Introductory Information about Quantum Dots and their Applications

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Abstract:

Quantum dots (QDs), a type of nanoparticles, have displayed promising applications within many scientific fields. A QD is a nanoscale semiconductor particle with unique quantum mechanical properties. These tiny structures, typically ranging from 1 to 10 nanometers in diameter, exhibit distinct electronic and optical behaviors due to their size-dependent quantum confinement effects. Their applications improve upon quality, energy consumption, and efficiency in LEDs, batteries, catalysts, solar energy, and more. This review article goes over the fundamentals of nanochemistry as a whole, before proceeding into more in-depth procedures on synthesizing quantum dots and delving into various applications today. The key points of this article are to introduce scholars who are new to the field of quantum dots in the fundamentals of quantum chemistry before elaborating on the improvements quantum dots have brought to many fields. This article covers in-depth enough to grasp most concepts behind these applications, but as a whole, this field is still relatively new, in which case new applications and improvements of quantum dots can be found. In the future, quantum dots may become a key to advancing society, with possible applications in medicinal processes, more efficient energy storage, better energy generation, and quantum computing, in addition to what QDs already improved within those fields.

1. Introduction:

Discovered in 1982 by Alexey Ekimov and Valerii Kudryavtsev, QDs have been making a bigger presence in the world as scientists discover more about them [1]. An example of the application of QDs can be found in the quest for sustainable and efficient energy solutions, the field of solar cell technology has witnessed a paradigm shift with the emergence of quantum dot solar cells [2]. As our reliance on renewable energy deepens, understanding the merits and challenges posed by quantum dot solar cells in comparison to their conventional counterparts becomes pivotal. QDs have also been shown to be prevalent in bio-luminescent applications, lighting, energy, catalytic usage, and more. Their properties mainly depend on size, but ligands and shells have also been shown to affect the properties of these nanoparticles. The key model for understanding these properties is the "particle-in-the-box" idea, which then explains band gaps and how they can contribute to allowing QDs to display semiconductor properties [3]. Due to the specific ways of manufacturing QDs, many of their properties can be controlled, specifically band gaps, which allow for control of optical and conductive properties. These have shown to be key in improving many of the applications described above. For catalysts, QDs allow for a cheaper and possibly better alternative to expensive catalysts like platinum or palladium [4]. For lighting, the adjustable optical properties of LEDs to quantum dot light-emitting diodes (QLED), have a wider color spectrum, better color, more energy efficiency, and other benefits. From these two shallow examples, one can already notice the many contributions quantum dots have to society. This literature review is aimed at providing a dense but still understandable start to the many sides of QDs. It is meant to be a simplification of pre-existing research such that new developments in QDs can refer to this document as an explanation for those dipping their toes into such a field. The scope of this review is to cover most fundamentals of QDs and capture the most important details and novel applications of QDs.

This review will cover a surface-level introduction to the fundamentals needed to understand quantum dots and their manipulative properties, while also giving insight on the many applications of quantum dots in our current society. Basic ideas like particle in a box, band theory, and a few other topics will be discussed first in section two, continuing into the general synthesis of quantum dots and the factors influencing quantum dot properties due to synthesis. After that, we will explore the improvements quantum dots have brought into LEDs followed by a dive into photovoltaic applications of light absorption for solar cells and efficiency improvements in sections five and six. To wrap up the article we discuss the application of quantum dots into batteries and fuel cells.

2. Quantum Dot Fundamentals

2.1 Wave-Particle Duality

Wave-particle duality is the theory that particles can sometimes behave like waves and waves can behave like particles. A simple example of this theory is the wave nature of light, which is Young's double slit experiment, where a diffraction pattern was displayed when light was shined through two slits. If light had been simply a ray of photons (particles in light), then no diffraction pattern would have been shown. After further research, de Broglie predicted that all moving objects with mass will display a wavelength and thus exhibit wave-like properties.

$$\lambda = \frac{hc}{mvc} = \frac{h}{mv} \tag{1}$$

Lambda refers to wavelength; h refers to Planck's constant; m refers to mass; v refers to velocity; and c refers to the speed of light

With Eq. 1 the idea that all moving objects with a mass will have a wavelength is then dubbed the de Broglie wavelength. Inspecting this equation it is key to notice that objects with larger masses will have near zero wavelength, which explains why we cannot notice the wavelengths of moving objects with the naked eye, but objects on the nanoscale can exhibit new properties. These properties (which are beyond the scope of this review), include ideas like quantum tunneling [5], where particles can pass through barriers deemed impossible due to the wave-like nature; quantum interference [6], which encapsulates the constructive/destructive nature of waves, helping determine particle distribution; nanophotonic effects, where light-matter interactions become even stranger with an ability to contain light within subwavelength dimensions. A good way to visualize wave-particle duality is with the analogy of a pool and rocks. When you throw a rock into a pool, the water surface would ripple in a wavelike fashion, propagating outwards. If you instead tried to skip the rock, the rock seems to have a trajectory, while still leaving waves behind on each skip. If we notice how the rock has a continuous path and is more localized, similar to a particle. However, it also leaves behind many ripples, exhibiting wave-like properties with interference, diffraction, and more.

