Quantum Dots: Nano-Crystals that can Revolutionize Technology

Angad Mehta

T.Y.B.Tech. (Dyes)

Angad Mehta : Color has always fascinated me. My research interests are various ways to get novel hi-tech application colorants. I am interested in various color and chemical constitution relationships. I am also interested in heterocyclic organic chemistry.

Abstract

Quantum dots, also known as nanocrystals, belong to a special class of materials known as semiconductors, which are crystals composed of elements from the II-VI, III-V, or IV-VI groups of the periodic table. They absorb in the entire visible spectrum as well as change the crystal size. Quantum dots of the same material, but with different sizes, can emit light of different colors. Using quantum dots as photo absorbers helps to boost the efficiency of solar cells from the existing 20-30% to around 42%. Quantum dots linked to biological molecules, such as antibodies, have shown promise as a new tool for detecting and quantifying a wide variety of cancer-associated molecules. Quantum dot infrared photodetectors — technology may provide new imaging techniques with applications in medical and biological imaging, environmental and chemical monitoring, night vision and infrared imaging from space. Using multiple quantum dots, each with a distinct color, a method is developed for accurately mapping lymphatic flow from more than one drainage basin which is one of the most difficult tasks for an oncologist. Quantum Dot-Organic Light Emitting Device (QD-OLED) may one day replace LCDs as the flat-panel display. When quantum dots replace transistors in computers cracking highly encrypted codes is possible in seconds.

Keywords: Quantum dots, Semiconductors, Bio markers, Infrared photodetectors, Quantum computers.

1. Introduction

Quantum dots, also known as nanocrystals, belong to a special class of materials known as semiconductors, which are crystals composed of elements from the II-VI, III-V, or IV-VI groups of the periodic table. Semiconductors are a cornerstone of the modern electronics industry and make possible applications such as the Light Emitting Diode and personal computer. Semiconductors derive their great importance from the fact that their electrical conductivity can be greatly altered via an external stimulus (voltage, photon flux, etc), making semiconductors critical parts of many different kinds of electrical circuits and optical applications. Quantum dots are unique class of semiconductor because they are so small, ranging from 2-10 nanometers (10-50 atoms) in diameter. At these small sizes materials behave differently, giving quantum dots unprecedented tunability and enabling applications, never seen before, in science and technology. Quantum dots are useful because of their ability to absorb in the entire visible spectrum as well as their easy tunability by changing the crystal size. Despite the existence of ongoing work in the area of quantum dots for over a decade, the field remains one of the most interesting and cutting-edge areas of science!

2. Physical structure

Quantum dots containing electrons can also be compared to atoms: both have a discrete energy spectrum 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. The quantum dot host material, in particular its band structure, does therefore play an important role for all quantum dot properties. 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. Like in atoms, the energy levels of small quantum dots can be probed by optical spectroscopy techniques. In quantum dots that confine electrons and holes, the interband absorption edge is blue shifted due to the confinement compared to the bulk material of the host semiconductor material. As a consequence, quantum dots of the same material, but with different sizes, can emit light of different colors.

3. Quantum Dots - Quantum Confinement

Quantum dots are also made out of semiconductor material. The electrons in quantum dots have a range of energies. The concepts of energy levels, bandgap, conduction band and valence band still apply. However, there is a major difference. Excitons have an average physical separation between the electron and hole, referred to as the Exciton Bohr Radius. This physical distance is different for each material.In bulk, the dimensions of the semiconductor crystal are much larger than the exciton bohr radius, allowing the exciton to extend to its natural limit. However, if the size of a semiconductor crystal becomes small enough that it approaches the size of the material's exciton bohr radius, then the electron energy levels can no longer be treated as continuous - they must be treated as discrete, meaning that there is a small and finite separation between energy levels. This situation of discrete energy levels is called quantum confinement, and under these conditions, the semiconductor material ceases to resemble bulk, and instead can be called a quantum dot. This has large repercussions on the absorptive and emissive behavior of the semiconductor material.

4. Quantum Dots - A tunable range of energies

Because quantum dots' electron energy levels are discrete rather than continuous, the addition or subtraction of just a few atoms to the quantum dot has the effect of altering the boundaries of the bandgap. Changing the geometry of the surface of the quantum dot also changes the bandgap energy, owing again to the small size of the dot and the effects of quantum confinement. The bandgap in a quantum dot will always be energetically larger; therefore, we refer to the radiation from quantum dots to be "blue shifted" reflecting the fact that electrons must fall a greater distance in terms of energy and thus produce radiation of a shorter, and therefore "bluer" wavelength.

5. Size Dependent Control of Bandgap in Quantum Dots

As with bulk semiconductor material, electrons tend to make transitions near the edges of the bandgap.

However, with quantum dots, the size of the bandgap is simply controlled by adjusting the size of the dot. Because the emission frequency of a dot is dependent on the bandgap, it is therefore possible to control the output wavelength of a dot with extreme precision. In effect, it is possible to tune the bandgap of a dot, and therefore specify its "color" output depending on the needs.

