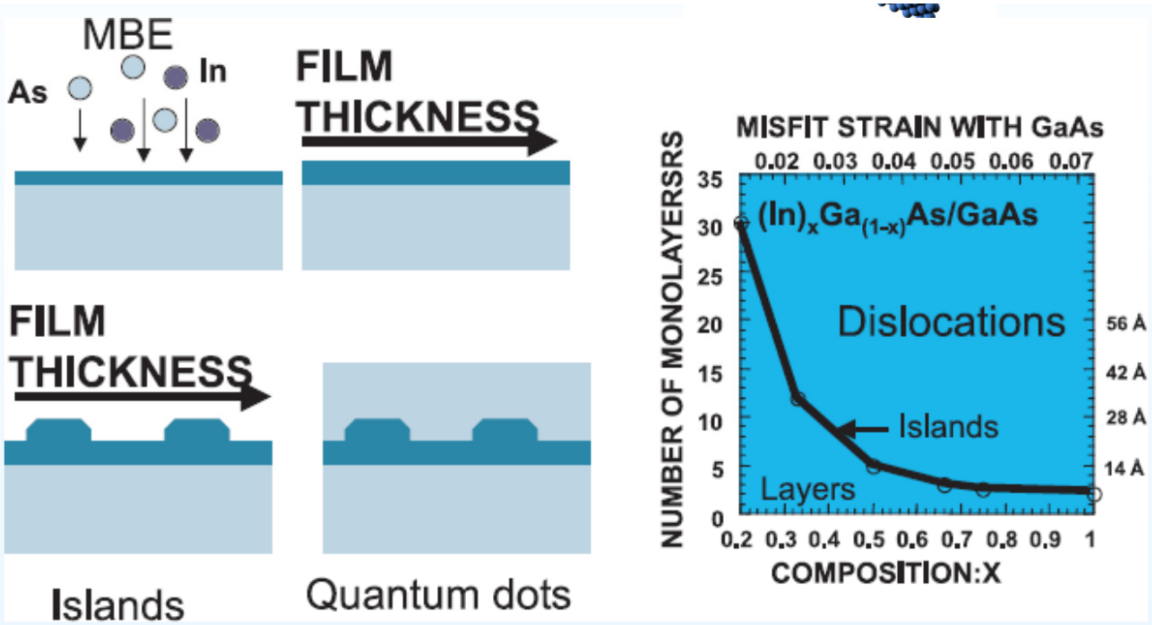
In This Lecture:

- Excitons in Quantum Dots
- Optical Spin Injection
- Application: Biexciton cascade

Self-Assembled Quantum Dots

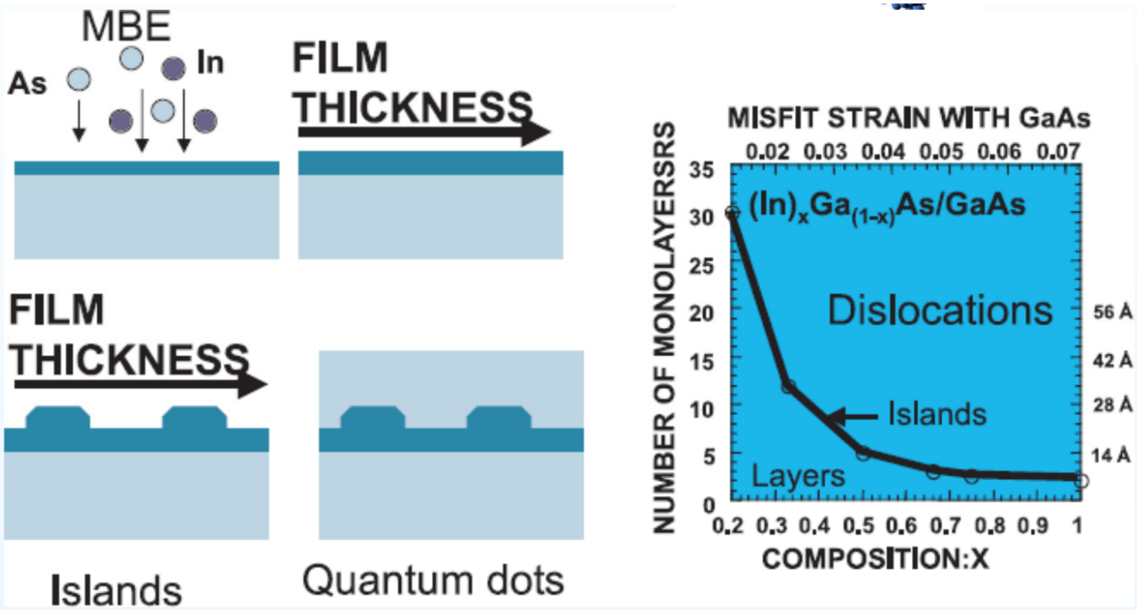


Ref: P. M. Petroff, in *Single Quantum Dots*, P. Michler (ed.) (Springer, Berlin, 2003)

