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Semiconducting Nanomaterials: Quantum Dots and their Optoelectronic Applications

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Abstract

Quantum dots are man-made small size particles or nanoscale particles of a semiconducting material with diameter in the range 2-10 nanometers. The most significant property of Quantum dots is fluorescence. Quantum dots have outstanding optical and electronic applications owing to their bright, pure colors along with their ability to emit a spectrum of whole colors coupled with their high efficiencies, longer lifetimes and high extinction coefficients. This chapter discusses some novel optoelectronic applications of Quantum dots.

Keywords Quantum dots (QDs), applications, optical, electronic, LED, photodetector

Introduction

Quantum dots (QDs) are manmade nano nanocrystals roughly spherical and traditionally with a core structure that can transport electrons. When ultraviolet light falls on these nanoparticles, they emit light of various colors. The process of light emission from QDs is called photoluminescence (PL), because it happens due to excitation and subsequent deexcitation of the photons. As QDs are of very small size, the electrons in these particles are confined in a small space which is called quantumconfinement[1]. According to Pauli's exclusion principle, when the radius of a semiconductor particle is smaller than the exciton Bohr radius, there is quantization of energy levels. Due to quantized energy levels of these quantum particles[2], these are closer to atoms than bulk materials and this leads to them being nicknamed "Artificial atoms".

The semiconducting materials, whose radius is of the order of nanometer and have almost zero dimension, have been known as QDs. The conductivity of semiconductors is ascertained by the difference of energy level between valence band and conduction band.Valence band has bound electrons while conduction band has very few free electrons at room temperature. By acquiring energy thermally or by absorption of photon (light) electrons may gain energy and can enter the conduction band from the valence band and leave a positively charged hole in the valence band. This difference of energy between valence band and conduction band is known as

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band gap energy and expressed in electron volts. It specifies that the electron must get this energy to enter the conduction band from the valence band. The excited electron and hole taken as a pair are called an “exciton”. Once the electron is excited to the conduction band it may relax back to its ground state through radiative recombination with a hole and there is emission of photon with the same energy as the band gap as shown in fig.1. QDs as a semiconductor materials[3] exhibit size dependent energy states due to the confinement of the electron hole pair or charge carriers in 3-Dim. When the size of the crystals decreases the bandgap increases hence more energy is required to excite the QD particle, at the same time more energy is released when the QD returns to its originally relaxed condition.

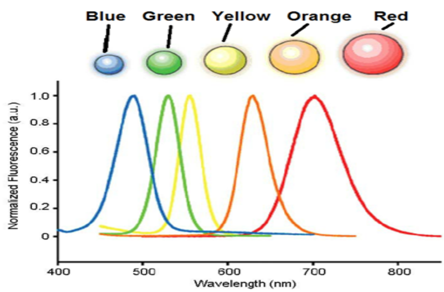

Fig. 1

The color of emitted light depends upon energy released and energy released depends upon the size of a QD of the same type. As the size increases the color of emitted light shifts[4] from red to blue in this way a QD can emit any color of light from the same material simply by changing the size of the dot, this is called the tuned property of QD shown in fig.2. The ability to tune optical and electronic properties by changing the crystal size is regarded as the most important aspect of QD properties.

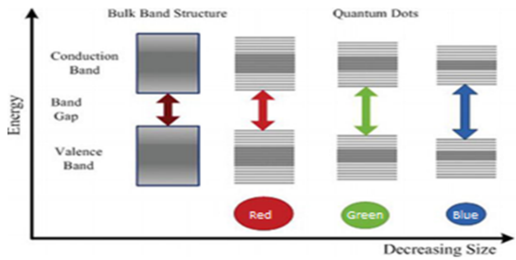

Fig. 2

These nano QDs can be made of single material with uniform internal compositions, or it may be multicomponent. The efficiency and brightness of the QD can be improved by growing shells of another higher band gap semiconductor material around them. These new types of QDs are known as core-shell QDs (CSQDs) or core shell semiconductor nanocrystals (CSSNCs) e.g,CdTe,COOH functionalized, fluorescence electromagnetic wavelength 610 nm powder. Another type of QD is formed by alloying together two semiconductors with different band gap energies. These exhibit remarkable properties different from those of their parent semiconductor. This type of QDs is called alloyed QDs e.gCd Se S / ƵS fluorescence electromagnetic wavelength 630 nm, 6 nm diameter, 1 mg/mL in toluene.

