Semiconductor Quantum Dots

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Outline

Introduction

Different types of Quantum Dots (QD)

Photoluminescence spectroscopy of QDs

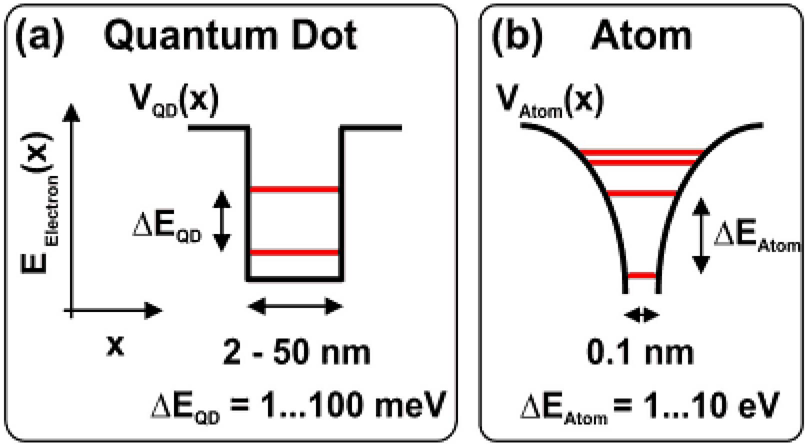
Coherent optical control of exciton in QDs

Introduction

A semiconductor QD is a simple nanostructure which is confined in all three dimensions that normally contains thousands to hundreds of thousand atoms.

They are generally composed of atoms from groups II and VI elements (e.g. CdSe and CdTe) or groups III and V elements (e.g. InP and InAs) of the periodic table.

Their three dimensional confinement is responsible for their unique optical and electronic properties. They exhibit quantized energy levels like an atom.



Introduction

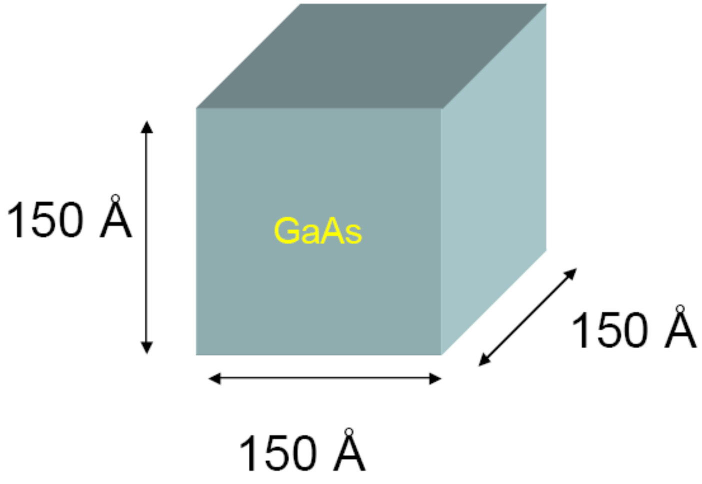
How small do we need our dot?

Energy spacing between quantum levels (like 1S, 2S, etc. in a hydrogen atom) be larger than the thermal energy – kT

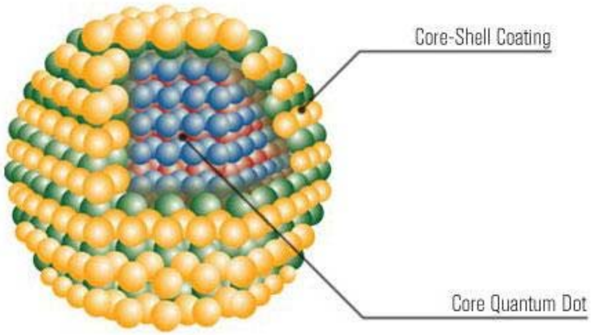
At room temperature (300K), kT=26meV

ΔE for a 150 Å box in GaAs is ~75meV

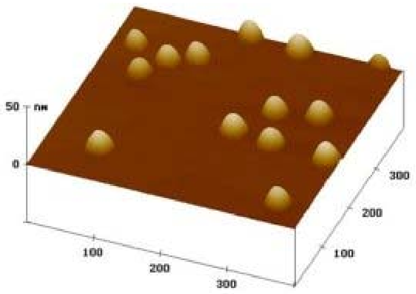
Or smaller!



