# Review of impact of potential new RoHS substance restrictions for Indium-Phosphide


## Abstract

Nanosys analysis of InP Quantum Dot usage in the EU for the period from 2018 – 2028. Includes market analysis for EU display market and Quantum Dot component designs.


November 2019

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# Section 1 – InP Quantum Dots and the Display Market

## Display Industry 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 1950's through early 2000's 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 LCD just a few years later. Today a new crop of emerging technologies such as Quantum Dot, OLED and microLED are vying for their chance to replace LCD as the leading display technology.

While new technologies may emerge frequently in displays, overall demand for displays on an area basis grows fairly steadily in this mature industry. This is in part due to long replacement cycles for large displays such as TVs and also 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.

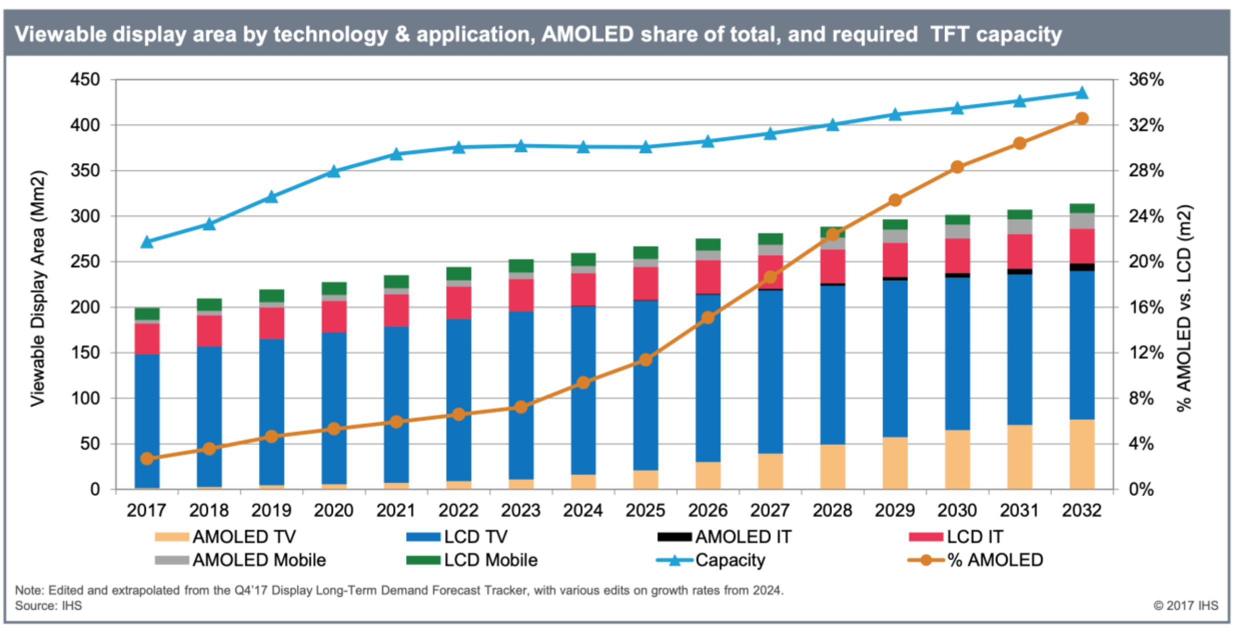


*Figure 1 IHS Markit "Q4 '17 Display Long-Term Demand Forecast Tracker"*

The fundamental economics of the industry would suggest that extreme changes in overall area demand are unlikely. Figure 1 shows IHS Markit's long term forecast for worldwide display demand from 2017 through 2032. According to IHS, worldwide display demand for the year 2028 is expected to be approximately 290 million square meters across all technologies and markets.[1] Over the period of 2018 to 2028 this amounts to a worldwide compound annual growth (CAGR) rate for display area demand of just 3.3% across mobile, monitors, televisions as well as LCDs and OLEDs.

IHS separately forecasts that the strongest growth for displays will come from emerging regions such as China, Asia Pacific and Latin America in the coming decade. Developed regions such as the European Union have maintained a very steady demand in recent years with only minor fluctuations in demand in response to events and prices. The EU, for example, consumed 43 million TVs in 2018 which accounted for roughly 20% of worldwide demand. By 2022, that share is expected to decline to just under 18% of worldwide demand as other markets grow more rapidly.[2]

Looking ahead at EU display demand from 2018 through 2028, we can expect these macro trends to continue: 1) overall display area growth will remain slow and steady and, 2) the EU's share of market will continue to decline as emerging markets begin to take more share. The important question to ask, then, is how will Quantum Dot technologies based on InP perform over this time period?

## Estimated Volumes of InP in Display Applications in the EU, 2018 – 2028

In preparing this report, Nanosys reviewed third-party forecasts from leading display industry analysts at Display Supply Chain Consultants (DSCC), IHS Markit, Supply Chain Market Research (SCMR) and Yole. Additionally, we have included insights from our own internal forecasts. Nanosys is the market-leading supplier of Quantum Dots and Quantum Dot technology. We maintain highly accurate data on the sell-through of our technology into global markets and are well positioned to make forward-looking forecasts for emerging Quantum Dot technologies.

