# **Electronic Supplemental Information**

Comparative Cradle-to-Gate Energy Assessment of Indium Phosphide- and Cadmium Selenide-Quantum Dot Displays Shauhrat S. Chopra\* and Thomas L. Theis

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#### 1. Introduction to Quantum Dots

Quantum dots (QDs) are semiconductor nanocrystals with diameters in the range of 2-10 nanometers. These engineered nanocrystals demonstrate properties that are not observed for semiconductor compounds in their bulk form. The most useful of these unique electronic properties is fluorescence through which quantum dots produce distinctive colors determined by the size of the particles.

Quantum dots can be classified on the basis of their composition and structure in three ways.

- Core-type QDs: Made of single component materials with uniform internal compositions. One can fine-tune the electro- and photoluminescence properties of these particles by varying their size. Nanocrystals composed of *CdSe*, *CdTe*, or *CdS* are examples of coretype QDs.
- 2) Core-shell QDs: A shell is added to the core nanocrystal, which is mostly a coating of a different semiconducting material. The augmentation of the core further improves photoluminescence quantum yield, an indicator of emission efficiency. For example, CdSe/ZnS QDs have CdSe in the core and ZnS in the shell.
- 3) Alloyed Quantum Dots: Most recently, multicomponent QDs have been developed with both homogeneous and gradient internal structures to provide tunability without changing crystallite size. An example of an alloyed QD is  $CdS_xSe_{1-x}/ZnS$ , which can emit light of different wavelengths just by changing the composition.

Unique size and composition tunable photophysical properties of these semiconducting nanoparticles make them attractive for a variety of applications and new technologies. Optical applications of QDs for LEDs and solid-state lighting, photovoltaics, and displays are by far the most promising. The properties of QDs that allow them to emit bright, pure colors, as well as produce a large variety of colors efficiently that last longer makes them ideal material to be utilized for creating the next-generation display technologies.

## 2. Status of QD-enabled Display Technologies

Increased application of QD technology is expected in displays for consumer devices. Key factors behind this likely growth is ability of QD displays to produce a much wider color gamut with little re-engineering of existing LCD panels. Conventional LCDs tend to produce robust blues, but much weaker red and green peaks. However, QD-enhanced LCDs produce strong emission peaks in all three primaries: red, blue, and green by integrating QDs with the backlight and tweaking the color filters in the LCD stack.

## 3. Cadmium Vs. Cadmium-free QDs

QD displays provide an elegant approach to dramatically improve the performance of LCD units. However, like most emerging technologies, there are uncertainties about QDs that may

challenge the widespread adoption of this technology. Majority of studies investigating QDs have focused on nanoparticles with cadmium <sup>1</sup>. Since cadmium is a toxic, heavy metal whose utilization in consumer products is banned in the European Union as per ROHS guidelines. For this reason, QDs composed of alternative materials (especially non-heavy metals) with relatively lower toxicity have been much aspired.

Indium-based QDs are the most promising cadmium-free options that can be used in display technologies. There are already instances of display devices and lighting equipment (like Samsung SUHD QD TVs) that incorporate Indium Phosphide core-shell QDs to produce RoHS compliant consumer products. While Indium-based QD displays have lower risks from a material hazards point of view, it still does not have comparable photoluminescence quantum yield to Cadmium-based QDs. For this reason, more comprehensive, systematic environmental analysis of different QD types used in displays is needed for the development of safer and sustainable QD displays that do not compromise on the overall color performance. While the legislation restricting the use of heavy metals are getting stricter, it is critical to compare cadmium and cadmium-free (InP) QDs throughout their life cycles before making policies that would affect the course of the industry. A life cycle assessment study will provide regulators with the necessary information to make tough decisions, and avoid any unintended environmental consequences and risks of their directives.

In this paper, we are specifically concerned with the cradle-to-gate LCA of *CdSe/ZnS/CdZnS* and *InP/ZnSSe/ZnS* core/shell/shell QD-enabled displays. This information will enable a comparative assessment of the environmental performance of alternate QD material production and the devices in which these nanomaterials may be subsequently used. For performing a robust LCA, one of the most crucial steps is life cycle inventory compilation.

