# Cadmium-Free Quantum Dots for Display and Lighting Technologies

Andrew Gooda and James Harris (Nanoco)
Jake Joo and Andrew Lee (Dow)

RoHS Targeted Stakeholder Meeting
13th December, 2013

# Biographies

## ANDREW LEE

**Qualifications:**
MBA, Harvard Business School
BS Mechanical Eng, Seoul National University

**Experience:**
Dow Chemical – Business Director
Hyundai Motors – product manager
4 years software engineer/marketer

## ANDREW GOODA

**Qualifications:**
BSc(Eng) Mechanical Eng, Imperial College London
CEng MIMechE and MIET
MBA, Durham University
PGC Sustainable Business, Cambridge University

**Experience:**
Nanoco – Manufacturing Director
ICI – Engineer through to Site Director
Croda -– Site Director

## JAKE JOO

**Qualifications:**
Specialize in nanocrystal synthesis and display/energy device integration
Ph.D. in Materials Science and Eng, MIT
BS in Materials Science, Seoul National University

**Experience:**
Dow Chemical – nanomaterial research for display
Samsung Electronics – next gen BLU development

## JAMES HARRIS

**Qualifications:**
Ph. D. in Inorganic Chemistry, University of Manchester
Post Doc, University of Manchester
Post Doc, California Institute of Technology

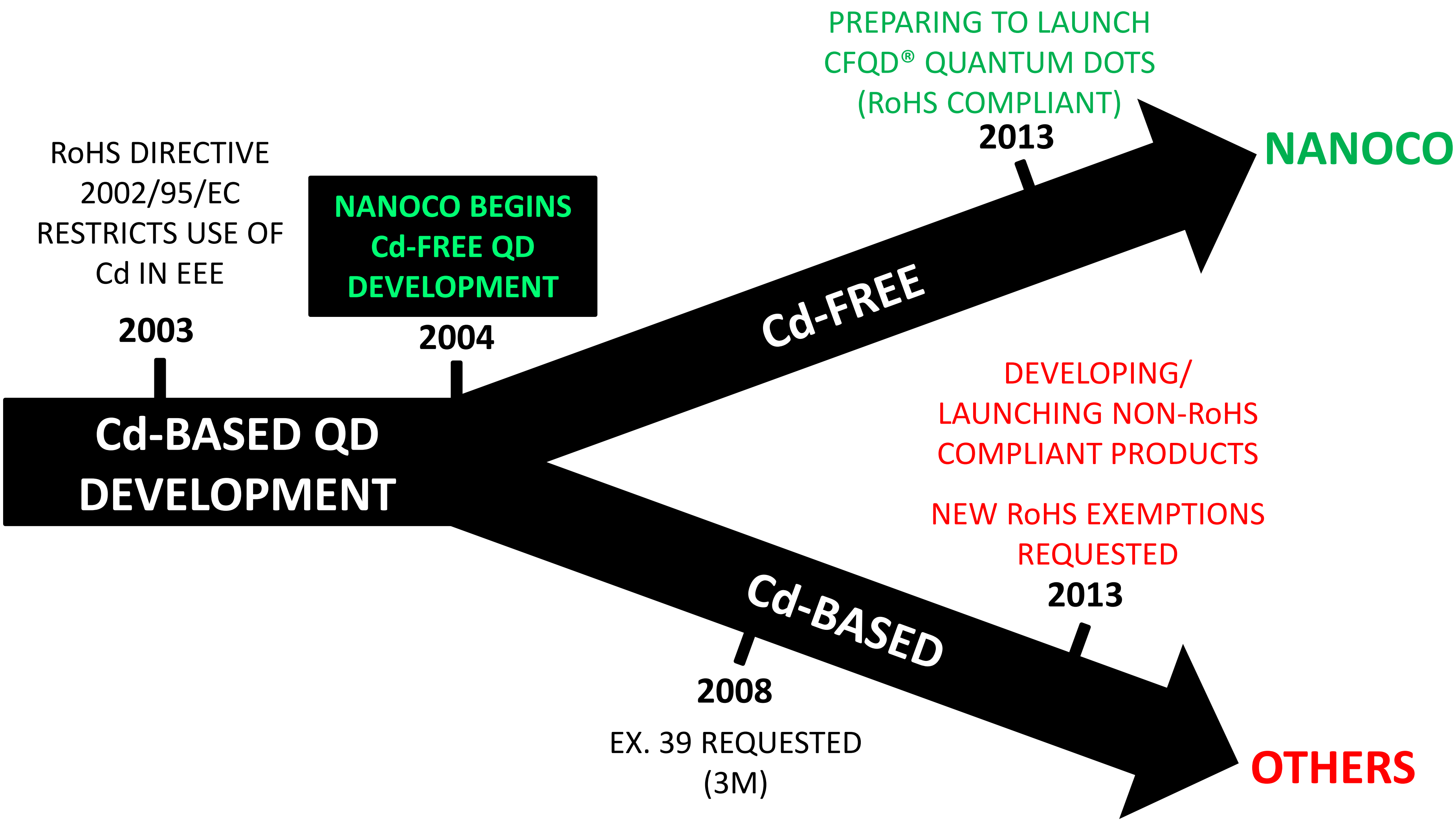
**Experience:**
Nanoco – Section Head of LED & CFQD® Quantum Dots
Oxford Biosensors – Cholesterol biosensor development

