White Paper

Quantum Dots will Power Display Products to the Next Level

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By

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Table of Contents

Introduction & Summary ........................................................ 4
Wide Color Gamut Overview .................................................. 6
Wide Color Gamut Options .................................................... 8
  OLED Displays .................................................................................................................. 8
  Emitting Structure ............................................................................................................. 8
  Micro-Cavity Structure ............................................................................................... 9
  Pixel Architecture ......................................................................................................... 10
  LCD Displays .................................................................................................................... 11
  Display Architecture ....................................................................................................... 11
  Dimming Options ............................................................................................................. 11
  WCG by Phosphor-Enhanced LEDs ................................................................................. 13
  WCG by Adjusting Color Filtering ................................................................................. 15
  Quantum Dot Displays .................................................................................................... 16
    Quantum Dot Technology ............................................................................................... 16
    Quantum Dot Film .......................................................................................................... 19
    Quantum Dot Tube ......................................................................................................... 24
    On-chip LED Devices with Quantum Dots ................................................................. 25
    Electrically Driven Quantum Dots ................................................................................. 27
Conclusion .................................................................................... 27

Table of Figures

Figure 1: Various 2D Color Standards using u’v’ Coordinates ........................................... 6
Figure 2: Comparison of Gamut Coverage Metrics ............................................................... 8
Figure 3: OLED Structure ...................................................................................................... 9
Figure 4: Micro-Cavity Structure in OLEDs ...................................................................... 9
Figure 5: 0D, 1D and 2D Dimming Options ......................................................................... 12
Figure 6: Phosphor Coated LED Structure ........................................................................ 13
Quantum Dots will Power Display Products to the Next Level

Figure 7: Spectral Profile of White LED with YAG Phosphor ................................................................. 14
Figure 8: Spectrum of Sony WCG X850B TV based on Sharp LED with PSF Red Phosphor from GE (Source: AVS Forum) ............................................................................................................. 14
Figure 9: Osram's QC LED Schematic ................................................................................................... 15
Figure 10: Quantum Dot Size Determines the Emission Wavelength ....................................................... 16
Figure 11: Basic Elements of a Quantum Dot .......................................................................................... 17
Figure 12: Structures of Cadmium-based and Cadmium-Free Quantum Dots ....................................... 18
Figure 13: Structure of a Quantum Dot from Crystalplex ..................................................................... 18
Figure 14: Structure of Edge-lit LCD with Quantum Dot Film ............................................................. 19
Figure 15: Narrowband RGB Light Passes thru the Wideband RGB Color Filter Array ................. 20
Figure 16: Quantum Dot Film Structure ............................................................................................... 20
Figure 17: Post Calibration Color Gamut and Tracking (top) and Color Accuracy (bottom) of the Samsung KS9500 in HDR Mode (source: HDTV Test) .................................................................................. 21
Figure 18: Color Volumes of the Samsung KS9500 and LG G6 HDR TVs ........................................... 22
Figure 19: Color Space for Vizio 65" Reference TV (Source: Vizio) ....................................................... 23
Figure 20: Color Gamut Measurement of the Philips 27" Monitor with ColorIQ QD Optic ......... 24
Figure 21: Overlapping of the Absorption and Emission Spectra Reduces Light Output and Efficiency ............................................................................................................................................. 26

Table of Tables

Table 1: Summary of the Basic Wide Color Gamut Displays Approaches ........................................ 5
Table 2: Summary of QD Suppliers and Partners .............................................................................. 5
Quantum Dots will Power Display Products to the Next Level

**Introduction & Summary**

Quantum Dot (QD) technology is now in a range of LCD displays, offering a wide color gamut (WCG) that is consistently bigger than that offered by OLED displays and other LCD technologies. When coupled with High Dynamic Range (HDR), these displays offer some of the best picture performance on the market. WCG and HDR displays are clearly the next wave of technology that is moving from the high-end toward mainstream adoption very quickly.

In this white paper, we will provide an overview of the three main options to create a WCG display: OLEDs, quantum dot LED/LCDs and enhanced phosphor LED/LCDs. Then, we will take a deeper dive into the technology behind quantum dots, the various ways and places it can be integrated into LCD displays, along with the strengths and weaknesses of each approach.

Perhaps the most exciting near term potential of quantum dots is their ability to become air stable and therefore embedded in the color filter array of the LCD display. This configuration will create a step change in power efficiency for LCD displays? Why, because current approaches use blue LEDs and quantum dot to generate white light at the backlight, which is then modulated by the LCD and filtered into red, green and blue components by the color filter array. If the quantum dots are placed in the color filter, only a blue backlight is needed with conversion to red and green light happening in the color filter. This could reduce power consumption by one-half to two-thirds.

And, quantum dot technology has applications in many other markets such as solar cells, biomedical, instrumentation, quantum computers and more, thus providing a rich source of additional technology investment and innovation to feed the display industry.

As will be discussed in this white paper, Table 1 summarizes some of the main features of the basic display approaches to generate wide color gamut displays.

