Nanosys Response to Oeko Questionnaire on Cadmium Quantum Dot (Cd-QD) applications and their substitutes

Consultation as part of the RoHS Cd-QD Follow-up Study

Öko-Institut's Clarification Questions

In the past assessment, the main argument for an exemption was that for alternative non-cadmium materials, the quantum efficiency and reliability under on-chip operating conditions had not been resolved yet.

The consultants understood that an alternative technology for on-surface quantum dots based on indium phosphide (InP) would reach a comparable performance level to that of Cd-QDs by about 2020. Thus, it was concluded that Cd-QDs are no longer used in on-surface display applications placed on the EU market.

1. *Can you confirm that such development took place, meaning that Cd-free quantum dot alternatives, providing a comparable performance level to that of* ***on-surface*** *Cd-QDs, are available on the market and therefore an exemption is no longer required for Cd-QD in on-surface display applications?*
   If not,
   a. *please specify for which applications you regard an exemption as necessary: lamps/ displays, consumer/ laboratory, mobile/ stationary, and*
   b. *please explain why you consider an exemption to still be justified, providing technical data and evidence to support your views.*

Heavy Metal Free Quantum Dots (HMF-QDs) have advanced significantly since 2019. Compared to Cadmium QDs (Cd-QDs), the latest HMF-QD materials deliver similar optical performance at the QD materials level and superior performance in consumer devices. In this report, we will show that HMF-QD performance improvements at both the materials and device levels have closed the performance gap with Cadmium-containing QDs such that exemptions are no longer required for display or lighting products.

Despite recent advances in HMF-QD performance, Cadmium-based QDs continue to be sold in the EU. According to Nanosys internal market data, approximately 30% of quantum dot displays entering the EU in 2022 will contain some amount of intentionally added Cadmium. These Cadmium-based displays are still allowed to enter the EU under two conditions: 1) the still-in-effect Exemption 39A and, 2) an emerging range of components with less than 100 parts per million (ppm) of Cadmium.

Sub-100ppm Cd-QD components are expected to continue shipping into the EU and growing in volume, regardless of the outcome of this review and any potential changes to exemption 39A. Most sub-100 ppm Cd components contain at least the same amount of Cadmium by weight as the previous generation of Cd-QD components. The reduction in ppm is achieved by increasing the thickness and weight of the homogenous layer.

We believe this trend toward "Low Cadmium" display components is the result of a misunderstanding of the intent and spirit of RoHS. Shipping a component with the same amount of Cadmium in a larger, heavier package to reduce the ppm denominator subverts Article 4 of the Restriction on Hazardous Substances (RoHS) directive, which states that, *"Member States shall ensure that EEE placed on the market… does not contain the substances listed in Annex II."* [1]

We understand that the component-level ppm limits for hazardous substances defined by RoHS were intended to allow manufacturers some flexibility in terms of raw materials sourcing by allowing some trace amounts of unintentionally added hazardous substances to enter the EU. We do not believe the RoHS regulations were created as a license to intentionally load electronic components with hazardous substances up to the maximum limit or to encourage the development of new types of heavier, larger components to enable more hazardous substances to enter the EU.

Progress in HMF-QD development continues at a rapid pace. We believe additional investment in researching and developing Cadmium-based QD for emerging display and lighting applications is no longer necessary. HMF-QD technology can more than meet market needs for display performance today and in next-generation products that are expected to ship over the next five years.

Quantum Dot Materials Performance

Quantum dots of all types emit pure light with near-perfect efficiency. Internal Quantum Efficiency (IQE) is a figure of merit for comparing the performance of QD materials of different types. IQE measures the efficiency with which QDs down-convert incoming photons. It is the ratio of photons-in to photons-out, expressed as a percentage. In general, quantum dots with higher IQE translate to more efficient components and therefore more efficient devices.

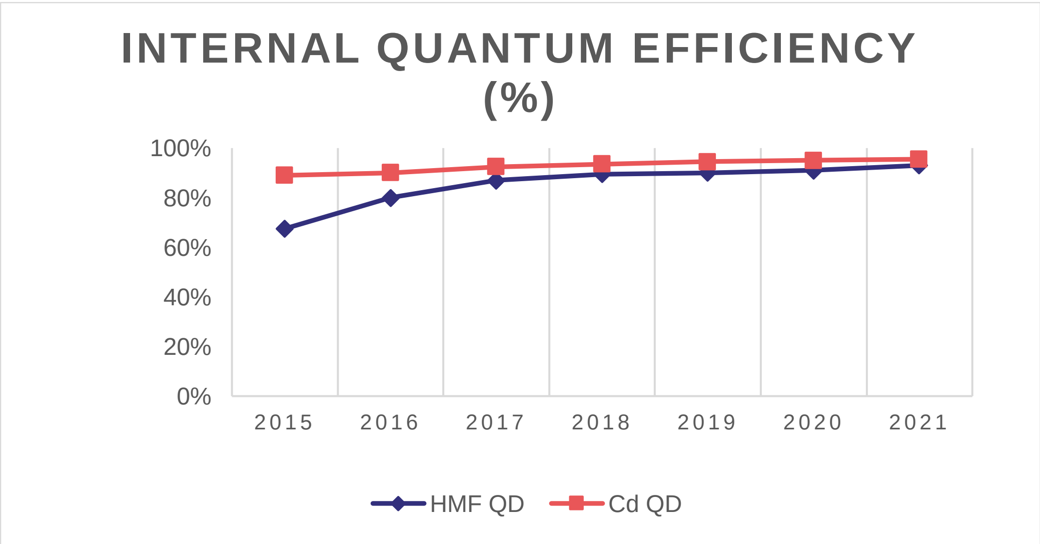

Figure 1 IQE of HMF-QD compared to Cd-QD, 2015 – 2021

We examined the rate of improvement in IQE for HMF-QD technology and compared that to the IQE of Cd-based QDs from 2015 to 2021. The results are shown in Figure 1. Here we can see that both QD formulations have improved and are now approaching or above 95% IQE. Cd-QD maintains a slight edge in IQE, however, this advantage does not necessarily translate to an advantage in full device performance as we will see in the next section.

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[1] OJ L 174, 1.7.2011, p. 92.

Device Performance

Advances in display making have enabled the latest generation of display products based on HMF-QD to deliver similar or better performance compared to Cd-QD products across *all relevant performance metrics.* Today's HMF-QD displays deliver incredible picture quality with more color and more luminance per watt of power consumed. There are several figures of merit to consider when making performance comparisons for quantum dot displays. These include:

- **Color Gamut:** In 2012, the International Telecommunications Union (ITU) standardized the color gamut for Ultra-High Definition (UHD) television with Rec.ITU-R BT.2020 (BT.2020).[2] Color gamut is commonly expressed in terms of a display's area coverage ratio of BT.2020 in the CIE 1931 color space. The best HMF-QD displays on the market today deliver nearly 90% coverage of the BT.2020 standard. This matches the best Cd-QD displays.
- **Peak Luminance**: is expressed in "nits" or Candelas per square meter. Industry-standard practice is to measure the luminance of a white patch covering 10% of the display's viewable area. The latest High Dynamic Range (HDR) content delivers a more realistic picture with darker darks and brighter brights. According to the UltraHD Alliance, to deliver a premium HDR experience, displays should be capable of reproducing at least 1,000 nits of peak luminance.[3] The best HMF-QD displays on the market can deliver more than 2,000 nits and the same is true for Cd-QD displays.
- **Color Volume**: an emerging area of display metrology that considers color and luminance together. The signal for UltraHD TV can contain colors across the entire BT.2020 range at up to 10,000 nits. The ITP color volume metric developed by Dolby and later standardized by ITU in 2019 with BT.2100 describes what percentage of colors in the HDR signal a display can reproduce.[4,5] Even the best, market-leading consumer displays are only able to reproduce about half of the color volume in the BT.2100 signal today. It is a goal of the industry to create displays that can fully reproduce this standard so that consumers can fully, and accurately experience content at home, exactly as content creators intended. Therefore, future display technologies should offer a path towards achieving 100% coverage. The best HMF-QD displays on the market in 2022 can reproduce 52% of 10,000 cd/m² BT.2020 ITP coverage while the leading Cd-QD displays reach a similar but slightly lower level of 48% coverage.
- **Power Efficiency**: Nits/Watt is an accepted way to measure how efficiently a display can create light. The best HMF-QD displays on the market can produce 11.7 nits/watt in their most power-intensive setting with high brightness, wide color gamut, and HDR content while the best Cd-QD displays deliver 6.8 nits/watt in the same setting. Please note that this result is for the power consumed by the full device, not just the display. It, therefore, reflects a variety of components and design choices that different TV makers used in developing their products.

For this study, we pulled publicly available data from the review site RTINGS.com on a selection of five HMF-QD LCD displays compared to five similar Cd-QD LCD displays.

