

# Quantum Dots: An Introduction

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**Abstract**— The use of semiconductors has greatly increased in the last century. As new technologies start to rely more and more on semi-conductors, their shortcomings are more and more apparent. Traditional semi-conductor devices have been found to be too big and too slow. As engineers search for a faster and more adaptable alternative to conventional semiconductors they have discovered quantum dots, a new form of semiconductors that model atoms. Being only nanometers in size, these pseudo-atoms take semi-conductors to a whole new level and can allow devices to work almost at the speed of light. Furthermore, quantum dots have numerous applications in optical technologies, mediums, and industries. This paper reviews the basics of quantum dot, its properties and some applications. Semiconductor quantum dot (QD) is a promising material for the next generation high speed optical communication devices.

**Keywords**— Quantum dot, Electronic state density, Quantum well, Quantum computing, Quantum dot Lasers, Quantum dot semiconductor optical amplifier.

## 1. INTRODUCTION

During the past few years, research in semiconductors has taken on, quite literally, new dimensions. Their numbers are two, one and zero. Electrons in recently developed devices can be confined to planes, lines or mathematical points- quantum dots [1].

Planes, lines and dots are mathematical constructs. They have no physical extent. How is it possible to make them in a real, three-dimensional material? The answer lies in quantum mechanics and Heisenberg's uncertainty principle. The position of an object (an electron, for instance) and its momentum cannot both be known to arbitrary precision. As an electron is more closely confined, its momentum must be more uncertain. This wider range of momenta translates to a higher average energy. If an electron were confined in an infinitely thin layer, its energy would also be infinite.

In general, the energy of electrons in a semiconductor is limited by their temperature and by the properties of the material. When the electrons are confined in a thin enough layer, however, the requirements of the uncertainty principle in effect override other considerations. As long as the electrons do not have enough energy to break out of confinement, they become effectively two dimensional.

This locution is not just an approximation. Quantum well confines electrons or holes in one dimension and allow free propagation in two dimensions. Quantum wire confine electrons or holes in two spatial dimensions and allow free propagation in the third. Those confined in a quantum dot are not free in any dimension. This confinement is shown in Fig. 1. For common semiconductors, the length scale for a free conduction electron is about 100 angstroms. (One angstrom is  $10^{-10}$  meter, approximately the radius of a hydrogen atom.) An electron

inside a cube of semiconducting material 100 angstroms on a side is essentially confined to a point.

Quantum dots are man-made "droplets" of charge that can contain anything from a single electron to a collection of

several thousand [2]. Their typical dimensions range from nanometers to a few microns, and their size, shape and interactions can be precisely controlled through the use of advanced nanofabrication technology.

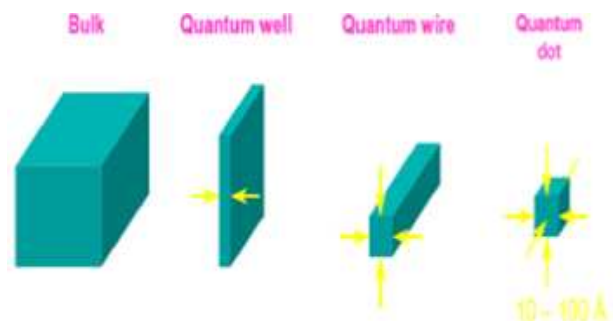


Fig. 1: Confinement of different structures.

## 2. HISTORY

Engineering of less than three-dimensional semiconductors began during the early 1970s, when groups at AT&T Bell Laboratories and IBM made the first two-dimensional "quantum wells".

The first hints that zero-dimensional quantum confinement was possible came in the early 1980s, when A. I. Ekimov and his colleagues at the Ioffe Physical-Technical Institute in St. Petersburg noticed unusual optical spectra from samples of glass containing the semiconductors cadmium sulphide or

cadmium selenide. The samples had been subjected to high temperature; Ekimov suggested tentatively that the heating had caused nanocrystallites of the semiconductor to precipitate in the glass and that quantum confinement of electrons in these crystallites caused the unusual optical behaviour [1].