# Agenda

1. Quantum dots and RoHS
2. Overview of quantum dot applications
    a. Displays
    b. Solid-state lighting
    c. Commercialisation plan
3. Summary
4. Questions

# Quantum Dots and RoHS

# Quantum Dots and RoHS



# Dow and Cadmium-Free Quantum Dots

- Dow was interested in partnerships related to Quantum Dot technologies
- Dow Electronic Materials did not believe that Cadmium containing Quantum Dots in consumer electronics represented a positive direction for meeting its Sustainability goals.
- Customers have uniformly asked for Cadmium-free Quantum Dots
- A partnership with Nanoco met company requirements for:
  - A Cadmium free product
  - An advanced stage product.
  - Leveraging Dow’s expertise in manufacturing
  - Utilising Dow’s expertise and customer base in sales and marketing

# Quantum Dots, RoHS and Exemptions

- RoHS from 2003 targeted cadmium following EEC decision (88/C 30/01)
- Exemption 39 [3M request, 2008] intended for cadmium "on-chip" use with LEDs
- Encapsulation of cadmium

  "not an argument in line with Article 5(1)(b) since only the **impracticability of substitution or its negative effects** can be taken into consideration"[1]
- Ex. 39 granted for

  "**Cadmium in colour converting II-VI LEDs (< 10 µg Cd per mm$^2$ of light-emitting area) for use in solid state illumination or display systems**" until 1$^{st}$ July, 2014

  Light-emitting area = LED chip surface area
- Exemptions to allow manufacturers time to develop RoHS compliant products
  - Cd-based QDs further developed by applicants rather then create Cd-free QDs
  - **No commercial products Ex. 39 compliant yet launched in EU**[2]
    - Current Cd-based QD products on market appear as "on-edge" or "on-surface" instead of Ex. 39 compliant "on-chip"

[1] Adaptation to Scientific and Technical Progress Under Directive 2002/95/EC, 2008, p. 243

[2] Swedish Authority response to 2013 RoHS Exemption consultation

# Indium

- CFQD® quantum dots contain main group elements & indium, an EC recognised critical material
- Indium is not RoHS restricted
- Current global indium resource 50 – 100 years[1]
  - Global indium production increasing – reduced reliance on China
  - 65 % of annual indium supply is generated by recycling
  - Strategies to recover indium from LCDs already developed
- Indium global sourcing 1408 tonnes (2012)[2]
- CFQD® quantum dots in LCDs ("on-surface") ⟶ 0.5 – 1.0 % available indium per annum

[1] C. Mikolajczak and B. Jackson, Availability of Indium and Gallium, Indium Corporation Tech Paper, 2012: http://www.indium.com/reclaim-and-recycle/#whitepapers

