THE GLOBAL MARKET FOR QUANTUM DOTS

Applications, production and producers

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The Global Market for Quantum Dots to 2030

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1 Research scope and methodology

1.1 Report scope

The report covers the main quantum dot suppliers and application developers. The market is also forecasted from 2015 through to 2030. End user markets and applications are also outlined. The overall strategy of this market report is to apply a highly multi-disciplinary approach to a focused set of scientific questions. This will result in a detailed and comprehensive assessment of the quantum dots market.

The overriding objective of The Global Market for Quantum Dots to 2030 is to contribute new knowledge to the market for quantum dots and to provide a body of new information and a new tool that industry and governments can use to begin to assess these materials.

The specific technical objectives are:

[1] To investigate the market opportunity for quantum dots by sector.

[2] To assess the current state of the quantum dots market.

[3] To profile applications developers and producers in quantum dots

1.2 Market definition

The properties and behaviour of materials at the nanoscale varies significantly in comparison to the microscale. The properties of nanoparticles (also referred to as nanopowders or nanocrystals) display enhanced electrical, optical, magnetic and chemical properties from the bulk material of which they are made.

Two primary factors cause nanomaterials to behave significantly differently than bulk materials: surface effects (causing smooth properties scaling due to the fraction of atoms at the surface) and quantum effects (showing discontinuous behaviour due to quantum confinement effects in materials with delocalized electrons). These factors affect the chemical reactivity of materials, as well as their mechanical, optical, electric, and magnetic properties.

The fraction of the atoms at the surface in nanoparticles is increased compared to microparticles or bulk. Compared to microparticles, nanoparticles have a very large surface area and high particle number per unit mass. For illustration, one carbon microparticle with a diameter of 60 µm has a mass of 0.3 µg and a surface area of 0.01 mm2. The same mass of carbon in nanoparticulate form, with each particle having a diameter of 60 nm, has a surface area of 11.3 mm2 and consists of 1 billion nanoparticles. The ratio of surface area to volume (or mass) for a particle with a diameter of 60 nm is 1000 times larger than a particle with a diameter of 60 µm.

As the material in nanoparticulate form presents a much larger surface area for chemical reactions, reactivity is enhanced roughly 1000-fold. While chemical reactivity generally increases with decreasing particle size, surface coatings and other modifications can have complicating effects, even reducing reactivity with decreasing particle size in some instances.

The atoms situated at the surface have less neighbours than bulk atoms, resulting in lower binding energy per atom with decreasing particle size. A consequence of reduced binding energy per atom is a melting point reduction with

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particle radius, following the Gibbs-Thomson equation. For example, the melting temperature of 3 nm gold nanoparticles is more than 300 degrees lower than the melting temperature of bulk gold.

An example of a class of materials that clearly exploits quantum effects is quantum dots-synthesized nanostructures with sizes as small as a few nanometres. The electronic behaviour of quantum dots is similar to that of individual atoms or small molecules, and quantum dots are regarded as akin to artificial atoms. Notably, the confinement of the electrons in quantum dots in all three spatial directions results in a quantized energy spectrum.

Another result of quantum confinement effect is the appearance of magnetic moments in nanoparticles of materials that are non-magnetic in bulk, such as gold, platinum, or palladium. Magnetic moments result from several unpaired electron spins in nanoparticles formed of several hundred atoms. Quantum confinement also results in quantified changes in the ability to accept or donate electrical charge (or electron affinity), also reflected in the catalytic ability.

1.2.1 Categorization

Table 1: Categorization of nanomaterials.

Category	Nanomaterial
Inorganic non-metallic nanomaterials	• Titanium dioxide (TiO2) nanoparticles • Silicon dioxide (SiO2) nanoparticles • Zinc oxide (ZnO) nanoparticles • Aluminum hydroxides and aluminum oxo-hydroxides, diiron trioxide (ferric oxide, hematite, Fe2O3) nanoparticles • Triiron tetraoxide (ferrous-ferric oxide, magnetite, Fe3O4) v • Cerium dioxide (CeO2) nanoparticles • Zirconium dioxide (ZrO2) nanoparticles • Calcium carbonate (CaCO3) nanoparticles • Indium tin oxide (ITO) nanoparticles • Antimony tin oxide (ATO) nanoparticles
Metals and metal alloys	• Gold (Au) nanoparticles • Silver (Ag) nanoparticles • Platinum (Pt) nanoparticles • Palladium (Pd) alloy nanoparticles • Copper (Cu) nanoparticles • Iron (Fe) nanoparticles • Nickel (Ni) nanoparticles • Cobalt (Co) • Aluminium (Al) • Manganese (Mn) • Molybdenum (Mo).
Carbon-based nanomaterials	• Fullerenes (C60) • Carbon nanotubes (CNT, SWCNT, MWCNT) • Carbon nanofibers (CNF) • Graphene. • 2D allotropes.
Nanopolymers and dendrimers	• Polymer nanoparticles (e.g. polyalcylbenzenepolydiene nanoparticles PABPDM) • Polymer nanotubes • Nanowires and nanorods • Nanocellulose

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Category	Nanomaterial
	• Nanostructured polymer-films (polyalcylthiophene-films, polystyrene-polyethylene oxide.
Quantum dots	• Cadmium telluride and cadmium selenide • Cadmium-free quantum dots.

Source: Future Markets, Inc.

1.3 Research methodology

The research methodology design adopted for this specific study includes a combination of data collected from the primary and secondary sources. Both, the primary sources (in-house experts, industry leaders, market players, and independent consultants) and the secondary sources (a host of paid and unpaid databases) have been used, along with the analytical tools, to build the forecast and predictive models.

1.4 Assumptions and limitations

- The global quantum dots market has been classified on the basis of type, end-user industry, and region
- The regional areas have been segmented into: Asia-Pacific, Europe, North America, Rest of the World (RoW)
- The base year considered for the calculation of the market size is 2015. Instances where the market size for the FY2015 were not available from the primary or secondary sources, the values were estimated based on the Delphi method
- The market size was estimated for the FY2015 and projected from the year 2015 to 2030.
- The compound annual growth rate (CAGR) was calculated between FY2015 and FY2030.

1.5 Primary research

A series of interviews were conducted via email and phone with quantum dots company representatives, academics, technology suppliers, technical experts, trade association officials, and consulting companies. In addition, service providers and end users were contacted to evaluate current and future demands. The market was then quantified for relevant application impact and the main prerequisites for commercial success were identified including performance of the technology, supplier distribution, legislation, pricing of competing products, sale of complementary products, industry environment and demographics of the customer. Market revenues were forecast based on current revenues generated by companies marketing quantum dots products, market penetrations in key end user markets of these products and future estimated growth in these markets.

1.6 Secondary research

Secondary encompassed a comprehensive and exhaustive search of the literature on quantum dots. Secondary sources included journals and related books, trade literature, marketing literature, technology roadmaps, other product/promotional literature, annual reports, analyst reports, conference proceedings and other publications. An extensive patent analysis was conducted to gauge technological innovation and to determine research activity as it applies to new product development.

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2 Executive summary

QDs are compound semiconductor particles several nanometres in diameter, which absorb light and then emit it with a high level of brightness and purity. Changing the diameter of the particle changes the wavelength emitted. The narrow half-width of QDs' emission spectra makes colours easy to distinguish. QDs also have a high attenuation coefficient and good longevity. Until around 2013 they were mainly only used in research due to their unproven reliability and high cost.

Quantum Dots (QDs) are now utilized in a range of optoelectronic devices, including LCD TVs, light-emitting devices (LEDs), solar cells, security tags, photodiodes, QD lasers, thermoelectric materials, photoconductors and field-effect transistors, while QD solutions have been used in applications including in vivo and in vitro imaging, sensing and labelling techniques. They are a proven and scaled technology and relatively low cost for the high-end applications they add value to. The global market is also moving from cadmium-based to heavy metal free, RoHS compliant QD materials

The next wave of QD display products will incorporate quantum dots on glass, quantum dot colour filters (QDCF) for microLEDS and displays, perovskite QDs and inkjet printed QDs. These areas are all under development by major electronics manufacturers such as Samsung and LG Display.

Table 2: Market summary for the quantum dots market.

Category	Assessment	Trend
Market age	Development	Increasing
Revenues (at the component level) 2017	$750 million-$2.3 billion	Increasing
Potential revenues by 2025 (at the component level)	>$21 billion	Increasing
Potential revenues by 2030 (at the component level)	>$43 billion	Increasing
Base year market growth rate (2015)	>200%	Increasing
Forecast period market growth rate	15%	Increasing
Price sensitivity	High for some applications, low for LCD-TVs	Decreasing
Competitors (Active market competitors in base year)	4-5 main producers	Stable
Degree of competition (Low=1, High=10)	9	Increasing
Degree of technical change	High	Increasing

Source: Future Markets.

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2.1 Growth in high definition TV demand

The global market for quantum dots in LCD TVs has grown greatly in the past few years and its growth potential is considerable in the next decade, while companies are also starting to look at longer-term applications in the display industry. QDs are used as down-converters for back-lighting in liquid-crystal displays (LCDs) to improve colour gamut in high gamut standard and ultrahigh definition (UHD) televisions.

Figure 1: QLED TV from Samsung.

Image credit: Samsung.

The trend in consumer displays in 2019 is towards wider color gamuts and High Dynamic Range (HDR) with high peak luminance. Key trends for TVs over the next five years are:

- Lower-cost.
- Flexibility and thinness.
- Enhanced display performance.
- Greater pixel density.

These trends will be met through the use of quantum dot TVs.

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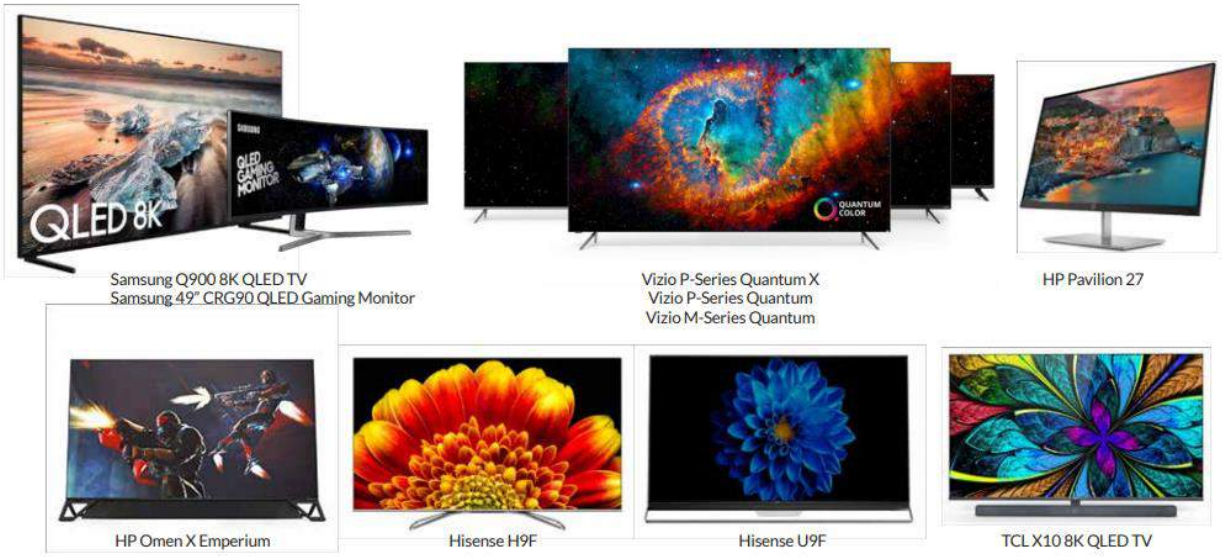

Figure 2. QD display products.

Table 3. Quantum dot display products.

Brand	Model	Type	Size (diagonal inches")
Acer	Iconia 10 Tab	Tablet	10"
	Predator Z271UV	Monitor	27"
	Predator X27	Monitor	27"
	Predator BFG65	Monitor	65"
AOC	AG273UG	Monitor	27"
ASUS	ROG PG27UQ	Monitor	27"
	ROG Swift PQ35VQ	Monitor	35"
	ROG PG65	Monitor	65"
Cello	C55SFS4K QLED	TV	55"
Gome	Maxreal 86	TV	86"
Haier	LE55Q9800U	TV	55"
Hisense	75U9	TV	75"
	65U9	TV	65"
	75P8	TV	75"
	65P8	TV	65"
	55S1U31	TV	55"
	65S1U31	TV	65"
	65E9A	TV	65"
	55E9A	TV	55"
	ULED XD	TV	65"
	Sonic One	TV	65"
	H9F	TV	55"
	H9F	TV	65"
	H9F	TV	75"

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Brand	Model	Type	Size (diagonal inches”)
JVC	JVC 65	TV	65"
	JVC 55	TV	55"
Philips	43M6VBRAB	Monitor	43"
	65-9603	TV	65"
	55-9603	TV	55"
Polaroid	PDK55U	TV	55"
PPTV	65Q900	TV	65"
Samsung	2019 QLED TV Lineup	TV	43”-85”
	Q900 8K TV	TV	65”,75”,82”,85” & 98”
	The Frame	TV	43”, 49”, 55” 65
	Serif TV	TV	43” 49” 55”
	CRG9	Monitor	49”
TCL	X6 QLED	TV	85"
	55X5C	TV	55"
	65X5C	TV	65"
	55X6	TV	55"
	65X6	TV	65"
	65Q960C	TV	65"
	55Q960C	TV	55"
	75X8	TV	75"
	65X8	TV	65"
	55X8	TV	55"
	75X8	TV	75"
	65X8	TV	65"
	55X8	TV	55"
	X10 FIBA	TV	75"
Vestel	QDTV65	TV	65"
Vizio	P-Quantum	TV	65"
	43 M-Series Quantum M7	TV	43"
	50 M-Series Quantum M7	TV	50"
	55 M-Series Quantum M7	TV	55"
	65 M-Series Quantum M7	TV	65"
	50 M-Series Quantum M8	TV	55"
	55 M-Series Quantum M8	TV	55"
	65 M-Series Quantum M8	TV	65"
	65 P-Series Quantum P9	TV	65"
	75 P-Series Quantum P9	TV	75"
	65 P-Series Quantum X	TV	65"
	75 P-Series Quantum X	TV	75"
	85 P-Series Quantum X	TV	75"

Source: Future Markets, Inc.

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2.1.1 QD advantages

The use of quantum dots in TVs allows for improved brightness and colour intensity in high definition LED/LCD TVs. Utilizing QDs produces more heavily saturated and precisely defined primary colours from blue LEDs than can be achieved from the relatively broad and thus imprecise light spectrum associated with white LEDs. QDs can be easily integrated into the manufacturing process for LCDs, offering comparable colour performance at significantly lower cost in comparison to OLEDs, especially in the TV market. Main current market for QDs at the materials level are (in order of market size):

1. Display additives
2. Solid-state lighting
3. Diagnostics (imaging)
4. Academic & research
5. Other biomedical applications (Drug delivery, biosensors)
6. Other energy applications (Solar, batteries, thermoelectrics)
7. Sensors.

At the component level, displays are by far the largest market, following by lighting, and these sectors will witness the largest growth through to 2030. There is now a strong pull from the market and customers to introduce QD based high colour gamut LCD displays, as consumers seek improved visual experiences and producers seek new product opportunities in a saturated market.

2.2 Market growth since 2013

Markets for QDs include TV displays and smartphone displays, solar cells, security tags, security inks, sensors, quantum dot lasers, quantum dot transistors, photonic crystals, bio-imaging, quantum dot solar windows, biomarkers, solid-material-based memory, thermoelectric materials, quantum dot computers, artificial photosynthesis and light emitting diodes (LEDs).

The market up to 2013 mainly catered to specialized applications, with a small number of companies selling QDs directly to researchers, using the particles to develop their own products or licensing their technologies to partners. Product launches in 2013 changed the commercial picture. Sony's 2013 line of Triluminos LCD televisions utilized edge-mounted red and green QDs from QD Vision to optically down-convert some of the television's blue LED backlight. In early 2013, 3M and Nanosys introduced a prototype of quantum dot enhancement film (QDEF) targeted at LCD manufacturers.

The QD market exploded in 2015, driven by the use of QD film in application in products such as LCD displays for TVs, computers, tablets, cellphones etc. Electronics giants Samsung produce high-end QD-TVs utilizing QDs to improve colour performance and improve power efficiency.

2.3 QD-TVs market

Samsung is the market leader in QD TVs. The company adopted QLED name for its highest level 2017 TVs in place of its previous SUHD sub-brand. These QLED TVs are uniquely encased in a new metal alloy sheath that renders the QDs less susceptible to oxidation and also allows for better positioning in the TV's structure, allowing for more efficient colour and light. The company utilizes cadmium-free (InP-based) QDs which they have synthesized with high luminescence efficiency (> 90%) and narrow bandwidth (< 40 nm) simultaneously by controlling the oxidized interface and narrowing their size distribution.

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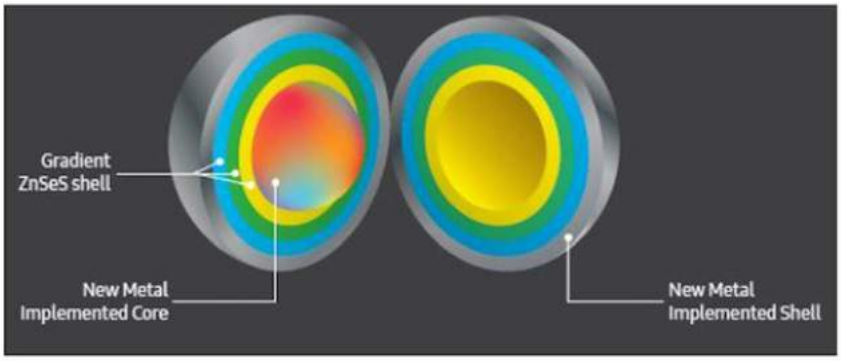

Figure 3: Samsung QDs utilized in range of QLED TVs.

Image credit: Samsung.

According to the company, metal-clad QDs have the following advantages:

- High levels of brightness (Q9F models can achieve 2000 nits of peak brightness).
- Improved colour volume.
- Impervious to screen burn.
- Low power consumption.

2.4 The Quantum Dot market in 2019

TV displays still dominate the end user segment for QD-based products with a fast growing market for QD monitors. The use of QDs in solar conversion windows is also being heavily backed this year with a number of companies developing prototypes and funding multi-million dollar investments. The price of large QD-TVs is also falling. In July 2018, Vizio launched the P-Series Quantum 65-inch 4K HDR smart TV (PQ65-F1). In 2019, a number of manufacturers will be offering sub $1000 models.

The market is moving towards more advanced application of quantum dots in TVs with major producers, especially Samsung developing technologies beyond Quantum Dot Enhancement Film (QDEF) such as:

- QD Glass on LGP.
- Quantum dot colour filters (QDCF) for microLEDS and displays.
- Active Matrix Quantum-dot Light Emitting Diode (AMQLED).

2.5 Cadmium vs. cadmium free

Various types of quantum dots currently exist, but in general, quantum dots are made of semiconductor materials such as CdSe, CdS, InP, ZnS, InP/ZnS, CuInS2, CuInSe2(CIS:copper indium selenide or sulfide), AgS, and PbS etc. However, these materials are relatively expensive and toxic, especially Cd, Se, and Pb. These toxic heavy metals are unfavourable and occasionally prohibited for use in many industrial areas. Therefore, many in the industry view it essential to develop toxic metal-free quantum dots, which exhibit a high light emitting quantum efficiency and stability as good as those of the expensive and toxic metal-based quantum dots.

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2.5.1 Cadmium QDs

CdSe/ZnS quantum dots are utilized as they deliver high quantum efficiency as well as to meet the lifetime requirements in display applications. The high quantum efficiency, typically >88%, is necessary for QD film based backlights to deliver higher power efficiency (12% - 45% more energy efficient than traditional LED-LCDs for colour gamut sizes from 70% NTSC to 100% NTSC). However, the technology requires RoHS exemption to be applied in LCD displays because of the use of Cadmium. Cadmium QDs are still widely used in TVs in the China market.

2.5.2 Cadmium-free QDs

Cadmium-free QDs are RoHs compliant but its level of performance is less than CdSe QDs. A Cd-based system has 13% larger gamut area than InP system. There are difficulties in making InP QDs without surface defects due the aforementioned oxidation problems. The large size distribution of InP QDs also causes broad emission spectrum and the poor colour purity. Most QD manufacturers have developed cadmium-free QDs, to circumvent restrictions on the use of cadmium in certain markets.

2.5.3 European commission ban use of cadmium in TVs and displays

The European Commission (EC) undertook a lengthy review of the use of cadmium-based quantum dots in displays and LED lighting, following the rejection by the European Parliament in 2015 of a previous proposal to extend their use. The report recommended a further 3 year extension. However, after concerns were expressed by Member States and environmental NGOs the EC decided to end their use in LED lighting and give the minimum period of 2 years only for use in displays.

Cadmium-based quantum dots in TVs and displays will be effectively banned in Europe from 31st October 2019, as part of the Restriction of Hazardous Substances (RoHS) Directive.

2.5.4 Perovskite quantum dots

Organometal halide perovskites quantum dots have been developed in the past few years and are now coming to commercial prominence. They are attractive for display application due to their high optical properties including:

- high PLQY
- narrow FWHM
- tunable emission wavelengths.

Figure 4: Perovskite quantum dots under UV light.

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Image credit: Fuji Pigment.

2.5.5 Carbon and graphene quantum dots

Carbon quantum dots and graphene quantum dots (CQDs, GQDs) represent relatively new members of the carbon nanomaterials family. Studies have demonstrated that quantum confinement could appear in graphene with finite size and edge effects-graphene quantum dots (GQDs).[1] GQDs display properties derived from both graphene and carbon dots, combining the structure of graphene with the quantum confinement and edge effects of CDs. They possess unique optical and electrical properties such as:

- strong photoluminescence
- biocompatibility
- exhibit band gap (unlike graphene sheets).

As a result they are being widely investigated for applications in optoelectronics, biomedicine and sensors.

2.6 Quantum Dot Revenues 2015-2030

Table 4: Total QD-based component revenues 2015-2030 ($M), conservative and optimistic estimates.

Year	Conservative estimate (M$)	Optimistic estimate (M$)
2015	1,750	2,550
2016	6,600	7,480
2017	5,600	8,200
2018	7,220	8,550
2019	8,000	10,720
2020	9,750	11,250
2021	10,400	13,650
2022	11,313	14,250
2023	12,840	16,800
2024	15,120	20,625
2025	15,731	21,742
2026	18,877	26,091
2027	20,263	31,309
2028	22,290	37,571
2029	23,404	41,242
2030	24,519	43,206

Source: Future Markets, Inc.

