Quantum Dots and Wide Color Gamut Display Technologies
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Eric Virey is a Senior Market and Technology Analyst at Yole Développement. Eric is a daily contributor to the development of LED, OLED, and Displays activities at Yole, with a large collection of market and technology reports as well as multiple custom consulting projects: business strategy, identification of investments or acquisition targets, due diligences (buy/sell side), market and technology analysis, cost modelling, technology scouting, etc. Thanks to its deep knowledge of the LED/OLED and displays related industries, Eric has spoken in more than 30 industry conferences worldwide over the last 5 years. He has been interviewed and quoted by leading media over the world.

Previously Eric has held various R&D, engineering, manufacturing and business development positions with Fortune 500 Company Saint-Gobain in France and the United States.

Dr Eric Virey holds a Ph-D in Optoelectronics from the National Polytechnic Institute of Grenoble. Eric is also author / co-author of multiple reports (examples below) and contributed to various custom projects.

- LED Packaging
- LED Front End Manufacturing
- III-V Epitaxy
- Bulk GaN
- GaN on Silicon
- Status of the LED Industry
- Sapphire Market & Applications
- Phosphors and Quantum Dots
- Organic TFTs
- MicroLED Displays
The report provides an extensive review of Quantum Dots and other Wide Color Gamut technologies for displays.

The report does not cover non-display applications of Quantum Dots (photovoltaic, biology, imaging...)

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OBJECTIVE OF THE REPORT

• Understand the Current Status of Wide Color Gamut (WCG) Display Technologies:
  • What is driving WCG and High dynamic Range (HDR)
  • Which technologies can be used?
  • The OLED vs LCD battle who’s winning?
  • Display panel unit forecast for each WCG technology

• Focus on Quantum Dot technologies:
  • The different types of QDs: Cd-based and Cd-free, Quantum rods, Platelets..
  • Manufacturing technologies
  • Understand the 3 generations of QD displays: Backlight color converter (Film, on-chip), Color filter, Electroluminescent QDs
  • Impact of environmental regulations.
  • Detailed forecast: unit shipments per display size, application, types of QDs, types of designs (QD films, QDCF, Hybrids…)

• Competitive Landscape and Supply chain
  • Identify key players in technology development and manufacturing.
  • Supply chain overview.
REPORT METHODOLOGY

Market forecast methodology

Market segmentation methodology

USES
- Variant
- Quasi segments

CLIENTS
- Commercial key success factors behaviour and competitor behaviour matrices

APPLICATIONS
- Segments

BEHAVIOUR
REPORT METHODOLOGY

Technology analysis methodology

- Define the key parameters
- Understand the requested specifications per parameter and application
- Define the competing technologies and the potential evolutions of the technologies
- Define the roadblocks and challenges to be overcome
- Establish the technology roadmaps and maps
- Experts discussions

Information collection

- Analysts’ processing to answer your needs and questionings on market size, positioning, technical challenges...
- Trade shows, stand visits, and participation
- Analysis of the presentations, websites, publications, white papers...
- Ordering of materials, equipment, devices
- Designers
- System designers
- DoSAT
ACRONYMS

- **AMOLED**: Active Matrix OLED
- **a-Si**: Amorphous Silicon (TFT)
- **BLU**: Backlight Unit
- **CapEx**: Capital Expenditure
- **CF**: Color Filters
- **CGEF**: color Gamut Enhancement Film (Samsung)
- **CRT**: Cathod Ray Tube
- **EL-QD**: Electro-luminescent Quantum Dot
- **EOTF**: Electro-Optical Transfer Function
- **EQE**: External Quantum Efficiency
- **ETL**: Electron Transport Layer
- **FHD**: Full High Definition (1920 x 1080)
- **FMM**: Fine Metal Mask
- **FOV**: Field OfView
- **FWHM**: Full Width at Half Maximum
- **HIL**: Hole Injection Layer
- **HD**: High Definition
- **HDR**: High Dynamic Range
- **HTL**: Hole Transport Layer
- **IGZO**: Indium Gallium Zinc Oxide (TFT)
- **ITO**: Indium tin Oxide
- **LCD**: Liquid Crystal Display
- **LED**: Light Emitting Diode
- **LTPS**: Low Temperature Polysilicon
- **NTSC**: National Television System Committee
- **OEM**: Original Equipment Manufacturer
- **OLED**: Organic Light emitting Diode
- **OTR**: Oxygen Transmission Rate
- **PFS**: Potassium Fluoride Silicon (phosphor)
- **PPD**: Pixel Per Degree
- **PPI**: Pixel Per Inch
- **QD**: Quantum Dots
- **QDCF**: Quantum Dot Color Filter
- **QDEF™**: Quantum Dots Enhancement Film (Nanosys)
- **QHD**: Quad High Definition (2560x1400 to 3440x1440)
- **QY**: Quantum Yield
- **RGB**: Red Green Blue
- **RoHS**: Restriction of Hazardous Substances.
- **SDR**: Standard Dynamic Range
- **SID**: Society For Information display
- **TFT**: Thin Film Transistor.
- **UHD**: Ultra High Definition
- **WCG**: Wide Color Gamut
- **WOLED**: White OLED
- **WVTR**: Water Vapor Transmission Rate
- **YAG**: Yttrium Aluminum Garnet (phosphor)
COMPANIES CITED IN THE REPORT