Over the ten years from 2018 to 2028, we forecast three broad trends:

1) LCD will continue to be the dominant display technology on both a volume and area basis, even as it begins to lose share to new entrants.
2) CdSe-based Quantum Dots will continue to maintain approximately 35% market share worldwide for QDEF applications.
3) Two new Quantum Dot technologies will enter the EU market during this timeframe in addition to QDEF. These will include the QD-OLED hybrid and Quantum Dot Electroluminescent (QDEL) configurations. With QD-OLED largely serving as a bridge technology in the premium segment until QDEL is fully commercialized.

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[1] IHS Markit, "Q4 '17 Display Long-Term Demand Forecast Tracker," presented by Charles Annis at IHS' Global Display Virtual Event 2017 on 16 May 2017

[2] IHS Markit "Strategies for the Global TV Market Webinar," November 12, 2018

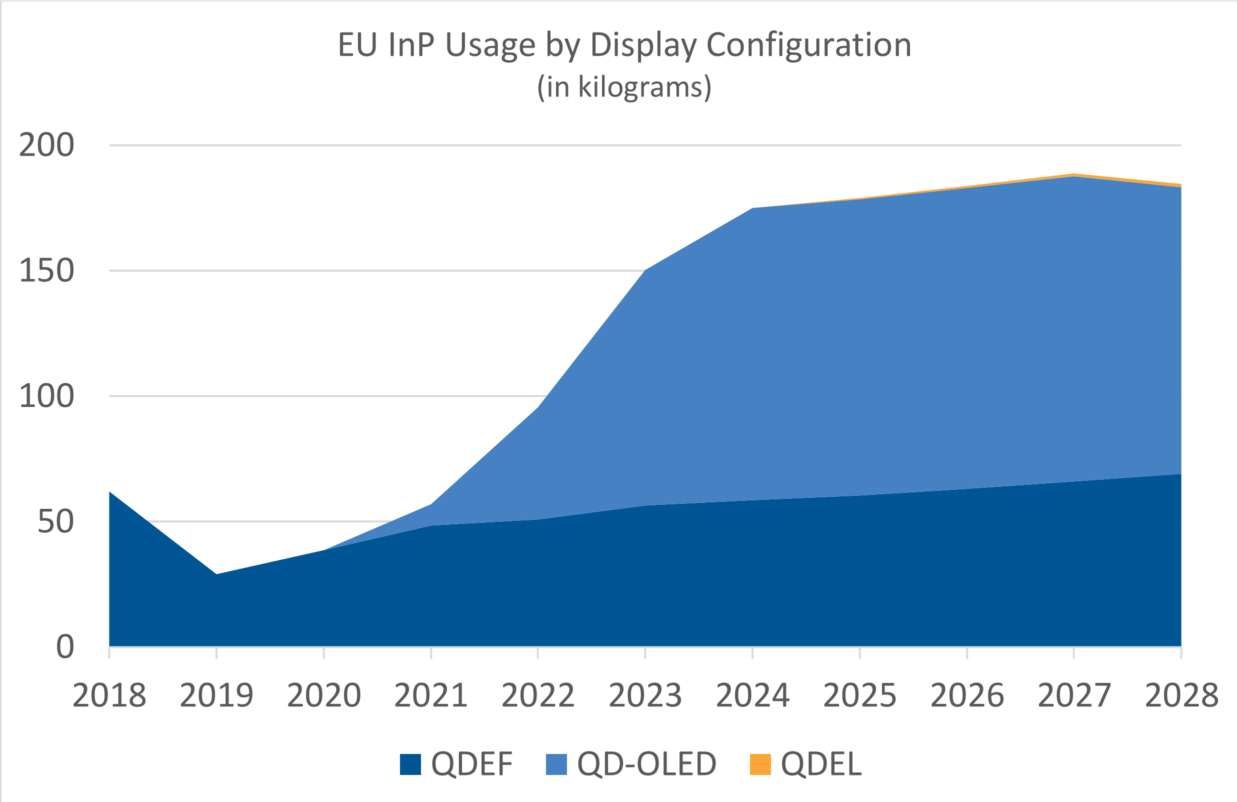


*Figure 2 Nanosys forecast for InP in display applications in the EU 2019-2029. InP content in EU displays is projected to peak at ~190kgs in 2027. Source: Nanosys internal forecast including market data from SCMR, Yole & DSCC reports.*

Nanosys forecasts EU InP volumes will peak at approximately 190 kilograms/year in 2027 and begin to decline rapidly from there as new, ultra-efficient Quantum Dot technologies are commercialized. The following section provides more detail on each configuration's contribution to this forecast.