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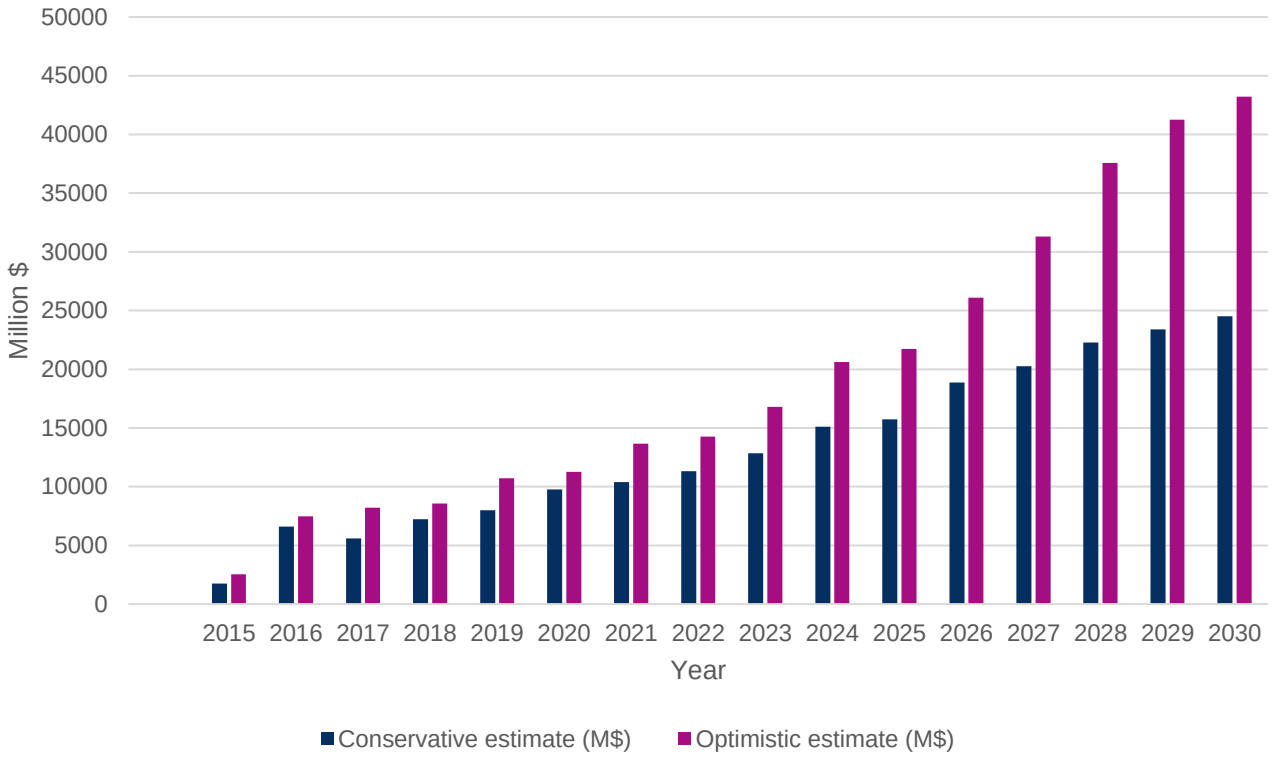

Figure 5: Total QD component revenues 2013-2030 ($M), conservative and optimistic estimates.

Source: Future Markets, Inc.

2.7 Market drivers and trends

Table 5: Market drivers and trends for quantum dots.

Driver	Trend
Growth in demand for high definition displays	High luminescence efficiency and tunable saturated colour plus improvements in the past few years in terms of stability, brightness and processability has pushed quantum dots to the forefront of high-colour display applications. With a colour performance that achieves 100% of the NTSC standard compared to 60–70% from most mainstream Liquid Crystal Displays (LCD) designs, QD-based hybrid LEDs have made significant inroads as a disruptive technology in the displays market in the past two years. They exhibit: • external quantum efficiencies >10% for all three fundamental colours (>18% for green) • device lifetimes of >300 khours • extreme tuned colour fidelity. • there is no new fab investment needed for QD adoption.
Cheaper than OLED	While they outperform QD-TVs in a number of areas, large screen OLED-TVs are currently not viewed as cost effective for the mass market (models are priced around

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Driver	Trend
	$6000). Issues with cost are likely to be addressed in the coming years, as are reliability and process issues, but at present QD-TVs are the cheaper alternative as they are easy to integrate into existing LCD manufacturing.[2] LCD-TVs will remain the mass market choice for a number of years, due to their low cost and the difficulty in compelling customers to move beyond LCD. Beyond vast improvements in colour performance, OLED manufacturers will experience difficulties in compelling consumers to change from LCD, especially as LCDs meet a vast percentage of consumer needs. The addition of QDs has allowed LCD manufacturers to correct the colour performance issues, making market penetration even more difficult for OLEDs.
Growth in renewable and low-power energy consumption market	Demand for solar power is rising rapidly, with annual double digit growth expected over the next few years. Governments are pushing for new solar technologies and there is strong demand from private/public sectors investors in developing countries. Improving solar conversion efficiencies and the flexibility of nanomaterials is driving their demand in photovoltaics. Twenty-two per cent of global electricity is spent on lighting and conversion to more efficient lighting solutions is being undertaken. Fluorescent & LEDs offer huge savings with power efficiency gains but are hindered by poor colour and use of mercury, opening up opportunities for QD-enables Solid-State Lighting (SSL). According to Osram, 1/3 of the electricity (900 billion kWh) for lighting could realistically be saved utilizing SSL.
Need for improved, easy to use medical diagnostics and imaging	Medical imaging reagents allow clinicians and healthcare providers to determine whether a tumour is malignant or benign and enables to locate any metastatic cancerous sites in the body. According to the Union for International Cancer Control (UICC), worldwide cancer cases are estimated to rise by almost 75% and reach approximately 25 million over the next two decades. For traditional biological applications, QDs have already begun to replace traditional organic fluorophores to serve as simple fluorescent reporters in immunoassays, microarrays, fluorescent imaging applications, and other assay platforms.
Growth in anti-counterfeiting market	Counterfeiting is a major problem, causing the global economy billions of dollars per year. Sales of counterfeit products can greatly affect sales revenues, erode brand value and public trust, pose health risks for citizens, lead to product recalls and are a particular problem in the pharmaceuticals, airplane parts, auto parts, and designer clothing sectors, among others. Advantages of utilizing QDs for anti-counterfeiting and security products include: • Difficulty in counterfeiting specific uniform nanomaterials as these materials cannot be produced by standard equipment. • Functionalisation of nanomaterials requires a high standard of training • The special multifunctional surface, magnetic, fluorescent, and infrared properties of nanomaterials and patterns created thereof can create unique profiles
Need for improved sensors	Increasing personal health awareness has resulted in the growth of the home diagnostics and point of care (POC) markets. First generation POC diagnostics are not regarded as being of sufficient standard and effectiveness due to limited sensitivity capabilities, slow response and poor accuracy. Printed biosensors for the point of care (POC) market are a future and key development opportunity. POC devices and systems offer lower cost routes towards continuous monitoring of patients and reduce dependency on primary health systems. QDs offer up to 300-fold improvement in LF test strip sensitivity due to their unique and tunable photoluminescence, and physicochemical properties.

Source: Future Markets.

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Table 6: Impact of market drivers for the quantum dots market.

Rank	Driver	1-2 years	3-4 years	5-8 years
1	Growth in demand for high definition displays and TVs	High	High	High
2	Price compared to OLED	High	High	Medium
3	Need for improved diagnostics and imaging	Medium	High	High
4	Need for improved sensors	Medium	Medium	High
5	Growth in anti-counterfeiting market	Medium	High	High
6	Growth in renewables and low power energy	Low	Low	Medium

Source: Future Markets.

2.8 Market challenges

Table 7: Market challenges for quantum dots.

Challenge	Description
Restrictions on cadmium	QDs are typically composed of toxic heavy metals (e.g. cadmium and lead), which restricts their use in certain products and markets. Dow and Nanoco claim to have solved these issues via their cadmium free QD technology. According to the companies' current performance of cadmium free quantum achieve 95% to 96% of the Digital Cinema Initiative standard for TVs. A number of cadmium-based QD producers are also developing cadmium free QDs. However, the wider industry view is that cadmium based QDs are significantly better for application in displays. Restrictions on cadmium QDs will likely force most producers and OEMs to move to cadmium-free QDs in the next couple of years.
Cost	Prices for QDs range are upwards of $1 million/ kg. However, mass production is predicted to drive prices down to >$500 kg. With the development of new synthesis and manufacturing approaches and the graduation of QDs from specialty to commodity markets, it is expected that the price of QDs will benefit greatly from economies of scale, allowing for rapid penetration into a number of markets. Materials currently available are considered too costly and too hazardous (CdSe and InP are carcinogens) for certain market.
Scalability	Manufacturing quantum dots is a technical challenge during scale-up and can result in large batches of quantum dots that have poor size consistency and very low yields. Further, injection-based synthesis methods that rely on air-sensitive (and toxic) chemicals are inherently expensive leading to high prices (e.g., ~$10,000/gram for CdSe/ZnS QDs).
Competition from OLED in displays	Traditional Liquid Crystal Displays (LCD) offer only a fraction of the colours that are visible to the human eye, and can only reach 70% of the colour performance of organic light-emitting diodes (OLEDs). OLEDs are thinner, have a clearer picture and utilize significantly less power. However, they also suffer from a number of drawbacks, especially cost for application in large display panels. QD films and resins used in LCD-display backlights are regarded as superior to LCD and comparable to OLED (QDs are easily integrated into existing LCD displays).
Dispersion and solubility	Dispersion issues restricts the use of QDs for diagnostics and therapeutics. QDs dispersed in nonpolar solvents gradually aggregate and lose their fluorescence intensity, even in the dark. QDs enter cells very slowly and tend to become trapped in endosomes or other

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Challenge	Description
	vesicles following cellular entry. Therefore, methods to improve QD solubility, cellular uptake, and biodelivery are needed.

Source: Future Markets.

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3 Quantum dots

3.1 Properties

Quantum dots (QD) were first characterized in 1983 by Brus as small semiconductor spheres in a colloidal suspension.[3] They generally refer to nanoscale particles of conventional semiconductors that are subject to the quantum-confinement effect, though other nanomaterials of similar optical and redox properties are also named as QDs (such as carbon quantum dots and graphene quantum dots) even in the absence of strictly defined quantum confinement.

They are clusters of inorganic, highly efficient phosphor crystalline semiconductor nanoparticles (NP), arranged in binary (e.g. CdSe, CdTe, GaAs, InAs, AlN, SiC and etc.) or ternary compounds (e.g. InGaN, InGaP, InGaAs and etc.). The size of a QD typically ranges from 3-7 nm.

QDs are produced by processing materials such as Cadmium Selenide, Cadmium Sulphide, Cadmium Telluride, Indium Arsenide, and Silicon. Cadmium Selenide and Cadmium Sulfide, have been the most widely produced. Types of semiconductor quantum dots are:

- Binary quantum dots
- Alloyed quantum dots
- Core/shell quantum dots: “type-I”
- Core/shell quantum dots: “type-II”
- Quantum dot/quantum well nanocrystals
- Transition-element-doped quantum dots.

Quantum dots used in LCD films until recently are typically cadmium selenide (CdSe)/Zinc sulphide (ZnS) core/shell nanocrystals.

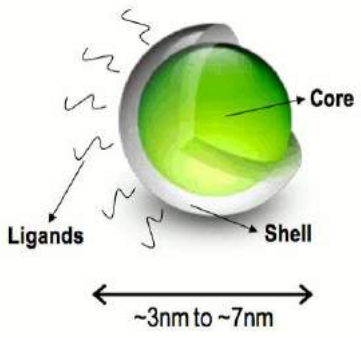

Figure 6: Quantum dot schematic.

Image source: 3M.

Their electronic and optical characteristics are closely related to the size and shape of the individual crystals. The colour of light that they emit varies with the size of the dot, shifting toward the blue end of the spectrum, as they get smaller (generally resulting in shorter emission wavelength).

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By utilizing a core/shell nanocrystal structure, where the optically active core of the quantum dot is one material (CdSe or InP based) and the shell (ZnS-that protects the core and increases efficiency) is a different material, high photo luminescent quantum efficiency (i.e., high energy photon to low energy photon conversion efficiency) can be obtained. By controlling different synthesis conditions, e.g. precursor; ligand concentrations; temperature; and time of the reaction, QDs of different sizes can be obtained. QD emission can be tuned across most of the visual spectrum by controlling the size of the quantum dot as it is fabricated; larger quantum dots emit light of longer peak wavelengths.

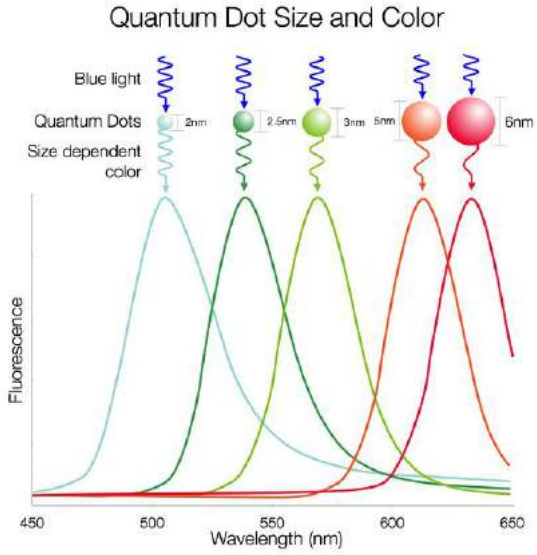

Figure 7. Quantum dot size and colour.

The colour of a quantum dot depends on the size of the particle; different sizes produce different wavelengths.

Source: Nanosys

QDs have unique absorption and emission properties that differentiate them from conventional fluorescent dye molecules. Specifically, QDs have broad absorption range from ultraviolet (UV) to visible, but exhibit distinct emission spectrum with narrow full width at half maximum (FWHM) (typically 10-40nm). Desirable properties of QDs across a range of applications include:

- Size-tuneable bandgap/fluorescence.
- Narrow & bright emission.
- Broadband & efficient absorption.
- Low-cost/scalable synthesis.
- Solution processible.
- High quality: Low polydispersity & single-crystalline.

3.2 Synthesis

Quantum dots are typically synthesized via solution chemistry (carefully controlled precipitation processes). QDs designed for usage in biological systems are mostly applied in solution (colloidal form). By controlling different synthesis conditions, e.g., precursor and ligand concentrations, temperature and time of the reaction, quantum dots of different sizes can be obtained. Chemical synthesis of quantum dots is generally divided into organic and water phase

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approaches. The organic phase method produces quantum dots, which are generally capped with hydrophobic ligands and therefore are not suitable in biomedical applications.

Quantum dots used in light control films are typically CdSe/ZnS core/shell crystals. These CdSe/ZnS quantum dots have been optimized to deliver high quantum efficiency as well as to meet the lifetime requirements in display applications. Typically, two different sized quantum dots, nominally green and red emitting, would be incorporated into the polymer film.

The biggest challenges surrounding quantum dot technology have been the use of cadmium and scalability for mass production. Nanoco and Dow claim to have solved these issues. Nanoco's 'molecular seeding' method does not require high temperature, involves inexpensive, readily-available precursors, has no harsh conditions, and is easy to control.

Table 8: Chemical synthesis of quantum dots.

Method	
Organic phase method	
Colloidal synthesis	• Benchtop. Most of these processes can be carried out in small quantities in the lab. Larger quantities can be difficult to produce as precise temperature control is required. • Cheapest method. • Three component system composed of precursors, organic surfactants, and solvents. • Typical dots are made of binary alloys such as cadmium selenide, cadmium sulfide, indium arsenide, and indium phosphide. • The size of the resulting quantum dots can typically be tuned by changing the temperature, pH, or length of the reactions.
Lithography	• Imprint lithography is best suited for producing QDs in this method. • Quantum wells are covered with a polymer mask and exposed to an electron or ion beam. A negative image is formed on a hard SiO2 wafer using electron-beam lithography. This mold is used as a stamp and is physically pressed onto a silicon layer to form the QDs. • Method allows for precise positioning and size control of the QDs. • Disadvantages: slow, contamination, low density, defect formation.
Epitaxy	Patterned Growth • Semiconducting compounds with a smaller bandgap (GaAs) are grown on the surface of a compound with a larger bandgap (AlGaAs). • Growth is restricted by coating it with a masking compound (SiO2) and etching that mask with the shape of the required crystal cell wall shape. • Used to make QD lasers. Disadvantage: density of quantum dots limited by mask pattern. Self-Organized Growth • Uses a large difference in the lattice constants of the substrate and the crystallizing material. When the crystallized layer is thicker than the critical thickness, there is a strong strain on the layers. The breakdown results in randomly distributed islets of regular shape and size. • Disadvantages: size and shape fluctuations, ordering.
Water phase method	
Cap exchange	• Environmentally benign • Inexpensive • QDs' native hydrophobic ligands replaced with hydrophilic molecules that have higher affinity for the QD surface.

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Method	
	• The most popular anchoring molecules utilize thiol groups. Others include amines, phosphonic acids, and carboxylic acids.
Native surface modification	• Adding a silica shell to the nanoparticles using a silica precursor during the polycondensation renders QDs water-soluble. • Various synthesis strategies are used that have effectively solubilized CdSe or CdSe/ ZnS quantum dots.

Source: Future Markets, Inc.

3.3 Types

3.3.1 Cadmium Selenide, Cadmium Sulfide and other materials

QDs are produced by processing materials such as Cadmium Selenide, Cadmium Sulphide, Cadmium Telluride, Indium Arsenide, and Silicon. Cadmium Selenide and Cadmium Sulfide, have been the most widely produced. Types of semiconductor quantum dots are:

- Binary quantum dots
- Alloyed quantum dots
- Core/shell quantum dots: “type-I”
- Core/shell quantum dots: “type-II”
- Quantum dot/quantum well nanocrystals
- Transition-element-doped quantum dots.

Quantum dots used in LCD films are typically cadmium selenide (CdSe)/Zinc sulphide (ZnS) core/shell nanocrystals. CdSe/ZnS quantum dots are optimized to deliver high quantum efficiency as well as to meet the lifetime requirements in display applications. The high quantum efficiency, typically >88%, is necessary for QD film based backlights to deliver higher power efficiency (12% - 45% more energy efficient than traditional LED-LCDs for colour gamut sizes from 70% NTSC to 100% NTSC).

3.3.2 Cadmium free quantum dots

Cadmium free quantum dots are produced by Nanoco and a number of other companies. Cd-free quantum dots, e.g., InP based core/shell nanocrystals, are currently under research and development by numerous research institutions and companies. At present, according to sources, these Cd-free quantum dots still suffer from low quantum efficiencies which results in half the energy efficiency of Cd-based quantum dots in display backlights. Furthermore, Cd-free quantum dots have wider emission spectra than cadmium based dots, resulting in reduced colour gamut size in LCD applications. 3M state that Cd-Free QD film result in 20-40% lower system efficiency than the standard QD film solution. However, this has been refuted by Dow and Nanoco. According to Nanoco, the optical emission performance Cd-free currently meet the requirements for commercial LCD screens, in terms of enhanced screen colour range and lifetime (at least 30,000 hours).

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3.4 Perovskite quantum dots

Perovskite quantum dots (PQDs) have been developed in the past few years and are now coming to commercial prominence due to their excellent photophysical properties, low heavy metal content and low cost fabrication. The development of PQDs dates back to the discovery in 2012 of enhanced PL emissions in nanosized perovskite embedded in meso-Al2O3.[4] Research publications on these materials have grown significantly after highly luminescent colloidal perovskite QDs were first reported in 2015.[5] [6] [7]

They possess exceptional optical properties including:

- high brightness
- tuneable emission wavelength
- high colour purity
- high defect tolerance.

PQDs are being developed as alternative down-conversion materials in phosphor-converted light-emitting diodes (pc-LEDs) for lighting and next-generation of display technology.

Synthesis methods for PQDs include:

- Hot Injection Method.
- Ligand Assisted Reprecipitation (LARP).
- Mechanochemical Methods.
- In situ formation strategy within inorganic and polymer matrices.

These methods have numerous shortcomings that researchers have sought to rectify recently with new synthesis methods.[8] [9]

3.4.1 Properties

The emission colours of PQDs can be tuned by changing the chemical compositions. In contrast, the traditional III-V or II-VI semiconductor QDs can only tune their emission colours by sieving the QD sizes.

Table 9. Comparative properties of conventional QDs and Perovskite QDs.

	Conventional QDs	**Perovskite QDs**
Chemical constitution	Covalent compound	Ionic compound
Structure	Core-shell, alloyed, etc.	Homogenous
FWHM	30-50 nm	15-50 nm
Quantum yield	>90%	>90%
Cost	High	Low
Fabrication	Ex-situ	Ex-situ/In-situ

Source: Future Markets, Inc.

The most common perovskite quantum dots (pQDs) are called lead halide pQDs. They have the chemical formula APbX 3, where:

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- A can be either an organic component (e.g. methylammonium (MA) or formamidinium (FA)) or an inorganic atom, most commonly caesium (Cs).
- X is a halogen (either chlorine (Cl), bromine (Br) or iodine (I)).

The choice of halide affects the emission wavelength, as explained below:

- APbCl 3 dots give blue-like emission
- APbBr 3 dots give green-like emission
- APbI 3 dots give red-like emission

Just like MCQDs, the emission wavelength can be fine-tuned through the dot size, or through creating mixed-halide dots – where 2 different halogens are present in the same dot. Because they don't contain volatile organic compounds within the dot itself, caesium pQDs tend to be more robust over time compared to MA or FA-based dots.

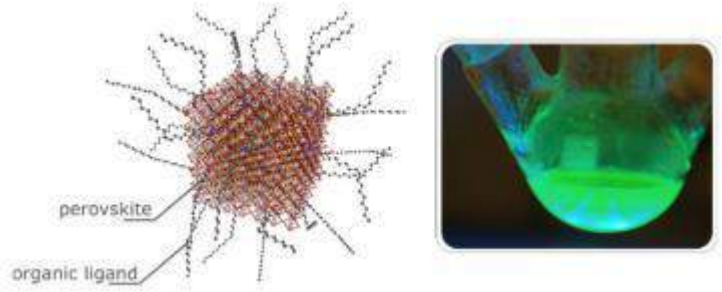

Figure 8. A pQLED device structure.

Right: A green pQLED in operation, based on CsPbBr 3 pQDs.

Source: Ossila.

While pQDs are still in the research phase, the technology is progressing quickly and there have been several demonstrations of bright, efficient electro-emissive pQLEDs. There remain some questions regarding the long-term stability of pQDs, but their low cost, ease of fabrication, and compatibility with current and future manufacturing techniques make them an exciting prospect for the future of display and lighting technologies.

Figure 9: Perovskite quantum dots under UV light.

Image credit: Fuji Pigment.

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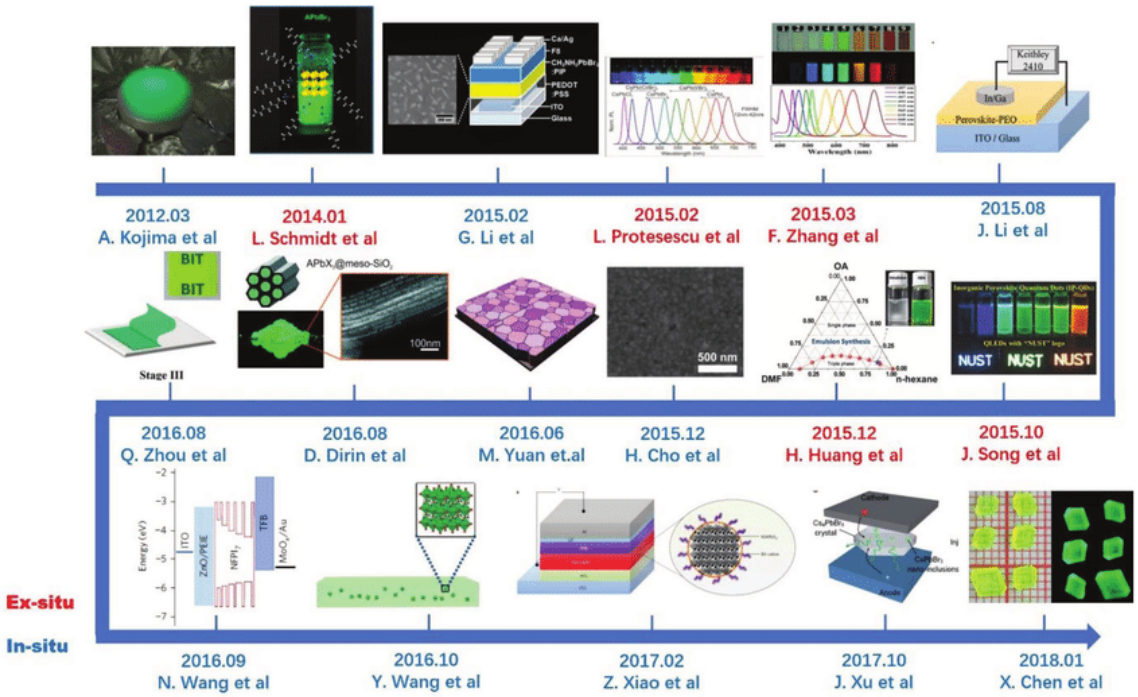

Table 10. Development roadmap for perovskite QDs.

