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Quantum Dots: An Overview of History, Synthesis and Applications

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ABSTRACT

Quantum dots (QDs) are a landmark development in the field of nanotechnology. These zero-dimensional semiconductors, unlike their physical attributes, have enormous capacity to store energy within themselves. This energy is contained in several thousands of electrons that constitute the nanoparticles. QDs are synthesized by both organic and inorganic methods, the choice being dependent upon the desired efficacy of the resultant product. The optical and electronic properties of these particles are dependent upon the transitions of constituent electrons between the valence and conductance bands and this phenomenon is exploited in synthesizing QDs to be employed as biomarkers. As biomarkers, these particles find many clinical applications, in an array of *in vivo* and *in vitro* techniques, ranging from drug delivery systems to interstitial target tracking. The present review article discusses the historical development, structural aspects, methods of synthesis and various applications of QDs in the medical and other fields.

INTRODUCTION:

Quantum dots constitute a new class of materials that is neither molecular nor bulk. They have the same structure and atomic composition as bulk materials, but their properties can be tuned using a single parameter, the particle's size. For example, the optical absorption and emission of CdSe quantum dots can be tuned across nearly the entire visible range of the optical spectrum. This is possible because the energy bandgap of CdSe quantum dots varies between 1.8 eV (its bulk value) to 3 eV. Other material properties that are tuneable by quantum dot size include redox potentials[1], melting temperature[2], and solid-solid phase transitions,[3] to name just a few.

The discovery of quantum dots, and the ability to synthesize such materials with high accuracy but relatively simple chemical methods, was an important step in the development of nanoscience and nanotechnology. The core principle of nanoscience is that, at the scale of nanometres, materials and particles attain new, size-dependent properties that can be harnessed and controlled for novel applications. The tools of chemistry are an indispensable enabler of nanotechnology, with applications in areas as diverse as biotechnology, catalysis, sensing, medical diagnostics, electronics, photonics, and quantum technology.

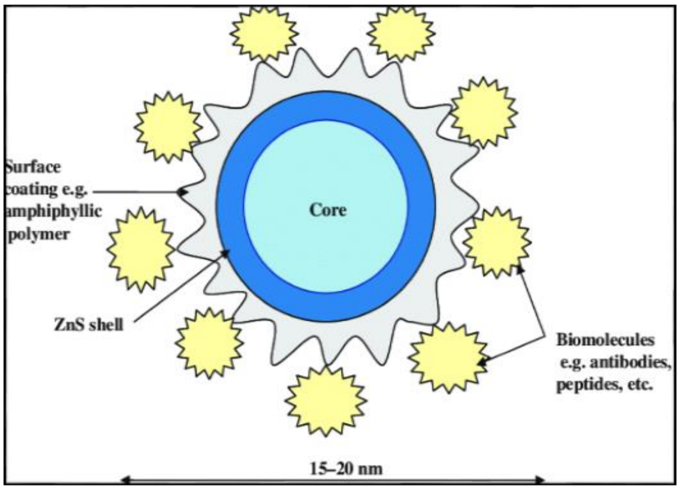
Today it is possible to produce quantum dots with highly controlled, size-dependent properties using relatively low-cost, solution-phase batch chemistries that make these revolutionary materials widely available. With an estimated total market size of USD 4 billion in 2021, quantum dots are used as high-quality light emitters in illumination and in display technology,[4] as well as for biomedical imaging.[5] Ongoing nanotechnology research also explores applications of quantum dots in infrared photodetection, solar energy conversion, light-emitting diodes, diagnostics and photocatalysis.

HISTORY:

The first discovery of quantum size effects in nanoparticles was made in the context of coloured glass. Historically, glassmakers knew very well that dopants such as gold, silver, cadmium, sulphur, and selenium could be used to change the optical properties of glass. For example, optical filters with different cut-off frequencies, so-called Schott glasses, were produced by controlling the type and amount of dopant as well as the details of the thermal process after melting of the glass.[6] It was also understood that the glass properties were related to the inclusion of 'colloidal particles' in the glass, but the details of the mechanism had not been investigated.[7] In 1979, Alexei Ekimov began working on doped glasses at the S.I. Vavilov State Optical Institute.[7] He aimed to understand the chemical composition and structure of colloidal particles in coloured glasses, as well as the mechanism of their growth.[7] Using techniques familiar to him from his Ph. D. training in semiconductor physics, he and his co-workers measured the optical absorption spectrum of heat-treated silicate glasses with additions of Cu and Cl of the order of a few percent, above the solubility limit of the matrix. At the cryogenic temperature of 4.2 K, the team found exciton lines similar to those observed in CuCl thin films, but the shapes of which varied with details of the heat treatment.[8] The researchers attributed this observation to the formation of a crystalline phase of CuCl in the glass matrix as a result of phase decomposition of a supersaturated solution during heat treatment. Furthermore, by varying temperature and duration of the heat treatment, they were able to control the average size of CuCl crystals forming in the glass melt.[9] Using small-angle X-ray scattering, they determined average crystal sizes in the range from a few nanometres to tens of nanometres and confirmed that crystal size varied with heat treatment time, as expected from a theoretical model[10] of recondensation growth that also predicted the observed narrow size distribution.[9]

Crucially, the wavelength of the observed CuCl exciton absorption lines varied systematically with the size of the nanocrystals: the position of the absorption line was increasingly blue-shifted for smaller crystals down to nanocrystals as small as a few nanometres.[11,12]

Ekimov immediately attributed this observation to quantum size effects,[11,12] giving reference to the observation of quantum size effects in MBE-grown, two-dimensional quantum wells a few years before.[13] As qualitatively expected from textbook quantum mechanics for a single particle confined in a spherical infinite well, the absorption line shifted with the inverse square of the average particle radius.