Quantum dot technology seems to offer the biggest color gamut of the various approaches today. Table 2 summarizes the known suppliers of QD materials along with their partners.
# Quantum Dots will Power Display Products to the Next Level

## Wide Color Gamut Options

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<thead>
<tr>
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<th>OLED</th>
<th>LCD with Enhanced phosphor</th>
<th>LCD with Enhanced Color filters</th>
<th>Quantum Dots</th>
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<tr>
<td>Black level</td>
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<td>Dark Details</td>
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<td>- for Cd-based QDs</td>
<td>+ for Cd-free QDs</td>
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*Table 1: Summary of the Basic Wide Color Gamut Displays Approaches*

<table>
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<tr>
<th>QD Material Supplier</th>
<th>Film</th>
<th>Optic</th>
<th>Blue LED &amp; QD</th>
<th>CFA</th>
<th>QLED (Electrically Driven QD)</th>
<th>Cadmium-based</th>
<th>Cadmium-Free</th>
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<tr>
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<td>Light Technologies (IP, development)</td>
</tr>
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</table>

*Table 2: Summary of QD Suppliers and Partners*
Wide Color Gamut Overview

Wide Color Gamut is a generic term that in fact, has no clear definition in the display industry. Currently, a display is considered to be WCG if it has a gamut in excess of the Rec. 709 color gamut for video applications or beyond sRGB color gamut for printing or web-based applications. In reality, Rec. 709 and sRGB share the same RGB primaries, but use slightly different gamma curves to describe the steps between the various colors and gray levels.

The ITU has ratified a new standard called ITU-R BT.2020 that specifies a new color gamut for UHD TV that is generally referred to as “2020.” It expands the range of colors considerably beyond the RGB primaries of rec. 709/sRGB. The 2020 spec is a “container” that includes new coefficients for defining colors. While many camera systems are capable of capturing at or close to the full 2020 color gamut, display systems are generally not capable of displaying the full 2020 color gamut. For video content, the 2020 specification does not require content to be captured, mastered and delivered with the full range of colors – it just requires the content use the 2020 color primaries and description coefficients. Since most flat panel displays do not achieve the full 2020 color gamut, mastering of content is often done in a smaller color gamut. So far, most are choosing the DCI-P3 color gamut to master content aimed at the home. This is the same color gamut used to master for theatrical releases as well. This color gamut contains a range of colors that is in between rec. 709 and BT.2020.

These color gamuts, along with “Pointer’s gamut” are shown in Figure 1.

![Figure 1: Various 2D Color Standards using u’v’ Coordinates](image)

In discussing the color performance of a display, one must always ask what “mode” it is in (standard, cinema, vivid, etc.) and if the display has been properly calibrated. Calibration is typically done in a reference mode which can carry different names depending upon the brand (cinema or movie is typical).
Calibration for SDR and HDR content needs to be done separately as well. Calibration tunes the TV to help ensure it reproduces the most accurate colors, white point and gray scale that it can. SDR calibration would ensure colors are accurate for the rec. 709 color gamut, but color calibration for HDR content is different. Here, standards are still emerging. One can always measure the color performance of the display, but what it should be calibrated to is an open question.

For example, should the TV be calibrated for the full BT.2020 color gamut and have colors that track from white directly toward these 2020 primaries – even if the display can’t produce those primaries? Or, should the TV be calibrated to the DCI-P3 color gamut with tracking from the white point to the P3 primaries? This sounds more logical as most content is being mastered to the DCI-P3 color gamut, but either approach may yield incorrect colors (P3 content on a 2020 calibrated display or 2020 content on a P3 calibrated display). Ideally, HDR content will have the metadata that will describe the color primaries it was mastered to allowing the TV to go into the proper calibrated mode to display those colors accurately.

Other modes are set by the manufacturer and often move the white point (usually toward the blue) to get more brightness and sometimes more colors. Some consumers prefer these modes but they will not accurately reproduce what the content creators intended.

Another issue with discussing color gamut is “coverage”. Figure 1 shows a 2D representation of color gamut and the performance of the display can be shown on such diagrams. However, color representation is really a 3D volume, so the 2D diagrams of Figure 1 are only valid at one luminance level. Methods to characterize the color volume of WCG displays exist, but have not been widely adopted by the display or TV industry.

As a result, most descriptions of the color performance are limited to specs such as “100% of P3” or “91% of 2020”. There are several additional issues with such descriptions. First, if one manufacturer described coverage as a % of P3 and another as a % of 2020, there is no easy way for consumers to easily tell which color gamut is larger. The industry should consider a recommended best practice to choose one or the other for more easy comparison.

Secondly, “percentage of coverage” can refer to two types of coverage. Does the display cover 100% of the area of the P3 color gamut, for example, or does it cover 100% of the P3 gamut.

These are quite different measurements as illustrated in Figure 2. In this case, the area of P3 and the area of the measure display color gamut are identical, so a display maker may report “100% of P3.” However, the RGB primaries of the measured display gamut do not align with the P3 primaries. The common area of the two (textured portion) is the other way to report “gamut coverage” and in this case may only be perhaps 90% of P3. Again, the industry should consider a recommended best practice to choose one method for common reporting for better end user comparison (preferably the percentage of gamut metric – either P3 or 2020).
This issue of percentage of coverage assumes a continuation of the 2D color gamut description. But since color is a 3D parameter with luminance being the other parameter not part of the 2D description, moving to a color volume representation may be desirable as well.

