3M™ Quantum Dot Enhancement Film (QDEF)

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Contents

Executive summary 1

How quantum dots work 2

Why narrow spectral peaks matter 2

More crayons in the box: A brief overview of color gamuts.................................4

How more color affects viewers 5

Practical matters: Integrating quantum dots into the LCD 6

3M QDEF performance: Efficiency and durability 7

Are quantum dots inevitable? 8

What's next? 9

Executive summary

With 3M™ Quantum Dot Enhancement Film (3M QDEF), conventional LCDs have the potential to express 50 percent more color—an improvement that translates to a more powerful visual experience for viewers and a stronger impact for advertisers.

Since the early 1980s, scientists have known that molecule-sized spheres of nano-semiconductor materials—dubbed quantum dots—have the potential to expand the range of colors that can be expressed by liquid crystal displays.

Now, after decades of research and development, the first products containing quantum dots are coming to market. These displays will have the ability to express as much as 50 percent more color than earlier LCDs—resulting in color performance approximately equal to or exceeding that offered by commercialized organic light-emitting diode (OLED) displays.

Manufacturers view the introduction of quantum dots as a transformative moment in the evolution of LCDs. Soon, consumers will experience the full impact of an expanded color gamut. Initial research suggests that viewers strongly prefer larger color gamuts and identify those gamuts with a meaningful increase in display quality. Other research indicates that consumers pay more attention to displays with higher color gamuts—an issue of particular importance for differentiating devices and messaging in retail environments.

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How quantum dots work

In simple terms, quantum dots convert color.

More precisely, a quantum dot will absorb relatively short wavelengths of light and emit a narrow spectrum of light at slightly longer wavelengths. Because the wavelength of the emitted color is determined by the size of the dot, the emission is predictable and tunable. Smaller dots produce shorter wavelengths; larger dots produce longer wavelengths.

For example: when blue photons (with a wavelength around 450 nanometers) strike a 3-nanometer quantum dot, it emits a saturated green light. When those blue photons strike a 7-nanometer dot, it will produce a saturated red light. (Figure 1.) The degree of control is remarkable; by tailoring the size of the dot, the emitted light can be tuned to within approximately 1 nanometer of the desired wavelength.

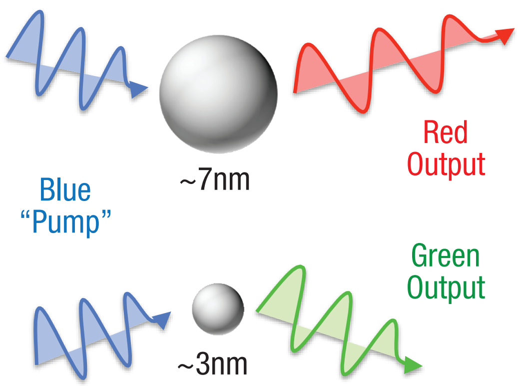

Figure 1. When struck by blue photons, 7-nm quantum dots produce red light and 3-nm dots produce green light.

When these green- and red-producing dots are combined with the blue light emitted by light-emitting diodes (LEDs, see below), the result is a white light with narrow spectral peaks in the three primary colors.

Why narrow spectral peaks matter

To understand the significance of these narrow primary peaks, it is necessary to review how light is generated and applied in an LCD:

1. Currently, the light source in a standard LCD backlight unit (BLU) is an array of LEDs. Because LEDs typically emit a bluish light, they are treated with a phosphor—usually of yttrium, aluminum and garnet (or YAG—so they produce a white light.
2. This white light shines through a color filter in the LCD panel. The color filter is made up of thousands (or, often, millions) of red, blue and green subpixels; the light flowing through each of these subpixels is controlled to produce each pixel's color. (For example: to create a yellow-orange pixel on the screen, its red and green subpixels must be illuminated while no light flows through its blue subpixel.)
3. Ideally, the white light from the BLU will have most of its energy centered to the primary red, blue, and green wavelengths. When the white light has significant concentrations of other wavelengths (pink, for example, or yellow), those non-primary, intermediate colors can leak through the color filter. In a conventional color filter, for example, a red subpixel will transmit a band of wavelengths greater than 570 nm (a mix of yellow, orange, and red). This mix of wavelengths prevents the LCD from producing a pure red.

