



QUANTUM DOTS AND THEIR APPLICATIONS: A REVIEW

Divij Sharma

The Indian School - Al Ghubra, P.O. Box 1887, C.P.O. Seeb, Postal Code: 111, Muscat, Sultanate of Oman

ABSTRACT

Nanoparticles or nanocrystals are of great scientific interest as they are effectively a bridge between a bulk material and atomic or molecular structures. A bulk material should have a constant physical properties regardless of its size, but at nanoscale this is often not the case. When the size and dimension or dimensions of a material are reduced from a large or a macroscopic size to a very small size, the properties remains same at first, then small changes begin to occur.

Thus, nanostructures are the structures whose dimensions are between the molecular range and a microscopic range i.e. between 0.1 nm to 100 nm. Their classification can be made as Quantum Well, Quantum Wire and Quantum Dot. If one dimension is reduced to a nano-range and the other two dimensions remains large, then we obtain a structure called as QUANTUM WELL.

If two dimensions are reduced and one is large we obtain QUANTUM WIRE, further reducing all the three dimensions to a nano range, the structure obtained is of QUANTUM DOT. In other words we can define quantum dots as structures whose size is less than the exciton bohr radius of the semiconducting material. The word quantum is associated with these three types of nano structures because the changes in properties arise from the quantum mechanical nature of physics in the domain of ultra small, thus the charged particles in the nanostructures are governed by the laws of quantum mechanics rather than classical physics leading to significant changes in their physical and electrical properties. These effects are pronounced maximum in QUANTUM DOTS structures as the quantum confinement is along all the three spatial dimensions in these structures and because of this reason, they are best suited for nonlinear optical device applications such as tunable lasers, ultra fast optical switching devices, optical computing, optical waveguides, communication network, infrared detectors and many more.

KEYWORDS : Bandgap, Conduction Band, Energy Level, Valence Band, Exciton, Exciton Bohr Radius, Quantum Confinement

1. INTRODUCTION

1.1 OVERVIEW

Dimensionality is an important factor to govern the electronic structures of semiconductor nanocrystals, such as quantum dots or quantum wires are of intense scientific interest, their electronic structures can be tailored by their sizes and shapes, leading to many new applications.

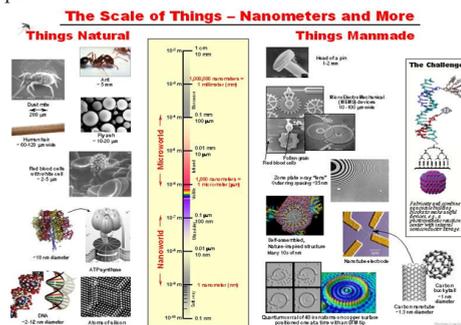


Fig. 1.1: Comparison of the size of various nanostructures and other microstructures

Thus, The properties of semiconducting materials are often referred to without any reference to their size. It is only in the regime of nanometer scale that the physical properties of a material start varying with its size. It has been observed in recent past that restricting the movement of charged particles in any dimension produces vast variation in the optical, electrical, thermal and other properties from those properties, which are observed in their bulk phase.

The recent impressive progress in the fabrication of low dimensional semiconductor structures made it possible to reduce the effective dimensions from three dimensional bulk materials, to quasi-two dimensional small well systems, to quasi-one dimensional quantum wires, and even to quasi-zero dimensional quantum dots. The physical properties of these small isolated crystallites, now called nanocrystallites, may differ substantially from those of bulk material of the same local structure and composition. When semiconductor particles are reduced in scale to nanometer dimensions, their linear and non-linear optical and electro-optical properties start deviating from those of the bulk material having same composition but relatively large size. These deviations in the physical properties are expected because of the fact that all quasi-particles (e.g. conduction electrons, excitons, phonons etc.) are confined within the boundaries of crystallites. These quantum confinement effects in such semiconductor systems with reduced space dimensions have attracted considerable attention.