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[2] Rec. ITU-R BT.2020-2, *Parameter Values for Ultra-High Definition Television Systems for Production and International Programme Exchange*, ITU, Geneva, Switzerland, 2015.

[3] HDR TV: What is HDR, and What Does High Dynamic Range Imply for TV?, UltraHD Alliance, 2018. https://alliance.experienceuhd.com/news/hdr-tv-what-hdr-and-what-does-high-dynamic-range-imply-tv

[4] Perceptual color volume, white paper, Dolby Laboratories, Inc., 2017. https://www.dolby.com/us/en/technologies/dolby-vision/measuring-perceptual-color-volume-v7.1.pdf

[5] Rec. ITU-R BT.2100-2, *Image parameter values for high dynamic range television for use in production and international programme exchange*, ITU, Geneva, Switzerland, 2018.

Each of the ten TVs we looked at was placed on the market in 2020 through 2022 and is still available to purchase in the retail channel. All the products are global models which, while purchased in the US or Canada for this study, are also available in the EU with only minor design changes. The sizes included were limited by the size of TVs that RTINGS measured. To control for display size, which has the largest impact on display power consumption, we selected a similar mix of 65” and 55” TVs based on each QD technology. All the TVs we chose were LCDs with Full Array Local Dimming (FALD) backlights. Finally, all power consumption comparisons were made using RTINGs “Max Power Consumption” metric, which looks at power consumption for the TV in its highest performance setting with HDR turned on. We believe HDR is the most appropriate mode to look at since a key benefit of QD technology is to deliver improvement in these high performance features related to HDR video.[6]

Brand names have been obfuscated here as non-disclosure agreements prevent Nanosys from disclosing customer-specific information such as which brands are using which type of QD technology. All the TVs in this study were produced by globally recognizable, leading brands and are among the best-performing TVs on the market of any type. We encourage the Öko Institut to explore the incredible amount of data available at the RTINGS.com site to draw their own conclusions.

[6] OLED and LED TV Power Consumption and Electricity Cost, RTINGS, 2021. https://www.rtings.com/tv/learn/led-oled-power-consumption-and-electricity-cost

Name	QD Type	TV Size	Max Power Consumption	Peak HDR Luminance 10% Window (nits)	Nits/Watt Efficiency	% DCI-P3 coverage (xy)	% BT.2020 coverage (xy)	10,000 cd/m² Rec 2020 ITP Coverage	RTINGs Picture Quality Score Mixed Usage
TV 1	HMF	65”	183	1786	9.76	89.75%	65.26%	45.20%	8.5
TV 2	HMF	65”	175	2054	11.74	94.42%	71.76%	52.10%	8.6
TV 3	HMF	65”	181	869	4.80	89.65%	65.15%	34.80%	7.7
TV 4	HMF	65”	164	1000	6.10	94.17%	71.29%	35.10%	7.9
TV 5	HMF	55”	179	1609	8.99	95.92%	72.06%	48.30%	8.6
TV 6	Cd	65”	242	505	2.09	94.12%	74.12%	26.40%	7.7
TV 7	Cd	65”	232	969	4.18	92.03%	69.44%	39.70%	8.1
TV 8	Cd	55”	219	986	4.50	91.01%	69.72%	37.30%	7.8
TV 9	Cd	65"	275	1705	6.20	98.56%	77.95%	47.80%	8.6
TV 10	Cd	55"	154	1051	6.82	91.53%	69.61%	34.50%	8.3

Table 1 RTINGs TV Performance Data for HMF and Cd-QD TVs 2020 – 2022

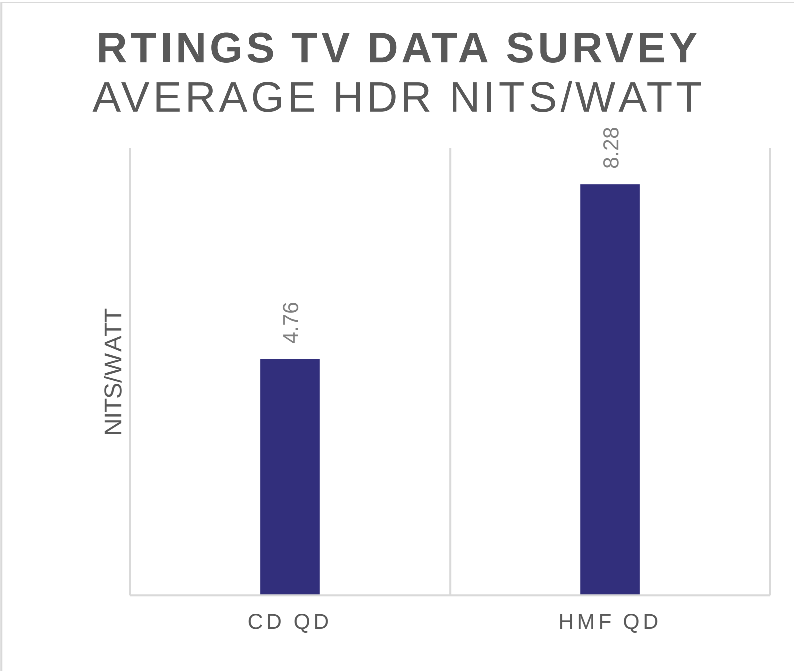

Figure 1 Average nits/watt efficiency of Cd-QD TVs vs HMF-QDs in Nanosys’ survey of RTINGs data

On average, we found that HMF-QD displays deliver 1.75X more power efficiency in terms of nits per watt compared to Cd-QD displays. Color efficiency for HMF-QD displays is superior as well with an average of 18% more color gamut coverage per watt and 44% more color volume coverage per watt compared to Cd-QD TVs in the study.

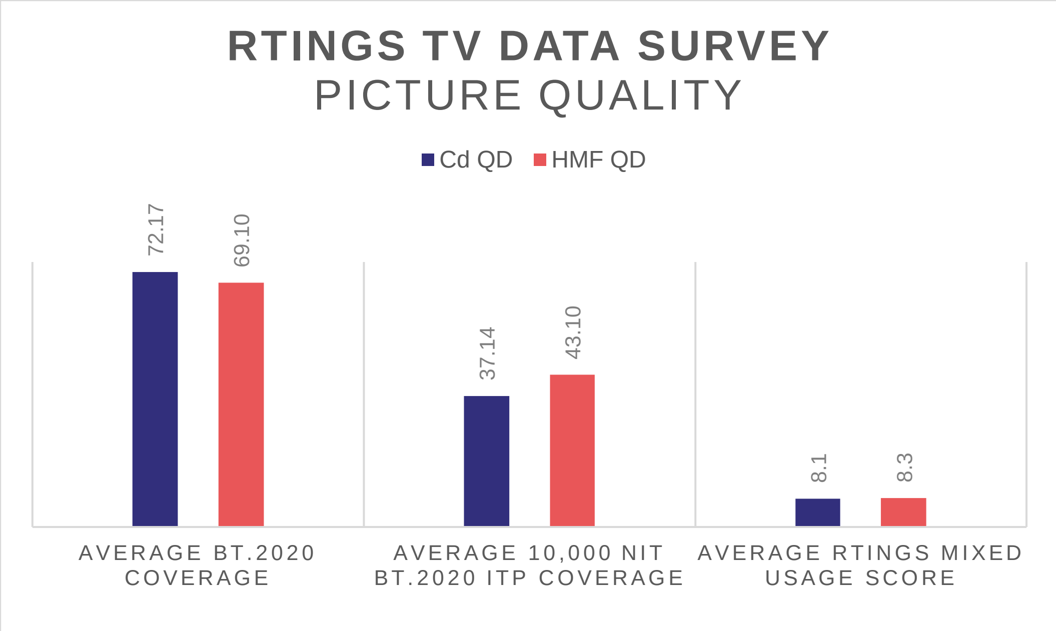

Figure 3 Picture quality data for Cd-QD and HMF-QD TVs in Nanosys survey of RTINGs data

Overall, the HMF-QD TVs also delivered better picture quality with more brightness and color volume while the Cd-QD sets showed a slight advantage in BT.2020 color gamut coverage. RTINGs “Mixed Usage” picture quality scores were even.

This survey of quantum dot TVs currently available in the market clearly indicates that Cd-QD no longer offers a substantial advantage in terms of picture quality or power efficiency that cannot be replaced by alternatives. Looking ahead, HMF-QD TVs in the market today are already offering superior performance on Color Volume coverage, an important metric for the next decade of TV picture quality advancements.

