QD VISION

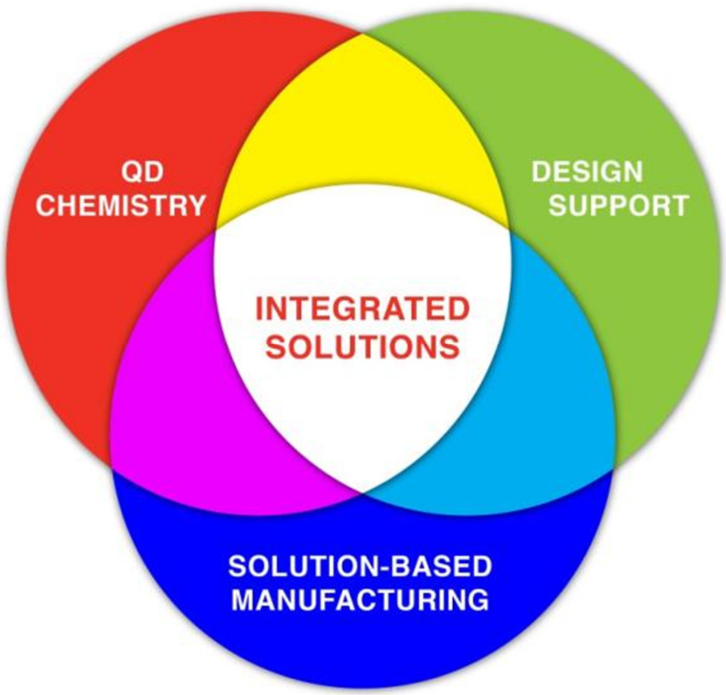
Stakeholder Presentation to OEKO Institute

Freiburg, December 2013

Outline

- Brief QD Vision Background
- Commitment to Responsible Design
- Products for Lighting & Display
- Key Technology Comparisons
- Conclusions

About QD Vision



- Founded in May 2005 - MIT roots
- First QD Products to market in Display and LED Lighting
- World's largest QD Mfg. facilities
- 150+ employees – Global operations
- Color IQ™ optics shipping in high volume since Q1-2013
- Multiple MP lines qualified, operating
- High yield production processes for both QDs and final optic assembly
- ISO9000/14001, Green Partner status

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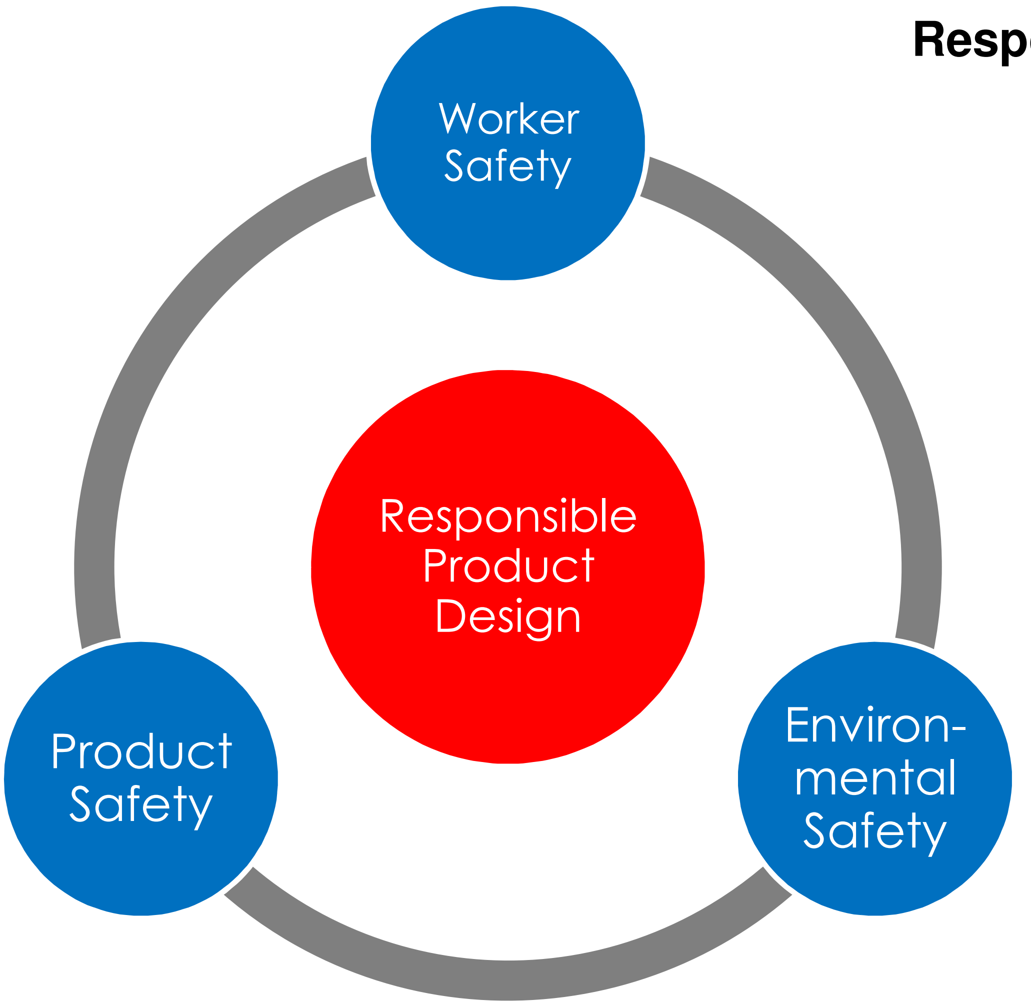
Commitment to Responsible Development



Responsible Development Permeates Product Design

1. Worker Safety – 2x NIOSH Studies
2. **Product – Multiple Layers of Packaging**
3. Life Cycle Risk Analysis – Disposal Study; Net Environmental Benefit

QD Vision shares leadership responsibility via *e.g.* US National Academies of Sciences Nano-EH&S Research Strategy Committee

EH&S Community Collaboration

QD Vision has proactively established EH&S community collaborations

- US NIOSH – Chuck Geraci, Ph.D., and team
  - Established QD R&D occupational health and safety best practices
  - Presented in US and Taiwan
- University of Massachusetts – Prof. Ellenbecker and C. Tsai, Ph.D.
  - Product safety feedback studies
- Formerly Conservation Law Fund Ventures – Jo Anne Shatkin, Ph.D.
  - Life cycle risk assessment – "the most comprehensive LCRA ever performed for a nano-material" presented at Society for Risk Analysis Annual Meeting, 12/7/09
- Brown University – Profs. Robert Hurt and Agnes Kane
  - EPA STAR Grant, end-of-life fate studies
  - ES&T paper published in February, Liu *et al.*
- Frequent invited speaker at e.g. US EPA OPPT and OECD WPMN

