Quantum Dots: Solution for a Wider Color Gamut

What is QD and why it’s the next big thing for large format displays?

With the evolution of display technology, the industry has come to demand lifelike experiences and true, saturated colors. This trend has caused color space standards to evolve as well. With the introduction of BT2020 protocol, display manufacturers are looking to cover about 76% of color space comprehended by the human eye, which also means covering 100% of NTSC, sRGB, Adobe RGB and DCI-P3 color spaces.

The process of quantum dot technology adoption in the display market began in 2007. As of today, quantum dot technology remains the best pathway to achieve BT2020 standard compliance as it offers the widest gamut possible with tunable primary colors and increased system efficiency.

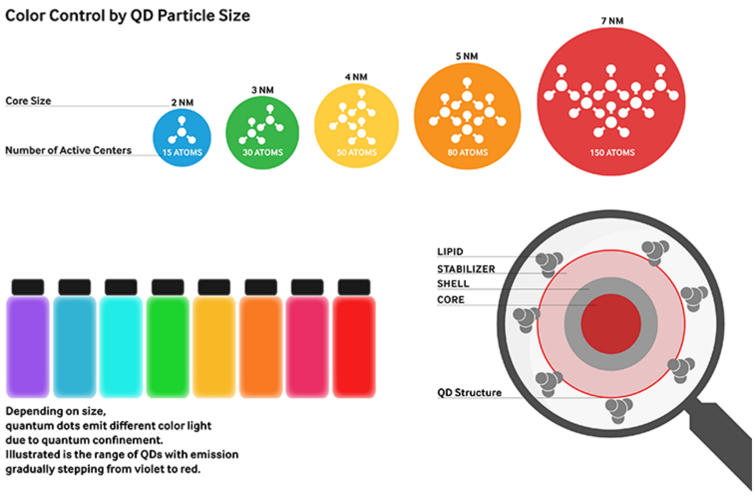
In this whitepaper, we uncover the principles of the quantum dot technology, its application to the public information display market, advantages, disadvantages and implementations.

What are quantum dots?

Quantum dots (QDs), also knowns as QDs or fluorescent semiconductor nanocrystals, are tiny, single crystals ranging from 2-10nm in diameter, which is equivalent to 15-150 atoms. QDs size and shape can be easily and precisely controlled by the duration, temperature, and ligand molecules used in the process of synthesis—in other words, by reaction time and conditions.

A quantum dot only emits one color, which is determined by its size. The bigger QDs are red and are usually as big as 7nm (150 atoms) in diameter, while green particles are about 3nm (30 atoms) in diameter. Blue QDs are the smallest—their core size is about 2nm (15 atoms) in diameter. Because of their tiny size, blue particles are very vulnerable and challenging to work with. For this reason, red and green QDs are most frequently used in panel technologies.

The unique properties of quantum dots enable us to generate spectrally narrow primaries with full width at half maximum (FWHM) [1] of 30-54 nm based on quantum dots type, resulting in the widest color gamut coverage possible.



A quantum dot consists of the core, shell, stabilizer and lipid.

Types of QDs by the core material

In the display industry, QD's **core** is usually synthesized using cadmium selenide (CdSe), indium phosphide (InP), or silicon (Si). **Cadmium-based QDs** were the first ones to be used in the industry and they have yielded the best performance, achieving 100% of DCI-P3 color gamut protocol. Cadmium allows for the highest internal quantum efficiency—over 90%. The drawback of this material is that it is toxic in high doses and its use is restricted by RoHS.

Their **indium-based** counterparts were able to cover 90-96% of DCI-P3 color space. For example, Samsung Display's SUHD panels are currently able to achieve 96% of DCI-P3. Indium QDs reach about 80% internal quantum efficiency—with new technologies able to yield up to 90% efficiency. Products utilizing indium quantum dots are RoHS compliant, but much more expensive than cadmium ones. Indium QD technology has evolved substantially over the last decade, able to generate green QDs with less than 40 nm FWHM, and red QDs with FWHM under 54 nm, covering 96% of DCI-P3 color space.