Especially interesting are the modified electronic and optical properties of these structures, which are controllable to a certain degree through the flexibility in the structure design.

Nanostructures are the structures whose dimensions are between molecular range and microscopic range i.e. between 0.1 nm to 100 nm. The size of the nanostructures confines the movement of the charged particles within this barrier. A comparison of relative size of various nanostructures and microstructures is shown in figure 1.1. Nanostructures may be classified as Nanostructured Surface (or Quantum Well), Nanotube (or Quantum Wire) and Nanoparticle (or Nanocrystal, or Quantum Dot), if the movement is restricted in one direction, two directions or all the three directions, respectively. Quantum dots may also be defined as the structures whose size is less than the mean free path of the quasi-particles (conducting electrons, excitons, phonons, etc.), or, less than the exciton Bohr radius of the semiconducting material. Under these confined conditions, the charged particles in the nanostructures are governed.

1.2 PROPERTIES OF QUANTUM DOTS

When the crystallite is smaller than mean free path of quasi-particles then quantization of quasi-particle wave vector becomes important. Quantization of electronic states can also have profound consequences. From a scientific point of view, quantum dot can be considered as a laboratory to test approximations to the quantum theory. The emergence of sharp excitonic peaks at the room temperature and the blue shift in the absorption edge with decreasing size, observed in absorption spectra of quantum dots are due to quantum size effect (i.e. dependence of electro-optical properties on size). The thermodynamics of a quantum dot is also of particular interest. The large depression in melting point of quantum dots with a free surface is observed with decreasing size. This could be explained in terms of large surface to volume ratio that quantum dots have.

It is well known that in two-dimensional structures, the ground state binding energy of Wannier excitons is four times larger than in the corresponding three-dimensional material. Therefore, exciton effects are easily observable in two-dimensional systems even at room temperatures. Since these exciton resonances are strongly modified through the application of external fields or by the excitation of additional carriers in the system, the nanostructures show pronounced room temperature optical nonlinearities. It is important to note that all these variations in the electrical, optical and thermal properties are achieved in the semiconductor materials by just reducing their size and not by altering their chemical composition. Some of the important properties that are observed in nanostructures that arise due to the quantum confinement effect are as follows.

The continuous band structure of the semiconductor material splits into discrete energy levels as shown in figure 1.2.

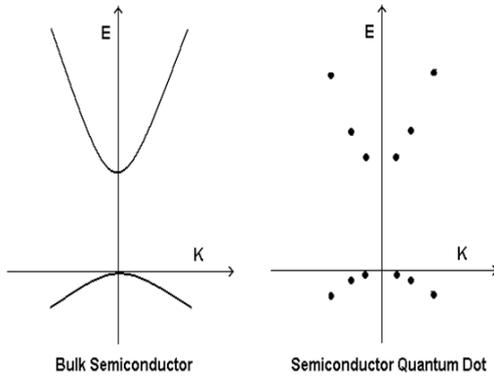


Fig. 1.2: Schematic plot of Energy spectrum in Bulk Semiconductor and Semiconductor Quantum Dot.

- These discrete energy levels reduce the absorption spectra to a set of discrete peaks. For this reason, Quantum Dots are sometimes called artificial atoms or hyper-atoms.
- The change in the band structure also contributes to increase in the fundamental band gap of the semiconductor. This blue shift is so large that the band gap of the semiconductor nanocrystals can be tailored anywhere in the whole visible spectrum.
- There is emergence of sharp excitonic peak at room temperature. A clear excitonic peak can be seen in the absorption spectra of a semiconductor quantum dot shown in figure 1.3. It may be observed, that as the size of the quantum dots decreases, the excitonic peak becomes more dominant. Also, the energy of the excitonic peak shows the blue shift, as discussed above.