The initial observation of quantum size effects by Ekimov was determined to be in the so-called weak confinement regime, characterized by quantum size effects of the exciton as a whole, but not of the electron and hole individually.[14] Subsequently, also the intermediate and strong confinement regimes[14] were demonstrated.[16]

Ekimov's discovery of semiconductor quantum dots in a glass matrix showed that it was possible to observe profound signatures of quantum size effects not only in thin films but also in suspended, independent nanoparticles produced by a relatively simple traditional glass process. However, a limitation of Ekimov's ground breaking discovery was that his team's quantum dots were 'frozen' in glass and not suitable for further processing.

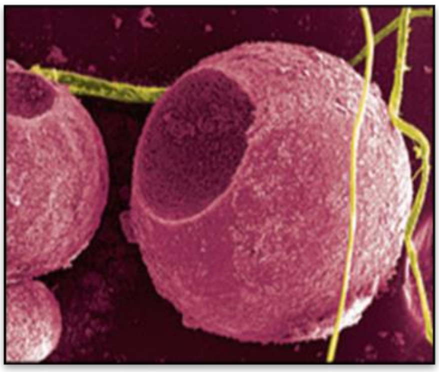
STRUCTURE:

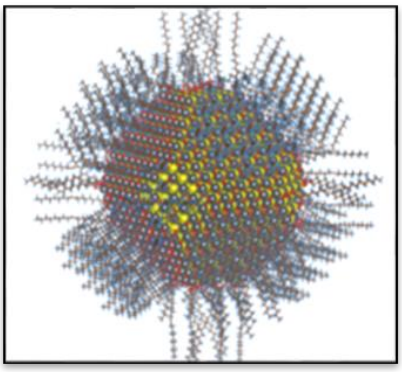
Quantum dots comprise a structure of only a few thousands of atoms and have a semiconductor core [like cadmium selenium (CdSe), lead selenium (PbSe), or indium arsenide (InAs)] and an outer shell [zinc sulphide (ZnS), cadmium sulphide (CdS)] to prevent toxicity.

SYNTHESIS:

Quantum dots with gradually stepping emission from violet to deep red. There are several ways to fabricate quantum dots. Possible methods include colloidal synthesis, self-assembly, and electrical gating.

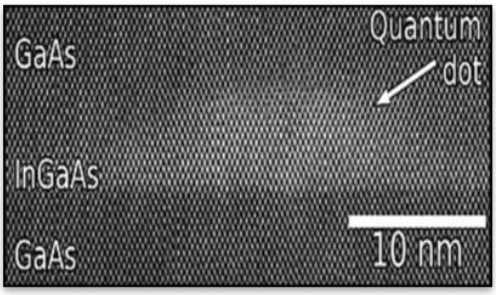
a. Colloidal synthesis:





Colloidal semiconductor nanocrystals are synthesized from solutions, much like traditional chemical processes. The main difference is the product neither precipitates as a bulk solid nor remains dissolved. Heating the solution at high temperature, the precursors decompose forming monomers which then nucleate and generate nanocrystals. Temperature is a critical factor in determining optimal conditions for the nanocrystal growth. It must be high enough to allow for rearrangement and annealing of atoms during the synthesis process while being low enough to promote crystal growth. The concentration of monomers is another critical factor that has to be stringently controlled during nanocrystal growth. The growth process of nanocrystals can occur in two different regimes: "focusing" and "defocusing". At high monomer concentrations, the critical size (the size where nanocrystals neither grow nor shrink) is relatively small, resulting in growth of nearly all particles. In this regime, smaller particles grow faster than large ones (since larger crystals need more atoms to grow than small crystals) resulting in the size distribution focusing, yielding an improbable distribution of nearly monodispersed particles. The size focusing is optimal when the monomer concentration is kept such that the average nanocrystal size present is always slightly larger than the critical size. Over time, the monomer concentration diminishes, the critical size becomes larger than the average size present, and the distribution defocuses.

b. Cadmium sulphide quantum dots on cells:



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There are colloidal methods to produce many different semiconductors. Typical dots are made of binary compounds such as lead sulphide, lead selenide, cadmium selenide, cadmium sulphide, cadmium telluride, indium arsenide, and indium phosphide. Dots may also be made from ternary compounds such as cadmium selenide sulphide. Further, recent advances have been made which allow for synthesis of colloidal perovskite quantum dots. These quantum dots can contain as few as 100 to 100,000 atoms within the quantum dot volume, with a diameter of approximately 10 to 50 atom diameters. This corresponds to about 2 to 10 nanometres, and at 10 nm in diameter, nearly 3 million quantum dots could be lined up end to end and fit within the width of a human thumb.