## Overview of Quantum Dot Configurations for Displays, 2018 – 2028

There are three display configurations expected to utilize InP Quantum Dots over the next 10 years: Quantum Dot Enhancement Film (QDEF), Quantum Dot-OLED (QD-OLED) and Quantum Dot-Electroluminescent (QDEL).

### "On-Edge" and "On-Chip" Configurations

It should be noted that the "on-edge" and "on-chip" configurations referenced in the Oko Institute's "ROHS Annex II Dossier for Indium phosphide" are not expected in the market over this timeframe.[3] "On-edge" QD configurations of all types have been discontinued and "on-chip" is not expected to be commercialized using InP Quantum Dots.

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[3] "ROHS Annex II Dossier for Indium phosphide", Oko Institut, Accessed 11/1/19, https://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/4th_Consultation/Indium_phosphide_RoHS_Dossier_v2_final_20190925.pdf

The highest stability reported for InP QDs in an on-chip application so far has been 90% retention at <200mW LED power in 100 hours.[4] This compares to an application requirement of 30,000 hours at 1W LED power, or roughly a factor of 1500x shorter than the requirement. With this as the most advanced work reported, at the present time there is no evidence that InP Quantum Dots will ever be commercialized for "on-chip" use in conjunction with high-power LEDs typically used in LCD backlights and general lighting applications, and certainly not within the next 10 years. For the foreseeable future, the market for high power LEDs with "on-chip" phosphors with narrow spectral emission will be served by Narrow Band Phosphors (NBP) such as Potassium Fluorosilicate (KSF).

## Quantum Dot Enhancement Film (QDEF)

Quantum Dot Enhancement Film (QDEF), also known as "on-layer" or "on-surface", 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.

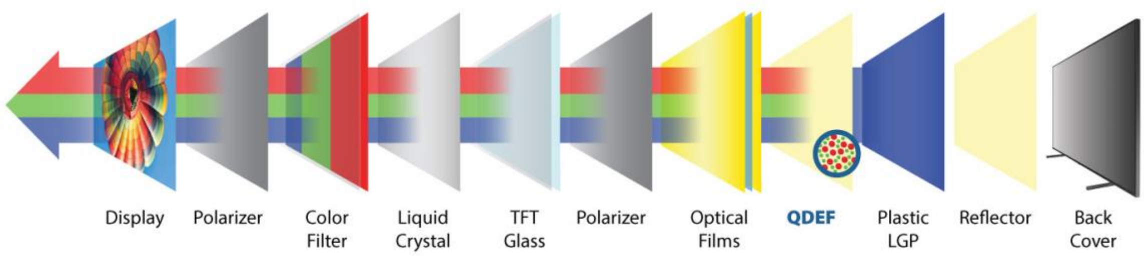


*Figure 2: Exploded diagram of an LCD display with QDEF technology inside. Source: Nanosys website*

QDEF was first commercialized with CdSe Quantum Dots in 2013 and in 2015 the world's first Cadmium Free QDEF products based on InP Quantum Dots were commercialized. Today, InP QDEF is the market-leading Quantum Dot display technology for displays with roughly 65% worldwide share of the Quantum Dot display market.[5]

QDEF is the only currently commercialized Quantum Dot technology for displays available in the market. 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. One notable exception is the smartphone market. No QDEF displays have ever been shipped into the smartphone market.

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[4] Eun-Pyo Jang, et al, "Near-complete photoluminescence retention and improved stability of InP quantum dots after silica embedding for their application to on-chip-packaged light-emitting diodes,", 2018, *RSC Advances,* 18, doi: 10.1039/C8RA00119G

[5] 3rd party analyst DSCC predicts 7.5 million Quantum Dot TVs of all types will be sold in 2019. Cd-Free market share based on statement from Samsung: "Samsung expects to sell over 5 million QLED TVs in 2019", Yonhap News Agency, Accessed 10/24/2019, link: https://en.yna.co.kr/view/AEN20190907002600320