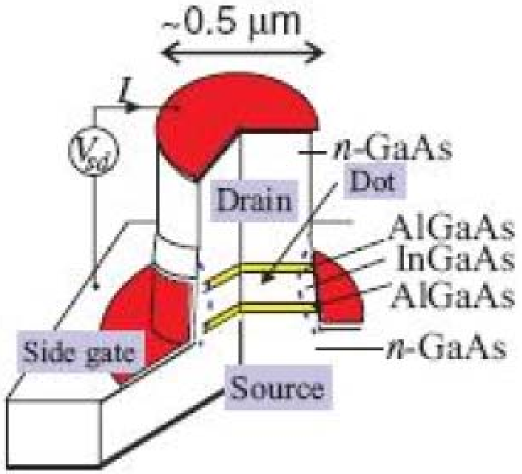
Different types of QDs



Nanocrytal QDs



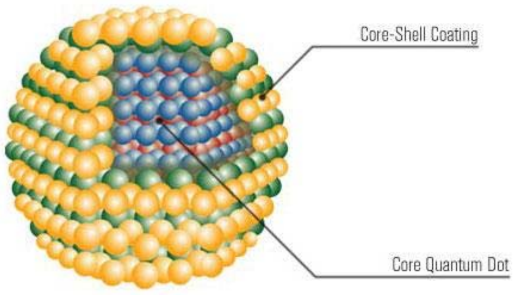
Self-assembled QDs



Vertical QD in a Pillar

Nanocrytal QDs

Nanoparticle which consists of only a few hundred to a few hundred thousand atoms can be synthesized by colloidal chemistry.
They are often called nanocrystal QDs. (NQDs)

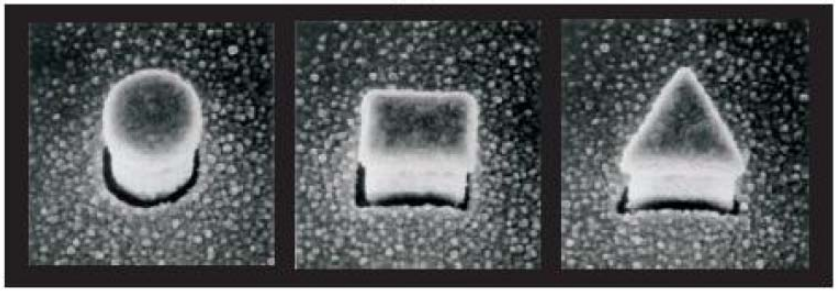


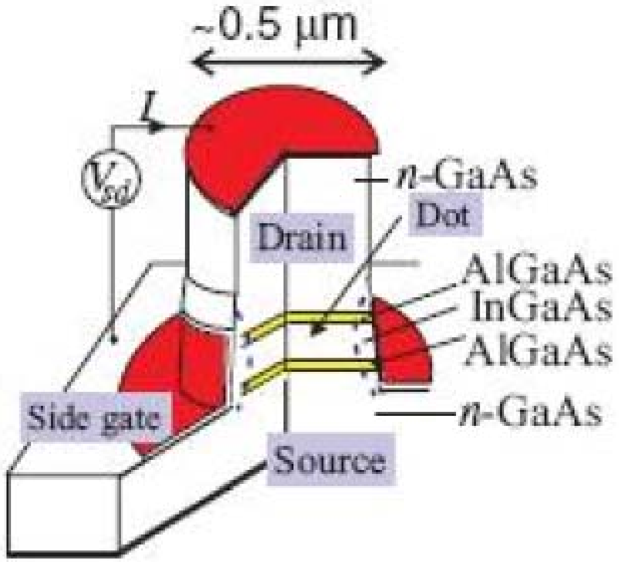
CdSe NQDs
A dot of radius 2.4 nm has an energy gap of about 2 eV and emits a orange color.

A dot of radius 0.9 nm has an energy gap of about 2.7 eV and emits a blue color.

Vertical QDs in a Pillar

Current nanofabrication technology(lithography, etching) allows us to precisely control the size and shape of the dots.