Goal is to launch product with environmental benefit, by bringing EH&S information into the development process early

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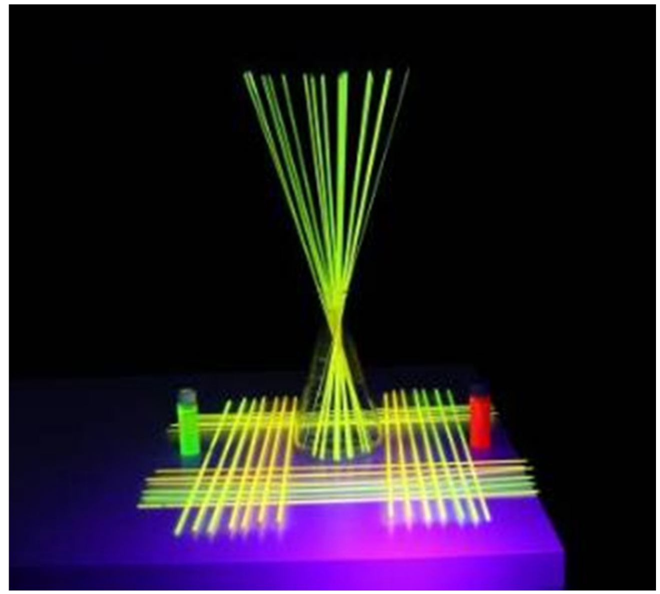
QDs operate in two modes

Photoluminesence (PL mode)

- Activated by light energy
- Downconversion of color from other light sources
- Any light with shorter wavelength (higher energy)
- "Color IQ™ components"

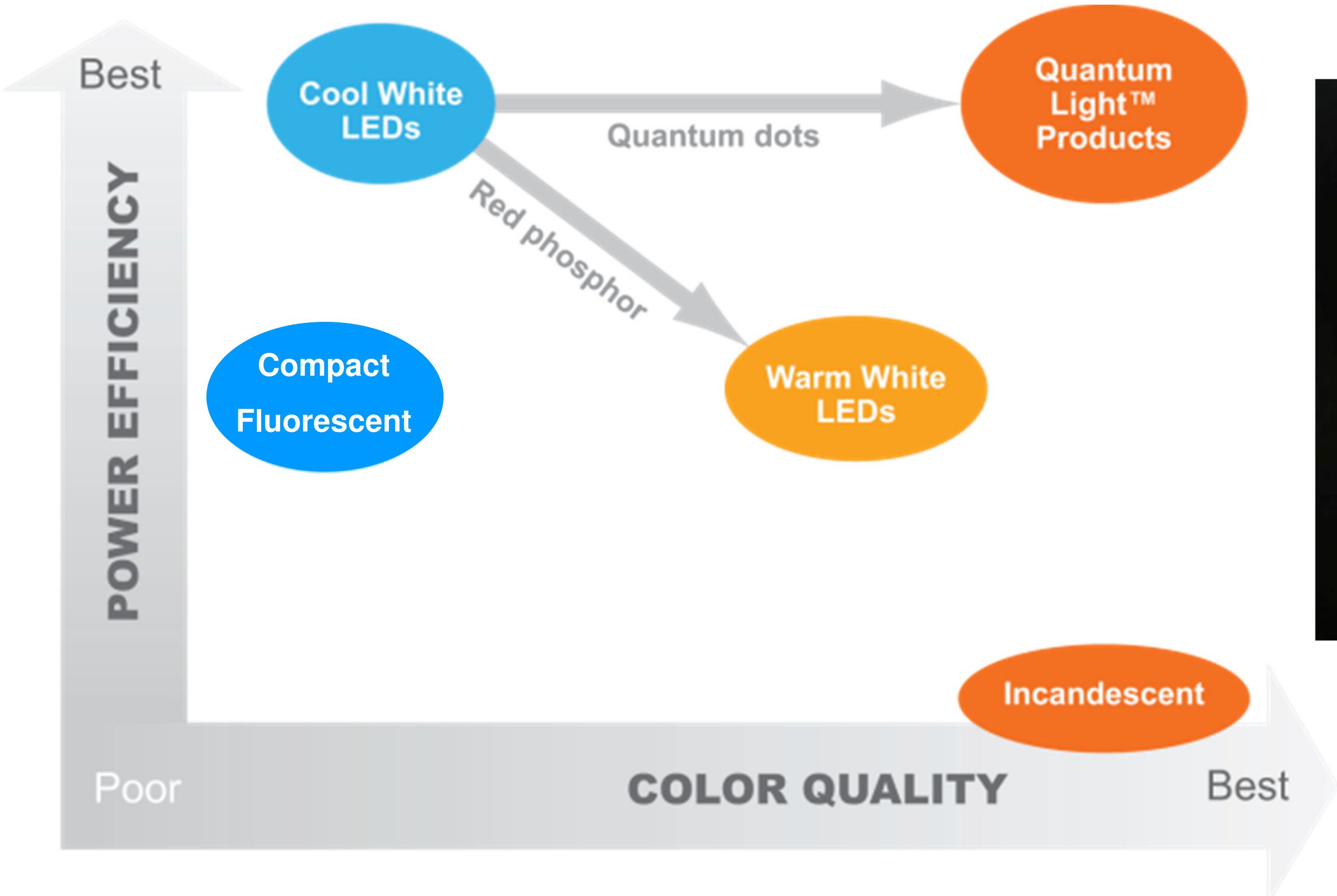


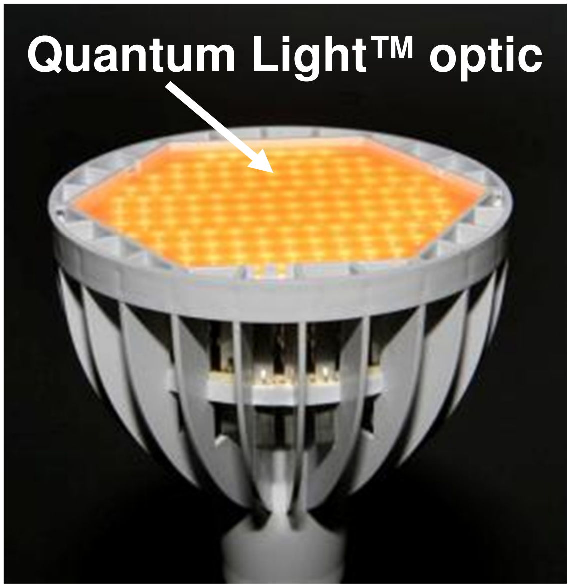
Electroluminescence (EL mode)