2. *Are Cd-QD used in* ***on-chip*** *configurations in lighting and or displays on the market? If so,*
   a. *how do they compare with alternative lighting/display technologies with respect to technical performance, reliability and environmental, health and consumer safety impacts?*

   b. *Please explain if an exemption for such applications is justified in your view, providing technical data and evidence to support your views.*

On-Chip QD in Displays
“On-chip” QD configurations are not currently available on the market in transmissive displays such as LCDs in either Cd-QD or HMF-QD formulations. On-chip QD solutions are simply not yet able to meet the high performance and reliability requirements for this demanding application. The brightness (photon flux) required for on-chip QD integrated into blue mini-LEDs in LCD backlights is prohibited by both Cd and HMF-QD's current reliability limitations. In such a configuration the blue photon flux required to generate the desired white backlight is at least 100X higher than the on-surface solution (where the QD film is placed at a distance from the light source and after the diffuser

film). Lifetimes of more than 30,000 hours are required for TV applications and the QD technology has not matured enough to deliver lifetimes under the photon fluxes required for this application.[7,8]

The prospects for market adoption of on-chip QD for direct view emissive microLED displays are quite different. The blue photon flux required for a direct view microLED display is much lower than the flux required by an LED backlight implementation. This makes it possible to use HMF-QD in direct view emissive displays, even at current performance levels. One example is the QD-OLED display sold by Samsung Display Corporation which uses HMF-QD for “on-chip” color conversion. We will talk more about this display later.

Direct view emissive microLED displays are beginning to enter the market at the extreme high end of the premium segment in TVs, in many cases costing over $80,000. These microLED TVs use a combination of 24.9 million native red, green, and blue emitting microLED or miniLED chips to produce an UltraHD resolution image. Production is slow and costly right now, however, nearly every large player in the display industry is working hard to bring production costs for microLEDs down.

Nanosys believes mass market consumer microLED displays may become possible in the next five years with the help of on-chip Quantum Dot Color Conversion (QDCC) technology. On-chip QD is viewed as a leading solution to simplify microLED display manufacturing, lower production costs, and accelerate time to market. See question 5 for more detail on this display architecture.

Cadmium and HMF-QDs are currently being evaluated by the industry for on-chip color conversion in direct view microLED displays. In fact, at the Society for Information Display’s recent Display Week 2022 tradeshow held in San Jose, California, there were several demonstrations of microLED displays using QDCC. Every public QDCC display demonstration at Display Week 2022 used Cadmium quantum dots.[9]

As mentioned above, HMF-QDCC materials for on-chip applications are ready today and are already shipping into the market in QD-OLED products. QD-OLED is a new type of display, introduced by Samsung Display Corporation in late 2021 and launched into the market by Samsung Electronics, Sony, Dell and MSI in TV and monitor products during the first half of 2022.[10]

QD-OLED displays use a blue OLED emitter to generate light combined with a layer of inkjet printed red and green QDCC materials. Each pixel contains three subpixels, one that is clear to pass through blue light, one with green QDCC to down convert blue into green, and one with red QDCC to down convert blue into red. See Appendix C for more details on how this architecture works.

QD-OLED is quite similar to on-chip LED applications in that the QD’s must be patterned, are placed very close to the emitter, and must down-convert essentially 100% of the blue light to achieve good color and efficiency performance.

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[7] Highly Stable White Light-Emitting Diodes Based on Quantum-Dots Dispersed Into the Backlight Lens for Display Backlight, IEEE Photonics Journal, 2019. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8712506

[8] Quantum Dot Based White LEDs for General Illumination, LED Professional, 2017. https://www.led-professional.com/resources-1/articles/quantum-dot-based-white-leds-for-general-illumination

[9] Nanosys, Every Quantum Dot Display at SID Display Week 2022 in under 3 minutes, 2022. https://youtu.be/yIzkLrXdLZ8

[10] Linus Tech Tips, Samsung just made everything else OBSOLETE, 2022. https://youtu.be/Piteu5gyKq0

In terms of performance, QD-OLEDs have been widely regarded by independent reviewers as the best TV and monitor products ever made. The Samsung S95B QD-OLED TV received a 9.1 mixed usage score from RTINGS.com and is currently the highest scoring TV on the website.[11] In terms of raw picture quality performance, this set delivers over 1,000 nits of peak luminance, more than 86% coverage of BT.2020, and 51.7% BT.2020 color volume coverage.

Every QD-OLED product on the market in 2022 uses HMF-QD technology. There should be no doubt that HMF-QD can deliver on-chip performance for direct view display applications today.

Lighting

There are no HMF-QD on-chip LEDs for lighting and Nanosys is aware of only a single on-chip Cd-QD LED product currently available for purchase in the EU. This Cd-QD LED delivers high CRI with mid-power for task lighting in indoor applications. It does not address the full solid-state general lighting application space. Cd-QD LED products currently available achieve improved color and efficiency performance through a mix of red and green-emitting conventional phosphors with some red-emitting Cd-QD mixed in. Nanosys analysis of the available devices shows that Cd ppm levels are below 100ppm in a homogenous layer (see section “2. c. iii” below for information on homogenous layers in on-chip applications).

At the same time, the development of HMF-QD solutions for lighting is increasing and market adoption is expected in the next five years. For example, Nanosys is working closely with the US Department of Energy to develop HMF-QD alternatives for on-chip applications in lighting and display backlights. The objective of the DoE project is to develop red HMF-QDs that improve LED power efficiency by reducing “wasted” light emission (>650 nm) and that can be used for color conversion under high-flux operating conditions.

Under this program, Nanosys investigated the root causes of HMF-QD instability under high flux with the goal to improve HMF-QD materials that deliver stable, efficient, high-CRI lighting. We have demonstrated HMF-QDs with a breakthrough LT70 lifetime of 5,000hrs at 5 W/cm^2 at 50°C and a quantum yield of 90%.

[11] Samsung S95B TV Review, RTINGS.com, 2022. https://www.rtings.com/tv/reviews/samsung/s95b-oled

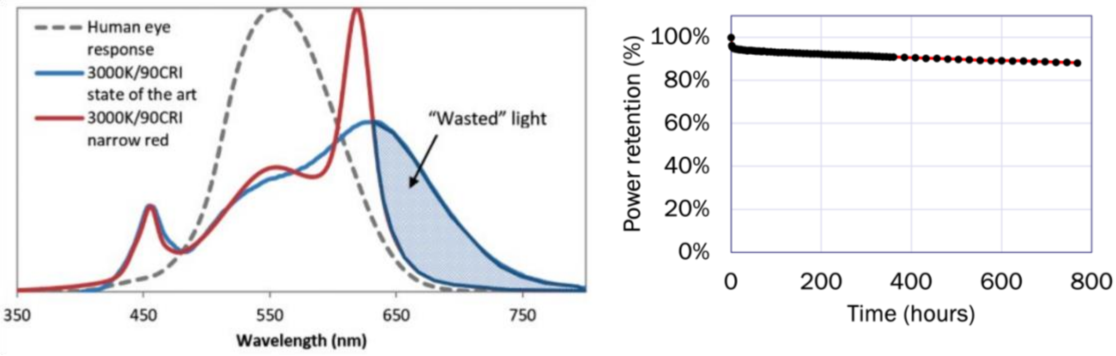

Figure 4 (Left) Chart demonstrating the efficiency advantage of narrow line-width QD emission for high CRI general lighting by shifting photons into the visible range. (Right) Nanosys demonstrates progress in HMF-QD for on-chip lighting applications with breakthrough reliability.

Given advancements in the performance of heavy metal free alternatives and the current availability of <100ppm Cadmium solutions for lighting, Nanosys believes an exemption for Cadmium is not justified for either lighting or display applications.

c. *How high are the mass and concentration (ppm, mg/mm^2 screen or LED area) of Cd in such applications?*
   Direct view and backlight

   i. *How is the amount expected to change in the next 5 years?*

   ii. *How do the mass and concentration of Cd relate to each other in terms of: Cd per mm^2 screen area/LED, concentration by weight in homogeneous materials, ppm, weight per screen/lighting application?*

   iii. *Which part of Cd-QD/ LEDs/ screens/ solid-state lighting is regarded as the homogeneous material?*

If the requested exemptions (i.e. 5 µg /mm^2 for on-chip) are adopted, Nanosys believes that the amount of Cadmium entering the EU will increase significantly.

We believe further study on the validity of the 100ppm RoHS limit for Cadmium in CE components is worthwhile to address the current trend towards increased Cadmium content by weight with lower Cadmium ppm levels through component optimization.