4. The white light produced by a YAG LED contains many of these non-primary, intermediate colors. It has a narrow peak in the blue range but the remaining energy is spread across the rest of the visible spectrum. When this light passes through a conventional color filter, the spectral output is not saturated. (Figure 2.)

Backlight Color Interaction with Color Filters

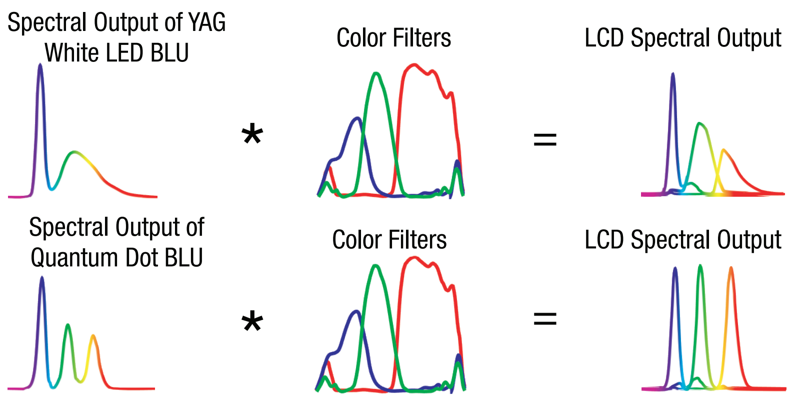

Figure 2. When the light from a conventional "white" YAG LED passes through a color filter, the greens and reds appear unsaturated. When light from an LED is converted by quantum dots instead of a yellow phosphor, it has concentrated peaks and final colors are saturated.

5. In contrast, when the BLU combines an untreated (bluish) LED with red and green quantum dots, it generates a white light with most of its energy in the primary red, green and blue wavelengths. When this light passes through a color filter, the LCD produces concentrated peaks in the primary wavelengths, which can be mixed to create a larger gamut with more vivid colors.[i]

   As a result, a quantum dot display can produce a larger color gamut—one that is as much as 50 percent larger than the gamut that can be produced by a conventional white YAG LED. (Figure 3.)

Display Color Gamuts

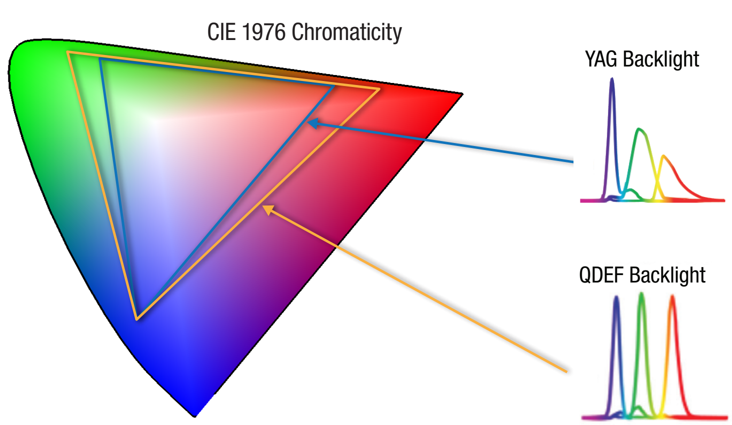

Figure 3. The color gamut produced by a display with a quantum dot-equipped backlight can be approximately 50 percent larger than the gamut produced by the same display with a conventional white YAG LED backlight.

More crayons in the box: A brief overview of color gamuts

Color is an experience. It is how our brain detects and represents differences in the wavelengths of light reaching the eye. Ideally, our display technologies would be able to produce all of the colors the human eye can see. To date, no display can do this.

The term color gamut is used to describe the pallet of colors encompassed by a standard or that a given display can represent. "Color gamut" can also be used to describe the range of colors produced by natural phenomena (for example, all monochromatic light or the light reflected from surfaces).

As it relates to image or video encoding, color gamuts typically define red, green, and blue primaries. All other colors are created by mixing these "primary" colors. An example is the National Television System Committee (NTSC) standard established for color televisions in the 1950s. The standard for contemporary HDTVs is Rec 709; for color monitors, the standard is the sRGB gamut (for **s**tandard **R**ed-**G**reen-**B**lue). (Figures 4, 5.)