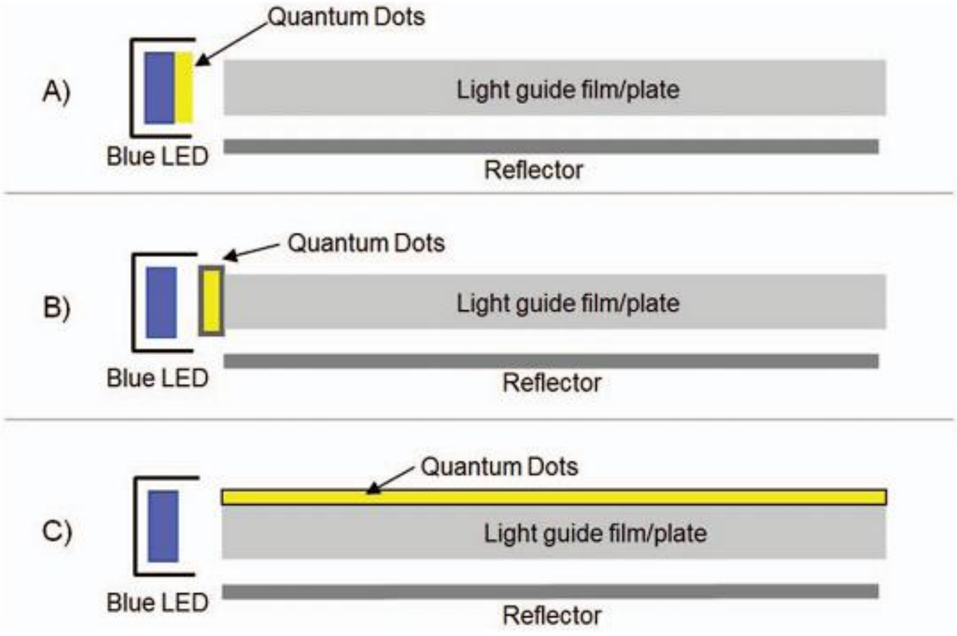
[2] Indium Market update Indium Corporation August 2013

# Overview of Quantum Dot Applications

1. **Displays**
2. **Solid-State Lighting**

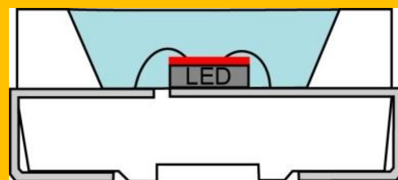
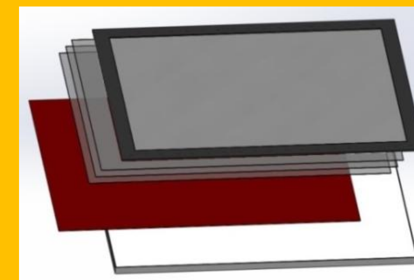
# Integration Strategies for QD into Displays

- Three potential strategies to integrate quantum dots into conventional LCD BLUs:[1]
  - **A)** "on-chip"
  - **B)** "on-edge"
  - **C)** "on-surface"

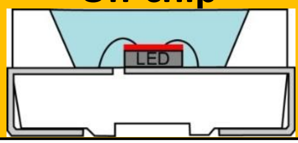


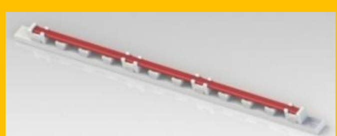
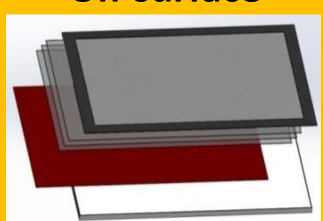

[1] S. Coe-Sullivan, W. Liu, P. Allen and J.S. Steckel, *ECS J. Solid State Sci. Technol.*, 2013, **2**, R3026

# Integration Strategies for QD into Displays

| | ON-CHIP | ON-EDGE | ON-SURFACE |
|---|---|---|---|
| |   |  |  |
| **QD INTEGRATION** | QDs placed directly within LED package, which is coupled to light guide | QDs placed between LED package and light guide | QDs placed in thin film, covering entire display surface |
| **OPERATING TEMPERATURE** | high<br>(~ 150°C) | moderate<br>(between that of on-surface and on-chip) | near room temperature |
| **MATERIAL USAGE** | low | moderate | high |
| **PROS & CONS** | • Most efficient approach<br>• Need to withstand high temperatures<br>• Need a cost effective way of sealing against oxygen | • Assembly issues<br>• Need additional room in the device<br>• Capillary is fragile (potential for exposure to QD resin) | • Ease of mass production<br>• Lower optical flux and heat<br>• Easy to incorporate into an existing device same assembly |

# Integration Strategies and RoHS Exemptions

| BLU DESIGN | EST. LIGHT-EMITTING AREA | MAX. Cd "ALLOWED" (EX. 39) |
|---|---|---|
| On-chip   | 48 mm$^2$ (surface area of LED chips[1]) | **480 µg** *(10 µg/mm$^2$)* |

| BLU DESIGN | EST. COMPONENT SURFACE AREA | Amount of Cd Per Exemption Request |
|---|---|---|
| On-edge  | 1.0 x 10$^4$ mm$^2$ (surface of glass capillaries[2]) | [2013-2] **100,000 µg** *(10 µg/mm$^2$)* |
| On-surface  | 4.4 x 10$^5$ mm$^2$ (display area[3] 40" screen) | [2013-2] **4,400,000 µg** *(10 µg/mm$^2$)* <br> [2013-5] **88,000 µg** *(20 µg/cm$^2$)* <br> 200x Ex.39 |