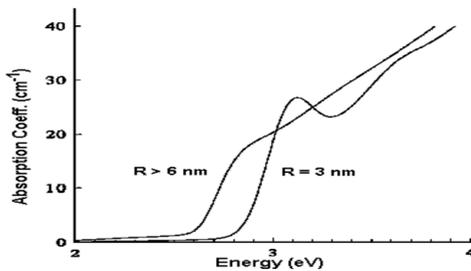


Fig. 1.3: A typical absorption curve for CdS quantum dot.

- Quantization of density of states is also observed in the quantum dots. Figure 1.4 shows the idealised density of states for one band of the semiconductor structure. It may be seen from the figure that for the case of 3D structure, the energy levels are continuous whereas for the case of 0D structure (or, Quantum Dot), the energy levels are discrete.
- There is a significant reduction in the effective mass of the electrons and other particles.
- The radiative rate for the lowest optical excitation ranges from several nanoseconds down to picoseconds.

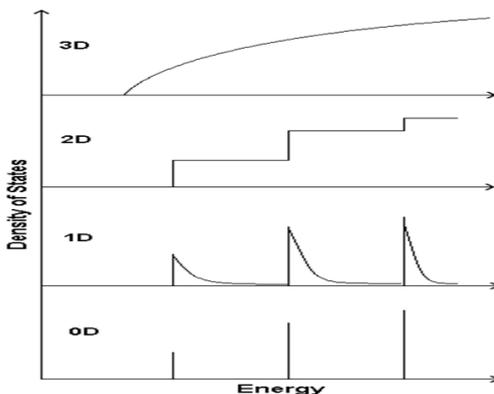


Fig. 1.4: Idealised Density of States for one band of semiconductor structure of 3, 2, 1, and 0 dimensions.

- There is a large enhancement in the nonlinear optical properties (Significant increase in the values of third-order and other higher order nonlinear susceptibility)
- The static dielectric constant of the quantum dots reduces significantly.
- The binding energy increases many folds in the Quantum Dot structures as compared to their bulk value.
- Extrinsic doping level is very low.
- A very large depression in the melting point is observed.

1.3 APPLICATIONS OF QUANTUM DOTS

Since last decade, Semiconductor Quantum Dots have attracted great attention in all the fields of science, be it electronics, physics, chemistry, biochemistry, microbiology or surgery. With such a vast variety of applications, the subject has truly become an interdisciplinary subject. Among these various applications of the quantum dots, a few applications from different fields of science are listed below.

- Semiconductor doped glasses are commonly used as sharp cut-off coloured glass filters. These coloured glass filters are available commercially in the market. The experimental work carried out in this dissertation is done on such type of coloured glass filter, RG 850 marketed by Schott Inc.
- Intensive work is being carried on semiconductor quantum dot lasers. Semiconductor quantum dot lasers have the great advantage of extremely low threshold voltage. This is achieved because the volume of the active material is very small and also, because of modifications in the density of states of the semiconductor material. Another major property of these semiconductor quantum dot lasers is that they show very less temperature dependence. They also exhibit narrow gain spectra.
- Large nonlinearity and a short response time are essential for low power & fast optical switching devices, optical computing and optical waveguide communication network.
- Infrared light detectors are a topic of current research for mid and far infrared applications such as infrared spectroscopy for chemical analysis, remote sensing and atmospheric communications. At present, commercial infrared light detectors are principally based on HgCdTe, and while their performance parameters such as detectivity and responsivity remain excellent, their deficiencies such as non uniformity of HgCdTe wafers, important for imaging, as well as difficult manufacturing technology remain well known.

Quantum dot infrared detectors, in comparison with conventional detectors, offer important advantages in regard to the performance parameters such as responsivity, detectivity and normal incidence operation. Standard quantum dot detectors respond to a single radiation wavelength or to a narrow spectral band.