The diameter of the dot is a few hundred nanometers and its thickness is about 10 nm. The dot is sandwiched between two non-conducting barrier layers, which separate it from conducting material above and below.

Vertical QDs in a Pillar

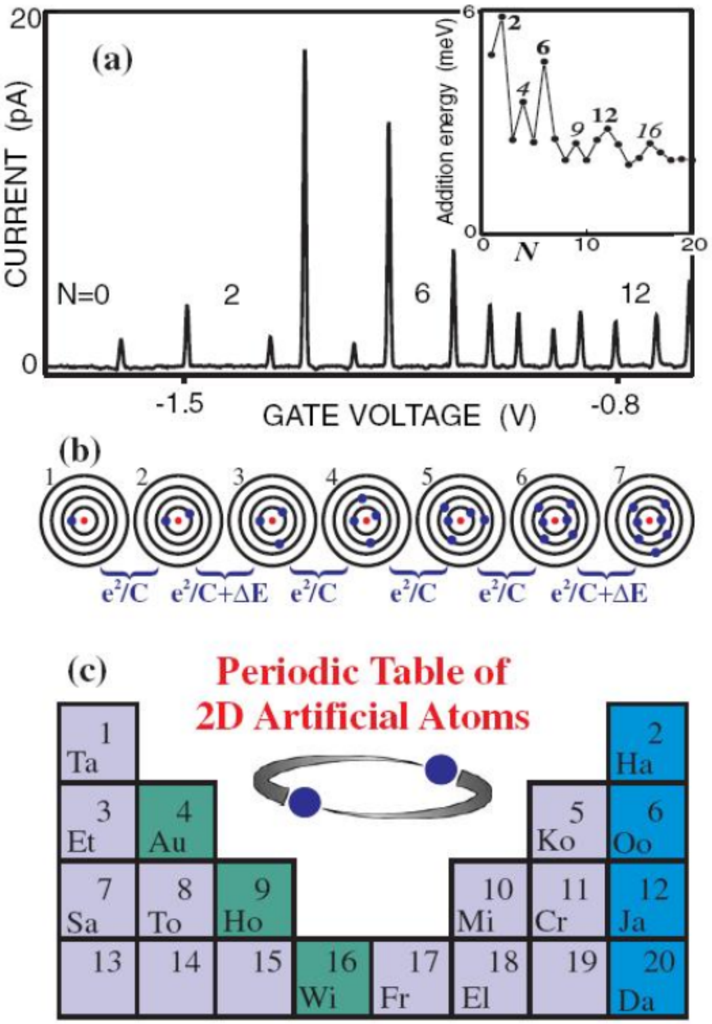
Coulomb blockade

By changing gate voltage, we can control the number of the electrons in the QD.

Analogy for real atoms

QDs are suitable for experiments that cannot be carried out in atomic physics.

A magnetic flux-quantum in an atom typically requires a B-field as high as 106 T, whereas for dots this is of order 1 T.

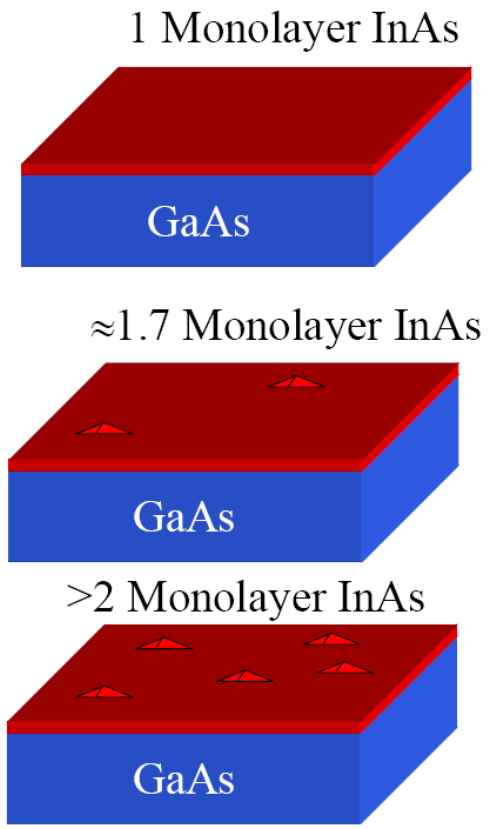


Self-assembled QDs

Self-assembled quantum dots are fabricated by molecular beam epitaxy (MBE), when a material is grown on a substrate to which it is not lattice matched.

