RoHS stakeholder Consultation 2019 on Indium Phosphide

Please provide estimations as to when InP QD "on-chip" configurations can be expected to be market ripe.

Please estimate the development of volumes of use of InP in display applications over the next 10 years. In this respect, please explain how this relates to the distribution of displays to different configurations ("on layer", "on edge" and "on-chip") and to different display types (television, monitor, tablet, smartphone, etc.).

If additional data shall not be received, it shall be assumed that:

- The current growth rate of InP QD technology with a doubling of sold units every three years will continue over the next 10 years;
  - We find this to be a fair estimate of the market, given the information at our disposal (compound annual growth rate (CAGR) ~26 %[1]).
- As a further assumption, the specific amount of InP required will not decrease;
  - We do not have any data to dispute this. Current QD research is focussed on increasing the absorbance per overall mass of the QDs, which can be achieved by reducing the relative size of the shell layer on the semiconductor core surface. For a QD having an InP core, this would leave the mass of InP used unchanged.
- Resulting in approx. 600 kg of InP used in display applications per year in Europe in 2028.
  - We find this a fair estimate for InP QD use "on-layer", given the information at our disposal.

We find the consultants' estimate for the amount of InP QDs used in "on layer" applications to be fair, given the current data available to Nanoco. In addition, we would like to emphasise that we consider "on-edge" technology to now be redundant in the display industry, and we believe that "on-chip" technology is unlikely to be adopted for displays in the near future. The main driver for both on-edge and on-chip technologies was a reduction in QD material usage, to alleviate the high QD cost, for integration into the display market. However, the cost of QD production has fallen rapidly in the past few years, outstripping the cost benefit of investment for manufacturers to develop the technology to implement QDs in these lower mass usage, higher performance requirement configurations.

We would also like to draw attention to new QD-containing display configurations that will be entering the market shortly. These configurations are classed as QD-OLED and QD-µLED, and have a similar configuration to "on-chip" applications with two key differences: light density requirements will be far lower, and a far higher volume of QDs will be used for colour conversion per display. Devices of this type will consist of a blue OLED or µLED array with pixelated red and green QD colour conversion layers deposited on top to generate an RGB display (see **Figure 1**).

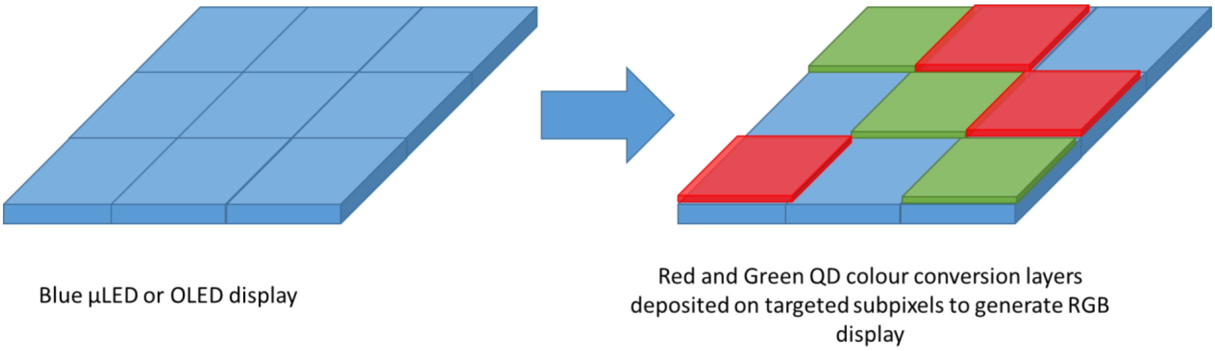

Figure 1: Diagram illustrating the structure of QD-OLED- or QD-µLED-type devices currently under development.

Projected numbers for sales volumes and mass of QDs used in these devices are difficult to estimate, due to the technology just completing the development stage, but we have generated a figure based on the information available from market reports (see **Table 1**). In **Table 1**, the projected display m^2 values are taken from the Yole Développement report on *Quantum Dots and Wide Color Gamut Display Technologies* from 2017,[1] using figures originally projected for QD colour filter devices, as this technology is made redundant by QD-OLED and QD-µLED configurations. A CAGR of 26 % was applied to the figures to double sales every three years, as with the on-layer-based projected figures, providing an estimated 58 Mm^2 display screen area to be sold worldwide in 2028. For the mass of QDs for each display, we have used figures from industry sources which have quoted 2.8 g of QD material per m^2 of display. Finally, the percentage mass of InP in InP-based QDs is estimated using figures from a recent Samsung patent application published in September 2019[2] where stoichiometries for several configurations of red and green InP QDs developed by Samsung are quoted. We have taken an average of the InP mass % for all the QD configurations quoted and have assumed 25 % of the total QD mass will be contributed by organic ligand material, resulting in InP mass % values of 9.4 % and 3.1 % for red and green InP QDs, respectively. A further assumption is that the mass of QDs used on each display will be split evenly between red and green QD types. Using these figures, we reach an estimate of 10 tonnes of InP used worldwide for this application. Since the European share of the global TV market is ~ 20 %,[3] this would equate to around 2 tonnes of InP used within Europe.