Again, there are methods to describe color volume today but the issue of volume of a gamut or just a volume number is an area of discussion. Since these discussions will take time, perhaps the industry can first agree on 2D color coverage best practices while discussion color volume best practices.

Finally, we have the issue of color accuracy. One common method is to use the ΔE 2000 metric. Most agree that a ΔE 2000 measurement of less than 1 means the presented color is indistinguishable from the absolute correct color. In reality, displays that show color performance across most colors with a ΔE 2000 of less than 3 are considered to be very good and well calibrated.

While ΔE 2000 is often reported for a calibrated display report, there is no consumer-facing specification to describe color accuracy. Perhaps the industry should consider a best practice recommendation for reporting color accuracy of its displays (probably in the most accurate mode and out-of-box – i.e. before any calibration as most consumers do not do this).

**Wide Color Gamut Options**

**OLED Displays**

*Emitting Structure*

Organic Light Emitting Diodes (OLEDs) have been commercialized as TVs, mainly led by LG Electronics. OLEDs are emissive displays which means they create their own light at each pixel, like CRTs and PDPs.
At the device level, each OLED pixel is a p-n junction that emits lights. It is created with a series of layers sandwiched between an anode and cathode to drive the current (Figure 3). In addition, there are two basic configurations:

- Top emitting
- Bottom emitting

Most OLED manufacturers have now adopted the top emission architecture as it increases the efficiency of the device and increases the light output by effectively increasing the percentage of emitting area of the pixel.

A display device is created by a matrix of OLEDs. OLEDs are current-driven devices so their light output is dependent upon the current at each pixel location. Each pixel typically has several transistors and a network of row address lines to select each row in sequence while the column drivers deliver current for each column as needed to create the light needed for each pixel in that row.

Micro-Cavity Structure

Recently, we have seen the implementation of micro-cavity structures in OLED displays as shown in Figure 4.
To accomplish this, the thickness of the OLED emitting layer needs to be adjusted at the sub-pixel level to create a cavity that creates constructive interference, effectively narrowing the emission bandwidth of that sub-pixel. This allows more saturated colors and a wider color gamut to be achieved. The trade-off with this approach is additional manufacturing complexity to control these thicknesses to a high degree and a narrowing of the viewing angles of the display. A blue or green shift in some OLED TVs has been reported, primarily due to this micro-cavity structure. This means that these TVs can have viewing angle issues.

Finally, OLEDs are also very sensitive to oxygen and moisture. Even a tiny pin prick in the barrier layer can lead to complete display failure. While we are seeing improvements in barrier layers for OLEDs, this still remains a critical process and the displays are still more expensive than LCDs.

**Pixel Architecture**

From a commercial implementation point of view, there are two basic architectures for OLED displays:

- Red, green and blue OLED subpixels – led by Samsung for mobile displays
- White emitting OLED material with WRGB color filters – led by LG for TVs

We will focus our discussion on TV class displays, where the key advantage of OLEDs is their very dark black level – a pixel can have no current so it is completely black. However, coming out of black has been an issue with current OLED TVs. There seems to be a big jump from total black to the first black levels meaning there is a loss of details in the dark shadows.

There are also concerns about the lifetime of the blue OLED material. The only commercial implementation of white OLEDs for displays uses a triple layer of blue fluorescent and yellow phosphorescent materials. Development of a longer lifetime blue phosphorescent material is needed (or something else).

Recently, two companies (Cynora and Kyulux) have developed new TADF blue emitting OLED materials that show promise for extending the lifetime and efficiency (up to 20% external vs. 5% currently), but they are not yet in commercial production – and probably won’t be for another two years.

The peak emission of OLEDs is somewhat limited in comparison to LCDs, where it is much easier to increase the light output of the backlight. The best OLEDs today can achieve at most 500-600 nits of the peak luminance. The brightest LCD TVs today are about 1800 nits.

This brightness limitation also affects the color rendering capabilities of the OLED display. At low luminance levels, the best OLED displays can show close to the full P3 color gamut. But as luminance increases, the display is unable to maintain this color gamut. At the peak luminance levels, the color gamut is only a fraction of the low luminance gamut. That means fireworks could look white on an OLED but they may be properly displayed as green on a QD LCD TV.

Can OLEDs get to a 2020 color gamut? That remains unclear as new materials will have to be developed and this takes time and expense. Ink jet patterning or solution processing of RGB OLED sub-pixels may be one answer to high resolution, WCG TV-class displays, but these
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technologies are not yet in mass production. Plus, OLEDs will need to have an answer to their brightness limitations in the long run.

Moreover, LG is the only major supplier of TV-class OLED panels and yields on their 55” and 65” products are thought to be in the 50% range. In addition, material costs are higher than LCDs, which together, makes OLED TVs 2X to 4X more costly than comparable HDR/WCG LCD TVs. LG, and other producers who will come on-line in the next few years, must improve yields and reduces costs if they hope to compete long terms in the TV market.