- Quantum Dots are finding applications in the field of medicine and surgery also. Lymph node’s primary job is to trap and remove harmful substances, such as cancer cells, from the body. To find the sentinel node (i.e., the lymph node closest to a tumor) a blue dye and a radioactive tracer is injected in the vicinity of the tumor, and then a radioactivity detector is used to pick out the general location of the sentinel lymph node. Even as on today, the technique is imprecise and it is difficult to locate the sentinel lymph node. If the sentinel lymph node is not found, many lymph nodes must be removed and sampled, potentially leading to lymphedema, among other side effects.

Dr. Frangioni’s group is among the first to explore the potential medical applications of quantum dots, which are nanometer-sized metallic crystals that can be manufactured to emit light at specific wavelengths in response to illumination. For this, emission in the near-infrared spectrum is preferred, because skin and other tissues are partially transparent at this wavelength, allowing direct visualization of quantum dots from the outer surface of tissues. Furthermore, the quantum dots are shielded in an organic coating and tweaking the synthesis so that the particles would be approximately 15-20 nanometers in size, which is the right size to flow freely through the lymphatic vessels but still be trapped by lymph nodes. When injected into the thigh of a pig, a small amount of quantum dot solution quickly collected in and illuminated the sentinel lymph node, allowing it to be surgically removed with a minimal incision.

Another application, even more important one is targeting the tumors themselves. One problem with cancer surgery is uncertainty that the cancer has been completely removed. Even small cancerous fragments that escape notice can reseed a tumor. Quantum dots brightly illuminate cancerous tissue, thus cancerous cells can be completely removed thereby greatly improving the success of cancer surgery.

Pharmaceutical field

In the pharmaceutical domain, for example, liposomes, polymer based micro and nanoparticles have been subjects of intense research and development during the last three decades. In this scenario metallic particles, which use was already suggested in the first half of the '80, are now experiencing a real renaissance. In the field of diagnosis, magnetic resonance imaging is one of the first and up to now the most developed application of metallic particles. But beside this application, a very new generation of biosensors based on the optical properties of colloidal gold and fluorescent nanocrystals, called quantum dots seems to be ready to be implemented in diagnosis and medical imaging. Concerning therapeutic applications, the potentialities of metal nanoparticles to help fulfilling the need of time and space controlled release of drugs has been intuited for a long time. It should also be used for the detection of active ingredients with fluorescence.

Bimodal Molecular Imaging

The synthesis of quantum dots with a water-soluble and paramagnetic micellar coating as a molecular imaging probe for both fluorescence microscopy and MRI. The quantum dots preserve their optical properties and have a very high relaxivity. Targeting ligands can be coupled to these pQDs via maleimide or other functional groups. In this study, the paramagnetic quantum dots were functionalized by conjugating them with cyclic RGD peptides and were successfully targeted to human endothelial cells in vitro. We infer that this nanoparticulate bimodal contrast agent may be of great use for the detection of (tumor) angiogenesis.

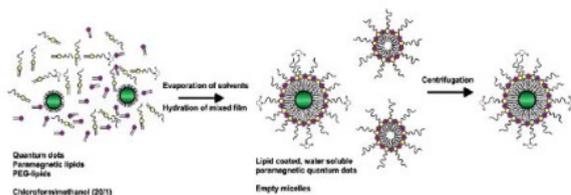


Figure: Schematic representation of the preparation of QDs with a paramagnetic micellar coating

1.4 UNDERSTANDING QUANTUM DOTS

Extremely large surface – to – volume ratio in the nanocrystalline regime is largely responsible for the properties of nanocrystals. To give an idea, the variation of surface – to – volume ratio with the radius of a sphere is plotted in figure 1.5

To investigate the changes in the various properties of the quantum dots and to understand why these properties vary so much from their bulk properties, it should be understood that these quantum dots are so small in size that number of atoms / molecules in a typical quantum dot are of the order of 102. Therefore, these nanometer-size semiconductor crystallites should be described in the same way as very large molecules.