Procedure:

- In and As atoms falling on a clean GaAs substrate initiate the wetting layer
- 7% lattice mismatch between InAs & GaAs, build up in strain & surface energy
- Onset of island growth mode at a critical thickness
- Increasing the film thickness further introduces misfit dislocations (undesired)

Self-Assembled Quantum Dots

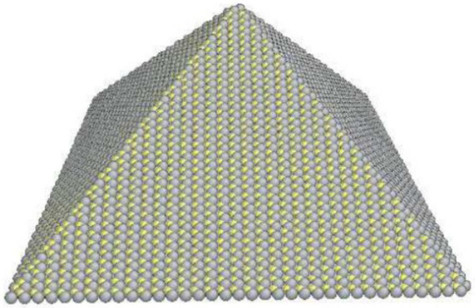


Ref: P. M. Petroff, in *Single Quantum Dots*, P. Michler (ed.) (Springer, Berlin, 2003)

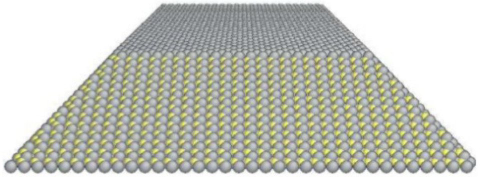
Advantages:

- Smooth defect free epitaxial atomic layers (high quantum efficiency)
- Low lateral QD density (ease in isolating suitable QD)
- Ease in vertical stacking & alignment (coupled QDs)
- Well characterized: charge, exciton, spin dynamics

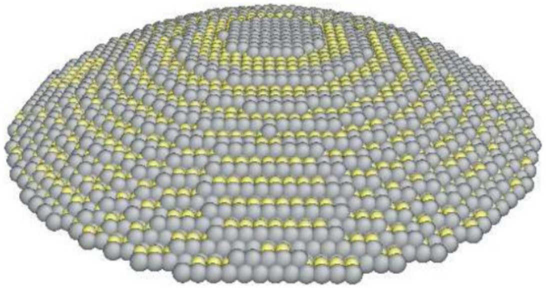
Self-Assembled Quantum Dots



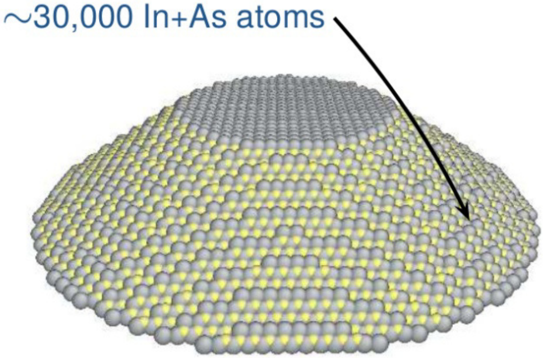
$\{101\}$-facetted Pyramid on (001)



Truncated Pyramid on (001)

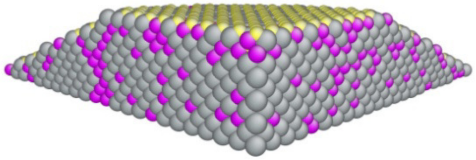


Lens on (001)

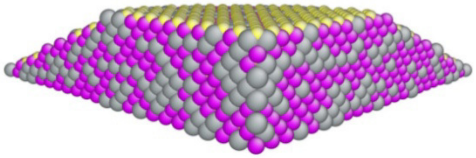


~30,000 In+As atoms

Truncated Cone on (001)

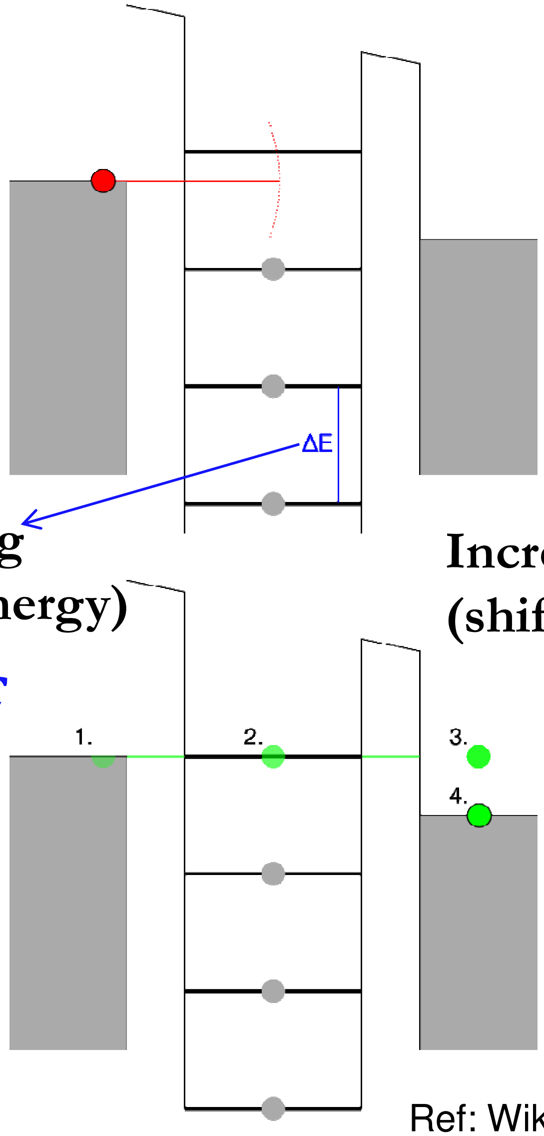


In$_{0.7}$Ga$_{0.3}$As



In$_{0.4}$Ga$_{0.6}$As

Coulomb Blockade [through tunnel barriers]