Ekimov's hypothesis turned out to be true, but it took years of work by groups at Corning Glass, IBM, City College of New York and elsewhere to sort out the correct glass preparation techniques and convincingly demonstrate quantum confinement. Meanwhile Louis E. Brus and his co-workers at Bell Labs were making colloidal suspensions of nanocrystallites by precipitation from solutions containing the elements that make up semiconductors.

The term "quantum dot" was coined by Mark Reed.

### 3. ELECTRONIC STATES DENSITY

The bulk semiconductors have the energy bands. MOCVD and MBE techniques provide an ability to control layer thickness to within 1 nm. When the thickness of the active layer is small enough then electrons and holes act as if they are confined to a quantum well. Such confinement leads to quantization of the energy bands into subbands. The main consequence is that the joint density of states  $\rho(\epsilon)$  acquires a staircase-like structure [3]. Such a modification of the density of states affects the gain characteristics considerably and improves the laser performance.

Quantum well has continuous staircase-like electronic states density while the electronic state density of quantum dot is discrete. Fig. 2 shows the electronic state density of 2D, 1D and 0D confined structures [4].

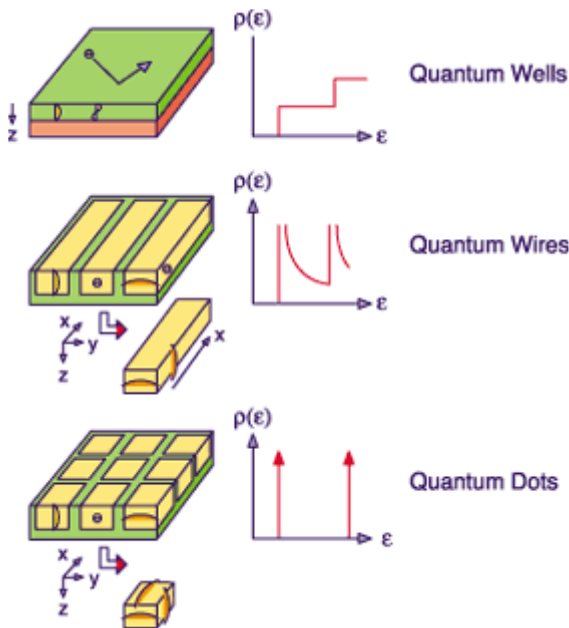


Fig. 2: Electronic states density of 2D, 1D and 0D confined structures.

### 4. QUANTUM DOT: AN ARTIFICIAL ATOM

Quantum dots containing electrons can also be compared to atoms: both have a discrete energy spectrum as shown in Fig. 3 and bind a small number of electrons. In contrast to atoms, the confinement potential in quantum dots does not necessarily show spherical symmetry. In addition, the confined electrons do not move in free space, but in the semiconductor host crystal. Typical energy scales, for example, are of the order of ten electron volts in atoms, but only 1 millielectron volt in quantum dots. Quantum dots with a nearly spherical symmetry or flat quantum dots with nearly cylindrical symmetry can show shell filling according to the equivalent of Hund's rules for atoms.

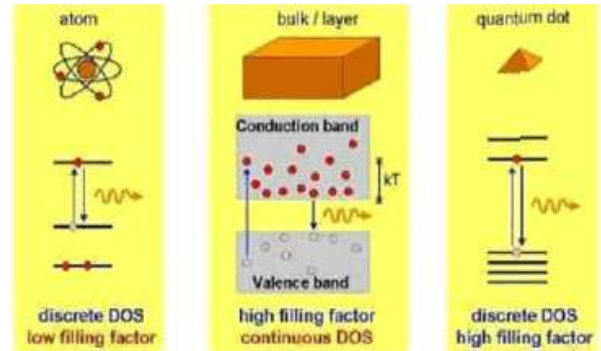


Fig. 3: Energy spectrum comparison

In contrast to atoms, the energy spectrum of a quantum dot can be engineered by controlling the geometrical size, shape, and the strength of the confinement potential. Also in contrast to atoms it is relatively easy to connect quantum dots by tunnel barriers to conducting leads, which allows the application of the techniques of tunnelling spectroscopy for their investigation. Like in atoms, the energy levels of small quantum dots can be probed by optical spectroscopy techniques. That's why quantum dots are nicknamed as artificial atoms.

