to many improvements of laser system
- Although Q-dot lasers are fairly new they provide new and very promising applications