Level spacing
(Charging energy)

$\Delta E = e^2/2C$

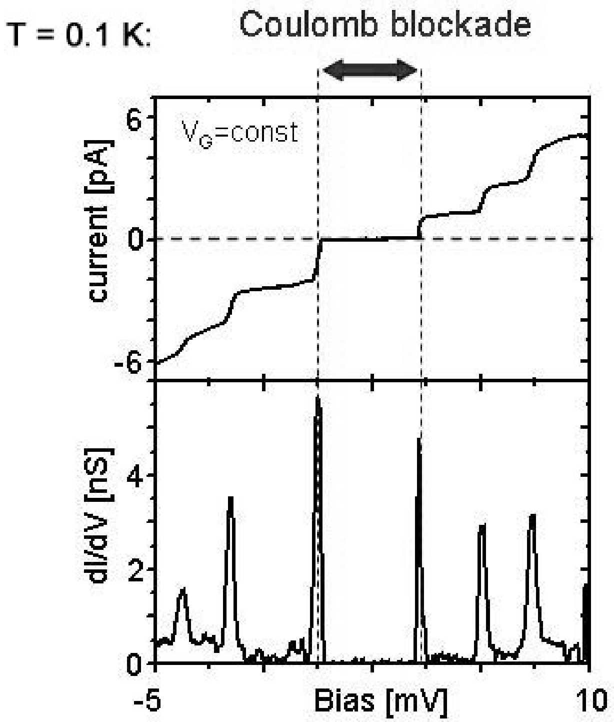
Blockade

Increase gate bias
(shift the levels)

No-blockade

(Resonant tunneling)

Ref: Wikipedia



Ref: Ralph Group, Cornell U.