6. Mass production Techniques

In large numbers, quantum dots may be synthesized by means of a colloidal synthesis. Colloidal synthesis is by far the cheapest and has the advantage of being able to occur at benchtop conditions. It is acknowledged to be the least toxic of all the different forms of synthesis.Highly ordered arrays of quantum dots may also be self assembled by electrochemical techniques. A template is created by causing an ionic reaction at an electrolyte-metal interface which results in the spontaneous assembly of nanostructures, including quantum dots, on the metal which is then used as a mask for mesa-etching these nanostructures on a chosen substrate.Yet another method is pyrolytic synthesis, which produces large numbers of quantum dots that self-assemble into preferential crystal sizes. Recently a team of researchers from Purdue University reported and published a paper on the newly developed technique of the synthesis of quantum dot[1]. The characteristic property of this synthesis was that the quantum dots were prepared by sonic energy. The properties that these quantum dots displayed were comparable to those displayed by the commercially available quantum dots.

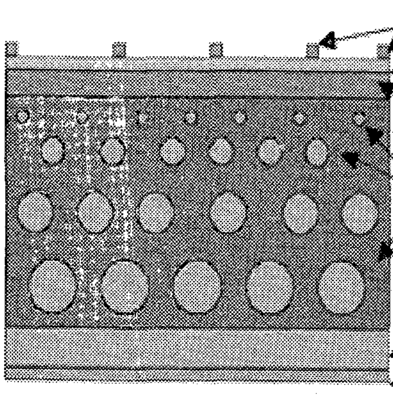
7. Novel Applications

Being quasi-zero dimensional, quantum dots have a sharper density of states than higher-dimensional structures. As a result, they have superior transport and optical properties, and are being researched for use in diode lasers[4], amplifiers, and biological sensors.Quantum dots are one of the most hopeful candidates for solid-state quantum computation. By applying small voltages to the leads, one can control the flow of electrons through the quantum dot and thereby make precise measurements of the spin and other properties therein. With several entangled quantum dots, or qubits, plus a way of performing operations, quantum calculations might be possible. Another cutting edge application of quantum dots which is also being researched is, as an artificial fluorophore for intra-operative detection of tumors using fluorescence spectroscopy. In modern biological analysis, various kinds of organic dyes are used. However, with each passing year, more flexibility is being required of these dyes and the traditional dyes are simply unable to meet the necessary standards at times. To this end, quantum dots have quickly filled in the role, being found to be superior to traditional organic dyes on several counts, one of the most immediately obvious being brightness (owing to the high quantum yield) as well as their stability (much less photodestruction). For single particle tracking, the irregular blinking of quantum dots is a minor drawback. Currently under research as well is tuning of the toxicity, quantum dots can also be used in various solar panels. Quantum dots produce as many as three electrons from one high energy photon of sunlight.When today's photovoltaic solar cells absorb a photon of sunlight, the energy gets converted to at most one electron, and the rest is lost as heat. This could boost the efficiency of panels produced in research labs from today's 20-30% to 42% or even more to about 60% by the use of various types of quantum dots. Quantum dots also aid the imaging studies in cancer.The researchers are also exploring further applications of quantum dot systems, such as quantum dot dressed state lasers, optical modulators and quantum logic devices.

Details of Some of the Novel Applications

7.1 Use of Quantum dots in intermediate bandgap Solar Panels

Construction of an intermediate bandgap solar cell:



Intermediate-bandgap solar cell. An Experimental setup for chemical bath production of quantum dots.[2]

Quantum dots of CdSe and $CuInS_2$ can be used in intermediate-bandgap solar cells. Using quantum dots in a solar cell to create an intermediate band will allow the harvesting of a much larger portion of the available solar spectrum. Theoretical studies predict a potential efficiency of 63.2%, which is approximately better by a factor of 2 than any state-of-the-art devices available today. This technology is also applicable to thin-film devices; where it offers a potential four-fold increase in power-to-weight ratio over the state of the art[2].

Intermediate-bandgap solar cells require that quantum dots be sandwiched in an intrinsic region between the photovoltaic solar cell's ordinary p- and n-type regions (see the preceding figure). The quantum dots form the intermediate band of discrete states that allow subbandgap energies to be absorbed. However, when the current is extracted, it is limited by the bandgap, not the individual photon energies. The energy states of a quantum dot can be controlled, by controlling the size of the dot. Ironically, the ground-state energy levels are inversely proportional to the size of the quantum dots. The most studied quantum dots prepared by this method have been of CdSe.[2]

7.2 Biological Uses of Quantum Dots

7.2.1 Quantum Dots as Biological Markers

Quantum dots linked to biological molecules, such as antibodies, have shown promise as a new tool for detecting and quantifying a wide variety of cancer-associated molecules. Bioconjugated quantum dots are generally used to detect disease markers.Because quantum dots come in a variety of colors, it is possible to use a uniquely colored quantum dot for each biomarker being assayed. Multiplexed imaging and computer-aided analysis of the resulting fluorescence emitted by the quantum dots then provide quantitative results for each biomarker.[5]