Image: American Chemical Society.

PQDs are attractive for display application due to their high optical properties including:

- high PLQY
- narrow FWHM
- tune
- able emission wavelengths.

Even when compared to well-developed CdSe and InP QDs, prototype colour conversion LEDs based on perovskite QDs show superior colour performance and improved luminous efficiency (120% NTSC, 109 lm/W), enabling enhanced LCD panels.[10] The performance of perovskite QD-based EL devices now approaches that of other conventional QDs, and demonstrates promise for use in flexible displays.

Table 11. Properties of perovskite QLEDs comparative to OLED and QLED.

	OLED	QLED	pQLED
Processing route	Generally thermal evaporation, solution processing is possible	Solution (ink-jet printing, spincasting)	Solution (ink-jet printing, spincasting)
Display manufacturing cost	High	Medium	Low
Brightness	~500 cm/m^2	2000 cd/m^2	3800 cd/m^2

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Colour gamut (rec. 2020)	~70%	~80%	>100%

Source: Future Markets, Inc.

PQDs usually show a poor crystallinity, relatively low photoluminescence quantum yield (PLQY), and poor stability based on synthesis methods such as injection. These limitations have hindered the use of PQDs in practical applications.

The structural and optical stability of PQDs is the main challenge. It has been reported that the disintegration of CsPbX3 QDs, accompanied by the photoluminescence (PL) quenching, is accelerated by polar organic solvents and water or under ultraviolet irradiation. To address this stability issues, surface ligand regulation is widely utilized to retain the colloidal and structural integrity of PQDs.

3.4.2 Applications

Table 12. Applications of perovskite QDs.

Market	Application
Electronics	• Light-emitting Diodes (LEDs)[11] • MicroLEDs • Single Photon Sources • Photodetectors • Quantum computing
Energy	• Solar Cells
Other	• Lasers

Source: Future Markets, Inc.

3.4.3 Producers

In September 2018, Quantum Materials Corp., a manufacturer of Cadmium-free quantum dots, developed a continuous flow manufacturing process to produce stable, low cost, high purity perovskite quantum dots (PQDs). Quantum Materials Corp has developed a high-volume production process that produces extremely high purity PQDs with significantly improved stability. China-based QD developer Zhijing Nanotech has demonstrated a perovskite-QD film (PQDF) for application in LCD-TVs.[12] Avantama AG has developed a proprietary 1-step synthesis process for PQDs and has a production capacity of 1kg perovskite/day in suspension form.

Table 13. Perovskite quantum dot producers.

Company	Products
Avantama AG	The company produces Perovskite-based QD films and Cadmium free quantum dot display materials.

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Company	Products
Green Science Alliance Co., Ltd	Produces perovskite quantum dots composite materials.
Ossila	UK-based producer of Perovskite Quantum Dots.
Quantum Solutions	Produces Perovskite Quantum Dots.
Zhijing Nanotech Co., Ltd.	Produces a range of perovskites quantum dots

Source: Future Markets, Inc.

3.5 Carbon quantum dots (CDs)

3.5.1 Properties

Fluorescent carbon nanoparticles, carbon dots (C-dots) or carbon quantum dots (CQDs) are a recent class of carbon nanomaterials that are potential competitors to conventional semiconductor quantum dots. CQDs are spherical carbon particles with a size less than 10 nm. They are composed mainly of Sp3 hybridized carbon, usually amorphous and they can show in XRD the (100) plane of the basal planar of graphite.

CQDs possess:

- comparable optical properties to conventional QDs.
- low toxicity.
- tunable fluorescence.
- environmental friendliness.
- good water solubility.
- low-cost .
- synthesis is simple.
- surface passivation and functionalization of CQDs allow for the control of their physicochemical properties.

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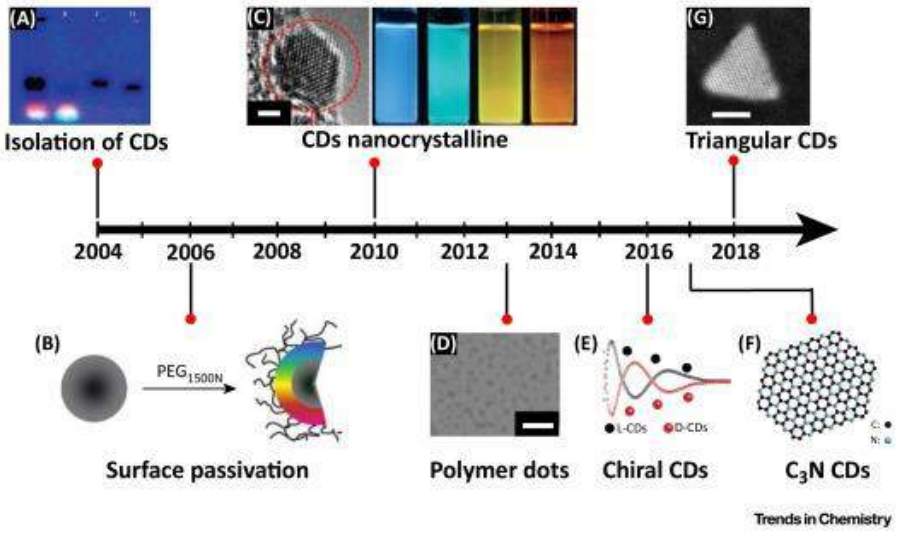

Figure 10. Carbon dots development.

(A) Fluorescent CDs were first obtained via traditional gel electrophoresis of crude single walled carbon nanotube (CNT) suspensions in 1% agarose gel. The electrophoretic profile was measured under UV light. Reproduced with permission.[13] (B) Illustrative schematic of poly(ethylene glycol)-passivated CDs. Reprinted with permission.[14] (C) Crystalline CDs: high-resolution transmission electron microscopy image (HRTEM, left) and size-dependent fluorescence images of aqueous solutions under UV-light excitation (right); scale bar = 2 nm. Reprinted with permission.[15] [16](D) HRTEM image of polymer dots; scale bar = 20 nm. Reprinted with permission.[17] (E) Circular dichroism spectrum of chiral CDs. Reprinted with permission.[18] (F) The chemical structure of the C3N CDs. Reprinted with permission.[19] (G) Aberration-corrected high-angle annular dark-field scanning transmission electron microscopy images of triangular CDs; scale bar = 2 nm.

3.5.2 Applications

Main applications are in chemical sensing, biosensing, bioimaging, drug delivery, photocatalysis and electrocatalysis.

Table 14: Applications of carbon quantum dots.

Markets	Applications	Benefits
Filtration	Photocatalytic Energy Conversion	• Excellent electrocatalytic activity.
Sensors	Biosensing	• Sensitive to minute perturbations. • Intimate biomolecular. interaction (size comparable to a biomolecule) for improved detection sensitivity and selectivity.
	Electrochemical Sensors	• Large specific surface area. • Abundant edge sites.

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Markets	Applications	Benefits
		• Intrinsic catalytic activities.
Biomedicine	Bioimaging agents[20]	• Stable emission. • Good dispersibility. • Low toxicity. • Long emission lifetime. • Biocompatibility with cells and macromolecules.
	Drug delivery	• Carriers for drug delivery while allowing simultaneous visual monitoring of releasing kinetics.
	Cancer therapy	• Exhibit strong photodynamic effect and the associated phototoxicity can been used to kill cancer cells.
	Anti-bacterials agents	• Photoinduced redox processes under visible/natural light illumination.[21] • Can be used against multidrug-resistant bacteria based on their strong capacity in disruption of microbial membranes.

Source: Future Markets, Inc.

3.6 Graphene quantum dots (GQDs)

Graphene quantum dots (GQDs) are a subset of carbon quantum dots-hybridization is different for the two materials. GQDs are in sp2 hybridization whereas CDs in sp3. GQDs are crystalline whereas CQDs are amorphous. GQDs are a disc shaped single layer (less than 20 nm size) and CQDs are spherical shaped particles (less than 10 nm size).

GDs are composed of single or very few graphene lattices (<10) that have quantum confinement effect and edge effects. Unlike graphene sheets, they exhibit band gap that is responsible for their unique electrical and optoelectronic properties.

GQDs are promising materials as substitutes for Cd, Ir, Ga, S, Se and P quantum dots (QDs) and possess unique structural and photophysical properties. Compared with QDs, GQDs are potentially superior due to their high photostability against photobleaching and blinking, biocompatibility, and low toxicity.

3.6.1 Properties

Theoretical and demonstrated properties include:

- high quantum yield
- high electrical conductivity
- high thermal conductivity
- excellent photostability
- biocompatibility
- highly tunable photoluminescence (PL)
- exceptional multi-photon excitation (up-conversion) property
- low-toxicity.

They are potentially important in the biomedical field as they are water-soluble, they can be decorated exploiting different chemical approaches and they possess intrinsic characteristics of fluorescence.

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Table 15: Comparison of graphene QDs and semiconductor QDs.

Types	Optical properties			Stability	Toxicity	Cost
	Quantum yield	Emission	Half-height			
Graphene QDs	90+ %	380-570nm (no red)	>40nm (ca. 70nm)	Yes	No	Low
Semiconductor QDs	• CdSe 10-25% • ZnSe/CdSe 30-50%	480-640nm	40nm>	No	Yes	High

Source: KRI, Inc.

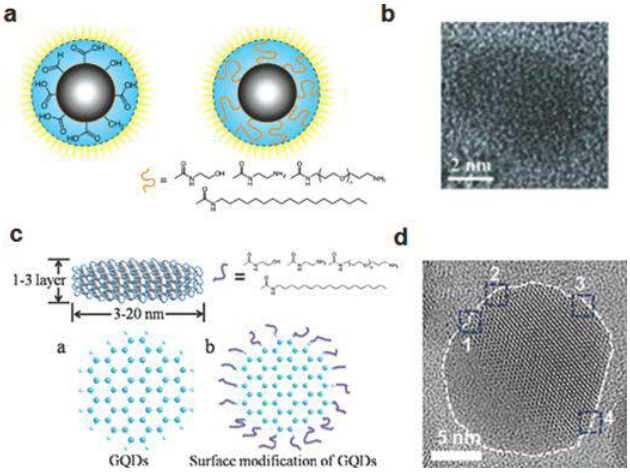

Figure 11: Schematic of (a) CQDs and (c) GQDs. HRTEM images of (b) C-dots and (d) GQDs showing combination of zigzag and armchair edges (positions marked as 1–4).

Image credit: RSC.

3.6.2 Synthesis

There are two main strategies for synthesizing GQDs:

Top-down method: Graphene oxide is manufactured then the graphene sheet is cut through controlled oxidation or the reduction process to the desired size to fabricate GQDs. Specific approaches for preparation include:

- molecular assembly of carbon ring structures
- chemical exfoliation of graphite nanofibers[22]
- chemical synthesis
- modification of graphite nanoparticles
- electron beam lithography
- pulsed laser synthesis
- microwave pyrolysis [23] [24]
- hydrothermal graphene oxide reduction, resulting in the fracture of GO sheets into ultra-small pieces.[25] [26] [27] [28]

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Bottom-up method: Low molecular weight compounds are polymerized to nm-size to obtain GQDs. Various carbon starting materials are utilized.

The bottom-up approach only produces a small quantity of GQDs, limiting its use. The top-down method potentially offers low-cost and high yield and is the main focus of commercial production. There are several technical hurdles that need to be overcome for successful production with low synthesis yields at present due to aggregation that limit industrial scale-up.[29] [30] Also the synthesized GQDs currently display low quantum yield, poor control of the emission wavelength and optical instability.[31] Researchers have recently turned their attentions to developing new methods for synthesis.

3.6.3 Applications

GQDs be used in various applications, such as sensing, consumer electronics, computer storage, medical imaging, sensing, solar cells and energy storage.

Markets	Applications
Optoelectronics, electronics and photonics	• Optoelectronics (LEDs).[32] [33] [34] • Photodetectors.[35] • Sensors. • Quantum computing.
Energy	• Batteries and supercapacitors.[36] • Fuel cells. • Photovoltaics. • Lighting (OLED).
Biomedicine and healthcare	• Bioimaging (e.g. membrane markers, cancer cell imaging, protein analysis, cell tracking).[37] [38] • Biosensors. • Theranostic agents. • Cancer therapy.
Other	• Catalysis.[39] [40] • Printing.[41]

Source: Future Markets, Inc.

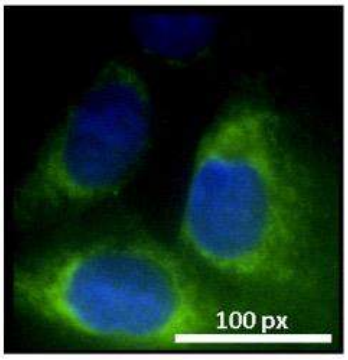

Figure 12: Green-fluorescing graphene quantum dots.

Source: Rice University.

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The advantage of GQDs is that demonstrate comparable properties to cadmium-based QDs but without the potentially hazardous health and environmental effects, and at lower cost. In the coming years, they could be utilized as inexpensive and eco-friendly alternatives to QDs for opto-electronic devices such as displays and lighting devices. The shape and reduced size of GQDs offer substantial advantages over graphene in terms of edge sites and biomedical applications.[42] GQDs strong photoluminescence can be tailored for specific applications by controlling their size, shape, defects, and functionality.

Figure 13: Graphene quantum dots.

The solutions of GQDs emits blue light (460 nm) when excited with 365 nm UV beam.

Source: ACS Materials.

3.6.3.1 Pricing

GQDs are currently commercially available, with materials selling for up to $2.5 million/kg, although recent producers have manufactured materials for less. Competing materials such as high quality, non-toxic Cadmium Quantum Dots selling for up to $8 million/kg.

3.7 Quantum rods

3.7.1 Properties

Quantum rods are rod shaped semiconductor nanocrystals. Desirable properties include:

- tunable narrow emission bands
- polarized emission
- lower self-absorption compared to other quantum materials.

3.7.2 Applications

Applications are in fluorescent biological labels, biological labeling, photovoltaic devices and light emitting diodes.

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4 Technology readiness level (TRL)

Applications listed below have been commercialized or experimentally fabricated and theoretically examined.

Basic concept	Tech concept	Proof of concept	Lab tested	Field tested	Basic prototype	Final prototype	Fully tested	In operation
		Quantum switches Quantum computing				QD MicroLEDs Inkjet printed displays		Edge optic LCDs in TVs
		Printable solar cells			QD colour filter TVs AMQLED QD Glass LGP			On surface LCDs in TVs
			Thin film solar cells		On chip LCDs in TVs			Biosensors
		Solar windows		Flexible displays				Medical contrast agents
		Drug delivery	Photodynamic therapy				QD lasers	
					Infrared imaging			
					Greenhouse films	Security inks & tags		
							Image sensors	
RESEARCH		APPLIED R&D		DEMONSTRATION			COMMERCIAL	

Figure 14: Technology Readiness Level (TRL) for quantum dots.

Source: Future Markets, Inc.

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5 Quantum dots industry analysis

5.1 Licensing, collaborations and partnerships

Most QD manufacturers have established partnerships and collaborations as a key strategy so that they can share the expertise to develop better QD based products and solutions. The business model is typically:

- Partnership: QD producers work in close collaboration with companies seeking to develop QD-based products and applications, ofter under Joint Development Agreements.
- Licence revenue: QD producer receives licence revenue from licensee (e.g. Nanoco and Dow Chemical Company).
- Materials sales: QD producer supplied materials to customers in the display (in coordination with licensee), lighting, solar and life sciences markets.

Quantum Dots are considered a platform technology and most QD producer possess extensive patent portfolios (Nanoco has >360 patents and patent applications covering process, materials, surface chemistry, devices and solar). Nanosys has over 300 patents and patent applications covering:

Processing techniques

- Core-shell nanocrystal growth and coating methods
- Control of size, shape, and composition
- Ligand and matrix material synthesis
- Hermetic sealing and packaging
- Device component manufacturing.

Key Materials

- Core-shell Quantum Dots
- Quantum dots of uniform size
- Quantum dot composites
- Important compositions
- Encapsulated QD materials

Surface Chemistry

- Surface control
- Dispersion technology
- Coating technology
- Functionalization

Quantum Dot Device Applications

- Emphasis on LCD backlights, displays, notebook computers, TVs, and mobile devices

Quantum Dot Devices

- White light emitting devices
- Color conversion devices

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- Specific device architectures
- LED Filters
- Electrical and optically pumped devices.

5.2 Supply chain

Figure 15: Schematic of typical commercialization route for quantum dots producer.

Source: Future Markets.

In terms of progressing from raw materials to final products the following process is typical:

1. Raw materials for the commercial production of QDs purchased from chemical supply companies.
2. Samples or raw materials sent to customers (brand owners)
3. Formulation trials to produce trial products
4. Consumer testing, regulatory compliance and formulation finalized
5. Production trials and scale up for commercial production
6. Pre-production orders
7. Commercial production.

QD technology comes to market in component form. However, QD producers are involved more than most nanomaterials producers in participating at this level of the supply chain. The market for LCD displays is very competitive, and as a result new QD start-ups tend to focus on niche applications. UbiQ, LLC has identified potential markets including:

Table 16: Quantum dots market structure.

Tier	Companies
Chemicals producers	• Supply of raw materials in bulk e.g. indium, cadmium.
Quantum dot IP	• Large coroporations, start-ups and research centres. **Example companies** • Samsung • Nanosys

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Tier	Companies
	• Nanoco • Quantum Materials Corp • Nanjing Technologies
Quantum dot/resin manufacturers	• Sales directly to component makers. • Sales directly of QD materials and films to OEMs-NDAs signed followed by sample agreements. • QD producer formulates, manufactures and supplies product samples to OEM or component makers specifications for evaluation and testing. • Sales directly to research community. • Component development in collaboration with OEMs. • Partnering with film coating companies (e.g. Nanosys and 3M). • Licensing and joint development agreements with application developers and OEMs. **Example companies** • Hansol/Samsung • Nanosys • Nanoco
Film Manufacture	• Purchase QDs from producers and incorporate into products. • Produce materials in-house or in collaboration with QD producers. • QD producers in collaboration with OEMs to develop final product. **Example companies** • SKC Haas • MNTech • GloTech • Kolon • LMS • WAH Hong • EFUN Technology • Jun Ron • Shine On • Fujifilm • Dexterials • Hitachi Chemical • Exciton • Nitto Denko • Konica Minolta
Panel manufacturers	**Example companies** • Samsung Display • Sharp • JDI • LGD • Panasonic LCD • NEC • China Star • AUO • Innolux • BOE • CEC-Panda • HKC Display • Others

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Tier	Companies
End users (OEM) and brand owners	• Develop products in house-materials with materials purchased from QD producers. • Develop products in collaboration with QD producers. • Display makers developing products in collaboration with QD producers and component makers. • OEMS direct sales to global end user markets (e.g. Hisense, ASUS). • Samsung • LG • TCL • Hisense • Sony • Skyworth • TPV (Philips) • Vizio • Others

Source: Future Markets, Inc.

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6 Quantum dots regulations

Nanomaterials will improve the performance of many products in the future but at the same time they exhibit unknown properties and thus may expose humans and the environment to new risks. As display manufacturers seek to use QDs for new colour and efficiency performance in their products there are significant environmental, health and safety criteria that impact new product development. The toxicity and high costs of typical QD materials-namely cadmium selenide and indium phosphide- limit their application beyond displays, despite the fact the are the highest performing QD materials currently available.

Alternative materials to cadmium continues to be an area of research interest both in industry and academia. However, QD materials that do not contain heavy metals in their core or shells exhibit less optical stability and efficiency with broader emission spectra.

Cadmium-based QD materials are subject to regulation limitations in a number of global regulatory environments, which may hinder their uptake in certain applications. In the European Union (EU), Cadmium-based QD materials are subject to the RoHS (Regulation on Hazardous Substances) Act and REACH. A number of QD manufacturers sought exemptions to their use in consumer applications. In 2014, the EU offered a temporary exemption for the use of cadmium-based Quantum Dots for display applications. The main shortcoming of QDs is their toxicity. Cadmium has a toxicity (LD50) of 100 – 300 mg/kg (rats and mice, oral). Therefore, its use has potential significance for both health and the environment.

The Recommendation from the Scientific Committee on Occupational Exposure Limits for cadmium and its inorganic compounds (SCOEL/SUM/136) of February 2010 stated that e exposure during recycling activities of LCD televisions shows that the risk is controlled, meaning that no effect on the health of the workers involved is to be anticipated when taking into account the operational conditions and risk management measures.

6.1 Europe

In Europe, regulation regarding nanomaterials is covered by REACH. Recommendation on the definition of nanomaterials were issued in 2011 and defines nanomaterials as '"Nanomaterial' means a natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50 % or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm - 100 nm".

In specific cases and where warranted by concerns for the environment, health, safety or competitiveness the number size distribution threshold of 50% may be replaced by a threshold between 1 and 50%. By derogation from the above, fullerenes, graphene flakes and single wall carbon nanotubes with one or more external dimensions below 1nm should be considered nanomaterials. There are product specific nanomaterials regulation for cosmetics, food safety and biocides. France, Sweden, Denmark and Belgium have implemented nanomaterials registries.

In France, required information includes the identity of the declarant, information about the properties of the nanomaterial, uses of the substance and the identity of the professional users (confidential information).

In Belgium, data collection will begin in 2015 and Danish registration opened on 20 June 2014 and is compulsory for producers and importers of mixtures and products containing nanomaterials. The first registration period ended on 30 August with few registrations. The Belgium and Danish nano registers contain a long list of exemptions for registration among other substances that are exempt from REACH registration.

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The use of Cd and other heavy metals (Pub and Hg) in electrical and electronic equipment (EEE) is restricted by the EU's RoHS legislation (max. permitted concentration of Cd is 0.01 wt. % (100 ppm). However, the use of cadmium in solid state lighting and displays is currently exempt.