3M (US), Acer (TW), Amazon (US), American Elements (US), AOC (TW), Apple (US), ASUS (TW), AU Optronics (TW), Avantama (CH), BASF Venture Capital (DE), BenQ (TW), BOE (CN), Brunel University (UK), CANDots (DE), CEC Panda (CN), Changhong (CN), Chiefway (TW), Chunghwa Picture Tubes (TW), Citizen (JP), Crystalplex (US), CSOT (CN), Cyrium Technologies (CA), Daejoo (KR), Dai Nippon Printing (JP), Denka (JP), Dolby (US), Dotz Nano (US), Dow (US), Eco Flux (KR), Efun (TW), Everdisplay (CN), Everlight (TW), Exciton (CN), Foxconn (TW), GE / Current powered by GE (US), GLOTEC (KR), Grundig (DE), Hannstar (TW), Hansol Chemical (KR), Hisense (CN), Hitachi Chemical (JP), HKC (CN), Huawei (CN), I-Component (KR), Innolux (TW), Intematix (US), Irrilliant (US), Japan display (JP), JOLED (JP), Jufei Opto (CN), Juhua (CN), Kateeva (US), KDX (CN), KIST (KR), Kodak (US), Kolon (KR), Konica Minolta (JP), Konka (CN), Kyulux (JP), Kyung Hee University (KR), LeEco (CN), Lextar (TW), LG Chem (KR), LG Display (KR), LG Electronics (KR), LMS (KR), Loewe (DE), Luminisyn (US), Merck (DE), Mesolight (US), Mitsubishi Chemical (JP), Mitsui Tochelio (JP), MNTech (KR), Najing Tech (CN), Nanoco (UK), Nanophotonica (US), Nanosquare (KR), Nanosys (US), Nationstar (CN), Navillum Technologies (US), Nexdot (FR), NHK (JP), Nichia (JP), Nitto Denko (JP), NS Materials (JP), Ocean Nanotech (US), Osram (DE), Pacific Light Technologies (US), Panasonic (JP), Philips (NL), PixelDisplay (US), PlasmaChem (DE), Poly Optoelectronics (CN), QD Vision (US), Qlight Nanotech (IL), Quantum Materials Corp (US), Quantum Technology Group (US), Refond (CN), Royole (CN), Sakai display (JP), Samsung (KR), Sangbo (KR), Seiki (CN), Seoul National University (KR), Sharp (JP), Shinwha (KR), SKC Haas (KR), Skyworth (CN), Sony (JP), Storedot (IL), Strem chemical (US), Suijing Opto (CN), SUSTech (CN), Taiwan Nanocrystals (TW), Tapex (KR), TCL (CN), Technicolor (FR), TEL (JP), Tianma (CN), Tongfang (CN), Toray (JP), Toshiba (JP), Toyoda Gosei (JP), TPY (CN), Truly (CN), Ubi QD (US), Unity Opto (TW), University of Florida (US), Verlase (US), Visionox (CN), Vitriflex (US), Vizio (CN), VP dynamics (TW), Wah Hong (TW), Wooree (KR), Zhonghuan Quantum (CN).
LCD displays consist primarily of two sheets of polarizers and a cell of 2 glass plates with liquid crystals sandwiched between them.

Grooves are defined on the glass plates to force the crystals to align in a specific direction. Crystals in contact with the top plate are oriented at 90° compared to the bottom plate. In between the plates, the crystals continuously rotate to match each surface orientation.