Gamut	Common Purpose
NTSC (1953)	National Television System Committee. Analog television standard.
sRGB	"Standard" IT and Internet color gamut.
Rec 709	Current HDTV standard. Identical primaries to sRGB.
Adobe RGB	Common in high end displays. Useful for coverage of printing color space. Adobe RGB output supported by many DSLR cameras.
DCI P3	Current digital cinema standard.
Rec 2020	Proposed standard for UHD content.

Figure 4. Common color gamuts and their purposes.

Gamut	Relative Size
NTSC	100%
sRGB	87.2%
Adobe RGB	101.7%
DCI P3	109.5%
Rec 2020	150.2%

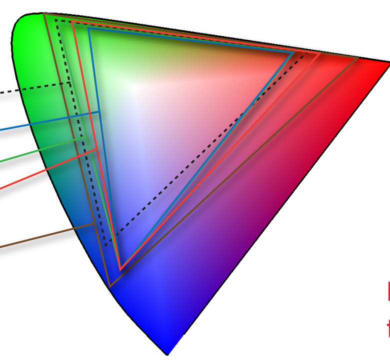

Figure 5. Various color gamuts relative to the CIE 1976 Chromaticity Diagram.

Often the color gamut of a display is described by its relationship to standard color gamuts. The color gamut of most LCD TVs, for example, is around 100 percent of the Rec 709 standard or 87 percent[1] of the older NTSC standard. Next-generation UHD TVs will be expected to achieve the Rec 2020 standard, which is 150 percent of the NTSC standard. Other devices, such as some tablets and notebooks, can have considerably smaller gamuts.

Manufacturers can now produce high performance displays, using either quantum dots, OLEDs or specialized color filters. The color gamuts of these high performance displays are usually described in terms of the Adobe RGB or Digital Cinema Initiatives (DCI) P3 standards. Adobe RGB is closely associated with printed media while DCI P3 is more aligned with video creation.

Although Adobe RGB offers a slightly wider range of greens, DCI P3 is a larger gamut offering both enhanced reds and greens when compared to the sRGB standard.

The OLED displays found in some handheld devices express approximately 100 percent of Adobe RGB. Displays using quantum dots and standard color filters can generate an even larger gamut – achieving a green similar to conventional OLED displays, but with the deeper red associated with the DCI P3 standard.

[1]As represented in the CIE 1976 color space. One will frequently see values such as 71 or 72 percent, which are derived in the older CIE 1931 color space.

How more color affects viewers

A growing body of literature demonstrates the broad and often surprising range of influence color has on humans. This realization has led to pink walls in jails (to reduce aggressiveness) and blue street lights to deter crime and suicides. Red has been shown to increase vigilance, which might explain why it works well on stop signs.

Certainly, black and white images can be stunning and memorable. (Skeptics are invited to review the photos of Walker Evans and Ansel Adams.) But in general, color has been shown to make a deeper impression, and colored images are easier to recall than images in black and white.[ii]

Recent research by 3M suggests that a larger color gamut translates to increased viewer attention and a stronger impact. Specifically, a pilot eye-tracking study found that content with a larger color gamut receives more attention—as measured by aggregated fixation or dwell time—than content with a lower color gamut.[iii] Related research shows viewers prefer more saturated colors. This is true for cartoons and video games (where viewers do not have preconceived notions about the appropriateness and accuracy of colors) and for most real world objects.[iv]

A higher color gamut also influences opinions about the devices on which the content is displayed: research by 3M indicates that when brightness is held constant, consumers will reliably assign a higher quality score to devices with a larger color gamut.

Finally, larger gamuts can produce beneficial ancillary visual effects. Additional colors create the impression of brightness without increasing the backlight's actual illumination (and the energy required to drive that illumination).[v]

A higher color gamut also influences opinions about the devices on which the content is displayed.

Practical matters: Integrating quantum dots into the LCD

Quantum dots' durability can be affected by exposure to heat, oxygen and water vapor. These sensitivities have helped to shape the strategies for integrating quantum dots into LCD manufacturing.