LCD Displays

Display Architecture

An LCD consists of several major subsystems

- LED backlight
- TFT substrate
- Color filter substrate

The backlight creates white light over the entire surface area of the display. The TFT (Thin Film Transistor) substrate has transistors at each sub-pixel which controls how much light passes thru each sub-pixel. Generally, a full color pixel is composed of red, green and blue sub-pixels with the light of each sub-pixel individually controlled. The color filter substrate separates the white light coming through each sub-pixel into red, green and blue components. Since these subpixels are small and close together, we perceive the combination of the luminance as a single color from a single pixel.

Polarized light from the backlight is “twisted” by the LCD panel and passes through a second polarizer oriented at 90-degrees to the first one. When a voltage is applied to a pixel, the twisting is changed and reduces the amount of light that is passes. This creates the “black state” in an LCD.

All LCD displays now use LEDs in the backlight to create white light. They are typically aligned along an edge of the display (edge lit) or in a matrix across the area of the display (direct lit). LEDs can be modulated to vary their light output as well. This enables the ability to add a second level of light modulation to the display. This can be used to greatly reduce the black level.

Dimming Options

In general, there are three ways to modulate the LED light:

- 0D – global dimming
- 1D – line or segment dimming
- 2D – area or zone dimming

With global dimming, the entire backlight illumination is turned up or down. When global dimming is coordinated with the content playback, the display as the ability to shift its dynamic range. In other words, for darker scenes, the peak output of the LEDs is lowered so that the
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native contrast range of the LCD panel is shifted downward to a lower light level region. This has the benefit of allowing image processing to adjust the gamma curve and tone mapping to provide an improved image in these dark scenes. However, any bright parts of the scene will now be reduced in luminance as well. Figure 5a illustrates such dimming.

![0D Global Dimming](image1)

![1D Segment Dimming](image2)

![2D Area or Zone Dimming](image3)

**Figure 5: 0D, 1D and 2D Dimming Options**

With line or segment dimming, horizontal segments of the backlight are illuminated at different times. This technique was developed to help reduce motion smear but can also be used to increase the dynamic range of the display when coordinated with the content.

Since there are segments that can be modulated separately it is possible to *simultaneously* increase the luminance in one area of the display and decrease it in another area. For example, one can run the backlight at full in the upper part of the picture if this represents sky, while lowering it in the bottom of the picture if this is a part that is in shadows. This allows for the creation of an HDR display.

The third approach, 2D dimming, can be accomplished two ways. In one approach, the LEDs are mounted in an array directly in back of the LCD panel. Each LED can be modulated...
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directly essentially creating a backlight with resolution. The more LEDs and finely spaced they are, the finer the resolution and the greater the fidelity of the HDR image.

Segmented, edgelit backlights can also be used to create zone dimming as well. In this case the LEDs are mounted on the top and/or bottom of the display to create vertical segments. To create 2D dimming, the vertical segments are driven with different illumination levels that are coordinated with the scanning of the horizontal address lines.

The white light in the backlights can be generated using a number of different technologies. Each has its trade-offs in terms of performance, cost, design and manufacturability – including their ability to create wide color gamut displays. This light must pass through the red, green and blue color filters at the front of the display. Any light that is generated at the backlight that is outside of these three passbands, can leak light into an adjacent passband. This reduces the color capabilities of the display. In general, the more narrow the spectral width of the red, green and blue light emitted by the backlight, the more efficient it becomes and the wider color gamut the display can reproduce. Below we discuss several methods for producing WCG in LCD displays.

**WCG by Phosphor-Enhanced LEDs**

The majority of LCD display use LEDs to create white light using a blue LED overcoated with a YAG yellow phosphor (Figure 6). The blue light acts as an optical pump to the phosphor which down-converts the light to a broad spectrum centered around yellow so as to create green and red light as well.

![Figure 6: Phosphor Coated LED Structure](image)

Optically-pumped phosphor conversion operates on a different principle than quantum dots. While the QD emission of often narrow (25-35 nm for Cd-based and 40-50 nm for Cd-free FWHM), the phosphor emission is usually much broader (100-150 nm for the YAG:Ce phosphor in Figure 7).

The YAG phosphor white LED is quite efficient, inexpensive and produces decent white light. But it is not optimal for achieving a wide color gamut. Typical LCD displays using this type of white LED can obtain 35-55% of BT2020 or 45-75% DCI-P3 (in u’v’) of color gamut. One popular solution is adding red and green phosphors to the blue LED. This increases the light in red and green, but comes at a cost of lower lumen light output – as much as 30-40% lower than comparable white YAG LEDs. Recent developments are improving the efficiency, however. For example, Sharp has released a RG phosphor blue LED that loses only 3% of the
luminance compared to the YAG LED. Sharp and Nichia have also licensed a new red phosphor material called PFS that appears to be better than europium doped nitride red phosphors.

![Figure 7: Spectral Profile of White LED with YAG Phosphor](image)

The new material has been developed by GE and is called potassium fluorosilicate doped with manganese (PFS or KFS). This creates a narrow red line emission with a FWHM of less than 10nm! This allows a sharper red primary with less chroma bleed vs. the europium phosphor. These red phosphors can be combined with a yellow or a green phosphor to be blue-pumped by the LED.