Silicon QDs are safe but hugely inefficient—providing only 30-50% of internal quantum efficiency. They also cannot compete with other QDs in terms of color gamut coverage.

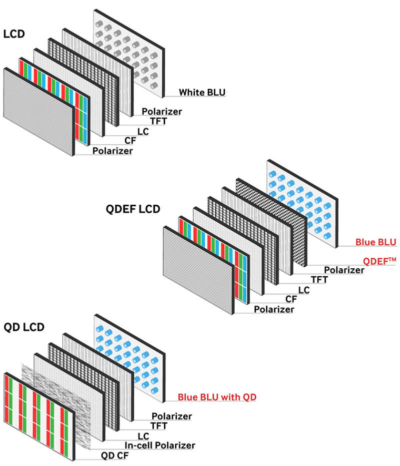
Particle shell

QD shell technology is currently the most important component because the core itself can be easily dismantled and is very vulnerable. This shell is put in place to stabilize the structure. Most frequently a QD shell is made of zinc sulphide (ZnS) for cadmium QDs. For indium quantum dots an intermediary shell is needed—often made of zinc selenide (ZnSe).

How do quantum dots work in displays?

Quantum dot technology is most successfully employed in the new generation of LED-backlit LCDs. These displays are utilizing similar principles and mechanisms. In a typical LED LCD, the white light from LED is diffused and directed through a polarizer. It then encounters a layer of liquid crystals where it is blocked or passed through a layer of color filters and then through another polarizing filter, generating a color value for each pixel.

Quantum Dot Display Evolution



Quantum dot displays have a similar process of pixel color production. However, QD panels use blue LED light rather than white. The top layer of the display has red and green QDs and a blank pixel, rather than RGB color filter. The blue LED light is passed through the blank pixels to generate blue hues, while red and green QDs are in charge of red and green colors.

There are four options for arranging quantum dots within a display panel:

1. **QD Dot: in-chip**
   One of the first approaches to the QD technology was to embed quantum dots in the chip. This technology never made it to mass production. This is because when located so close to the LED, quantum dots are exposed to very hot temperatures, reaching over 200ºC. While the in-chip approach is the most economical and cost-efficient, the heat impact is detrimental to quantum dots performance. Some companies are working on QD technology that would be heat resistant and will be able to withstand over 260ºC aiming to conquer illumination/lighting industry.

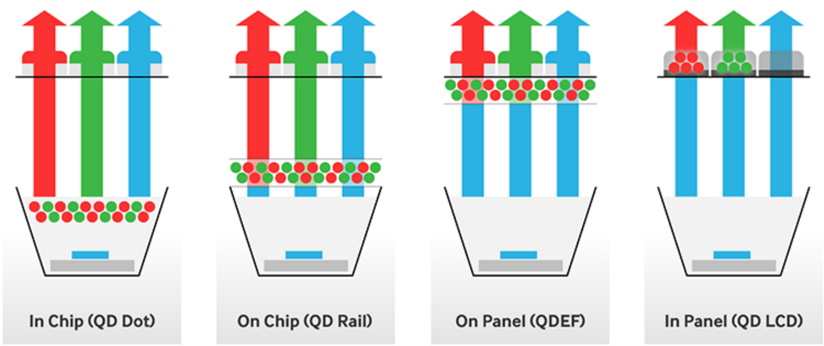
2. **Rail QD: on-chip**
   This technology arranges QDs in a tube—so called a “quantum rail” adjacent to the LED. It was used by Sony in their 2013 QD TV release. The product was retrieved the following year most likely due to the heat resistance shortcoming. In this location, QDs are too close to LED packaging where temperatures can reach about 100ºC.