2.2 Particle in a Box Model

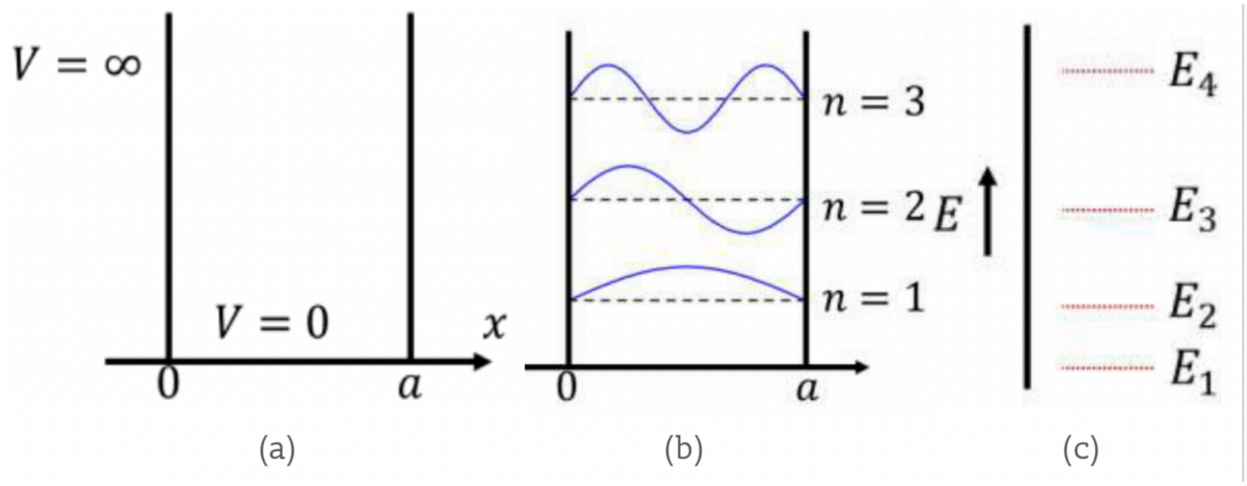


***Figure 1**. Model of a particle-in-a-box with infinite potentials outside the box and zero potential inside **(a)**. The solution to the particle-in-a-box model results in simple sinusoidal wave function **(b)** and discrete energy levels **(c)**. Reproduced from Arabboyevich, M. I. (2023, June 20). QUANTUM DOT PHYSICS. https://bestpublication.org/index.php/ozf/article/view/7070*

The "particle-in-a-box" model is one of the simplest models to explain the properties of the band gap within quantum dots and is a derivation from Schrodinger's equation. To begin, imagine an electron that is bound within a box of length *a*. Outside the box, there is infinite potential while within the box there is no potential (**Fig. 1a**). An analogy for this situation would be something like a guitar, where the ends of the strings are the boundary for our box. Now when you pluck the string to make noises, a pattern will emerge within the string, similar to the energy patterns of our particle within the box. The specific notes that the guitar string can create can be further expanded within the analogy to represent the specific energy levels the particle can cover, creating a dead zone where no particle can exist. In this analogy, the guitar string serves as a visual representation of the confined space (the box) where the particle's wave function exists. The quantized energy levels of the particle correspond to the quantized frequencies of the guitar string's vibrations. Just as the guitar string can only vibrate at certain allowed frequencies, the particle in a box can only exist at certain allowed energy levels [1]. For a more mathematical way to explain “particle-in-a-box”, refer to [1].

After creating the visualization of Schrodinger’s equation upon our model of a particle in a box (**Fig. 1b**), we can notice a few trends. Specifically, the electron is bound to specific energy levels (**Fig. 1c**) and is forbidden in spaces between those levels. Additionally, a quadratic relationship can be drawn between the energy and the size of the box. Given these two ideas, we can draw the basis for the size-dependent properties of QDs and the relationship with the band gap.

2.3 Band Theory

With the creation of our particle-in-a-box model and the idea of energy levels, we can begin explaining band theory. Band theory is mainly dependent on the theory of molecular orbitals, which is a method of categorizing electrons from an atom or molecule into possible energy levels. Molecular orbital theory can be used to explain properties that other theories can’t, such as the paramagnetism of oxygen (O2 can be attracted to magnets in a liquid state). To expand this into band theory, one must step up the number of orbitals to visualize a larger trend. With lots of energy levels to utilize in molecular orbitals, it is easier to categorize them into “bands” where molecular orbitals start becoming unrecognizable due to how indifferent their energy levels are. To simplify, a band is just a collection of the orbital levels. The bands that electrons commonly inhabit at a ground state are referred to as the valence band, and empty energy levels are referred to as the conduction band (**Fig. 2a**).

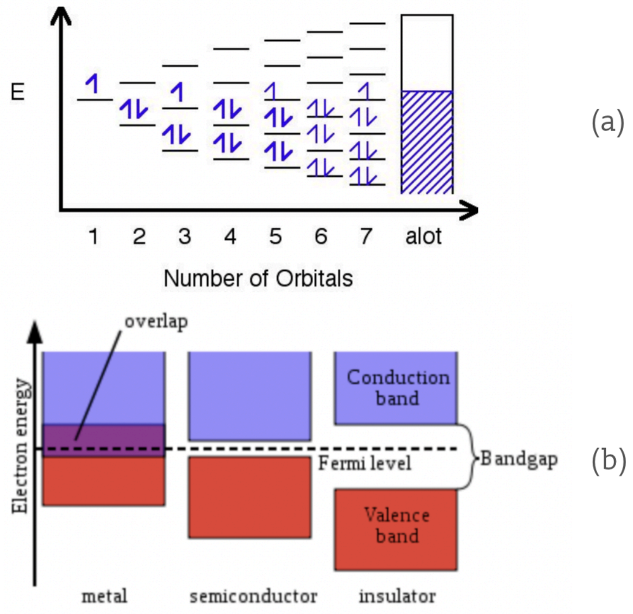


Figure 2. *Model of distinct energy levels and electrons at ground state filling up orbitals, and a simplification of similar energy levels into a band **(a)**. Model of band structures of different conductive materials, displaying the difference in band gaps between materials with different conductivities **(b)**.*

*(**Figure 2a.**) Reproduced from Libretexts. (2021, August 3). 12.2D: Band Theory of Semiconductors. Chemistry LibreTexts. https://chem.libretexts.org/Courses/Kutztown_University_of_Pennsylvania/CHM_320%3A_Advanced_Inorganic_Chemistry_textbook/12%3A_Structures_and_Energetics_of_Metallic_and_Ionic_solids/12.02%3A_Bonding_in_Metals_and_Semicondoctors/12.2D%3A_Band_Theory_of_Semiconductors*

*(**Figure 2b.**) Reproduced from Libretexts. (2020, July 14). 23: Band theory. Chemistry LibreTexts. https://chem.libretexts.org/Ancillary_Materials/Worksheets/Worksheets%3A_Inorganic_Chemistry/Structure_and_Reactivity_in_Organic_Biological_and_Inorganic_Chemistry/Chem_125_Worksheets/23%3A_Band_Theory*

The Fermi level displayed in (**Fig. 2b**) is the energy level at which 50% of electrons will be found. Utilizing this information, it is shown after much research that the band theory model of conductors, semiconductors, and insulators looks similar as shown above.