Data for emerging technologies, especially synthesis of novel nanoparticles, is hard to come by. For this reason, we use patent literature from two companies involved in QD manufacturing- QD Vision Inc. and Nanosys Inc<sup>2-8</sup>. While majority of the latest patents by QD Vision detail the synthesis of CdSe multishell QDs, Nanosys has been producing patents on the synthesis of one of the cd-free alternate, InP multishell QDs. Following inventory data has been compiled from a collection of patents filed by both these companies.

# a. Description of Colloidal Synthesis of Red and Green-emtting CdSe-multishell QDs<sup>2, 6</sup>

The synthesis of CdSe QD begins with the creation of a core seed by combining quantum dot precursors in a solvent at a particular reaction temperature, and then quenching the reaction mixture to stop nucleation. The cadmium precursor is made by adding cadmium acetate in trioctylphosphine (TOP) at 100°C, to a reactor with trioctylphosphine oxide and octadecylphosphonic acid mixture, which is heated to 310°C,at which point the selenium

precursor, diisobutylphosphine selenide (DIBP-Se) dissolved in 1-Dodecyl-2-pyrrolidinone (NDP), is injected into the reactor. Submerging the reactor in a frozen squalene bath forms CdSe seed core.

In the second step, the CdSe QD cores obtained in the first step are grown to produce cores of desired size. The temperature of the seed core solution is increased to 240°C (after squalene bath), when cadmium oleate in TOP and DIBP-Se in TOP is added.

The third step involves overcoating of CdSe cores with ZnS. For this, 1-octadecene and zinc oleate in TOP are mixed with the CdSe cores from the 'growth' step, and the temperature is increased to 300°C. Subsequently, octanethiol is injected into the mixture. The fourth step involves addition of CdZnS shell to the core at the same temperature by injecting a mixture of zinc oleate in TOP, cadmium oleate in TOP and octanethiol. Finally, CdSe core/shell/shell QD material is obtained as a precipitate and dispersed in toluene for storage.

The resulting multishell CdSe QDs have a Fixed-width-half-maximum (FWHM), an indicator of color accuracy, of 28 nm for red and 35 nm for green-emitting nanocrystals. The quantum yield, an indicator of emission efficiency, is greater than 90% for both red and green-emitting QDs.

b. Description of Colloidal Synthesis of Red and Green-emtting InP-multishell QDs <sup>4, 5, 7</sup>

Like the CdSe QD core synthesis described above, the InP QD core synthesis is also a two step process, synthesis of core seed and further core enrichment to the desired size. InP QD core seed are prepared by combining indium precursor, mixture of indium acetate, TOPO and lauric acid, with a phosphine precursor, tris(trimethylsilyl) phosphine ((TMS)<sub>3</sub>P) in TOP, at 260°C for about 1 min. The reaction is cooled to room temperature and InP core seed are precipitated.

The second step involves core enrichment by adding 1-octadecene and indium laurate precursor to the InP core seed obtained from the first step. The reaction temperature is held at 230°C for two hours. The temperature is decreased to 140°C and hexanoic acid is added to complete the InP core synthesis process.

Once the InP cores of the desired size are produced, suitable precursors are reacted in the presence of a ligand to initiate the shell formation steps. The first 0.5 monolayer thick ZnSSe shell is formed by addition of diethyl zinc, bis(trimethylsilyl) selenide, and hexamethyldisilthiane in ODE. The reaction is set at 140°C for 30 mins. The second 2 monolayer thick ZnS shell is created by reacting diethyl zinc and hexamethyldisilthiane in ODE. After shelling reactions, the reaction temperature is cooled to room temperature and ligand, dodecenyl succinic acid (DDSA), is added to the dot solution. Finally, InP core/shell/shell are obtained and dissolved in hexane for storage.

The resulting multishell InP QDs have a FWHM of 45 nm for red and 40 nm for green-emitting nanocrystal. The quantum yield for red-emitting QD is about 65% and 70% for the green-emitting InP QD.