Idealized image of colloidal nanoparticle of lead sulphide (selenide) with complete passivation by oleic acid, oleyl amine, and hydroxyl ligands (size ≈5 nm).

Large batches of quantum dots may be synthesized via colloidal synthesis. Due to this scalability and the convenience of benchtop conditions, colloidal synthetic methods are promising for commercial applications.

c. Plasma synthesis:

Plasma synthesis has evolved to be one of the most popular gas-phase approaches for the production of quantum dots, especially those with covalent bonds. For example, silicon and germanium quantum dots have been synthesized by using nonthermal plasma. The size, shape, surface and composition of quantum dots can all be controlled in nonthermal plasma. Doping that seems quite challenging for quantum dots has also been realized in plasma synthesis. Quantum dots synthesized by plasma are usually in the form of powder, for which surface modification may be carried out. This can lead to excellent dispersion of quantum dots in either organic solvents or water (i. e., colloidal quantum dots).

d. Fabrication:

The electrostatic potential needed to create a quantum dot can be realized with several methods. These include external electrodes, doping, strain, or impurities. Self-assembled quantum dots are typically between 5 and 50 nm in size. Quantum dots defined by lithographically patterned gate electrodes, or by etching on two-dimensional electron gases in semiconductor heterostructures can have lateral dimensions between 20 and 100 nm.

Some quantum dots are small regions of one material buried in another with a larger band gap. These can be so-called core–shell structures, for example, with CdSe in the core and ZnS in the shell, or from special forms of silica called ormosil. Sub-monolayer shells can also be effective ways of passivating the quantum dots, such as PbS cores with sub-monolayer CdS shells.

Quantum dots sometimes occur spontaneously in quantum well structures due to monolayer fluctuations in the well's thickness. Atomic resolution scanning transmission electron microscopy image of an indium gallium arsenide (InGaAs) quantum dot buried in gallium arsenide (GaAs).

Self-assembled quantum dots nucleate spontaneously under certain conditions during molecular beam epitaxy (MBE) and metalorganic vapour-phase epitaxy (MOVPE), when a material is grown on a substrate to which it is not lattice matched. The resulting strain leads to the formation of islands on top of a two-dimensional wetting layer. This growth mode is known as Stranski–Krastanov growth. The islands can be subsequently buried to form the quantum dot. A widely used type of quantum dots grown with this method are indium gallium arsenide (InGaAs) quantum dots in gallium arsenide (GaAs). Such quantum dots have the potential for applications in quantum cryptography (that is, single-photon sources) and quantum computation. The main limitations of this method are the cost of fabrication and the lack of control over positioning of individual dots.

Individual quantum dots can be created from two-dimensional electron or hole gases present in remotely doped quantum wells or semiconductor heterostructures called lateral quantum dots. The sample surface is coated with a thin layer of resist and a lateral pattern is then defined in the resist by electron beam lithography. This pattern can then be transferred to the electron or hole gas by etching, or by depositing metal electrodes (lift-off process) that allow the application of external voltages between the electron gas and the electrodes. Such quantum dots are mainly of interest for experiments and applications involving electron or hole transport and they are also used as spin qubits. A strength of this type of quantum dots is that their energy spectrum can be engineered by controlling the geometrical size, shape, and the strength of the confinement potential with gate electrodes. These quantum dots can be easily connected by tunnel barriers to conducting leads, which allows the application of the techniques of tunneling spectroscopy for their investigation.

Complementary metal–oxide–semiconductor (CMOS) technology can be employed to fabricate silicon quantum dots. Ultra small (20 nm × 20 nm) CMOS transistors behave as single electron quantum dots when operated at cryogenic temperature over a range of −269°C (4 K) to about −258°C (15 K). The transistor displays Coulomb blockade due to progressive charging of electrons (holes) one by one. The number of electrons (holes) confined in the channel is driven by the gate voltage, starting from an occupation of zero electrons (holes), and it can be set to one or many.

e. Viral assembly:

Genetically engineered M13 bacteriophage viruses allow preparation of quantum dot bio composite structures. It had previously been shown that genetically engineered viruses can recognize specific semiconductor surfaces through the method of selection by combinatorial phage display. Additionally, it is known that liquid crystalline structures of wild-type viruses (Fd, M13, and TMV) are adjustable by controlling the solution concentrations, solution ionic strength, and the external magnetic field applied to the solutions. Consequently, the specific recognition properties of the virus can be used to organize inorganic nanocrystals, forming ordered arrays over the length scale defined by liquid crystal formation. Using this information, Lee et al. (2000) were able to create self-assembled, highly oriented, self-supporting films from a phage and ZnS precursor solution. This system allowed them to vary both the length of bacteriophage and the type of inorganic material through genetic modification and selection.

f. Electrochemical assembly:

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, onto the metal which is then used as a mask for mesa-etching these nanostructures on a chosen substrate.

g. Bulk manufacture:

Quantum dot manufacturing relies on a process called high temperature dual injection which has been scaled by multiple companies for commercial applications that require large quantities (hundreds of kilograms to tons) of quantum dots. This reproducible production method can be applied to a wide range of quantum dot sizes and compositions.