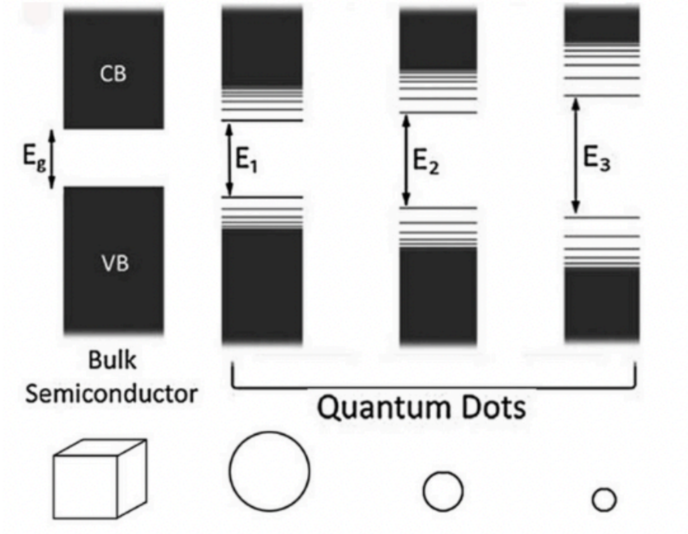


Figure 4. *Illustration of size-dependent bandgaps; Reproduced from G. Dong et al., Frontiers in Materials 2, 1 (2015).*

To pull this back to QDs, however, their band gaps are dependent upon the size of the nanoparticle due to the "particle-in-a-box" model and the de Broglie wavelength of the QDs. This helps scientists manipulate the conductive properties of QDs to their liking by manipulating the size of QDs during synthesis.

2.4 Electron-Holes

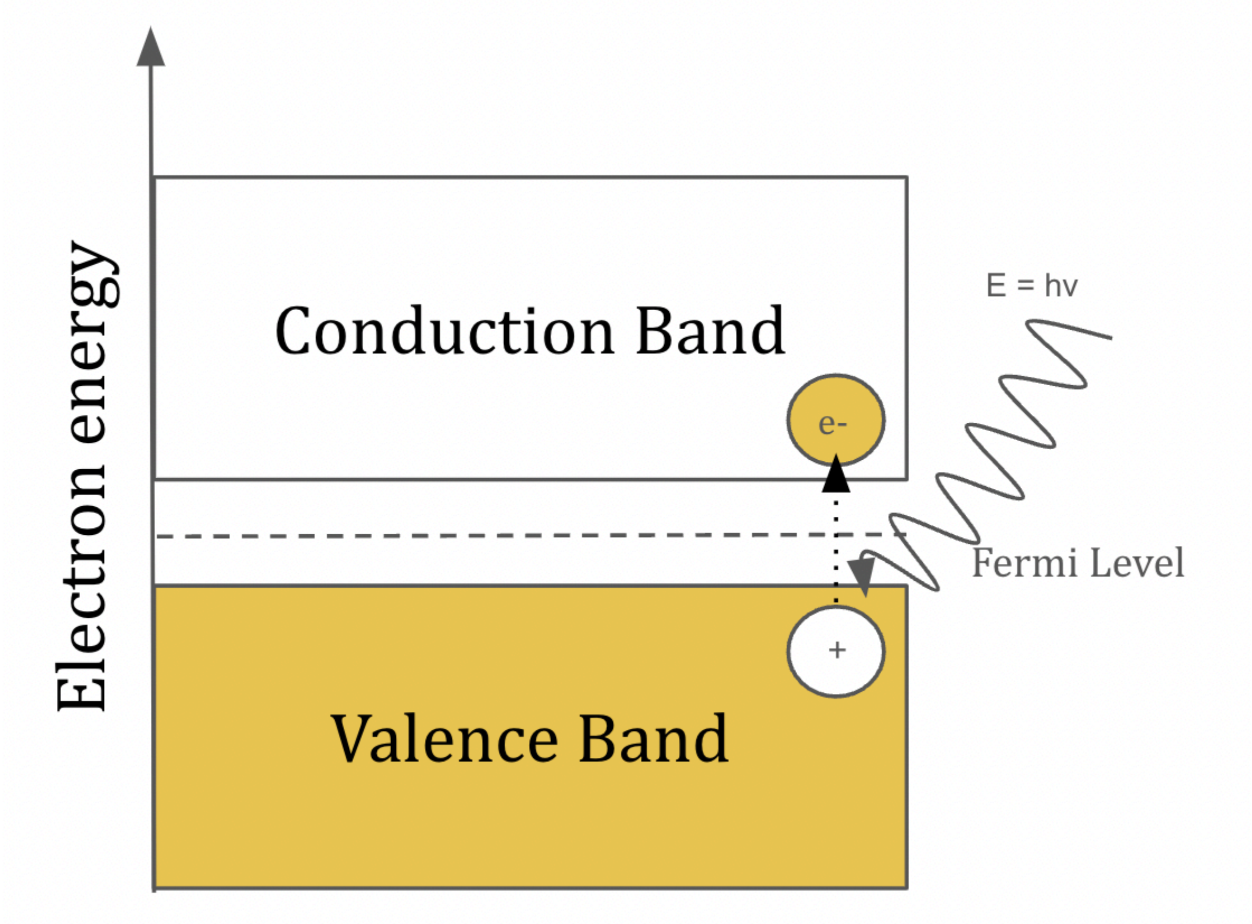


Figure 5. *Illustration of an electron in an excited state, leaving behind a positively charged hole and thus creating the conceptual pair.*

Electron-holes are a concept useful in semiconductor research, with the use of it explaining the movement of charge carriers. Continuing from the idea of the conduction band and the valence band, one must ask what happens when an electron is excited into the conduction band from the valence band. Of course, the electron jumps into the conduction band and leaves an “electron hole” within the valence band. The “electron hole” left behind can be regarded as a positive charge carrier as it’s surrounded by the other electrons within the valence band, which fill in the hole and create a flow of positive charge (as other electrons will fill in the hole that is created from the filling in of the other hole). Electron mobility in the conduction band and hole mobility in the valence band contribute to the overall electrical conductivity of the semiconductor. When an electric field is applied across a semiconductor, electrons move in the direction of the field in the conduction band, and holes move in the opposite direction in the valence band, creating an electric current. Doping is the intentional introduction of impurities into a semiconductor to modify its electrical properties. For electron-holes, doping can be used to control the concentration of electrons and holes in materials, influencing their conductivity and behavior. In quantum dots, the band structure creates more interesting electron-hole effects.

