Quantum Confinement

Quantum Confinement is the spatial confinement of electron-hole pairs (excitons) in one or more dimensions within a material. When one or more of the dimensions of a solid are reduced sufficiently, its characteristics notably depart from those of the bulk solid.

The confinement of particles, usually electrons or holes, to a lowdimensional (nano)structure leads to a dramatic change in their behaviour and to the manifestation of size effects that usually fall into the category of **quantum-size effects**.

One of the most immediate observations when reducing the size of materials to the nanometer scale is the confinement in the movement of electrons due to the quantum confinement effect. This leads to discretization of electron energy levels depending on the confinement size of the material.

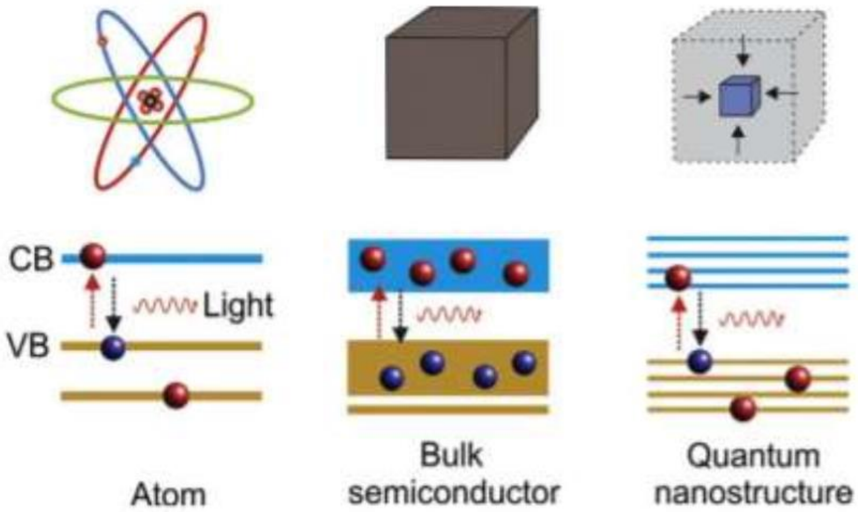

Figure1: Schematic diagram showing energy band structures in atom, bulk material, and quantum nanostructure

In a bulk material the number of energy states increases substantially to form nearly continuous bands of states. When the particle size decreases with the size becoming comparable to the deBroglie wavelength of electrons or mean free path of electrons, Electron-hole pairs become spatially confined. As a result, the energy difference between energy bands is increased with decreasing particle size. This is very similar to the famous particle-in-a-box scenario and can be understood by examining the Heisenberg Uncertainty Principle. The Uncertainty Principle states that the more precisely one knows the position of a particle, the more uncertainty in its momentum (and vice versa). Therefore, the more spatially confined and localized a particle becomes, the broader the range of its momentum/energy. Thus leading to an increased energy level spacing (i.e) larger bandgap. The bandgap of a spherical quantum dot is increased from its bulk value by a factor of $1/R^2$, where R is the particle radius.

The resulting low dimensional materials exhibits interesting novel optoelectronic, physicochemical, mechanical, and magnetic properties not shown by the corresponding large-scale structures of the same materials. Suitable control over the dimensions and the composition of such materials leads to profound properties and responses tailored to achieve new devices and technologies.

Although metals and semiconductors both have been investigated over the past decade, semiconductor nanostructures have successfully demonstrated applications and entered the consumer market.

Classification of Low-Dimensional (nano) strucutures:

Quantum structures are mainly classified according to the number of degrees of freedom in the particle momentum, or the number of reduced dimensions they have, or more precisely, the number of degrees of freedom experienced by electrons and holes inside the material.

Accordingly, quantum nanostructures can be divided into the following classes:

Quantum Well (QW): These are thin film structures with thickness on the order of a few nanometers, and are usually deposited on rigid substrates. They are also defined as two-dimensional (2D) structures because the particle is free to move in two directions, while restriction of particle motion occurs in the other direction. They can be experimentally realized by epitaxial growth of ultrathin layers consisting of semiconducting materials of varying composition.

Quantum Wire (QWr): These are one-dimensional (1D) structures in which electrons are free to move in one direction, while quantization occurs in the remaining two directions. They appear like tubes and wires with diameters in the nanometer range and lengths of several micrometers.

Quantum Dots (QDs): They are also identified as semiconductor nanocrystals, nanoparticles, clusters, colloidal nanostructures, and zero-dimensional (0D) objects. These are nanosized crystals composed of several tens to a few thousand atoms. Electrons are quantized in all three directions.

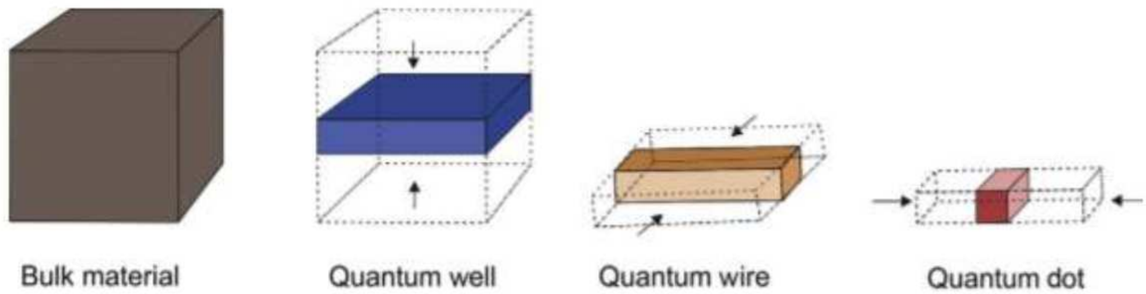

Figure 2: Schematic diagram for quantum nanostructures; bulk material, quantum well, quantum wire, quantum dot.