6.1.1 Cadmium exemption in TVs and lighting

Under a 2011 European Directive on RoHS (Restriction of Hazardous Substances Directive), the use of cadmium in TVs and lighting was to be permitted until 1 July 2014, after which it would be illegal. The use of cadmium in displays and lighting is exempt as cadmium quantum dots provide good energy efficiency and colour performance.[43]

After a six-month review process, it was concluded that the use of Cadmium in QD films used for solid state lighting and display lighting applications would not weaken the environmental and health protection afforded by the REACH Regulation. An Exemption was recommended allowing the use of Cd-containing quantum dots in display applications. The recommendation stated that cadmium was allowed for use

"in components for display lighting applications, containing downshifting cadmium based semiconductor nanocrystal quantum dots, where the cadmium per display screen area is limited to less than 0.2 ug/mm2". Therefore, all currently shipping and planned display products using QDs are compliant by a significant margin.

In January 2015, the European Commission (EC) adopted a Delegated Act that would allow cadmium in displays in Europe until June 2018. In May 2015 the European Parliament voted 618 to 33 to reject the Delegated Act. The European Parliament considered the European Commission's justifications for maintaining cadmium exemptions as "manifestly incorrect". The EC subsequently decided to reassess the exemption and their view is that the current exemption remains valid until a full reassessment of it is complete and a new delegated Directive adopted.

The QD film in an LCD application contains up to 20 µg of Cadmium per cm^2 of screen area, which is contained within a physical device. Therefore, disposal, according to some companies, it is unlikely to be environmentally hazardous. The companies involved in the process believe there are no substitute display types that can provide desired performance characteristics in terms of colour performance, energy consumption and scale. They also state that the performance level of Cd-free QD films are not currently viewed as being acceptable and OLEDs cannot yet be made into large-size displays. Both technologies also suffer from increased energy consumption. These claims have been refuted by Cd-free QD producers.

6.1.2 August 2017 ruling

In August 2017 it was announced that the European Commission will prohibit cadmium from TVs and displays sold in Europe from October 2019, as part of the Restriction of Hazardous Substances (RoHS) Directive.[44]

6.2 United States

In order for new chemical substances manufactured in the US to be sold for commercially purposes, the producer most undertake the following process:

1. Submission of a pre-manufacturing notice (PMN) to the Environmental Protection Agency (EPA).
2. The EPA can take a variety of actions. Typically, they place the chemical on the Toxic Substances Control Act (TSCA) chemical inventory without restriction or, as has been the case with carbon nanotube materials, placing the chemical on the inventory with restrictions (most commonly through a section 5(e) Consent Order and/or a Significant New Use Regulation or SNUR).

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3. SNURs that are issued as submissions under the TSCA New Chemicals Program are specific to the manufacturing, processing and use that the manufacturer (or importer) and downstream clients are undertaking.
4. The outcome of this process is that each product is treated as a separate new chemical substance, by producer.
5. The National Institute of Occupational Safety and Health (NIOSH) works closely with manufacturers to review their manufacturing processes and to assess any potential for release of the chemical substance thereby ensuring that no nanomaterials are released and that adequate protections for workers are in place.

The EPA has proposed a one-time reporting and recordkeeping requirements on nanoscale chemical substances in the marketplace. The agency is proposing to use TSCA to collect existing exposure and health and safety information on chemicals currently in the marketplace when manufactured or processed as nanoscale materials. The proposal will require one-time reporting from companies that manufacture or process chemical substances as nanoscale materials. The companies will notify EPA of:

- certain information, including specific chemical identity;
- production volume;
- methods of manufacture; processing, use, exposure, and release information; and,
- available health and safety data.

Market restrictions are greater for cadmium-based products in Europe and Japan than in the United States. Cadmium-based QDs are regulated under the EPA Toxic Substances Control Act.

6.2.1 Low Volume Exemption (LVE)

Until 2015, all Quantum Dot manufacturers in the US manufactured materials under the EPA's Low Volume Exemption (LVE) rule. This rule was designed to enable pilot manufacturing of new materials under certain conditions with strict controls from the EPA.

6.2.2 New Chemicals Program

EPA's New Chemicals Program is designed to minimize potential risks to human health and the environment from new chemicals sold on the market. Anyone who plans to manufacture or import a new chemical for commercial purposes is required, under section 5 of the Toxic Substances Control Act (TSCA), to provide the EPA with advance notice before beginning the activity.

The EPA New Chemical review process starts with a Premanufacture Notice, or PMN, which must be submitted at least 90 days prior to the manufacture or import of the chemical. Upon submission of a PMN the EPA conducts a thorough review of the chemical to determine if it poses any unreasonable risk and whether or how that risk may be controlled. EPA toxicologists, chemists, biochemists, engineers, and experts in other disciplines work together to conduct a thorough review, predicting the potential risks to humans or the environment from each new substance.

If no unreasonable risks are found during the EPA's evaluation, the company may submit a Notice of Commencement (NOC) to list their chemical with the EPA and begin manufacturing.

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6.3 Asia

Japan has not yet developed labelling requirements or definition regarding nanomaterials. Currently, it has no jurisdictional framework specifically designed to address nanomaterials, nor regulations containing provisions defining the size of chemicals. However, there are restrictions in place on the use of cadmium in consumer products.

In 2011, the Ministry of Economy, Trade and Industry (METI) created the Committee on Safety Management for Nanomaterials to increase knowledge on risk management of nanotechnologies. The Ministry of the Environment has also established nanomaterial safety working groups and conducted preliminary surveys on the safety of nanomaterials in occupational settings. The domestic market for QD-TVs in China is Cadmium-based and there are no current restrictions on their use in displays.

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7 Markets for quantum dots

Table 17: Markets, benefits and applications of quantum dots.

Market	Benefits	Application
Batteries	• Improved cycling and storage capacities. [45] [46] [47] Can withstand thousands of charge/discharge cycles, prolonging battery life expectancy considerably.	• Anodes, cathodes and electrolytes in Li-ion (LIB) batteries.
Biomedicine	• Photoluminescent quantum efficiency, narrow emission spectral band, tunability, and photostability.[48] [49] [50] • Highly fluorescent and stable probes for cellular and molecular imaging. Increased brightness allows for sensitive detection. • Biocompatible. Increased brightness allows for sensitive detection. High photostability allowing for long-term monitoring and ease of use. • Narrow emission peaks allow for simple multiplexing. • Ease of illumination via multiple excitation sources. • Easily conjugated to a variety of biomolecules.	• QD fluorescence resonance energy transfer sensors, quenching sensors, and barcoding systems for highly-sensitive genetic and epigenetic detection of diseases, multiplexed identification of infectious pathogens, and tracking of intracellular drug and gene delivery. • Alternatives to organic dyes and fluorescent proteins for various cellular and biomedical imaging.
Electronics (Displays)	• When compared to LCD-TVs, QD-enhanced LCD-TVs use one fifth of the power. • QDs allow for improved battery life in other electronic devices such as smartphones and tablets. • In comparison to organic light-emitting diodes (OLEDs), QDs have a longer operating lifespan lifespan, and are significantly cheaper to produce. • Electrically excited QD thin-film LEDs have reached EQEs of >18% (IQEs of 90%), with a brightness of 50,000 cd/m^2 at only a few volts.[51]	• TVs. • Monitors. • Tablets. • Smartphone displays.
Lighting	• Very narrow emission peaks (< 35 nm). This enables the implementation of adjustable emission spectra tailored to the eye sensitivity curve resulting in improved colour rendition and efficacy. • Broad blue absorption. • Reduced power consumption. • Colour tuneable. • High quantum yield (QY). • Fast radiative decay times-(ns compared to µs). • High luminous efficacy of radiation. • Efficacy improvements due to narrow spectrum: 20-40% benefit for WW. • Soluble. • Customizable spectrum allows high colour rendering index (CRI): >90 easily obtained.	• Solid-state lighting. • General lighting, office and retail lighting, specialty lighting and agricultural (lights utilized in plant growth).[52]

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Market	Benefits	Application
	• Fewer LEDs required in a luminaire. • Even light distribution from QD films. • Customizable films size and shapes. • Easy product integration. • Smaller drivers and heatsinks required.	
Photonics	• Utilizes index coupling grating on GaAs material systems.[53]	• Lasers.
Security & anti-counterfeiting	• Superior optical properties and enhanced photochemical and thermal stabilities. • Offer the ability to specifically control absorption and emission spectra to produce unique validation signatures. QDs emit different wavelengths of visible light under UV excitation; the different spectra act as the anti-counterfeit code.[54]	• Ideal fluorophores for ultra-sensitive, multicolour, and multiplexing applications in anti-counterfeiting label and security identification such as passports and ID cards. • Security inks and taggants.
Sensors	• Up to 300-fold improvement in LF test strip sensitivity demonstrated.[55] • Size-adjustable, bright fluorescence, strong resistance against photo bleaching, narrow band-edge luminescence and excellent compatibility with biological molecules.[56]	• Lateral flow (LF) or immunochromatographic (IC) test strips. • Gas and chemical sensors.[57] • DNA Biosensing. • Blood sampling. • Biological imaging. • Immunoassays. • Glucose biosensors. • Detection of pathogens. • Drug discovery. • Food safety detection.[58] • Pesticide detection.[59]
Solar	• Easily tuned to absorb light at any wavelength and are photochemically robust.	• Schottky QD Junction solar cells. [60] • Silicon/PbS QD film devices. [61] • QD-sensitized solar cells (QDSSC).
Thermoelectrics	• They achieve a significantly higher figure of merit (ZT) than traditional thermoelectric (TE) bulk polycrystalline materials. They can potentially boost energy conversion efficiency to 20-30% depending on temperatures.	• Cooling and waste heat recovery.

Source: Future Markets, Inc.

7.1 Revenues 2013-2030

Table 18: Total QD-based component revenues 2013-2030 ($M), conservative and optimistic estimates.

Year	Conservative estimate (M$)	Optimistic estimate (M$)
2015	1,750	2,550
2016	6,600	7,480
2017	5,600	8,200

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Year	Conservative estimate (M$)	Optimistic estimate (M$)
2018	7,220	8,550
2019	8,000	10,720
2020	9,750	11,250
2021	10,400	13,650
2022	11,313	14,250
2023	12,840	16,800
2024	15,120	20,625
2025	15,731	21,742
2026	18,877	26,091
2027	20,263	31,309
2028	22,290	37,571
2029	23,404	41,242
2030	24,519	43,206

Source: Future Markets, Inc.

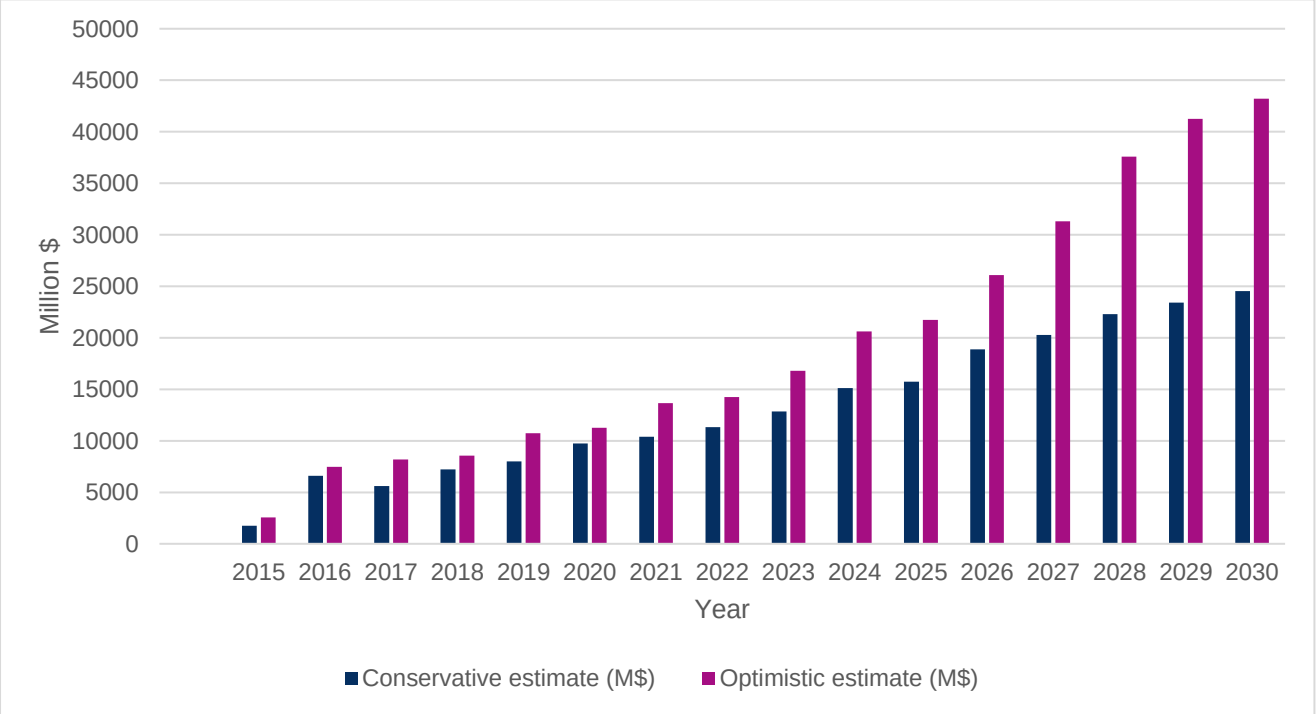

Figure 16: Total QD component revenues 2013-2030 ($M), conservative and optimistic estimates.

Source: Future Markets, Inc.

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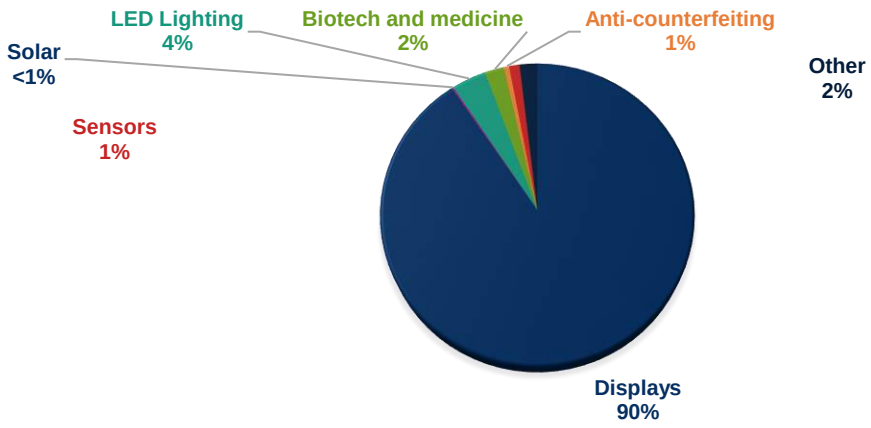

Figure 17: End user markets for QDs 2018, %.

Source: Future Markets, Inc.

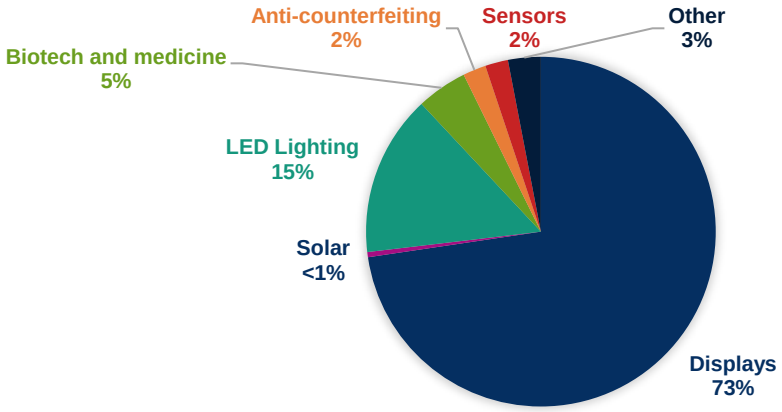

Figure 18: End user markets for QDs 2030, %.

Source: Future Markets, Inc.

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7.2 Production and pricing

7.2.1 Production capacities

Most QD producers have scaled up production to meet the growth in market demand.

Table 19: Production of quantum dots.

Company	Production capacity
Nanoco/Dow Chemical	>800 kg/year > 2,000 kg/year in 2016 4,800 kg/year in 2017
Nanosys, Inc.	2,500 kg/year
Nanoco	400 kg/year
Quantum Materials Corp.	2,250 kg/year

Source: Future Markets, Inc.

7.2.2 Prices

Current costs of quantum dots are ~$200 per gram for general sale. As most producers work with companies on joint development projects prices vary based on volume and other services.

Table 20: Example prices of quantum dots.

Company	Prices
CrystalPlex	$300-$450/25mg
Navillum	~$125/25g
NN-Labs	Cadmium based QDs: $400/100 mg Cadmium free QDs: $1300/100mg
Quantum Materials Corp.	$200/g
UbiQD, LLC	100 mg - $200 500 mg - $900 1g - $1500

Source: Future Markets, Inc.

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7.3 Market for quantum dots, by region

The main demand for quantum dots is in the Asia-Pacific market, from optoelectronics companies. Niche applications and biomedical demand are mainly found in North American and European markets (e.g. biomed and sensors).

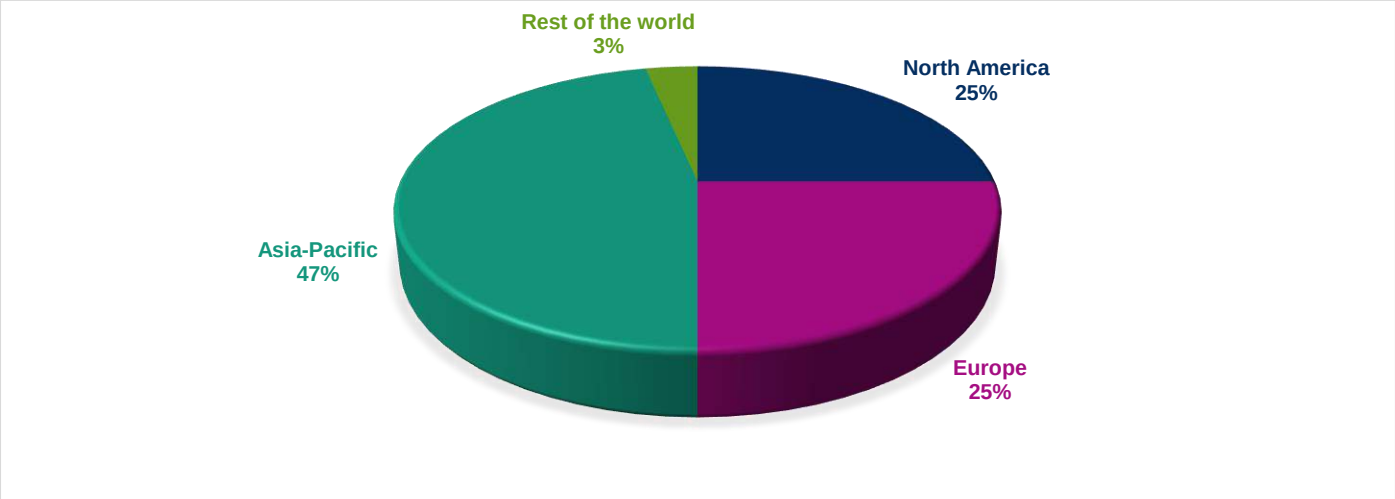

Figure 19: Demand for quantum dots 2017, by region.

Source: Future Markets, Inc.

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8 QUANTUM DOTS IN TVS/DISPLAYS

Table 21: Market snapshot for quantum dots in TV/displays.

Category	Assessment	Trend
Market age	Early maturity	Increasing
Revenues (at the component level) in 2015	$400 million-$500 million	Increasing
Potential revenues by 2027	>$12.5-20 billion	Increasing
Base year market growth rate (2015)	>233%	Increasing
Forecast period market growth rate	31.2%	Increasing
Price sensitivity	Low	Decreasing
Competitors (Active market competitors in base year)	4-5 main producers	Increasing
Degree of competition (Low=1, High=10)	9	Increasing
Degree of technical change	Medium	Increasing

Source: Future Markets.

8.1 Market drivers and trends

As well as enabling novel approaches to display designs, nanomaterials are also incorporated into display components, such as transparent electrodes, thin film transistors, coatings, sensors, transparent conductors, and infrared and visible photodetectors. Multinational companies Toshiba, Motorola, Hitachi, Sony, Panasonic, Philips and Samsung are all developing nanomaterial-based display technologies, utilizing a variety of nanomaterials including graphene, carbon nanotubes, silver nanowires and quantum dots (QD). High luminescence efficiency and tunable saturated colour plus improvements in the past few years in terms of stability, brightness and processability has pushed quantum dots to the forefront of high-colour display applications.

With a colour performance that achieves 100% of the NTSC standard compared to 60–70% from most mainstream Liquid Crystal Displays (LCD) designs, QD-based films have made significant inroads as a disruptive technology in the displays market over the last few years. Quantum Dot Enhacement Film' (QDEF) replaces the phosphor coating and diffuser film in the display backlights. They exhibit:

- external quantum efficiencies >10% for all three fundamental colours (>18% for green)
- device lifetimes of >300 khours
- extreme tuned colour fidelity.

Sony (Triluminos) introduced QD-enhanced TVs in 2013, and Samsung are betting on the technology in their SUHD TV line-up after pulling out of OLED-TV production. They are competing with LG Electronics, who are developing OLED TVs for the mass market (although LG has also developed QD-TVS-LG “Color Prime” UF9400). Panasonic, TCL and Sharp have also developed quantum dot-based LED-LCD 4K TVs.[62] Samsung shipped approximately 2 million QD-TVs in 2017.

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Figure 20: Samsung QD-LCD TVs, UHD range.

Image credit: Samsung.

Figure 21: Samsung QLED TV range.

Image credit: Samsung.

Table 22: Market drivers and trends for quantum dots in LCD TVs and Displays.

Driver	Trends
Improved performance with less power	The significant increase in energy consumption globally has led to a market push for environmentally-friendly and renewable energy sources.[63] When compared to LCD-TVs, QD-enhanced LCD-TVs use one fifth of the power. QDs also allow for improved battery life in other electronic devices such as smartphones and tablets. In comparison to organic light-emitting diodes (OLEDs), QDs have a longer operating lifespan life span, and are

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Driver	Trends
	significantly cheaper to produce. Electrically excited QD thin-film LEDs have reached EQEs of >18% (IQEs of 90%), with a brightness of 50,000 cd/m^2 at only a few volts.[64]
LOWER COST COMPARED TO OLED	While they outperform QD-TVs in a number of areas, large screen OLED-TVs are currently not viewed as cost effective for the mass market (models are priced around $6000). Issues with cost are likely to be addressed in the coming years, as are reliability and process issues, but at present QD-TVs are the cheaper alternative as they are easy to integrate into existing LCD manufacturing.[65] LCD-TVs will remain the mass market choice for a number of years, due to their low cost and the difficulty in compelling customers to move beyond LCD. Beyond vast improvements in colour performance, OLED manufacturers will experience difficulties in compelling consumers to change from LCD, especially as LCDs meet a vast percentage of consumer needs. The addition of QDs has allowed LCD manufacturers to correct the colour performance issues, making market penetration even more difficult for OLEDs.

Table 23: Impact of market drivers for quantum dots in the LCD TVs/Displays market.

Rank	Driver	1-2 years	3-4 years	5-8 years
1	Growth in demand for high definition displays and TVs	High	High	High
2	Price compared to OLED	High	Medium	Low
3	Need for improved image sensors	High	Medium	Medium

Source: Future Markets.

8.1 Display performance progress

Table 24. Example QD display products by manufacturer.