Coulomb Blockade vs Excitons in QDs

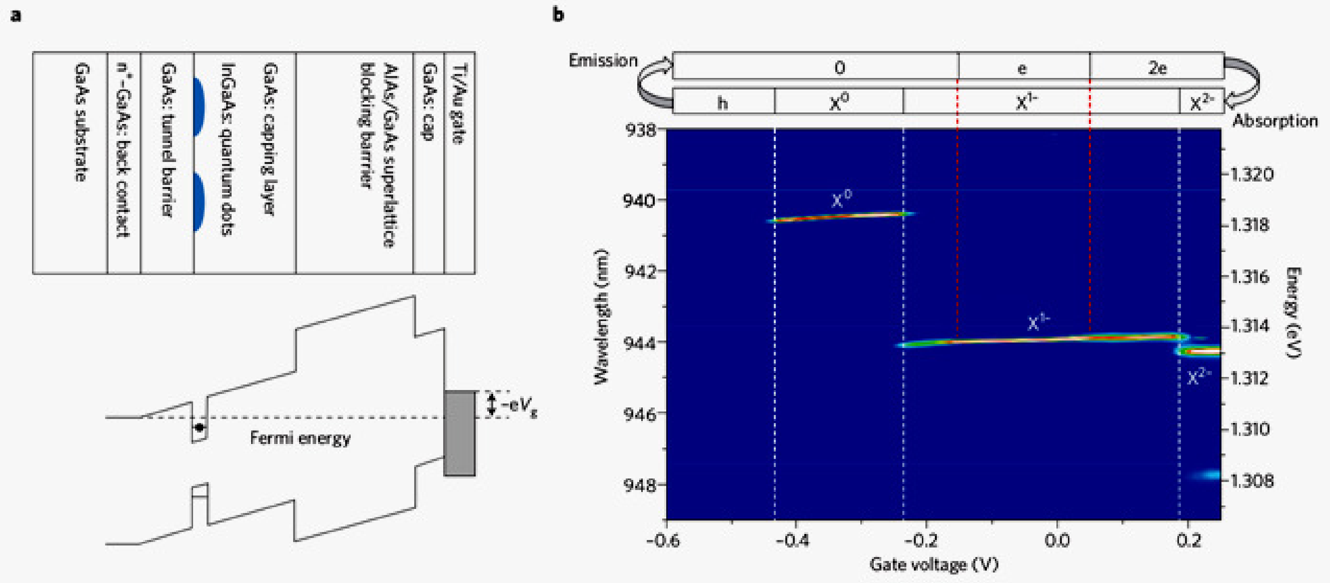
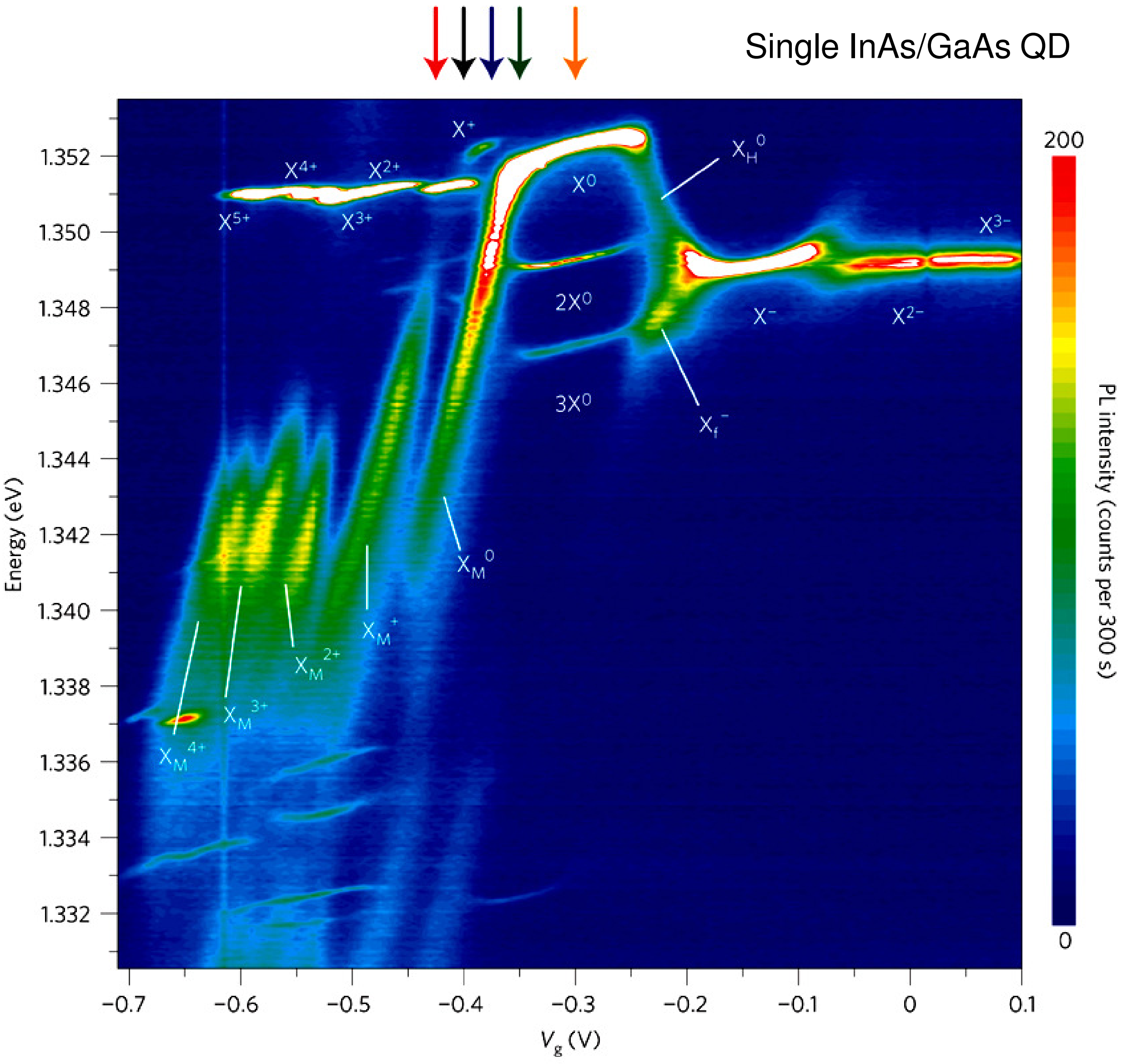