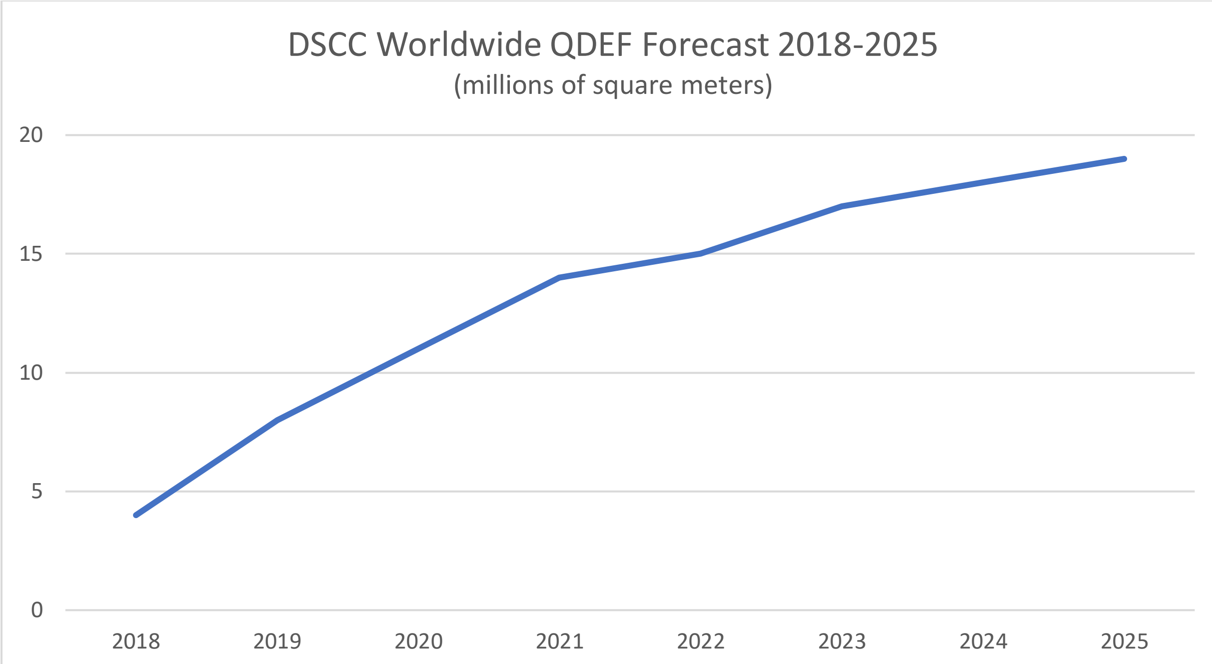


*Figure 3 DSCC 2019 forecast for worldwide QDEF demand from 2018 through 2025.*

DSCC forecasts that worldwide demand for QDEF displays will grow from 4 million square meters in 2018 to 19 million in 2025.[6] Growth is strong but will begin to flatten in later years as investment in LCD technology slows.

Nanosys is among the world's leading suppliers of InP-based Quantum Dots and technology for QDEF. Nanosys internal forecasting shows that approximately 520,000 square meters of InP-based QDEF displays were shipped into the EU in 2018. This is based on EU display market share of roughly 20% and InP QD share of 65%.

Full 10-year forecasts are not available for QDEF from third party sources. Extrapolating on DSCC's growth rate, Nanosys sees demand for InP-based QDEF in the EU continuing to grow steadily through 2028 with 2.4 million square meters of demand that year. As an LCD-based technology, we expect to see continued growth in demand for QDEF through the full 10-year period. LCD displays will remain the dominant technology by volume during this period according to all analysts we surveyed and the value of QDEF will remain viable in this market.

### Quantum Dot OLED (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

[6] Ross Young, "DSCC Display Market Outlook: Will LCD Continue to Dominate?", *IMID*, 2019

display replace the color filter array and generate light right at the plane where the image is reproduced.[7]

A QD-OLED display relies on a blue OLED layer operating as a backlight 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, absorbs the blue light and down converts it into green and red light, respectively. 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.

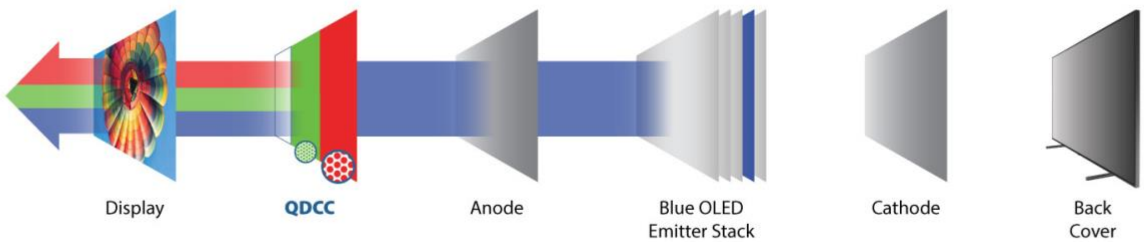


*Figure 3: Exploded diagram of a QD-OLED display showing blue OLED emitters with patterned red and green QDCC layers on top. Note that only the red QDCC layer is expected to utilize InP in this application. Source: Nanosys website*

QD-OLED displays are expected to utilize a mix of QD-types. Only the red subpixel is expected to be based on InP QD at this time. InP green quantum dots are not able to meet the requirements for this application, and so green color conversion will be handled by a new QD-type that has not yet been disclosed and blue QD are not needed in this configuration.

QD-OLED displays are nearing commercialization. Samsung recently announced plans to invest more than $10 billion into two new QD-OLED display manufacturing lines.[8] The new QD-OLED manufacturing lines are expected to come online beginning in 2021. SCMR analysts project that initial volumes will be quite small with just 200,000 units produced in the first year.[9] This will ramp to approximately 3 million units by 2025 as the manufacturing lines begin to reach full capacity and demand for the technology slows.

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[7] 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.