Company	Model	Size
Hewlett Packard	Pavillion 27	27”
	Omen X Emperium	65”
Vizio	P-Series Quantum X	65” & 75”
	P-Series Quantum	65” & 75
	M-Series	43”-65”
Hisense	H9F	55”-65”
	U9F	75”
	ULED XD	65”
TCL	X10 QLED 8K TV	75”
	8-Series	65”
	TCL QD Bezel-Less Glass TV	65”
Samsung	2019 QLED TV Lineup	43”-85”
	Q900 8K TV	65”,75”,82”,85” & 98”
	The Frame	43”, 49”, 55” 65
	Serif TV	43” 49” 55”
	CRG9 Monitor	49”

Source: Future Markets, Inc.

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8.2 Applications

8.2.1 LCDS vs. OLEDs vs. QD-LCDs/QLEDs

Traditional Liquid Crystal Displays (LCD) offer only a fraction of the colours that are visible to the human eye, and can only reach 70% of the colour performance of organic light-emitting diodes (OLEDs). OLEDs are thinner, have a clearer picture and utilize significantly less power. However, they also suffer from several drawbacks, especially cost for application in large display panels. QD films and resins used in LCD-display backlights are regarded as superior to LCD and comparable to OLED (QDs are easily integrated into existing LCD displays).

QD are approximately 10-50% more efficient than standard LCDs. They function by converting light of one colour into a different colour within a precise wavelength range that can be tailored via control of the QD particles. QDs produce narrow output spectral distributions that are easily tuneable in peak wavelength to match any set of LCD colour filters. QDs are also capable of doing this with high efficiency, leading to a reduction in energy consumption. However, traditional LCDs are relatively inexpensive to produce in large screen sizes, and consumers will generally choose the right price over the right colour. Quantum Dots are being used as a platform technology for multiple display technologies including LCD, OLED, microLED and emissive QD.

The traditional LCD market is mature and very competitive, with revenues falling after high capital spending. Therefore, the incorporation of QDs into LCD devices is of increasing importance, especially in the face of future competition from OLED-TVs. The great benefit of QDs is their easy integration into existing LCD supply chain, with white LEDs replaced by blue LEDs.

Table 25: Advantages and disadvantages of LCDs, OLEDs and QDs.

Technology	Advantages	Disadvantages
LCD	• Cheap to manufacture. • Low power consumption. • High resolution density.	• Poor blacks and contrast. • Narrow colour gamut- Display only a fraction of the colours that are visible to the human eye. Can only reach about 70% of the colour performance of OLEDs. • ED light source does not meet the requirement for narrow colour peaks. • Lack of saturated green and red. • Thicker panel. • Lower sunlight legibility. • Poor energy efficiency. • As backlight in displays a substantial fraction of the emitted light from white LEDs (wLEDs) needs to be filtered out leading to efficiency.
OLED	• OLED manufacturers claim larger size OLEDs can be built that will provide a comparable colour gamut to QD film. • Energy usage likely to reduce significantly in the next few years. • Superior response time to LCD. • More vivid colour and better contrast ratio (in dark ambient). • Flexibility.	• Energy consumption of an OLED display is significantly higher than QD film LEDs (as high as three times that of a cadmium-based QD-LCD). • Cadmium generated in waste from the additional electricity generation required to operate OLEDs exceeds the amount of cadmium present in an equivalent QD film.

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Technology	Advantages	Disadvantages
	• Superior contrast ratio, viewing angles and response time compared to QD-LCDs. • Thinner and lighter than QD-TV (no backlight required). • Response time less than 0.001 milliseconds (approx. 1,000 times faster than LDC).	• Mass production issues for applications in large-size displays- OLEDs cannot currently be made in acceptable yields except in small sizes and cannot be made in larger sizes in sufficient quantities. • Expected to have high production costs for at least a few more years. • Yields and capital spending requirements will keep costs high.
QD-LCDs	• Emission colour can be tuned by simply changing their dimensions. • Significantly larger range of colours (60%-100% improvement over LCD). • Colour gamut of 125% (OLEDs is 108%). • Quantum efficiencies (EQEs) >10% for all three fundamental colours red, green, and blue (21% EQE, 82 cd/A for green). • Device lifetimes of >280K hours. • Reported narrow QLED emission spectra (full width at half maximum < 30 nm) and well-controlled peak wavelengths generate a Color gamut covering >170% of the National Television System Committee (NTSC) 1987 Color space and 90-95% of the Rec. 2020 colour space. • Relatively low-cost fabrication using solution processing. • Power consumption: more energy efficient than OLEDs (> 2 times) at the same colour purity.	• Toxicity of cadmium, and regulations thereof in key markets. • Reduced optical performance of cadmium-free QDs. • In low temperature environments, QD-TVs colour gamut may decrease. • In dark environments, QD-TVs colour gamut not at same level as OLEDs. • Stability difficulties when exposed to high flux of blue photons and high temperatures.

Source: Future Markets, Inc.

In October 2019, the cadmium quantum dots exemption ends in Europe and all imported and produced QD TVs must incorporate cadmium free QDs. However, cadmium free QD TVs are still sold widely, especially in the Chinese market.

8.2.2 QD-LCD TVs/QLEDs

The use of QDs in LCDs could be described as bridging the gap between LCD and OLED. QD down converters in LCD-displays now offer a variety of high colour performance devices for applications ranging from 3” diagonal hand held smart phones to +85” diagonal TVs. Market research indicates that people clearly prefer these high colour displays.

QD-LCD TVs harness the optically induced emission (photoluminescence) of QDs for use in the backlighting of LCDs. The LED light source in traditional LCDs does not meet the requirements for narrow colour peaks-therefore QDs are utilized to correct this due to their narrow emission spectra, tuneable wavelength and high quantum yield (QY). Incorporation of QDs allows for strong emission peaks in all three primaries: red, blue, and green.

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They are easily integrated into LCD manufacturing via modification of the backlights and colour filters inside the LCD stack. Energy savings are associated with improved efficiency of the LED backlights. The majority of current technology is the result of over two decades of extensive research and development on CdSe/ZnS quantum dots. QD-LEDs possess unique properties of the tunable emission wavelengths via:

- Controlling the size of QDs.
- Highly saturated emission.
- Narrow emission with small full width at half maxima (FWHM).
- Solution processing.
- Compatibility with flexible substrates.

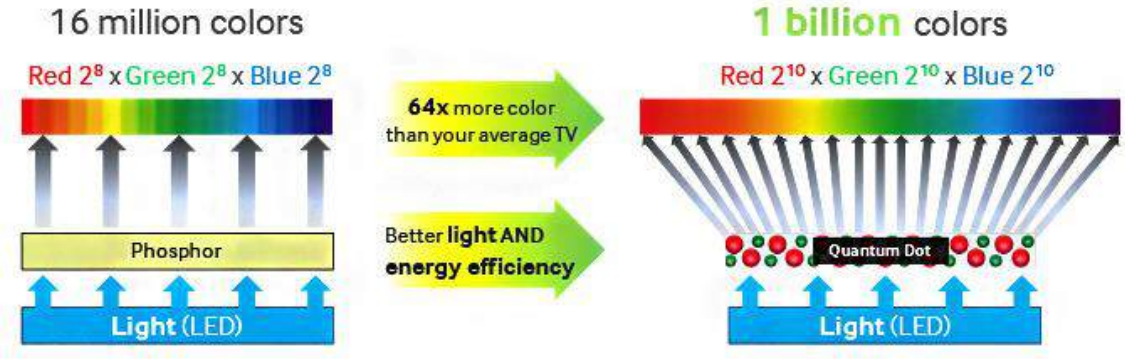

Figure 22: Quantum dot LED backlighting schematic.

Image credit: Samsung.

Upcoming QD applications include QD-OLED and QD-MicroLED, followed by EL-QD and QD-TADF hybrids. QD-MicroLEDs for small screens and EL-QDs seem the most likely technologies to hit the market in the next 18 months, with Nanophotonica stating that they will have an EL-QD prototype ready by early 2020.

8.2.3 QD-Micro-LEDs

MicroLEDs are brighter, smaller, lighter, and more energy-efficient and have a longer operating life compared with other display technologies. QDs which can emit red, green, and blue colors have been incorporated into micro-LED arrays in display technology. Inorganic microLEDs will greatly impact the display market as light emitting pixel elements (similar to OLEDs) for application in Microdisplays for wearable electronics, mobile electronics and Augmented /Virtual Reality (AR/VR). Similar to OLED, microLEDs do not require a backlight.

MicroLED developer Plessey Semiconductor has a partnership with Nanoco to integrate Nanoco's cadmium-free quantum dots into micro-LED displays.

Using electroluminescent quantum dot colour converters in microLEDs, instead of mixing red, blue and green LED chips, QDs can be applied to a single color blue microLED array that is much simpler to make. Patterned, photo-emissive QDs can then convert blue light into both red and green at the appropriate sub pixel locations. QD color converters can significantly reduce the defect rate that is associated with pick and place manufacturing. Development has mainly focused on cadmium based QDs but recent research has focused on InP-based ELQD displays.

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Figure 23: The Wall microLED display.

Image source: Samsung.

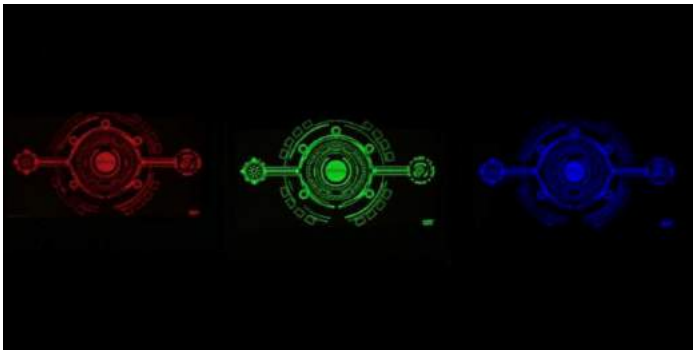

Figure 24: Individual red, green and blue microLED arrays based on quantum dots.

Image: Plessey.

For virtual reality (VR) and augmented reality (AR) applications, image quality can be improved considerably using quantum dots. Micro-LED panels coated with QDs has been investigated.

8.2.4 Electroluminescent quantum dots

Electroluminescent quantum dots (EL QDs, also called QD-LEDs), emit light when they are exposed to an electric current. A display with pixels based on electroluminescent quantum dots (a technology often called QDEL) would emit red, green, and blue photons in response to electrical signals, much like OLED displays

Displays made with EL QDs are much brighter than OLED panels as well as thinner and simpler to manufacture than current LCD panels (inkjet printable)-and are able to reproduce a wider color gamut. Main players in this area are Nanosys and Nanophotonica.

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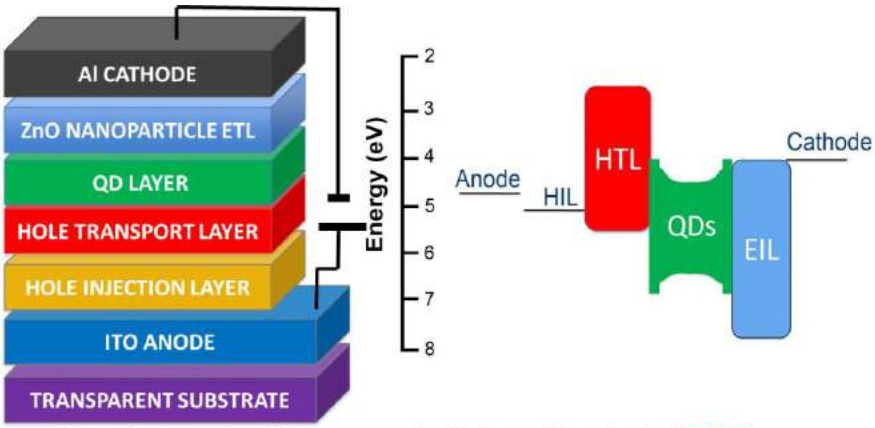


- All solution processable quantum dot light-emitting diode (**QLED**)
- Solvent orthogonality enables multilayered structure
- Good charge confinement in QD
- Good electron injection from ZnO NPs

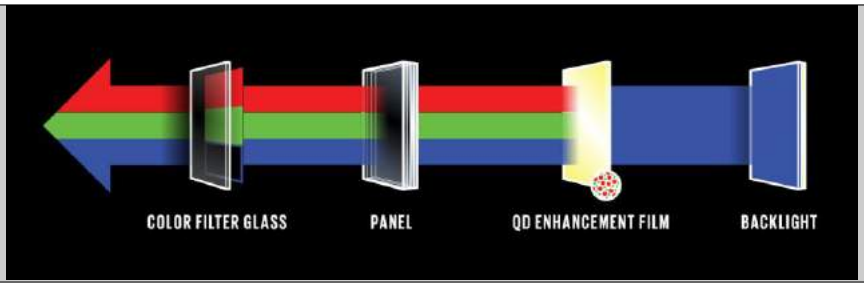
Figure 25. Schematic of EL-QD stack.

Electroluminescent Quantum Dot displays (QDEL) are fundamentally disruptive to the display market. Unlike OLEDs or LCDs, QDEL devices can be made using only solution processing. This means devices can be significantly lower cost to manufacture, opening up many new applications for displays where today only printed materials are used. This kind of ultra-low cost printed display technology is making rapid progress towards commercialization.

8.3 Synthesis and manufacturing

The synthesis of colloidal QDs is scalable, with the key technical challenge to maintain monodispersity. The manufacturing cost of QD-LEDs can be broadly divided into the cost of raw materials and the fabrication costs of processing these materials. Because QD-LEDs and OLEDs are fabricated using a similar toolbox of thin-film processing techniques (for example, ink-jet and micro-contact printing, and thermal evaporation and sputtering), QD-LED commercialization has benefitted from the manufacturing infrastructure and expertise developed for OLED production. Aside from the QDs themselves, the materials typically employed in QD-LEDs (metals, metal oxides and organic small molecules) are also very similar to those found in OLEDs.

Table 26: Types of QD-TV displays.

Type	
Photo-Enhanced Quantum-Dot TV	

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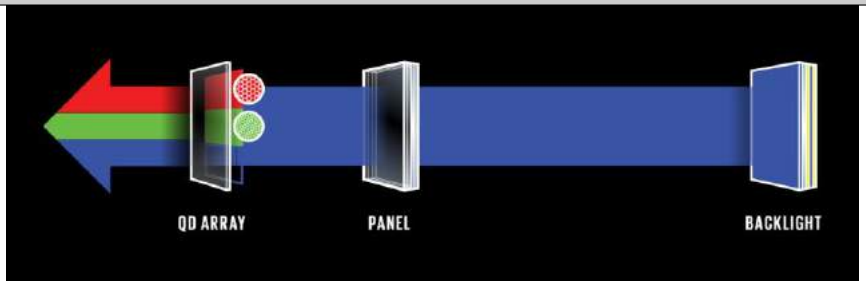
Set-up
QDs inserted between an LED array and colour filters purify the television's backlight to improve colour reproduction.

Advantages
• Deep colour at high peak luminance • Low cost • No burn-in • Manufactured using existing LCD infrastructure • Available now

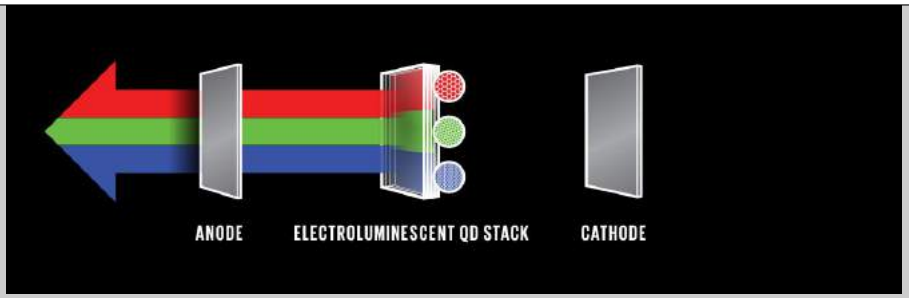
Photo-Emissive QD TV



Set-up
QDs replace the filters and become the red and green subpixels themselves; the blue backlight excites the dots and creates the blue subpixels.

Advantages
• Wide viewing angle • Potential threefold jump in efficiency and brightness over LCDs • Manufacturers can use existing LCD infrastructure.

Electro-Emissive QD TV



Set-up
QDs emit light themselves when an electric current is applied-no backlight is involved.

Advantages
• Perfect viewing angle • Perfect black levels • Potential low-cost manufacturing • Fast refresh rate • Flexible substrates • No filters needed • Long lifetimes.

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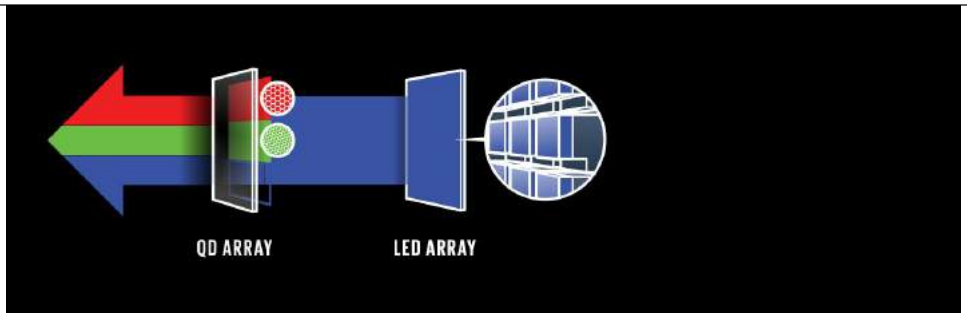
Micro-LED TV With QDs	 **Set-up** Array of microscopic monochrome LEDs, with quantum dots providing colour conversion for the red and green subpixels. **Advantages** • Perfect viewing angle • No filters needed • Perfect blacks • Brightest technology • Fast refresh rate • Flexible substrates possible.

8.3.1 Integration into LCDs

There are three methods to integrate quantum dots into conventional LCD back light units (BLUs):

- On-chip.
- On-edge (edge-optic).
- On-surface (film).

When using QD film, the only other change to the LCD system that is necessary is to substitute the white LEDs with blue LEDs (nominally by using the same GaN LEDs but without the YAG phosphor). The total amount of QDs needed, as well as the ratio of green to red dots, depends on a number of factors. These include:

- The desired colour specifications of the display.
- The amount of light recycling (number and efficiency of light reflections) in the BLU.
- The properties of the colour filters in the panel.

The concentration of QDs, and therefore, the concentration of cadmium in QD films depend on these factors and the total thickness of the film. However, no more than 20 µg of cadmium/ cm^2 of screen area should be used for any application. Typically, only 3-5 µg of cadmium/cm^2 of screen area is used.

Table 27: Approaches for integrating QDs into displays.

	On-Chip	On-edge (edge-optic)	On-Surface (film)
QD Integration	• QDs placed directly within LED package (directly on the blue LED dye), which is coupled to light guide.	• QDs placed between LED package and light guide.	• QDs placed in thin film on top of the light guide plate, covering entire display surface.
Operating temperature	• High (~ 150°C).[66]	• Moderate (between that of on-surface and on-chip).	• Near room temperature (Resulting in Improved system lifetime).

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QDs usage	• Low (Small surface area). In the single pass configuration a higher concentration of quantum dots are required.	•Moderate (Medium surface area). In the single pass configuration a higher concentration of QDs are also required.	•High (Largest surface area). • Significantly lower concentration of quantum dots needed due to multiple light reflection.
Pros & cons	• Most efficient approach. • Need to withstand high temperatures. • Need a cost effective way of sealing against oxygen • QDs are exposed to extreme light flux and temperature conditions resulting in reduced life and performance levels. Therefore, this is not viewed as viable for product integration for a number of years.	• Assembly issues. • Need additional room in the device. • Capillary is fragile (potential for exposure to QD resin). • Method is not scalable to smaller screen sizes due to bezel constraints.	• Ease of mass production. • Lower optical flux and heat. • Easy to incorporate into an existing device-same assembly.

Source: Future Markets, Inc.

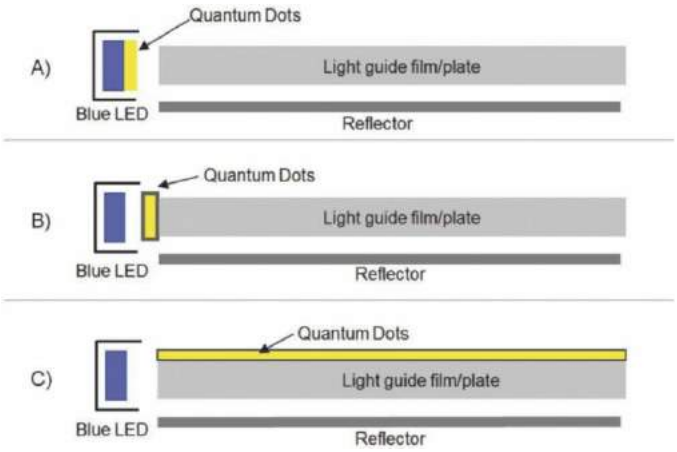

Figure 26: Methods for integrating QDs into LCD System. (a) On-chip (b) On-edge. (c) On-surface.

Quantum dot manufacturers have developed products that are easily integrated into the existing LCD manufacturing process. As outlined in the above table, ideally QDs would be deposited directly on the LED (“on-chip”). However, currently available QDs degrade at the high temperature utilized in processing. Main current methods for integration are edge optic and film.

8.3.1.1 On-edge (edge optic)

QD Vision utilizes the on-edge configuration, whereby QDs are placed in a glass tube above the LED bars that are located on the edge of the screen. This configuration is most suitable for large displays, less so for mobile displays. It is viewed as cost effective for commercialization and is incorporated into a number of mass produced QD-TV products. [67]

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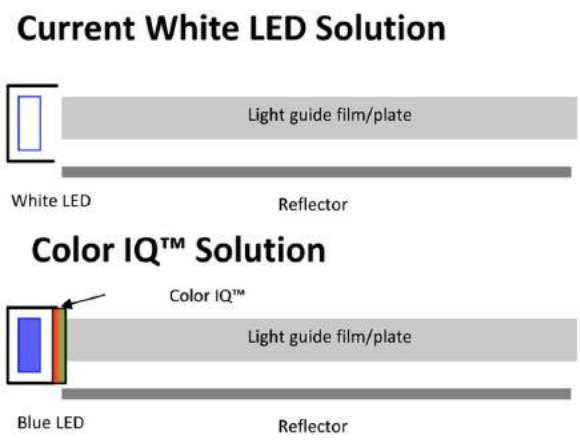

Figure 27: On-edge configuration.

Image credit: QD Vision.

8.3.1.2 On-surface (film)

Nanosys and 3M utilizes the on-surface configuration whereby QDs are embedded between optically transparent films and placed over the entire backlight surface. The film based method is more expensive than on-edge but is the better candidate for incorporation into high dynamic range (HDR) TVs. This is the most widely used method at present.

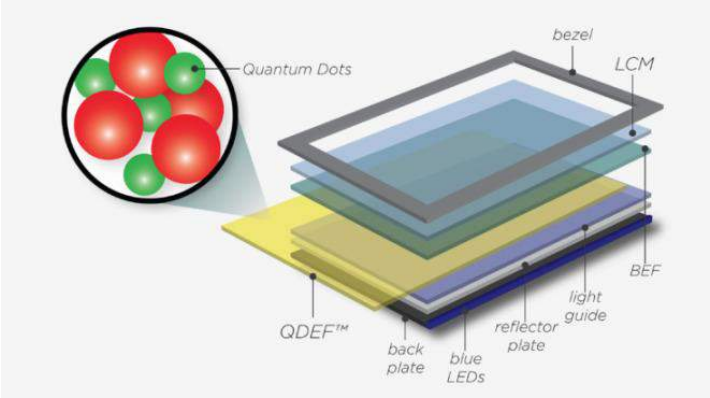

Figure 28: QD-film integration into a standard LCD display.