Figure 2 | Coulomb blockade of a single quantum dot. a, Layer structure of a typical heterostructure for experiments controlling the charge state of a quantum dot (top). A layer of self-assembled quantum dots is embedded in a vertical tunnelling structure. The quantum dots are in tunnel contact with the Fermi sea in the n^+ layer; the blocking barrier prevents current flow to the surface; a Schottky gate on the surface allows control of the vertical electric field. Typically, the tunnel barrier (GaAs) is 12–40 nm thick, the capping layer 10–150 nm thick, blocking barrier >100 nm thick and the Schottky gate is a semi-transparent metal layer, for example, 5–10 nm of Ti/Au. A voltage applied to the gate, V_g, tunes the energy of the first confined electron level relative to the Fermi energy as shown schematically in the band diagram (bottom). At low temperature and large electric field, the quantum dot conduction level lies above the Fermi energy and is therefore unoccupied; when the conduction level lies below the Fermi energy but close to it (shown), the conduction level is singly occupied (shown); at more positive V_g it is doubly occupied. **b**, The photoluminescence from a single quantum dot in a vertical tunnelling structure is shown as a function of V_g at a temperature of 4.2 K. The steps in the photoluminescence energy correspond to charging events. X^0 refers to the neutral exciton (an electron–hole pair); X^{1-} to the negatively charged trion (a two electron–one hole complex); X^{2-} the doubly charged exciton (a three electron–one hole complex). Note that the charging event without a hole, $|0\rangle \rightarrow |e\rangle$, takes place at slightly more positive V_g than the charging event with a hole, $|X^0\rangle \rightarrow |X^{1-}\rangle$, on account of the Coulomb energies: the electron–hole on-site Coulomb energy is larger than the electron–electron on-site Coulomb energy. Conversely, the $|e\rangle \rightarrow |2e\rangle$ charging event takes place at more negative V_g than the $|X^{1-}\rangle \rightarrow |X^{2-}\rangle$ charging event as the X^{2-} state has a total of three electrons, the 'third' forced to occupy the first excited conduction level by the Pauli principle. The main features in the photoluminescence characterization correspond to charging events in the initial state, the exciton state (white dashed lines). However, charging events in the final state are revealed by hybridization effects in the X^{1-} plateau (red dashed lines)[102]. Probing a single spin with resonant laser excitation involves working in the V_g window defined by the two dashed red lines. Experimental data in panel **b** provided courtesy of Paul Dalgarno.

Ref: Warburton, Nature Materials 2014

A zoo of excitons in a single QD



Single InAs/GaAs QD

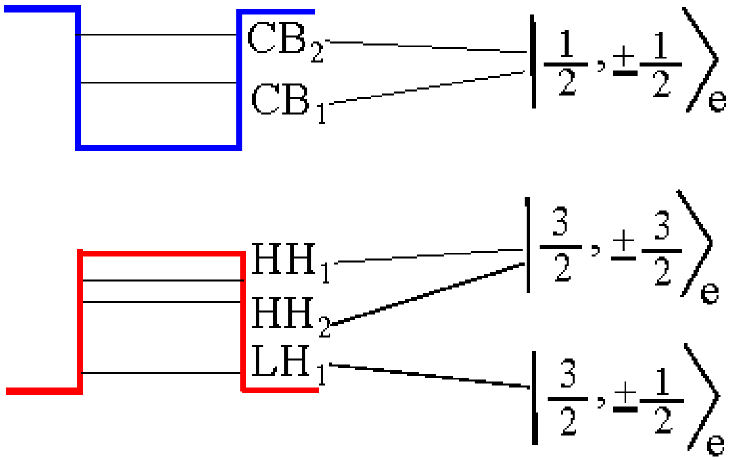
Ref: Kleemens, Nature Physics 2010

How to control spin with light?

- **Using the conservation of angular momentum (selection rules)**

First, consider the single-particle states [in electron picture]:

[Assume a small magnetic field that splits spin degeneracies]

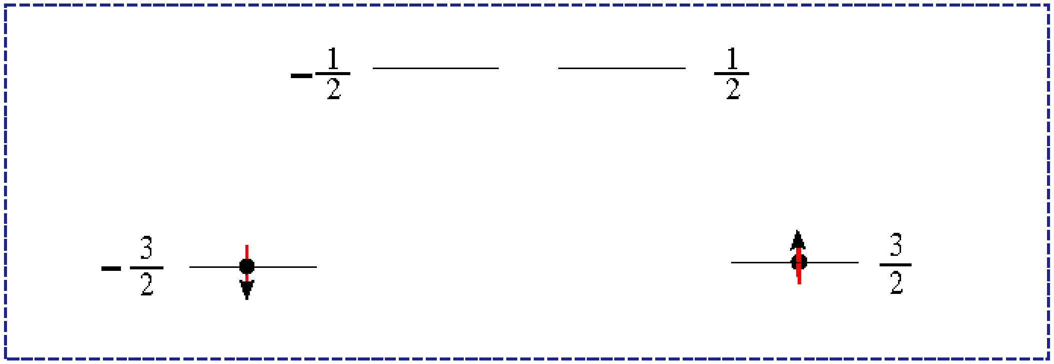


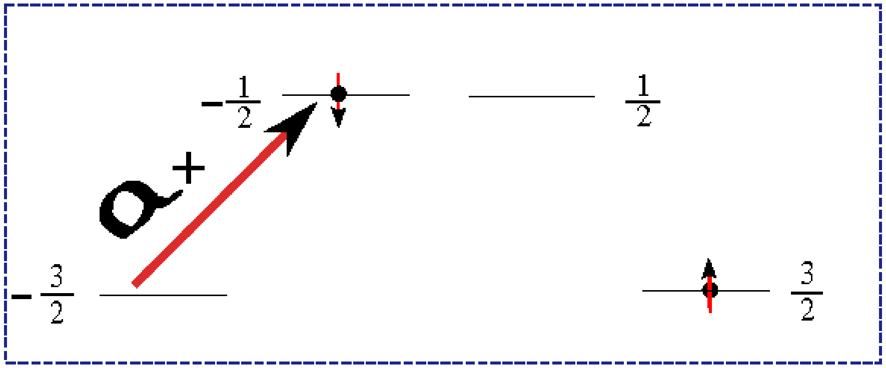
How to control spin with light?