[8] https://www.reuters.com/article/us-samsung-display-investment/samsung-display-to-invest-11-billion-by-2025-amid-industry-oversupply-idUSKBN1WP077

[9] SCMR "AM Supply Chain Commentary: Samsung QD/OLED Unit volume forecast," 10 October 2019

| SDC QD/OLED Yearly Unit Volume Forecast | | | | | |
|---|---|---|---|---|---|
| | *2021* | *2022* | *2023* | *2024* | *2025* |
| Units | 200,480 | 1,090,120 | 2,351,037 | 2,982,476 | 3,094,604 |
| Δ | | 443.8% | 115.7% | 26.9% | 3.8% |
| Source: SCMR LLC | | | | | |

*Figure 4 SCMR's Samsung Display Corporation (SDC) QD/OLED Yearly Unit Volume Forecast*

QD-OLED is viewed within the display industry as a "bridge technology" between QDEF and QDEL displays. While QD-OLED offers important image quality benefits such as improved brightness, black level and off-axis viewing, it is not expected to remain in the market once electroluminescent QDEL technology is broadly commercialized.

Ten-year forecasts for QD-OLED technology are not currently available. Based on available data from SCMR and other sources, Nanosys forecasts that approximately 40,000 square meters of QD-OLED displays will ship into the EU beginning in 2021. We see demand for InP-based QD-OLED in the EU peaking at 600,000 square meters per year in 2027. In the period from 2026 to 2029, we anticipate that QD-OLED market share will begin to be disrupted by the availability of QDEL.

### Quantum Dot Electro Luminescent (QDEL)

Quantum Dot Electro Luminescent technology (QDEL), is the future of Quantum Dots. QDEL displays are similar to OLED devices in that the Quantum Dots convert electricity directly into photons.

QDEL devices offer distinct advantages over OLEDs including lower cost, higher brightness, improved power efficiency and more accurate color reproduction.

Heavy metal free QDEL technology is making rapid progress towards commercialization but remains in the research and development phase. At the 2019 SID DisplayWeek show, Nanosys announced record-setting external quantum efficiency (EQE) of greater than 16% for red and green InP QDEL materials.[10] Work still needs to be done to improve the lifetime of QDEL materials.

[10] Ippen, C, Guo, W, Zehnder, D, et al. High efficiency heavy metal free QD-LEDs for next generation displays. *J Soc Inf Display*. 2019; 27: 338– 346. https://doi.org/10.1002/jsid.780

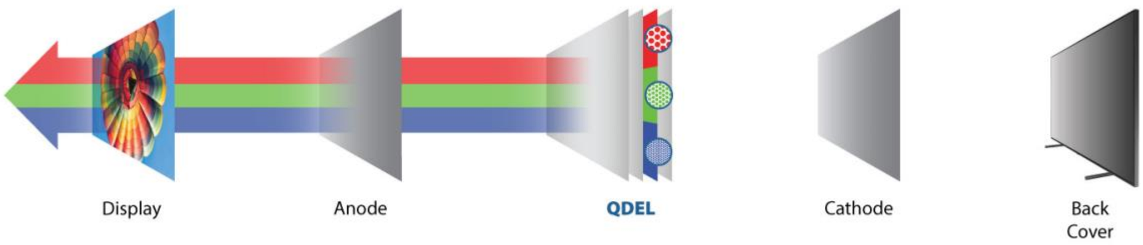


*Figure 4: Exploded diagram of a QDEL display showing Quantum Dots producing red, green and blue light. Note that blue QDs will not be based on InP in the QDEL configuration. Source: Nanosys website*

The analysts at Yole forecast QDEL displays will be commercialized beginning in 2024 with an initial run of 300,000 displays ramping to 1.5 million in 2025.[11] Ten-year forecasts for QDEL technology are not available.

Yole's forecast lines up with Nanosys internal EU forecast of 60,000 square meters of QDEL display area in 2024, ramping to nearly 1 million square meters in 2028 as the technology enters a period of rapid growth and begins to displace QD-OLED in the premium segment.

## Amount of InP Required Per Display

The amount of InP required on a per display basis is expected to broadly decline over the next 10 years. This reduction will be driven by two key factors: improvements to existing technologies and the emergence of new configurations that require significantly less material such as QDEL.