We believe the Sony “Triluminous” WCG displays uses Blue +RG phosphors for the light source. It is unclear if they have yet migrated to LEDs with the new PFS phosphor, however, as the company is tight lipped about its backlight technology. A comment on AVS Forum reported measuring the spectrum of a Sony X850 UHD TV and this spectrum suggests the use of the PFS red phosphor (Figure 8).

![Figure 8: Spectrum of Sony WCG X850B TV based on Sharp LED with PSF Red Phosphor from GE (Source: AVS Forum)](image)
One concern with phosphors is their decay time which may be as long as 20 ms for some materials. For fast-moving content in an HDR display, this can be much longer than the length of the frame and cause blur/ghosting.

In addition, the wide FWHM of green is still a big problem in terms of reaching high coverage of BT 2020.

Osram has also announced that it has developed a phosphor hybrid LED. Called Quantum Colors LEDs (QC LEDs), the device is based upon a blue LED with a green quantum well structure and red phosphor (Figure 9). This is apparently NOT a quantum dot technology but a semiconductor quantum well that uses interferometry (constructive interference) to emits green when pumped by blue light.

![Image of Osram's QC LED Schematic](image)

The technology was developed partly in the SSL4EU and Hi-Q-LED projects, funded by the EU and German Ministry of Education and Research (BMBF). LEDs using the technology have a narrow green peak, with full width half maximum of 30nm. Another claimed advantage is in lifetime. QC LEDs ‘should’ last for at least 30,000 hours and cover 100% of the P3 gamut or 80% of the 2020 color gamut. However, Osram can tune the green to a peak of, for example, 530 nm rather than 540nm to optimize the gamut to maximize for the Rec. 2020 coverage. Osram also said that its choice of P3 in its release was just as an example.

In early 2016 Osram said it may be in use in TVs by the end of 2016. That will not be the case as it will be mid-2017 before commercially available.

**WCG by Adjusting Color Filtering**

Another method to increase the color gamut of a display is to redesign the TFT color filters or to add additional filters elsewhere in the TV. These changes always result in a loss in luminance unless compensated for with more brightness, for example.

At the panel level, manufacturers have the option to consider changing the bandpass characteristics of the color filters. Typically, there is a little cross over between the blue and
green filters and between the green and red filters. This can be reduced to increase the gamut and allows greater native color saturation by trading off brightness and efficiency. We believe some UHD HDR TVs employ this approach.

Adjusting the color filtering can only take you so far, however. Achieving a P3 color gamut is possible, but power goes up. Achieving P3 and 1000 nits may not be very practical as the power goes way up. Achieving 2020 is not really practical at all – even at high power levels, which is not useful.

Perhaps the better use of color filter adjustments is in combination with quantum dot technology. For example, 3M and Nanosys have demonstrated that they can reach 93.7% of the 2020 color gamut with a slight change in the red and green color filter technology. The current color filters have a slight overlap in the blue and green, which is enough to desaturate the blue and reduce color space coverage. Modeling by 3M suggests that up to 97% of the 2020 gamut is possible with further blue filter modifications.

Quantum Dot Displays

Quantum Dot Technology

Quantum dots are semi-conductor nanocrystals that also absorb light of higher energy and re-emit light at a longer wavelength, or down-convert it. The best materials on the market do so very efficiently, with a quantum efficiency of nearly 100%. Quantum dot (QD) materials can be used in a variety of applications such as lighting, medicine, solar cells and displays.

For most suppliers of QD materials, it is the size of the quantum dots that determines the down conversion wavelength (Figure 10) with smaller dots outputting shorter wavelengths and larger dots outputting longer wavelengths. For display applications, two sizes of quantum dots are required: one for the green (~3nm) and one for the red (~6nm). These are designed to absorb blue LED light, which also provides the light for third primary in the display.

The spectral width of the converted light is mainly determined by the range of sizes of quantum dots. The spectral width depends upon the composition and manufacturing process, but
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for red and green QDs ranges from 25 to 60 nm Full Width Half Maximum (FWHM). A narrow spectrum is desired to get close to the 2020 primaries.

Quantum dot emission wavelength and the range of wavelengths can be adjusted in the manufacturing process, enabling control of wavelengths with nanometer-level precision. Tight control of the manufacturing process is also critical to be sure the quantum dots are fabricated within a narrow size range. These features allow the quantum dots to be tuned to meet the needs of an application without changing the material system or their surrounding matrix. This is an advantage in development because the materials system can be developed, tested for performance and reliability, and qualified before fixing the final emission profile (mixture of red and green quantum dots and blue light pass through). It also allows the emission to be precisely optimized for a given display, enabling higher BT 2020 coverage.

![Figure 11: Basic Elements of a Quantum Dot](image)

As shown in Figure 11, quantum dots have three key elements to their structure:

- Core
- Shell
- Ligand

The core provides the key luminescence of the quantum dot by adsorbing blue light and re-emitting at green or blue (in displays anyway). The shell layer helps to confine the emission and passivate defects in the structure. The ligand layer provides additional protection against oxidation to help ensure stability.