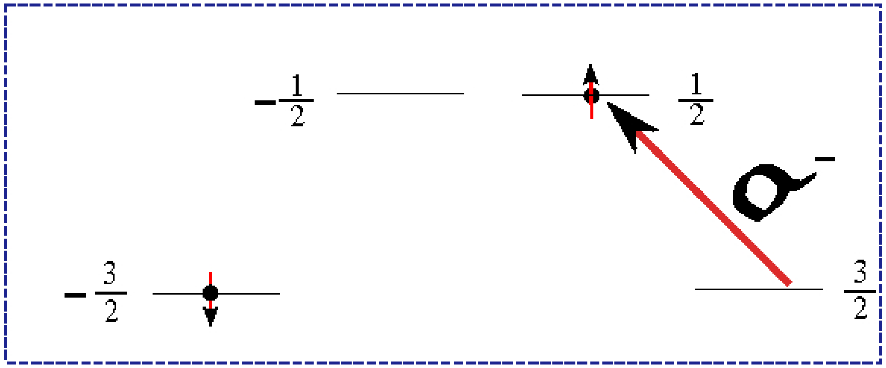
Using the conservation of angular momentum (selection rules)

Next, consider allowed transitions for circularly-polarized light: $\underbrace{\sigma^+ \;/\; \sigma^-}_{\text{Carries ang. mom. } +\hbar \,/\, -\hbar \text{ along the quantization axis}}$

[In electron picture]