3. Quantum Dot Production

3.1 Techniques for Quantum Dot Synthesis

3.1.1 Colloidal synthesis

Colloidal synthesis of quantum dots follows a pretty general process of

1. Selecting reactant materials (typically metal cations and chalcogens), and mixing said materials in solution
2. Heating the solution (100 to 300 degrees Celcius) to start the nucleation phase, where small nanocrystals begin forming from the clumping of atoms
3. Then the synthesis enters the phase of growth, where factors like the temperature and reactant concentration come heavily into play to control the growth rate and thus the size
4. At this stage comes shape and size control + surface passivation, where one could add ligands or capping agents (e.g. Oleylamine) to prevent the growth of nanoparticles, "capping" them at a certain size that is needed
5. The resulting solution is then purified of possible side products and starting reactants

This process also allows scientists to take aliquots of the solution mid-reaction to obtain quantum dots at a series of sizes. One of the Nobel Prize in Chemistry of 2023 scientists Moungi Bawendi developed this method, later dubbed the hot-injection synthesis method [1]. Going into more detail of the hot-injection synthesis method:

1. Pyrolysis of organometallic reagents into a hot coordinating solvent with a high boiling point (nucleation phase)
2. The rapid drop in temperature and dilution of supersaturated precursor reactants lead to controlled growth
3. Reheating of solution to obtain desired growth speed to stabilize colloidal dispersion
4. NPs can then be filtered/selected via size-dependent precipitation and purification

3.1.2 Organometallic synthesis

Organometallic synthesis of NPs can be generalized into the idea of reducing organometallic compounds to produce metallic NPs. Commonly, this is done through either chemical reduction through the use of reducing agents like borohydrides or hydrazine or others, with the other common method being thermal reduction using heat to decompose organometallic materials into metallic NPs [7].

Examples:

Hydrolysis of Titanium Isopropoxide (Ti{OCH(CH3)2}4) into Titanium Dioxide NPs

Thermal decomposition or reduction of ferrocene(Fe(C5H5)2) into Iron NPs

In general, organometallic synthesis involves reducing the organometallic material into just metallic nanoparticles [8].

3.1.3 Other methods

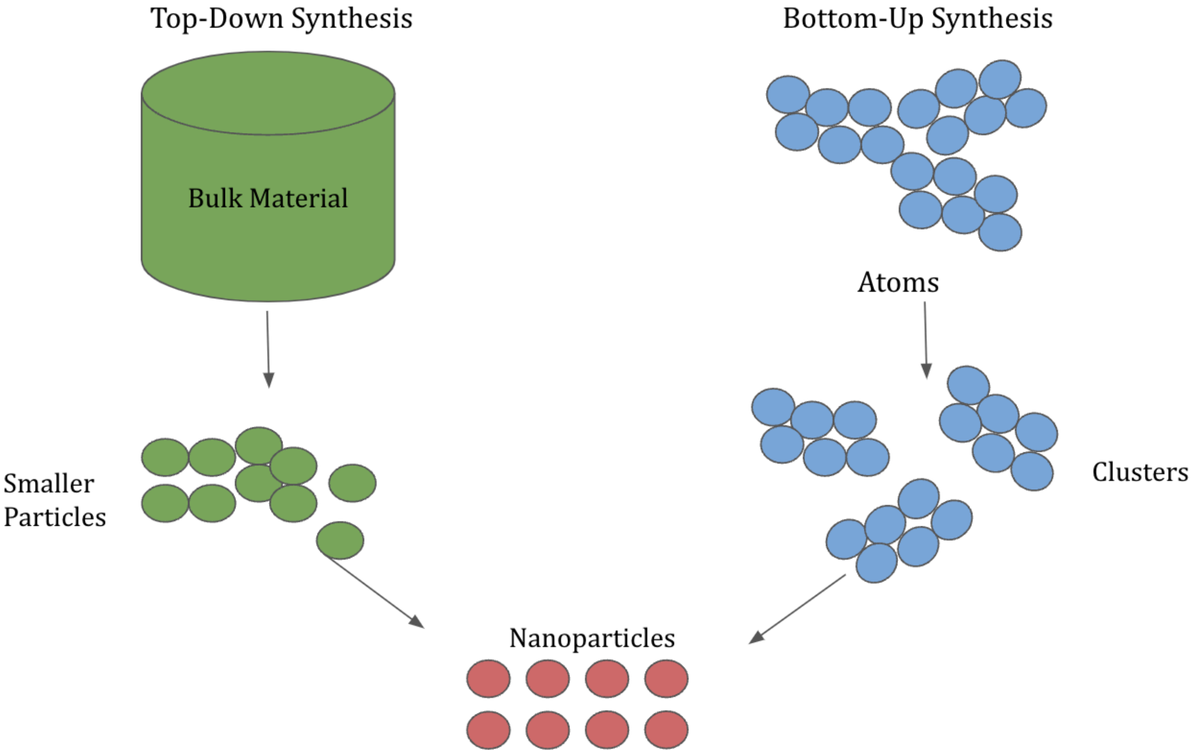


Figure 6. *Illustration of the two categories of nanoparticle synthesis*

Synthesis of NPs can generally be categorized into two main groups: bottom-up synthesis and top-down synthesis, as depicted by (**Fig. 6**). Bottom-up synthesis refers to the building-up of nanoparticles from smaller components, with examples being sol-gel (injection/colloidal methods) and chemical reduction, where the NPs are synthesized through the aggregation of atoms or molecules into eventual NPs. Top-down synthesis is the creation of NPs by breaking down larger materials into NPs, with the main example today being the creation of semiconductor chips/wafers through lithography or other methods.

3.2 Factors Influencing Quantum Dot Properties

3.2.1 Size control

Size control is important because of what we covered before (De Broglie Wavelengths and band gaps), and it's a huge part of what scientists spend to discover from experimenting with NPs. The ability to control a majority of properties of NPs through size control is very important.

