Chapter

Introductory Chapter: Quantum Dots

Faten Divsar

1. Introduction

Quantum dots are small regions defined in the semiconductor materials with the same size of the distance in an electron-hole pair [1]. The physics of quantum dots has been a very active and fruitful research topic. Their unique optical, photochemical, semiconductor, and catalytic properties are due to the quantum confinement. To date, chemistry, physics, and materials science have provided methods for the production of quantum dots and allow tighter control of factors affecting, for example, particle growth and size, solubility and emission properties. This book deals with the electronic and optical properties of quantum dots as an artificially fabricated device. These dots have proven to be useful systems to study a wide range of physical phenomena. These characteristics provide the potential applications of quantum dots in photovoltaic and laser devices, thin-film transistors, light-emitting diodes, and luminescent labels in biology and medicine. Some of these applications are discussed in separate sections in this book.

2. What are quantum dots?

Quantum dots are colloidal fluorescent semiconductor nanoscale crystals that were firstly produced in the early 1980s [2]. These artificial semiconductor nanoparticles typically have unique optical, electronic, and photophysical properties that make them appealing in promising applications in fluorescent biological labeling, imaging, solar cells, composites and detection and as efficient fluorescence resonance energy transfer donors [3]. Sufficiently miniaturized semiconductor particles show quantum confinement effects, which limit the energies at which electron hole pairs are present in the particles. Based on the relationship between the energy and wavelength of light (or color), the optical properties

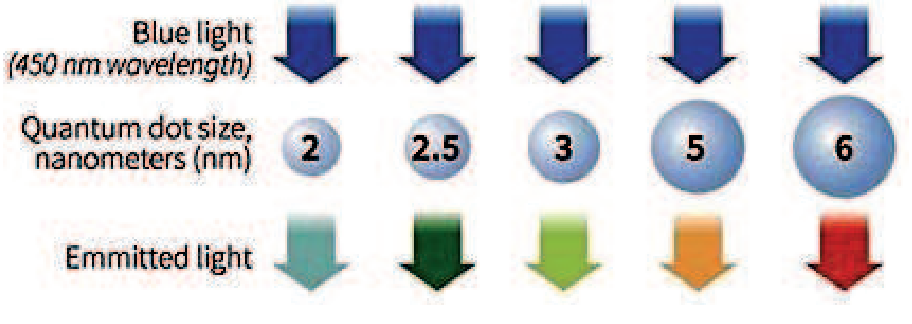

Figure 1.
Conversion of the light spectrum into different colors depends on the quantum dot size (image: RNGS Reuters/ Nanosys).

of the particle can be delicately varied depending on its size. Therefore, only by controlling the size of quantum dots, various particles with different colors can be produced to emit or absorb specific wavelengths of light [4]. As shown in **Figure 1**, different sized quantum dots emit different color light due to quantum confinement.

The physics of quantum dots counterpart with a lot of the behaviors that naturally occurring in atomic and nuclear physics of the quantum system.

3. Quantum size effects

In quantum dots, the size of particle is smaller than the Bohr radius of the electron-hole pair distance, excitons, leading to quantum confinement. During this state, the energy levels become discrete and can be predicted by the particle in a box model. The possible discrete energy levels of the electrons in such quantum dots depend on their size and accordingly to their bands gap [5]. As well, optical properties of quantum dots with sizes smaller than the de Broglie wavelength naturally depend on their electrical properties.

As shown in **Figure 2**, quantum dots as excellent luminescent materials show broad excitation range with narrow and symmetric emission spectra after excitation. Their emissions are typically much narrower than emissions of common fluorophores or organic dye molecules. In fact, the absorption of the wavelength of light with the energy equal to the band gap energy promotes the electron from the valence band to the conduction band. Afterward, the exited electron relaxes directly from the conduction band to the valence band the and emits a photon [6].

Quantum dots are becoming, nowadays, one of the fast growing and most exciting research subjects. The unique physical and optical properties of quantum dots have made them attractive tools and vectors for research in molecular biology, material science, chemical analysis, etc.

Nowadays, nanocrystals are usually prepared with atoms from groups II–VI, III–V, or IV–VI in the periodic table and eventually become many different types of quantum dots (**Table 1**).

The quantum dots can also be created by combining these systems such as GaAs–ZnS, GaAs–ZnTe, InP–ZnS, InP–ZnSe, and InP–CdS [10].

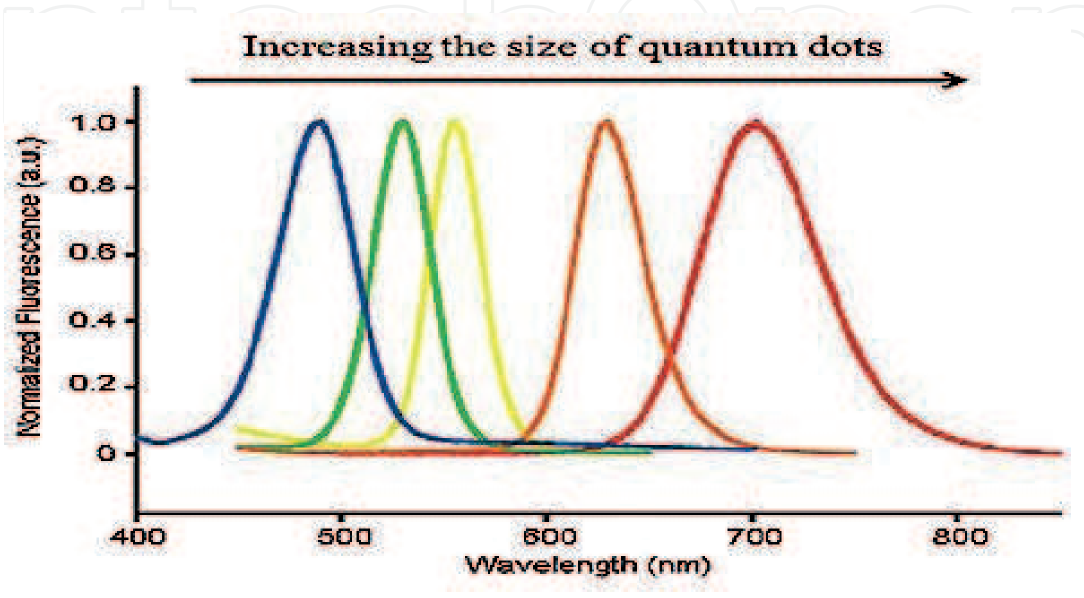

Figure 2.
Size-dependent fluorescence spectra of quantum dots.