[1] Based on the LED chip size, the light-emitting area of each LED light bar, comprising 48 twin-chip LED chip packages, each consisting of two 0.5 mm x 0.5 mm LED chips, is 48 x 2 x 0.5 mm x 0.5 mm = 24 mm$^2$

[2] The surface area of each oval shaped capillary with dimensions of 2 mm x 4 mm x 510 mm was estimated to be [(2 mm x π) + 4 mm] x 510 mm = 5244 mm$^2$

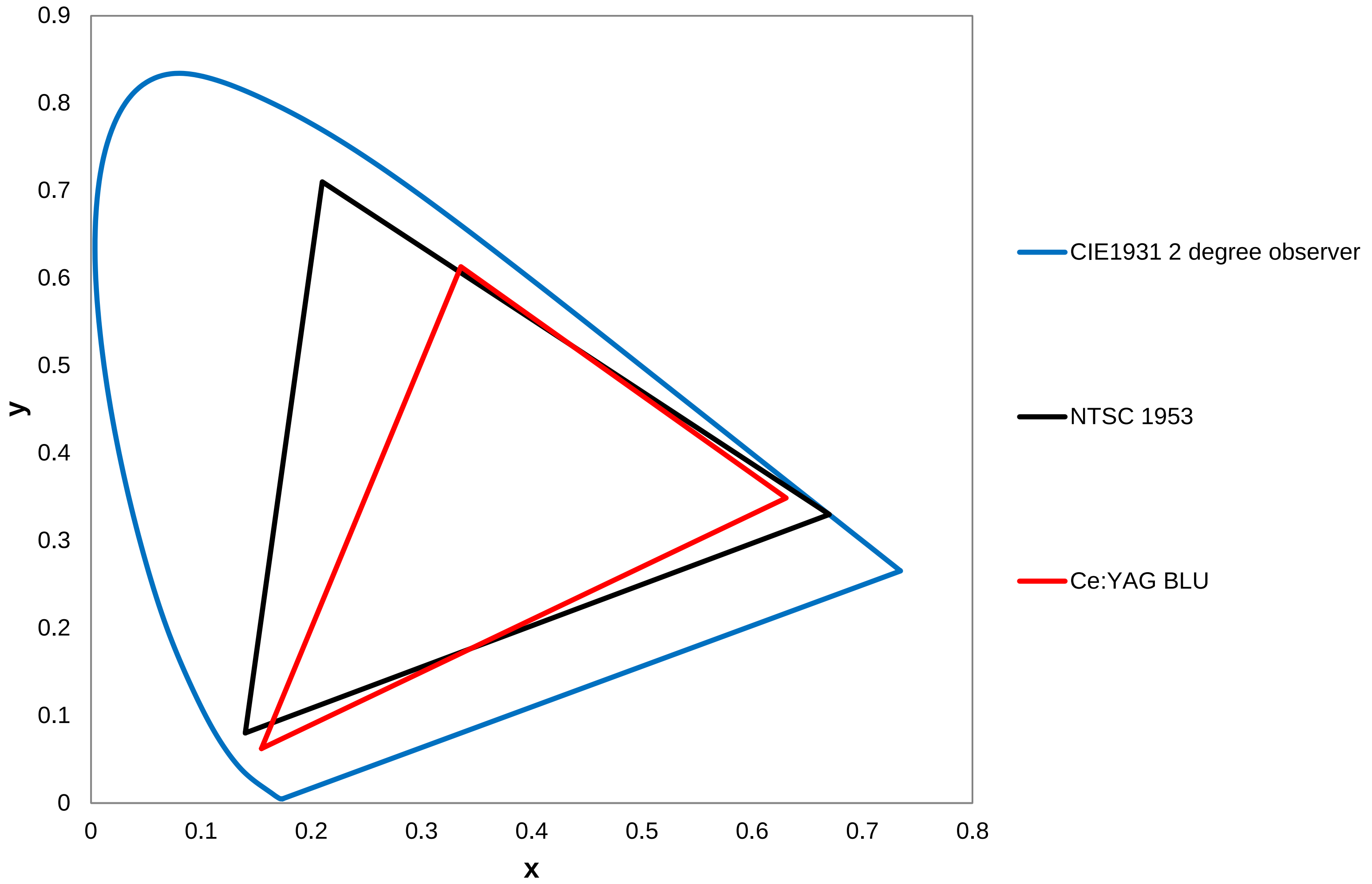
[3] The screen dimensions for a 40", 16:9 display are 34.86" x 19.61"; 34.86" x 19.61" x (25.4 mm/")$^2$ = 4.4 x 10$^5$ mm$^2$