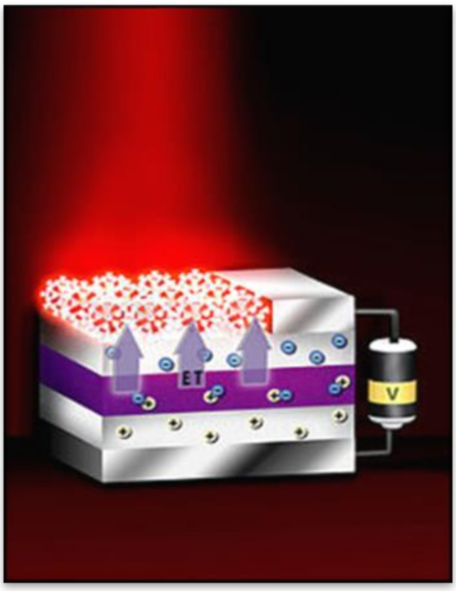
The bonding in certain cadmium-free quantum dots, such as III–V-based quantum dots, is more covalent than that in II–VI materials, therefore it is more difficult to separate nanoparticle nucleation and growth via a high temperature dual injection synthesis. An alternative method of quantum dot synthesis, the molecular seeding process, provides a reproducible route to the production of high-quality quantum dots in large volumes. The process utilises identical molecules of a molecular cluster compound as the nucleation sites for nanoparticle growth, thus avoiding the need for a high temperature injection step. Particle growth is maintained by the periodic addition of precursors at moderate temperatures until the desired particle size is reached. The molecular seeding process is not limited to the production of cadmium-free quantum dots; for example, the process can be used to synthesise kilogram batches of high-quality II–VI quantum dots in just a few hours.

Another approach for the mass production of colloidal quantum dots can be seen in the transfer of the well-known hot-injection methodology for the synthesis to a technical continuous flow system. The batch-to-batch variations arising from the needs during the mentioned methodology can be overcome by utilizing technical components for mixing and growth as well as transport and temperature adjustments. For the production of CdSe based semiconductor nanoparticles this method has been investigated and tuned to production amounts of kilograms per month. Since the use of technical components allows for easy interchange in regards of maximum throughput and size, it can be further enhanced to tens or even hundreds of kilograms.

In 2011 a consortium of U.S. and Dutch companies reported a milestone in high-volume quantum dot manufacturing by applying the traditional high temperature dual injection method to a flow system.

On 23 January 2013 Dow entered into an exclusive licensing agreement with UK-based Nanoco for the use of their low-temperature molecular seeding method for bulk manufacture of cadmium-free quantum dots for electronic displays, and on 24 September 2014 Dow commenced work on the production facility in South Korea capable of producing sufficient quantum dots for "millions of cadmium-free televisions and other devices, such as tablets". Mass production is due to commence in mid-2015. On 24 March 2015, Dow announced a partnership deal with LG Electronics to develop the use of cadmium free quantum dots in displays.

h. Heavy-metal-free quantum dots:



In many regions of the world there is now a restriction or ban on the use of toxic heavy metals in many household goods, which means that most cadmium-based quantum dots are unusable for consumer-goods applications.

For commercial viability, a range of restricted, heavy-metal-free quantum dots has been developed showing bright emissions in the visible and near-infrared region of the spectrum and have similar optical properties to those of CdSe quantum dots. Among these materials are InP/ZnS, CuInS/ZnS, Si, Ge, and C.

Peptides are being researched as potential quantum dot material.

APPLICATIONS:

Quantum dots are particularly promising for optical applications due to their high extinction coefficient and ultrafast optical nonlinearities with potential applications for developing all-optical systems. They operate like a single-electron transistor and show the Coulomb blockade effect. Quantum dots have also been suggested as implementations of qubits for quantum information processing, and as active elements for thermoelectric.

Tuning the size of quantum dots is attractive for many potential applications. For instance, larger quantum dots have a greater spectrum shift toward red compared to smaller dots and exhibit less pronounced quantum properties. Conversely, the smaller particles allow one to take advantage of more subtle quantum effects.

A device that produces visible light, through energy transfer from thin layers of quantum wells to crystals above the layers.