Table 1: Projected figures for QD-OLED/QD-µLED screens sold with corresponding QD masses used up to 2028. Sales figures for displays up to 2022 are from Yole Développement with subsequent years calculated with a CAGR of 26 % to double sales every 3 years.

	2019	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**
Displays sold (Mm^2)	1	6	10	14	18	23	29	36	46	58
Mass dots used (kg)	4183	15489	27466	40303	50782	63985	80621	101583	127994	161273
InP worldwide (kg)	261	968	1717	2519	3174	3999	5039	6349	8000	10080
InP Europe (kg)	52	194	343	504	635	800	1008	1270	1600	2016

However, it should be noted that the figure of 2 tonnes is a top estimate, assuming that all QD-OLED and QD-µLED displays on the EU market between 2019 – 2028 utilise InP-based QDs. If other types of QDs, as discussed in our previous consultation response and below, are integrated into QD-OLED and QD-µLED displays, we would expect this figure to decrease. Recent examples in the market have shown companies manufacturing prototype displays with green halide perovskite quantum dots in this format.[4] Further, we are not aware of any such displays currently on the market and we believe it could be 1 – 2 years before any such products reach the consumer market. Thus, the projected figures in **Table 1** could be 1 – 2 years ahead of the actual situation, *i.e.* a figure of 1.3 tonnes in 2028 may be a more realistic top estimate, again assuming that all QD-OLED and QD-µLED displays on the EU market utilise InP-based QDs, with a lower figure being more likely if other types of QDs are also integrated into such displays.

It should also be noted that as the QD-OLED and QD-µLED markets grow, the CAGR for on-layer QD displays may decrease.

Please estimate the development of volumes of use of InP in lighting applications over the next 10 years. In this respect, please explain how this relates to the development of the distribution of lighting equipment to different configurations ("on layer", "on edge" and "on-chip").

We do not have access to any market data relating to QDs in lighting. On-edge technology is redundant for displays, and is not applicable to lighting. Currently, remote film-based integration strategies dominate for QD-based lighting, however, as on-chip solutions become viable, we expect this configuration to dominate, due to the economic advantages provided by the lower material usage.

As discussed below, we are not aware of any InP QD-based lighting products currently on the EU market.

Please provide data on the specific amount of InP needed for lighting compared to CdSe.

Experimental work with Nanoco partners has seen a mass loading requirement of 5 times more Cd-free quantum dot material than for CdSe-based quantum dots for film (on-layer) applications. It should be taken into consideration, however, that the mass ratio of Cd in a CdSe-based quantum dot will be significantly higher than the InP mass loading ratio in Cd-free quantum dot materials. Thus, despite the significantly higher mass loading values required, the amount of InP used compared to Cd could be significantly less if a swap of materials occurred.

If additional data shall not be provided, it shall be assumed that:

- The market share of Cd-based lighting applications, which was estimated with 5 % in 2015 and causes a CdSe consumption of 8 kg, will be taken as a starting point;
- As a further assumption, the specific amount of InP is double the amount of CdSe;
- By 2028, the market share for Cd-based QDs in all lighting applications is expected to reach 80 %, resulting in ~ 256 kg of InP used in lighting applications per year in Europe.

We believe that the amount of InP that would be used in lighting applications has been vastly overestimated. Currently, QDs are predominantly used in niche, high colour-rendering index (CRI) lighting applications, and we expect this to be the case for the foreseeable future. For example, a horticultural lighting apparatus comprising Nanoco's CFQD® quantum dots, based on an alloy comprising indium and other elements, in a remote film (*i.e.* on-layer), is available in the EU. Other niche lighting products have been launched on the consumer market in the US, such as Christmas tree lights[5] launched in 2009 by Holiday Creations/Diogen Lighting and Evident Technologies, and stage/film lighting[6] from Mole-Richardson in 2013.

In terms of general lighting, QD Vision's Quantum Light Optic product, which incorporated cadmium-based QDs in a remote lens, was, we understand, withdrawn from the US market in 2011 due to lifetime issues. Recently, Osram has launched the OSCONIQ® S 3030 QD mid-power LED, which we understand contains cadmium-based QDs. We believe that on-chip integration will be the only technology for general lighting, as on-edge technology appears to be redundant and remote film (on-layer) technology has unacceptable off-state appearance for consumers.