# Quantum Dots: Benefits

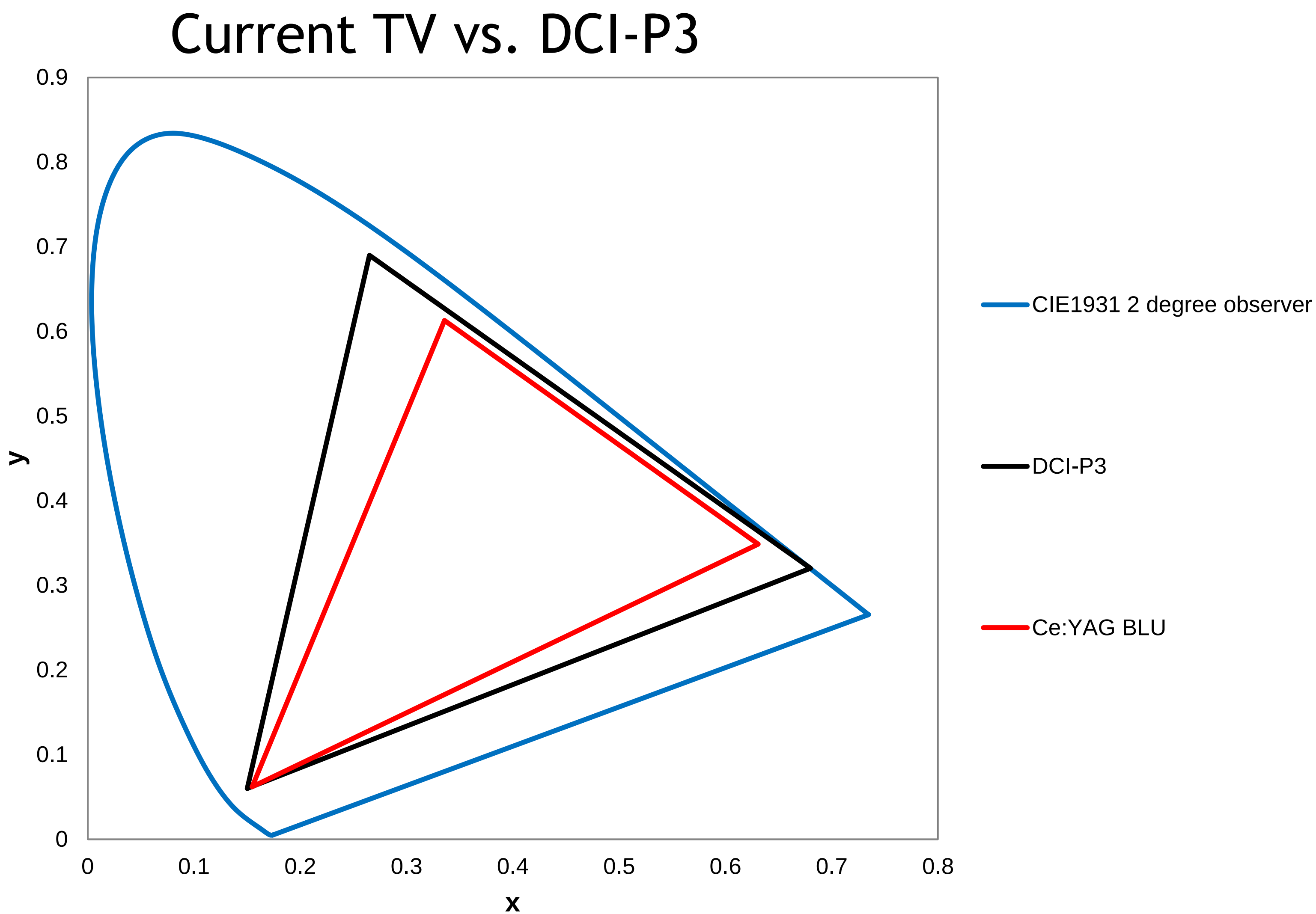
- CFQD® quantum dots offer performance benefits for display and solid-state lighting technologies
  - Improved colour performance
  - Improved efficiency
  - Improved efficacy with high colour rendering