When photons are pumped into a semiconductor, electrons are excited into the conduction band, leaving behind holes in the valence band. Binding the electrons with their hole counterparts result in bounded electron-hole pairs, or excitons.

Quantum dots can best be described as false atoms. The primary material that a quantum dot is made out of is called a "hole", or a substance that is missing an electron from its valence band giving it a positive charge. The primary material is extremely small, which is why it is called a dot, and at that size, electrons start to orbit it. Since quantum dots do not have protons or neutrons in the center, their mass is much smaller. Since the mass at the center is smaller than that of an atom, quantum dots exert a smaller force on the orbiting electrons causing an orbit larger than that of a regular atom (Fig. 4).

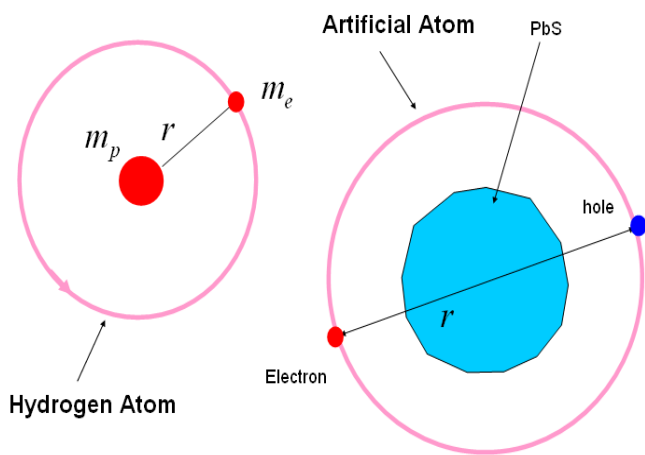


Fig. 4: The orbit comparison of quantum dot with hydrogen atom.

### 5. PROPERTIES

The composition and small size (a few hundred to a few thousand atoms) gives these dots extraordinary optical properties that can be readily customized by changing the size or composition of the dots. Quantum dots absorb light, then quickly re-emit the light but in a different color. Although other organic and inorganic materials exhibit this phenomenon—fluorescence—the ideal fluorophores would be bright and non-photo bleaching with narrow, symmetric emission spectra, and have multiple resolvable colors that can be excited simultaneously using a single excitation wavelength. Quantum dots closely fit this ideal. With a mass that small, scientists are able to precisely calculate and change the size of the band-gap of the quantum dot by adding or taking electrons. The band-gap of a quantum dot is what determines which frequencies it will respond to (Fig. 5 [5], [6]), so being able to change the band-gap is what gives scientists more control and more flexibility when dealing with its applications .

One of the optical features of small excitonic quantum dots immediately noticeable to the unaided eye is coloration. While the material which makes up a quantum dot defines its intrinsic energy signature, more significant in terms of coloration is the size. Thus quantum dots of the same material, but with different sizes, can emit light of different colors. The physical reason is the quantum confinement effect. When electrons and holes (exciton pairs) generated by photons are confined within a space, or quantum box, smaller than the Bohr exciton radius (i.e., the normal, off-the-shelf, preferred, bulk material electron-to-hole distance of an exciton pair), the semiconductor's band gap widens and its fluorescence shifts towards the blue as shown in Fig. 6 & 7 [7]. The smaller that box, the bluer the fluorescence. Conversely, the looser the confinement, the bigger the quantum box, the redder the fluorescence. Eventually, one enters the infrared and the invisible. The fluorescence is generated when electron and hole recombine. The restricted confinement requires additional energy and this causes the wavelength shift.