Image credit: Nanosys, Inc.

8.3.1.3 QD colour filter (QDF)

Quantum dot colour filters (QDCF) offer numerous advantages over the film configuration and the technology is being developed by Samsung, Nanosys and Nanoco. Advantages include:

- Improved brightness/efficiency.
- Wider viewing angles.
- Lower light flux and temperature.
- Thinner display.

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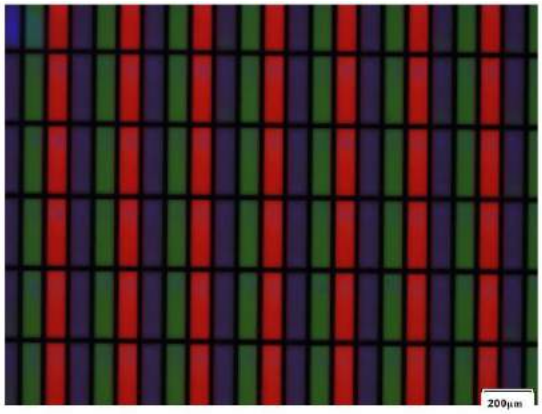

Figure 29: Inkjet-printed pattern on a QDCF.

Image credit: DIC.

8.3.1.4 On-chip

In the on-chip configuration (also called drop-in solution), QDs reside within the LED package itself (replacing phosphors) and implementation is viewed as important for reducing cost and increasing the flexibility of a QD solution for future display applications. However, they have not been implemented thus far due to the high temperature used in processing, radiant flux, and environmental demands of the on-chip architecture.

There are several companies developing on-chip technology for QLED-TVs and they potentially will offer the lowest cost TVs as re-design of TVS are not required. It also works for all sizes of displays and lighting, and the technology has been commercialized for mid-power LED lighting.[68] QDs have failed as a drop-in solution into the LED package because the LED operating temperature and blue flux intensities caused dramatic thermal quenching and fast photodegradation.[69] [70] [71]Nevertheless, an on-chip phosphor application in silicone is preferred over remote phosphor configurations as it provides the lowest cost and lowest complexity solution for LED use in lighting and display applications. However, it may not eventually be used in LED displays as applications of QD colour filters may be on the market sooner.

8.3.1.5 QD Glass LGP

Samsung Display has demonstrated QD Glass 65” TV and 31.5” monitors. These displays employ a new backlight technology where QD are coated directly onto a Glass light guide plate (LGP).

Figure 30: Samsung 8K 65" QD Glass.

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Image credit: Samsung.

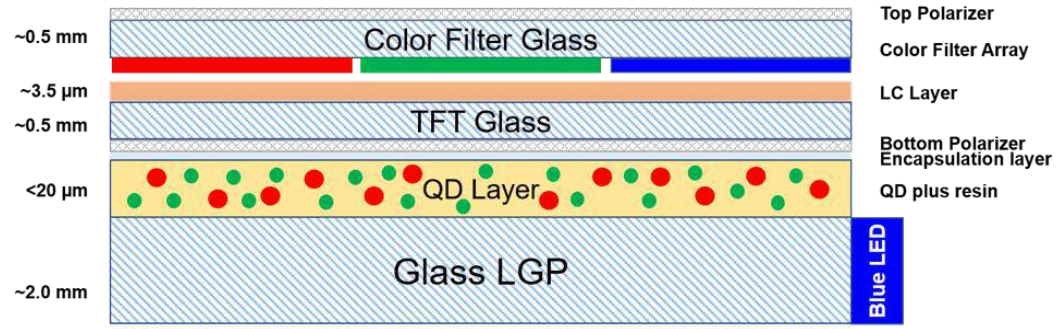

Figure 31: Schematic of Quantum Dot on Glass.

8.3.1.6 Quantum dot/OLED hybrid

Samsung is collaborating with Canon and Kateeva to develop a pilot line for QD/OLED hybrid display technology.[72]

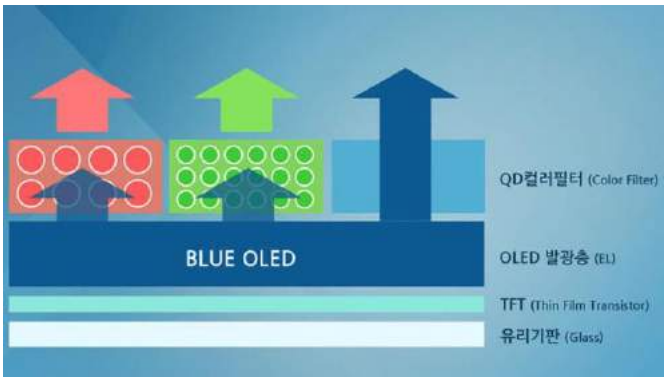

Figure 32: QD/OLED hybrid schematic.

8.3.1.7 Quantum converters with red phosphors

In December 2015, Osram announced a new quantum colours conversion technology for LCDs based on a green quantum converter which is combined with red phosphor on a blue chip. The company claim the product is superior to currently available QD films and over 50% less expensive.8According to the company “For a 55in Ultra HD TV with 100% DCI coverage, the complete cost of the light source can be as low as €55.” The green peak is narrow (30nm full width at half maximum) for distinct colours - Osram claims 100% DCI colour space coverage and >80% of REC2020.

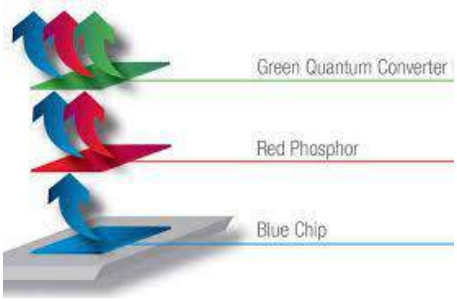

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Figure 33: Quantum phosphor schematic in LED TV backlight.

8.3.2 Flexible displays

There is increasing demand for flexible and wearable displays for application in smartphones, automotive displays, and wearable smart devices . Flexible displays are essentially very thin display screens that can be printed onto flexible or stretchable materials and then attached to other surfaces or produced in a variety of shapes. Main flexible display technologies are:

- Flexible LCDs.
- FOLED, Flexible AMOLED.
- E-paper: Electrophoretic, Cholesteric LCDs.
- Electrowetting Displays (EWD), Electrochromic Displays.
- Interferometric Modulator Technology.

The use of advanced materials and developments in processing techniques is enabling displays with unique form factors that the current rigid glass substrate-based displays cannot support. Flexible displays can be very thin and lightweight, have unique form factors, and be highly rugged and not prone to breakage on impact unlike rigid and flat glass substrate-based displays.

The flexible form factors such as having an arbitrary shape, ability to be curved, conformal, bendable, foldable, and rollable can enable a variety of new applications and products for the displays and electronic components markets. Applications are in:

- “Paper” like displays for E-paper, E-book, wearable computers and rollable displays.
- Low-end phones that are robust and can be manufactured using low-cost roll-to roll processes.
- High-end multi-media devices with unique designs and high functionality.

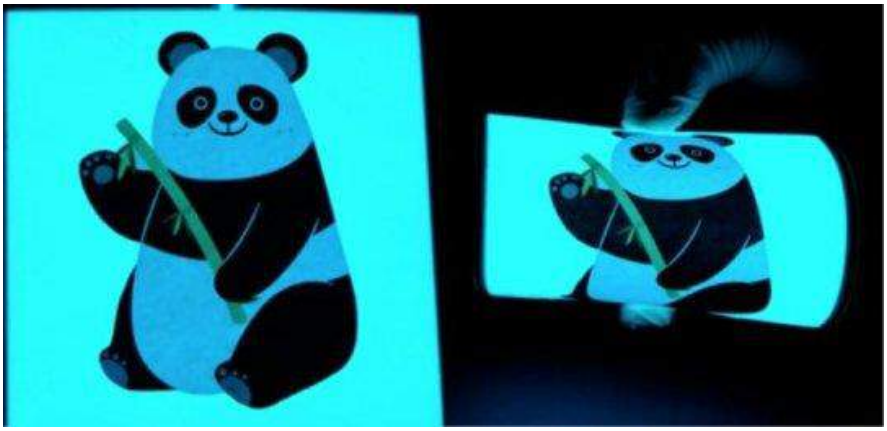

Figure 34: Carbon nanotubes flexible, rechargeable yarn batteries incorporated into flexible, rechargeable yarn batteries.

Credit: American Chemical Society.[73]

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8.3.2.1 Inkjet printed QD displays

A number of companies such as Kateeva and TCL are developing inkjet-printed QDs for application in displays. In March 2018 Nanosys and DIC announced a breakthrough using inkjet printing to produce QD color conversion devices for application in microLEDs. The technology could help solve manufacturing yield issues for microLEDs.[74]

Figure 35: Ink-jet printed 5-inch AM-QLED display (80 dpi).

Source: TCL.

8.3.2.2 Flexible QLEDs

Flexible quantum dot light emitting diodes (QLEDs) are highly desired due to their advantages of foldability, lightweight, and potential applications in lighting and displays. QLEDs can be printed on films that can curve, bend and stretch.[75]

The device structure of flexible/wearable QLEDs are mainly adopted from standard QLEDs with several modifications to achieve high deformability. The performance and stability of QLEDs are largely dependent on the choice of charge transport layers (CTLs) materials and this greatly impacts their application in flexible electronics. ZnO nanoparticles have been utilized that display good performance for flexible displays.[76] Cellulose nanofiber has been investigated as a translucent diffuser film optoelectronic devices such as thin-film silicon solar cells and organic light-emitting devices and combined with Quantum Dots for foldable transparent and photoluminescent E-Paper.[77]

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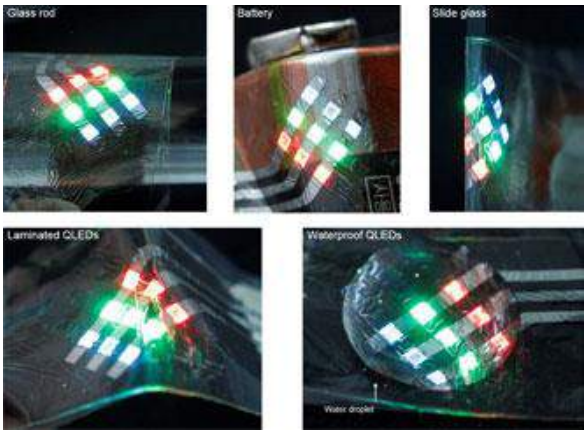

Figure 36: Flexible & stretchable LEDs based on quantum dots.

Image credit: Institute for Basic Science.

8.4 QD-LCD products

8.4.1 Commercialization timeline for quantum dot display products

Table 28: Commercialization timeline for QD display products.

Year	
1980	Quantum dots discovered.
2001	Nanoco Technologies founded. Nanosys founded.
2004	QD Vision founded.
2005	White-light quantum dots discovered at Vanderbilt University.[78]
2007	Researchers develop white light generation controlled and tuned by multi-color quantum-dot–quantum-well emitters.[79]
2008	Researchers develop White Light-Emitting Diodes with Excellent Color Rendering.[80]
2010	Highly luminescent, multiply passivated green- and red-light-emitting quantum dots are used as color converters in InGaN blue LEDs.[81]
2013	Sony's line of Triluminos LCD televisions utilized edge-mounted red and green QDs from QD Vision to optically down-convert some of the television's blue LED backlight.
2015	Electronics giants Samsung and LG produce high-end QD-TVs utilizing QDs to improve colour performance and improve power efficiency. Hisense launch the first LCD TV using photoluminescence quantum dots in 2015.
2016	Samsung unveils new line of SUHD TVs incorporating QDs. AUO produce complete series of 55, 65, 75 and 85-inch UHD 4K quantum dot curved LCD TV displays
January 2017	Samsung, TCL and TPV Philips unveil new range of QLED TVs.

Source: Future Markets, Inc.

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The main quantum dots suppliers in the QD-TV sector are Nanosys, Inc. (license their technology to 3M) and QD Vision. Nanoco is the main player in cadmium-free QDs, although a number of cadmium QD producers are producing cadmium-free QDs to precipitate regulatory hurdles.

Figure 37: Samsung CF791 QD monitor.

Sony was the first company to offer TVs with QD film technology in 2013. Samsung Electronics, LG Electronics and TCL also sell QD-enhanced TVs. Chinese company Tongfang Global is producing QD-TVs, utilizing QD Vision's technology.[82] Most companies utilize Cd-based QDs due to the larger colour gamut they provide. Samsung utilizes cadmium-free QDs in it's Nanocrystal based TV products and is working with Dow Chemical using Nanoco's QDs in future product development.[83]

Figure 38: Acer Z271UV Quantum Dot monitor.

Image credit: Acer.

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8.5 Industry and research developments 2013-2019

Table 29: Commercial development and research highlights in quantum dots in LCDs and OLEDs 2013-2019.

Month	
January 2013	• Sony demonstrates QD Vision's quantum dots in its high-end Bravia television at the Consumer Electronics Show. • Dow Electronic Materials and Nanoco Group plc. announce they have entered into a global licensing agreement for Nanoco's cadmium-free quantum dot technology. Under the terms of the agreement, Dow Electronic Materials has exclusive worldwide rights for the sale, marketing and manufacture of Nanoco's cadmium-free quantum dots for use in electronic displays.
April 2013	• QD Vision raises $20 million in financing to further expand its production capacity. • QD Vision reports achieving 18 percent External Quantum Efficiency, which puts QLEDs near the fundamental efficiency limit of the technology. • Nanosys expands into a new, high-capacity production facility in Milpitas, California. The 60,000 square foot facility will produce over 1,000 kilograms of quantum dots per year.
May 2013	• 3M announces it is in the final stages of scale-up for its new 3MTM Quantum Dot Enhancement Film (QDEF).
June 2014	• Quantum Materials Corp. announces producing 250 kilograms of quantum dots per annum. • QD Vision, Inc., announces the BOE Technology Group Co., Ltd. (BOE), China's largest LCD panel maker, is producing prototypes of 23.6" and 27" monitors featuring QD Vision's Color IQTM optics and ShineOn's LED backlight solution. • Nanosys, Inc. announces LMS Co., Ltd. has been qualified by Nanosys to utilize QDEF technology for its Quantum Light Accumulation Sheet (QLAS).
January 2015	• Samsung and Nanosys announce they have entered a multi-year agreement whereby Samsung Electronics will adopt Nanosys's QDs in its products. • Philips and AOC, adopt QD Vision's Color IQ™ quantum dot technology to deliver industry-leading colour performance for their new 27" high-performance LCD monitors.
June 2015	• Nanosys announces that it has become the first and only Quantum Dot manufacturer to complete the United States Environmental Protection Agency's (EPA) New Chemicals Program review process for its Quantum Dot materials and components.
September 2015	• AU Optronics Corp., Nanosys and 3M announce a AUO ALCD (Advanced LCD) technology which pairs 3M's Quantum Dot Enhancement Film, made with quantum dots produced by California-based Nanosys, Inc., with AUO's backlight components, thus allowing an exceptionally wide Color gamut and high dynamic range for UHD 4K TV panels up to 85 inches. • QD Vision, Inc. announces that Tongfang Global, Ltd. will produce "wide Color gamut" televisions based on QD Vision's Color IQTM quantum dot technology.
October 2015	• Vizio unveils "The 65" Reference Series QD-TV.[84]
November 2015	• QD Vision announces $22 million funding.
December 2015	• Osram announces a new quantum colours conversion technology for LCDs based on a green quantum converter which is combined with red phosphor on a blue chip. The company claim the product is superior to currently available QD films and over 50% less expensive.[85]
January 2016	Samsung announces the launch of the quantum dot TV KS9500 series. The TV features cadmium-free QDs, licensed from Nanosys, Inc.

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March 2016	Nanoco changes the terms of its agreement with long-term development partner Dow Chemical from exclusive to non-exclusive.
July 2016	Nanoco signs a long-term deal with Wah Hong Industrial, an Asian provider of optical films for displays.
August 2016	• Samsung unveils QD CFG70 Curved Gaming Displays.
September 2016	• LG Display and Samsung announce the establishment of dedicated QLED R&D initiatives. • Samsung announces the launch of a new quantum dot super ultra-high definition TV line-up. The company unveiled the KS9800 88-inch quantum dot TV. • TCL launch 65” QUHD Curved 4K TV Xclusive X1 Series
December 2016	• Nanoco Group plc has acquired a group of patents from the Eastman Kodak Company (“Kodak”) in connection with the use of quantum dots in electroluminescent displays. • Quantum Materials Corp has begun shipping high performance red and green cadmium-free quantum dot sample sets to Uniglobe Kisco, Inc. • Korean electronics giant Samsung has confirmed the acquisition of US-based quantum dots producer QD Vision.
January 2017	HiSense announced the H10D series of TVs, useing quantum dot display technology.
April 2017	Acer launch the Predator X27 monitor incorporating QDs.
April 2017	Samsung, HiSense and TCL form a new 'QLED Alliance', to promote QLED TVs.
May 2017	Kyulux and Nanoco will co-develop a future-generation hybrid OLED / QLED display technology that combines Kyulux's hyperflourescent emitters and Nanoco's heavy metal free quantum dots (CDQDs).
August 2017	Apple publish a patent "Quantum Dot LED and OLED Integration for High Efficiency Displays."[86]
August 2017	Quantum Materials Corp (QMC) says it has achieved 99.5 percent quantum yield efficiency for the company’s pure red (630 nm emission peak) cadmium-free quantum dots.
June 2018	Vizio launch new P-Series Quantum TV that is significantly less expensive than other quantum dot based models. The product is $600 less than the equivalent 65 inch model from Samsung.
January 2019	Plessey Semiconductors and Nanoco Technologies announce a partnership to shrink the pixel size of monolithic microLED displays using Nanoco’s cadmium free quantum dot (CFQD® quantum dots) semiconductor nanoparticle technology.
May 2019	Quantum Materials Corp has produced a 100% cadmium-free 55 inch QDX™ quantum dot display technology that achieves an industry-leading 95% Rec. 2020 colour gamut coverage. The company is working with display manufacturers, film manufacturers and chemical companies to bring this technology to market as a superior and lower cost QD-based display solution. In addition, incorporating QDX quantum dot infused films into LCD displays can materially increase colour gamut levels over the current standard of phosphor driven technology and significantly improve overall viewer experience.

Source: Future Markets, Inc.

8.6 Global market for quantum dots in TVs and displays

The limitations of LCDs and the cost and mass production issues with OLEDs have opened up a significant market opportunity for QD-TVs. OLED and QD-LEDs are the main candidates for wide colour gamut televisions, followed by reflective displays.[87] More than 97% of display applications of QDs are in TVs with smartphones and tablets comprising the rest of the demand.

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Samsung is the clear market leader in quantum dot film TVs, followed by Hisense and other, mainly Chinese suppliers. Samsung and Hisense account for >90% of the market. Hisense have strong representation in the China market.

8.6.1 QD-TV unit sales 2016-2030

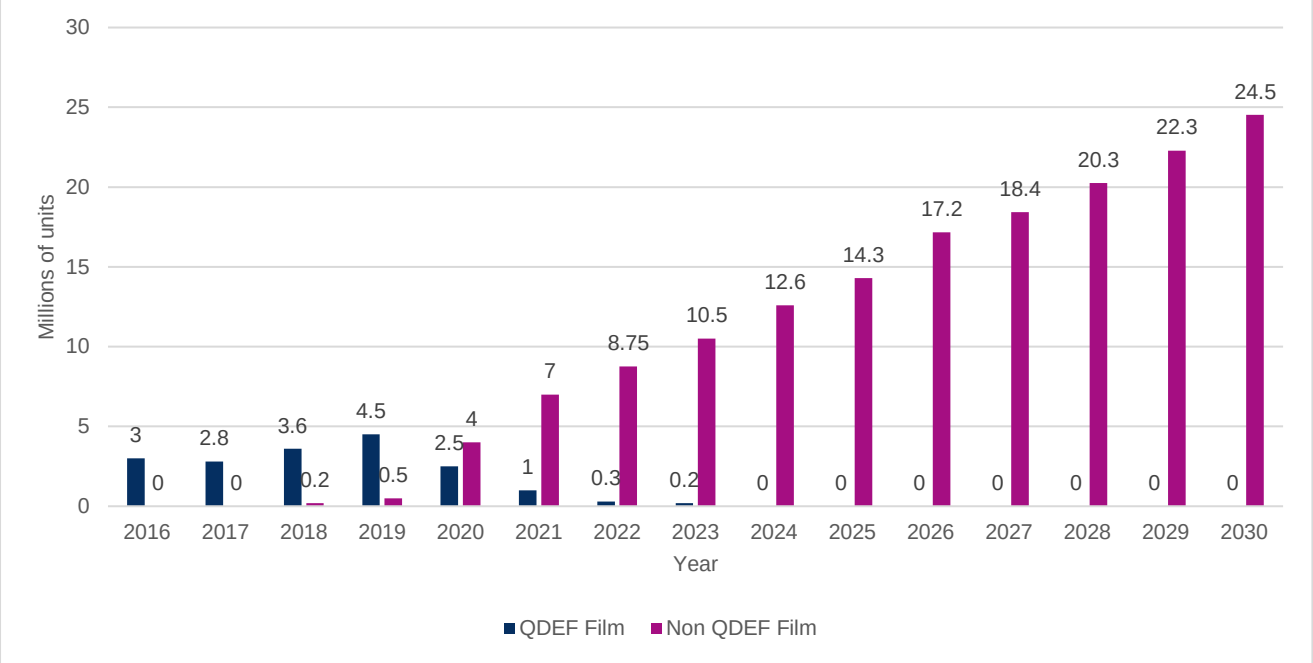

Figure 39: QD-TV unit sales 2016-2030, conservative estimates.

Source: Future Markets, Inc.

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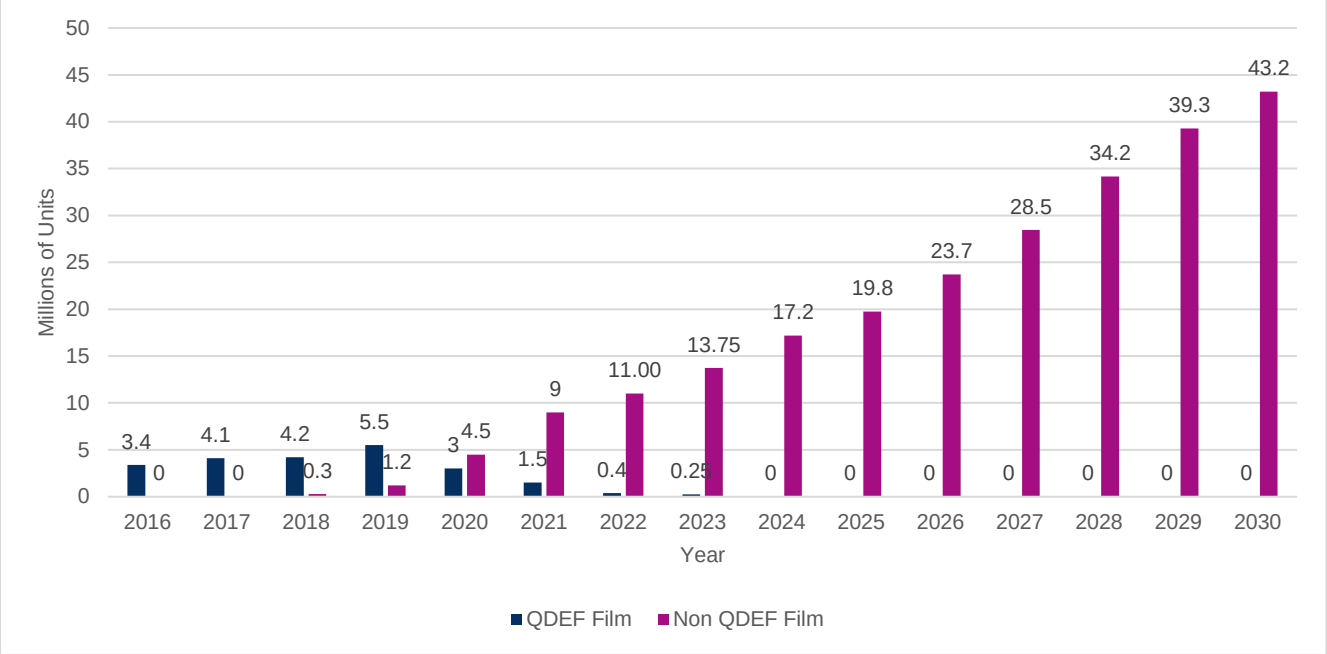

Figure 40: QD-TV unit sales 2016-2030, optimistic estimates.

