



Quantum Dot Physics: A Guide to Understanding QD Displays

Abstract

This whitepaper aims to establish the foundation for a thorough understanding of the science behind the quantum dot (QD) technology and its popular and promising application in quantum dot displays. Equipped with this knowledge, you will be able to confidently follow the technology evolution as the industry is making new breakthroughs and is further improving upon QD utilization in displays.

As nanotechnology has already become a vital foundation of the high-end displays, we expand upon [the topic of quantum dots](#) to examine the key properties of the QD semiconductor particles and fundamental principles of their operation.

Quantum dots fundamentals

What are quantum dots?

Quantum dots (QDs) are tiny semiconductor particles 2-10 nm (nanometers, 10^{-9}) in diameter. Because of their small size, these particles have unique optical and electrical properties. For example, when exposed to light, quantum dot crystals emit light of particular frequencies.

The size and shape of quantum dots can be precisely controlled by adjusting reaction time and conditions, thus making this nanotechnology scalable and useful for display applications.

How do quantum dots work?

Let's dig deeper into quantum physics (do not be intimidated though) to explore why quantum dots (QDs) are able to emit light and why the wavelength of the light (which determines color) they produce is contingent on the particle size.

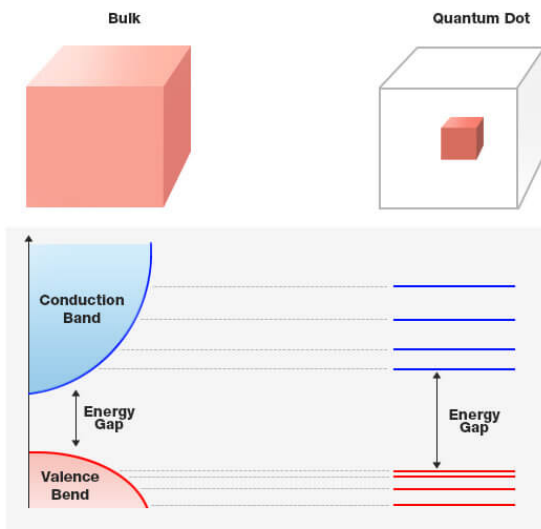
The process of light emission in QDs is called photoluminescence (abbreviated as PL), as it occurs because of the excitation by photons. Under the influence of light, photons get excited and "jump" up to a higher energy band. This is followed by the process of relaxation, during which photons can relax non-radiatively ("fall back") into a lower-lying state or recombine and re-radiate.



The band gap—which is the difference in energy levels between the top of the valence band and the bottom of the conduction band determines the wavelength of the emitted light.

What makes quantum dots unique?

In regular semiconductors like silicon (also known as bulk matter), the bands are formed by the merger of adjacent energy levels of a very large number of atoms and molecules. However, as the particle size reaches the nano-scale and the quantity of atoms and molecules decreases substantially, the number of overlapping energy levels decreases, causing the width of the band to increase. As QDs are so tiny, they have a higher energy gap between the valence and conduction bands, compared to the bulk matter.



Thus, the unique properties of quantum dots are explained by two nano-scale phenomena: quantum confinement effect and the discrete nature (quantized) of the electronic states of these particles.

Quantum confinement effect

Quantum confinement effect is the change in the atomic structure of the particle observed when the energy band is affected by the shifts in the electronic wave range. Because the wave range is comparable to the particle's size, electrons are constrained by the wavelength boundaries. Hence, quantum dots' properties are size-dependent, and their excitations are confined in all three spatial dimensions.

Confinement energy is the key property of a quantum dot that explains the relationship between QDs size and the frequency of light they emit.

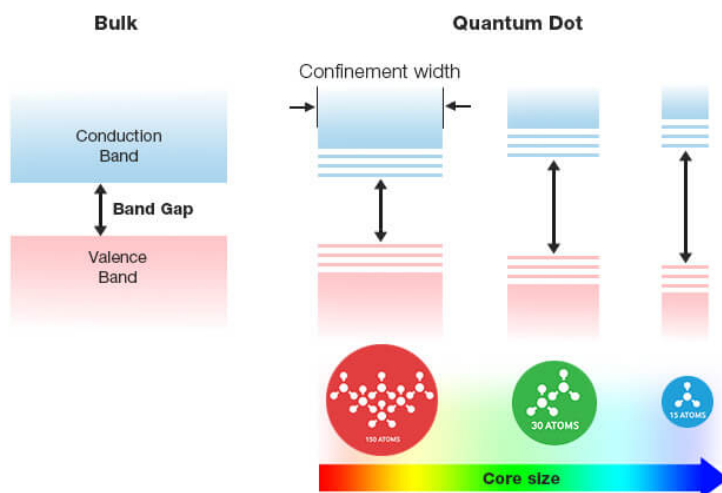
Quantized (or discrete) electronic states of QD

Because of the small size of QD particles, the quantum confinement effect causes a large band gap with observable discrete energy levels. Such quantized energy levels in quantum dots lead to electronic structures that are in between single molecules, which have a single gap, and bulk semiconductors, which have continuous energy levels within bands.