# CFQD® Quantum Dot Device Performance

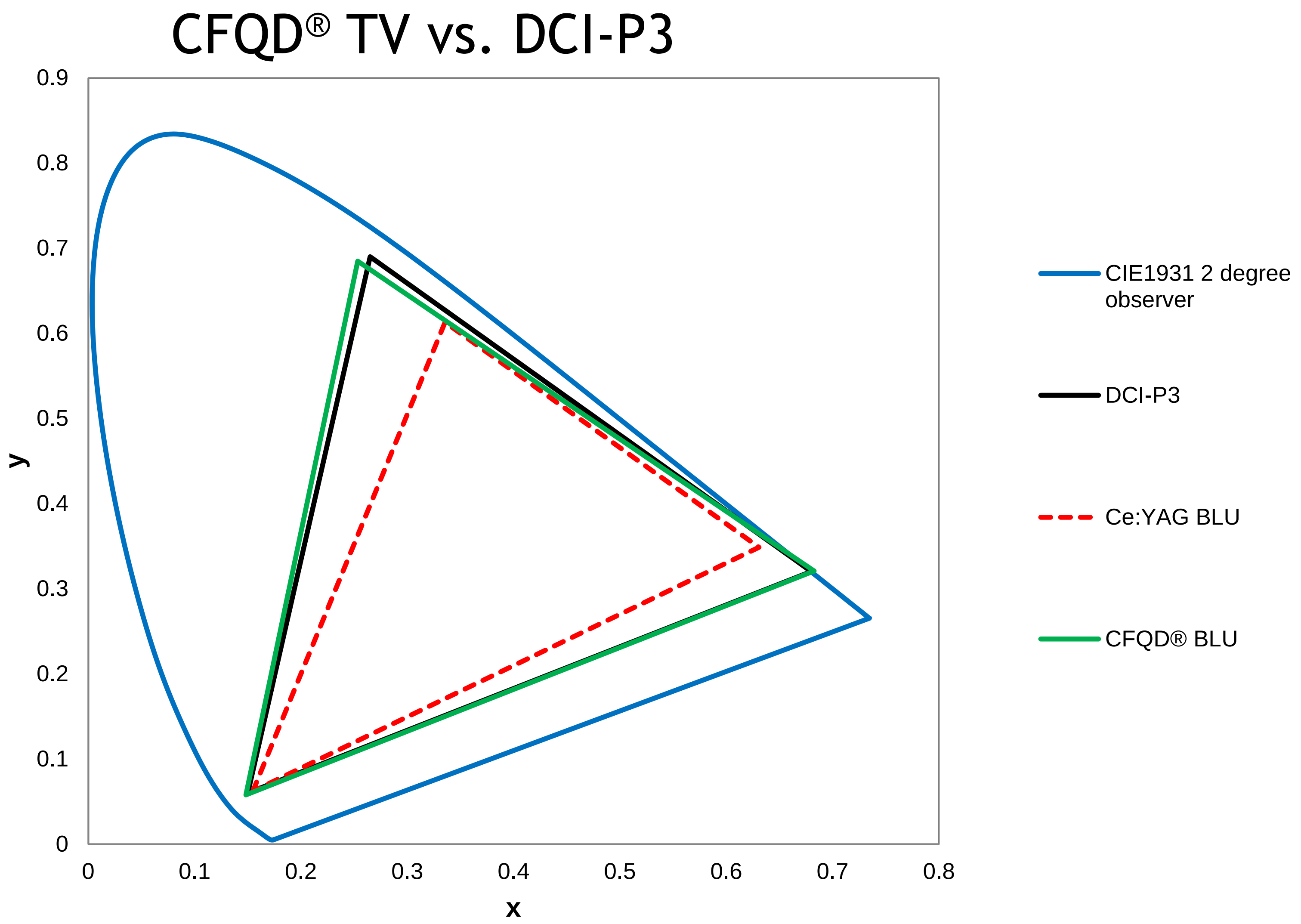
## Current TV vs. NTSC 1953



# CFQD® Quantum Dot Device Performance



# CFQD® Quantum Dot Device Performance



# Quantum Dot Device Performance

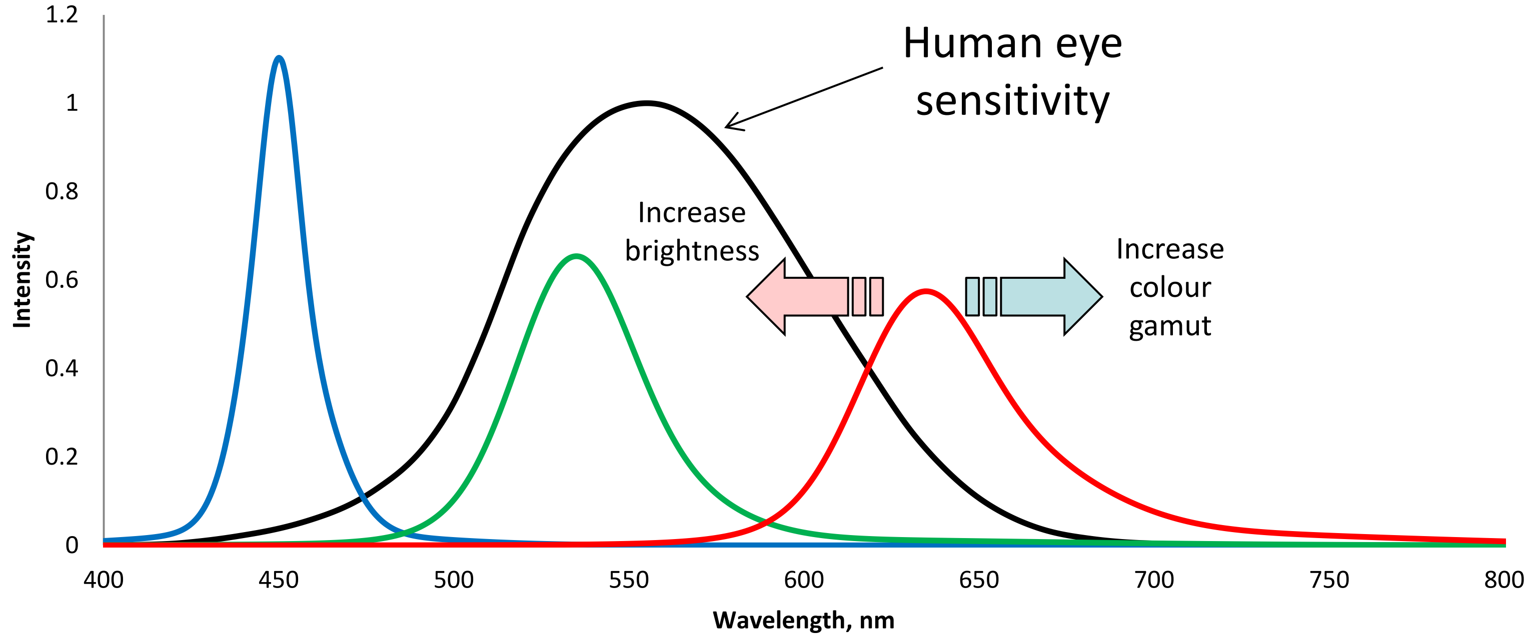
- In CIE 1931 colour space:

| BLU* | NTSC 1953 OVERLAP, % | DCI-P3 OVERLAP, % |
|---|---|---|
| **Ce:YAG (TV)** | 65 | 71 |
| **Cd-BASED QUANTUM DOT FILM (TABLET)** | 71 | 77 |
| **Cd-BASED QUANTUM DOT CAPILLARY (TV)** | 91 | 90 |
| **CFQD® QUANTUM DOT FILM (TV)** | **87** | **97** |

*Measured by Nanoco

# Quantum Dot TV Efficiency

- Efficiency is influenced by many factors
  - LEDs, LGP, optical films, colour filter density, backlight spectrum, colour conversion efficiency of light conversion material (PLQY)