When a light polarized in the same direction as the crystals enter on one side, the light polarization rotates smoothly with the crystals and exit on the other side. If it matches the orientation of the exit polarizer, the light will go through: the pixel is “on”

By applying an electric field to the crystals, the liquid crystals untwist and the polarization of the light exiting does not match that of the exit polarizer → the pixel appears black.
HIGH DYNAMIC RANGE

- The best 2017 consumer LCD TV delivers XX Nits while the best OLED peak at XX Nits.
- The 10,000 peak brightness recommended by Dolby is equivalent to looking directly at a fluorescent tube (very bright but not painful to look at). On the black side, 0.0001 nits is very dark but can be seen by the human eye after a minute or two in a completely dark room.

UHD Alliance dynamic range standards for consumer displays exceeds that of digital cinema.

UHDA “OLED” standard: less than XX black and more than XX peak

UHDA “LCD” standard: less than XX black and more than XX peak

Best available 2017 QD-LCD (Samsung Q9): XX black to XX peak

Cinema (movie theatre): XX to XX
ADVANTAGES FOR DISPLAY: POLARIZATION

• The emission is strongly polarized linearly in the plane that contains the long axis of the rod. The polarization ratio \([1]\) of a single rod can reach up to XX%.

• If the QR orientation in a conversion film could be controlled so as to features rods all aligned in the same direction, the resulting overall polarized emission would strongly reduce absorption from the first polarization filter in the LCD structure, thereby significantly improving the energy efficiency of the system.

[1] Defined as the ratio of the difference of each polarization intensity divided by the total intensity: \(\frac{I_{//} - I_{\perp}}{I_{//} + I_{\perp}}\)
MAJOR COLOR GAMUT IN THE CIE 1931 AND 1976 SPACES

* the ACES API standards make use of “imaginary colors” and pokes out of the color spaces (the ACES AP0 that will be used for encoding features an even broader gamut exceeding 100% of the CIE color space)
The SUHD series introduced at the CES in January 2015 was Samsung’s first range of TV with enhanced color gamut and brightness. The first models to hit the market a month later were using quantum dots films in the backlight.

However, at the time the cost of quantum dots films was still high (~ $XX for a 55” TV) due to the low environmental stability of the QDs which required expensive moisture and oxygen barrier (~$XX/TV).

To reduce cost, Samsung collaborated with XXX to develop a notch filter film based on organic molecules. The film, called “Color Gamut Enhancement Film” (CGEF) provided extra absorption in the yellow part of the spectrum to enhance saturation of the green primary from the white LEDs.
In 2014, the PFS: Mn$^{4+}$ phosphor (also known as “KSF”) entered the market. This material, developed by GE, exhibits very narrow emission bands at 613, 631, 636 and 648 nm with FWHM in the 3-4 nm range. The strongest emission at 631 nm is almost ideally positioned for BT.2020 coverage (630 nm primary).

By combining a green oxynitride phosphor with PFS, it is possible to achieve up to XX% NTSC coverage[1] and increased display efficiency with standard color filters. Higher values are possible with more selective filters, although at the expense of lower efficiency.

[1] in CIE 1931. Up to XX% in CIE 1976

PFS further improves performance over nitride red phosphors.

Comparison of Nitride and PFS wide color gamut LEDs (illustration: Yole, gamut and efficiency data: Sharp 2016)
COLOR FILTERS IN TRADITIONAL DISPLAYS

• In traditional LCD displays, white light constituted of the 3 primaries emerges from the liquid crystal cell and enters the color filters.

• Roughly 2/3rd of that total light is therefore absorbed by the filters at each subpixels, leading to very low overall efficiency of an already optically complex display stack.

• The overall optical efficiency of an LCD display is typically only about XX%.
• In standard LC displays, the liquid crystal cells is constituted by the TFT glass on the bottom and the color filter substrate on the top: the two structures are assembled together with spacers and a sealant before being filled up with the liquid crystals.

• In the cell, the liquid crystals align on each plate thanks to structures or “grooves” created on each surface, either by mechanical action (rubbing a cloth in one direction) or more elaborated methods (ion beams, photo-alignment, PSA etc.).

• This surface structuring is usually performed either on the ITO electrode if present[1] or, in most cases on a polyimide (PI) layer added at the surface of the color filters.

• In the new structure, the polarizer must be inserted into the cell, and receive the pattern to align the liquid crystal. This poses a variety of challenges:
  • Polarizer materials can withstand temperature up to 90-100° C but curing the PI layer requires > 200° C baking.
  • Polarizers have rougher surfaces than the PI coating.