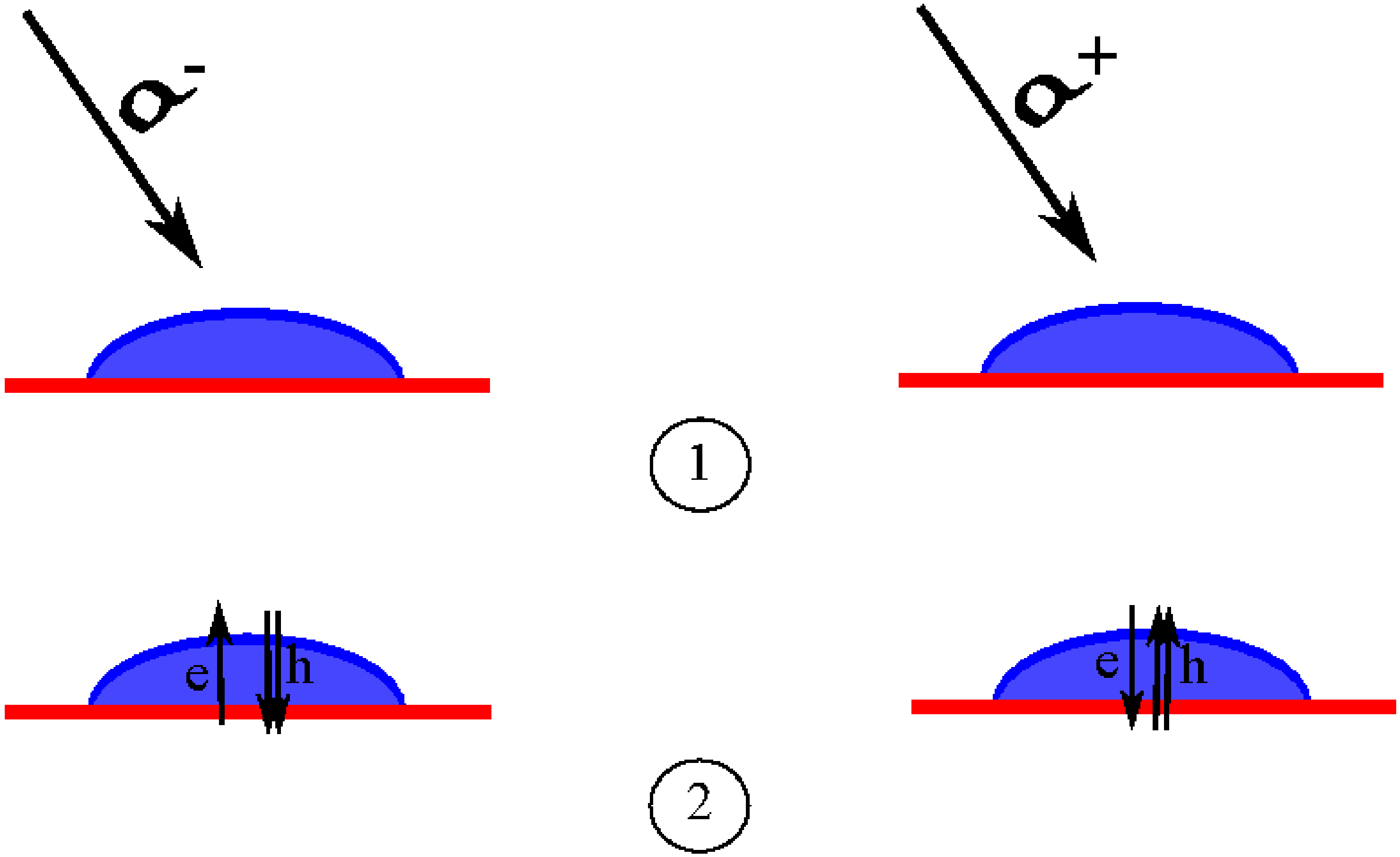






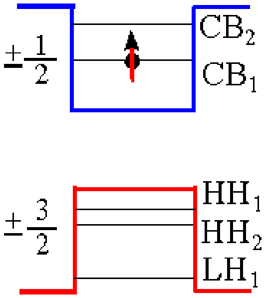
How to control spin with light?

In summary, for HH-CB resonant illumination we know what electron spin orientation will be injected to the CB of the QD

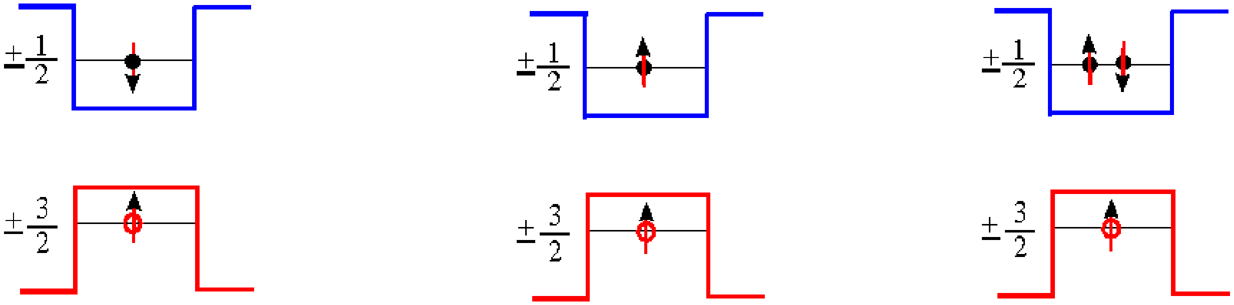


Basic exciton family in QDs

[In electron-hole picture]

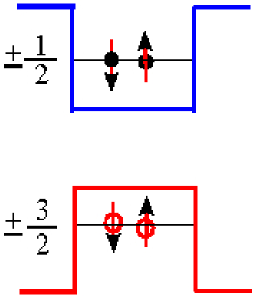


Single-Particle



(bright) (dark) (charged)