In one approach, quantum dots are encapsulated in a glass tube or "rail," which is positioned directly in front of the LEDs that are ranged along the side of the display. When blue light strikes this rail, a portion of it is immediately converted to red and green light and a portion is transmitted, creating the red, green and blue primaries. The disadvantage of this architecture is that the dots can be exposed to high heat and high flux from the LEDs; this can affect the dots' efficiency and lifetime. In addition, rails add another mechanical element that must be located along the edge of the display, which affects design flexibility and is not practically scalable to smaller display sizes with limited bezel area. Finally, this method requires a reconfiguring of current display manufacturing processes.

3M Quantum Dot Enhancement Film (QDEF) provides an alternative mechanism for deploying quantum dots. This approach reduces exposure to high heat and flux conditions. Integrating the film into current manufacturing processes is relatively simple and straightforward.

3M QDEF is a stack of three layers: an upper barrier film, a middle quantum dot matrix material layer containing quantum dots dispersed in polymer, and a lower barrier film. (Figure 6.) The amount of quantum dots and the ratio of green to red dots are influenced by the color specifications of the display, the degree of light recycling in the BLU, the properties of the color filters and the overall thickness of the film.

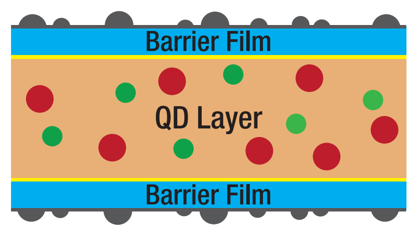

Figure 6. 3M QDEF construction: a stack of two barrier films and a film of quantum dots dispersed in a polymer matrix.

The protective barrier film represents a significant innovation in terms of flexibility, transparency and permeability.[vii] It, too, is a stack of ultrathin layers with a combined thickness (in the current construction) of just 55 microns. Once laminated, these layers form a barrier to water vapor and oxygen that is several orders of magnitude more impermeable than conventional packaging grade barrier films.[viii] It has a water vapor transfer rate of less than 1×10^{-3} grams per square meter per day at 20°C. As a result, it provides extraordinary protection while being optically clear and flexible. It is also thinner, lighter, more flexible and more impact-resistant than glass.

(This combination of characteristics means 3M's barrier film technology has the potential to be a valuable component in applications besides 3M QDEF, such as in solar panels and as a replacement for glass in OLED displays.)

Because 3M QDEF has diffusive properties, it can be integrated into existing LCD manufacturing processes as a replacement for the diffuser film. The diffuser is commonly positioned in the backlight between the lightguide and the light control films that direct and recycle light. The BLU's other components—including the reflector, prism films (such as 3M Brightness Enhancement Film or BEF) and reflective polarizer—remain in place. (Figure 7.)

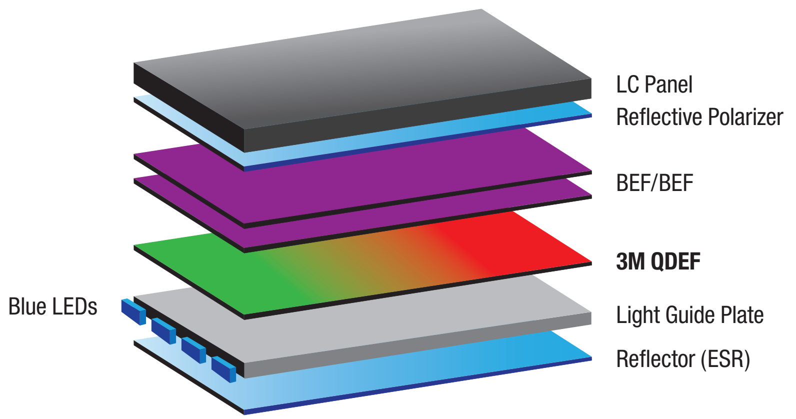

Figure 7. Introducing 3M QDEF is minimally disruptive to typical LCD architecture. Because 3M QDEF has diffusive properties, it can replace the current diffuser film in a backlight unit (as shown here) while other components remain in place. The only other significant mechanical change required is the replacement of traditional white LEDs with blue LEDs.