Key factors for size control are precursor concentrations (and also what the precursors are), reaction temperature, and surfactants (there are SO many things that affect size control).

For the choice of precursor and precursor concentrations, the explanation is that: different precursor materials may react differently, and the concentration of precursor solutions affects the rate of reaction and thus the dispersion of nanoparticles within the solution, which can then affect the aggregation of said nanoparticles and the growth rate, resulting in different sizes if not controlled properly.

The reaction temperature can affect the size of nanoparticles as well mainly through how increased temperature leads to increased reaction kinetics, which leads to the creation of smaller NPs due to more nucleation and faster growth, but can also lead to larger NPs if not controlled.

With surfactants, NPs can be controlled to a greater degree as it’s the addition of growth-restricting materials, kinda like when you’re boiling eggs and you drop them into ice water to stop the cooking and end up with a perfectly soft-boiled egg 😀

In the same sphere, ligands, surfactants, and capping agents, (dendrimers, polymeric stabilizers, polyoxometalates, etc) can be utilized like the ice water to inhibit NP growth and stop it at a certain size.

3.2.2 Surface Functionalization

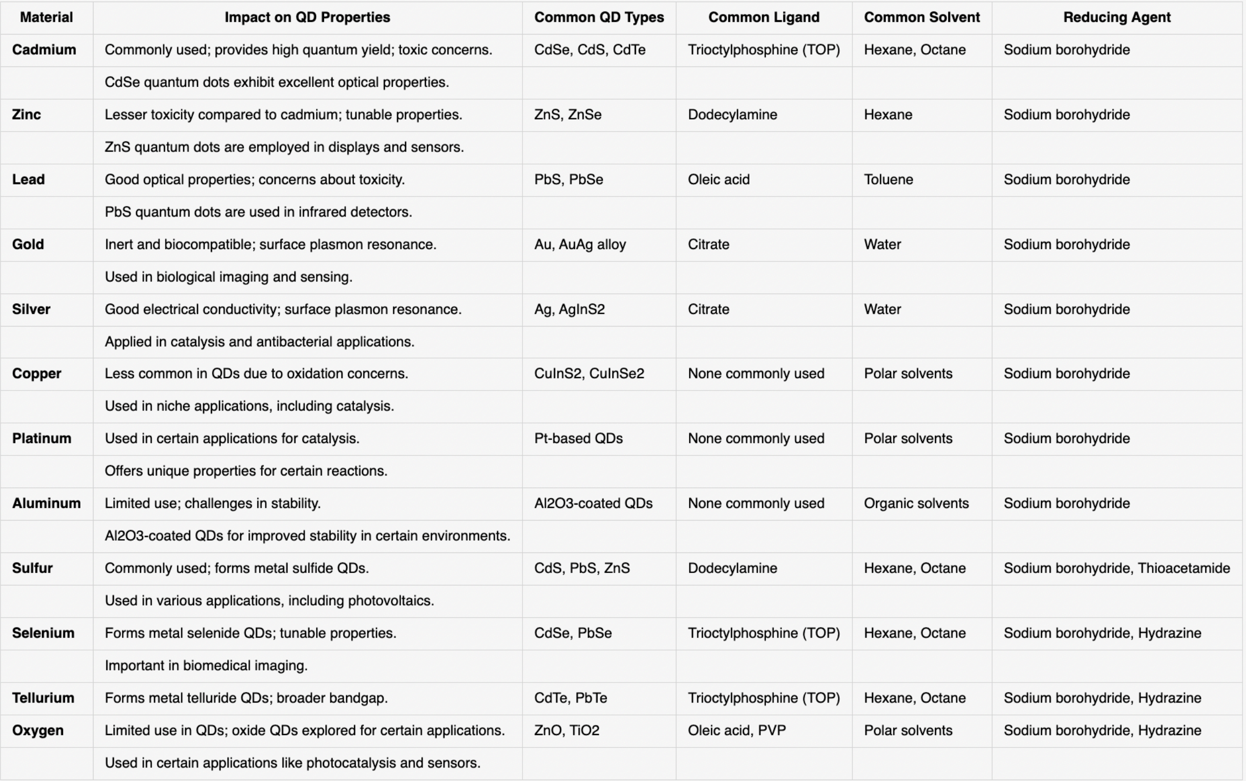
Surface functionalization is mainly achieved through (as the name suggests), adding ligands or other attachments to the surface. This can be done through chemical functionalization through reacting attachments to the nanoparticle surface, or physical adsorption through the use of intramolecular forces like hydrogen bonding, Van Der Waal forces, etc to attach modifications to the nanoparticle surfaces. Examples of types of surface modifications include but are not limited to:

- Ligands - can help stabilize NPs, prevent agglomeration, and a few chemical properties
  - Example: Aliphatic ligands, such as alkylamines (e.g., octylamine, hexadecylamine) and alkylphosphines, provide hydrophobic coatings and enhance the quantum dots' stability in organic solvents.
- Polymers - biocompatibility, stability
  - Example: Polyvinyl Alcohol, or PVA, is a water-soluble polymer that can be used for surface functionalization of quantum dots in aqueous environments. It provides stability and prevents QD aggregation.
- Functional groups - amino, carboxyl, thiol, and hydroxyl groups, to allow for additional chemical reactivity
  - Example: Carboxyl Groups (-COOH), are often introduced through ligands like carboxylic acids or acid-functionalized polymers. They provide a negative charge on the QD surface, improving water solubility and facilitating conjugation with biomolecules.