As Figure 12 shows, there are variations on this basic structure that include graded/core structures, multishell structure and quantum well structures that are all designed to offer improvements in performance or stability, but may have other manufacturing trade-offs.

Two basic types of quantum dots are fabricated today: Cadmium-based and Cadmium-free (mainly based on Indium Phosphide). Cadmium-free is desired in countries where there is more concern about the hazards of toxic materials like Cadmium such Japan and Europe. Cadmium-based quantum dots were commercialized first and offer higher efficiency overall. Cadmium-
quantum dots will power display products to the next level

free is still behind in terms of efficiency (~10% less efficient than Cd-based) and color gamut coverage (less than 80% of 2020 vs. over 90% for Cd-based). Since Cadmium-based Quantum Dots offer better performance, the choice of which one to use is based on sensitivity to regulatory and environmental issues.

Figure 12: Structures of Cadmium-based and Cadmium-Free Quantum Dots

TVs that use Cadmium-based quantum dot materials are current exempted for the Restriction on Hazardous Substances (RoHS) requirements on this material in Europe. But in a vote in May 2016, members agreed to not extend this exemption. In addition, major companies have already decided that their products will use Cadmium-free quantum dot materials, so it seems likely this will become the dominate approach for displays. In the meantime, Nanosys has released a new material called Hyperion quantum dots which combines Cd-based green and Cd-free red materials into a single film. This can reach 90% gamut coverage of BT 2020 and still meet the RoHS requirements, so no exemption needed. This should reach mass production in early 2017.

Figure 13: Structure of a Quantum Dot from Crystalplex
All QD materials suppliers except Crystalplex fabricate QDs as described above. Crystalplex uses a different formulation that uses a mixture of CdSe and CdS. All the quantum dots produced this way have the same size of about 8 nm with the conversion wavelength determined by the gradient from the CdSe core to the CdS surface (Figure 13). The QDs are then given a ZnS shell and are finally passivated using an Al2O3 layer.

According to the company, this technology provides high stability, high quantum efficiency (> 80% for all colors), narrow emission bandwidth (~30 nm FWHM for all colors) and very low manufacturing cost.

Researchers are also working on quantum rods which have the potential to emit polarized light. Q-Rods have a smaller overlap between the absorption and emission spectra than Q-Dots, which means there is less quenching of the output when the Q-structures become more concentrated. There is also a higher outcoupling efficiency because the distribution of emitted light is directed more toward the normal to the film plane. This remains an area of research for the time being, however.

**Quantum Dot Film Technology**

Film-based QD solutions mean that the red and green quantum dots are placed inside a film that is attached over the emitting surface of the backlight. Blue LEDs, either edge mounted or direct type, illuminate the film (Figure 14).

The film is engineered to pass some blue light and convert the rest of the blue light to red and green in the right proportion to produce the specified white color point. The RGB components of the backlight are now have a fairly narrow spectral band, which is then passed through the color filter array with a wider spectral bandwidth (Figure 15).

The film-based configuration offers low optical power density, which is a factor in QD lifetime. But QD materials, like most semiconductor materials, need protection from oxygen, water and heat. That means the addition of barrier layers must be added to the film (Figure 16).
Such films have seen significant improvement recently in terms of performance and cost reduction.

**Figure 15:** Narrowband RGB Light Passes thru the Wideband RGB Color Filter Array

![Diagram of narrowband RGB light passing through wideband RGB color filter array]

**Figure 16:** Quantum Dot Film Structure

![Diagram of quantum dot film structure]

**Color Gamut and Color Volume Performance**

Film-based QD solutions have been commercialized by 3M, Hitachi Chemical, Samsung, Wah Hong Industrial Corp and Uniglobe Kisco using QD materials from Nanosys, Nanoco and Quantum Materials. TVs and monitors using these films are now in the market from companies like Samsung, Vizio, Hisense, TCL and others. Laptops, tablets and medical monitors have also been introduced by Asus, Amazon and Tianma.

The color gamut coverage of these products will be based upon design decisions made by the manufacturer where they can often trade off wider color gamut for less optical efficiency. In TVs, the color gamut is often larger than the DCI-P3 gamut allowing calibration for accurate colors for P3 mastered content.

Figure 17 shows the results for the most recent Samsung QD HDR TV, the KS9500 as evaluated by HDTV Test. The data was captured after calibration of the TV in HDR mode.
Quantum Dots will Power Display Products to the Next Level

The top graphic shows the color tracking for six colors with 0, 25%, 50%, 75% and 100% saturation. The squares represent the ideal location of the color for the selected color gamut as displayed in the xy chromaticity diagram.

The left chart shows how the TV tracks colors from white to the DCI-P3 primaries, while the right chart shows how they track toward the BT2020 primaries, which are located at the vertices of the triangle. As was mentioned earlier, there is some debate in the industry as to which primaries the display should track to. This TV can support both modes, but cannot reach the full saturation points of BT2020 as it is not capable of this. However, it can reproduce about 96% of the DCI-P3 color gamut. Since Ultra-HD Blue-ray discs are mastered in the DCI-P3 color space, this may be the more important one to measure.