Why does this quantum physics matter for display technology?

Let's tie this quantum physics back to the quantum dot in displays.

Unique properties of quantum dots—caused by their unusually high surface-to-volume ratios—explain why these nanocrystals can produce distinctive colors determined by the size of the particles.



As the size of the crystal decreases, the difference in energy between the highest valence band and the lowest conduction band increases. More energy is then needed to excite the dot, and at the same time, more energy is released when the quantum dot returns to its original relaxed state.



Because of this phenomenon, quantum dots can emit any color of light from the same material if their size is altered. What's more, due to the high level of control possible over the size of the nanocrystals produced, quantum dots can be tuned during manufacturing to emit the desired color of light.

Sound great, doesn't it? However, all these benefits also come with a set of challenges specific to employing QDs in displays.

What are the QD implementation challenges?

Photobleaching

One of the challenges in scaling nanotechnology for utilization in displays is the irreversible degradation of quantum dot particles, referred to as photobleaching. Photobleaching can occur because of the exposure to light at high frequencies, heat, or humidity. Corrosion and oxidation of QD molecules generate surface trap states as non-radiative recombination channels.

Because of photobleaching, quantum dot molecules permanently lose their ability to emit light. Unprotected QD molecules, on average, will have a lifespan under 1,000 seconds (amounting to almost 17 minutes). Due to the nature of display technology using backlight to illuminate semiconductor particles, quantum dots would need to be constantly exposed to the light source at longer wavelengths.



Photoluminescence (PL) blinking

QD application in displays based on their size-tunable light emission is further compromised by what's called PL blinking—a photoluminescence intermittency in nanocrystal emission. Such blinking happens because of one or both excited carriers escape to the surface of the quantum dot crystal.

Auger recombination

Auger recombination is a similar Auger effect which occurs in semiconductors. An electron and electron-hole (electron-hole pair) can recombine giving up their energy to another electron (in the conduction band), increasing its energy.

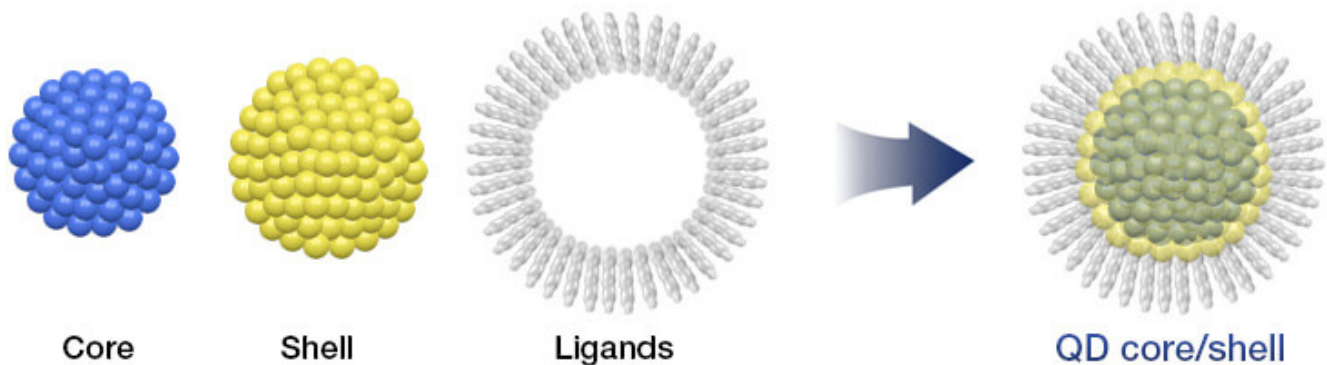
Auger recombination occurs when an excited electron recombines and instead of emitting light, transfers the energy to a nearby electron (or hole), creating a “hot” electron (hole). In QD, these nonradiative processes are to be minimized, because our goal is to have the maximum emission of light. Auger recombination is a loss process that considerably reduces the efficiency of quantum dots.

Making QDs work in displays

Keeping these major obstacles in mind, let's explore how the leading panel makers package this technology for use in displays.

Improving QD strength

To achieve stability and establish resistance to photochemical reactions, manufacturers strengthen QD structure by employing core-shell design. In this case, the nanocrystals are made of a quantum dot semiconducting core material, surrounded by a semiconductor shell and surface ligands to reduce the core's vulnerability.



Shell helps achieve effective elimination of surface states and confinement of the electron-hole charge carriers, allowing for enhanced quantum yield and improved stability. What's more, the shell also provides protection against environmental changes and photo-oxidative degradation.

Another protection mechanism is the surface modification of quantum dots with functional **ligands**, fine-tuning their physiochemical properties and fluorescence emission behaviors. Not only do ligands physically protect nanocrystals from the surrounding environment, they also enhance the photoluminescence quantum yield because of the effective passivation for electron traps, thus helping to prevent the Auger recombination effect.