In fact, it would not be correct to use the term 'semiconductor particles' in relation to these small crystallites, as they do not possess semiconducting features. This term is used only to refer to the bulk crystal whose properties will be reached in the case of an infinitely increasing particle size. So, the properties of the quantum dots should be deduced from the properties of atoms rather than crystals. Quantum Chemical consideration provides an opportunity to reveal the development of crystal-like properties starting from the atomic and molecular level.

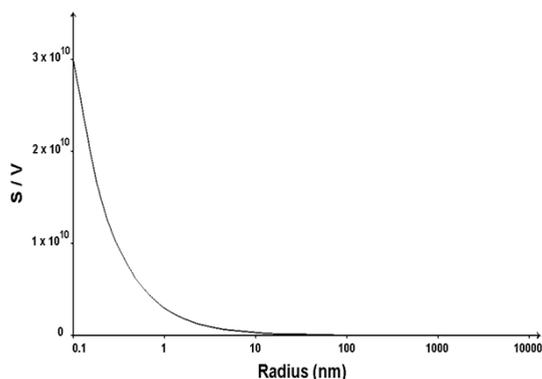


Fig. 1.5: Variation of surface-to-volume ratio with the radius of a sphere.

To show the basic steps from atom to cluster and from cluster to crystal, let us consider an example of a silicon atom, silicon cluster and silicon crystal. The four-electron sp^3 hybridised Si atoms assembled in a cluster can be described using the basis orbitals that are bond, rather than atomic, orbitals between the nearest neighbour atoms as shown in figure 1.6. They are bonding orbitals (σ) and antibonding orbitals (σ^*). As the number of atoms in the crystallite grows, each of the localized bond orbital sets forms molecular orbitals extended over the crystallite that finally develop into conduction band and valence band. The highest occupied molecular orbital (HOMO) becomes the top of the valence band, and the lowest unoccupied molecular orbital (LUMO) becomes the bottom of the conduction band. The HOMO – LUMO spacing tends to become the band gap energy of the bulk crystal. The difference of the HOMO energy and vacuum energy determines the ionization potential, whereas the difference of the LUMO energy and vacuum energy can be associated with the electron affinity.

The modeling of energy states of Cd_nS_m , Cd_nSe_m , Cd_nTe_m using extended Huckel technique clearly shows that

- The energy of the HOMO – LUMO transition, ΔE_{HL} , decreases as the size of the cluster increases i.e. ΔE_{HL} for $Cd_{54}S_{63}^{18-}$ is less (~ 2.8 eV) as compared to the HOMO – LUMO transition energy for $Cd_{12}S_{14}^{+}$ (~ 4.3 eV)
- As the number of molecules in the cluster increases, tendency to form the energy bands increases.

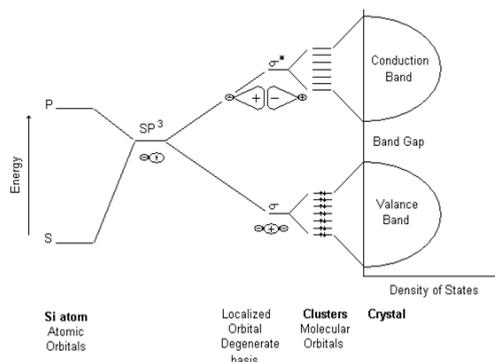


Fig. 1.6: Evolution of silicon atomic orbitals into crystal energy bands.

1.5 HISTORICAL OVERVIEW OF GROWTH OF QUANTUM DOTS

Probably the initial quantum dot systems were made many hundred years ago by people who created coloured glasses by melting a certain amount of semiconductor materials, such as ZnS or ZnSe together with the usual glass material. The very dilute system of semiconductor crystallites in the glass absorbs light at the characteristic wavelengths, leading to a colouring of the glass. However, the size of these early nanocrystallites was not well controlled which leads to a substantial distribution of sizes and also material composition. In the late seventies of this century, more controlled attempts to create quantum dots inside another matrix material started. These attempts have been intensified during the eighties and early nineties. Originally, majority of investigations concentrated on quantum dots embedded in glass matrices or suspended in colloidal solutions. These crystallites have more or less spherical shapes and may be fabricated with very small radii (between 1 and 100 nanometers, nm). The growth of semiconductor quantum dots in glasses is still one of the two most-used techniques. Besides the growth of quantum dots inside a glass matrix, the synthesis of semiconductor crystallites in liquid solvent is second one of the currently used techniques.

