The Properties and Applications of Quantum Dots

Quantum dots (QD) are zero-dimensional materials, which can confine electrons and exhibit quantum mechanical behavior. Quantum dots are considered as a special class of semiconductor whose energy gap and energy levels spacing depends on the size of the particles. Due to this we can observe many interesting electronic properties of quantum dots.

The Properties of Quantum Dots

Quantum dots were discovered by the Russian Physicist Alexey I. Ekimov in 1981. These nanoparticles have diameters ranging from 2 nanometers to 10 nanometers. Their electronic characteristics differ depending on their size and shape. The image below shows the glass tubes with quantum dots of perovskite nanocrystals with different colors. By varying the synthesis reaction time, we can get different nanocrystalline size exhibiting different colors.

Quantum dots emit light when excited and the smaller dots emits higher energy light. Manufacturers can accurately control the size of a quantum dot and as a result they are able to ‘tune’ the wavelength of the emitted light to a specific color.

Quantum dots find applications in several areas such as solar cells, transistors, LEDs, medical imaging and quantum computing, due to their unique electronic properties.

Optical Applications

The high extinction coefficient, longer lifetime and high efficiency of a quantum dot make it perfect for optical use. Quantum dots of very high quality can be ideal for applications in optical encoding and multiplexing, due to their narrow emission spectra and wide excitation profiles.

Light Emitting Diodes

Quantum dot light emitting diodes (QD-LED) and ‘QD-White LED’ are very useful for manufacturing the displays for electronic devices because they emit light in highly specific Gaussian distributions. QD-LED displays can render colors very accurately and use much less power than the traditional displays.

Photodetectors

Quantum dot photodetectors (QDPs) can be produced from traditional single-crystalline semiconductors or solution-processed. Solution-processed QDPs are ideal for the integration of several substrates and for their use in integrated circuits. These colloidal QDPs find use in machine vision, surveillance, spectroscopy and industrial inspection.

Photovoltaics

Quantum dot solar cells are much more cost-effective when compared to their silicon solar cells counterparts. They can be produced by simple chemical reactions and can reduce the manufacturing costs.

Operational efficiency can be significantly improved by using quantum dots. In traditional silicon p-n junction solar cells, when a photon hits the solar cell with energy greater than that of the bandgap of silicon, it excites a single electron with energy equivalent to that of the silicon bandgap. But when a photon hits the solar cell with energy less than the bandgap of silicon, it is transmitted by the silicon and does not contribute to the output power. The theoretical peak solar efficiency for a silicon p-n junction solar cell is 33.7%.

Quantum dots can offer a significant increase in efficiency, by using dots of varying sizes on top of each other, with the largest band gaps on top. Incoming photons will be transmitted until reaching a layer with a bandgap smaller than the photon energy. With enough layers, each photon will excite an electron with an energy very close to its own energy, and only a small amount of energy is wasted. When the number of layers approaches infinity, the efficiency approaches a theoretical thermodynamic limit of 86%.

Biological Applications

The latest generation of quantum dots has great potential for their use in biological analysis applications. They are widely used to study intracellular processes, tumor targeting, in vivo observation of cell trafficking, diagnostics and cellular imaging at high resolutions.

Quantum dots have proven to be far superior to conventional organic dyes because of their high quantum yield, photostability and tuneable emission spectrum. They are 100 times more stable and 20 times brighter than traditional fluorescent dyes.

The extraordinary photostability exhibited by quantum dots make them ideal for use in ultra-sensitive cellular imaging. This allows several consecutive focal-plane images to be reassembled into three-dimensional images at very high resolution.

Quantum dots can target specific cells or proteins using peptides, antibodies or ligands and then it can be used to study the target protein or the behavior of the cells. Researchers have found out that quantum dots are far better at delivering the siRNA gene-silencing tool to target cells than currently used methods.

Recent studies have suggested that adding light activated particles to antibiotics can combat the increasing problem of drug-resistant infections. The kinds of chemicals released after light has hit the quantum dot can be modified by changing the size. Researchers at the University of Colorado have developed antibiotics with quantum dots which releases a superoxide enzyme, when the size of the quantum dot is modified. This stresses the bacteria, making it more vulnerable to antibiotics which were previously been immune to. This could be incredibly important for the future, with the amount of drug-resistant infections continually rising.

Quantum Computing

Quantum dots have paved the way for powerful ‘supercomputers’ known as quantum computers. Quantum computers operate and store information using quantum bits or ‘qubits’, which can exist in two states – both on and off simultaneously.

This remarkable phenomenon enables information processing speeds and memory capacity to be significantly improved when compared to conventional computers.

The Future of Quantum Dots

Quantum dots are zero dimensional and exhibit sharper density of states than structures of higher dimensions. This explains their excellent optical and transport properties, which are currently being studied for potential uses in amplifiers, biological sensors and diode lasers.

The broad range of real-time applications of quantum dots in the field of biology is expected to be very useful in many research disciplines such as cancer metastasis, embryogenesis, lymphocyte immunology and stem cell therapeutics.

In the future, researchers believe that quantum dots can be used as the inorganic fluorophore in intra-operative tumor detection by using fluorescence spectroscopy.

A startup company called Store Dot, has fabricated a new battery which can charge a phone from dead to full in about 30 seconds. The Store Dot’s technology uses quantum dots which are actually peptides that have been modified to have certain properties like optical or the ability to generate charge when strained. This battery is about five times more powerful than the traditional ones. This is due to the use of quantum dot nanocrystal solution instead of the electrolyte used to generate electrons in traditional batteries. The company is currently working on scaling down the size of the battery and the expected cost of the charger is about $30.