For example, since 2017, improvements in Quantum Dot manufacturing and component design have enabled a 75% reduction in InP content for QDEF displays currently on the market. Table 1 shows Nanosys ICP analysis of InP-based QDEF films from two of the top-selling products in 2017 and 2019, confirming this trend. Additional reductions in InP content of QDEF may be possible over the next 10 years. Such breakthroughs are difficult to forecast, therefore, for the purposes of this report we maintain a constant rate of 0.029 grams per square meter from 2019-2028.

| | 2017 Samsung TV: SUHD KS9000 | 2019 Samsung TV: Q70 |
|---|---|---|
| QDEF InP Content ($g/m^2$) | 0.12 | 0.029 |

*Table 1: 2017-2019 InP Content in Samsung Televisions. Source: Nanosys measured data*

[11] Yole Développement, "Next Gen TV Technologies: Technology Forecast 2018-2025"

### Estimating InP Content for Display Configurations

As noted in the section above, each display configuration uses Quantum Dot technology in different ways, requiring differing amounts of QD and therefore InP. Table 2 contains a summary of Nanosys estimated InP content for each display configuration on a per-square-meter basis from 2019-forward. It is important to note that overall display area is a more important consideration than display application. Quantum Dot loading differences between display product types such as smartphones, monitors and televisions should be expected to have little impact on the amount of InP per square meter.

| Display Configuration | InP ($g/m^2$) |
| --- | --- |
| **QDEF** | 0.029 |
| **QD-OLED** | 0.21 |
| **QDEL** | 0.0016 |

*Table 2: InP content by display configuration. Source: Nanosys internal data*

Over the next ten years, the emergence of QDEL technology will be a major driver in reducing InP in displays. QDEL devices, which use InP for only red and green colors in an extremely thin layer just nanometers across, are expected to require only 0.0016 grams of InP per square meter. We therefore expect the amount of InP in the European market to peak at 184.7 kilograms in 2027 and begin to decline from that point forward.

## Section 2 – Non-Display Applications for InP Quantum Dots

### Lighting Applications for InP Quantum Dots

Nanosys does not ship products into the lighting market and therefore cannot comment on the future volumes of such a product. However, Nanosys forecasts the lighting market will consume very little InP in the EU over the next ten years due to the low InP content of lighting products that are likely to be commercialized.

So-called “on-chip” LED lighting products will not be commercialized in the next ten years. Technical limitations preclude InP QDs from use as an on-chip converter in high powered LED lighting applications (see Section 1 above).

However, QDEL devices are expected to offer significant power and brightness benefits to the lighting market when they begin commercialization in 2024. QDEL emitters, particularly blue, will out-perform organic light-emitting (OLED) materials in the next 5-10 years. Compared to OLED lighting products, QDEL devices offer an order of magnitude higher brightness and significantly lower power consumption due to low voltage requirements.

### Comparing InP to CdSe QD in Lighting Applications

For additional context on QD in the lighting market, it is useful to look at CdSe QD deployment in this market. While there had been previous, unsuccessful attempts to commercialize Quantum Dots in lighting,[12] the only CdSe-based Quantum Dot lighting product on the market in 2019 became available in the second half of 2019 in the form of a single, specialty lighting product. This specialty product, available today from Osram, contains an extremely small amounts of CdSe QD using the "on-chip" configuration.[13] This product is available for purchase and Nanosys internal analysis shows that it contains roughly 0.3μg of Cd per LED. It is worth noting in this context that this Cd content is well below 100ppm of Cd by weight in the coated layer.

Nanosys does not make or sell this product and therefore cannot comment on sales volumes. However, we believe it would be appropriately characterized as a niche or specialty product with extremely low market penetration worldwide. Nanosys believes Oko's assumption in the *RoHS InP Dossier* that, "Cadmium-based QDs in lighting applications, which was estimated with 5% in 2015 and causes CdSe consumption of 8kg," is incorrect.

As noted in the above section on displays, Nanosys estimates that QDEL devices for lighting applications will consume 0.0016 grams of InP per square meter of light emitting area. Even if QDEL is widely adopted in the lighting market in 2024 and beyond, InP content will remain quite low.

Oko's estimate of 256kg/year of InP use in the lighting market would theoretically support approximately 160 million square meters of light-emitting area. Nanosys believes this assumption is incorrect and InP usage in the lighting market will be near zero through 2028.

### Photovoltaic Applications of InP QD

Nanosys is not aware of any PV modules available commercially or in development using InP Quantum Dots. InP offers little-to-no efficiency advantage compared to materials such as silicon and cadmium-telluride (CdTe) that make up the bulk of the solar market today. InP is unlikely to be commercialized in the solar market over the next ten years.

## Section 3 – Risk of Emission and Hazard Profile

### Core-Shell Structure

Commercially available InP-Quantum Dots are composed of a "core-shell" structure wherein the InP core is surrounded by one or multiple shells, typically comprised of a lattice-matched semiconductor compound such as zinc selenide. As a result, InP is never directly exposed to end users from the manufacturing process through to a product's end-of-life.

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[12] "Nexxus Lighting and QD Vision Unveil World's First Commercial Quantum Dot / LED Lamp Line," https://www.businesswire.com/news/home/20090505006321/en/Nexxus-Lighting-QD-Vision-Unveil-World's-Commercial

[13] "Quantum Dots from Osram Make LEDs Even More Efficient," https://www.bloomberg.com/press-releases/2019-05-20/quantum-dots-from-osram-make-leds-even-more-efficient

InP itself is not an input to the InP/ZnS Quantum Dot manufacturing process, therefore the Quantum Dot manufacturing does not pose an added risk of exposure to humans in the supply chain. In the InP QD manufacturing process the InP cores are made and encapsulated in a shell in situ before it is ultimately incorporated into a film or device. Manufacturing InP/ZnS Quantum Dots does not, for example, involve transporting quantities of pre-made InP through communities where there may be some risk of spillage.