[1] for In Plane Switching (IPS) LCD panels, both electrodes are on the TFT glass.
While these individual LEDs can also be turned off individually, their limited quantity (a few hundreds at best) causes at least some light bleed around the object.

The effect is more pronounced when bright objects much smaller than the individual dimming zones must be displayed against a very dark backdrop, for example, fireworks or starlight on a dark sky.

To limit this halo effect, LCD image processor will typically reduce the luminance in the area containing both the dark background and the super bright image so the effect is a peak luminance that is actually lower than what the TV can theoretically deliver.

Pixel level dimming could be done with LCD by stacking up two LC cells (one in the backlight, one in the traditional LC cell. However, this dramatically reduces brightness, efficiency and increase costs. This solutions is therefore only used in some professional display used in video editing.

Another promising technology to improve LCD local contrast is microLED based backlights (next pages).
QD-based solution are expected to dominate WCG technology through the period and be featured in XX% of WCG panels in 2022.
• With high efficiency, good stability, a well positioned center wavelength and a very narrowband emission, PFS has gained a prominent position in the display industry.

• Easy “on-chip” implementation when combined with green β-SiAlON offers a cost efficient, Cd-free drop-in replacement solution compatible with any existing LCD display with up to 120 Hz refresh rate.

• As a result, we expect phosphor solutions to retain a significant market share in entry-level to mid-range WCG TVs of all sizes.

• However, QD films cost decrease and performance increase on a regular basis. Unless a narrow band green phosphor enters the market, the performance gap between phosphors and QD films is expected to keep widening. Higher performance QD-CF are also set to enter the market. We therefore expect pure phosphor solutions to lose market share on the high end portions of the market.

In 2017, PFS is featured in XX% of WCG TVs. This share will decrease to XX% by 2022 and QD cost decrease and performance keep increasing.
2017-2022 QD FILM ASP COST BREAKDOWN AND FORECAST

• Barrier costs in QD films have dropped rapidly since 2015, allowing rapid film cost reductions.

• Further reduction is expected as air stable QDs are developed allowing barriers with simpler structures. Ultimately, it is expected that the barrier could consist in 1 or 2 layers of simple food grade barrier.

• In addition, a growing number of barrier suppliers are entering the market, increasing competition.

• The pressure on QD manufacturers is also significant: display OEM expect QD suppliers to deliver ever improving performance and stability at lower prices.

• Increasing competition with the entrance of Chinese players as well as improving manufacturing techniques could reduce material cost to below $XX/m² by the end of the forecasting period.

• Combined with lower barrier cost, volume effects and increased competition that will pressure margins, we expect the price of QD film to decrease to ~$XX/m² by 2022.
• Overall QD adoption in monitors will reach XX% by 2022. The total surface of QD-based panels for monitors is anticipated to grow at a XX% CAGR, increasing from XX millions of m² in 2017 to XX millions by 2022.

• QDs will be deployed exclusively as films due to the higher cost of QD color Filters (QDCF) and limited incentives to deploy the technology on the monitor market where OLED competition is not as strong as in TVs.

QD adoption will increase rapidly in high performance monitor but remain low overall.
RoHS ENVIRONMENTAL REGULATIONS

- Cadmium is a restricted substance in most countries due to potential adverse health and environmental impact. The European Restriction of Hazardous Substances (RoHS) limits the cadmium content in devices or components used in consumer electronic products to less than 100 ppm (0.01%) per weight. Other countries or organizations also have restrictions on Cd. For example, the IEEE 1680 standard also limits cadmium to <100 ppm and recommends < 50 ppm as good environmental practice.

- The restrictions apply to each homogeneous material in the product. This means that the limit does not apply to the weight of the finished product, or even to a component, but to any single substance that could (theoretically) be separated mechanically—for example, the sheath on a cable or the tinning on a component lead.

- In the case of a display, the 100 ppm limit therefore applies to the QD optic (tube) or to the QD containing film (not even including the film barrier) used to convert the blue light from LEDs into white light.

Cadmium concentration in any individual component or sub-component is restricted to < 100 ppm weight.
Discover more related reports within our bundles here.
As TV makers struggle to trigger replacement cycles, Wide Color Gamut (WCG) and High Dynamic Range (HDR) and their notable picture quality improvements are the next growth drivers for the industry. Various technologies are competing to deliver those features. In the short and mid-term, the best-positioned ones are OLED and the well-established, dominant, LCD technology supercharged with narrow-band phosphor LEDs or quantum dot (QD) color converters in the backlight unit.