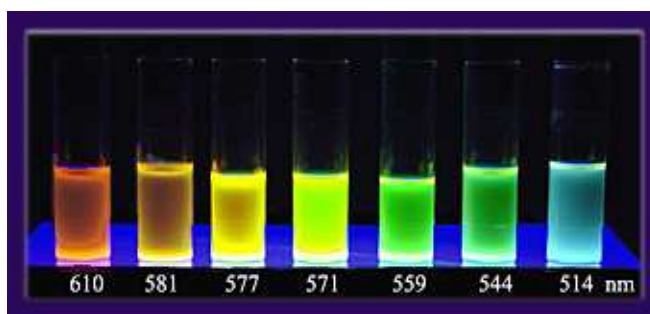


Fig. 6: Fluorescence emitted from quantum dots. Blue fluorescence can be emitted from small particles of approximately 2 nm in diameter, green from ~3 nm particles, yellow from ~4 nm particles, and red from large particles of ~5 nm.

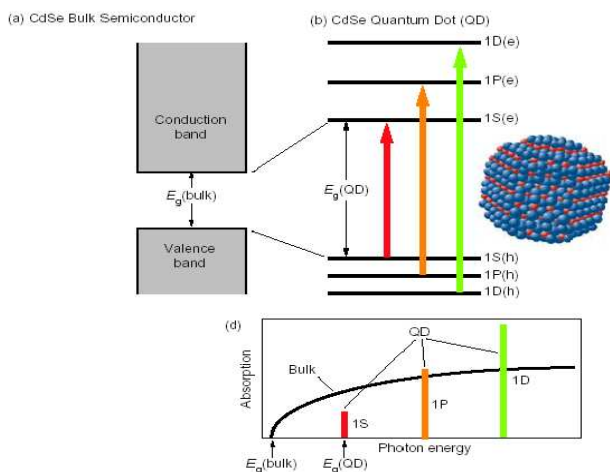


Fig. 5: Frequency and band-gap dependence.

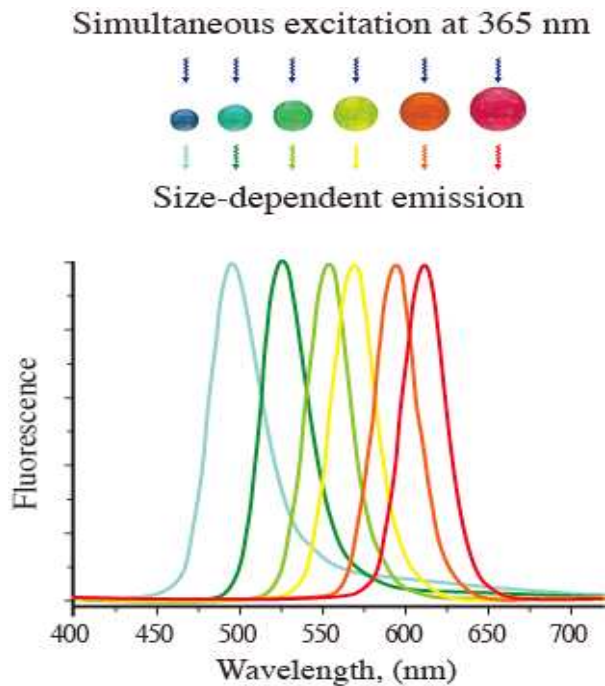


Fig. 7: Fluorescence spectra depending on the size of quantum dots.

The larger the dot, the redder (the more towards the red end of the spectrum) the fluorescence. The smaller the dot, the bluer (the more towards the blue end) it is. The coloration is directly related to the energy levels of the quantum dot. Quantitatively speaking, the bandgap energy that determines the energy (and hence color) of the fluoresced light is inversely proportional to the square of the size of the quantum dot. Larger quantum dots have more energy levels which are more closely spaced. This allows the quantum dot to absorb photons containing less energy, i.e. those closer to the red end of the spectrum. Recent articles in nanotechnology and other journals have begun to suggest that the shape of the quantum dot may well also be a factor in the colorization, but as yet not enough information has become available. Furthermore, it was shown that the lifetime of fluorescence is determined by the size of the quantum dot. Larger dots have more closely spaced energy levels in which the electron-hole pair can be trapped. Therefore, electron-hole pairs in larger dots live longer causing larger dots to show a longer lifetime. Just as in an atom, energy levels are quantized due to confinement of the electrons. In some quantum dots, even if one electron leaves the dot there is significant change in properties of dot.