Until recently, mostly direct-gap semiconductor materials have been used in preparation of quantum dots. Most typical are III-V and II-IV compounds, but also CuCl and CuBr are being studied extensively. Quantum confined nanocrystallites of group II-VI compound semiconductors, embedded in glass matrix have great potential for optical device applications due to non-linear optical properties and ultra fast response times. A slow response is associated with high non-linearity and a compromise has to be reached between the two. Even though vast majority of quantum dot systems is based on direct-gap semiconductors, recently indirect-gap quantum dots have been realized. It has been found that intensity of these quantum dots is enhanced by many orders of magnitude over indirect-gap bulk material.

The most of research activities in the low dimensional semiconductor area have been carried out on confinement studies using photoluminescence, X-ray scattering, Raman scattering and absorption spectroscopy etc. These experiments usually done on commercially available coloured glass filters and semiconductor doped glasses (SDG) prepared in the laboratory using melt quenching technique. When coloured glass filters are used for preparing the samples, a large residual zinc concentration changes basic properties of samples. The quantum dots provide us with a rich material system in which optical properties can be tailored by changing particle size and composition. In some cases if we coat the semiconductor with metals such as Ag and Au, the nonlinear effects can be enhanced. The basic technological goal is to control their opto-electronic and vibrational properties in order to tailor the material for optical, electro-optical and nonlinear optical applications.

First nanocrystallites of ZnS, ZnSe and other semiconductor materials, embedded in glass matrix were made few centuries ago to create coloured glasses by melting a certain amount of these semiconductor compounds along with the usual glass material. The sizes of these early nanocrystallites were not controlled and hence there was huge size dispersion. Attempts to create quantum dots in glass matrix in a controlled manner started in eighties. Ekimov *et al.* During the years 1981 to 1985, Warnock and Awschalom in 1985 and 1986, Borelli *et al.* in 1987, Liu and Risbud in 1990 and Waggon *et al.* in the year 1991 were the few persons who started the study of the quantum dot structures embedded in glass matrix.

Besides the growth of quantum dots inside the glass matrix, the synthesis of semiconductor nanocrystallites in liquid solvents is also one of the commonly used techniques. The nanocrystallites, in this method are formed by near-room-temperature precipitation. This method offers the advantage of manipulating the nanocrystallites even after the original growth has taken place. The method has been investigated by Brus during the years 1984 to 1991. Rossetti *et al.* in 1984, Weller *et al.* in 1986, Alivisatos *et al.* in 1988 and others also contributed in the development of this method. Even though the method is very promising, the materials produced are, in many respects, not superior to the semiconductor-doped glasses.

Many other host materials were also investigated. Semiconductor microcrystallites has also been grown in a crystal matrix by Tsuboi in the year 1980 and inside ionic materials by Masumoto *et al.* in 1989. Hilinski *et al.* in the year 1988 investigated the possibility of growth of semiconductor nanocrystals inside polymer films. Wang and Herron (in 1990), Wang *et al.* (in 1989), Gratzel (in 1989), Nozue *et al.* (in 1990) and Tang *et al.* (in the year 1991) demonstrated the growth of nanocrystals inside the cavities of certain zeolites. Dameron *et al.* have reported even the biosynthesis of quantum dots in certain yeasts in 1989. Though quantum confinement induced absorption shifts have been observed in these materials, but generally no strongly pronounced optical resonance have been reported. One of the major disadvantages of these microcrystallite systems is that the due to the interaction of the semiconductor material with the host material, structural modifications and additional broadening mechanism have sometimes been observed.