4. Materials for Quantum Dots

4.1 Precursors for Quantum Dot Synthesis

***Table 1**. Description of precursor and the properties attached*



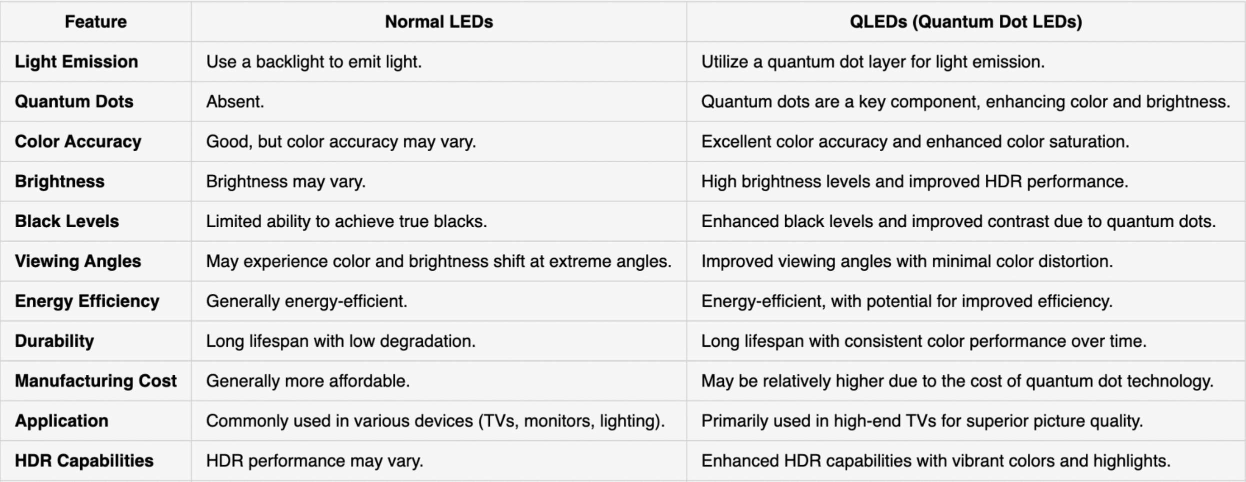
Material	Impact on QD Properties	Common QD Types	Common Ligand	Common Solvent	Reducing Agent
Cadmium	Commonly used; provides high quantum yield; toxic concerns.	CdSe, CdS, CdTe	Trioctylphosphine (TOP)	Hexane, Octane	Sodium borohydride
	CdSe quantum dots exhibit excellent optical properties.				
Zinc	Lesser toxicity compared to cadmium; tunable properties.	ZnS, ZnSe	Dodecylamine	Hexane	Sodium borohydride
	ZnS quantum dots are employed in displays and sensors.				
Lead	Good optical properties; concerns about toxicity.	PbS, PbSe	Oleic acid	Toluene	Sodium borohydride
	PbS quantum dots are used in infrared detectors.				
Gold	Inert and biocompatible; surface plasmon resonance.	Au, AuAg alloy	Citrate	Water	Sodium borohydride
	Used in biological imaging and sensing.				
Silver	Good electrical conductivity; surface plasmon resonance.	Ag, AgInS2	Citrate	Water	Sodium borohydride
	Applied in catalysis and antibacterial applications.				
Copper	Less common in QDs due to oxidation concerns.	CuInS2, CuInSe2	None commonly used	Polar solvents	Sodium borohydride
	Used in niche applications, including catalysis.				
Platinum	Used in certain applications for catalysis.	Pt-based QDs	None commonly used	Polar solvents	Sodium borohydride
	Offers unique properties for certain reactions.				
Aluminum	Limited use; challenges in stability.	Al2O3-coated QDs	None commonly used	Organic solvents	Sodium borohydride
	Al2O3-coated QDs for improved stability in certain environments.				
Sulfur	Commonly used; forms metal sulfide QDs.	CdS, PbS, ZnS	Dodecylamine	Hexane, Octane	Sodium borohydride, Thioacetamide
	Used in various applications, including photovoltaics.				
Selenium	Forms metal selenide QDs; tunable properties.	CdSe, PbSe	Trioctylphosphine (TOP)	Hexane, Octane	Sodium borohydride, Hydrazine
	Important in biomedical imaging.				
Tellurium	Forms metal telluride QDs; broader bandgap.	CdTe, PbTe	Trioctylphosphine (TOP)	Hexane, Octane	Sodium borohydride, Hydrazine
Oxygen	Limited use in QDs; oxide QDs explored for certain applications.	ZnO, TiO2	Oleic acid, PVP	Polar solvents	Sodium borohydride, Hydrazine
	Used in certain applications like photocatalysis and sensors.				

The two groups of precursors for the majority of quantum dot synthesis are metallic precursors and chalcogen precursors (**Tab. 1**), for example: Cadmium, Zinc, Lead, Sulfur, Selenium, and Tellurium [8]. But precursor refers to starting materials as a whole, so we'll also discuss stuff like ligands (covered in the part before), solvents (typically toluene, hexane, octadecane; is the medium in which synthesis is done), and reducing agents, which control the nucleation rate and NP growth.

5. Quantum dots in LEDs

5.1 Efficiency improvements

Table 2. *Comparison between normal LEDs and QLEDs*



Feature	Normal LEDs	QLEDs (Quantum Dot LEDs)
Light Emission	Use a backlight to emit light.	Utilize a quantum dot layer for light emission.
Quantum Dots	Absent.	Quantum dots are a key component, enhancing color and brightness.
Color Accuracy	Good, but color accuracy may vary.	Excellent color accuracy and enhanced color saturation.
Brightness	Brightness may vary.	High brightness levels and improved HDR performance.
Black Levels	Limited ability to achieve true blacks.	Enhanced black levels and improved contrast due to quantum dots.
Viewing Angles	May experience color and brightness shift at extreme angles.	Improved viewing angles with minimal color distortion.
Energy Efficiency	Generally energy-efficient.	Energy-efficient, with potential for improved efficiency.
Durability	Long lifespan with low degradation.	Long lifespan with consistent color performance over time.
Manufacturing Cost	Generally more affordable.	May be relatively higher due to the cost of quantum dot technology.
Application	Commonly used in various devices (TVs, monitors, lighting).	Primarily used in high-end TVs for superior picture quality.
HDR Capabilities	HDR performance may vary.	Enhanced HDR capabilities with vibrant colors and highlights.

Quantum dots have been put into use in LEDs and improved LEDs greatly due to their vast potential in optics due to the effects of band gaps (**Tab. 2**). The inclusion of quantum dots into LEDs is hence dubbed QLED. One of the key defining parts of QLEDs is their control and range, created through the scale of control scientists have over the size of quantum dots. The size of an NP is extremely important as it helps determine many characteristics, one of those being the color and optical effects of the nanoparticle. Additionally, quantum dots can be engineered to have high photoluminescence quantum yields, meaning a significant portion of the absorbed energy can be (and will be) re-emitted as light. This allows for energy saving as less energy is lost. Also, QLEDs are more stable than traditional LEDs, allowing for longevity and more reliable LEDs.

