Introduction to Quantum Dot Display Technology

September, 2015
John Ho, jho@qdvision.com
Quantum Dot Adoption is Accelerating

Companies Demonstrating Quantum Dot Displays in 2015

- KONKA
- LG
- SAMSUNG
- TCL
- Hisense
- Skyworth
- SHARP
- PHILIPS
- AOC
- CHANGHONG

"We forecast by 2025, 60% of TVs will have quantum dots in them; 51% of monitors will adopt quantum dot."
- Dr. Jennifer Colegrove, CEO, Touch Display Research Inc.

"TVs using QD technology will become available in 2015, with 1.3 million shipping worldwide. Shipments of quantum dot TVs are expected to grow to 18.7 million in 2018.
- DisplaySearch Quarterly TV Design and Features Report"
Quantum Dot TV Products by Retail ASP

Source: IHS/Displaysearch, JD.com, Gome.com.cn, Samsung.com, Amazon.com, Retail Stores
Overview

- QDV Introduction
- What are quantum dots (QDs)?
- How are QDs used in displays?
- How do QDs work?
- Impacts on image quality
- Path to BT. 2020
About QD Vision

- Founded in 2005, operations in Lexington, Massachusetts, USA
- MIT roots with many staff from MIT
- Over 250 patents and patents pending
- Launched the world’s first Color IQ™ quantum dot displays in 2013
- World’s largest quantum dot manufacturing facilities
- Currently developing products with the top Chinese TV and Monitor manufacturers
What are Quantum Dots?

- Quantum from Quantum Mechanics (physics on a nanoscale)
- Dot from the spherical shape

1. Spectrally pure, light-emitting nanocrystals
2. Color determined by size and core elements
3. World’s most efficient color conversion material

Same material, increasing size
# How Are QDs Used in Displays?

<table>
<thead>
<tr>
<th>Film</th>
<th>Edge Optic</th>
<th>On-chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>QD Film</td>
<td>QD Optic</td>
<td>LGP</td>
</tr>
<tr>
<td>LED</td>
<td>LED</td>
<td>LGP</td>
</tr>
<tr>
<td>LGP</td>
<td>LGP</td>
<td>QD LED</td>
</tr>
</tbody>
</table>

![Diagram of QD display configurations]

*Source: Nanosys Online Media Kit, LumenMax Optoelectronics*

**Operating Flux, Temperature**
How Do QDs Work?
Light Source + Color Filters = Display Spectrum

Quantum Dot FWHM 30nm

White LED

BLU Level

Wavelength (nm)

400 440 480 520 560 600 640 680

pixel

CFA

WLED
**BLU + CFA Spectra: WLED**

- **BLU Level**
  - Quantum Dot: Wavelength (nm) 380, 460, 540, 620, 700, 780
  - FWHM 30nm

- **White LED**

- **Green leakage**
  - Wavelength (nm) 380, 460, 540, 620, 700, 780

- **Blue Channel**

- **Pixel**
  - CFA
  - WLED
**BLU + CFA Spectra: WLED**

**Quantum Dot**
- FWHM 30nm

**White LED**

**BLU Level**
- WLED
- BLU + CFA Spectra

**Blue Channel**
- Green leakage

**Green Channel**
- Red leakage
**BLU + CFA Spectra: WLED**

**WLED Technology**
- Wide FWHM reduces gamut
- CFA channel leak reduces gamut

**Blue Channel**
- Green leakage
- 85nm

**Green Channel**
- Red leakage

**Red Channel**
- Blue-Green Leak
- 56nm

**Quantum Dot**
- FWHM 30nm

**White LED**
- BLU + CFA Spectra: WLED

**Pixel**
- CFA
- WLED
**BLU + CFA Spectra: QDs**

**BLU Level**

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Blue Channel</th>
<th>Green Channel</th>
<th>Red Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td></td>
<td></td>
<td>380</td>
</tr>
<tr>
<td>460</td>
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<td>540</td>
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<tr>
<td>700</td>
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<tr>
<td>780</td>
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<td>780</td>
</tr>
</tbody>
</table>

- **FWHM**
  - 380-540 nm: Quantum Dot FWHM 30nm vs. WLED FWHM 30nm
  - 540-700 nm: Quantum Dot FWHM 85nm \(\rightarrow\) 30nm
  - 700-780 nm: White LED

**QD Technology**
- Less CFA channel leak
- Narrower FWHM
- Results in higher gamut, higher efficiency

**Less green leak**
- Blue Channel
- Green Channel
- Red Channel
Color Gamut Is Determined By Spectral Distribution

Leakage between RGB channels limits gamut area

72% NTSC
Color Gamut Is Determined By Spectral Distribution

Tunable, pure QD emission separates RGB channels achieving full gamut

Quantum Dot

FWHM 30nm

380 460 540 620 700 780

100% NTSC
Summary of QD Impacts on Image Quality Perception

- Luminance vs. Gamut tradeoff
- H-K effect
- Observer Metamerism
Fundamental Trade-off Between Luminance and Color Gamut

- Spectrum overlap with photopic response yields luminance.
- Assuming **same number** of photons output by both TVs, Color IQ measures 16% fewer nits than WLED.
  - 336 nits vs. 400 nits.
QDs Can Improve Display Quality Score (DQS)

- Relative DQS scores indicate viewer preference
- 9 out of 10 people would prefer Color IQ over WLED
- 3 out 4 people prefer Color IQ to RGph
- At 120% NTSC area, Color IQ TV could be 50% luminance of WLED TV and maintain DQS

Source: 3M’s Display Quality Score Whitepaper

*3M’s global study includes 6 countries (US, Japan, China, Korea, Poland, and Spain), over 200 participants, and >110K data points
For WCG Displays, Nits ≠ Brightness

<table>
<thead>
<tr>
<th></th>
<th>NTSC Area</th>
</tr>
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<tbody>
<tr>
<td>Color IQ TV</td>
<td>101.6%</td>
</tr>
<tr>
<td>Saturated</td>
<td>68.3%</td>
</tr>
<tr>
<td>Desaturated</td>
<td>52.4%</td>
</tr>
</tbody>
</table>

Desaturated  Saturated

Equal Luminance
Observer Metamerism Increases with Narrower Primaries

Source: “Mean Observer Metamerism and the Selection of Display Primaries”, MD Fairchild et al.
How to Achieve Maximum Overlap of Rec. 2020?

- Full gamut can only be achieved in theory
- Primaries originally developed by NHK:
  - Covers all existing gamut standards and real object colors
  - Compatible with potential laser wavelengths
  - Located on loci of constant hue
How to Achieve Maximum Overlap of Rec. 2020?

- Red and green phosphor primaries are too wide

- Addition of thicker color filter material will dramatically reduce system efficiency

- Large FWHM of primaries limits RG ph to ~85%
How to Achieve Maximum Overlap of Rec. 2020?

- Low Green LED efficiency, and differential aging, and temperature performance remain key challenges

- Large FWHM of green primary limits gamut to < 90%

- Prohibitive cost/complexity
How to Achieve Maximum Overlap of Rec. 2020?

Lasers provide best performance, but are not practical

- Full gamut nearly achieved
- Speckle and observer metamerism remain key technical challenges
- Prohibitive cost/complexity
How to Achieve Maximum Overlap of Rec. 2020?

- Assumes Ideal Color Filters and 25 nm FWHM QDs

- In practice, only ~93% gamut coverage achieved due to blue and green color filter leakage

- Getting to visually indistinguishable coverage of BT. 2020 requires adding tolerance to RGB primaries