3. **Quantum Dot Enhancement Film (QDEF): on-panel**

Most QD TVs available in the market now use QD sheet or film located in the top of the light-guide plate. Locating QD film behind the glass panel but in front of the color filter eliminates the proximity to the LED package and keeps QDs cool. To make white color, blue LED and red and green phosphor are required. For QDEF panel, we need blue LED and red and green QDs. QD act like phosphor in this case to transform the blue light into red or green. Samsung Electronics has been using sheet technology and indium QDs for over 3 years for SUHD QD TVs.

4. **QD LCD: in-panel**
   A number of manufacturers are currently working on the new QD-enabled panel technology where QDs are embedded in display glass on the top of LC layer. With this deployment, we will be able to achieve efficiencies that are over 50% higher than those of the conventional LCDs. These panels will also be able to deliver the widest viewing angles in the industry and cover 100% of the DCI-P3 protocol.

Possible QD Arrangements within the Panel



Advantages of the quantum dot technology

Quantum dot technology offers a number of advantages due to the unique properties of QDs.

High peak brightness

Quantum dot light has a sharp and narrow emission peak due to a radiative recombination of an exciton. QDs emit pure red and green light that is being refracted with the blue light through panel layers. High peak brightness results in the larger differential between the brightest and the darkest parts of the image, enabling support for high dynamic range (HDR) displays.

Color saturation and the widest color gamut possible

Quantum dot technology delivers up to 40-50% in color gamut increase and is currently the only technology that puts us in the proximity of achieving BT2020 color space (as well as 100% DCI-P3 coverage). QDs generate pure color and because there is so little wasted light, we are able to achieve vivid hues, and punchier, more saturated colors.

Lower energy consumption

As we start with the high energy blue light and refract it to lower energy states to create green or red, quantum dot displays result in a much higher efficiency and reduced power consumption.

Improved color accuracy

Quantum dots allow for precise tuning and control of the light emissions resulting in purer, cleaner whites and accurate, true to life colors.

Ability to leverage existing supply chain

QD technology doesn't require major adjustments to the manufacturing process, therefore not affecting the supply chain and corresponding costs. The technology is more cost-effective than OLED.

Disadvantages

There are a few challenges the technology presents that need fine-tuning before QDs become mainstream.

Vulnerability of quantum dots

Quantum dot particles are affected by water, heat and humidity and require isolation. Barrier film is currently used as an isolating layer to protect QDs from decomposition from humidity. In addition, QDs are very susceptible to high temperature and need to be located away from the heat sources, such as LED light to maintain quantum efficiency. At the temperatures of 100ºC or more quantum efficiency of the particles drops to less than 50%. Therefore, QD-enabled devices cannot be operated under extreme hot weather conditions. QD arrangement, proximity to LED within the panel and packaging, are critical for the QD display performance.

Regulatory barriers for cadmium solutions

While cadmium-based QDs result in the superior performance and broader color gamut, the material is toxic at high levels and is currently disapproved by RoHS. Regulatory agencies around the world are keeping a close eye on cadmium solutions. In the meantime, the industry is working on improving indium-based technologies to deliver similar performance and efficiency.

High manufacturing cost

QD technology is much more expensive than conventional LCD manufacturing. However, QDs are still cheaper than OLED display, and with mass production, quantum dot display production will gain enough efficiencies to become relatively inexpensive.

Conclusion

Cadmium-free, film-based quantum dot systems have been shaking the display landscape over the last three years. QD technology available today already outshines large format OLED and is projected to deliver even better results and efficiencies moving forward. These advancements make producing a color range that is the closest to the color spectrum of the human eye achievable, delivering on the promise of true, lifelike visual experiences.

Get ready for the next frontier of display performance!

Want to learn more about quantum dot technology?

We have put together a list of great videos explaining QD in more detail and exploring where QD research is going next.

- CNET is telling the story of what the quantum dots are and how are they used in displays
- MIT's professor Luis Berga sheds light on the process of the quantum dot invention
- Harvard's Charlie Marcus on quantum information processing

[1] **Full width at half maximum (FWHM)** is the method of specifying spectral width calculated as a difference between points on the spectrum curve at which the function reaches half its maximum value.

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