#### 4. Life cycle inventory for QD synthesis

LCI data for all the materials required for QD synthesis are not available from the Ecoinvent database. To compile LCIs for some such raw materials, we used reaction chemistry and stoichiometry to model their synthesis process in SimaPro using LCI data for other materials. Details of material efficiency, reaction yields and other data on synthesis process like reaction temperatures were obtained from the cited literature. For other proprietary raw materials whose synthesis process was unknown, we used estimates of environmental impacts (specifically Cumulative Energy Demand) from tools based on their molecular structure <sup>9, 10</sup>. While a thorough process analysis provides significantly better results, it is acceptable to use this approach only if input information is missing.

Since the region influences the impacts, unit processes representative of Europe (RER) were given preference wherever possible. The unit processes considered include other regions like: Rest-of-the-World (ROW), global dataset (GLO) and Switzerland (CH).

a. Inventory data for manufacturing red and green-emitting CdSe/ZnS/CdZnS quantum dots

Tables below list the inventory data for QD synthesis used in our analysis.

Material	Quantity (g)	Corresponding LCI unit	
		process	
Core Seed			
ТОР	248.13	Literature <sup>11</sup>	
Cadmium Acetate	10.58	Created (details below)	
ТОРО	314.99	Literature <sup>11</sup>	
1-octadecylphosphonic acid	35.07	Finechem <sup>9, 10</sup>	
DiisobutylPhosphine selenide,	31.50	Finechem <sup>9, 10</sup>	
DIBP-Se			
N-dodecylpyrrolidone (NDP)	93.45	N-methyl-2-pyrrolidone	
		{RER}  production   Alloc	
		Def, U	
Core Enrichment			
1-octadecene	252.48	Finechem <sup>9, 10</sup>	

TABLE A. Inventory of materials for synthesizing 26.9 grams of Red-emitting CdSe multishell QDs

Cadmium oleate	28.7	Created (details below)
ТОР	141.27	Literature <sup>11</sup>
DiisobutylPhosphine selenide,	9.56	Finechem <sup>9, 10</sup>
DIBP-Se		
First and Second Shell		
1-octadecene	108.09	Finechem <sup>9, 10</sup>
Zinc oleate	49.63	Created (details below)
ТОР	201.93	Literature <sup>11</sup>
Cadmium oleate	57.4	Created (details below)
Octanethiol	74.18	Finechem <sup>9, 10</sup>

TABLE B. Inventory	of materials	for	synthesizing	19.8	grams	of	Green-emitting	CdSe
multishell QDs								

Material	Quantity (g)	Corresponding LCI unit process
Core Seed		
ТОР	202.76	Literature <sup>11</sup>
Cadmium Oleate	164.77	Created (details below)
ТОРО	192.00	Literature <sup>11</sup>
1-octadecene	1055.68	Finechem <sup>9, 10</sup>
1-octadecylphosphonic acid	82.00	Finechem <sup>9, 10</sup>
DiisobutylPhosphine selenide,		Finechem <sup>9, 10</sup>
DIBP-Se	42.78	
		N-methyl-2-pyrrolidone {RER}
N-dodecylpyrrolidone (NDP)	169.10	production   Alloc Def, U
Core Enrichment		
ТОР	159.55	Literature <sup>11</sup>
Cadmium oleate	64.83	Created (details below)
1-octadecene	332.95	Finechem <sup>9, 10</sup>
DiisobutylPhosphine selenide,		Finechem <sup>9, 10</sup>
DIBP-Se	0.15	
		N-methyl-2-pyrrolidone {RER}
N-dodecylpyrrolidone (NDP)	136.17	production   Alloc Def, U
First and Second Shell		
Zinc Oleate	312.38	Created (details below)
ТОР	945.17	Literature <sup>11</sup>
Octanethiol	121.39	Finechem <sup>9, 10</sup>
Cadmium oleate	57.4	Created (details below)

b. Inventory data for manufacturing red and green-emitting InP/ZnSSe/ZnS quantum dots