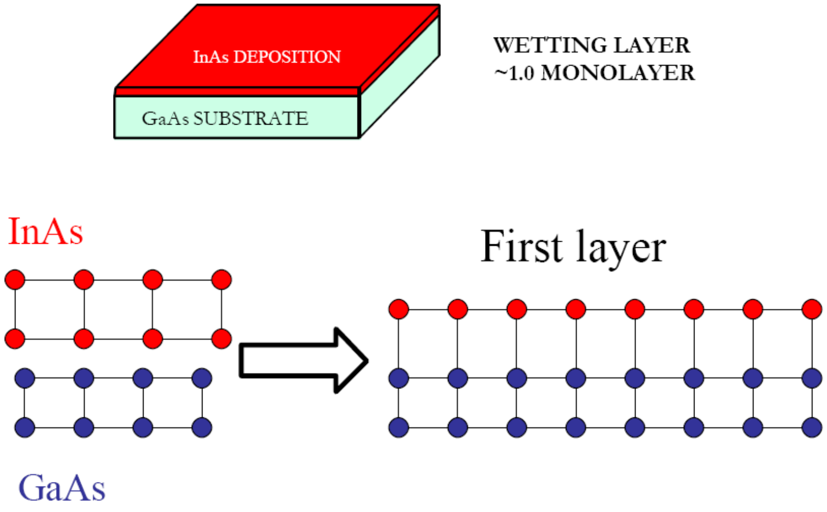
This growth mode is known as Stranski-Krastanov growth (SK growth).

Also known as 'layer-plus-island growth'.