- Activated by electronic energy
- Direct emission of colored light
- Requires charge transport films
- "QLEDs"

QD Optic For Solid State Lighting

Quantum Dots break tradeoff paradigm

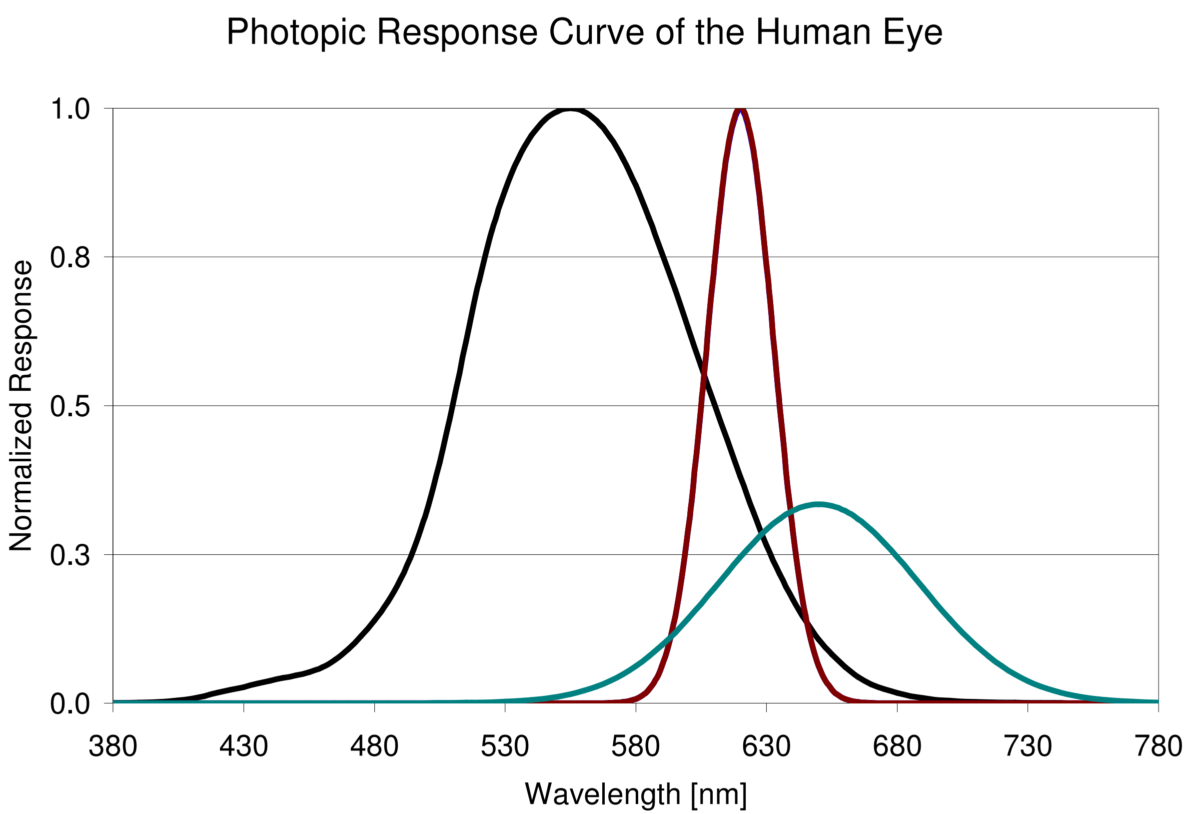




Nexxus R30 LED Array
2700K, 90+ CRI,
>60 LPW

QDs vs Red Phosphor

Impact of FWHM on Luminous Efficiency



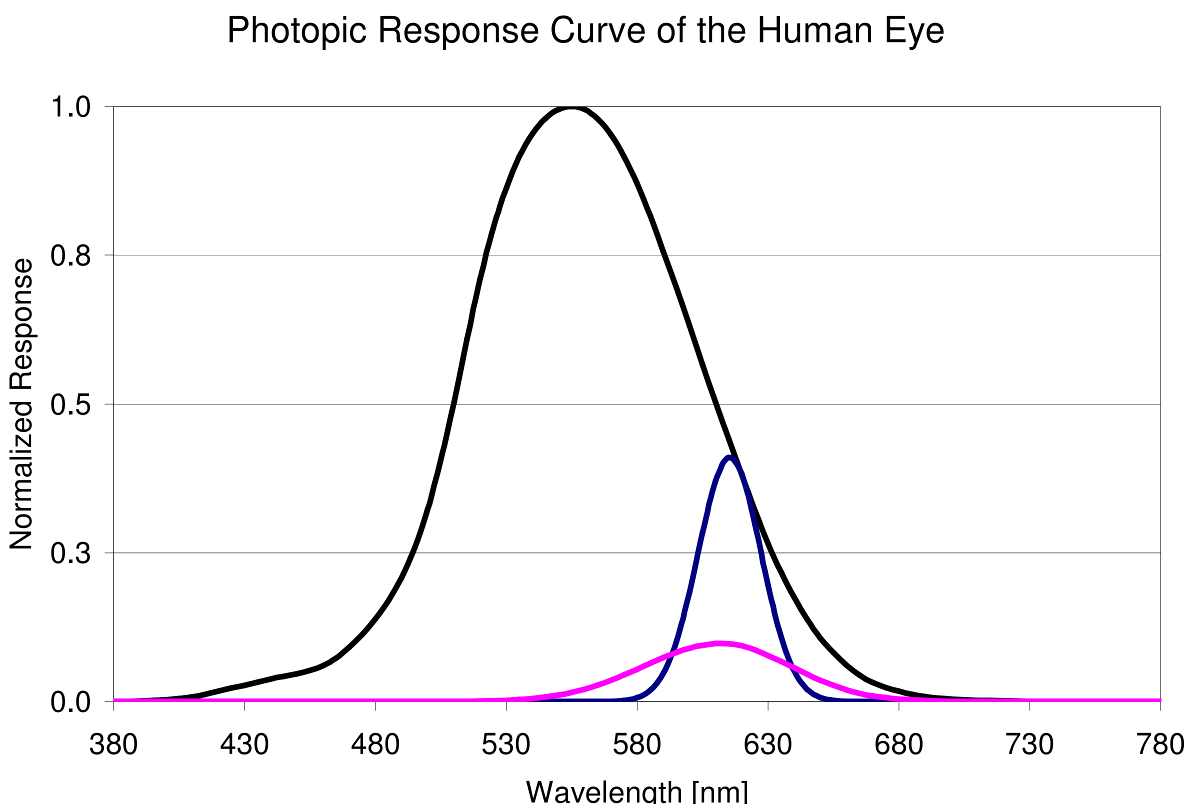
Two Gaussians
QD: 30nm FWHM, 620nm
Phosphor: 90nm FWHM, 650nm