Once on-chip QD technology is commercially viable, we believe that this will dominate the QD lighting market due to the economic benefits of the reduced material consumption compared to remote film (on-layer) QD technologies. However, with the lower material usage of on-chip technology, we believe that even with an increased market share, the overall amount of QDs used in lighting applications would decrease.

Nanoco is not aware of any lighting products comprising InP QDs that are currently available on the EU market. Overall, we believe that the amount of InP used in lighting applications in 2028 will be considerably lower than that estimated by the consultants.

Stakeholders are requested to provide contributions on possible emissions, their quantities as well as their hazard profile.

Nanoco does not have any data to contribute beyond that which it provided in relation to the 2018 consultation response.

For display screens, for the plastic components, including the QD film, Nanoco expects them to most likely either be shredded or incinerated, or to be disposed of in landfill. According to ToxNet, of the US library of medicine, the US EPA stipulates solid waste containing InP may become characterised as hazardous waste when subjected to testing for reactivity, and if so characterised, must be managed as hazardous waste. For lighting equipment containing InP QDs, information on the relevant waste treatment process was not provided by the stakeholders. The consultant therefore assumes that roughly the same waste treatment approach as for screens is applicable. Stakeholders are requested to comment on this assumption and to provide information if necessary.

For film-based (on-layer) lighting products incorporating InP QDs, we expect a similar waste treatment approach as for display screens. When on-chip lighting products become available, we anticipate that InP-based QD chips may be incinerated or disposed of in landfill, but are unlikely to be shredded due to their small dimensions.

Concerning lighting, no explicit information concerning possible substitutes was provided by the stakeholders. However, in the view of the consultant, it appears to be reasonable to assume that the same substitutes as for display could also apply for lighting. In order to validate this assumption, stakeholders are requested to provide input on this issue.

Some of the substitutes proposed for display are also applicable to lighting, while others are poorly suited to lighting, as tabulated below.

Further information as to additional substitutes to InP, their potential hazardousness and their applicability as substitutes in the wide array of InP-based applications is sought.

SUBSTITUTE	APPLICABILITY TO LIGHTING	TOXICITY
OLEDs	We envisage that OLEDs would only be used in niche lighting applications, as it is difficult to achieve the brightness necessary for general lighting, as well as cost implications.	We are not aware of any toxicity concerns relating to OLEDs.
Cd-based QDs	Cd-based QDs could potentially be used as a substitute for InP QDs in any lighting application in which InP QDs are suitable.	High toxicity. Already restricted under RoHS. Peer-reviewed toxicity studies have concluded that InP-based QDs are a "safer alternative" to CdSe-based QDs.[7]
$CuInS_2$-based QDs	$CuInS_2$ nanoparticles typically have a broad emission full-width at half-maximum (FWHM; typically 80 – 120 nm), which may be particularly suitable for general lighting applications.	We are not aware of any toxicity concerns relating to $CuInS_2$-based QDs.
CFQD® quantum dots	Nanoco's CFQD® quantum dot material is an alloy of indium and other elements. CFQD® quantum dots could be used as a substitute for InP QDs in any lighting application in which InP QDs are suitable. As with InP QDs, the thermal stability of CFQD® quantum dots is not yet sufficiently high for commercial on-chip lighting solutions. The use of this material in lighting by other manufacturers would be possible based on a licence that would be granted by Nanoco by commercial agreement.	*In vitro* toxicity studies on CFQD® quantum dots*, published in a peer-reviewed journal, have reported no reduction in cell viability after incubation for 48 hours and negligible haemolysis, up to the highest tested concentration of 200 nM.[8] The CFQD® quantum dots were found to be at least 20 times less toxic than commercially available Cd-based QDs. Genotoxicity studies show the CFQD® quantum dots to be non-mutagenic. Overall, the data suggest that CFQD® quantum dots have low toxicity.
Halide perovskite QDs	Halide perovskite QDs offer high quantum yields (QYs), but their FWHM values are very narrow (as low as 12 nm). We only envision that they would be used as the red component in lighting applications. Yet, a number of issues need to be addressed before halide perovskite QDs can be incorporated into EEE. These include their poor stability (*e.g.* to light, oxygen, moisture and heat), their toxicity, and, if they were to be used as both the red and green component, their undergoing rapid ion exchange when combined. It is our understanding that while green halide perovskite QDs may be	Halide perovskite QDs take the form ABX_3, (A = CH_3NH_3, CH_5N_2, Cs; B = Pb, Sn; X = I, Br, Cl). However, thus far, research into lead-based halide perovskite QDs is showing significantly more promise than for tin-based materials.