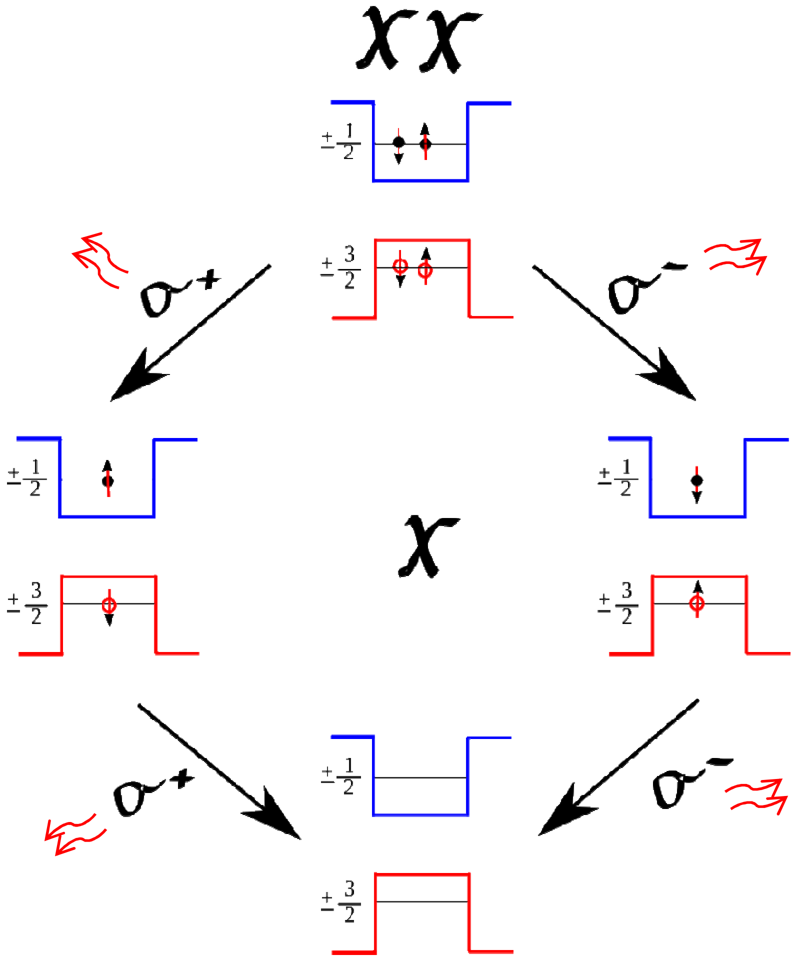
Exciton



Biexciton

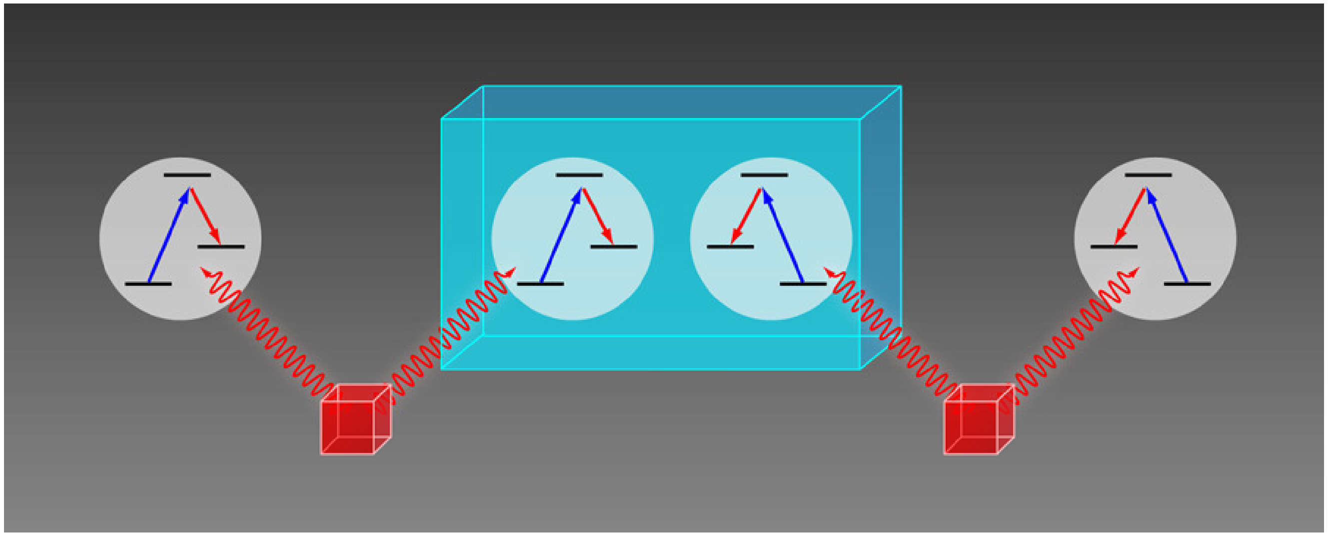
For InAs QDs:
$E_X \sim$ 20-30 meV,
$E_{XX} \sim$ 4 meV

An application: Biexciton Cascade



Entangled Photon pairs: $$\frac{1}{\sqrt{2}}\left[|\sigma^-\rangle_{XX}\otimes|\sigma^+\rangle_{X}+|\sigma^+\rangle_{XX}\otimes|\sigma^-\rangle_{X}\right]$$

Need for Entangled Photon Pairs



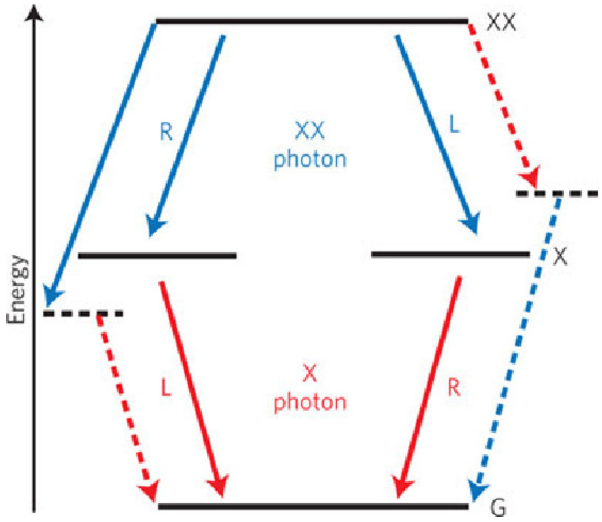
Ref: physics.aps.org

- Quantum repeaters for long distance quantum communications (say, QKD)
- Several quantum computations protocols
- Entanglement swapping / quantum teleportation
- High degree of entanglement is required
- Frequency splitting between two arms should be smaller than radiative decay rate

Entangled Photon Pair Production in QDs

Biexciton cascade has its own **technical difficulties:**

- QD elongation and strain cause in-plane asymmetry of the exciton wave function
- Hybridizes and splits the bright exciton spin states via the exchange interaction
- Two photons become collinearly polarized (either H or V)
- Their "colors" are fully correlated with their polarizations
- From the colors "which-way" information leaks out
- Destroys the entanglement between the two now-distinguishable decay paths
- Spectral filtering can erase "which-way" information, restoring entanglement



D. Gershoni, Nat. Photon. **4, 271 (2010)**