Material	Quantity (g)	Corresponding LCI unit process
Core Seed		
ТОРО	0.86	Literature <sup>11</sup>
ТОР	0.51	Literature <sup>11</sup>
Lauric acid	0.54	Created (details below)
Toluene		Toluene, liquid {RER}  production
	1.19	Alloc Def, U
Ethanol		Ethanol, without water, in 99.7%
		solution state, from ethylene {RER}
	2.71	ethylene hydration   Alloc Def, U
Indium acetate	0.25	Created (details below)
Tris(trimethylsilyl) phosphine	0.04	Created (details below)
Core Enrichment		
1-octadecene	0.005	Finechem <sup>9, 10</sup>
Indium laurate	5.00	Created (details below)
hexanoic acid	0.70	Finechem <sup>9, 10</sup>
First and Second Shell		
1-octadecene	0.002	Finechem <sup>9, 10</sup>
Diethyl zinc	0.083	Created (details below)
Bis(trimethylsilyl)selenide	0.008	Created (details below)
Hexamethyldisilthiane	0.073	Created (details below)
Ligand		
Dodecenyl succinic acid (DDSA)	0.45	Created (details below)
Ethanol	42.60	Ethanol, without water, in 99.7%
		solution state, from ethylene {RER}
		ethylene hydration   Alloc Def, U

TABLE C. Inventory of materials for synthesizing 25 mg of Red-emitting InP multishell QDs

TABLE D. Inventory of materials for	synthesizing 25 mg o	of Green-emitting InP	multishell
QDs			

Material	Quantity (g)	Corresponding LCI unit process
Core Seed		
ТОРО	0.21	Literature <sup>11</sup>
ТОР	0.12	Literature <sup>11</sup>
Lauric acid	0.20	Created (details below)

Toluene		Toluene, liquid {RER}  production
	0.29	Alloc Def, U
Ethanol		Ethanol, without water, in 99.7%
		solution state, from ethylene {RER}
	0.85	ethylene hydration   Alloc Def, U
Indium acetate	0.10	Created (details below)
Tris(trimethylsilyl) phosphine	0.04	Created (details below)
Core Enrichment	·	-
1-octadecene	0.005	Finechem <sup>9, 10</sup>
Indium laurate	0.5	Created (details below)
hexanoic acid	0.7	Finechem <sup>9, 10</sup>
First and Second Shell	·	
1-octadecene	0.0023	Finechem <sup>9, 10</sup>
Diethyl zinc	0.131	Created (details below)
Bis(trimethylsilyl)selenide	0.013	Created (details below)
Hexamethyldisilthiane	0.12	Created (details below)
Ligand		
Dodecenyl succinic acid (DDSA)	0.45	Created (details below)
Ethanol	42.60	Ethanol, without water, in 99.7%
		solution state, from ethylene {RER}
		ethylene hydration   Alloc Def, U

Note: Training data for Finechem covers a wide range of organic chemicals. Tool best used to estimate life cycle inventory of organic compounds.

TABLE E. Life cycle inventory of materials required for synthesis of Green and Red CdSe multishell QDs

Material	Quantity (g)	Input material in grams	Comment
Cadmium Acetate	10.58 g	<b>5.13 g;</b> Cadmium, semiconductor- grade {RoW}  production   Alloc Def, U	Reaction Stoichiometry <sup>12</sup>
		<b>3.66g;</b> Oxygen, liquid {RER}  market for   Alloc Def, U	
		<b>5.51 g</b> ; Acetic acid, without water, in 98% solution state {RER}  acetic acid production, product in 98% solution state   Alloc Def, U	
Cadmium Oleate	28.7 g	<b>10.6 g;</b> Fatty acid {RoW}  production, from vegetable oil   Alloc Def, U (for Oleic acid)	Synthesis process description <sup>13</sup>
		15.65g;Cadmium,semiconductor-grade{RoW} production   Alloc Def, U	
		<b>1.12 g;</b> Oxygen, liquid {RER}  market for   Alloc Def, Ua	
Zinc Oleate	18 g	<b>2.61 g;</b> Zinc {GLO}  primary production from concentrate   Alloc Def, U	Synthesis process description <sup>14</sup>
		<b>9.70 g;</b> Hydrochloric acid, without water, in 30% solution state {RER}  hydrochloric acid production, from the reaction of hydrogen with chlorine   Alloc Def, U	