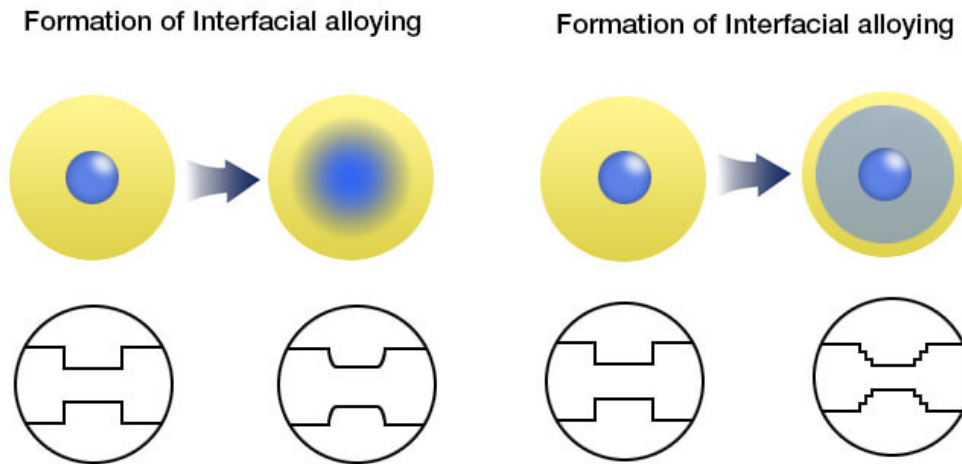
Reducing PL blinking and Auger recombination

Such improved QD structure also helps reduce the photoluminescence blinking and Auger recombination. Shell provides an energy barrier preventing carriers from escaping to the surface. As the shell is surrounding the core, it is used to effectively confine photo-generated charge and limit it solely to the core. This is achieved through using shell and core materials with low lattice mismatching to ensure that the excited carriers are restricted to the narrower band gap.

By maintaining charge neutrality, the shell helps avoid Auger recombination effect, suppress PL blinking, and hence improve the photoluminescence.

Further enhancements to modern quantum dot material

To further reduce the Auger recombination, modern quantum dot materials have another layer between the core and the shell — called the middle shell. Introduction of the intermediate layer substantially reduces the Auger recombination by reducing the intra-band transition.

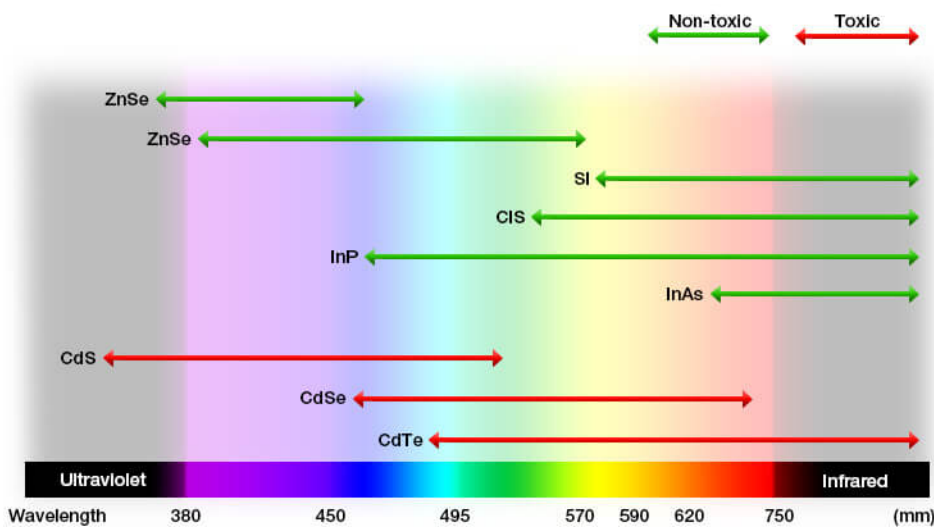


Visible QD semiconductors

Next, let's look at the materials that are used in quantum dot display technology to achieve desired photoluminescence of the visible range.

Different materials due to their chemical composition and properties can generate various sizes of quantum dots and determine their emission maxima. Human eye can detect light with the wave range of 380-750 nm, corresponding to 789-400 THz frequency range, and would require 3.26 eV-1.65 eV of photon energy to produce.

Quantum dots can be synthesized from a range of semiconductor materials. Out of the most common materials used in display technology, cadmium selenide (CdSe) and indium phosphide (InP) cover the visible wavelength range at highest internal quantum efficiency levels (80-100%).



Quantum dots also have narrow, symmetric emission spectra, resulting in highest color purity saturated emission colors.

Learn more about [principles of color generation](#) or [QD implementation in displays](#).

Conclusion

In this whitepaper we covered basic functional principles of nanocrystal technology and its application in displays. As science is still making further advancements to address the challenges of QD implementation and structural improvements, stay tuned for the follow up on the topic. Next, we'll discuss how QD application in displays will evolve and why.

Credits:

We are grateful to Prof. Heesun Yang, Dept. of Material Science and Engineering, Hongik University for sharing his notes and resources.

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