Source: Future Markets, Inc.

Table 30: QD-TV unit sales 2016-2030, conservative and optimistic estimates.

Year	Conservative estimate (Millions units)		Optimistic estimate (Millions units)	
	QDEF film	Non-QDEF film	QDEF film	Non-QDEF film
2016	3	0	3.4	0
2017	2.8	0	4.1	0
2018	3.6	0.2	4.2	0.3
2019	4.5	0.5	5.5	1.2
2020	2.5	4	3	4.5
2021	1	7	1.5	9
2022	0.3	8.75	0.4	11
2023	0.2	10.5	0.25	13.75
2024	0	12.6	0	17.2
2025	0	14.3	0	19.8
2026	0	17.2	0	23.7
2027	0	18.4	0	28.5
2028	0	20.3	0	34.2
2029	0	22.3	0	39.3
2030	0	24.5	0	43.2

Source: Future Markets.

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8.6.2 QD Monitor Unit sales 2015-2030

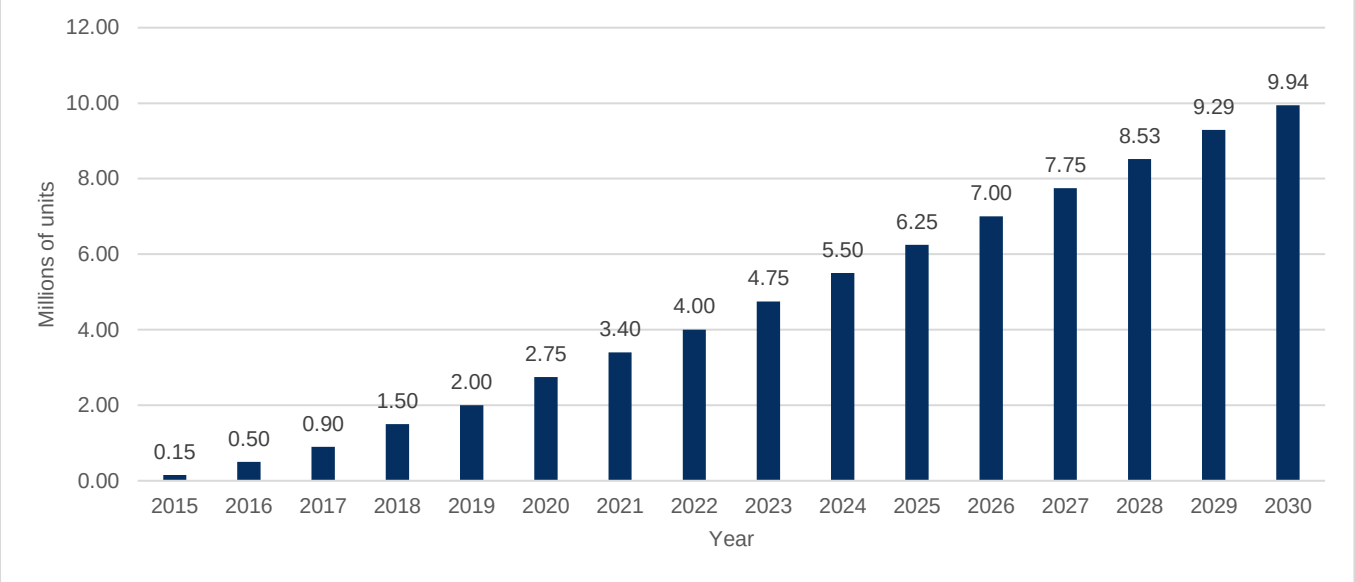

Figure 41: QD Monitor Unit sales 2015-2030.

Source: Future Markets.

8.7 Quantum dot TV and display companies

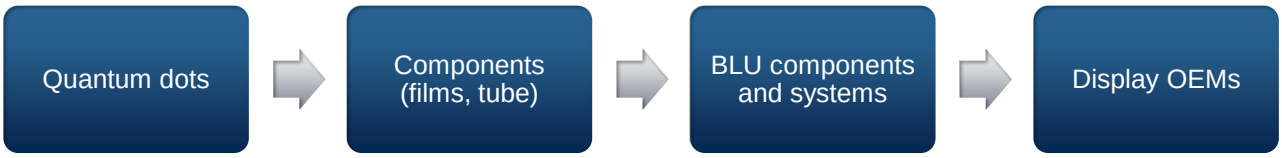

Figure 42: QD-LCD supply chain.

Source: Future Markets.

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9 QUANTUM DOTS IN PHOTOVOLTAICS

Applications of QDs in the energy sector are mainly in photovoltaics and solid-state lighting. Battery and thermoelectric applications are also under commercial development. QDs potentially provide major advantages as photovoltaic materials in next generation solar cells. They can be easily tuned to absorb light at any wavelength and are photochemically robust.

Table 31: Market snapshot for quantum dots in photovoltaics.

Category	Assessment	Trend
Market age	Development	Increasing
Revenues (at the component level) in 2015	<$5 million	Increasing
Potential revenues by 2030	>$375 million	Increasing
Base year market growth rate (2015)	>23%	Increasing
Forecast period market growth rate	23%	Increasing
Price sensitivity	High	Decreasing
Competitors (Active market competitors in base year)	<10 companies, mainly start-ups	Increasing
Degree of competition (Low=1, High=10)	7	Stable
Degree of technical change	High	Increasing

Source: Future Markets.

9.1 Market drivers and trends

Table 32: Market drivers and trends in quantum dots in photovoltaics.

Driver	Trends
Rising demand for solar power	Demand for solar power is rising rapidly, with annual double digit growth expected over the next few years. Governments are pushing for new solar technologies and there is strong demand from private/public sectors investors in developing countries. There has been rapid progress in the last few years in nanostructured photovoltaic devices. Nanomaterials are leading to new opportunities for the production of cheaper, high efficiency efficient, smaller and lighter solar cells with a higher output voltage. QDs, metal oxide nanopowders and carbon nanotubes are at the forefront of new photovoltaics applications allowing for low cost, low temperature fabrication. With improvements in efficiency and lifetime, nanomaterials will potentially provide improved third generation photovoltaic devices at a price substantially lower than that offered by 1st and 2nd generation technologies, opening up new markets for solar.
Need for cost-effective solar	Large scale implementation of photovoltaics will require further significant reductions in cost and significant increases in efficiency. The growing solar photovoltaic market needs

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Driver	Trends
technology for wider adoption	to reduce costs to reach grid parity. The industry is targeting solar cell production costs of lower than $1/W. Although conventional PV cells provide good efficiencies, they are not viable for large-scale deployment because of the aforementioned high costs. On the other hand, inorganic and organic thin-film semiconductor-based PV cells have low material and fabrication cost, but their large-scale performance is poor. First generation solar cells are made from bulk silicon, either single crystalline and polycrystalline silicon and make up the majority of the market. Second generation encompasses thin films. Third generation soar cells promise lost-cost and high-efficiencies-greater than 20% efficiencies with costs similar to second generation. Nanomaterials are a key component of third generation solar devices, providing the material requirements to significantly, rather than incrementally, improve photovoltaic cell performance beyond that of present devices. Nanostructured materials grown with low-cost, bottom-up approaches usually have crystalline nature and, therefore, are promising candidates to achieve cost-effective PV cells. In addition, ordered nanostructures have demonstrated intriguing optical and electrical properties favouring photon broadband absorption and photocarrier collection. This suggests a potential route towards next-generation, high-efficiency PV devices. Efficiencies for nano-enabled solar cells are significantly less than those of conventional wafer silicon cells at present. However, they are cheaper and more eco-friendly as their production demands less time, material and energy.
Need for new materials to overcome conventional silicon solar cell shortcomings	Most current photovoltaic cells are based on crystalline silicon. With silicon solar cells reaching its theoretical efficiencies, new materials and novel architectures are needed for higher light harvesting, higher efficiencies, reduced carbon fingerprint and reduced environmental impact both during fabrication and final disposition, with the challenge of maintaining or reducing the costs and keeping the stability of the modules. In conventional silicon solar cells significant problems include: • Photons with energies less than the semiconductor bandgap are not harvested. • High processing complexity. • Fabrication is expensive, as they require use of the highest purity silicon. • Those with energies much larger than the bandgap produce hot-carries and upon cooling down (thermalization) the excess energy gets wasted as heat. Therefore, novel materials or structures with tunable bandgap or intermediate band that can be tuned to match the spectral distribution of solar spectrum are crucial. In photovoltaic devices, doped semiconductor CQD films are combined with a metal (Schottky junction cells) or with another semiconductor (CQD−CQD or CQD−titanium dioxide p−n junctions, CQD−CQD−zinc oxide p−i−n junctions), along with asymmetric electrodes, to form a complete functional device. The efficiency of quantum dot based solar cells has increased from approx. 2% > 13% since 2010.

Source: Future Markets.

Table 33: Impact of market drivers for quantum dots in the photovoltaics market.

Rank	Driver	1-2 years	3-4 years	5-8 years
1	Rising demand for solar power	High	High	High
2	Need for cost-effective solar energy	High	High	Medium

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Rank	Driver	1-2 years	3-4 years	5-8 years
3	Need for new materials	Medium	High	High

Source: Future Markets.

9.2 Applications

There has been rapid progress in the last few years in nanostructured photovoltaic devices. Nanomaterials are leading to new opportunities for the production of cheaper, high efficiency efficient, smaller and lighter solar cells with a higher output voltage.

QDs, metal oxide nanopowders and carbon nanotubes are at the forefront of new photovoltaics applications allowing for low cost, low temperature fabrication. With improvements in efficiency and lifetime, nanomaterials will potentially provide improved third generation photovoltaic devices at a price substantially lower than that offered by 1st and 2nd generation technologies, opening up new markets for solar.

9.2.1 Nanomaterials in solar cells

Nanomaterials utilized in solar cells to address third generation approaches include:

- Semiconducting polymers and oligomers
- Conducting nanomaterials
- Dyes
- Fullerenes
- Liquid crystals
- Metal Oxides

They find application in solar cells as:

- Nanocrystalline thin-film layers
- TiO2 nanoparticles in dye solar cells
- Fullerene derivatives as electron acceptors
- Nanolayers in stack cells
- Graphene electrodes.
- Quantum dots for bandgap tuning
- Nanostructured anti-reflection layers
- Quantum wells for bandgap tuning
- Metal nanoparticle plasmonic solar cells
- Polymer-nanowire based hybrid solar cell

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9.2.2 Advantages of quantum dots in photovoltaics

QDs possess the following advantages over microstructures (bulk) single junction solar cells:

Table 34: Advantages of quantum dots in photovoltaics.

Advantage	Description
Tunable bandgap	• QDs have a tunable bandgap as a result of size variation as well as formation of intermediate bands. Therefore, there is the ppossibility to realize light absorption in wide solar spectrum regions.
Flexibility & transparency	• In contrast to traditional semiconductor materials that are crystalline or amorphous, QDs can also be moulded into a variety of different types, in two-dimensional (sheets) or three-dimensional arrays. • QDs can easily be combined with organic polymers and dyes which opens up opportunities for flexible, printable solar cells. • Fully transparent.
Simple fabrication	• QDs can be processed to create junctions on inexpensive substrates such as plastics, glass or metal sheets. • Colloidial synthesis of QD solar cells has allowed for cheap manufacture, whereby a thin film of QDs is applied via a layer-by-layer spin-coating method. QD solution is placed on a substrate which is then spun until the desired thickness is achieved.
High conversion efficiency	• Compared to silicon, QDs have much wider absorption features. • Theoretical conversion efficiency limit of 70.4%, compared to just 32% for single-junction silicon cells. • QDs do not lose the efficiency over time and are resistant to weather conditions. • The solar-power conversion efficiencies of colloidal quantum dot solar cells have advanced from sub-1% reported in 2005 to the current record value of 9.2%.[88]

Source: Future Markets, Inc.

9.2.3 Types of quantum dot solar cells

9.2.3.1 Metal—semiconductor/ Schottky QD junction solar cell

Schottky QD Junction solar cells are fabricated from QD layers that are sandwiched between a metallic electrode and ITO counter electrode deposited on transparent glass substrate to act as photo-electrode. The highest reported efficiency using a PbS nanocrystal Schottky junction is 5.2%.[89]

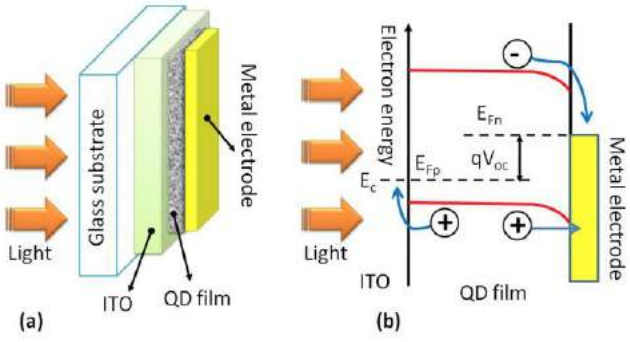

Figure 43: (a) Schematic of Schottky barrier quantum dots based solar cell.

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(b) Band diagram of Schottky solar cell.

Table 35: Schottky QD Junction solar cells.

QD solar cell type	Advantages	Disadvantages	Maximum reported efficiency
Schottky QD Junction solar cells	• Easy to fabricate. • Limited number of interfaces.	• Limited in device performance • Fermi level pinning at the metal−CQD interface imposes an upper bound on the open-circuit voltage that is well below the voltage predicted from consideration of the CQD band gap alone.	5.2%

Source: Future Markets, Inc.

9.2.3.2 Silicon/QD Film Hydrid Solar Cells

Hybrid devices that are a hybrid of silicon-based solar cells (amorphous silicon) and QDs have been developed.[90] The silicon/PbS QD film devices demonstrated external quantum efficiencies of 7% at infrared energies and 50% in the visible and a power conversion efficiency of up to 0.9%

9.2.3.3 Silicon/Graphene QD Film Hydrid Solar Cells

In December 2015, researchers utilized graphene quantum dots (GQDs) in solutions of PEDOT:PSS. The solutions were applied to silicon substrates to achieve efficiency of 13.22% in Si/PEDOT:PSS hybrid solar cells.[91]

9.2.3.4 Depleted-heterojunction QD solar cell

The depleted heterojunction QD solar cell architecture utilizes a nanostructured n-type metal oxide (TiO2 and ZnO are the most commonly used) in a p−n heterojunction with a p-type QD film (50−400 nm). A typical substrate consists of a glass or flexible transparent base and a thin transparent conductive oxide layer (usually ITO or fluorine-doped tin oxide (FTO)). The QD film and nano metal oxide are sandwiched between a conductive transparent electrode (glass coated with Tin Oxide SnO2F) and a back-reflective contact consisting of a deep work function metal such as gold or a highly doped oxide (MoO3) followed by silver or aluminum.

Although TiO2 has low carrier density (~1016 cm-3) compared to metal, a depletion region in the cells forms due to charge transfer to QD film. And because of high electron density in metal (~ 1022 cm-3), the depletion is negligible on its side of the cell. Maximum reported efficiency is 5.1%.[92]

9.2.3.5 QD-sensitized solar cells (QDSSC)

The most commonly used and investigated QD-sensitized solar cells (QDSSC) utilize CdSe QDs. These devices are fabricated using techniques such as sputtering, physical vapor deposition, and hot-wire chemical vapor deposition. In QDSSCs a QD bandgap is tunable and can be used to create intermediate bandgaps.

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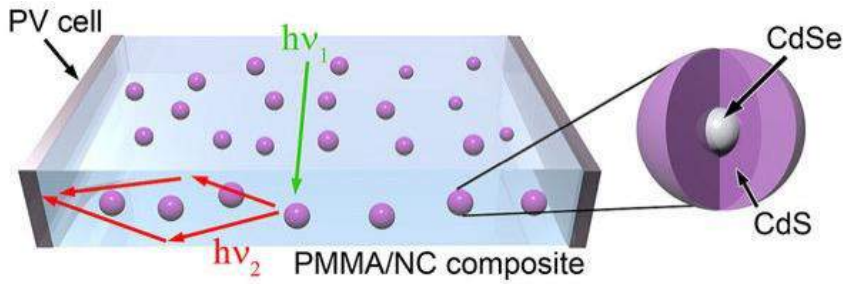

Figure 44: Schematic of QD Solar Cell.

Image credit: Los Alamos.

Upon the absorption of photons, the QDs generate excitons (i.e., electron-hole pairs). Subsequently, the electrons inject into the photoanode to generate photocurrent; scavenged by a redox couple, holes transport to the cathode. The overall power conversion efficiency (PCE) of a QDSSC is dictated by the light harvest efficiency, quantum yield for charge injection, and charge collection efficiency at the electrodes. The maximum theoretical efficiency of the solar cell is as high as 63.2%.

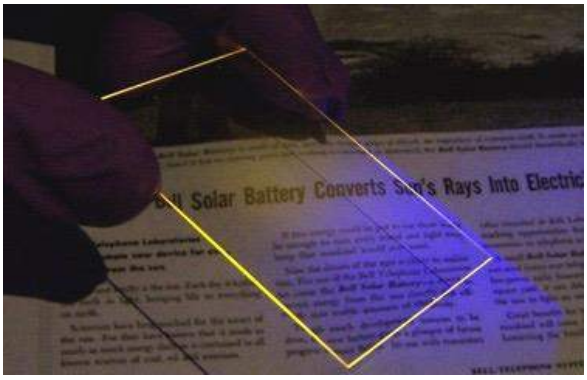

Figure 45: Doped quantum dot LSC.

Source: Nova Solar Technologies.

Table 36: Comparison of third generation solar cells.

	Quantum dot	Dye Sensitized	Polymer	Concentrated	Perovskites
Efficiency	7%-9%	~10%	~3-10%	~40%	31%
High temperature performance	Excellent thermal stability.	Poor in high temperature conditions.	Poor in high temperature conditions.	Excellent thermal stability.	Excellent thermal stability.
Cost	50% less than conventional silicon cells.	50% less than conventional silicon cells.	50% less than conventional silicon cells.	50% less than conventional silicon cells.	50% less than conventional silicon cells.
Installation time	Short installation time.	Short installation time.	Short installation time.	Long installation time.	Short installation time.

© Future Markets, Inc. 2019

Source: Future Markets, Inc.

9.2.3.6 Quantum dot solar windows

The use of quantum Dots can turn tinted windows into power sources for building-integrated sunlight harvesting. UbiQD, LLC is developing QD-coated windows for solar harvesting. It has been demonstrated that the windows capture approximately percent of direct sunlight, equivalent to approximately 30 watts of electricity/m^2.

Figure 46: QD coated solar windows.

Image credit: UbiQD LLC.

In January 2018, researchers at Los Alamos National Laboratory demonstrated a prototype of a quantum tuned, double paned, solar powered window.[93] Highly emissive manganese-doped quantum dots are coated onto the outside surface of the outer glass pane (top layer on the left image below) and a layer of copper indium selenide quantum dots onto the inner surface of the inside (bottom) pane.

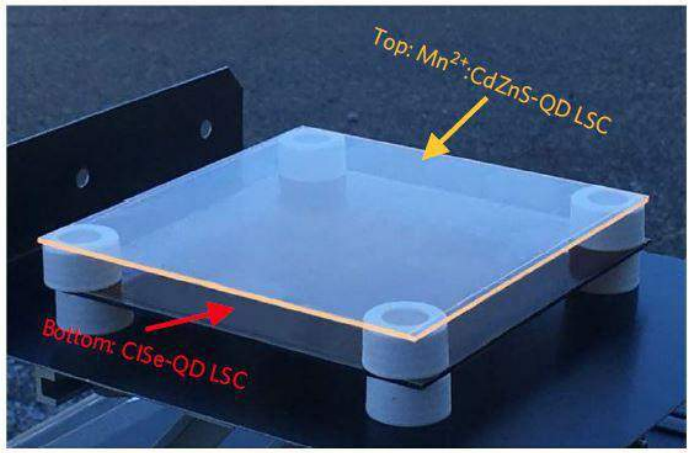

Figure 47: A layer of highly emissive manganese-doped quantum dots onto the outside surface of the outer glass pane (top layer on the left image below) and a layer of copper indium selenide quantum dots onto the inner surface of the inside (bottom) pane.

© Future Markets, Inc. 2019

Image credit: Los Alamos National Laboratory.

Polish company ML System SA is currently developing quantum dot solar glass with plans to invest $10.5 million in 2018 in product development.

Figure 48: QDSSC Module.

Image source: ML System S.A. Laboratory.

9.3 Market challenges

The scale of renewable energy challenges not only calls for highly efficient photovoltaic (PV) or photoelectrochemical (PEC) technologies but also abundant, inexpensive, and robust materials. However, significant challenges in material performance, bulk and interface defects, and controlled doping and physical properties must be overcome before the potentials of nanomaterials can be fulfilled.

Quantum-dot-sensitized solar cell (QDSSC) has been considered as an alternative to new generation photovoltaics, but it still presents low conversion efficiency. Other challenges include:

- Surface trap defects of QDs.[94]
- Low charge carrier mobility.
- Low open-circuit voltages that may be limited fundamentally by mid-gap states or inherent disorder in QD films.

Table 37: Market challenges rating for quantum dots in the solar market.

Market acceptability	
Cost	3
Competition from other materials	2
Scalability	2-3
Industry pull	4
Market push	5
Regulatory	5

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Consumer acceptance	5
Total score (out of 35): 28-29	

Source: Future Markets.

9.4 Industry and research developments 2013-2019

Table 38: Commercial development and research highlights in quantum dots in photovoltaics, 2013-2019.