	On-Surface QD Diffuser Plate	On-surface QD Film	On-Chip QD for OLED Displays	On-Chip QD microLED Displays	On-Chip QD Lighting	Electroluminescent QD Displays
Homogenous Layer Thickness	500 – 1000 µm	50 – 100 µm	7 – 10 µm	2 – 5 µm	300 – 500 µm	~0.03 µm
QD Weight % Concentration	0.06 – 0.12%	0.3 – 0.6%	20 – 30%	20 – 30%	0.025 – 0.1%	>80%
Cd ppm	30 – 55	85 – 280	6000 – 60,000 Green - Red	6000 – 60,000 Green – Red	60 – 240	24,000 – 200,000
Cd µg/mm²	<0.1	<0.05	0.3 – 0.5	0.15 – 0.25	4 – 16	~0.005
Cd per 65" TV	<117mg	58mg	350 – 580 mg	175 – 290 mg	~116mg	5.8mg

Table 2 Cd-QD Concentration in Homogenous Layer for Different Applications including on-surface, on-chip and electroluminescent QD implementations in displays and lighting

Defining "Homogenous Material" For Each Application

Nanosys understands "homogeneous material" to mean: material of uniform composition throughout that cannot be mechanically separated into different materials.

In theory, for this exemption we only want to consider the QD layer in a component, in reality, from a detection point of view, it may be hard to separate the QD layer from others. This is especially true for applications involving ultra-thin layers which can be less than a few microns.

Quantum Dot Enhancement Film (QDEF): The active QD matrix material at the center of a QDEF film is viewed as the "homogenous material" in this application. We ignore the "barrier" plastic films, which can be mechanically separated from the QD matrix, in ppm calculations.

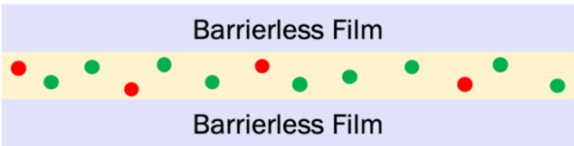

Figure 5 Construction of on-surface QD component showing QD homogenous layer

Quantum Dot Color Conversion (QDCC) for Direct View OLED or LCD Displays: The active color converting layer, separate from glass, black matrix, or other thin film encapsulation or light extraction or enhancement layers.

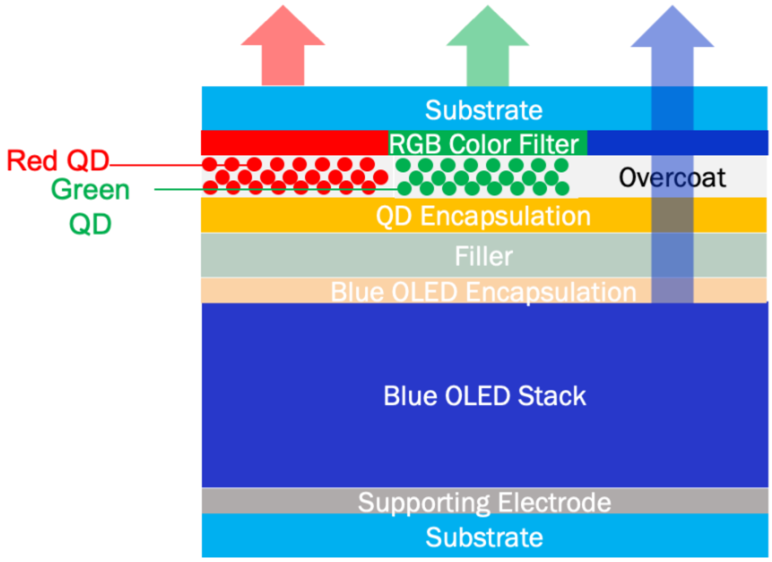

Figure 6 Construction of QDCC on OLED and µLED showing QD homogenous layer

Quantum Dot Color Conversion (QDCC) for Direct View MicroLED Displays: The active color converting layer, separate from black matrix, or other thin film encapsulation or light extraction or enhancement layers.

QD on-chip LEDs for Direct View Display Backlighting and Lighting Applications: In this application, QDs are volumetrically dispersed in the LED cup epoxy. We view the QD-epoxy layer as the homogenous layer in this case.

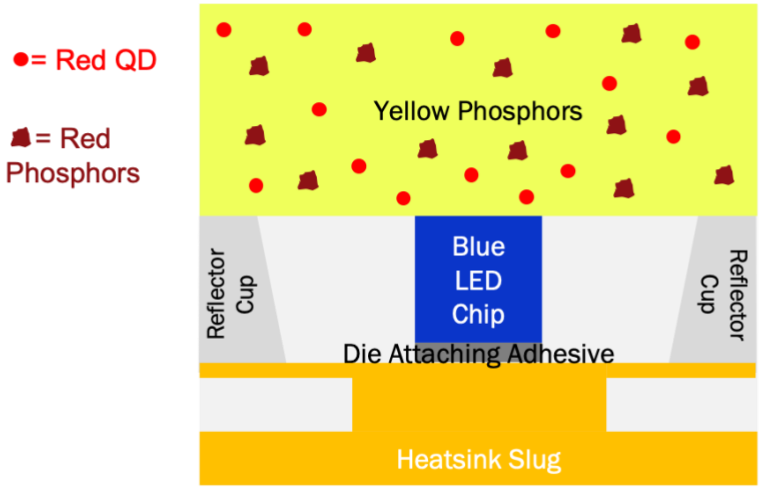

Figure 7 Construction of QD on-chip showing QD homogenous layer

Electroluminescent Quantum Dots: Nanosys calls this type of display "NanoLED." Here we would consider just the QD "electroluminescent" emission layer which is about 30nm thick.

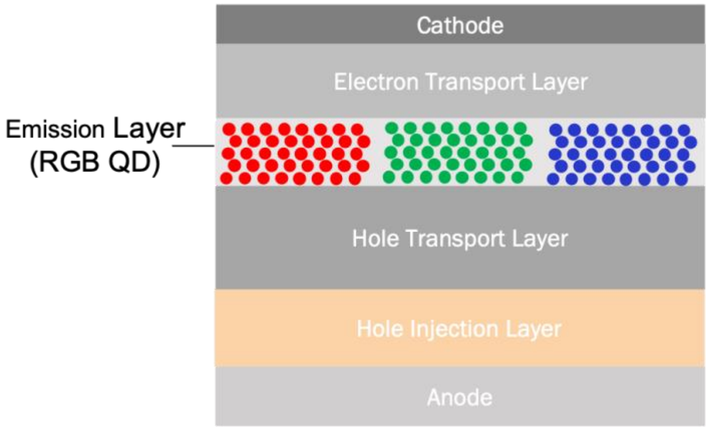

Figure 8 Construction of NanoLED showing QD homogenous layer

d. *How developed is the market of displays for RoHS compliant Cd-QD and for Cd-free QD for consumer/ professional, stationary/ mobile displays?*

The market for RoHS-compliant Cd-QD– under exemption 39A or with less than 100ppm Cd– and HMF-QD for displays of all types is well established. Most of the world's most recognizable consumer electronics brands have Quantum Dot products in their lineups today. These brands have created more than 850 unique display products since the very first products entered the market in 2013. These products include TVs, monitors, notebook PCs, tablets, medical displays, digital signage, professional reference monitors for content creation, and more.

Combined, QD display products have shipped more than 60 million units since 2013. Nanosys' internal market research estimates that HMF-QD currently makes up approximately 70% of all QD displays shipped both globally and in the EU. Many leading brands including Samsung, LG, Sony, HP, and Dell have successfully adopted a "zero-Cadmium" policy for their display products.

e. *How developed is the market of solid-state lighting for RoHS compliant Cd-QD and for Cd-free QD for consumer/ professional, stationary/ mobile displays?*

On-chip Cd-QD for solid-state lighting is in the early stages of development with negligible impact on the broader lighting market.

3. *Should an exemption be granted,*
   a. *are there additional applications where Cd-QD could be used and where it provides benefits to the environment, health and/or to consumer safety?*
   b. *what is the expected amount of Cd entering the EU market annually? Please specify clearly to which application area and for which configuration type your answer refers.*

Nanosys is not aware of any applications where Cadmium quantum dots provide substantial benefits to the environment, health, or to consumer safety.

In Figure 3 below we have modeled two scenarios for the expected amount of Cd entering the EU market annually for the period from 2022 – 2026. The model is based on a blend of Nanosys internal forecasting and DSCC's Quarterly Advanced TV Shipment Forecast Report.[12] The "Exemptions

[12] Quarterly Advanced TV Shipment Report, DSCC, 2022.

Denied" case here assumes that only on-surface applications continue to ship into the EU market throughout the forecast period. Some vendors of film and diffuser plate implementations have developed thicker, bulkier solutions using Cd-containing QDs which have less than 100ppm concentration. However, as noted elsewhere in this report, these on-surface QD films may contain as much as 100mg of Cd per square meter of display area! These components can be expected to continue to ship into the EU market with the same amount of Cadmium per square meter, regardless of the outcome of the exemptions considered here. Nanosys recommends the EU consider taking a more specific approach to the regulation of these components, as it has done for Mercury in cold cathode fluorescent tubes for LCD displays.[13]

If the exemptions are allowed, it should be assumed that display makers will place Cadmium-containing displays on the market even if HMF alternatives offer similar performance. This has been the case for on-surface components and we anticipate the same will be true for next-generation technologies like QD-OLED and QD on-chip for microLED. For example, we expect that a brand will enter the market in 2025 with a Cadmium QD-based version of QD-OLED. Proof of concept demonstrations of a Cd-QD-OLED display have been shown at display industry events already.