Conventional semi-conductors are used often in electrical circuits. However, they have limited ranges of tolerance for the frequency of the current they carry. The low tolerance of traditional semi-conductors often poses a problem to circuits, and many of its other applications. This is what makes the use of quantum dots so important. As they are fabricated artificially, different quantum dots can be made to tolerate different current frequencies through a much larger range than conventional ones. The use of quantum dots as semi-conductors offers more

freedom to just about everything involving the use of semi-conductors.

## 6. APPLICATIONS

Quantum dots are particularly significant for optical applications due to their theoretically high quantum yield. The ability to tune the size of quantum dots is advantageous for many applications. For instance, larger quantum dots have spectra shifted towards the red compared to smaller dots, and exhibit less pronounced quantum properties. Conversely the smaller particles allow one to take advantage of quantum properties. The main applications of quantum dots are listed below:-

**6.1. Quantum Computing:** A quantum computer is a device for computation that makes direct use of quantum mechanical phenomena, such as superposition and entanglement, to perform operations on data. Quantum computers are different from traditional computers based on transistors. The basic principle behind quantum computation is that quantum properties can be used to represent data and perform operations on these data. Large-scale quantum computers could be able to solve certain problems much faster than any classical computer by using the best currently known algorithms. On May 25th, 2011 it was announced that Lockheed Martin Corporation has entered into an agreement to purchase the world's first commercial quantum computing system from D-Wave Systems Inc

A classical computer has a memory made up of bits, where each bit represents either a one or a zero. A quantum computer maintains a sequence of qubits. A single qubit can represent a one, a zero, or, crucially, any quantum superposition of these; moreover, a pair of qubits can be in any quantum superposition of 4 states, and three qubits in any superposition of 8 [8]. In general a quantum computer with  $n$  qubits can be in an arbitrary superposition of up to  $2^n$  different states simultaneously (this compares to a normal computer that can only be in one of these  $2^n$  states at any one time). A quantum computer operates by manipulating those qubits with a fixed sequence of quantum logic gates. The sequence of gates to be applied is called a quantum algorithm.

**6.2. Quantum Dots LASER:** QD's other application is quantum dot laser which promises far more great advantage than the conventional lasers. Because QD lasers are less temperature dependent and less likely to degrade under elevated temperature, it allows more flexibility for lasers to operate more efficiently. Other benefits are low threshold currents, higher power, and great stability compared to the restrained performance of the conventional lasers. Respectively, the QD laser will play a significant role in optical data communications and optical networks.

**6.3. Quantum Dot LED(QLED):** The energy emitted from quantum dots as light, is close to 100% of the energy put into the system. This exceptionally high efficiency makes quantum dots appealing for use in lights and as individual colour pixels

in vibrant colour flat panel displays. For use in lighting, a layer of quantum dots can be sandwiched in between two electrically conductive layers. A current applied directly to the quantum dots between these layers will cause them to fluoresce and will be an extremely high efficiency light source.

The traditional LEDs suffer large application restrictions due to limitations in traditional semiconductors, including difficult to alter bandgaps and inflexible structure. QLEDs, made of quantum dots, can emit at any visible or infrared wavelength, and can be fabricated into plastic, coatings, paint, filters and other forms, allowing them to be used almost anywhere.

**6.4. White Light Sources:** The white-light quantum dots, by contrast, produce a smoother distribution of wavelengths in the visible spectrum with a slightly warmer, slightly more yellow tint. They produce a light spectrum closer to that of sunlight than normal fluorescent tubes or light bulbs. Of course, quantum dots, like white LEDs, have the advantage of not giving off large amounts of invisible infrared radiation, unlike the light bulb. This invisible radiation produces large amounts of heat and largely accounts for the light bulb's low energy efficiency.