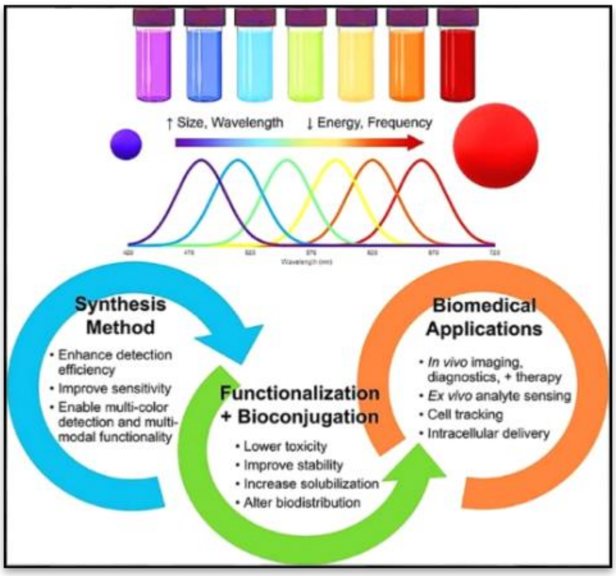
Being zero-dimensional, quantum dots have a sharper density of states than higher-dimensional structures. As a result, they have superior transport and optical properties. They have potential uses in diode lasers, amplifiers, and biological sensors. Quantum dots may be excited within a locally enhanced electromagnetic field produced by gold nanoparticles, which then can be observed from the surface plasmon resonance in the photoluminescent excitation spectrum of (CdSe) ZnS nanocrystals. High-quality quantum dots are well suited for optical encoding and multiplexing applications due to their broad excitation profiles and narrow/symmetric emission spectra. The new generations of quantum dots have far-reaching potential for the study of intracellular processes at the single-molecule level, high-resolution cellular imaging, long-term in vivo observation of cell trafficking, tumour targeting, and diagnostics.

CdSe nanocrystals are efficient triplet photosensitizers. Laser excitation of small CdSe nanoparticles enables the extraction of the excited state energy from the quantum dots into bulk solution, thus opening the door to a wide range of potential applications such as photodynamic therapy, phtovoltaic devices, and molecular electronics.

1. Subcutaneous record-keeping:

In December 2019, Robert S. Langer and his team developed and patented a technique whereby transdermal patches could be used to apply an identification tattoo to people with invisible ink to store information subcutaneously. This was presented as a boon to "developing nations" where lack of infrastructure means an absence of medical records. The technology, which is assigned to the Massachusetts Institute of Technology, uses a "quantum dot dye that is delivered, in this case along with a vaccine, by a microneedle patch." The research "was funded by the Bill and Melinda Gates Foundation and the Koch Institute for Integrative Cancer Research.”

2. Biology:



In modern biological analysis, various kinds of organic dyes are used. However, as technology advances, greater flexibility in these dyes is sought. 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 extinction coefficient combined with a comparable quantum yield to fluorescent dyes) as well as their stability (allowing much less photobleaching). It has been estimated that quantum dots are 20 times brighter and 100 times more stable than traditional fluorescent reporters. For single-particle tracking, the irregular blinking of quantum dots is a minor drawback. However, there have been groups which have developed quantum dots which are essentially nonblinking and demonstrated their utility in single-molecule tracking experiments.

The use of quantum dots for highly sensitive cellular imaging has seen major advances. The improved photostability of quantum dots, for example, allows the acquisition of many consecutive focal-plane images that can be reconstructed into a high-resolution three-dimensional image. Another application that takes advantage of the extraordinary photostability of quantum dot probes is the real-time tracking of molecules and cells over extended periods of time. Antibodies, streptavidin, peptides, DNA, nucleic acid aptamers, or small-molecule ligands can be used to target quantum dots to specific proteins on cells. Researchers were able to observe quantum dots in lymph nodes of mice for more than 4 months.

Quantum dots can have antibacterial properties similar to nanoparticles and can kill bacteria in a dose-dependent manner. One mechanism by which quantum dots can kill bacteria is through impairing the functions of antioxidative system in the cells and down regulating the antioxidative genes. In addition, quantum dots can directly damage the cell wall. Quantum dots have been shown to be effective against both gram- positive and gram-negative bacteria.

Semiconductor quantum dots have also been employed for in vitro imaging of pre-labelled cells. The ability to image single-cell migration in real time is expected to be important to several research areas such as embryogenesis, cancer metastasis, stem cell therapeutics, and lymphocyte immunology.

One application of quantum dots in biology is as donor fluorophores in Förster resonance energy transfer, where the large extinction coefficient and spectral purity of these fluorophores make them superior to molecular fluorophores. It is also worth noting that the broad absorbance of QDs allows selective excitation of the QD donor and a minimum excitation of a dye acceptor in FRET-based studies. The applicability of the FRET model, which assumes that the Quantum Dot can be approximated as a point dipole, has recently been demonstrated.

The use of quantum dots for tumour targeting under in vivo conditions employ two targeting schemes: active targeting and passive targeting. In the case of active targeting, quantum dots are functionalized with tumour-specific binding sites to selectively bind to tumour cells. Passive targeting uses the enhanced permeation and retention of tumour cells for the delivery of quantum dot probes. Fast-growing tumour cells typically have more permeable membranes than healthy cells, allowing the leakage of small nanoparticles into the cell body. Moreover, tumour cells lack an effective lymphatic drainage system, which leads to subsequent nanoparticle accumulation.