Area Under Curve
Equal for QD and Phosphor (i.e. same photon count)

Multiply QD and Phosphor spectra by photopic response curve

QDs vs Red Phosphor

Impact of FWHM on Luminous Efficiency

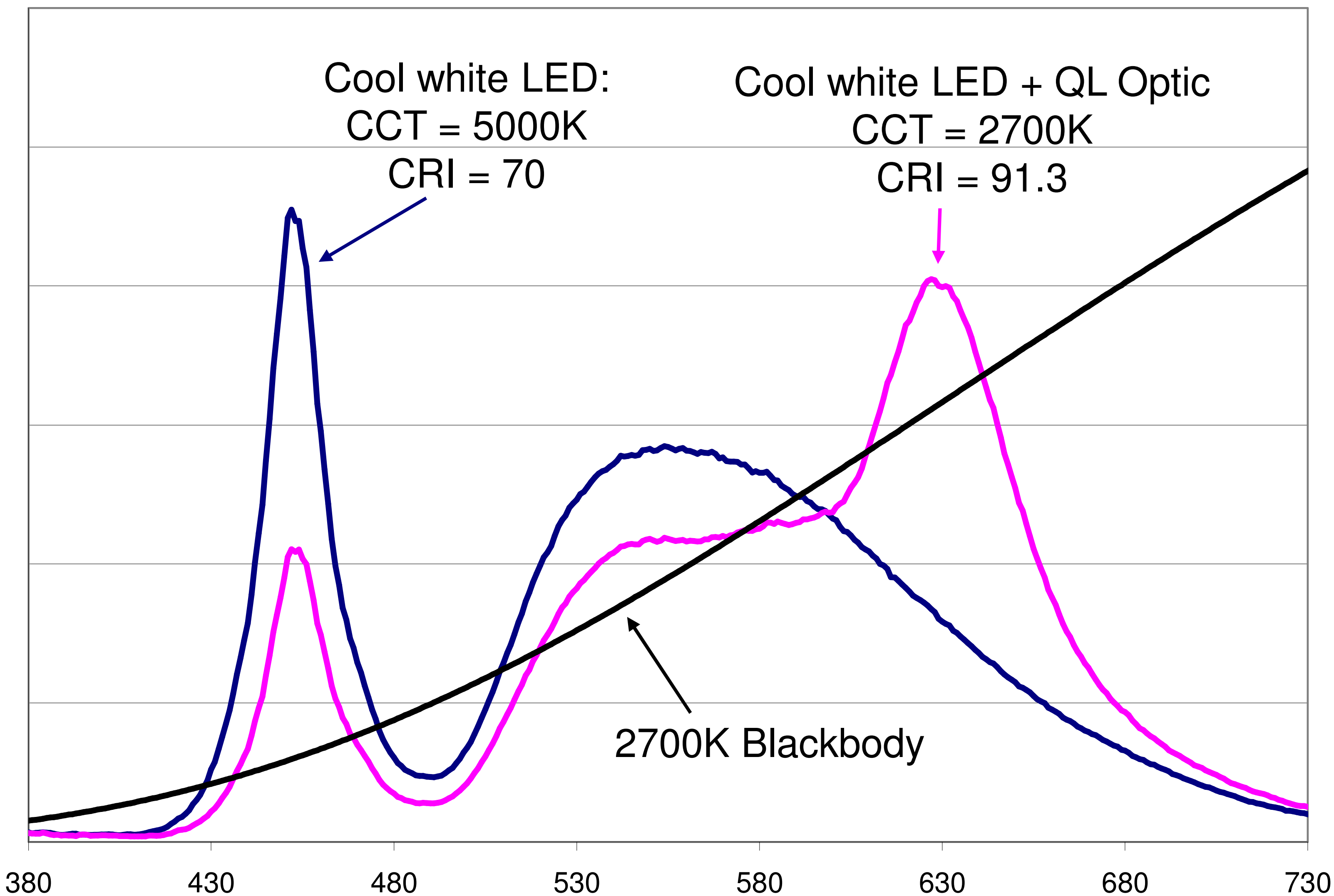


Convert to lumens
QD: 620 → 615nm
Phosphor: 650 → 610nm

Area under curve
Phosphor vs QD:
QD has 2X lumen advantage

Broad FWHM of phosphor significantly decreases luminous efficiency
This effect is continuous – 60nm FWHM has only half the benefit of 30nm

QDs Convert the Blue Light to Red

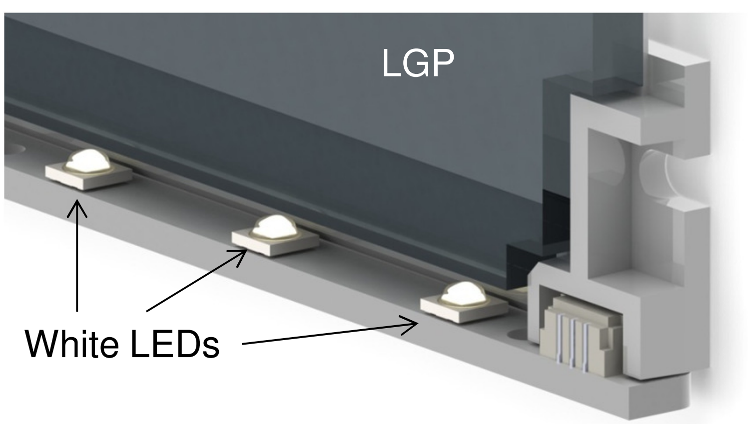


Color IQ™ Optical Component

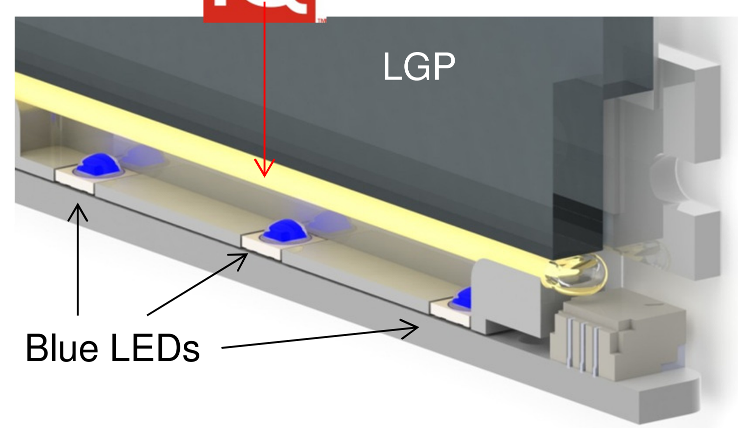
Color IQ™ Optics exceed OLED color with LCD fab