		<b>6.399 g;</b> Sodium hydroxide, without water, in 50% solution state {RER}  chlor-alkali electrolysis, membrane cell   Alloc Def, U	
		<b>45.19 g;</b> Fatty acid {RoW}  production, from vegetable oil   Alloc Def, U	
		<b>63.12 g</b> ; Ethanol, without water, in 99.7% solution state, from ethylene {RER}  ethylene hydration   Alloc Def, U	
		<b>59.89 g;</b> Water, deionised, from tap water, at user {RoW}  production   Alloc Def, U	
		<b>91.68 g;</b> Hexane {RER}  molecular sieve separation of naphtha   Alloc Def, U	
Lauric acid	4.8 g	<b>9.25 g;</b> Coconut oil, crude {RoW}  production   Alloc Def, U	1 Tbsp (13.5 g)Coconutoilcontains 7 g oflauric acid
Indium acetate	2.33 g	<b>1.83 g;</b> Indium {RER}  production   Alloc Def, U	Reaction Stoichiometry <sup>12</sup>
		<b>0.38;</b> Ozone, liquid {RER}  production   Alloc Def, U	
		<b>1.44 g;</b> Acetic acid, without water, in 98% solution state {RER}  oxidation of butane   Alloc Def, U	
Tris(trimethylsilyl)	32.92 g	<b>6.79 g;</b> Phosphane {GLO}	Reaction

phosphine		production   Alloc Def, U	Stoichiometry <sup>15</sup>
		<b>689.5 g;</b> Dimethyl ether {RER}  production   Alloc Def, U	
		<b>8.6 g;</b> Sodium {RER}  chloride electrolysis   Alloc Def, U	
		<b>886.6g;</b> Methylchloride {WEU}  production   Alloc Def, U	
		<b>491.61 g;</b> Silicon, metallurgical grade {NO}  production   Alloc Def, U	
Indium laurate	0.3 g	0.14 g; Indium acetate	Synthesis process
		<b>0.3 g;</b> Coconut oil, crude {RoW}  production   Alloc Def, U	description
Diethyl zinc	50.02 g	<b>2.6 g;</b> Hydrogen, liquid {RER}  hydrogen cracking, APME   Alloc Def, U	Reaction Stoichiometry <sup>16</sup>
		<b>105.4 g;</b> Bromine {RER}  production   Alloc Def, U	
		<b>74.14 g;</b> Sulfuric acid {RER}  production   Alloc Def, U	
		<b>23.17 g;</b> Ethanol, without water, in 99.7% solution state, from ethylene {RER}  ethylene hydration   Alloc Def, U	
		<b>54.5 g;</b> Methyl iodide {RER}  production   Alloc Def, U	
		<b>120 g;</b> Zinc {GLO}  primary production from concentrate	

		Alloc Def, U	
		<b>10 g;</b> Copper oxide {RER}  production   Alloc Def, U	
Bis(trimethylsilyl)selenide	8.56 g	<b>1.5 g;</b> Selenium {RER}  production   Alloc Def, U	Reaction Stoichiometry <sup>17</sup>
		<b>26.97 g;</b> Tetrahydrofuran {RER}  production   Alloc Def, U	
		<b>151.09 g;</b> Methylchloride {WEU}  production   Alloc Def, U	
		<b>83.77 g;</b> Silicon, metallurgical grade {NO}  production   Alloc Def, U	
		<b>0.82 g;</b> Lithium brine, 6.7 % Li {GLO}  lithium brine inspissation   Alloc Def, U	
		<b>1.55 g;</b> Naphtha {Europe without Switzerland}  petroleum refinery operation   Alloc Def, U	
Hexamethyldisilthiane	178.44 g	<b>142 g;</b> Sodium sulfate, anhydrite {RER}  Mannheim process Alloc Def U	Reaction Stoichiometry <sup>18</sup>
		<b>12 g;</b> Activated carbon, at plant/RER Mass	
		<b>2525 g;</b> Methylchloride {WEU}  production   Alloc Def, U	
		<b>1400 g;</b> Silicon, metallurgical grade {NO}  production   Alloc Def, U	

Dodecenyl succinic acid (DDSA)	186.46 g	<b>98 g;</b> Maleic anhydride {RER}  production by direct oxidation of n-butane   Alloc Def, U	le {RER}  <b>Reaction</b> kidation of <b>Stoichiometry</b> <sup>19</sup>
		<b>168.32 g;</b> N-olefins {RER}  production   Alloc Def, U	