* Note, for toxicity studies, red-emitting CFQD® quantum dots were surface-functionalised to provide water solubility.

	commercialised this year,[4,9] red halide perovskite QDs may be around 5 years away from commercial viability.	
Narrowband phosphors	At the 2019 Phosphor Global Summit,[10] Osram proposed its newly developed "Brilliant Blue", "Brilliant Cyan", "Brilliant Green" and "Brilliant Red" narrowband phosphors for general lighting.	We are not aware of any toxicity concerns relating to narrowband phosphors.

In order to understand the socioeconomic impacts of a potential restriction of InP in the various fields of applications as described in section 2, stakeholders are requested to provide information on the costs and benefits that can be associated with such a restriction of this substance in EEE under RoHS. Please make available quantitative data wherever possible. However, qualitative information is also considered to be helpful for the assessment of socioeconomic impacts.

The following table gives a requested structure for contributions. Concerning the impacts, information should be distinguished and specified according to the following scheme as far as possible:

- Impact on chemical industry;
- Impact on EEE producers;
- Impact on EEE users;
- Impact on waste management;
- Impact on administration.

FIELD OF APPLICATION	COSTS	BENEFITS
Displays and Lighting	The chemical industry would need to develop alternative QD materials using non-RoHS regulated materials. Given that the most mature QD technology is based on Cd-containing QDs, followed by InP, and lead halide perovskite QDs are under research, the choice of alternative material systems is limited.	
	EEE producers would either need to develop EEE incorporating non-RoHS regulated QDs, or develop alternative (non-QD) technologies with different integration strategies. In particular, the latter would involve significant investment in terms of time and cost.	
	If the use of InP in displays and lighting becomes restricted under RoHS, we envisage more exemption requests to allow the use of Cd- or Pb-based alternative QDs in EEE. Should Cd- or Pb-based	

	QDs be allowed,[†] consumers could potentially be exposed to toxic Cd or Pb, *e.g.* in the event of damage to the QD-containing appliance or in a house fire. Further, due to the research efforts involved in finding alternative materials, these alternatives may offer lower performance and/or come at a higher cost to the consumer.	
	In terms of waste management, if Cd- or Pb-based alternatives are allowed, these may have additional disposal considerations compared to InP, in order to ensure that toxic Cd and Pb do not leach into the environment.	Lighting or display apparatus containing $CuInS_2$ or CFQD® quantum dots are likely to be recycled in the same way as those currently used for InP QD displays.
	As discussed previously, two of the potential alternatives to InP QDs for displays and lighting include Cd- and Pb-based QDs. Thus, we would expect further RoHS exemption requests to facilitate the use of either InP QDs, or suitable alternatives in lighting and displays, particularly for Cd (as this is restricted to 100 ppm per homogeneous material compared to 1,000 ppm for Pb), leading to higher administrative costs.	

[1] *Quantum Dots and Wide Color Gamut Display Technologies*, Yole Développement, 2017
[2] T.H. Kim, E.J. Jang, D.Y. Chung, Y.W. Kim, Y. Won and O. Cho. US patent application publication no. 2019/0280231, published 12th September 2019
[3] Sigmaintell. *Global Large Size Display and TV Market Outlook*, Presented at SID Business Conference 2018, May 2018
[4] https://www.perovskite-info.com/csot-demonstrates-66-384x300-oled-display-uses-perovskite-quantum-dots-color
[5] https://www.nanowerk.com/news/newsid=7630.php
[6] https://molerichardsoncompany.wordpress.com/2015/04/07/mole-richardson-at-nab-show-2015-in-las-vegas/
[7] V. Brunetti, H. Chibli, R. Fiammengo, A. Galcone, M.A. Malvindi, G. Vecchio, R. Cingolani, J.N. Nadeau and P.P. Pompa, *Nanoscale*, 2013, **5**, 307
[8] E. Yaghini, H.D. Turner, A.M. Le Marins, K. Suhling, I. Naasani and A.J. MacRobert, *Biomaterials*, 2016, **104**, 182
[9] https://nanolumi.com/
[10] D. Bichler, F. Jermann, S. Lange, D. Baumann, S. Peschke, P. Schmid and M. Seibald. *Are There Limits for Narrow Band Phosphors?* Presented at Phosphor Global Summit 2019 – Quantum Dots Forum, La Jolla, 20th March 2019

[†] Note, due to the higher concentration of Pb allowed under RoHS compared to Cd, it may be possible to develop RoHS compliant products implementing Pb-based QDs.