5.2 Color tuning

Color tuning refers to the idea of precisely controlling the color of a quantum dot so that you can utilize it in QLEDs, coloring stuff, or whatever you desire. The main phenomenon behind this is quantum confinement (*vide infra*). Additionally, the color can be tuned through methods such as size control, core-shell models, alloys, and doping (but there are more methods). With size control, you can once again, modify the band gaps and thus manipulate optical properties. With core-shell structures, the change in wavelength medium at the nanoscale allows for interesting tuning of optical properties. The difference in bandgap can add shifts in wavelengths resulting in different optical effects than before. Alloys allow scientists to control the band gap even more, (this is used a lot for solar cells, covered in the next section), and thus control color tuning. Doping is adding “impurities” to change properties to a chemist’s liking, a general topic, but allows for precise addition of desired properties to a substance

5.2.1 Quantum confinement

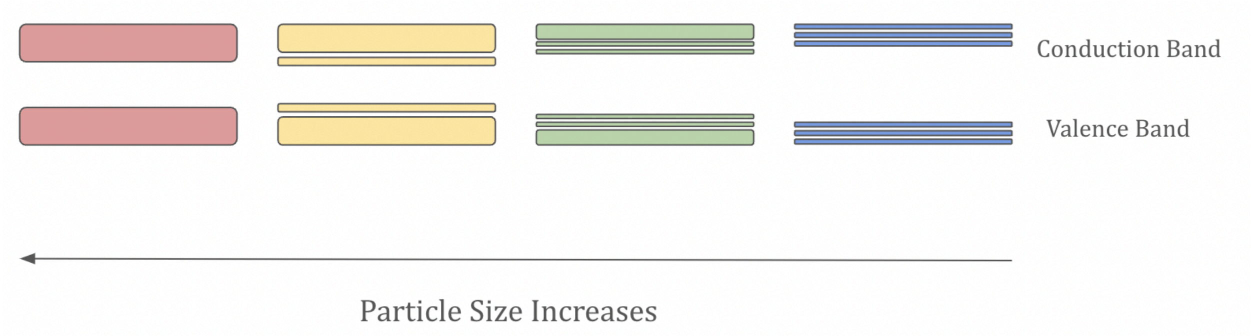


Figure 7. *Diagram depicting change in color in relation to change in particle size, due to difference in band gap*

Quantum confinement is the phenomenon that occurs when the motion charge carriers are restricted, typically due to the nanoscale of the material. This confinement creates quantized energy levels or discrete energy levels. As such, with quantum confinement effects being tunable due to the confinement being dependent on the size of the quantum dot, so comes tunable color as the manipulable band gaps create specific wavelengths of light (**Fig. 7**).

6. Quantum Dots for Solar Energy Harvesting

6.1 Multiple exciton generation (MEG)

MEG is a phenomenon exhibited by quantum dots concerning the idea of electron-holes. Generally, in a normal semiconductor, a photon can energize one electron to create an electron-hole pair, which are also known as excitons [9]. However, quantum dots can generate multiple excitons when the wavelength of the photon absorbed is greater than the size of the quantum dot, allowing for multiple charge carriers to be created from a singular photon (**Fig. 8**, further on). This creation of multiple charge carriers is more efficient in terms of energy transfer.

6.2 Quantum dots as catalysts

Catalysts are substances that increase the rate of a chemical reaction by providing an alternative pathway with lower activation energy, without being consumed or undergoing any net change themselves in the overall reaction. In other words, catalysts facilitate reactions by lowering the energy barrier that reactants must overcome to transform into products. Catalysts are key to the industrial side of chemistry as they're extremely useful to corporations for min-maxing yield and rate of reaction procedures. However, the best catalysts (platinum and palladium) are very expensive and rare. This brings in the possibility of utilizing quantum dots as typically the materials for producing quantum dots are cheaper and newer effects can be added [10]. Some examples would be cadmium sulfide (CdS) and cadmium telluride (CdTe), which have been studied for photocatalytic applications, such as hydrogen evolution reactions and pollutant degradation. Similar examples but for electrocatalysis would be quantum dots composed of materials like cobalt oxide (Co3O4), which can be used in similar reactions.

6.3 Photovoltaic applications

6.3.1 Light absorption and conversion

As stated many times above, quantum dots had a huge impact in improving appliances in the optical field. In terms of energy generation, solar cells can utilize quantum dots to great effect. MEG allows for a more efficient utilization of solar energy, as a single photon can contribute to the creation of multiple charge carriers (covered more in the next section). Essentially to generate charge, the electron-hole pair is split and utilized in a flow to generate electric current. When reaching electrodes within the solar cell, the current can then be harnessed for power. Another special advantage of quantum dots in solar cells is the ability for scientists to control the size, in which the size-tunability of quantum dots allows for more optimal band gaps for capturing a wider spectrum of solar light [11]. Scientists can also attach ligands or other structures and even customize semiconductors to include quantum dots to affect other desired properties.