The bottom chart shows the accuracy of these colors at the various saturation levels when tracking to the P3 primaries. All colors are below the DeltaE 2000 level of three, which is consider excellent and nearly indistinguishable from perfect.

![Figure 17: Post Calibration Color Gamut and Tracking (top) and Color Accuracy (bottom) of the Samsung KS9500 in HDR Mode (source: HDTV Test)](image-url)
A more advanced way to describe the color performance of the display is the show the measured color volume. There are several ways to do this but one popular method is to show it in La*b* coordinate space developed by CIE. Here, L represents the intensity of the light, while a* maps the red/green component and b* maps the yellow/blue components of the light.

![CIELAB - Samsung QD 65KS9500](image1)

![CIELAB - LG OLED 65G6P](image2)

*Figure 18: Color Volumes of the Samsung KS9500 and LG G6 HDR TVs*
Figure 18 shows the color volume of two HDR TVs in the La*b* space. The wire grid represents all the color at various luminance levels in the DCI-P3 color standard. The colored part represents the capabilities of the display to show all the colors in the DCI-P3 gamut. The percentage number shows the percentage of the DCI-P3 color volume that the display is capable of producing.

Other TVs will feature different levels of performance like the Vizio 65” Reference Series TV (RS65-B2), which uses the 3M/Nanosys QD film technology to achieve 120% of DCI-P3 or 87% of 2020, as shown in Figure 19. Note however, that this spec is now based upon area and not coverage of P3 (see Figure 2).

Looking at the P3 diagram suggests it can create colors in the cyan and purple ranges that are outside P3, but it cannot create the fully saturated (closest to the edge of the spectral locus, the horseshoe-shaped range of visible colors) red, greens and yellow along the top of the P3 triangle.

A review of the 2020 diagram shows that it can reach 87% of the full color volume, again being a little deficient in showing the fullest saturated colors. Part of the reason for this coverage was the choice of primaries that Vizio made. 3M and Nanosys have shown the ability to get to 93.7% of 2020 with slight adjustments of these primaries.

QD film solutions have only shown up in flagship products so far, but they now seem poised to expand toward the mainstream. Factors supporting this trend include:

- QD materials maker are investing heavily in scaling-up automated manufacturing lines to handle the increased volume of material required by the film. This has led to a significant cost advantage for material production with fully automated production,
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and very high production yields. As a result, these companies will have a cost advantage for the quantum dot material itself.

- New companies are entering the QD film making segment and investing in production capacity and technology. High quality barrier films were initially supply-constrained but now several new sources of high quality barrier film are ramping up production. And, with recent advances in the quantum dot material, the matrix material and the coating process, lower grade (and lower cost) barrier film to be used. Multiple equipment companies have also been investing heavily in optimizing throughput and overall cost of ownership allowing their customers to produce barrier film at a lower cost.

Quantum Dot Tube

Technology

One of the first methods that used quantum dots in a display device was based upon packaging them in resin inside a long slender glass tube. This is placed between the blue LEDs and the light guide in an edge-lit backlight. This is called the quantum dot edge optic option and has been commercialized by one company, QD Vision.

The concentrations of red and green converting quantum dots are engineered to pass some blue light and create red and green light in the proper proportions. The optic solution is sealed into a high precision glass tube, which acts as the barrier against moisture and oxygen, just like the QD film must do.

Figure 20: Color Gamut Measurement of the Philips 27” Monitor with ColorIQ QD Optic
As blue light passes through the optic, some of it is converted to red and green and some passes through into the lightguide. Since the dots are isotropic emitters, meaning they emit light at random in all directions, a significant portion of the converted light does not make it into the lightguide. It is possible to recapture some, but not all of this light by adding reflectors around the optic. This results in a reduction in efficiency compared to the film approach, which benefits from integration into a part of the display stack that recycles light very efficiently. In the film implementation, photons that head the ‘wrong way’ are automatically captured and sent back through the film by the display’s back-reflector.

As mentioned previously, a film-based approach can support a direct lit backlight for a 2D matrix of dimmable zones whereas the QD edge optic can only support edge lit backlights and 1D dimmable zones.

**Color Gamut and Color Volume Performance**

QD optic technology has been adopted by several TV makers including Hisense, Philips/TP Vision, Seiki and TCL. Monitors by Philips and AOC are also in the market. However, performance reviews of these monitors have not been very good overall.

For example, we found one evaluation done by Meko of the Philips E-line 27" 6E6 monitor launched at IFA 2015 that uses QD Vision's Color IQ quantum dot optic technology. The monitor got close (around 95%) of the way to AdobeRGB coverage (very similar to P3 primaries) and was just short of sRGB because of a slight offset of the red primary (Figure 20). This sounds impressive, but the white point was off the desired 6500K setting at between 7200 and 7400, depending on the brightness settings.

However, the biggest problem was that there was an area several centimeters wide on the left hand side of the screen that was quite down in brightness and slightly blue - so the QDs in red and green were not really having the full effect, it seemed. The area was over 20% less bright than the centre when we set the monitor close to the recommended calibration brightness of 200cd/m².