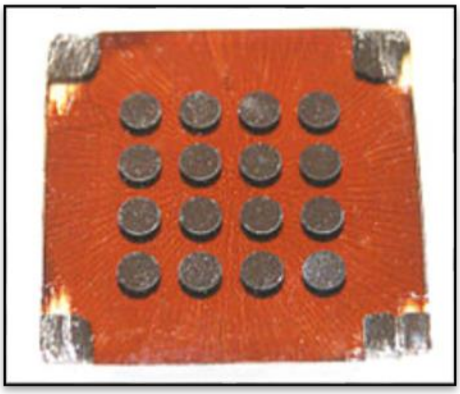
Quantum dot probes exhibit in vivo toxicity. For example, CdSe nanocrystals are highly toxic to cultured cells under UV illumination, because the particles dissolve, in a process known as photolysis, to release toxic cadmium ions into the culture medium. In the absence of UV irradiation, however, quantum dots with a stable polymer coating have been found to be essentially nontoxic. Hydrogel encapsulation of quantum dots allows for quantum dots to be introduced into a stable aqueous solution, reducing the possibility of cadmium leakage. Then again, only little is known about the excretion process of quantum dots from living organisms.

In another potential application, quantum dots are being investigated as the inorganic fluorophore for intra-operative detection of tumours using fluorescence spectroscopy.

Delivery of undamaged quantum dots to the cell cytoplasm has been a challenge with existing techniques. Vector-based methods have resulted in aggregation and endosomal sequestration of quantum dots while electroporation can damage the semi-conducting particles and aggregate delivered dots in the cytosol. Via cell squeezing, quantum dots can be efficiently delivered without inducing aggregation, trapping material in endosomes, or significant loss of cell viability. Moreover, it has shown that individual quantum dots delivered by this approach are detectable in the cell cytosol, thus illustrating the potential of this technique for single-molecule tracking studies.

3. Photovoltaic devices:

Spin-cast quantum dot solar cell built by the Sargent Group at the University of Toronto. The metal disks on the front surface are the electrical connections to the layers below.



The tunable absorption spectrum and high extinction coefficients of quantum dots make them attractive for light harvesting technologies such as photovoltaics. Quantum dots may be able to increase the efficiency and reduce the cost of today's typical silicon photovoltaic cells. According to an experimental report from 2004, quantum dots of lead selenide (PbSe) can produce more than one exciton from one high-energy photon via the process of carrier multiplication or multiple exciton generation (MEG). This compares favourably to today's photovoltaic cells which can only manage one exciton per high-energy photon, with high kinetic energy carriers losing their energy as heat. On the other hand, the quantum-confined ground-states of colloidal quantum dots (such as lead sulphide, PbS) incorporated in wider-bandgap host semiconductors (such as perovskite) can allow the generation of photocurrent from photons with energy below the host bandgap, via a two-photon absorption process, offering another approach (termed intermediate band, IB) to exploit a broader range of the solar spectrum and thereby achieve higher photovoltaic efficiency.

Colloidal quantum dot photovoltaics would theoretically be cheaper to manufacture, as they can be made using simple chemical reactions.

4. Quantum dot only solar cells:

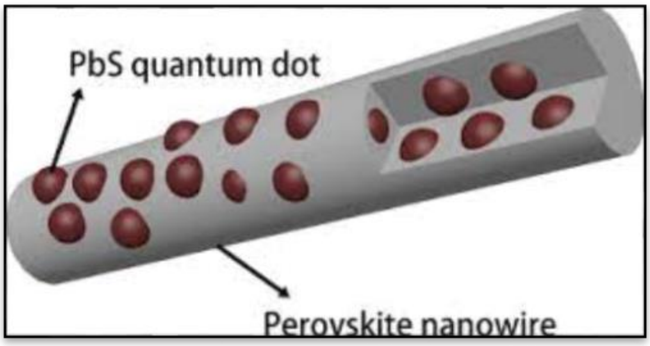
Aromatic self-assembled monolayers (SAMs) (such as 4-nitrobenzoic acid) can be used to improve the band alignment at electrodes for better efficiencies. This technique has provided a record power conversion efficiency (PCE) of 10.7%. The SAM is positioned between ZnO–PbS colloidal quantum dot (CQD) film junction to modify band alignment via the dipole moment of the constituent SAM molecule, and the band tuning may be modified via the density, dipole and the orientation of the SAM molecule.

5. Quantum dot in hybrid solar cells:

Colloidal quantum dots are also used in inorganic–organic hybrid solar cells. These solar cells are attractive because of the potential for low-cost fabrication and relatively high efficiency. Incorporation of metal oxides, such as ZnO, TiO2, and Nb2O5 nanomaterials into organic photovoltaics have been commercialized using full roll-to-roll processing. A 13.2% power conversion efficiency is claimed in Si nanowire/PEDOT:PSS hybrid solar cells.