- QDs influence backlight spectrum & conversion efficiency
- TV brightness influenced by eye sensitivity
- Increasing colour gamut = lower brightness
- QDs allow for increased efficiency of a high colour display compared to existing technologies

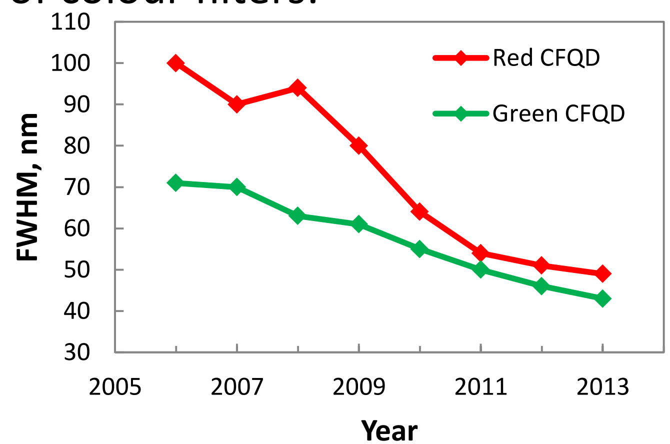


# Quantum Dot TV Efficiency

- Simulations allow prediction of performance and show trade-off between max brightness and max colour gamut
  - Increasing colour triangle leads to lower brightness
  - Narrower FWHM allows optimum brightness at a given colour triangle
- For same PLQY, can simulate relative brightness of CFQD® quantum dot and Cd-based quantum dot backlights through a standard set of colour filters:

| | DCI-P3 OVERLAP | RELATIVE BRIGHTNESS |
|---|---|---|
| NANOSYS[1] | 98 % | 112 % |
| QD VISION[2] | 95 % | 109 % |
| NANOCO[3] | 98 % | 100 % |

[1] R=628/36, G=533/32; taken from: J. Chen, V. Hardev, J. Hartlove, J. Hofler and E. Lee, *SID 2012 Digest*, 2012, 895
[2] R=628/30, G:528/32; measured from commercially available QD TV
[3] R=640/55, G=537/43



*CFQD® quantum dot FWHM v. year*

- Current CFQD® quantum dot performance requires small increase in light input to give same brightness

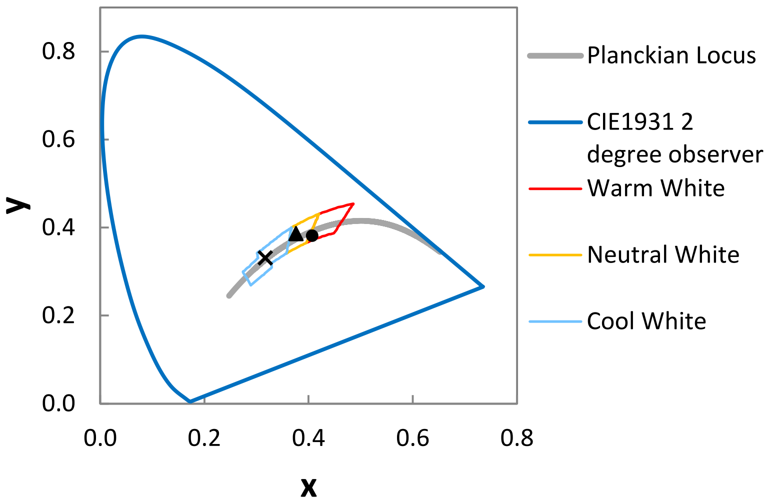
# CFQD® Quantum Dots for Solid-State Lighting

- White LED lamps made using CFQD® materials:
  - **CRI equal or better than those of traditional LEDs** with similar CCTs

| | 4,000 K CCT | | 5,000 K CCT | |
|---|---|---|---|---|
| | QD-LED | 2-5-8 NITRIDE | QD-LED | 2-5-8 NITRIDE |
| EFFICACY, $lm/W_{opt}$ | 150.4 | 195.0 | 191.5 | 227.6 |
| CRI | 93 | 76 | 94 | 87 |
| CCT, K | 4,326 | 4,353 | 5,437 | 4,909 |

Combination of a commercially available yellow-green RE phosphor and red CFQD® quantum dots :

- **cool, neutral and warm white CCT** (range: 6,300 K – 3,300 K)
- **high CRI** (> 90)
- **high efficacy** (100 lm/W for cold white, 84 lm/W for warm white)
- QD FWHM of 60 – 70 nm is ideal to maximise both efficacy and CRI at a target CCT



# Commercialisation Plan

**2014: Launch of CFQD® quantum dot TVs**

1st July: Ex. 39 expires

**2014**

**2016**

**2018**

**CFQD® QUANTUM DOT DEVELOPMENT**

**2015**

**2017**

**2019**

**2015: Launch of CFQD® quantum dot solid-state lighting expected**

Requested duration of exemptions from QD Vision and 3M

# Summary

- Cadmium is RoHS substance, indium is not
- According to Article 5(1)(a):
  - CFQD® quantum dot technology is **scientifically and technically practicable**
  - CFQD® quantum dots are **assured and reliable**
  - CFQD® quantum dots eliminate risk of **impact to health and environment of toxic cadmium** as alternative to cadmium-based QDs

- **CFQD® quantum dots are a viable alternative to meet market needs, hence no need of exemptions for Cd-based QDs**

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