- Color IQ optical components containing light-emitting semiconductor nanocrystal Quantum Dots (QDs).
- Improves typical LCD TV Color performance by 50%
- Best available Color-Efficiency combination
- QDs are tuned for optimized spectra, narrowband light emission
- Highly efficient, scalable manufacturing process

Current White LED Solution



COLOR IQ Solution



Ten Sony TV Models In the Market

Four Sony TV Series	N.America	S. America	Europe	Asia	RoW
XBR-65X900A XBR-55X900A 55", 65" (4K)	65 55	65 55	65 55	65 55	65 55
KDL-55W905A KDL-46W905A KDL-40W905A 40, 46" 55" FHD	55		55 46 40	55 46 40	55 46
KDL-55W950A KDL-46W950A 46", 55" FHD		55 46		55 46	
KDL-55W850A KDL-47W850A KDL-42W850A 42", 47", 55" FHD					55 47 42

These Sony TVs now available in: USA, Canada, Germany, France, U.K., Russia, Japan, Hong Kong, Taiwan, China, India, Australia, New Zealand, Vietnam, Indonesia, Singapore, Malaysia, Thailand, Philippines, Mexico, Brazil, Colombia, Peru.

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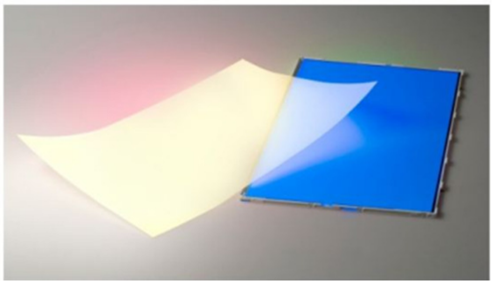
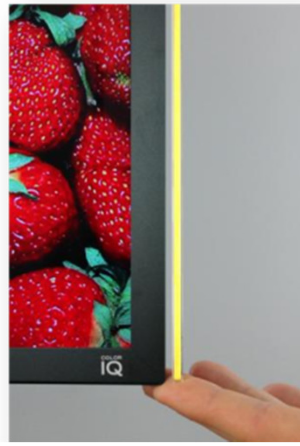
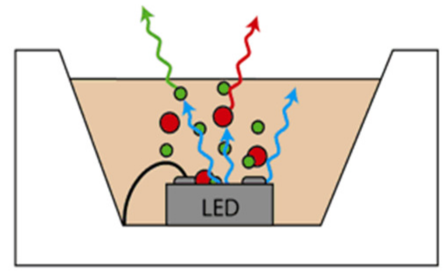
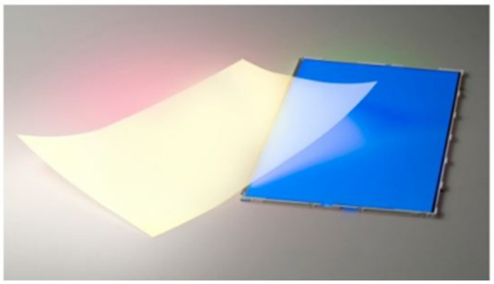
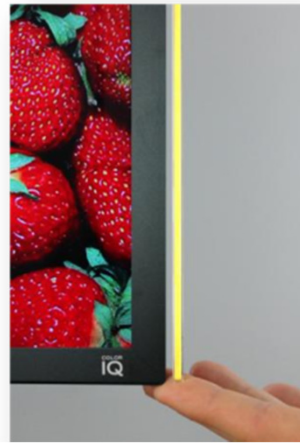
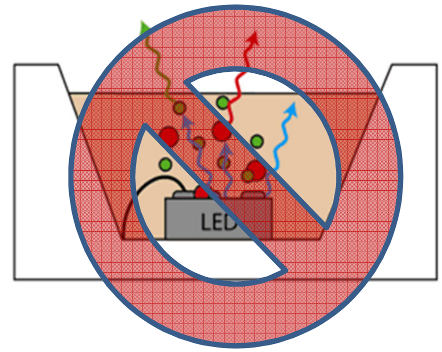
Comparing QD Products - Form

QD Film	QD Edge Optic	QD On LED Chip
		
▪ QDs in O_2 barrier films ▪ Film covers entire BLU ▪ Large amount of QD material per display ▪ In line roll process ▪ Operates at temperature of BLU surface	▪ QDs sealed inside glass optic ▪ Optic used on 1 or 2 edges of BLU ▪ Highly efficient use of materials per display ▪ Highly flexible white point options ▪ Operates at temps. near but not on LED	▪ QD materials mixed in LED encapsulant ▪ Packaged LEDs used in BLU ▪ Packaging costs per LED unclear ▪ Must survive LED junction temperature and O_2 exposure

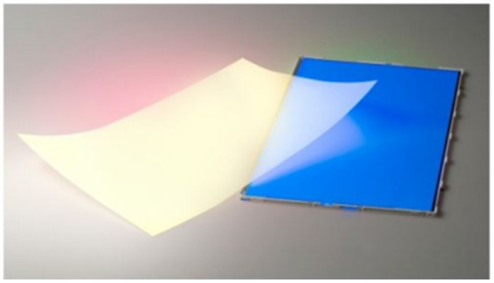
Comparing QD Products - Vendors

QD Film	QD Edge Optic	QD On LED Chip
	 	

▪ 3M with Nanosys Materials
▪ Contains Cadmium
▪ Amazon Kindle HDX 7"
  ▪ Shipping in EU
	▪ QD Vision with QD Vision Materials
	▪ Contains Cadmium
	▪ 10 models of Sony TV
	  ▪ HD/UHD
	  ▪ 40"-65"
	  ▪ 5 Models in EU
		▪ No Products on the Market

Comparing QD Products - Vendors

Cd QD Film



- 3M with Nanosys Materials
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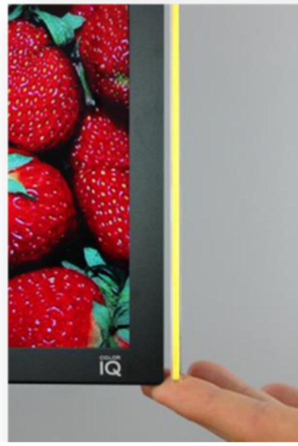
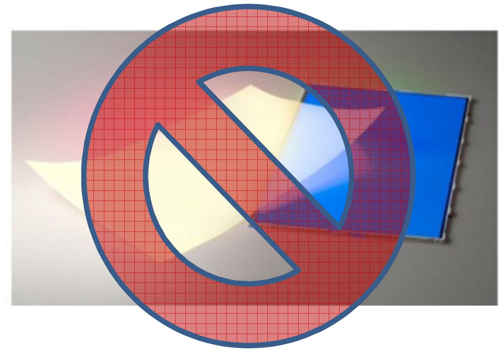
Cd QD Edge Optic