6. Quantum dot with nanowire in solar cells:

Another potential use involves capped single-crystal ZnO nanowires with CdSe quantum dots, immersed in mercaptopropionic acid as hole transport medium in order to obtain a QD-sensitized solar cell. The morphology of the nanowires allowed the electrons to have a direct pathway to the photoanode. This form of solar cell exhibits 50–60% internal quantum efficiencies.



Nanowires with quantum dot coatings on silicon nanowires (SiNW) and carbon quantum dots. The use of SiNWs instead of planar silicon enhances the antiflection properties of Si. The SiNW exhibits a light-trapping effect due to light trapping in the SiNW. This use of SiNWs in conjunction with carbon quantum dots resulted in a solar cell that reached 9.10% PCE.

Graphene quantum dots have also been blended with organic electronic materials to improve efficiency and lower cost in photovoltaic devices and organic light emitting diodes (OLEDs) compared to graphene sheets. These graphene quantum dots were functionalized with organic ligands that experience photoluminescence from UV–visible absorption.

7. Light-emitting diodes:

Several methods are proposed for using quantum dots to improve existing light-emitting diode (LED) design, including quantum dot light-emitting diode (QD-LED or QLED) displays, and quantum dot white-light-emitting diode (QD-WLED) displays. Because quantum dots naturally produce monochromatic light, they can be more efficient than light sources which must be colour filtered. QD-LEDs can be fabricated on a silicon substrate, which allows them to be integrated onto standard silicon-based integrated circuits or microelectromechanical systems.

8. Quantum dot displays:

Quantum dots are valued for displays because they emit light in very specific Gaussian distributions. This can result in a display with visibly more accurate colours.

A conventional colour liquid crystal display (LCD) is usually backlit by fluorescent lamps (CCFLs) or conventional white LEDs that are colour filtered to produce red, green, and blue pixels. Quantum dot displays use blue-emitting LEDs rather than white LEDs as the light sources. The converting part of the emitted light is converted into pure green and red light by the corresponding colour quantum dots placed in front of the blue LED or using a quantum dot infused diffuser sheet in the backlight optical stack. Blank pixels are also used to allow the blue LED light to still generate blue hues. This type of white light as the backlight of an LCD panel allows for the best colour gamut at lower cost than an RGB LED combination using three LEDs.

Another method by which quantum dot displays can be achieved is the electroluminescent (EL) or electro-emissive method. This involves embedding quantum dots in each individual pixel. These are then activated and controlled via an electric current application. Since this is often light emitting itself, the achievable colours may be limited in this method. Electro-emissive QD-LED TVs exist in laboratories only.

The ability of QDs to precisely convert and tune a spectrum makes them attractive for LCD displays. Previous LCD displays can waste energy converting red-green poor, blue-yellow rich white light into a more balanced lighting. By using QDs, only the necessary colours for ideal images are contained in the screen. The result is a screen that is brighter, clearer, and more energy-efficient. The first commercial application of quantum dots was the Sony XBR X900A series of flat panel televisions released in 2013.

In June 2006, QD Vision announced technical success in making a proof-of-concept quantum dot display and show a bright emission in the visible and near infrared region of the spectrum. A QD-LED integrated at a scanning microscopy tip was used to demonstrate fluorescence near-field scanning optical microscopy (NSOM) imaging.

9. Photodetector devices:

Quantum dot photodetectors (QDPs) can be fabricated either via solution-processing, or from conventional single-crystalline semiconductors. Conventional single-crystalline semiconductor QDPs are precluded from integration with flexible organic electronics due to the incompatibility of their growth conditions with the process windows required by organic semiconductors. On the other hand, solution-processed QDPs can be readily integrated with an almost infinite variety of substrates, and also postprocessed atop other integrated circuits. Such colloidal QDPs have potential applications in visible- and infrared-light cameras, machine vision, industrial inspection, spectroscopy, and fluorescent biomedical imaging.

10. Photocatalysts:

Quantum dots also function as photocatalysts for the light driven chemical conversion of water into hydrogen as a pathway to solar fuel. In photocatalysis, electron hole pairs formed in the dot under band gap excitation drive redox reactions in the surrounding liquid. Generally, the photocatalytic activity of the dots is related to the particle size and its degree of quantum confinement. This is because the band gap determines the chemical energy that is stored in the dot in the excited state. An obstacle for the use of quantum dots in photocatalysis is the presence of surfactants on the surface of the dots. These surfactants (or ligands) interfere with the chemical reactivity of the dots by slowing down mass transfer and electron transfer processes. Also, quantum dots made of metal chalcogenides are chemically unstable under oxidizing conditions and undergo photo corrosion reactions.

QUANTUM DOTS AND HEALTH AND SAFETY:

Some quantum dots pose risks to human health and the environment under certain conditions. Notably, the studies on quantum dot toxicity have focused on particles containing cadmium and have yet to be demonstrated in animal models after physiologically relevant dosing. In vitro studies, based on cell cultures, on quantum dots (QD) toxicity suggest that their toxicity may derive from multiple factors including their physicochemical characteristics (size, shape, composition, surface functional groups, and surface charges) and their environment. Assessing their potential toxicity is complex as these factors include properties such as QD size, charge, concentration, chemical composition, capping ligands, and also on their oxidative, mechanical, and photolytic stability.