The change of the optical properties of a semiconductor with decreasing particle size was reported in 1926. Jaekel related the red-shift of the absorption onset observed for glasses containing CdS particles to the growth of the CdS particles. About forty years later Berry observed a blue shift of the absorption spectrum for small crystals of AgBr or AgI compared to macroscopic crystals. In the discussion of the origin of the blue-shift it was stated that this shift was not related to the widening of the band gap. However, some fifteen years later it was established that it was in fact the widening of the band gap that caused the observed blue-shift of the absorption spectrum. It is, looking back, surprising that it took until 1982 to relate the blue-shift in nanocrystalline semiconductor quantum dots to quantum size effects. For thin two-dimensional semiconductor layers quantum size effects were demonstrated some fifteen years earlier. With the invention of molecular beam epitaxy (MBE) at Bell Telephone Laboratories it became possible to grow low dimensional semiconductor structures, such as quantum wells (2-D semiconductor structures) and quantum wires (1-D semiconductor structures). Soon after the development of MBE very interesting physical properties were observed for low dimensional systems, like quantised energy levels of confined charge carriers. The synthesis of colloidal

suspensions of nanocrystalline semiconductor particles in the 1980s initiated an enormous amount of research on quantum dots (0-D semiconductor structures). Again it was shown that the absorption onset shifts to higher energies if the particles become smaller and the groups of Ekimov and Brus showed that the size dependency of the optical properties in these zero-dimensional semiconductor particles was due to so-called quantum size effects.

Quantum Dot Glossary II-VI, III-V, IV-VI

These refer to three separate types of semiconductor compounds- those compounds containing an element from Periodic Table Groups 2 and 6, those compounds containing an element from Periodic Table Groups 3 and 5, and those compounds containing an element from Periodic Table Groups 4 and 6.

BANDGAP

In this region, electron energy levels cannot exist in any form. The bandgap is a quantum mechanical phenomenon, and is the energy difference that is usually on the order of about one electron volt for most semiconductors. The bandgap separates the valence band from the more energetic conduction band, making it difficult for electrons to jump to the conduction band. In a regular semiconductor crystal, the bandgap is fixed owing to continuous energy states. In a quantum dot crystal, the bandgap is size dependent and can be altered to produce a range of energies between the valence and conduction band. Quantum mechanics dictates that the bandgap of a quantum dot will always be larger in magnitude.

CONDUCTION BAND

For our purposes, this band contains the energy levels that are above the bandgap and higher. Because the bandgap is always much larger than the distance between energy levels, not many electrons can jump the bandgap and cross into the conduction band from the valence band. The very small number of electrons naturally occupying the conduction band is due primarily to thermal collisions.

Electrons can also be stimulated to cross the bandgap if they absorb radiation with energy greater than or equal to the bandgap energy. This fact, and their subsequent emission of radiation as the electrons fall back down to the valence band, is the basis for the utility of quantum dots.

CONTINUOUS

The set of physical conditions where energy levels are separated by such a small amount of energy that for some processes, they may be treated as if they were not separated by any energy amount at all. This type of model works well for semiconductor crystals with large numbers of atoms and physical dimensions much greater than 10 nanometers. The most important repercussion of approximating energy levels as continuous is that under those conditions, the [bandgap](#) of a material may be treated as fixed and unchangeable.

DISCRETE

The set of physical conditions where energy levels are separated by enough energy that the addition or subtraction of one atom or electron to the crystal will measurably change the energy of the bandgap. This type of model works well for semiconductor crystals with a small number of atoms and physical dimensions on the order of 10 nanometers.

It is when a semiconductor crystal has discrete states that it can be defined as a quantum dot, and this is when it takes on useful and interesting properties. This is because adding or subtracting an atom is a process that is relatively easy to engineer, and with far reaching consequences- the crystal emits at a different (and specifiable, to within limits) wavelength. This specification and tunability would be impossible with a traditional semiconductor with continuous energy levels, because one atom is insignificant given the size of such a bulk semiconductor, which is many orders of magnitude larger in number of atoms than a quantum dot. This largeness of traditional semiconductors makes the change in bandgap so small, upon changing one atom, that it is impossible to measure or use gainfully- resulting in a fixed bandgap.