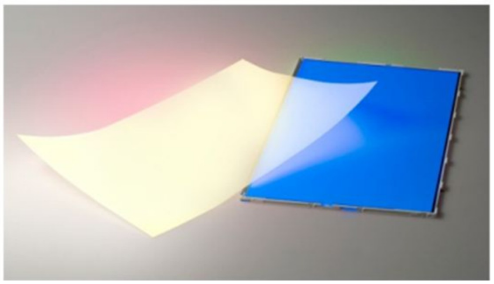
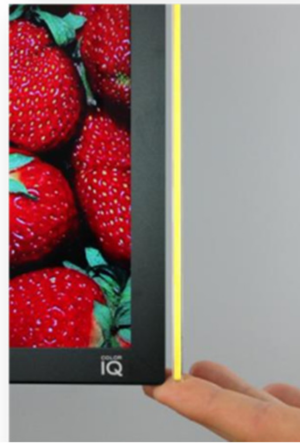
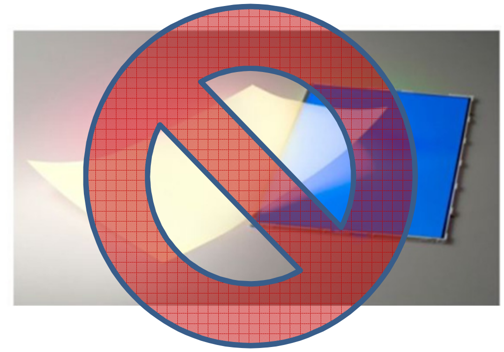
- QD Vision with QD Vision Materials
- Contains Cadmium
- 10 models of Sony TV
  - HD/UHD
  - 40”-65”
  - 5 Models in EU

Cd-free QD Film



- No Products on the Market

Comparing QD Products – Markets Today

Cadmium QD Film	Cd QD Edge Optic	Cd-free QD Film
		

Cadmium QD Film

- Fits into all display segments
- Cost challenge for larger areas (>20"?)
- Thickness problem for smaller areas
- Sweet spot is probably ~7-21"

Cd QD Edge Optic

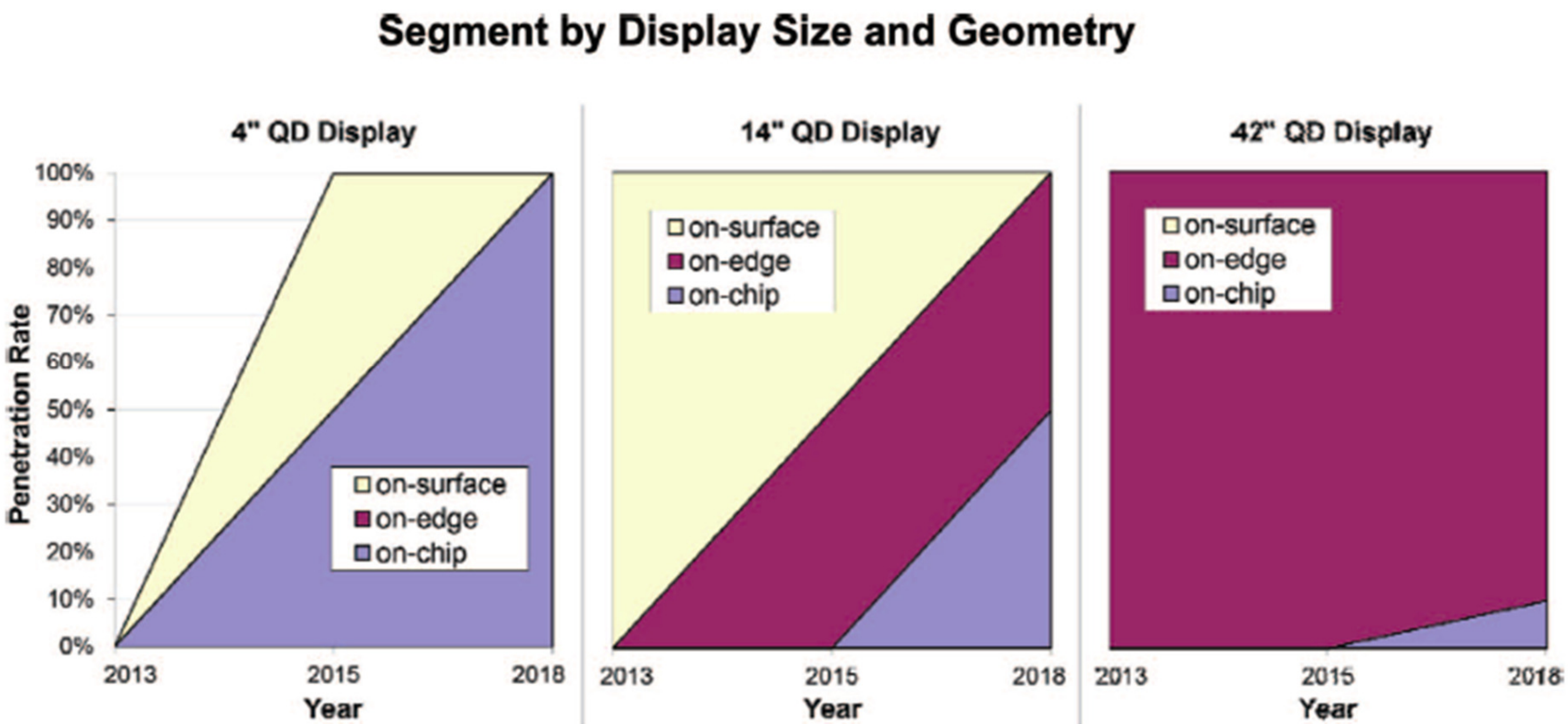
- Fits into all display segments
- Integration challenges for smaller area (<20"?)
- Sweet spot is ~21"+

Cd-free QD Film

- Fits into all display segments
- Cost, thickness challenges more severe
- Sweet spot narrower
- No markets currently served because of performance limitations

QD Product by Form – Projected Future

- Peer reviewed article on QD adoption
- Figure 3 from ECS Journal of Solid State Science and Technology, 2(2), R(2013), submitted 9/5/12
- Accurate prediction (so far) of how QD market will develop