Quantum Dots enable drastic enhancements of display color gamut. They do so with high efficiency, giving display makers headroom to increase brightness, contrast and gamut without increasing power consumption.

Their most common implementation is as color conversion films located in the LCD backlight unit. QDs in this form are drop-in solutions that can be easily deployed on all sizes of displays without any process change or capital expenditure (CapEx) required by display makers. QDs therefore enable the LCD industry to boost the performance of its products without major investment. This contrasts with OLEDs, which require building multibillion-dollar dedicated fabs. However QDs don't solve some LCD shortcomings. They still lag in terms of response times, black levels, viewing angles. Also, LCDs can't deliver pixel-level dimming, the strongest selling point for OLED displays. In the future, QDs could substitute for LCD color filters. Unlike films, this configuration requires some process changes in LCD manufacturing. However it would double the display efficiency, further improve color gamut and provide viewing angles similar to OLED. In the longer term, Electroluminescent QDs (EL-QD) could deliver OLED-like characteristics and performance, with improved brightness and stability.

LG Display is currently the only OLED TV panel manufacturer. The company announced that it will stop investing in LCD and build two new OLED TV manufacturing lines in Korea and China, slated to start production in late 2019. Cost and technology barriers to entry are high, and few other companies will be able to manufacture OLED TV panels in that timeframe. Unless OLED printing technologies progress fast enough to enable cost efficient manufacturing of large, full RGB displays, OLED TV adoption will therefore remain capacity-constrained to less than 12 million units per year until 2022.
QDs will take advantage of this window of opportunity to capture the lion’s share of the WCG TV market. Rapidly improving performance and decreasing cost enables adoption to spread into mid-range, sub-$1000 models. Display makers will use QDs to keep extracting more value from existing LCD manufacturing. For the long term however, many are hedging their bets and looking at both RGB printed OLED and EL-QDs. In the mid-term, QD Color Filter (QDCF) configurations represent an attractive opportunity to close the gap with OLED in term of viewing angles and widen it in term of gamut and efficiency. QDCF however requires some LCD manufacturing process changes. Although moderate compared to a new OLED fab, not every LCD maker will want to commit the required CapEx or even develop the technology.

Narrowband phosphors deliver performance close to QDs at much lower cost. The performance gap, however, is widening as QDs keep improving and the cost gap decreases. Phosphors will therefore lose market share in the premium segments, but overall volumes will grow significantly thanks to increasing penetration in mid-range products. We also expect narrowband phosphors to be the dominant solution for smaller WCG LCD displays.

In the longer term, both OLED and QD-enhanced LCD could face competition from new, disruptive technologies such as electroluminescent QDs or even microLEDs, which could drive a potential paradigm shift in self-emissive display technology. Other technological innovations could also disrupt the QD market. For example commercialization of a narrow-band green phosphor could eliminate the performance gap between phosphors and QD films and enable a more cost-effective solution.

AS DEMAND INCREASES, MORE PLAYERS WILL JOIN IN

In 2017, demand for QDs is dominated by Samsung. After the demise of pioneer QD-Vision, whose intellectual property was acquired by Samsung in 2016, Nanosys and Hansol are the only QD manufacturers supplying high volumes in 2017. This could change rapidly however as many more TV makers adopt QDs.

Nanoco and its new film partner Wah Hong seem closer than ever to scoring a design win. Quantum Materials in the US and NS Materials in Japan are other credible outsiders. In the fast-growing Chinese display industry, local QD maker Najing Tech is partnering with key manufacturers, accelerating the development of QD films and EL-QD and preparing to ramp up manufacturing.

Many more companies are investing at various levels of the supply chain to get their share of the material, film or barrier opportunities. 2016 saw a major IP battle between Nanosys and QD Vision. As new companies attempt to get their share of the pie, we expect established leaders to become increasingly aggressive in leveraging IP to block new entrants.

On the environmental front, cadmium (Cd)-free QDs dominate the market. Combined with the upcoming availability of fully RoHS compliant solutions such as Nanosys’ Hyperion or possibly hybrid green QD/narrowband red phosphors (PSF), this has prompted the European Commission not to renew a Restriction of Hazardous Substances (RoHS) Directive exemption that temporarily allowed higher cadmium content (a decision that should be ratified by the Parliament later this year). Cd-free solutions will therefore keep dominating the market, but will coexist with Cd-based yet RoHS compliant solutions. Most manufacturers, however, will stay away from any Cd-containing compositions.
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