6.3.2 Efficiency improvements

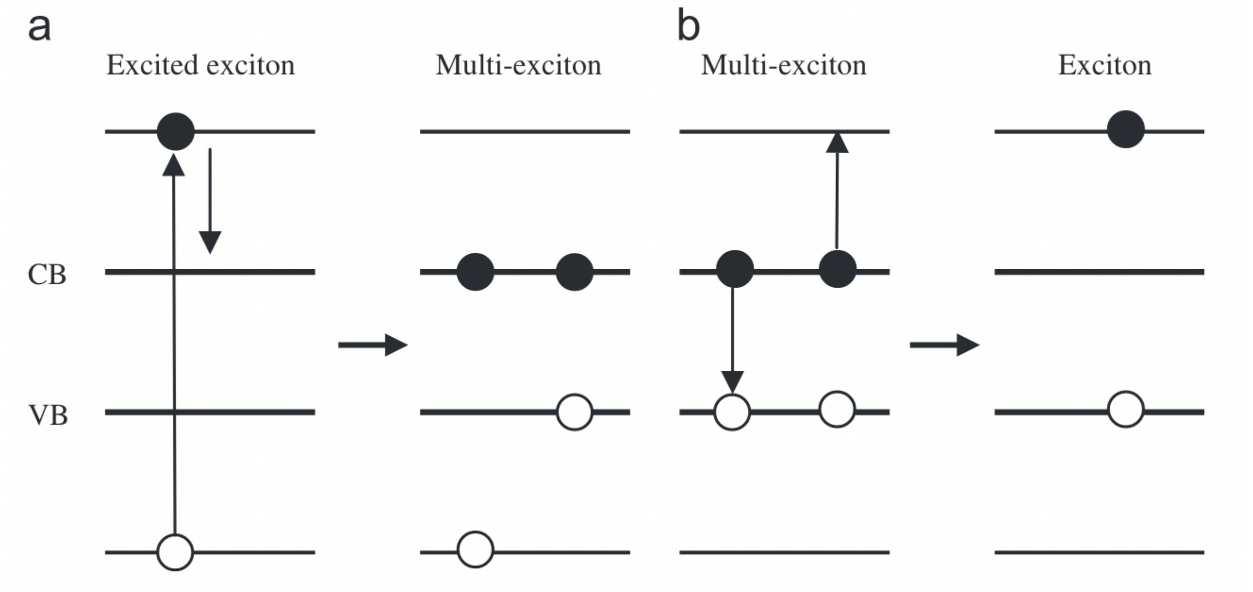


***Figure 8**. **(a)** impact ionization, **(b)** Auger process; Electrons (filled circles), holes (empty circles), conduction band (CB) and valence band (VB); Reproduced from Jun, H. K., Careem, M., & Arof, A. K. (2013). Quantum dot-sensitized solar cells—perspective and recent developments: A review of Cd chalcogenide quantum dots as sensitizers. Renewable & Sustainable Energy Reviews, 22, 148–167. https://doi.org/10.1016/j.rser.2013.01.030*

The key idea behind the possibility of efficiency improvement in solar cells is (*vide infra*), the idea of MEG. When creating multiple excitons, a phenomenon known as the Auger process can occur to recombine two or more excitons due to electrons falling back into their holes in terms of energy level (**Fig. 8b**). To counteract the Auger process, holes can be removed through a fast hole trap, which allows for more generation of excitons and less recombination.

7. Energy Storage Technologies

7.1 Quantum dots in lithium-ion batteries

7.1.1 Enhanced charge/discharge rates

A big part of quantum dots is how small they are. Let's first discuss how lithium-ion batteries work. Lithium-ion batteries, as the name suggests, utilize lithium ions to create a separation of charge that can be gathered at electrodes to create current. Essentially, lithium ions travel through an electrolyte to the cathode, leaving behind electrons in the anode and thus a separation of charge. The addition of quantum dots to this allows for incredible improvements in charge and discharge rates. The first way quantum dots can increase conductivity and general efficiency is the insane volume-to-surface area ratio that quantum dots and nanomaterials have. Due to this increased surface area, more sites for electron transfer are available, which allows for greater electron mobility and conductivity. Quantum dots can also act as really efficient charge carriers, allowing for easier transference of the charge left behind by the movement of lithium ions. Another useful method of battery enhancement using quantum dots is in electrodes, which can help stabilize the electrodes for less decay in recharging and optimize the electronic structure of the electrode, allowing for better charge and discharge.

7.1.2 Capacity improvements

A big part of a battery's capacity is its capacity retention after cycles of charging and discharging. Due to the surface area effects and very manipulative size of quantum dots, the volume expansion encountered in regular batteries can be avoided and thus decrease the decay caused by recharging batteries. A great example of nanochemistry usage in this field (not specifically quantum dots, but the idea is shown through this analogy) is the usage of nanotubes in Lithium-Silicon batteries. An amazing property of Li-Si batteries is the fact that it has a theoretical capacity of 10x other anodes, but experiences insane size expansion during recharging due to silicon's lattice structure expanding when accepting lithium ions. Researchers discovered that utilizing silicon nanowires instead of silicon film or regular particles allows for less strain on the material during the cycles of recharging (due to the size expansion) and thus allows for this amazing material to be used way more.

7.2 Hydrogen fuel cells

7.2.1 Hydrogen production

A major energy source that scientists have been trying to expand upon is the usage of hydrogen cells. These sources of energy are clean, renewable, and just a cool source overall. Essentially, hydrogen and oxygen are supplied to two separate electrodes, resulting in a transfer of electrons when hydrogen gets oxidized to produce the electrons, which then move to the opposite electrode to get utilized to produce water. The hydrogen evolution reaction (HER) is the primary process of generating hydrogen from protons and electrons. The HER typically occurs at the cathode of an electrochemical cell. The process involves the reduction of protons to form hydrogen gas. Electrocatalysts are often used to facilitate and accelerate the hydrogen evolution reaction and improve the efficiency of the cell [12]. As the HER is the creation of water utilizing a flow of electrons, if we were able to supply the hydrogen and oxygen needed from splitting water, it would be a renewable source. Where the idea is the energy needed to split water would be repurposed into electricity. So with that in mind, quantum dots can be used to harness light energy to split water, which can then in turn be used to generate electricity through the HER.

8. Conclusion

The field of quantum dots is rapidly gaining prominence across various applications, most notably in the realm of QLED technology. These minuscule entities, characterized by their tunable properties, are proving instrumental in offering unprecedented control over material characteristics. This versatility opens avenues for innovation in a spectrum of domains, extending well beyond the established applications.

Moreover, beyond the confines of this review, quantum dots are demonstrating notable utility in the realm of biomedical imaging. Specifically, their targeted application holds promise for advanced sensing capabilities within the human body, coupled with responsive fluorescence. The potential for quantum dots to discern and interact with specific materials at the nanoscale heralds a new era in biotechnology.

Looking forward, the trajectory of quantum dot research indicates a major shift towards material science. Techniques such as band gap manipulation, doping, surface modification, and material selection are being explored to yield cost-effective and superior materials tailored to specific applications. Despite their minuscule dimensions, quantum dots will exert a significant and enduring impact on society, steering technological advancements, particularly in fields such as medicine and electronics. The foray into the nanoscale landscape of quantum dots represents not merely scientific exploration but a transformative journey poised to redefine the contours of technology in the foreseeable future.

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