**6.5. Quantum Dot Semiconductor Optical Amplifiers:** Quantum-dot semiconductor optical amplifiers are developed as ultrawideband polarization-insensitive high-power amplifiers, high-speed signal regenerators, and wideband wavelength converters. Semiconductor optical amplifiers have several unique properties. Among them, ultrafast gain recovery on the order of a few ps, broadband gain, low noise figure (NF), high saturation output power, and high four-wave mixing (FWM) efficiency are of practical significance [9]. A semiconductor optical amplifier having a gain of  $> 25$  dB, noise figure of  $< 5$  dB, and 3-dB saturation output power of  $> 20$  dBm, over the record widest bandwidth of 90 nm among all kinds of optical amplifiers, and also having a penalty-free output power of 23 dBm, the record highest among all the semiconductor optical amplifiers, was realized by using quantum dots. By utilizing isotropically shaped quantum dots, the TM gain, which is absent in the standard Stranski-Krastanow QDs, has been drastically enhanced, and nearly polarization-insensitive SOAs have been realized for the first time. With an ultrafast gain response unique to quantum dots, an optical regenerator having receiver-sensitivity improving capability of 4 dB at a BER of

$10^{-1}$  and operating speed of  $>40$  Gb/s has been successfully realized with an SOA chip. This performance achieved together with simplicity of structure suggests a potential for low-cost realization of regenerative transmission systems.

**6.6 Single Electron Transistor:** In electronic applications they have been proven to operate like a single-electron transistor and show the Coulomb blockade effect.

**6.7 Medical Applications and Cancer Treatments:** Quantum dots can be encased within a shell tuned to mimic organic receptors within the body. These receptors can correspond to particular diseases, viruses or other items. The quantum dots will then seek out and attach to the disease en masse. Due to the

fluorescent nature of quantum dots the site of the problem is then made easily visible [8]. The number of receptors required on the surface of the dot is small compared to the surface area of the dot itself. This leaves a large amount of room to place other things on the dot. This can include various drugs for treating a disease the quantum dot has been tuned to find.

In this manner, quantum dots can be tuned to seek out cancer cells and deliver chemotherapy drugs directly to the cancer cells. This avoids poisoning healthy cells and therefore the awful side effects associated with cancer treatments.

**6.8 Quantum Dot Circuits:** Quantum dots are fast and As they are fabricated artificially, different quantum dots can be made to tolerate different current frequencies through a much larger range than conventional ones. This feature of QD can be used in circuits.

By adding "Quantum wires" to quantum dot, many quantum dots have been strung together in various shapes and structures as shown in Fig. 8 [10]. Hypothetically, these quantum dot /wire structures could be used in circuits in place of traditional wires.

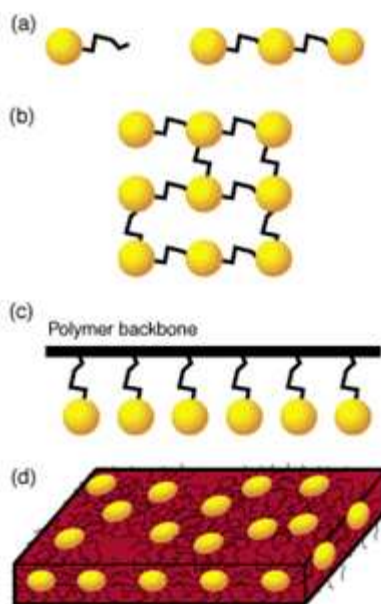


Fig. 8: With molecular tethers to link them together, quantum dot become the building blocks of nanostructures. They can be linked together as (a) molecules, (b) lattices, (c) attached to a polymer backbone or, (d) incorporated into a polymer thin film.

## 7. CONCLUSIONS

Quantum dots are new and innovative perspective on the traditional semiconductor. Quantum dots can be synthesized to be essentially any size, and therefore, produce essentially any wavelength of light. Quantum dots are particularly significant for optical applications due to their theoretically high quantum yield. The ability to tune the size of quantum dots is

advantageous for many applications. The future looks bright and exciting on all the possible applications of quantum dots.

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