The completed InP/ZnS Quantum Dots, because of the core-shell structure, pose very low risk of toxicity to humans. In fact, studies have shown that such core-shell InP/ZnS Quantum Dots are well-suited for in vivo use in humans. A recent study by the Center for Bio-Molecular Nanotechnologies and McGill University found that core-shell InP/ZnS posed "very low" toxicity risk to humans and offered "good bio-compatibility".[14]

### Component Design

All anticipated component designs for QD displays involve full encapsulation of the QD layer, thereby eliminating any potential for direct contact by the consumer.

Nanosys landfill leach studies show that even at the end of their useful lifetime and after standard landfill leach testing, Quantum Dots are not likely to be leached into the environment from display components. This will be discussed in more detail in the following section.

## Section 4 – Waste Management

Displays screens containing InP QDs could be collected as consumer equipment for TVs or as IT and telecommunications equipment for monitors. The plastic components, including the QD film, would most likely either be shredded and incinerated, or taken to landfill. We review each of these scenarios here.

When InP-based QDs are burned or dissolved, the indium and phosphorus are separated and form different compounds, such as indium oxide and phosphates, which are not classified as carcinogenic. Therefore, the hazard is neutralized before exposure can occur.

Disposal of InP-based QDs into the landfill stream is unlikely to result in release of InP content into the environment. Nanosys has conducted an extensive study on the behavior of CdSe-based QDEF films in the landfill.[15] Given the similarities in particle size, film component construction and chemistry, we believe the results of this study are equally valid for InP-based QDEF.

For the landfill study we obtained production QDEF from the display supply chain and subjected it to blue light exposure (as in a typical display) for a time consistent with its lifetime use. The exposed film was then analyzed for any release of cadmium onto the surface of the film by a

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[14] Virgilio Brunetti et al, "InP/ZnS as a safer alternative to CdSe/ZnS core/shell quantum dots: in vitro and in vivo toxicity assessment," *Nanoscale*, 2013,5, 307-317

[15] P-15-59 Film Release Characteristics Study Report, prepared 2/11/16 and submitted to the EPA by Otis Institute Inc on Nov 4$^{th}$ 2016

third-party EPA certified laboratory.[16] No cadmium was detected in any form on the surface of the aged film indicating that the quantum dots remained encased within the matrix of the film. Again, due to the similarity of composition, there is no reason to expect a different result for InP QDs.

The exposed material was then subject to standard EPA based leachate systems (mimicking time in landfill) and the leachate was analyzed by third party EPA certified laboratories for the release of detectable cadmium (either in ionic or nanocrystal form). After being subjected to the leaching studies no detectable Cd was released into the leachate in either elemental or QD form indicating that under normal environmental exposure in a landfill there would not be detectable escape of QD's from the disposed of film. Therefore, we believe there is little risk of InP exposure in the landfill waste stream.

Recycling is another possible path for InP Quantum Dot technology. The European Union has stringent regulations and high targets in terms of recycling of Electrical and Electronic Equipment Waste. It appears likely that the EU will achieve its target to recycle 85% of all electrical and electronic waste, thereby further reducing any chance of InP entering the environment.[17,18]

Indium is a valuable metal. The EU added indium to the 2017 list of Critical Raw Materials for the EU due to possible risks of supply shortage (scarcity) and its relatively high impact on the economy.[19] Therefore, we believe InP QDs make an excellent candidate for recycling. There may be sufficient incentive to set-up a recycling program to recycle indium content from Quantum Dot displays.

## Section 5 – Substitution

There are few possible substitutes for InP emitters available today for use in the display market. There are no other materials that can be used as alternative emitter materials for displays with improved performance required by the market and which do not face toxicity concerns of their own.

### Display Performance Requirements

The market has defined a core set of performance requirements for next generation displays. These include broadcast standards for color, resolution and peak luminance as well as refresh rate and power efficiency. InP QDs available in the market today are able to deliver all of these requirements. We discuss each briefly here.