The "Exemptions Allowed" case shown here includes the same level of on-surface applications and adds-in Cadmium-based on-chip QD for emissive displays including a portion of the QD-OLED market as well as microLED displays. Based on our model, allowing on-chip Cd-QD for display applications could lead to an explosion in growth for Cd entering the EU from 2025 on.

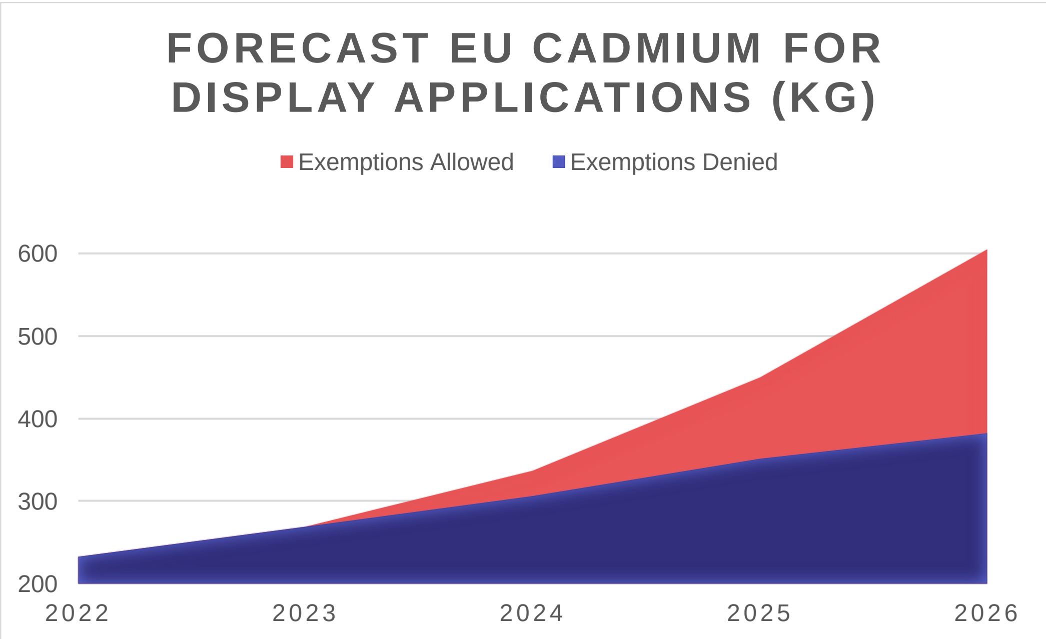

Figure 9 Nanosys forecast for Cadmium content displays in in kilograms in the EU from 2022 through 2026. The "Exemptions Allowed" forecast assumes the current exemptions under consideration are passed. "Exemptions Denied" assumes all exemptions under consideration are denied. Cadmium will continue entering the EU in displays without additional specific regulation for the RoHS 100ppm loophole.

4. *What **substitutes** are of relevance on the **substance level** (i.e., QD that do not include Cd such as InP and InGaN)?*

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[13] OJ L 402, 1.12.2020, p. 81.

a. *What is their status of development and in what applications on the market are they already applied?*

b. *How developed are dye-doped rather than quantum dot-doped nanoparticles?*

Heavy Metal Free Quantum Dots

Nanosys uses the term “Heavy Metal Free” Quantum Dot (HMF-QD) to refer to a range of Quantum Dot technologies that contain no heavy metals such as Cadmium and Lead. These materials include Indium Phosphide (InP), Silver Indium Gallium Sulfide (AIGS), Copper Indium Selenide (CIS), and Zinc Selenide/Telluride among others.

InP quantum dots are widely commercialized today with more than 70% market share and products in the market from many of the world’s leading global brands including HP, LG, Samsung, Sony, and Dell.

As noted above, HMF-QDs currently match Cd-QD in terms of picture quality performance and outperform them on efficiency. There are no technical obstacles to the adoption of HMF-QDs in either transmissive or emissive display types.

Other HMF-QD formulations such as Zinc Selenide are expected to enter the global market for consumer electronics beginning in 2023.

Lead Perovskites

Lead Perovskites have shown promise as a potential color conversion alternative to quantum dots and phosphors. They are being researched for use in on-surface films for LCDs as well as in on-chip and color conversion applications such as QD-OLED. In literature, Lead Perovskites promise excellent color performance with narrow FWHM that is on par with Cd-QD. However, Lead Perovskites are not yet stable enough to meet commercial reliability standards which typically require TVs to last >30,000 hours to 80% brightness.[14] Additionally, Lead Perovskites contain significant amounts of Lead and exhibit limitations in fabrication processability.[15]

Lead Perovskite components may become possible to produce in the next five years with less than the RoHS-required limit of 1,000 ppm for lead. However, these solutions are unlikely to be commercialized as an “environmentally friendly” alternative to CdSe QDs and given the increased concentration levels permitted, could result in more than one gram per square meter of lead entering the display ecosystem in the EU.

Phosphors

Another alternative to consider is phosphor materials such as Potassium Fluorosilicate (KSF). KSF is widely commercialized in LCD displays of all types today. However, KSF suffers from other performance limitations and toxicity concerns.

KSF phosphor cannot meet the higher color gamut requirements of the BT.2020 standard adopted in 2015. This color standard will drive the display market to use a deeper red emission which KSF

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[14] Zhang, C. et al, (2020), 86-3: Ultra-Stable Deep-Dyed Perovskite-Polymer Composites as Tunable Downconverters, *SID Symposium Digest of Technical Papers*, Volume51, Issue1 Pages 1303-1306. https://doi.org/10.1002/sdtp.14121

[15] Norman A Luechinger, (2022), 26-2: How perovskite quantum dots are supporting the rise of mini-LED based LCD displays, *SID Symposium Digest of Technical Papers*, Volume53, Issue1, Pages 299-302 https://doi.org/10.1002/sdtp.15479

cannot reach. Additionally, KSF has a slow response time on the order of milliseconds that precludes its use in high refresh rate displays demanded by the market. Such slow response may also cause eyestrain, especially in applications where the display is viewed for extended periods.

Finally, it appears that the natural decomposition of a KSF:Mn^{+4} microscopic material in acidic or alkaline conditions, like the potential conditions found in landfills, could result in both acute and chronic toxicity if the host matrix is compromised. Solutions of potassium fluorosilicate once compromised may form hydrofluoric acid, which is a weak base, and readily reacts with compounds containing calcium and magnesium including living tissue.[16] The US Government's National Oceanic and Atmospheric Administration (NOAA)'s CAMEO chemical database characterizes potassium fluorosilicate as, "highly toxic, may be fatal if inhaled, swallowed or absorbed through skin."[17] Long-term studies are needed to determine if decomposing microscopic phosphor has the potential to release metal ions, including potassium fluorosilicate (KSF), into the environment.

Organic Dyes

Certain fluorescent organic dyes have the potential to be used in color conversion technology to generate wide color gamut displays and serve the needs of the TV/monitor market. However, this field is still in its infancy and has not been qualified for display market adoption.[18]

c. *How do the substitutes compare to Cd-QD with respect to energy efficiency, light quality (CRI or colour gamut) and lifetime?*

See responses to sections 4(a) and 4(b) above.

d. *What are the environmental, health and consumer safety advantages and disadvantages of their use as compared to CD-QD?*

See responses to sections 4(a) and 4(b) above.

e. *Do the substitutes contain other substances of concern? Which and in what quantities?*

See responses to sections 4(a) and 4(b) above.

f. *Are obstacles to their application technical or economical?*

There are no substantial technical obstacles. HMF-QD is widely commercialized in both transmissive and direct view display applications. HMF-QD has been shown to deliver equivalent picture quality performance with superior energy efficiency compared to Cd-QD in end devices.

The primary driver for the continued adoption of Cd-QD today is economical. Costs for QD components, like all components in the CE supply chain, are driven by volumes. At the highest volumes, HMF-QD component cost is close to Cd-QD. However, at lower volumes, there is a price premium for HMF-QD components. This price premium, though small in terms of absolute dollar amount, has been making a difference in the extremely price-sensitive consumer electronics market.

[16] "Potassium Fluorosilicate", Centers for Disease Control, https://www.cdc.gov/niosh-rtecs/VV802C80.html, accessed 11/5/19.