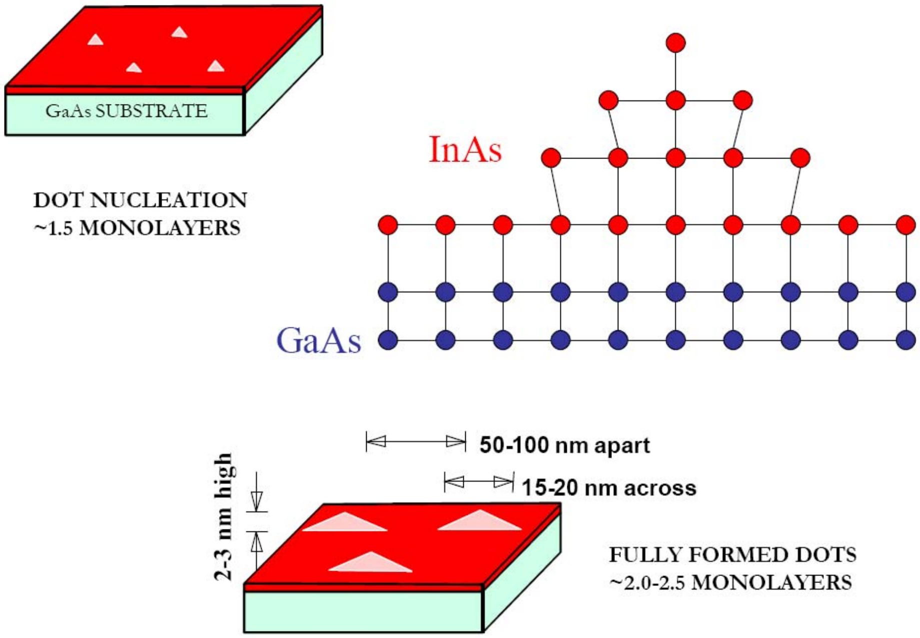


Self-assembled QDs

Stranski-Krastanov growth I



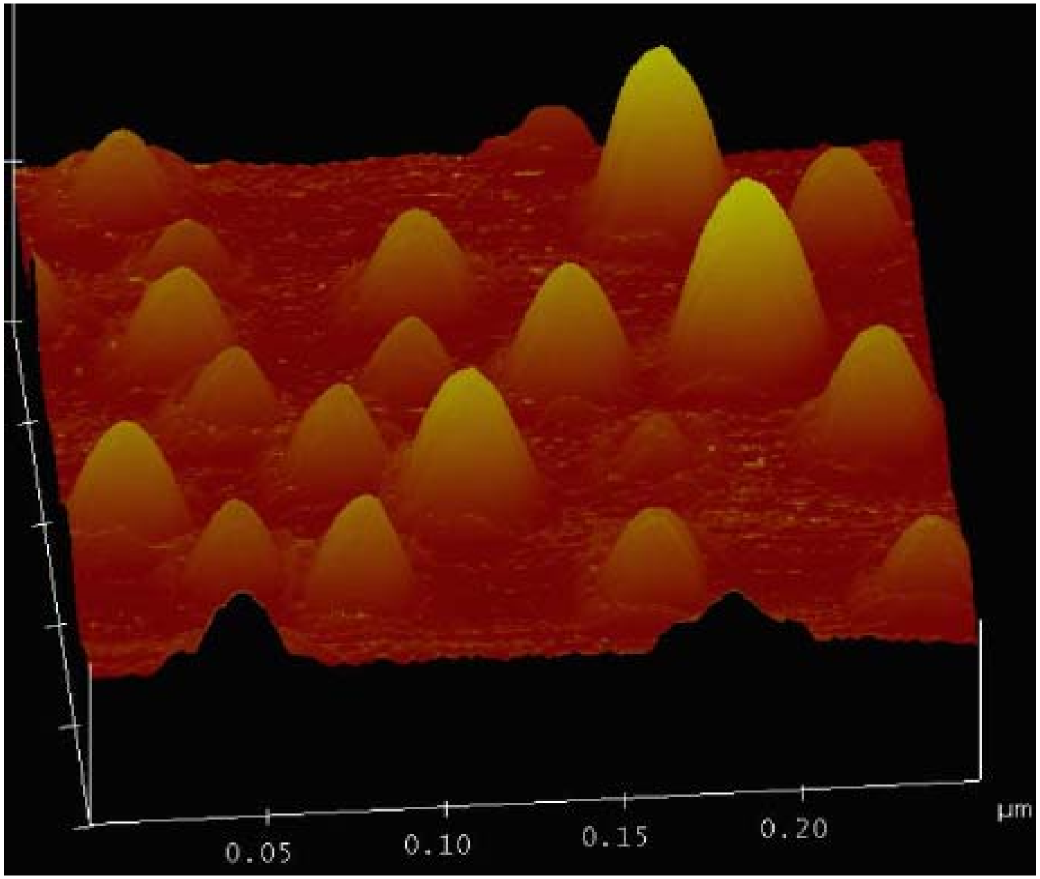
Stranski-Krastanov growth II



Self-assembled QDs

Main Limitations

- Size Non-Uniformity
- Disordered growth
- Difficulty accessing single dot

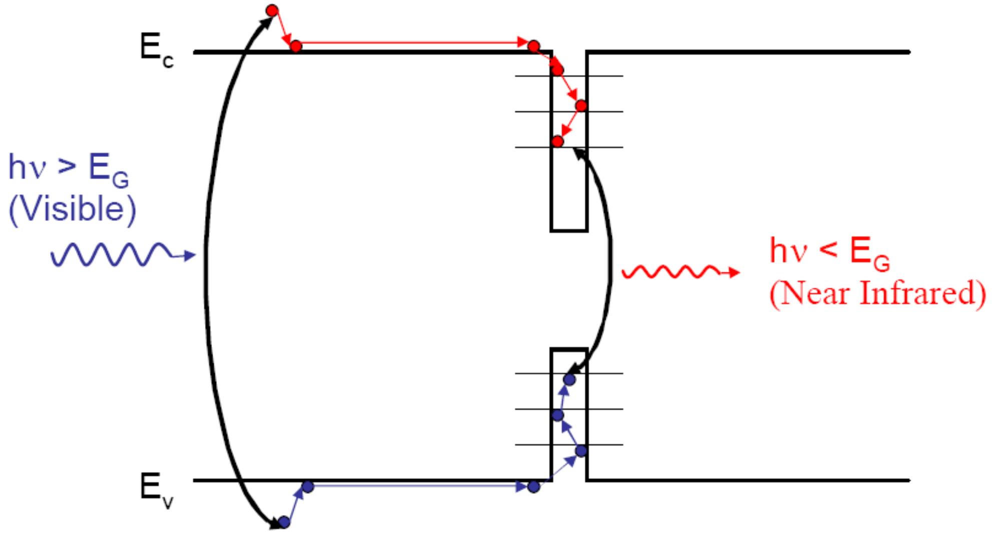


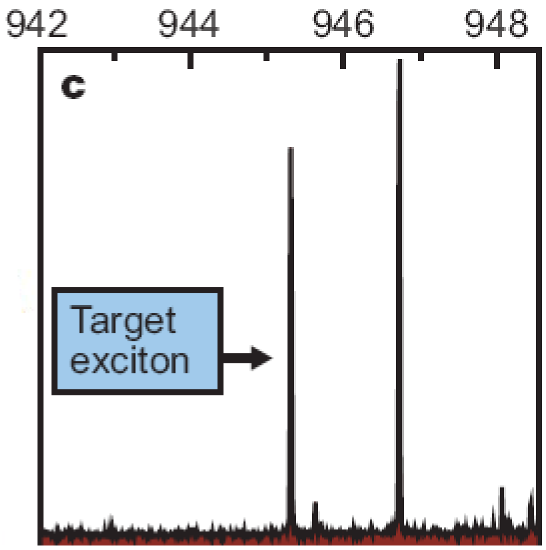
Photoluminescence

Photoluminescence (PL) spectroscopy

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





Photoluminescence

In order to study individual QD, it is necessary to reduce the size of the region in which the PL is or from which it is detected.