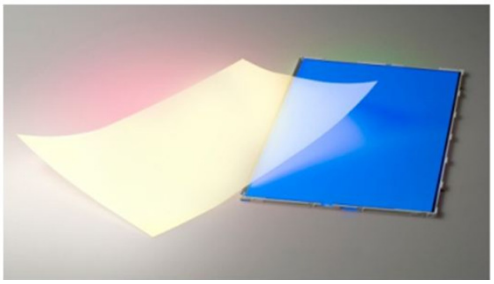


A Contradictory Story

- Article by Nanoco (overlapping authors with RoHS submission) in the same 2013 issue concludes:
- "Of the non-Cd QD systems, InP is the nearest to realizing application-ready material, yet improvements are still required. Perhaps most importantly, gains in QE in composites are required to enhance luminous efficacy, while narrower FWHMs are needed to improve color purity. For BLU applications, narrower FWHM will provide better color saturation and a larger color triangle, while for general lighting, narrower red emission will deliver more efficient light sources by reducing the proportion of light emitted in the long-red region where the human eye sensitivity is decreased and less lumen contribution is made. Thus, improvements in QE and FWHM may hold the key to achieving commercial SSL devices incorporating InP QDs."
- RoHS submission "Nanoco's CFQD™ cadmium-free quantum dots are not made from indium phosphide."
- "In this case, a quantum dot FWHM of 60 – 70 nm is ideal to maximise both efficacy and CRI at a target CCT."

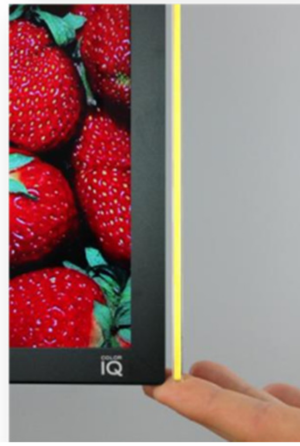
Comparing QD Products - Quantity

Cadmium QD Film



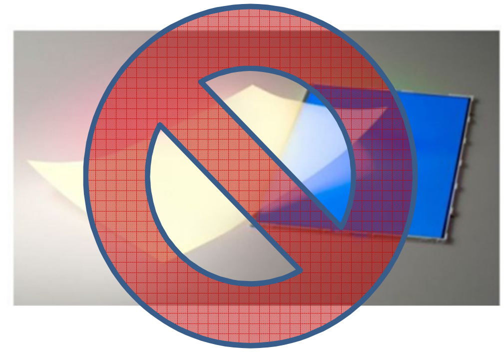
- 3M: 20ug/cm2 of screen area MAX
- 3-5 ug/cm2 typical
- ~40mg Cd per large area TV

Cd QD Edge Optic



- QDV: ~1.5mg Cd per large area TV
- Decreasing with future product generations
- ~ 0.15 ug/cm2 of screen area

Cd-free QD Film



- Lower absorption per mass = more QDs
- Project ~50ug/cm2 MAX of InP (Class 1b carcinogen)
- ~10ug/cm2 will likely be typical
- Cd-free edge optic not seen as even medium-term feasible

Formulas to Determine Net Cd Benefit

Total Cadmium emissions (edge-optic):

Net Cd Benefit = Cd reduction – Cd usage

= [power saved over life of TV * EU Cd liberated per kWh consumed] – Cd usage

= [25kWh * X% power reduction * 87 ug/kWh] – Cd usage

Example: 42" TV in QDV submission

Net Cd Benefit = 25 * 20 * 87 – 1500ug = 42mg

Formulas to Determine Net Cd Benefit

Air emissions only (edge-optic):

Net Cd Benefit = Cd reduction – Cd usage

= power saved over life of TV * EU Cd emission per kWh consumed – Cd usage

= 25kWh * X% power reduction * 3.8 ug/kWh – Cd usage

Example: 42" TV in QDV submission

Net Cd Benefit = 25 * 20 *3.8 – 1500ug = 400ug

Formulas to determine environmental benefits

- Estimation of environmental benefits in economic terms of reductions in CO_2 emissions:

1. Estimated reduction in CO_2 emissions = Projected sales * [carbon net saving per TV(tonnes) * conversion factor]
2. Economic benefits associated with reductions in CO_2 = estimated reductions in CO_2 emissions * SCC

Total environmental benefits : **euro 65,165,348**

- Conversion factor from carbon to CO_2: 12/44 (DEFRA, 2007)
- Social Cost of Carbon (euro 10.5/tonne)

Formulas to determine socio-economic benefit

- Quantification of economic benefits of energy saving:
  - Annual benefits: [projected sales * energy saving per TV * average price of the electricity (euro kw-hr)]/10 years

Total benefits (discounted over 10 years at 4%)= euro 2,858,720,924

(Average price of electricity in the EU = 0.1265 euro kW-hr)

Risk control during recycling activities

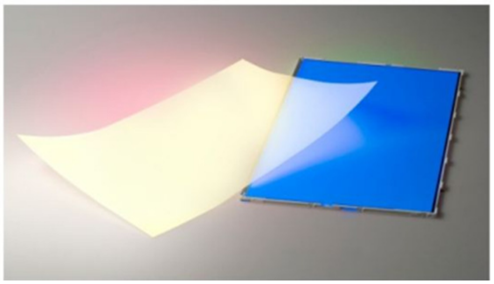
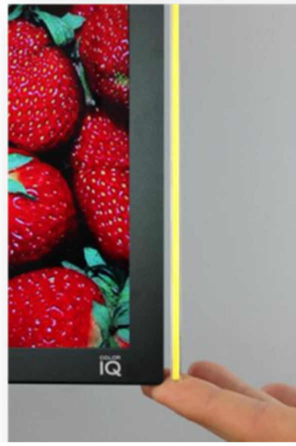
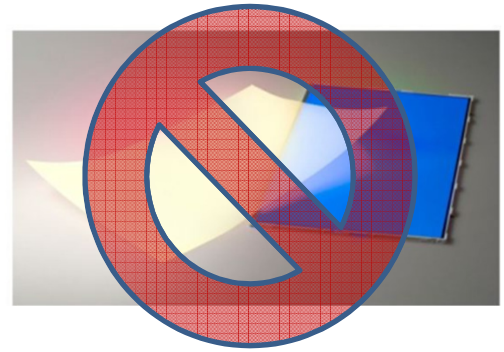
- The assessment of the hazard of cadmium during recycling activities of LCD televisions has been performed:
  - Recommendation from the Scientific Committee on Occupational Exposure Limits for cadmium and its inorganic compounds (SCOEL/SUM/136) of February 2010 was taken into account
  - Review of the information in the disseminated REACH dossier on cadmium was performed
  - The actual risk of exposure to Cadmium by workers during the recycling activities was assessed
  - A Risk Characterisation Ratio was calculated using the established DNEL for Cadmium

Result: risk is controlled during all recycling activities

Nanoco response lacks information regarding the socio-economic benefits of cadmium-free QD

