Self-Assembled InAs Quantum Dots

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- What are semiconductors
- What are semiconductor quantum dots
- How do we make (grow) InAs dots
- What are some of the properties of these dots
Energy Levels in an Atom

http://cat.sckans.edu/physics/hydrogenic.htm
Band Formation

Figure 3-3. Formation of energy bands as a diamond crystal is formed by bringing together isolated carbon atoms. (From Electrons and Holes in Semiconductors, by W. Shockley, © 1950 by Litton Educational Publishing Co., Inc.; by permission of Van Nostrand Reinhold, Co., Inc.)
Potential and Kinetic Energy

Energy

Position (x)

Friction

No Friction

$V(x)$
Energy Bands

Conduction Band

Mostly empty states, with a few electrons

E\textsubscript{c}

Bandgap – No states

E\textsubscript{G}

E\textsubscript{G} > 6 eV insulator
E\textsubscript{G} < 3 eV semiconductor

Valence Band

Mostly full states, with a few “holes”

E\textsubscript{v}

Electron Kinetic Energy

Hole Kinetic Energy

Position (x)
Heterostructures

Quantum wells will confine carriers in 1 dimension. They are still free in the other two. To be “quantum” the well must be fairly thin – typically <10 or a few 10’s of nm, rarely more than 100nm.
Quantum Wells, Wires, and Dots

- Quantum wells
  - Carriers confined in one direction, free to move in the other 2
  - Usually build up structures in layers, and the confinement is along the “z” axis – surface normal
- Quantum wires
  - Carriers confined in two directions, free in only 1
  - Requires lateral patterning (in the plane)
- Quantum dots
  - Carriers confined in all three directions – sort of like in an atom (sometimes called artificial atoms, but the potential is not 1/r)
How small do we need our dot?

- No single answer – depends on application
- Want it “quantum” so must be small enough to have well-defined states
  - Simple criterion: Energy spacing between quantum levels (like 1S, 2S, etc. in a hydrogen atom) be larger than the thermal energy – kT
  - At room temperature (300K), kT=26meV
  - Spacing between levels: $\Delta E \sim 1/L^2$ where L is the length of a side of a “box” (L = well width)
  - $\Delta E$ for a 150 Å box in GaAs is ~75meV
What we want

GaAs

Or smaller!

AlGaAs all around outside

150 Å

150 Å

150 Å

150 Å
Solution-grown quantum dots (nanocrystals)

Size-Sorted Colloidal Nanocrystals
MBE Growth

Officially: MBE = “Molecular Beam Epitaxy”

Really: MBE = “Mega-Buck Evaporator”
MBE – Growth chamber and ovens
Vacuum Evaporation

• Why vacuum?
  - Stop reactions with air (Al oven at ~1400ºC)
  - Stop impurities from getting into sample

Vacuum chamber

sources

Si
Al
Ga
In
As

Pump
What’s special about MBE?

• Grow very slowly, ~1 atomic layer/second
  – Have very precise control over layer thickness and composition
    • Mechanical shutters in front of sources can be opened and closed in < 1 sec.
    • Accurately control temperatures of sources, which controls rate at which different species reach surface
  – Need very high purity (1 part in $10^{10}$)
Etched Pillars and Dots

Lithography, etching, and TEM by Axel Schrer
Etched Pillars after a Hurricane?

Lithography, etching, and TEM by Axel Schrer
Vertical quantum dots in a pillar

Stranski-Krastanow Growth

1 Monolayer InAs
≈ 1.7 Monolayer InAs
> 2 Monolayer InAs

ovens
Si
Al
Ga
In
As

GaAs
Stranski-Krastinow Growth I.

InAs DEPOSITION
GaAs SUBSTRATE

WETTING LAYER
~10 MONOLAYER

InAs

GaAs

First layer
Stranski-Krastinow Growth II.