[17] https://cameochemicals.noaa.gov/chemical/4309, accessed on 11/5/19

[18] Khan, Y. et al (2022), Synthesis of fluorescent organic nano-dots and their application as efficient color conversion layers, Nature Communications Vol. 13, 1801 (2022); https://doi.org/10.1038/s41467-022-29403-4

This small price gap has been a barrier for brands that are not able to bring QD technology to as many units with as much efficiency as larger brands that can deploy the same film across several SKUs and many millions of units. Removing the exemptions is likely to drive volumes up for HMF-QD which will help to lower prices across the board, enabling smaller brands to offer HMF-QD solutions more easily and encouraging them to move away from Cadmium.

5. *What substitutes exist at the **device technology level** (alternative components or alternative lamp/display technologies)?*

Organic Light Emitting Diode (OLED)
Organic Light Emitting Displays (OLEDs) are a relatively new entrant to the display market and are often considered a competitor to Quantum Dot displays. OLEDs deliver excellent picture quality with some unique benefits such as thin form factors, low black levels, and excellent refresh rates. However, they are unable to meet all the market demands for display performance, are less efficient than alternatives like QD LCD, and are much more expensive than alternatives.

There are broadly three types of OLED display on the market today: 1) RGB OLED, which is commercialized for monitors, notebooks, tablets, mobile phones, and watches, 2) WRGB OLED, which is commercialized for large screen TVs, and small Micro Displays for VR/AR applications and, 3) QD-OLED which is commercially available in monitors and TVs. In addition, OLED technology enables advanced and distinct custom and unique lighting solutions. Examples of OLED lighting applications include architectural task-specific lighting engines and automotive lighting.[19]

OLED displays of all types are generally less power efficient compared to same-size LCDs for most types of content. RTINGs conducted a study comparing the power efficiency of OLED TVs to LCD TVs. They found that brightness and size were key drivers of power consumption. LCDs were more power-efficient than OLEDs across all brightness settings and sizes.[20]

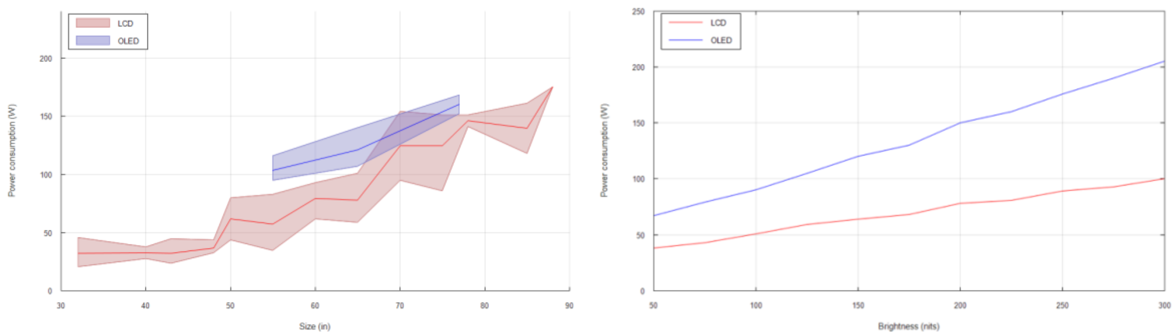

Figure 10 (Left) LCD and OLED Power consumption vs. TV size. (Right) LCD and OLED Power consumption vs. brightness. Source: RTINGS

OLED should not be considered a viable substitute for QD-LCDs of any type until OLED can deliver improvements in power efficiency.

MicroLED

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[19] https://www.oledworks.com/oled-lighting-products/

[20] OLED and LED TV Power Consumption and Electricity Cost, RTINGS, 2021, https://www.rtings.com/tv/learn/led-oled-power-consumption-and-electricity-cost]

MicroLED shows enormous promise as a substitute in terms of both picture quality and power efficiency. However, the current market reality is that microLEDs are prohibitively expensive, with TVs costing over $80,000, and their theoretical efficiency advantage has not yet been borne out. On-chip QD for microLED offers a potential path to accelerating the commercialization of microLED displays. The first QDCC products may enter the market in the next three to five years.

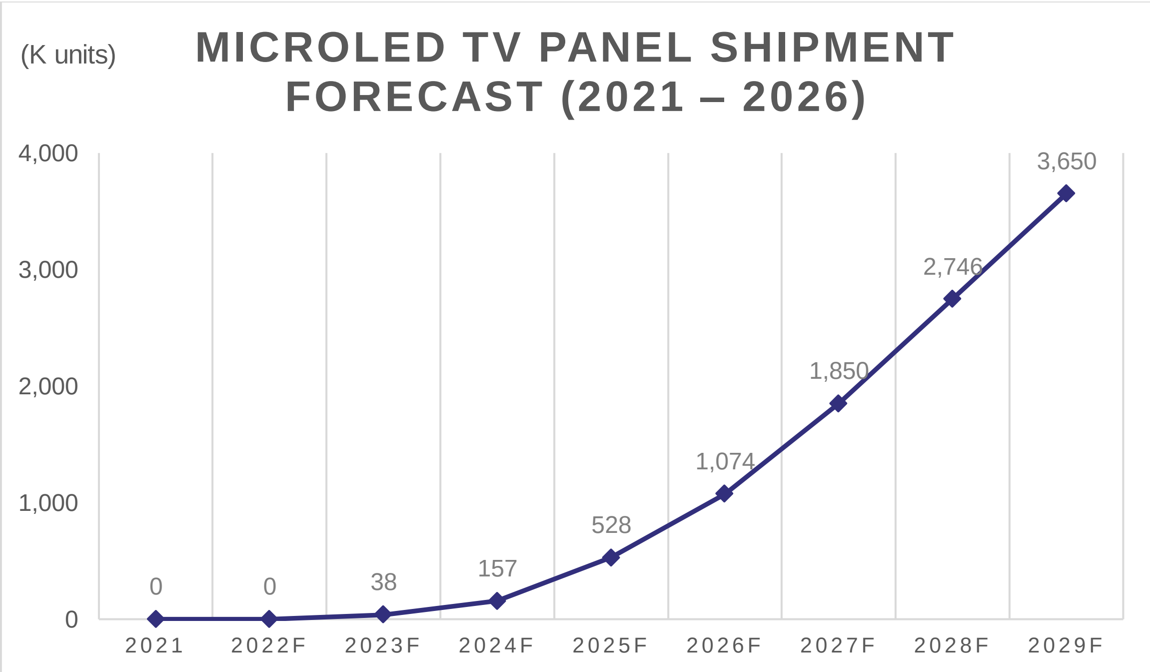

Figure 11 MicroLED TV Panel Shipment Forecast[21]

On-chip Quantum Dot Color Conversion (QDCC) technology is the next step in the evolution of quantum dot-based displays, featuring patterned subpixels of red or green QDs in place of traditional pigment-based color filters. The color 'conversion' approach, in which white light is generated by absorption of blue light and reemission of red or green, leads to higher efficiencies than the traditional color 'filtering' approach. Any blue light source including LED, microLED, and OLED can potentially be used as the backlight in these displays.

For direct view emissive microLEDs, specifically, on-chip QD presents a scalable alternative to the pick-and-place manufacturing method where blue, green, and red microLEDs are fabricated separately, diced, and then moved into position on the display panel. Since only blue LEDs are needed to drive the QD layer, the manufacturing process is greatly simplified.[22]

On-chip microLED QD technology will result in displays with higher efficiency, wider color gamut, and viewing angles, while reducing costs by utilizing existing photolithography or inkjet printing infrastructure. Quantum dot photoresist patterning can be used for applications across a variety of feature sizes, but will particularly benefit devices with high resolution, such as microdisplays for AR/VR, wearables, and mobile applications.

The development of on-chip HMF-QD and Cd-QD for microLED is advanced and products may enter the market in the next three to five years. For example, the most recent SID Display Week 2022 in

[21] Omdia "Micro LED Display Technology Market Report–2022"

[22] B. Boerger, N Van Wyck. 2017. "Rapid Assembly of Quantum Dots for MicroLED Micro-Displays." https://www.ledinside.com/knowledge/2017/11/rapid_assembly_of_quantum_dots_for_microled_micro_displays

San Jose, CA saw multiple microLED demonstrations using quantum dot color conversion.[23] Most of the public microLED QD demonstrations to date have been based on Cd-QDs.

NanoLED

Electroluminescent NanoLED is the future of Quantum Dots. NanoLED displays are like OLED devices in that the Quantum Dots convert electricity directly into photons.

HMF-QD NanoLED technology is making rapid progress towards commercialization but remains in the research and development phase. At the 2022 SID DisplayWeek show, Nanosys demonstrated record-setting HMF-QD external quantum efficiency (EQE) of greater than 16% for blue, 17.5% for green, and 21% for red. For context, commercial blue OLED EQE today is only about 7%. Work still needs to be done to improve the lifetime of NanoLED materials, but progress has been rapid. Red and green NanoLEDs are approaching commercial reliability levels today.