1. Focus laser spot
2. Shrink the size of the sample

Photoluminescence excitation (PLE) spectroscopy

The laser is scanned in frequency until it excites a local excited state of a QD and produces a single PL line.

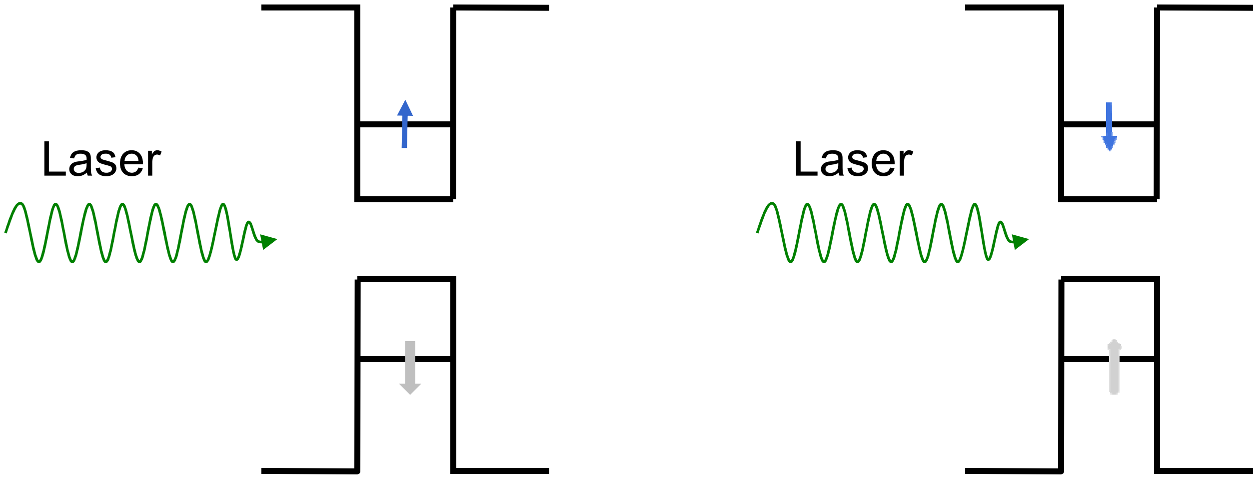
Reduce the numbers of QDs that contribute to PL line.

PLE gives the excited state spectrum of a quantum dot and can be performed on each of the sharp lines in a PL spectrum with higher precision.

Excitons

An exciton can be regarded as a well-defined single quasi-particle containing an electron and a hole in semiconductor. Exciton can be excited by external laser.