ENERGYLEVEL

The electrons of all materials may only have certain allowable energies as shown by quantum mechanics. It is customary to describe each of

these allowed energies as occurring at 'energy levels,' with the understanding that electrons can only exist at an energy level and not in between them. For example, a hypothetical electron may exist with 2 units of energy, or 3 units of energy, but not with 2.730459 units of energy.

Quantum mechanics additionally dictates that only 2 electrons can exist at any one energy level (Pauli Exclusion Principle). The result is that in any crystal, electrons will start filling the lowest energy levels first, and continue to fill levels with higher energies until no more electrons remain without energy levels.

The more atoms that are in a crystal, the smaller the distance between energy levels. The distance between levels never becomes zero- there is always some finite distance between energy levels, no matter how small. However, if the dimensions of a semiconductor crystal become much larger than the Exciton Bohr Radius of the material, then the distance between energy levels in the crystal becomes very small, and it is then convenient for our purposes to describe the energy levels as continuous, i.e. treating them as if they had no difference between them.

EXCITON

An exciton is the term used to describe the electron-hole pair created when an electron leaves the valence band and enters the conduction band. Excitons have a natural physical separation between the electron and the hole that varies from substance to substance; this average distance is called the Exciton Bohr Radius. In a large semiconductor crystal, the Exciton Bohr Radius is small compared to the crystal, and the exciton is free to wander throughout the crystal. In a quantum dot, the Exciton Bohr Radius is on the order of the physical dimension of the dot or smaller, and the exciton is confined. This second set of conditions is the Exciton Bohr Radius. In a large h is synonymous with having discrete, rather than continuous energy levels.

EXCITON BOHR RADIUS

This is the natural physical separation in a crystal between an electron in the conduction band and the hole it leaves behind in the valence band. The size of this radius controls how large a crystal must be before its energy bands can be treated as continuous. Therefore, the Exciton Bohr Radius can rightly be said to define whether a crystal can be called a semiconductor quantum dot, or simply a bulk semiconductor.

HOLE

It is convenient to describe the absence of an electron in a valence band energy state as a 'hole.' Holes can be treated as positively charged, and arise when a negatively charged electron jumps to the conduction band. The combination of the electron and the hole together is called an exciton.

QUANTUM CONFINEMENT

The set of conditions under which a crystal is on the order of or smaller than the Exciton Bohr Radius of its constituent compound. Under quantum confinement, energy levels may be treated as discrete. By definition, quantum dots are in a state of quantum confinement.

QUANTUM DOT

There are many acceptable definitions. For our purposes, a quantum dot is defined as:

1. A crystal of semiconductor compound (eg. CdSe, PbS) with a diameter on the order of the compound's Exciton Bohr Radius. Quantum dots have a range of useful electrical and optical properties that diverge in character from those of bulk material. Quantum dots are between 2 and 10 nanometers wide (10 and 50 atoms).
2. A novel kind of semiconductor that can be molded into a variety of new and useful forms and made into many devices that surpass the operating capacities of traditional semiconductors.
3. An electromagnetic radiation emitter with an easily tunable bandgap.

SEMICONDUCTOR

A material with electrical properties resembling those partially of insulators and partially of conductors. The application of external stimuli such as heat or voltage can radically alter the conductivity of a semiconductor. Semiconductors, especially Silicon and Germanium, are the cornerstone of the modern electronics industry.

VALENCE BAND

- This band contains all the electrons from the one with the lowest energy, to the one with energy just on the lower edge of the bandgap. Since electrons tend to occupy energy states with the lowest energy possible, the valence band's energy levels are usually almost completely full.