## c. Comparison of energy required for synthesis of Cd- and In-based QDs

Since the aim of the study is to provide a comparative cradle-to-gate life cycle assessment, we assume that the infrastructure and transportation required will be similar for both QD types. For this reason, we estimate the minimum energy required for synthesis of both QD types. Calculating energy requirement using standard specific heat equation for each step of the QD synthesis process provides an approximate comparison between the minimum energy used for CdSe and InP multishell QDs. The specific heat capacity (*Cp*) is empirically known for most standard materials, but in the case for proprietary materials *Cp* is most likely not known. To estimate the *Cp* of chemicals that are not available in the literature, we use the CHETAH program that uses Benson's method of group additivity to estimate the thermochemical properties of a chemical based on its molecular structure.<sup>20, 21</sup>

 TABLE F. Inventory of energy requirement at each step for synthesizing 1 gram of CdSe multishell QDs

	Green-emitting CdSe QD (J)	Red-emitting CdSe QD (J)
Core	25658.28	5362.99
Core Enrichment	NA	1127.85
First shell (ZnS)	2391.76	651.37
Second shell (CdZnS)	3587.87	20.14
Total energy	31637.92	7162.35

## TABLE G. Inventory of energy requirement at each step for synthesizing 25 mg of Greenand Red-emitting InP multishell QDs

	Green-emitting InP QD (J)	Red-emitting InP QD (J)
Core	209.20	662.91
Core Enrichment	419.80	660.16
First shell (ZnSSe)	8.92	7.00

Second shell (ZnS)	32.67	21.41
Ligand addition	4442.03	4442.03
Total energy	5112.63	5793.51

#### 5. Design configurations of QD display technologies

While the ideal QD display technology would be based on depositing the quantum dots directly on the LED, also known as 'on-chip' technology, such a technology is in its early stages due to low heat resistance of QDs. For now, enhancing backlights for LCD panels seems to be the main focus of manufacturers interested in QD display technologies.

Two types of QD-enhanced LCD backlit displays have been developed: 1) On-edge, and 2) On-surface technologies.

- 1) On-edge technology: Displays using this technology place a tube filled with quantum dots between the LEDs and the light guide plate. QD Vision Inc. is commercializing this approach.
- 2) On-surface technology: Displays also integrate quantum dots as a film. Nanosys designed this approach, and have partnered with 3M to develop a diffuser sheet loaded with quantum dots. Since diffuser sheets are present in conventional backlight units as well, there is no need to alter the design of LCD panels.



Figure S1. Illustrative representation of the two distinct configurations of QD incorporation in displays

#### 6. Distinct QD Display Technologies

Data for quantities of different QD materials required for displays of different sizes, and using competing technologies were retrieved from the request of exemption filed by QD manufacturers under the ROHS guidelines <sup>22</sup>. The data presented below is in grams/display, for which a range is estimated, where lower limit is representative of a smaller screen size and the upper limit for the larger screen size. This way we account for uncertainty, which using average screen sizes for different devices to convert functional unit from per mass basis to per device (mass/mm2) would not have been able to consider.

a. Inventory data for QD display production using competing nanomaterials and technologies

TABLE H. Amount of CdSe multishell QDs incorporated in On-surface displays determined based on screen size

	CdSe QD in grams (Lower	CdSe QD in grams
	Bound)	(Upper Bound)
TV (42" to 60+")	1.97	4.04
PC Monitors (15" to 25+")	0.70	1.41
Notebooks (10" to 17")	0.14	0.40
Tablets (7" to 10")	0.07	0.14
Smartphones (3.5" to 7")	0.003	0.01

TABLE I. Amount of CdSe multishell QDs incorporated in On-edge displays determined based on screen size

	CdSe QD in grams (Lower	CdSe QD in grams
	Bound)	(Upper Bound)
TV (42" to 60+")	0.075	0.15
PC Monitors (15" to 25+")	0.02	0.05
Notebooks (10" to 17")	0.005	0.01
Tablets (7" to 10")	0.002	0.004
Smartphones (3.5" to 7")	0.0005	0.002