Selection Rules in GaAs Quantum Dots



σ_- **polarized laser**

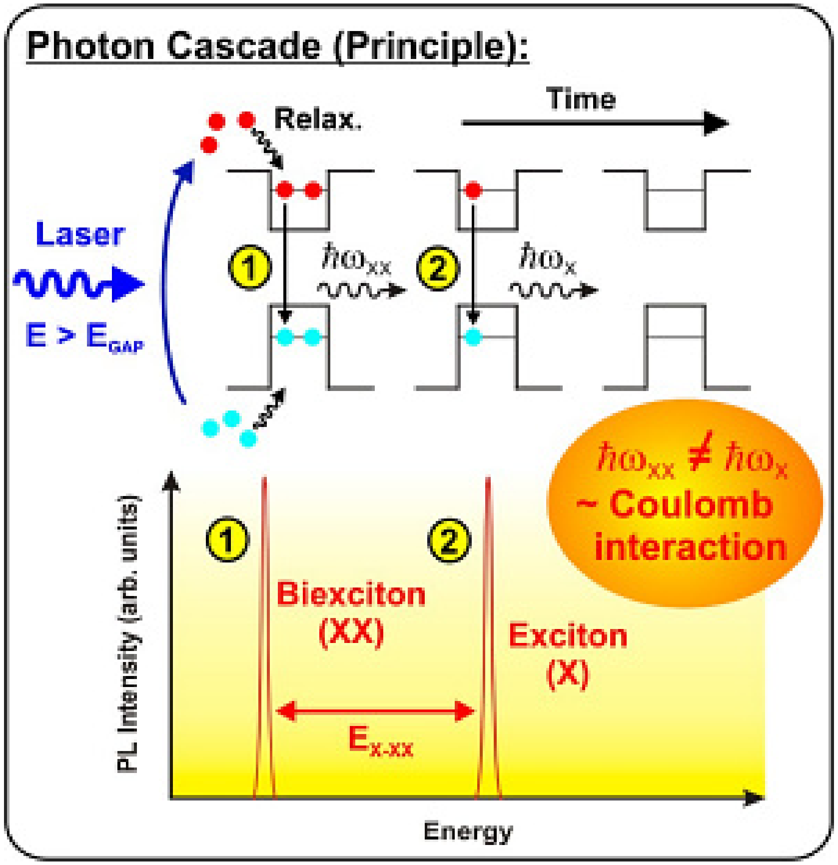
σ_+ **polarized laser**

Biexcitons

In addition to exciton, biexciton also exists in QDs. Under appropriate excitation conditions the s-shells can be filled with two electron-hole pairs.

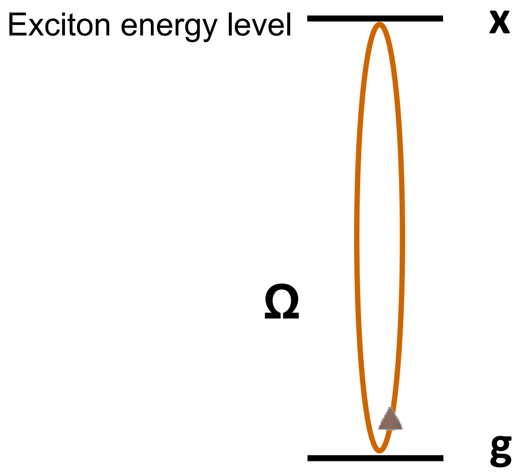
Due to both the attractive (e-h) and repulsive (e-e, h-h) Coulomb interaction between these carrier pairs the “biexciton” decay typically deviates in energy from the single exciton state.

This energy shift is often referred to as the biexciton binding energy.



Rabi Oscillation

Coherent Rabi Oscillation



$$P_g(t) = \cos^2(\Omega t/2)$$

$$P_x(t) = \sin^2(\Omega t/2)$$

$$\Omega t = \pi$$

A π-pulse corresponds to one-half of a Rabi oscillation.

A π-pulse can be used to fully invert a two-level system. In the case of excitons in quantum dots, a π -pulse represents the creation of an exciton with unity probability.

Control of the state of excitation of an individual quantum dot

Pump-probe

Summary

Nanocrystal Quantum Dots

- Improving semiconductor diode lasers

Vertical Quantum Dots

- Artificial atoms

Self-assembled Quantum Dots

- Optical control of exciton states

PL, PLE and pump-probe