Many studies have focused on the mechanism of QD cytotoxicity using model cell cultures. It has been demonstrated that after exposure to ultraviolet radiation or oxidation by air, CdSe QDs release free cadmium ions causing cell death. Group II–VI QDs also have been reported to induce the formation of reactive oxygen species after exposure to light, which in turn can damage cellular components such as proteins, lipids, and DNA. Some studies have also demonstrated that addition of a ZnS shell inhibits the process of reactive oxygen species in CdSe QDs. Another aspect of QD toxicity is that there are, in vivo, size-dependent intracellular pathways that concentrate these particles in cellular organelles that are inaccessible by metal ions, which may result in unique patterns of cytotoxicity compared to their constituent metal ions. The reports of QD localization in the cell nucleus present additional modes of toxicity because they may induce DNA mutation, which in turn will propagate through future generation of cells, causing diseases.

Although concentration of QDs in certain organelles have been reported in in vivo studies using animal models, no alterations in animal behaviour, weight, haematological markers, or organ damage has been found through either histological or biochemical analysis. These findings have led scientists to believe that intracellular dose is the most important determining factor for QD toxicity. Therefore, factors determining the QD endocytosis that determine the effective intracellular concentration, such as QD size, shape, and surface chemistry determine their toxicity. Excretion of QDs through urine in animal models also have demonstrated via injecting radio-labelled ZnS-capped CdSe QDs where the ligand shell was labelled with 99mTc. Though multiple other studies have concluded retention of QDs in cellular levels, exocytosis of QDs is still poorly studied in the literature.

While significant research efforts have broadened the understanding of toxicity of QDs, there are large discrepancies in the literature, and questions still remain to be answered. Diversity of this class of material as compared to normal chemical substances makes the assessment of their toxicity very challenging. As their toxicity may also be dynamic depending on the environmental factors such as pH level, light exposure, and cell type, traditional methods of assessing toxicity of chemicals such as LD50 are not applicable for QDs. Therefore, researchers are focusing on introducing novel approaches and adapting existing methods to include this unique class of materials. Furthermore, novel strategies to engineer safer QDs are still under exploration by the scientific community. A recent novelty in the field is the discovery of carbon quantum dots, a new generation of optically active nanoparticles potentially capable of replacing semiconductor QDs, but with the advantage of much lower toxicity.

ADVANTAGES OF QUANTUM DOTS:

The latest advances in technology have shown that QDs can really make valuable contributions to a wide range of applications substituting for many of the bulk, expensive, and inefficient materials.

- Quantum Dot formations absorb photons of light and then re-emit longer wavelength photons for a period of time. The high level of control possible over the size of the dot produced provides very precise control over the wavelength of the re-emitted photon. That means that the colour of the light emitted from the QD can actually be manipulated without significant cost or the use of high-end technology. Following this procedure, a full range of QDs can be manufactured, each with a narrow distinct emission spectrum.

- Another great benefit is the fact that they only require a small amount of energy in order to be excited and this can be achieved by a single blue or ultraviolet wavelength beam, regardless of the QD size. Both attributes reduce the costs dramatically.

- The high photostability and brightness of QDs make them suitable for high sensitivity applications like fluorescent tagging and live-cell imaging. Their fluorescence properties and their high resistance to metabolic degradation enable a wider range of experiments to be performed ignoring possible time barriers.

- QDs can be used in various forms, e.g., as small crystals in liquid solutions, as quantum dust, and in bead form. All these existing forms make their range of applications even wider.

- Another great aspect of QD manufacturing is that there are multiple methods to develop them easily and cost effectively. These methods include lithographic techniques, epitaxial techniques, and colloidal synthesis.

DISADVANTAGES OF QUANTUM DOTS:

Although the use of QDs is not so extensive yet, potential problems may arise during their application and manufacturing process.

- A potential drawback when used in biological applications is the fact that due to their large physical size, they cannot diffuse across cellular membranes. The delivery process may actually be dangerous for the cell and even result in destroying it. In other cases, a QD may be toxic for the cell and inappropriate for any biological application.

- Their quite extended lifetime may be a hindrance to certain applications that require QDs to biodegrade immediately after the experiment has been performed. In certain cases, however it is possible to remove the QDs by simply washing the cells with appropriate solutions.

- Additionally, Quantum Dots may blink and become invisible. Certain drawbacks on the QD surface may lead to quantum yield deterioration, meaning that the ratio of the emitted to the absorbed energy is rather low. Their low transmittance may stay undetectable or may demand high-sensitivity detection systems.

- In display and monitor industry, QDs are expected to be used in a new LED (light-emitting diode) variation, the QD-LEDs. However, the manufacturing of blue emitting QDs is a difficult process. It requires smaller sizes than the rest of the colour emitting dots and an amplified emission compared to the other colours, so that the human eye can detect the same signal.

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