Quantum Dot:

QDs are the class of materials in which quantum confinement effects can be evidenced. They are very small semiconductor crystals on the order of nanometer size, containing merely a hundred to a thousand atoms. As a result, they tightly confine electrons or electron-hole pairs called "excitons" in all three dimensions. Specifically, the term "quantum dot" refers only to semiconductor nanocrystals, whereas any other inorganic material in the nano regime is referred to as a "nanocrystal."

QDs exhibit electronic properties intermediate to those of bulk semiconductors and isolated molecules. The optoelectronic properties are determined by their size and shape and alter as a function of these variables. For example, when QDs are excited by a photon of energy hν (where ν is the frequency of the incident photon) those of comparatively larger size, at around 5–6 nm, emit energy in the wavelength of orange or red. The smaller QDs emit shorter wavelengths in the blue or green range. **As a consequence, these properties can be specifically tuned to have a desired output by altering the dot size and shape**.

QDs can be made from single-element materials, such as silicon or germanium, or from compound semiconductors, such as CdSe, PbSe, CdTe, and PbS. QDs are also sometimes referred to as "artificial atoms," as these materials exhibit discrete electronic states as seen in atoms and molecules.

Applications of Quantum Dot:

QDs find applications in many fields because of their unique properties,

1. Solar cells,
2. LEDs,
3. Transistors,
4. Displays,
5. Laser diodes,
6. Quantum computing and
7. Medical imaging.

Particularly, QDs are significant for optoelectronic applications due to their precisely tunable bandgap and emission colour. QDs are expected to deliver very high-efficiency solar cells, and have also proved to be superior to traditional organic dyes used in modern biological analysis.

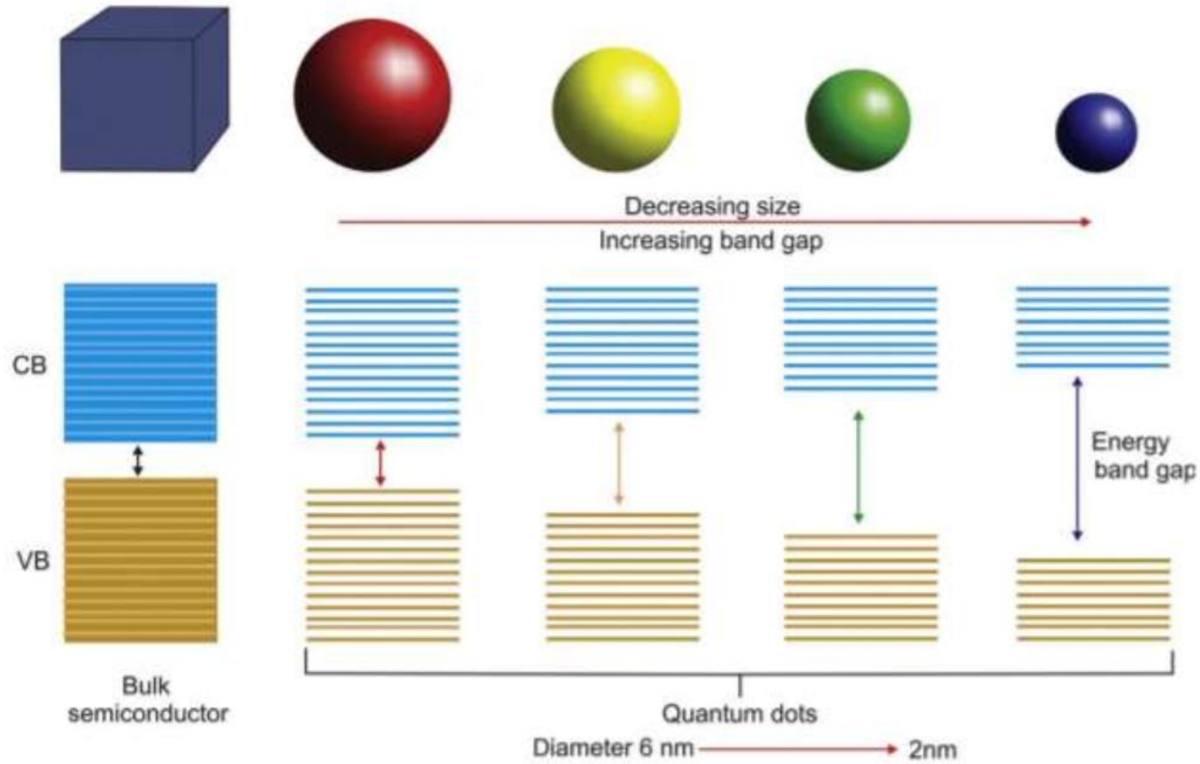

Figure 3: Energy band variation in quantum dots as the size is varied.

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