Optoelectronic Applications

QDs are particularly promising for optical applications, due to their optical properties arising from the quantum confinement of electrons and holes, when a QD glows on being shown ultra violet (UV) light, it produces a very pure light in a precise wavelength of red, blue or green. This application is used in electronics. QDs are being described here for some of their uses such as LEDs, Diode LASERS, Single-electron transistors, Single-photon sources, Flat screen displays, Optical amplifiers, memory and solar sensors, quantum computing and biomedical imaging. Also, the small size of QDs allow them to be suspended in solution which leads to possible uses in inkjet printing and spin coating.

LED:

QDs are widely used in light emitting devices i.e., LED. The narrow emission width and the tunability of emission wavelengths with simple changes in the size and composition make the QDs attractive for LEDs. The possibility of the fabrication of optoelectronic devices having QD based LEDs by reel to reel (RTR) processing and the compatibility of most of the QDs with light weight, flexible plastic substrates throws open the prospects for making low cost, large area flexible devices.

Conventional LEDs in TV (Liquid Crystal Display) screens produce white light used as a backlight that is filtered to achieve desired colors, a process that leads to less bright and muddier colors. However, in the new generation LCDs, the backlighting system consists of blue LEDs and a QD filter. This filter contains green and red QDs which convert some parts of blue light into green and red light because of the narrow band width of the resulting red, green and blue lights, the image appears brighter and more contrast on LCDs. This arrangement decreases energy consumption significantly. Recently visible colloidal QDs provide benefit for LEDs by their narrow emission line width of the order of 20-30 nm for CdSe and InP – based QDs. Intense and saturated colors, high luminescence and lower power consumption are obtained at the extreme by narrow spectra, which cover more than 90% of the stricter record color gamut[8] standard.

QDs are also used as phosphorus such as white lightning or horticultural lighting. In these applications the blue LED is used as the main source of light as it is the most efficient and cheapest LED. The application of QDs used as phosphorus convert a part of blue light into another light like LCDs. For white lighting, the blend consists of green and red QDs. The main advantage of using QDs in white lighting is that it achieves high color rendering index (CRI) and Correlated Color Temperature (CCT). These parameters measure the ability of a light source to reproduce colors of various objects in comparison to a natural light source.

In horticultural LEDs for green houses, red quantum dot polymer composites are promising for the efficient growth of the plants. The plant chlorophyll is most efficient in capturing red (600-700 nm wavelength) and blue (400-500nm wavelengths) waves of light and the green wave is reflected. Use of QDs also reduces the cost of power consumption.

Photodetector:

QDs are used in photodetectors for detecting both Infra Red (IR) and visible light. Photodetectors for IR light find application in night vision cameras, atmosphere spectroscopy for gas detection, biomedical imaging quality control and product inspection.

In photodetector, different types of QDs are used. A hybrid CNT/graphene film prepared by depositing CNTs on a single layer graphene[9] with a side-polished optical fiber is used to achieve a novel all-fiber photodetector. Lead sulfide (PbS) QD is the material used for photodetector. It has fantastic properties including size-controllable spectral sensitivity, a wide and tunable absorption range, cost efficient solution processability and flexible substrate compatibility. Photodetectors operating in the UV spectral range have been fabricated using a WS2 QD-graphene nanocomposite[10]. Phototransistors with balanced photodetection are obtained based on CsPbBr3 colloidal QDs with few layers of MOS2[11].

Conclusion

Because of highly tunable properties, QDs are of wide interest nowadays. But there are many challenges also while using QDs like photobleaching, photoluminescence blinking, auger recombination and others. Hence in order to achieve stability and establish resistance to photochemical reactions, manufacturers strengthen QDs structure by employing core-shell design which reduces the core’s vulnerability.

Modern QD materials have another layer between core and the shell, called the middle shell. Scientists are attempting to make quantum computers with QDs because these lead to less expensive and less time-consuming processing techniques. The optoelectronic applications of QDs according to analysts (Global Market, 2019)[12] predict that sales of products engineered with QDs will be potentially valued at more than five billion by 2030.

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