GaAs SUBSTRATE

DOT NUCLEATION
~1.5 MONOLAYERS

InAs

GaAs

2-3 nm high

50-100 nm apart

15-20 nm across

FULLY FORMED DOTS
~2.0-2.5 MONOLAYERS
Quantum Dots on the Surface
Overgrowth

- Apparently defect-free overgrowth
  - Good optical properties
  - Good electrical properties
Photoluminescence

Shine light on sample, and see what light comes out

1. Create electron-hole pairs
2. Carriers find local potential minima
3. Carriers recombine, producing photons

\( h\nu > E_G \) (Visible)

\( h\nu < E_G \) (Near Infrared)
Electroluminescence and Dot Size

Electroluminescence at 80K

Intensity (Counts/Sec)

Energy (eV)
Applications of Quantum Dots

• Improving semiconductor diode lasers
  – Change wavelength with dot size
  – Lower threshold currents (improve efficiency)
  – Trap carriers to avoid defects (blue lasers and light-emitting diodes)

• Mid-infrared detectors (thermal imagers)
  – See objects by the heat they give off

• Mid-infrared lasers??
Low Threshold Quantum Dot Lasers

Laser is sort of like luminescence experiment

**But** – you need more occupied than unoccupied states at the energy of your photons

⇒ Lots of electrons and holes, so lots of current

1. First semiconductor lasers (1962) needed very high currents since so many states in the semiconductor – only worked at low temperature

2. Quantum well lasers (1970’s and 80’s) – fewer states and confine carriers, so need less current ⇒ first continuous room-temperature diode lasers

3. Quantum dot lasers (~2000) – now even fewer states and carriers easily trapped in dots ⇒ lower currents
Quantum Dots in Blue Lasers

• Blue and ultraviolet lasers (hν ~ 3 eV)
  – Make white LEDs similarly

• Need wide-bandgap semiconductors – GaN, AlN, InN, and their alloys
  – Materials very difficult to grow
  – Huge numbers of defects – eat electron-hole pairs without producing light 😞
  – Quantum dots (InGaN) trap carriers even better than the defects, and emit light 😊
Mid-infrared Emitters (Lasers?)

- Many molecules (like the ones in automobile exhaust) have resonances in the mid-infrared. Currently no inexpensive, reliable way to measure low concentrations of these molecules.
  - Need good mid-infrared lasers - dots?

Unipolar (just electrons) so only show conduction band
• Get IR emission
  – Still weak emission, even at liquid nitrogen temperature (77K)
  – Long way to go before a laser
Problems With Quantum Dots

- Size Non-Uniformity
- Disordered growth
- Difficulty accessing single dot
Vertical Strain Alignment

Cleaved-Edge Overgrowth

Scribe mark

GaAs

InGaAs

GaAs
Cleaved-Edge Overgrowth

GaAs

InGaAs

GaAs

Scribe mark

(100)

(110)
Cleaved-Edge Overgrowth

GaAs

InGaAs

GaAs

(100)

(110)
Cleaved-Edge Overgrowth

GaAs

InGaAs

GaAs

(100)

(110)
Cleaved-Edge Overgrowth

GaAs

InGaAs

GaAs
Growth on (110) GaAs
InAs on (110) GaAs

5K

[Graph showing photoluminescence (PL) intensity vs. energy (eV) with peaks at 1.3 eV.]

[Diagram showing layered structure of InAs and AlAs on GaAs substrate.]
AFM of (110) InAs QDs
Near Field Scanning Optical Microscopy (NSOM)

Intensity [a.u.]

Energy (eV)

5K

750 uW

200 uW

20 uW

5 uW

1 uW

330 nW
Power Dependence of Single QD PL

Intensity (a.u.) vs Energy (eV) for different power levels:
- 500 uW
- 200 uW
- 100 uW
- 50 uW
- 5 uW
- 1 uW
- 200 nW

Noteworth features:
- 2.3 meV
- 3.7 meV

Device diagrams show
- X
- X'
- X''

Temperature: 5K
Mapping of (110) QDs

E=1.3325eV

E=1.3583eV

E=1.3622eV

E=1.40085eV

5K
New First Growth Sample

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Composition</th>
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<tbody>
<tr>
<td>750 nm GaAs</td>
<td>750 nm</td>
<td>GaAs</td>
</tr>
<tr>
<td>250 nm GaAs</td>
<td>250 nm</td>
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<tr>
<td>AlAs/GaAs</td>
<td></td>
<td></td>
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</table>

Cleaved-Edge Growth

- AlAs
- InAs
- InAs

Substrate
10nm GaAs Buffer, 0.55nm InAs

2.2 nm AlAs

10nm GaAs

0.55nm InAs

250 nm

20 nm
Future Applications of Quantum Dots

• Single photon emitters ("single photon on demand")
  – Needed for quantum cryptography – away to transmit information that is impossible to decode

• Spin "Qubits" for quantum computer

• Single-electron memories