**On-chip LED Devices with Quantum Dots**

**Technology**

So far, we have discussed the integration of quantum dots into films and into an optical element. The third approach, sometimes called QD-LEDs or QD on-chip LED, is to fabricate the device using a blue LED with quantum dot materials in close proximity. This is the highest optical density challenge, which is why it is not commercialized yet, plus there are many materials challenges to be solved. However, the QD-LED approach addresses many issues allowing the elimination of the QD optic or film and simply using QD-LEDs in edge or direct type LCD backlights.

QD-LEDs are not only attractive for the display industry they are very attractive for the lighting industry as well. Why? Because several types of quantum dots can be placed over the blue LED to create a spectrum not just based on narrow RGB peaks, but which has 4 or more quantum dot emitters. This creates light that has a high Color Rendering Index (CRI) meaning it is better emulates more natural lighting sources giving more consistent perceptions of color.
There are a number of requirements that must be met in order for quantum dots to be integrated into the LED device and replace phosphors-based solutions. For one, the quantum dots need to be stable in air and not sensitive to moisture. Secondly, they must be compatible with the silicones currently used by LED makers that overcoat the blue LED with embedded phosphors. Third, the color performance must be stable, not impact yields and be robust enough to go through subsequent solder, bake and packaging steps.

In the lighting industry, both on-chip and remote phosphor (actually using QDs) are being pursued. The remote location – slightly separate from the LED device, means lower optical density, easier thermal management, higher efficiency and longer lifetimes and color stability. This does not work for display devices, however.

**Color Gamut and Color Volume Performance**

Companies working on this approach include Nanoco, QD Vision, Nanosys, Crystalplex, Pacific Light Technologies and others.

Crystalplex for example, is working on a silicone with embedded QDs for direct LED encapsulation in low temperature applications (below 85C) and silicone systems with embedded QDs as a printable ink.

Pacific Light Technologies (PLT) says they have developed air-stable quantum dot materials and are working on both lighting and display solutions. This means no external protective air-moisture barriers are needed – a big advantage in these applications – and they are tailored for the high light flux environment near the blue LED.

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**Figure 21: Overlapping of the Absorption and Emission Spectra Reduces Light Output and Efficiency**

One other issue with developing quantum dot materials is self quenching. By design, the quantum dots are supposed to absorb light in one wavelength range and emit in another. But if
the self-absorption spectral range overlaps the emission spectral range, the emitted light can be reabsorbed, quenching or diminishing light output and overall efficiency. Figure 21 shows the absorption and emission spectra of a competitor’s QDs vs. their QDs, illustrating there is no overlap in their materials. This is particularly critical in the high flux environment near the blue LED surface.

PLT says they now have LED device customers working on QD-LED devices that could launch as soon as the end of 2016. First up will be an LED for lighting to be followed by a display-based application. The company will have news and specifications soon on both these applications. PLT appears to be the first company to commercialize this configuration. Its dots are cadmium-based, but the company is investigating cadmium-free materials as well.

**Electrically Driven Quantum Dots**

All of the quantum dot and quantum rod technologies discussed so far feature a photoluminescence mechanism whereby blue light down-converts to red or green light. Alternatively, quantum dots/rods can be driven electrically to excite blue, red and green light using an electroluminescent mechanism.

This approach, which will call electro-QD, creates a pn junction as with inorganic LEDs, with a quantum dot layer sandwiched between the p and n regions. Each sub-pixel would have either red, green or blue quantum dot material to emit at the desired wavelength.

The backplane architecture, materials and processes to create such a display are still in the development phase. And, since electro-QDs are electrically driven and emissive with narrow spectrums, the technology promises to offer very high contrast – similar to OLEDs or LED video walls, but with lower power than either of these options. The narrow spectrum could mean a wider color gamut than the competitors. Light output levels remain an unknown, however.

Not much information has been published about electro-LED fabrication approaches, but it is believed two approaches are under development at various companies: phase separation and contact-printing.

**Conclusion**

The approaches described above are not the only options being considered by researchers. For example, one approach is to embed the quantum dots in the color filter resin material. This could have a big impact on LCD device efficiency if it can be perfected – perhaps as much as 60% reduction in power vs. a conventional color filter LCD display.

In addition, hybrid approaches are being considered that combine OLEDs with quantum dots. Here, one idea is to use an OLED pixelated backplane to emit blue light. This light drives the blue subpixels, but the red and green subpixels would use quantum dots to down-convert red and green light by the blue light.

These and other ideas and approaches remain in the research phase and will not see commercialization for several years, it would seem.

Nevertheless, the existing quantum dot display solutions offer compelling solutions now and these will continue to improve.
But one thing the industry needs to work on is a consistent terminology for the various approaches that feature quantum dots. For example, the term “QLED” has been used to describe quantum dot materials on top of inorganic LEDs (photoluminescence mode); to describe an electro-QD (electroluminescent mode); or to describe a LED-based LCD TV with quantum dot technology. We suggest the term “QLED” refer to any LED/LCD TV that uses quantum dot technology.