3M QDEF performance: Efficiency and durability

Quantum dots are up to 15 percent more efficient than conventional white LEDs and color filters in achieving the sRGB standard.[ix] This improvement arises because a display equipped with quantum dots can express the sRGB gamut using a more transmissive color filter (e.g., CF65). Less light is needed from the BLU to achieve the desired display brightness, so less energy is consumed and, in portable devices, battery runtimes are extended.

For larger color gamuts (for example: Adobe RGB or DCI P3), the energy-saving benefit of quantum dot technology is even more pronounced. One alternative method for an LCD to express these larger gamuts is through the use of more saturated and less transmissive color filters. Because these filters block more light, the displays require much brighter backlight illumination, which requires more power.

Compared to displays using these more saturated color filters, quantum dot displays with more typical color filters (e.g., CF72) can be up to 50 percent more energy-efficient in expressing these larger color gamuts. (Figure 8.)

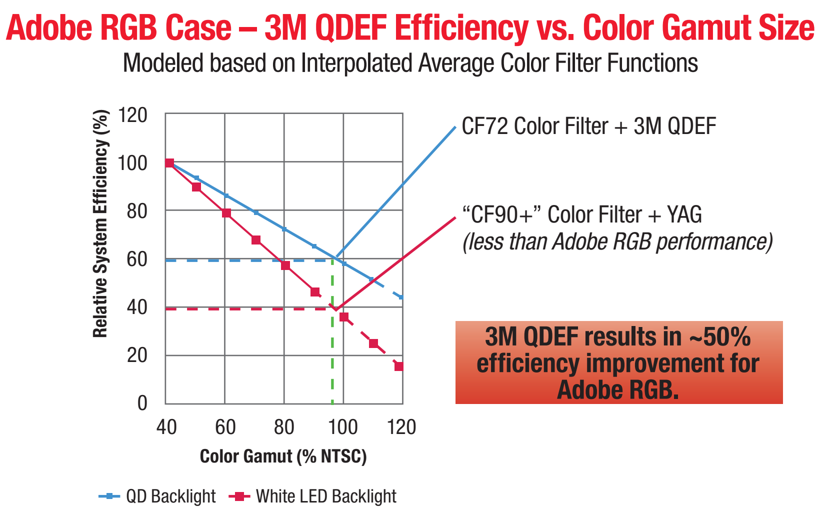

Figure 8. Modeling analysis showing relative LCD system efficiency. The Adobe RGB color gamut can be achieved using 3M QDEF or highly saturated color filters; the 3M QDEF displays are approximately 50 percent more efficient than displays using the more saturated (CF90+) color filters.

Given the ubiquity of LCDs, this constitutes a very significant reduction in potential energy use. Televisions and their set-top boxes use more power than any other consumer electronic device. They are the fifth largest consumer of residential electrical energy in U.S. homes; only air-conditioning, lighting, water-heaters and refrigeration account for more power consumption.[x] When the power consumed by computer monitors, laptops, smart phones and tablets is included, the outsized energy impact of LCDs becomes apparent.

(OLED displays offer a color gamut that can be roughly analogous to displays equipped with quantum dots, but comparisons of the two technologies' energy efficiency are difficult. The energy draw of an OLED display will vary according to the content, while the energy consumption for most LCDs is constant. As a result, OLEDs show energy advantages over LCDs under some conditions; in others, LCDs are clearly superior. In any case, larger OLED displays are still curiosities—expensive demonstrations of the technology's potential. Until the industry offers an affordable, mass market large-screen OLED device, any discussion of efficiency is theoretical.)

Accelerated aging tests indicate that the durability of quantum dots exceeds industry requirements. After exposure to standard tests (including thermal cycling and high humidity), first generation dots showed a lifetime of 20,000 to 30,000 hours, with typical failure from white point drift. Second-generation dots are expected to have greater than a 70,000-hour lifetime for most consumer applications.

Are quantum dots inevitable?

There is little controversy about the appeal of larger color gamuts. Previously noted research indicates that viewers pay more attention to images with larger gamuts and that consumers see a larger gamut as an indication of better device quality. Additionally, the popularity of OLED displays can be traced in large part to their expanded color gamuts.