[16] Curtis & Tompkins Laboratories, 2323 5th Street, Berkeley, CA

[17] European Parliament and of the Council, Waste Electrical and Electronic Equipment Directive

[18] Eurostat, Waste electrical and electronic equipment (WEEE) by waste management operations (2016)

[19] EU COM (2017), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU, Brussels, 13.9.2017, COM(2017) 490 final, available under: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2017:0490:FIN

- **Color Gamut**: In May of 2015, the International Telecommunications Union adopted the ITU-R BT.2020 standard for color gamut, enabling broadcast of content that contains a 70% wider range of colors than the HD standard (BT.709).[20]
- **Peak Luminance**: The latest High Dynamic Range content requires displays that are able to deliver high peak luminance. The latest content standards enable content producers to create content that can produce peaks as high as 10,000 nits.[21] Quality-standards setting organizations such as the UltraHD Alliance (UHDA) call for minimum peak luminance of at least 1,000 nits.[22]
- **Refresh Rate**: Display quality standards such as the VESA HDR specification for high performance monitors recommends high refresh rates.[23] High refresh rates can be 200 Hz and above in the most demanding applications, thus requiring a light emitter that is able to switch on and off with incredible sub-millisecond speed.
- **Efficiency**: It is a general market expectation that next generation displays should not consumer additional power compared to today's market leading LED-based LCDs.
- **Reliability**: State-of-the art displays should meet minimum industry-accepted lifetimes of 30,000 – 50,000 hours without degradation of image quality or burn-in defects.

### Alternative Quantum Dot Compositions

CdSe is currently used in the market and is able to deliver on all performance requirements for next generation displays with >90% coverage of the BT.2020 color gamut, peak luminance of over 2,000 nits, refresh rates of 200 Hz and power consumption equivalent to a standard LCD. CdSe Quantum Dots continue to offer superior performance compared to InP Quantum dots. However, in light of the ongoing EU regulatory review of cadmium usage in electronics, a number of display companies have favored use of InP as a cadmium-free alternative to CdSe.

Other quantum dot materials have not yet been demonstrated commercially. One of the more promising such technologies actively being researched is Lead Perovskites. Lead Perovskites offer excellent color performance but are not yet stable enough to meet commercial reliability standards.[24] Additionally, Lead Perovskites contain significant amounts of Lead. As a result, they are unlikely to be commercialized as an "environmentally friendly" alternative to either CdSe or InP QDs.

[20] BT.2020 : Parameter values for ultra-high definition television systems for production and international programme exchange, https://www.itu.int/rec/R-REC-BT.2020-2-201510-I/en, accessed 2019/11/5

[21] ST 2084:2014 - SMPTE Standard - High Dynamic Range Electro-Optical Transfer Function of Mastering Reference Displays, https://ieeexplore.ieee.org/servlet/opac?punumber=7291450, accessed 11/5/2019

[22] What is UHD Alliance Premium Certified?, https://www.cnet.com/news/what-is-uhd-alliance-premium-certified/, Accessed 11/5/19

[23] VESA High-performance Monitor and Display Compliance Test Specification (DisplayHDR CTS) Version 1.0, 27 November, 2017, www.vesa.org.

[24] Chen, H. et al, (2019), 37.3: Update on Photoluminescent Perovskites and Electroluminescent Quantum Dots. *SID Symposium Digest of Technical Papers*, 50: 406-406. doi:10.1002/sdtp.13511

## Phosphors

Another alternative to consider is phosphor materials such as Potassium Fluorosilicate (KSF) phosphor. 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 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.

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. [25] 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."[26] 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.

## OLEDs

Organic Light Emitting Displays (OLEDs) are a new entrant to the display market and often considered a competitor to Quantum Dot displays. However, it should be noted that while OLEDs offer some unique benefits such as thin form factors, low black levels and excellent refresh rates, they are unable to meet all of the market demands for display performance.

Current OLED TVs rely on color filters to produce red, green and blue from a two color (blue and yellow) backlight. The result is a system with poor color performance (~75-80% BT.2020) and low-efficiency that requires more power for lower brightness compared to standard LED LCD or Quantum Dot LCD.

Another unique dynamic facing the OLED industry is lack of manufacturing capacity. According to IHS Markit, OLED TV sales accounted for just 1% of the worldwide TV market in 2018. New OLED factories are expensive to build. At an estimated cost of over $3B for a new OLED fab, it is unlikely that OLED will be able to deliver significant market share on an area basis over the next 10 years.[27]

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

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

[27] LGD to start ordering equipment for its Guangzhou OLED TV fab next month, https://www.oled-info.com/lgd-start-ordering-equipment-its-guangzhou-oled-tv-fab-next-month, Accessed 11/5/19

# Section 6 – Socio-Economic Impacts

Quantum Dot displays are expected to become more affordable and widely available to consumers. Analysts project growth in adoption of both InP and CdSe Quantum Dots worldwide over the next ten years. InP materials offer manufacturers an important alternative to materials based on lead, cadmium and potassium fluorosilicate.

In the absence of InP-based QDs, there is significant risk that there will be a gap in the market until new materials can be developed. It should be noted that there is still no promising alternative material in sight as of today. During this time display technology would not deliver the performance demanded by the market. This delayed benefit would be passed on to EU consumers in the form of displays that do not meet global quality standards.

Additionally, replacing InP could have unintended negative impacts on the environment. If InP is replaced with one of the currently available alternatives such as OLED, this could lead to increased energy consumption and therefore pollution. Alternatively, if InP could be replaced by cadmium, lead or potassium fluorosilicate-based solutions that would seem to be in direct conflict with the principles of the RoHS regulations.