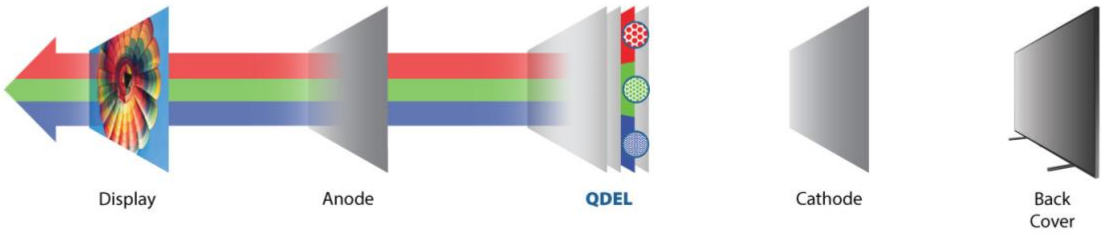

Figure 12 Exploded diagram of a NanoLED (or QDEL) electroluminescent display showing Quantum Dots producing red, green and blue light. Source: Nanosys

Demonstrations of NanoLED products have been shown at the SID Display Week tradeshow in 2022. BOE featured a 55” 8K TV using Cd-based QDs at their booth, while Sharp privately showed a smartphone-sized 6.1” NanoLED display using HMF-QDs.

NanoLED displays may be commercialized in the next three to five years.[24]

a. *As there are different display technologies on the market, some using white backlight and others not, would it be technically feasible to substitute white backlight and thus Cd-QD in all display applications?*

Cd-QD can easily be substituted by HMF-QD in all commercially available display applications today. Emerging direct view display applications such as QD-OLED are already using HMF-QD materials in the market. Rapid progress in the development of future on-chip and NanoLED technologies for direct view displays are well positioned to use HMF-QD. Due to its lower cost of implementation and easy integration into existing LCD technology, we believe the QD-enabled white backlight implementation will remain one of the major implementations for years to come.

Establishing an exemption for Cadmium in direct view displays now will only encourage the continued development of Cadmium QD for these future applications.

[23] Nanosys, Every Quantum Dot Display at SID Display Week 2022 in under 3 minutes, 2022 https://youtu.be/yIzkLrXdLZ8

[24] Yole Développement, “Next Gen TV Technologies: Technology Forecast 2018-2025”

b. As there are different lighting technologies on the market, is it technically feasible to use such technologies in all relevant SSL lighting applications where Cd-QDs are applied?

LEDs for general lighting applications with excellent color reproduction of over 90 CRI and efficiency of more than 95 lumens per watt performance are currently available.[25] These solutions do not rely on Cadmium. It is technically feasible to use these alternatives for all relevant SSL lighting applications where Cd-QDs are applied. We expect HMF-QD alternatives to become available in the next five years.

c. What are the environmental, health and consumer safety disadvantages of their use as compared to CD-QD? Do the substitutes contain other substances of concern? Which and in what quantities?

Some substitute phosphor materials may also contain hazardous materials. As noted above in section 4(a), it appears that the natural decomposition of a widely adopted red phosphor, KSF:Mn^{+4}, microscopic material in acidic or alkaline conditions, like the potential conditions found in landfills, and could result in both acute and chronic toxicity if the host matrix is compromised

d. Are obstacles to their application technical or economical?

There are no obstacles. Most high CRI, high-efficiency lighting technologies available today do not use Cadmium.

6. What are the main parameters of the energy usage of applications/ devices in which CD-QD (and their alternatives) are used? How does energy consumption change in relation to changes in the size, quality of light, periphery settings/ technology, contrast, and brightness? Please consider providing a comparison in tabular form.

Display energy consumption is the result of several factors from underlying technology to color gamut. We have addressed these above, especially in sections 1 and 5. In summary, the biggest factors that impact the energy use of display products are as follows:

1. Display Technology: As mentioned above in section 5, LCDs and OLEDs TVs deliver different efficiency performance levels. LCDs are inherently inefficient, only allowing about 5% of the light produced to pass through to the user. However, OLED TV displays of all types are generally even less power efficient compared to same-size QD-LCDs for most types of content. As of today, the white OLED implementation for OLED TV is the least efficient implementation for OLED displays.

2. Display size: Display size is the second most impactful factor in determining a display's energy consumption. Larger displays consume more power. Consumers tend to like larger displays and the average size of the display has historically increased consistently.

3. Resolution: Higher resolution displays require more pixels to fit into the same area. This means smaller pixels which, in turn, means smaller apertures and therefore more light blocked from passing through to the user. In addition, the driving electronics will also consume more power per unit area. Resolution can have a significant impact on display power consumption. For example, 8K TVs can consume up to 90% or 100% more power compared to 4K TVs with 25% of the number of pixels.

[25] https://store.waveformlighting.com/products/absolute-series-99-cri-led-linear-module

4. Brightness and Color gamut: High peak luminance (up to 10,000 nits) and high color gamut (up to 100% BT2020) also generally require more energy use, however, it is a goal of the industry to create displays that can fully reproduce this standard so that consumers can fully, accurately experience content at home, exactly as content creators intended. We believe such experience is crucial to the quality of life and shall be pursued as the future of the display industry. As we saw in section 1, increased color and brightness do not always come at the expense of energy efficiency, a good example of the multivariate nature of display design and energy consumption.

7. *Which are the expected treatment routes of applications containing Cd-QD at the end-of-life stage (e.g., lighting equipment and displays)?*

Nanosys does not participate in the end-of-life stage for consumer electronics products and cannot comment substantively.

Appendix A

Display Economics

The display industry is a large and continuously evolving industry. Like most industries, new technologies enter the display market and old technologies are disrupted on an increasingly regular basis. One needs only to think back on the change from Cathode Ray Tube (CRT) displays which were dominant from the 1950s through early 2000s and were rapidly displaced by CCFL backlit LCDs in a matter of just a few years. Of course, CCFL LCD displays were, in turn, replaced by LED backlight LCDs just a few years later. Today a new crop of emerging technologies such as Quantum Dot, OLED, microLED, and NanoLED are vying for their chance to replace LCD as the leading display technology.

These new technologies are considered part of the Advanced TV market. The display industry analysts at DSCC define “Advanced TV” as any TV with an advanced display technology feature, including all TVs with quantum dot technology of any type, all OLED TVs, 8K TVs of any type, and microLED TVs.[26]

While new technologies may emerge frequently in displays, overall demand for displays on an area basis grows steadily in this mature industry. This is in part due to longer replacement cycles for large displays such as TVs and because the manufacturing base requires massive investment to increase capacity. A new display factory typically requires a multi-billion-dollar commitment and can take several years to complete.

As a result, new technologies may see rapid growth initially as new fabs come online, followed by a longer period of slower growth as the available installed manufacturing capacity begins to match the overall demand for the technology.

[26] Bob O’Brien, “Advanced TV Market Growth Slowed in Q2’22”, DSCC Weekly Review, 6 September 2022

Appendix B

QDEF

Quantum Dot Enhancement Film (QDEF), also known as “on-surface QD”, is a thin film containing Quantum Dots that can be inserted into the backlight of an LCD display to improve color performance and energy efficiency.

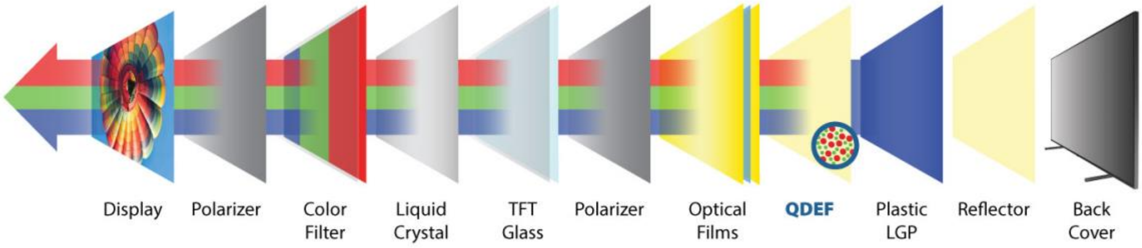

Figure B1 Exploded diagram of an LCD display with QDEF technology inside. Source: Nanosys

QDEF was first commercialized with CdSe Quantum Dots in 2013 and in 2015 the world’s first Cadmium Free QDEF products based on HMF Quantum Dots were commercialized. Today, HMF-QDEF is the market-leading Quantum Dot display technology for displays with approximately 70% worldwide share of the Quantum Dot display market.

