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Quantum confinement

- ***When the length of a semiconductor is reduced to the same order as the exciton radius, i.e., to a few nanometers, quantum confinement effect occurs and the exciton properties are modified. Depending on the dimension of the confinement, three kinds of confined structures are defined: quantum well (QW), quantum wire (QR) and quantum dot (QD)***

- ✓ The reduction in dimensionality produced by confining electrons (or holes) to a thin semiconductor layer leads to a dramatic change in their behavior.
- ✓ This principle can be developed by further reducing the dimensionality of the electron's environment from a two-dimensional quantum well to a one -dimensional quantum wire and eventually to a zero-dimensional quantum dot.
- ✓ The dimensionality refers to the number of degrees of freedom in the electron momentum ; in fact, within a quantum wire , the electron is confined across two directions, rather than just the one in a quantum well and so therefore reducing the degrees of freedom to one.
- ✓ In a quantum dot, the electron is confined in all three dimensions, thus reducing the degrees of freedom to zero.
- ✓ If the number of degrees of freedom are labeled as D_f and the number of directions of confinement are labeled as D_c then clearly:

$$\mathbf{D_f + D_c = 3}$$

Structure	Degree of Confinement (D_c)	Degree of freedom (D_f)
Bulk Material	0D	3D
Quantum Well	1D	2D
Quantum Wire	2D	1D
Quantum Dot	3D	0D

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Exciton Bohr Radius and Quantum Confinement

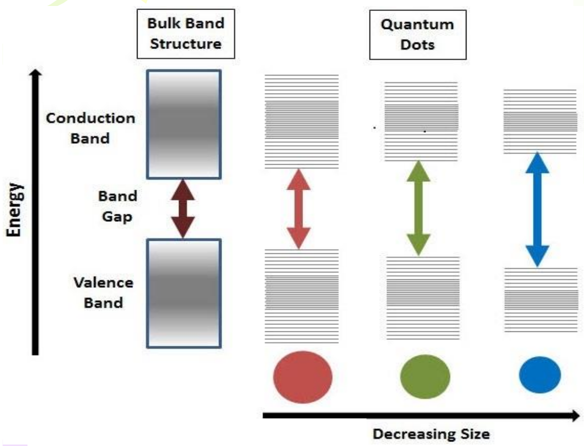
Bohr Radius (1913):

The most probable distance between the proton and electron in a hydrogen atom in its

Excitons are coupled electron-hole pairs via Coulomb attraction

$$a_0 = \frac{4\pi\varepsilon_0\hbar^2}{m_e e^2} = 0.529 \text{ Å}$$

$$a_{\text{exciton}} = \frac{a_0\varepsilon}{m^* / m_e}$$



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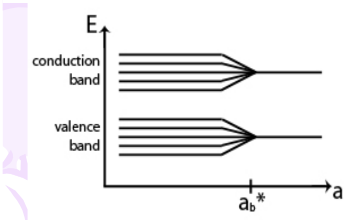
splitting of energy levels in quantum dots due to the quantum confinement effect, semiconductor band gap increases with decrease in size of the nanocrystal.



Quantum confinement of electronic particles in nanocrystals produces unique optical and electronic properties that have the potential to enhance the power conversion efficiency of solar cells for photovoltaic.

Quantum confinement of different nanostructures:

- ***Nanostructured materials are those with at least one dimension falling in nanometer scale, and include nanoparticles (including quantum dots, when exhibiting quantum effects), nanorodes and nanowires, thin films, and bulk materials made of nanoscale building blocks or consisting of nanoscale structures.***

In general, nanomaterials have extremely small size which having at least one dimension 100 nm or less.

In terms of directions of confinements, nanomaterials can be nanoscale in one dimension (eg. surface films), two dimensions (eg. strands or fibres), or three dimensions (eg. particles).

In terms of degree of freedom, Siegel classified the nanostructured materials as Zero dimensional (quantum dot), one dimensional (quantum wire), two dimensional (quantum well), three dimensional (bulk system) nanostructures as shown in the figure 1.