TABLE J. Amount of InP multishe	ll QDs incorporated in	<b>On-surface displays</b>	determined
based on screen size			

	InP QD in grams (Lower	InP QD in grams
	Bound)	(Upper Bound)
TV (42" to 60+")	79.18	161.60
PC Monitors (15" to 25+")	28.20	56.40
Notebooks (10" to 17")	5.60	16.00

Tablets (7" to 10")	2.73	5.60
Smartphones (3.5" to 7")	0.14	0.54

TABLE K. Amount of InP multishell QDs incorporated in On-edge displays determined based on screen size

	InP QD in grams (Lower	InP QD in grams
	Bound)	(Upper Bound)
TV (42" to 60+")	3	6
PC Monitors (15" to 25+")	0.8	2.05
Notebooks (10" to 17")	0.21	0.4
Tablets (7" to 10")	0.08	0.16
Smartphones (3.5" to 7")	0.02	0.07

## 7. Large-scale Adoption of QD Displays: On-surface technology





References

- 1. J. S. Steckel, J. Ho, C. Hamilton, J. Xi, C. Breen, W. Liu, P. Allen and S. Coe-Sullivan, *Journal of the Society for Information Display*, 2015, **23**, 294-305.
- 2. U.S. Pat., 20150021521 A1, 2015.
- 3. U.S. Pat., 20150368553, 2015.
- 4. U.S. Pat., 20150166342, 2015.
- 5. U.S. Pat., 20100276638, 2010.
- 6. U.S. Pat., 20150049491, 2015.
- 7. U.S. Pat., 20140001405, 2014.
- 8. U.S. Pat., 20150300600, 2015.
- 9. G. Wernet, S. Hellweg, U. Fischer, S. Papadokonstantakis and K. Hungerbühler, *Environmental science & technology*, 2008, **42**, 6717-6722.
- 10. G. Wernet, S. Papadokonstantakis, S. Hellweg and K. Hungerbühler, *Green Chemistry*, 2009, **11**, 1826-1831.
- 11. H. Sengul and T. L. Theis, *J Clean Prod*, 2011, **19**, 21-31.
- 12. P. Patnaik, Handbook of inorganic chemicals, 2003.
- A. M. Dennis, B. D. Mangum, A. Piryatinski, Y.-S. Park, D. C. Hannah, J. L. Casson, D. J. Williams, R. D. Schaller, H. Htoon and J. A. Hollingsworth, *Nano letters*, 2012, 12, 5545-5551.
- 14. S.-H. Choi, E.-G. Kim, J. Park, K. An, N. Lee, S. C. Kim and T. Hyeon, *The Journal of Physical Chemistry B*, 2005, **109**, 14792-14794.
- 15. H. Adolfsson, D. J. Ager, J. M. Aizpurua, T. Aoyama and K. M. Baines, Science of Synthesis: Houben-Weyl Methods of Molecular Transformations Vol. 4: Compounds of Groups 15 (As, Sb, Bi) and Silicon Compounds, Thieme, 2014.
- 16. C. Noller, Organic syntheses, 1932, 86-86.
- 17. L. Syper and J. Mlochowski, *Tetrahedron*, 1988, 44, 6119-6130.
- 18. J.-H. So, P. Boudjouk, H. H. Hong and W. P. Weber, in *Inorganic Syntheses*, John Wiley & Sons, Inc., 2007, DOI: 10.1002/9780470132609.ch11, pp. 30-32.
- R. Ramaswamy, P. S. Achary and K. Shine, *Journal of applied polymer science*, 1987, 33, 49-65.
- 20. W. H. Seaton, E. Freedman and D. N. Treweek, 1974.
- 21. S. W. Benson, F. Cruickshank, D. Golden, G. R. Haugen, H. O'neal, A. Rodgers, R. Shaw and R. Walsh, *Chemical Reviews*, 1969, **69**, 279-324.
- 22. Oeko-Institut, Joint Revaluation of Two Requests for Exemption, First Reviewed in 2013-2014, Related to Cadmium Quantum Dot Applications, http://rohs.exemptions.oeko.info/index.php?id=265, (accessed June 20, 2016).