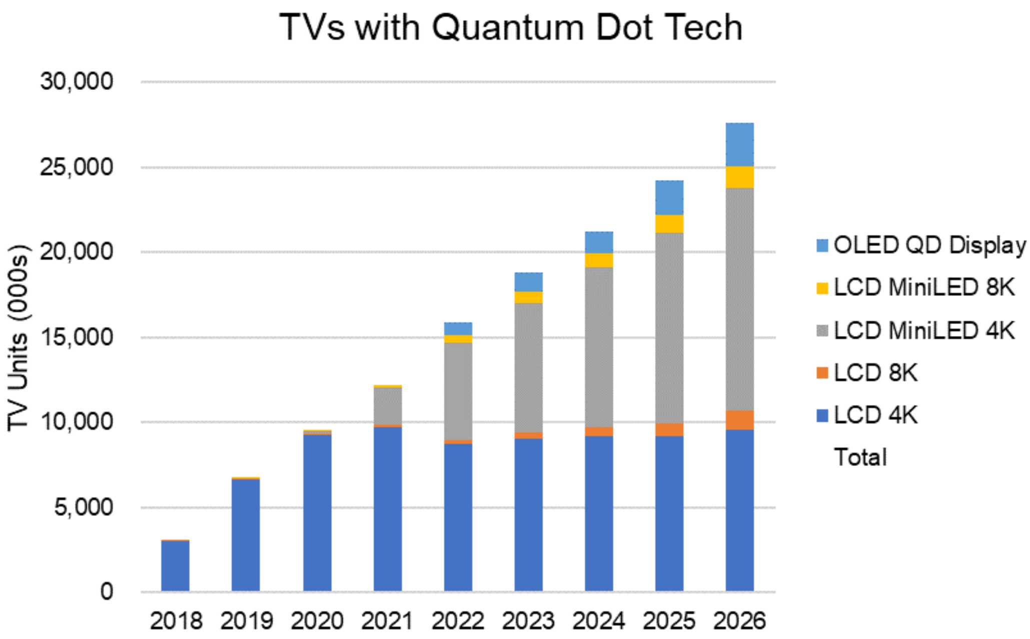

Figure B2 2022 DSCC forecast for TVs using quantum dot technology from 2018-2026

QDEF has been deployed in most display types, including tablets, notebooks, monitors, televisions as well as signage and other specialty displays such as medical monitors.

DSCC forecasts that worldwide demand for QDEF displays will grow from 15 million units in 2022 to 25 million in 2026.[27]

Included in this demand are miniLED TVs, which combine miniLED backlights with QDEF. 100% of miniLED TVs on the market today use QDEF on-surface QD technology. DSCC forecasts shipments of miniLED TVs using QDEF to grow rapidly from 6.2M units in 2022 to over 14M units in 2026.[28]

Nanosys is among the world's leading suppliers of HMF-QDs and technology for QDEF. Leading brands such as Samsung, LG, Sony, HP, and Dell only use HMF-QDs. However, Cd-based displays continue to ship into the EU today.

Nanosys sees demand for QDEF in the EU continuing to grow. LCD technology remains dominant in the display industry with a massive installed manufacturing base. Since QDEF is used in LCDs we expect to see continued demand for QDEF for the next ten years and beyond. LCD displays are forecast to remain the dominant technology by volume for large panels during this period according to a group of analysts we surveyed and the value of QDEF will remain viable in this market.

[27] DSCC's forecast shows approximately 15 million Quantum Dot TVs of all types were sold in 2021. DSCC Quarterly Advanced TV Report, 2022.

[28] Guillaume Chansin, "Quantum Dot Displays Start to Diversify Again", DSCC Weekly Review, 17 January 2022

Appendix C

QD-OLED

QD-OLED displays move the quantum dots from the backlight, where the technology is deployed in today's QDEF display products, to the front of the display. The quantum dots in a QD-OLED display replace the color filter array and generate light right at the plane where the image is reproduced.[29] QD-OLED displays should be considered an "on-chip" QD technology.

A QD-OLED display relies on a blue OLED layer operating as a lightsource to provide blue light as opposed to the white light of a conventional WOLED TV. The blue sub-pixel can simply pass the blue light with minimal losses. The green and red sub-pixels, each with a layer of green or red quantum dots instead of an absorbing color filter, absorb the blue light and downconverts it into green and red light, respectively.[30]

These QD subpixels can be seen in a video teardown analysis by Pete Palomaki of NanoPalomaki consulting.[31] Not only does each green and red sub-pixel solely emit the desired color (and thus provide a saturated color primary for the display), the light throughput of each sub-pixel can, in principle, be much higher than in a conventional LCD, thus offering improved energy efficiency. Commercial QD-OLED displays on the market today currently utilize HMF-QD for both the red and green subpixels. However, display makers have demonstrated QD-OLED prototypes based on Cd-QD. These Cd-based QD-OLED devices may ship into the EU in the next 2-3 years.

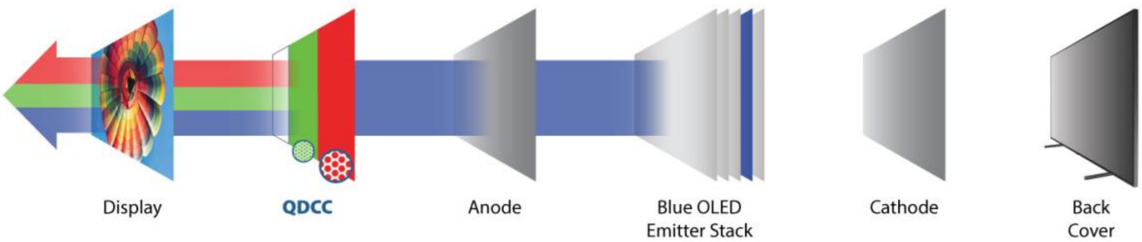

Figure C1 Exploded diagram of a QD-OLED display showing blue OLED emitters with patterned red and green QDCC layers on top. Source: Nanosys

QD-OLED officially entered the market in 2022 shipping in TVs from Samsung and Sony, and in monitors from Samsung, Dell, and MSI. DSCC projects over 500,000 QD-OLED TVs will ship from Samsung and Sony in 2022.[32] By 2026 shipments are expected to reach 1.5 million units.

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[29] Han, Chang-Wook, et al, (2017), 3-1: Invited Paper: 3 Stack-3 Color White OLEDs for 4K Premium OLED TV, *SID Symposium Digest of Technical Papers*, 48, doi: 10.1002/sdtp.11555.

[30] Luo, Z., Yurek, J. "Quantum dots: The technology platform for all future displays", Proc. SPIE 10940, Light-Emitting Devices, Materials, and Applications, 1094010 (1 March 2019)

[31] Palomaki, Peter. Destroying a QD-OLED - Part 2. YouTube, NanoPalomaki, 15 Aug. 2022, https://www.youtube.com/watch?v=o-LbIBRuyog&t=0s. Accessed 23 Sept. 2022.

[32] https://www.quantumdots-info.com/dscc-sees-qd-oled-tv-market-growing-500000-units-2022-15-million-units-2026

QD-OLED displays have won numerous awards from both online reviewers and associations such as CES 2022 Best of Innovation[33] and EISA Best Product 2022-2023.[34]

[33] "CES 2022 Innovation Award Product Samsung 65' Qd-Display Tv." Innovation Award Honorees, https://www.ces.tech/Innovation-Awards/Honorees/2022/Best-Of/S/SAMSUNG-65%E2%80%9D-QD-DISPLAY-TV.aspx.

[34] "Eisa Premium OLED TV 2022-2023 Sony XR-65A95K." EISA Expert Imaging and Sound Association, https://eisa.eu/awards/sony-xr-65a95k/.

Appendix D

QD-MicroLED ("on-chip")

As noted in Appendix E, on-chip Quantum Dot Color Conversion (QDCC) technology is the next step in the evolution of quantum dot-based displays, featuring patterned subpixels of red or green QDs in place of traditional pigment-based color filters. The color 'conversion' approach, in which white light is generated by absorption of blue light and reemission of red or green, leads to higher efficiencies than the traditional color 'filtering' approach. Any blue light source including LED, microLED and OLED can potentially be used as the backlight in these displays.

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On-chip microLED QD technology will result in displays with higher efficiency, wider color gamut and viewing angles, while reducing costs by utilizing existing photolithography or inkjet printing infrastructure. QDPR can be used for applications across a variety of feature sizes, but will particularly benefit devices with high resolution, such as microdisplays for AR/VR, wearables and mobile applications.

The development of on-chip HMF-QD and Cd-QD for microLED is advanced and products may enter the market in the next three to five years. For example, the most recent SID Display Week 2022 in San Jose, CA saw multiple microLED demonstrations using quantum dot color conversion.[36] Most of the public microLED QD demonstrations to date have been based on Cd-QDs.

[35] B. Boerger, N Van Wyck. 2017. "Rapid Assembly of Quantum Dots for MicroLED Micro-Displays." https://www.ledinside.com/knowledge/2017/11/rapid_asse mbly_of_quantum_dots_for_microled_micro_displays.

[36] Nanosys, Every Quantum Dot Display at SID Display Week 2022 in under 3 minutes, 2022. https://youtu.be/yIzkLrXdLZ8