Type	Quantum dots
IB-VI	Ag_2S, ZnAgS, CuS, $CuInS_2$, $CuInSe_2$
IIB–VI	CdS, CdSe, CdTe, ZnS, ZnSe, ZnTe, HgS, HgSe, HgTe
IIIA–V	GaAs, InGaAs, InP, InAs, InGaN
IV-VI	PbSe, PbS
IV	C, Si, Ge

Table 1.
Summary of different types of quantum dots [7–9].

4. Optical properties

Particle size is one of the most important aspects that can affect the optical properties of quantum dots. Of course, various other factors such as the shape and composition of quantum dots, as well as the methods and materials used in the synthesis of these particles also affect the optical properties and frequency of fluorescent light emitted or absorbed by these nanocrystals [11]. Therefore, by manipulating each of the effective factors, special quantum dots with specific properties can be prepared for different purposes.

5. Fabrication

Generally, there are two methods to synthesize nanomaterials including quantum dots, top-down and bottom-up (**Figure 3**). In the top-down synthesis approach, the bulk material is transferred to nanometer size using an electron beam or high-energy ions. The methods that fall into this category are electron beam lithography, reactive ion etching, focused beam lithography, and dip pen lithography [12]. However, these methods have limitations and disadvantages such as structural defects in the patterning and impurities in the quantum dots synthesized [13]. In the bottom-up methods, atoms or molecules are assembled step by step to produce nanomaterials. These synthesis approaches are highly diverse and generally

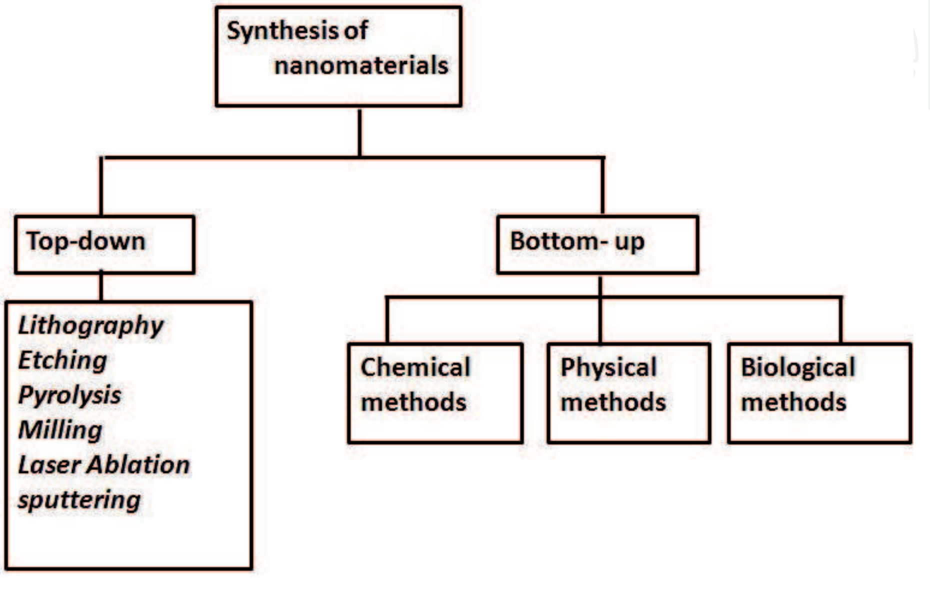

Figure 3.
Various methods for the synthesis of nanomaterials.

can be categorized as chemical, physical, and biological methods. The common bottom-up methods are derived from the development of atom or molecular self-assembly such as chemical reduction method, electrochemical method, microemulsion method, and physical/chemical vapor deposition techniques [14]. The main advantage of bottom-up approach is that they can generally synthesize homogenous nanostructures with perfect crystallographic and surface structures.

6. Potential applications

The unique optical and electrical properties of the quantum dots make them favorable for multitasking purposes. These particles emit light in visible and near-infrared region. Quantum dots are applied in electronics devices such as single electron transistors or micro-LED array, in energy applications as solar cells, photovoltaic devices, or light-emitting diodes [15]. In addition, they are also used in biological and medical sciences for imaging, labeling, detecting, and sensing. Quantum dots synthesized in organic solvents are insoluble in water. However, functionalizing the quantum dots with either hydrophilic functional groups, ligands, or by capping, organic coating can be used to transform them to aqueous soluble quantum dots. In biological applications, DNA oligonucleotide, aptamer, or antibody are grafted on quantum dots through thiol, amine, or carboxyl groups giving cross linking with molecules. Functionalized quantum dots are used for cell targeting, cell labeling, and drug delivery and in imaging. The advantages of quantum dots with respect to organic dye molecules are their high brightness, stability, and quantum efficiency [16, 17].

Author details

Faten Divsar
Department of Chemistry, Payame Noor University (PNU), Tehran, Iran

*Address all correspondence to: divsar@gmail.com

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