- Data required:
  - The environmental benefits in economic terms of reductions in CO_2 emissions should be based on:
    - ✓ The expected demand for the product
    - ✓ The estimated energy saving
    - ✓ The associated coal saving and relative carbon net saving
    - ✓ Social cost of the carbon or other alternative methods accepted in the literature
  - The economic benefits of energy saving should be quantified taking into account:
    - ✓ Foreseen sales
    - ✓ Estimated energy saving and the average usage of a TV
    - ✓ Price of electricity
- A comparison of the two technologies on a socio-economic basis is impossible due to lack of data, AND lack of product

Comparing – Quality & Efficiency

Cadmium QD Film	Cd QD Edge Optic	Cd-free QD Film
		
▪ 20+% efficiency advantage over next best available material (phosphors, not Cd-free QD) ▪ Full gamut (100% NTSC) is possible ▪ Uniformity, lifetime, reproducibility, quality controls all at market acceptable levels	▪ 20+% efficiency advantage over next best available material (phosphors) ▪ Full gamut (100% NTSC) is possible ▪ Uniformity, lifetime, reproducibility, quality controls all at market acceptable levels	▪ >20% efficiency deficit vs next best available material (Cd QD) ▪ 100% gamut possible, but deficit increases to >30% ▪ Uniformity, lifetime, reproducibility, etc. have not yet met market acceptable levels

Quality and Efficiency Model

- QD Vision refined model to estimate quality and efficiency trade-offs with customers
- We have verified high degree of model accuracy over a wide range of inputs, color filters, QD changes

CFA	QD used	Green PWL	Red PWL	NTSC Overlap	NTSC area ratio	Brightness ratio
Cupertino CFA						
blue PWL = 450 nm	QDV QD, FWHM = 35nm, 30nm	532nm	633 nm	95.20%	107.80%	100%
White CP: D65 (0.313, 0.329)						

- Set QDV performance as the baseline

Quality and Efficiency Model

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White CP: D65 (0.313, 0.329)	CFQD_Gaussian, FWHM=45nm	532	633	89.50%	98.70%	92%

- Calculate Cd-free performance with same peak wavelengths (PWL)

Quality and Efficiency Model

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CFA	QD used	Green PWL	Red PWL	NTSC Overlap	NTSC area ratio	Brightness ratio
Cupertino CFA	QDV QD, FWHM = 35nm, 30nm	535	622	89.40%	98.90%	114%
blue PWL = 450 nm	QDV QD, FWHM = 35nm, 30nm	532nm	633 nm	95.20%	107.80%	100%
White CP: D65 (0.313, 0.329)	CFQD_Gaussian, FWHM=45nm	532	633	89.50%	98.70%	92%

- Keep Cd-free color, and optimize QDV PWL

Quality and Efficiency Model

- Keep QDV color, and optimize Cd-free

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White CP: D65 (0.313, 0.329)	CFQD_Gaussian, FWHM=45nm	532	633	89.50%	98.70%	92%
	CFQD_Gaussian, FWHM=45nm	532	650	92.30%	105.30%	69%

Model (no hardware exists) predicts 22% efficiency benefit of Cd at 98% NTSC area, and 31% benefit at >105% NTSC area (>92% overlap).

Assessing Technology Status

- Is the Cd-free product ‘on the market’ in the EU? – NO
- Has a specific electronics product been announced? – NO
- Has a component level solution been announced? – NO
- Has a component manufacturing partner been announced? – NO
- Has a materials manufacturer scaled up production? – NO
- Has a materials manufacturer announced plans to scale up production? - YES

Low Confidence Supply Chain

Technology Licensor → Materials Production → Component Production → Consumer Electronics Device

MIT → QDV → Sony

MIT/Berkeley → Nanosys → 3M → Amazon

Univ. Manchester → Nanoco → Dow → Component Production?? → Consumer Electronics Device??

QD Press Over the Years

- "Nanoco Technologies Ltd. UK who have proprietary scale up technology have announced that they plan for scale up production within two years in Japan." Sept 2007
- "The 18-month development agreement, which was announced in September 2009, has a final milestone remaining and is on schedule for completion in early 2011. On completion, it is expected that a supply and license agreement will be negotiated with the partner." Aug 2010
- "This year, Nanosys commercialized its quantum dot technology with the QuantumRail™, a process-ready component that improves LED backlit display color gamut and efficiency, and has announced partnerships with LG Innotek and Samsung Electronics." Sep 2010
- "Nanosys, Inc., an advanced materials architect, today announced that its next generation LCD technology, the Quantum Dot Enhancement Film (QDEF™), is available to display manufacturers." May 2011
- "This step improvement gives us confidence that we will exceed the performance necessary for commercially feasible devices," said Seth Coe-Sullivan, Chief Technology Officer of QD Vision. "We intend to continue driving further improvements in device performance that will enable the next generation of flat panel displays offering consumers a better viewing experience, better economics and more user-friendly form factors than current-generation products." June 2006 (QLEDs)

QD Under Article 5 RoHS

Cd Quantum Dots

- Shown to have no negative impact on health ✓
- Shown to have positive net effect on environment✓
- Proven reliability in the market ✓
- Massive socio-economic calculated cost/benefit ratio according to EU gold standard ✓
- Life cycle extensively analysed✓

- Ongoing benefit if exemption is granted

Cd Free Quantum Dots

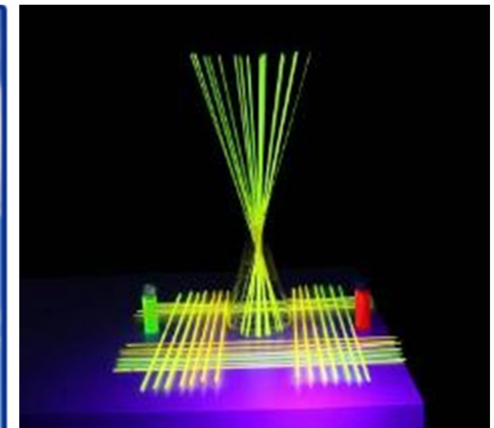
- Indium Phosphide also a CMR 1b, no analysis submitted of risk characterisation X
- No environmental energy saving benefit expected X
- Estimated time to market > length of exemption X
- No guarantee the technology will work in any product X
- No LCA performed X
- Immediate negative impact if substitution is forced

Conclusions

Quantum Dots are an environmentally beneficial nanomaterial technology bringing color with efficiency to LCDs, and are on the market in the EU today.

QD Vision's Color IQ:

- Scaled manufacturing and established supply chain
- The right geometry for low material utilization even in large areas
- … with a quantified net benefit to the economy and environment



Thank you for your invitation and attention!