The potential impact on attention and perceived quality—along with quantum dots' efficiency, durability and ease of integration—suggest that a widespread adoption of larger color gamuts through the use of quantum dots is highly likely.

That adoption could be hastened by the adoption of industry standards and improved color management software, which would minimize any concerns about available content for large-gamut displays.

To be clear: abundant large-gamut content is already available. Many contemporary films are produced with equipment that captures a large gamut (which must then be "down-converted" so that it can be shown on a television). Even the images captured by many of our personal cameras are down-converted to the sRGB standard. Furthermore, sRGB content can be rendered so that it can be shown on a device that is capable of expressing the Adobe RGB or DCI P3 gamuts. Finally, when content is produced using one large gamut (such as Adobe RGB) and shown on a display designed to express another large gamut (such as DCI P3) any inconsistencies can be "smoothed" by the display's color management software. (The color management software can be integrated into the device's chipset or it can be part of its operating system.)

Certainly, in devices with simple or outdated color management software, some color inaccuracies and oversaturation can arise when sRGB content is up-converted or when gamut differences must be smoothed. This is likely a transitional problem: as manufacturers introduce more large-gamut displays—using 3M QDEF, quantum dot rails, OLEDs or some other yet-to-be developed technology—the industry is expected to pay renewed attention to color management software.

At the same time, new content will increasingly be produced in Adobe RGB or DCI P3. This will reduce the frequency of up-converting, but occasional inaccuracies caused by smoothing will continue to occur until the industry can align on a single color standard.

What's next?

In the next few years, we can expect a profusion of displays that use quantum dots. The experience of LCD phones, tablets and—especially—televisions will change, becoming more realistic and immersive.

During this time, the current mechanisms for employing quantum dots (rails and 3M QDEF) will be refined. Other methods, such as a coating of dots on the backlight plate or another component, will almost certainly be explored.

From an industry perspective, it will be interesting to track how large-gamut, quantum dot-equipped LCDs will impact the demand for OLED displays.

Ultimately, quantum dot technology will affect content in new and exciting ways. The expanded color gamut is a new tool that will be wielded by videographers, filmmakers and other content creators. If they chose to do so, these artists will be able to more accurately reflect the world around us. Or they might apply the expanded palette to create new effects and express emotions and ideas in new ways that challenge and stimulate the imagination.

The expanded color gamut is a new tool that will be wielded by videographers, filmmakers and other content creators.

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[i] A. Lathrop. "Color as a Key Differentiator," IHS/SID 2013 Business Conference, Vancouver. (2013).

[ii] Wichmann, Felix A.; Sharpe, Lindsay T.; Gegenfurtner, Karl R. "The contributions of color to recognition memory for natural scenes." *Journal of Experimental Psychology: Learning, Memory, and Cognition*, Vol. 28(3), May 2002, 509-520.

[iii] Schumacher, J.F., Van Derlofske, J., Stankiewicz, B., Lamb, D., Lathrop A. (2013). "PQM: A Quantitative Tool for Evaluating Decisions in Display Design." *Information Display*, 29(3), 36-40.

[iv] Unpublished 3M research

[v] The Helmholtz-Kohlrausch effect. See: CIE Publication No. 17.4 International lighting vocabulary, Central Bureau of CIE, Vienna, 1988, see 845–02–34, p. 50

[vi] S. Cole-Sullivan, et al. "Quantum Dots for LED Down Conversion in Display Applications," JSS 2 (2) R3026-R3030. (2013).

[vii] F. B. McCormick. "Barrier Films for Displays, Lighting, & Flexible Electronics," Printed Electronics USA 2013. Santa Clara, California. (2013).

[viii] J. Chen, V, Hardev, and J. Yurek. "Quantum-Dot Displays: Giving LCDs a Competitive Edge through Color," *Information Display* 1/13, pp. 2-7. (2013).

[ix] J. Van Derlofske and K. Hanley. "Quantum Dot Enhancement Film (QDEF): High Color Gamut LCDs for Improved Visual Quality," Intel Ecosystem Symposium. Taipei, Taiwan. (2013).

[x] EIA Annual Energy Outlook 2012.

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