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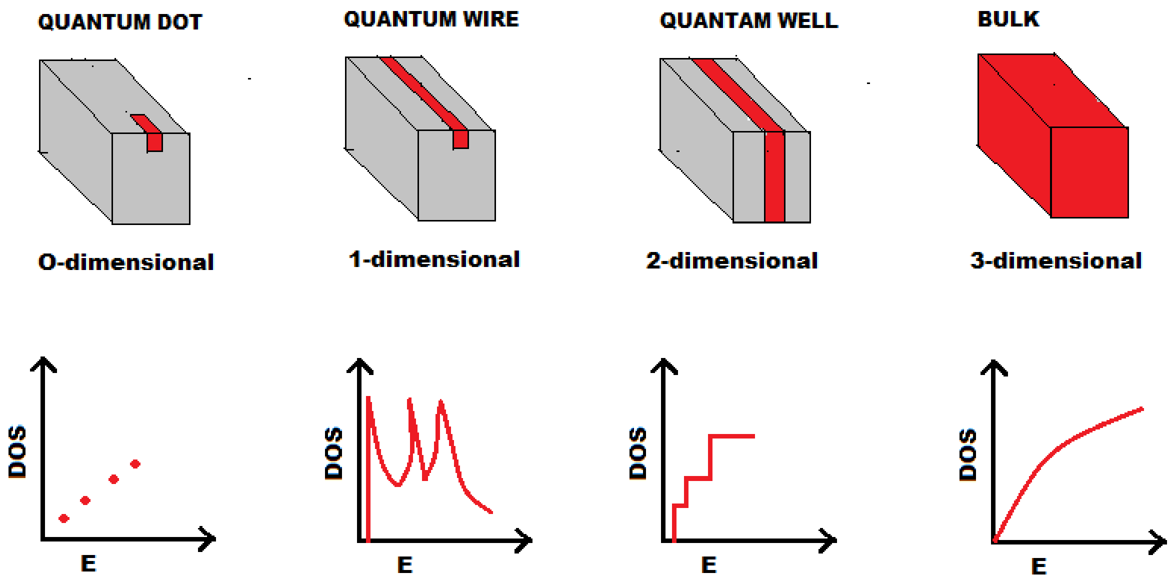

Figure 1: Quantum confinement of different nanostructures as 0-D, 1-D, 2-D and 3-D with their density of states (DOS) effects.

Zero-dimensional nanostructures:

- ✓ Zero dimensional nanostructure is called quantum dot (QD) nanocrystal. Generally, nanocrystal is a semiconductor crystal whose size is on the order of just a few nanometers.
- ✓ They contain anywhere from 100 to 1,000 electrons and range from 2 to 10 nanometers, or 10 to 50 atoms in diameter. QDs are unique because of their size and properties.
- ✓ Almost all materials system including metal, insulators and semiconductors show size dependent electronic or optical properties in the quantum size regime.
- ✓ Among these, the modification in the energy band gap of semiconductors is the most attractive one because of the fundamental as well as technological importance.
- ✓ Semiconductors with widely tunable energy band gap are considered to be the materials for next generation flat panel displays, photovoltaic, optoelectronic devices, laser, sensors, photonic band gap devices, etc.

One-dimensional nanostructures:

- ✓ One-dimensional nanostructures are called nanowires.

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- ✓ Nanowires are attracting much interest from those seeking to apply nanotechnology especially in solid-state electronics and diagnosis tool in medical sciences.

- ✓ Unlike other low-dimensional systems, nanowires have two quantum-confined directions but one unconfined direction (degree of freedom) available for electrical conduction.

- ✓ This makes nanowires to be used in applications where electrical conduction, rather than tunneling transport, is required.

Two-dimensional nanostructures:

- ✓ Two-dimensional nanostructure is referred as quantum well in nanoscience and nanotechnology.

- ✓ A quantum well is a particular kind of heterostructure in which one thin "well" layer is surrounded (sandwiched) by two "barrier" layers.

- ✓ Both electrons and holes perceive lower energy in the "well" layer, hence the name (by analogy with a "potential well").

- ✓ This layer, in which both electrons and holes are confined, is so thin (typically about 100 Å, or about 40 atomic layers) that we cannot neglect the fact that the electron and hole are both waves.

- ✓ In fact, the allowed states in this structure correspond to standing waves in the direction perpendicular to the layers. Because only particular waves are standing waves, the system is quantized, hence the name "quantum well".

- ✓ Quantum wells are thin layered semiconductor structures in which we can observe and control many quantum mechanical effects.

- ✓ They can be made to a high degree of precision by modern epitaxial crystal growth techniques.