7.2.2 Quantum Dots Aid Cancer Imaging Studies

One of the more difficult diagnostic tasks an oncologist faces is determining if cancer has spread to the lymphatic system, particularly when it is necessary to assess lymphatic drainage from two separate drainage basins.Using multiple quantum dots, each with a distinct color, researchers at the National Cancer Institute's Center for Cancer Research have developed a method for accurately mapping lymphatic flow from more than one drainage basin. Proper selection of quantum dot size improved their ability to map lymphatic flow from different regions of the body. Larger quantum dots, approximately 12 nanometers in diameter, proved optimal for imaging lymphatic flow from the upper extremities, while quantum dots of approximately 6 nanometers in diameter worked best for mapping lymphatic drainage from mammary glands. Quantum dots are also proving useful in labeling human blood cells, a finding that could help researchers answer questions about how these cells move through the body. Scientists at UCLA have shown that they can label all major types of human blood, specific types of blood cells by linking the quantum dots to antibodies that recognize molecules found on those cells. As a result, the investigators were able to identify different kinds of blood cells, such as leukemic cells and normal cells, in a mixture of blood cells with quantum dots[6].

7.2.3 Use of Quantum Dots Quantum Computations

Researchers at the University of Michigan have demonstrated that we can use quantum dot spectroscopy in cracking highly encrypted codes in a matter of seconds. By using short pulses of light to create light-matter interactions in quantum dots, tiny particles that change with the addition or deletion of electrons, the researchers found they could control the frequency in the optical network. This technology would power an optically driven quantum computer, which is capable of cracking highly encrypted codes in seconds, while the fastest existing desktop computer would take 20 years to do the same. Quantum computers are capable of massive parallel computations and this makes them very fast. Quantum dots replace transistors in these computers and our results show that it only takes a few billionths of a watt to drive it[7].

7.2.4 Quantum-dot LED

MIT researchers have combined organic materials with quantum dots to create a hybrid optoelectronic structure—a Quantum Dot-Organic Light Emitting Device (QD-OLED) that may one day replace liquid crystal displays (LCDs) as the flat-panel display of choice for consumer electronics. Unlike traditional LCDs, which must be lit from behind, quantum dots generate their own light. Depending on their size, the dots can be "tuned" to emit any color in the rainbow. And the colors of light they produce are much more saturated than that of other sources. This latest MIT QD-OLED contains only a single layer of quantum dots sandwiched between two organic thin films. The researchers have demonstrated organized assemblies over a 1-square centimeter area and the same principle could be used to make bigger components. In addition to being used for extraordinarily thin, bright flat-panel displays, the QD-OLEDs may also be used in a variety of other applications; to calibrate wavelengths for scientific purposes, generate wavelengths visible only to robot eyes. The MIT group envisions that QD-OLEDs will in time become complementary to OLEDs because they can be built on the same electronic platforms with compatible manufacturing methods.[8]

7.2.5 Quantum Dot Infrared Photodetector

Significant strides have been made in the development of quantum dot infrared photodetectors — technology that may provide new imaging techniques with applications in medical and biological imaging, environmental and chemical monitoring, night vision and infrared imaging from space. Conventional infrared photon detector technology for imaging applications typically requires that the detector be cooled to very low temperatures — approximately 77 degrees Kelvin. This cooling requirement adds significant cost, bulk and power consumption to the imaging systems, therefore limiting their usability. By using nanotechnology to form quantum dots, may well help to develop high-performance imaging techniques that can operate at higher temperatures. The development of an infrared photon detector that can operate at higher temperatures will enable the use of cheaper, lighter and more efficient cooling methods in the design of infrared imaging systems which will allow the use of infrared detectors in a much wider range of applications. Researchers at Northwestern's Center for Quantum Devices (CQD) made a great breakthrough in the development of high-performance Quantum Dot Infrared Photodetectors (QDIP). They have developed a QDIP that operates at room temperature with a peak detection wavelength in the technologically important middle wavelength infrared window; wavelengths between three and five microns are important because they are not susceptible to absorption by Earth's atmosphere. The QDIP is based on a hybrid indium arsenide quantum dot and an indium gallium arsenide quantum well structure grown on an indium phosphide substrate[9]. The specific detectivity and quantum efficiency at 150 degrees Kelvin were 4×1010 cmHz1/2/W and 35% respectively. This is a record high performance[10].

8. Conclusion

Thus, we can see that quantum dots find a wide application in almost an entire gamut of technical applications ranging from solar panels, lasers, quantum computations, biological fields digital displays and so on. All the above applications find widespread applications in latest technical researches as well as various biological issues, which in turn may lead to a path breaking discoveries and inventions for future generations. As it is said, "Good things come in small packages", quantum dots that are nano-crystals may well end up revolutionize the entire life-style of human beings.

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