Month	Development
December 2013	• Researchers at Los Alamos National Laboratory and Sharp Corporation use a new class of low-cost, low-toxicity CuInSexS2−x quantum dots to demonstrate sensitized solar cells with certified efficiencies exceeding 5%. The solar cells are based on a new generation of nontoxic quantum dots (not containing either lead or cadmium as do most quantum dots used in solar cells).[95]
May 2013	• Researchers at MIT set a new record for the most efficient quantum-dot cells, with 9% efficiency.[96]
July 2014	• Researchers at the University of Toronto have manufactured and tested a new type of colloidal quantum dots (CQD), that, unlike previous attempts, doesn't lose performance as they keep in contact with oxygen. The development could lead to much cheaper or even spray-on solar cells, as well as better LEDs, lasers and weather satellites.[97]
May 2015	• UbiQD LLC secures two intellectual property licenses: one exclusive license from Massachusetts Institute of Technology (MIT) and one nonexclusive license from Los Alamos National Security LLC (LANS). Both licenses relate to QDs that are substantially free of toxic elements – both in regards to their physical compositions, as well the elimination of such elements in the manufacturing process. The luminescent QDs covered in these patents have been demonstrated in a wide array of technologies including solar energy.
August 2015	• Researchers at Los Alamos National Laboratory develop large-area luminescent solar concentrators based on cadmium free quantum dots.[98] Applications are in solar window technology.
October 2016	Los Alamos National Laboratory research team demonstrates an important step in taking quantum dot, solar-powered windows from the laboratory to the construction site by proving that the technology can be scaled up from palm-sized demonstration models to windows large enough to put in and power a building.[99]
April 2017	Quantum Materials Corp and Freschfield PLC announce the execution of a funded collaboration agreement by which Quantum will work with Freschfield to integrate Quantum Materials Corp advanced Nanomaterials including quantum dot-based solar photovoltaics into Freschfield's SmartSkinz.
April 2017	UbiQD, LLC, achieve greater than 80% quantum yield, or optical efficiency, for its quantum dots over a broad spectrum from the visible to the near infra-red (550 nm to 1000 nm peak emission).
August 2017	Natcore Technology signs a Memorandum of Understanding with PSECC Solar Farms Ltd., a climate change mitigation company and developer of solar farms, under which PSECC would engage Natcore to develop solar projects within the United States.

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August 2017	UbiQD signs an exclusive agreement with at Western Washington University's Advanced Materials Science and Engineering Center and the University of Washington to license luminescent solar concentrator (LSC) technology.
November 2017	Researchers at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) create a solar cell using colloidal quantum dots, which achieved 13.4% conversion efficiency.[100]
March 2018	The National Science Foundation awards a phase II Small Business Innovation Research grant of $750,000 to UbiQD LLC.

Source: Future Markets, Inc.

9.5 Global market for quantum dots in photovoltaics

Photovoltaics (PV) is a fast-growing market with the PV installations witnessing CAGR of over 40% in the past decade. Governments are pushing for new solar technologies and there is strong demand from private/public sectors investors in developing countries. The global market for solar PV (including modules, system components, and installations) is estimated to be worth over $90 billion per annum.[101] 272 GW of installed capacity is forecast by 2020.

There are opportunities for nanomaterials in photovoltaics as low-cost, printable solar cells. The market for Si-wafer based PV technology is over 90%. The market share of thin film technologies was approximately 8-9% in 2015.

Quantum dots compete with organic photovoltaics and dye sensitized solar cells; and new organic metal halide perovskite solar cells with power conversion efficiencies surpassing 20%.[102] The mass market at present for these solar cells is very small, and the opportunities for QD solar cells are only likely to be realized in the medium–long-term. There are several companies developing printable photovoltaic solar cells, but mass production has not been realized.

Opportunities are in collaboration with cell or integrated cell and module manufacturers and third-generation PV companies. Companies in this market include First Solar, Sanyo, JA Solar, Sharp, Konarka, Sunpower, Kyocera Solar, Suntech, Motech and Yingli Solar.

The market is mainly being driven by start-ups who often work in collaboration with larger companies. These companies have raised over $2billion in investment in the last five years for product development. Module efficiencies for nanomaterials used in second and third generation photovoltaics range from 5-17.1% at present.

Current anti-reflective coated glass has yet to gain widespread penetration in sectors other than solar, although they have made some inroads into other applications. Therefore, there are opportunities for developing cheap, high-throughput nanocoatings.

Main demand is in the photovoltaics sector for solar cover glass, where over 60% of wafer based PV modules employ AR glass covers.[103] However, there is still a huge market for covering currently uncoated solar panels with AR coatings (over 300 million uncoated solar panels globally according to CSD Nano, Inc.) Market estimates for the global AR coatings market in 2014 is approximately $2.5 billion-$3 billion according to industry sources. The total addressable market for nanomaterials in solar panels/solar cells is approximately $9.5 billion.

Table 39: Total QD photovoltaic component revenues 2013-2030 $M), conservative and optimistic estimates.

Year	Conservative estimate (M$)	Optimistic estimate (M$)
2013	1	3

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Year	Conservative estimate (M$)	Optimistic estimate (M$)
2014	1.2	3.5
2015	1.3	4.2
2016	3	7
2017	7	10
2018	15	30
2019	37	55
2020	50	90
2021	60	115
2022	80	175
2023	105	250
2024	125	360
2025	145	470
2026	175	590
2027	205	675
2028	226	776
2029	248	893
2030	273	1027

Source: Future Markets, Inc.

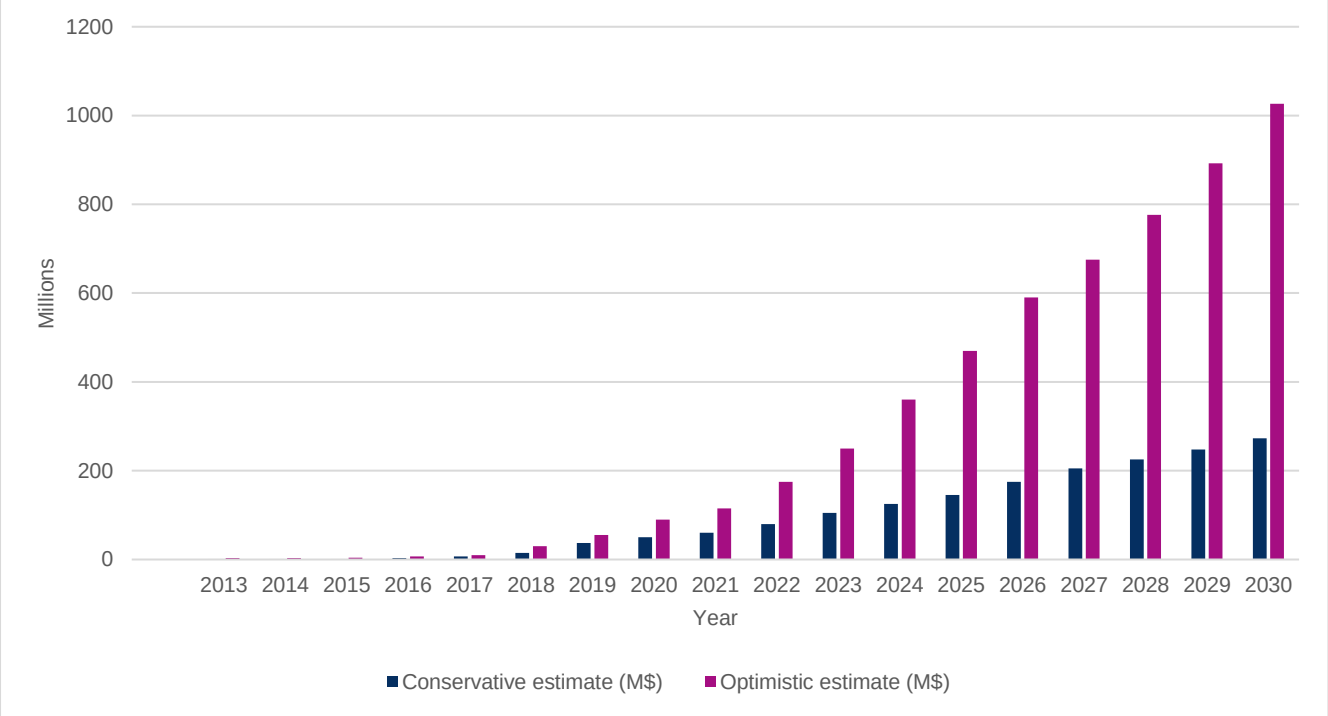

Figure 49: Total QD photovoltaics component revenues 2013-2030 ($100,000s), conservative and optimistic estimates.

Source: Future Markets, Inc.

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9.6 Quantum dot photovoltaics companies

Table 40: Quantum dots product and application developers in photovoltaics.

Company	Activity
Applied Quantum Materials, Inc.	Applied Quantum Materials Inc. is developing solar panel technology that can potentially be used in window panels, reducing the need for remote power generation and reducing greenhouse gas emissions.
ClearVue Technologies Limited	ClearVue Technologies Limited has signed a new Research Agreement with UNSW Sydney. The research project will explore the development of a transparent luminescent solar concentrator employing quantum dots (QD) demonstrating high quantum yield photoluminescence. The project includes as a milestone development of custom QD materials and a small-scale prototype. If the research project is successful, ClearVue would seek to further scale the prototype in conjunction with UNSW with a view to integrating the QD technology with its existing technology and products.
KRI, Inc.	The company design and fabricate silicon quantum dots solar cells. They are also developing graphene quantum dots.
ML System SA	The company is developing quantum dot solar glass.
Nanoco Technologies	The company develops quantum dot films for solar cells. Initial research has shown the use of quantum dots in photovoltaic materials can potentially improve sunlight conversion efficiencies to 40%-plus, compared to the 10-22% levels typically seen in today's commercial photovoltaic devices. They are working with Tokyo Electron on developing products for solar. In 2013 Nanoco announced achieving a solar cell efficiency of 12-13% nearing the 15% mark which is deemed commercially viable.
Natcore Technology	The company fabricates multilayer quantum dot films for solar cells in collaboration with Rice University.
Ocean Nanotech	The company's product line includes quantum dots, core shell quantum dots in organic solvents, nanocrystals for LEDs and solar cells, water soluble biocompatible nanocrystals, reaction buffers for conjugating nanocrystals to biomolecules, conjugation kits, and services to meet our customer needs.
QD Solar, Inc.	QD Solar Inc. develops photovoltaic cells using colloidal quantum dot technology. Its quantum dot technology combines silicon solar cells with infrared solar cells in a hybrid architecture to harvest more of the solar spectrum than silicon alone.
Quantum Materials Corporation	Quantum Materials Corp's goal is reducing estimated solar energy generation costs by 50 percent through the integration of quantum dots manufactured with the Company's continuous flow production and high speed roll-to-roll printing technology. This combination has the potential to dramatically reduce manufacturing equipment capital expenditures required to manufacture solar cells by up to 75 percent versus current solar cell production technologies.
UbiQD	The company is developing luminescent solar concentrating glass windows with quantum dot coating. The company aims to utilize CuInSexS2-x/ZnS QDs as a NIR fluorophore for luminescent solar concentrators (LSCs), an emerging transparent solar technology.

Source: Future Markets, Inc.

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10 QUANTUM DOTS IN LIGHTING

Table 41: Market snapshot for quantum dots in LED lighting.

Category	Assessment	Trend
Market age	Development	Increasing
Revenues (at the component level) in 2015	<$5 million	Increasing
Potential revenues by 2027	>$1.5 billion	Increasing
Base year market growth rate (2015)	36%	Increasing
Forecast period market growth rate	55%	Increasing
Price sensitivity	High	Decreasing
Competitors (Active market competitors in base year)	~10 companies	Increasing
Degree of competition (Low=1, High=10)	8	Stable
Degree of technical change	Medium	Increasing

Source: Future Markets.

10.1 Market drivers and trends

Table 42: Market drivers and trends for quantum dots in LED lighting.

Driver	Trend
Drop in production costs	The use of white LED lighting to replace incandescent and fluorescent lighting has been increasing in popularity as production costs have dropped and volumes have increased.
Need to develop low-cost lighting	From an environmental and economic perspective, the benefits of replacing incandescent bulbs with low-cost, environmentally friendly down converters in light-emitting diodes (LEDs) are apparent. The industry is also seeking to develop energy efficient lighting with a high quality colour spectrum, in which current is directly converted into photons via the process of electroluminescence. In the USA, the DOE plans to develop, by 2025, widespread usage of solid-state lighting (SSL) technologies that, compared to conventional lighting technologies have the following benefits: • Significantly more energy efficient. • Longer lasting. • Cost competitive. At present SSL is mainly used in the following applications: • Indicator lights on electronic devices. • Backlighting for colour displays in personal electronics (e.g., cell phones). • Automotive interior and exterior lighting. • Traffic signals. • Large-area outdoor displays.

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Driver	Trend
	Current limitations to widespread implementation of SSL technologies are cost and the difficulty in optimizing the technology for use in commercial spaces, offices and homes (due to technical limitations in producing a “true” white light).
Environmental regulation	Electricity for lighting purposes is one of the largest global consumers of energy. According to the Department of Energy (DoE) lighting represents 22% of US electricity consumption and 17% globally.104 The use of SSL will significantly reduce electrical power usage and production of atmospheric carbon. Doubling the average luminous efficacy of white lighting through the use of SSL would potentially decrease by 50% the global amount of electricity used for lighting.
Limited efficiency of phosphors in LEDs	SSL is based on blue light-emitting diodes combined with wavelength down conversion via phosphors. Currently utilized red phosphors do not satisfy all of the criteria for SSL, opening the door for commercial development of QDs. Due to broad emission bandwidths led phosphors suffer from severe efficiency loss as the temperature increases. QDs have numerous long-term and fundamental advantages over rare-earth phosphors, including: • Broad and a five-orders-of-magnitude-greater blue absorbance; • Relatively good accommodation of strain, which can enable a wide range of alloy compositions and emission wavelengths; • The possibility of active chromaticity tuning (through Stark-effect-based modification of absorption oscillator strengths) for higher functionality light. QD-based LEDs can achieve higher efficiencies at higher current densities because of higher spontaneous emission rates and reduced Auger recombination. If constructed properly, these QD-LEDs could offer a method to overcome Auger recombination and achieve breakthrough efficiencies.
Shortcoming with LED lighting technologies	Many LED lighting technologies still struggle with replicating colour and induce unwanted glare. They also suffer from efficiency issues. The use of QDs as downconverter materials can result is light with the colour performance of an incandescent bulb and the efficiency and economy of a LED. Down-converting materials are used to improve the performance, efficiency and colour choice in lighting applications. QDs absorb light of a particular first (available or selected) wavelength, usually blue, and then emit light at a second wavelength, usually red or green.
Improving flexibility	Challenges remain to enable highly flexible OLEDs. The flexibility of current OLEDs is mainly limited by the use of crack prone indium tin oxide (ITO), which serves as the transparent electrode. To overcome this limitation and enable flexible OLED, graphene has been developed as the transparent electrode. OLED made with graphene electrodes exhibit a level of performance that is not only suitable for display but also for general lighting.
Improving performance and costs of UV-LEDS	Current UV-LEDs display low performance capabilities; total external quantum efficiency is only a few percent (At 265 nm the external quantum efficiency is ~10 % at the best). Thermal management of these devices poses a problem that the use of nanomaterials such as nanowires and graphene can overcome. These devices also use very expensive substrates and materials. In most UVC LEDs, Internal Quantum Efficiency (IQE) is weak (due to lattice mismatch) and light is emitted through the substrate. Graphene’s high intrinsic thermal conductivity allows the alleviation of heat dissipation issues. QDs allow for up to 25% efficiency gain in solid state lighting.

Source: Future Markets.

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Table 43: Impact of market drivers for quantum dots in the LED lighting market.

Rank	Driver	1-2 years	3-4 years	5-8 years
1	Environmental regulation	Medium	Medium	High
2	Need to develop low-cost LED lighting	Low	Medium	Medium
3	Limited efficiency of phosphors in LEDs	Medium	Medium	High
4	Need to improve performance of UV-LEDs	High	High	High

Source: Future Markets.

10.2 Applications

10.2.1 LED lighting

Organic light emitting diodes (OLEDs) have improved remarkably over the past two decades. OLEDs are widely applied in high-end displays in consumer electronics. They are also emerging as a competitive low-cost product for general lighting. One differentiating feature of OLEDs from both conventional solid-state lighting and display technologies is their mechanical flexibility.

Quantum dots, Indium Gallium Nitride nanowire and Gallium Phosphide nanowires are the main types of nanomaterials investigated for application in LEDs. Most QD producers target the lighting market and Glo and Aledia are two start-ups who have receive significant investment to develop their nanowire technology.

Quantum dots are ideal candidates as the emitting layer in light emitting diodes (LEDs) due to their tunable colours, bright emission, solution processability, and stability. The most prevalent white LED utilized in solid-state lighting comprises a blue LED chip and yellow-emitting Y3Al5O12:Ce3+ (YAG:Ce) phosphor. The device provides high luminous efficiency (LE) and is low cost.[105] [106] However, they suffer from a number of drawbacks such as red deficiency. On-chip quantum dot downconverters are used as a direct replacement for red phosphor in LED lighting.

CdTe and CdSe-based QD and cadmium free QDs with high PL QY (~70%) and stability have been developed to overcome the drawbacks in LED lighting. QDs meet several criteria for improved SSL performance including:

- Precise peak emission placement (± 2 nm).
- Very narrow emission peaks (< 35 nm). This enables the implementation of adjustable emission spectra tailored to the eye sensitivity curve resulting in improved colour rendition and efficacy.
- Broad blue absorption.
- Reduced power consumption.
- Colour tuneable.
- High quantum yield (QY).
- Fast radiative decay times-(ns compared to µs).
- High luminous efficacy of radiation.
- Efficacy improvements due to narrow spectrum: 20-40% benefit for WW.
- Soluble.
- Customizable spectrum allows high colour rendering index (CRI): >90 easily obtained.
- Fewer LEDs required in a luminaire.
- Even light distribution from QD films.

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- Customizable films size and shapes.
- Easy product integration.
- Smaller drivers and heatsinks required.

QD phosphors also have very low optical scattering and the ability to create custom LED system spectral responses. QD phosphors films show potential for having quantum efficiencies greater than 90%, optical scattering losses of less than 5%, and very good temperature stability up to 150 ^{O}C. Applications are in general lighting, office and retail lighting, specialty lighting and agricultural (lights utilized in plant growth).[107]

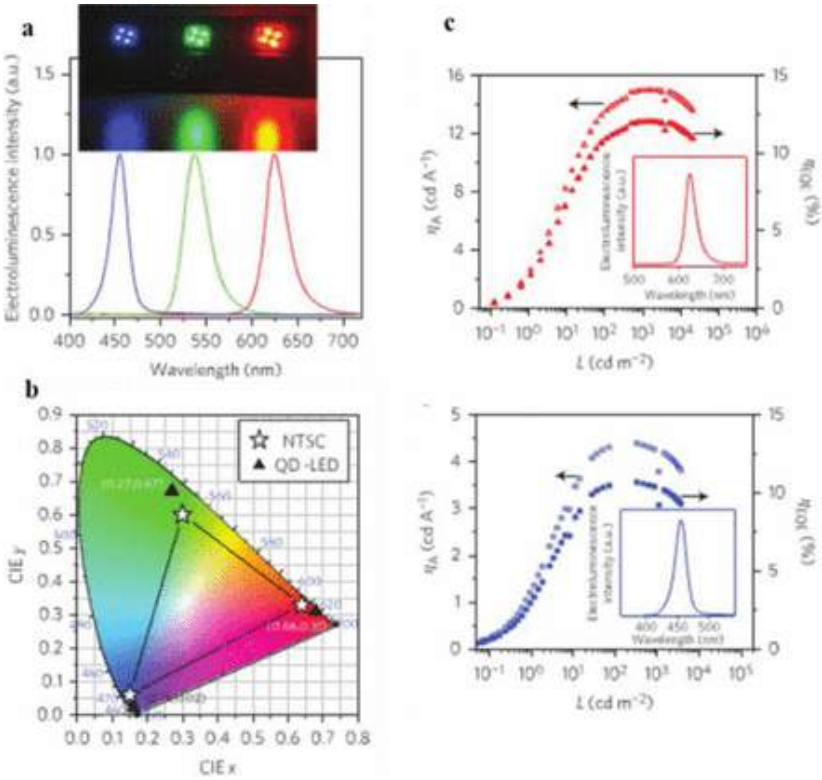

Figure 50: Fourth generation QD-LEDs.

(a) Normalized electroluminescence spectra and images of blue, green and red QD-LEDs. (b) CIE coordinates of the three QD-LEDs (triangles) compared to the NTSC colour standards (stars). (c) Current efficiency (ηA) and ηEQE as a function of luminance of the best performing red and blue QD-LED based on quantum dots. Inset: normalized electroluminescence spectrum of the red and blue QD-LEDs.

Image credit: Nature Photonics.

Colloidal quantum dot based white LEDs can be integrated into commercial products meeting the stringent reliability requirements for general illumination and providing LED efficiency gains of 5% to 15% over commercial phosphor based LEDs.

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Table 44: QD-LEDs and External quantum efficiencies (EQE).

Generation		EQE*
1st Generation	CdSe core or a core/shell QD –polymer bilayer or blend charge transport layer.[108]	>0.22%
2nd Generation	Monolayer of QDs sandwiched between two organic small molecule thin film CTLs.[109]	0.5%
	Fabrication QD-LEDs by microcontact printing the QD layer.[110]	2.7% for orange emission.
3rd Generation	Replaced both of the organic with inorganic charge transport layers (e.g. meta oxide thin films with increased conductivity and tunable energy bands) to increase stability in air.[111]	<0.1% (due to damage to QD layer during sputtering process).
4th Generation	• Hybrid organic and inorganic charge transport layers (CTL). • n-type layer usually a metal oxide (e.g. solution processed metal oxide nanoparticles). • QD layer not damaged during fabrication.	• Over 10% for Blue, green, and red QD-LEDs.[112] • Green QD-LEDs fabricated with the ZnSe rich QDs: 14.5%
	QD-LED fabricated using ZnCdS/ZnS graded core-shell QDs with 1-octanethiol capping ligands.[113]	• Blue QD-LEDs: 10.3%
	Electrically excited QD thin-films	>18% [114]

Source: Future Markets, Inc.

* The theoretical EQE maximum is 20%.

10.2.2 Horticultural lighting and greenhouse films

The horticultural lighting market is forecast to grow from $3.8bn in 2017 to $17.0bn in 2027 driven by:

- Growing populations
- Increased awareness of environmentally friendly farming practices
- Advent of high intensity vertical farming
- Urbanization

Quantum Dots can be fabricated to shift blue light energy from high efficiency GaN LEDs to red light, resulting in an ideal magenta spectrum for growing green plants. Quantum Dot illumination consumes far less energy for the same production output than traditional green house lighting, reducing the costs needed to control growing environments. Ultra high efficiency quantum dots convert the spectrum without optical losses, consuming far less and producing less heat than traditional greenhouse lighting.

Nanoco Lighting has produced Cold White Lighting, for application in horticultural lighting. Cd-free QDs are ideal candidates for optimizing plant growth systems, as QDs deliver the precise spectrum light that triggers plant flowering, growth, and reproduction.

QDs can also be utilized in other smart farming applications- can be coated on various structures such as glass, rigid plastic and flexible film to modify the solar spectrum in greenhouse films. This could trigger early fruiting and shorten crop cycles, leading to increased annual crop yields.[115]

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10.3 Market challenges

Although the market for LED lighting based on nanomaterials is very promising, current device integration and large-scale development has yet to be fully realized. Group III-nitride nanocrystals are promising candidates for lighting applications. However, development of colloidal QDs has issues with the synthesis of indium nitride (InN) nanoparticles, such as the long reaction time and the generation of indium metal as a by-product.

Table 45: Market challenges rating for quantum dots in the lighting and UVC market.

Market acceptability	
Cost	2
Competition from other materials	2
Scalability	2
Industry pull	4
Market push	2
Regulatory	5
Consumer acceptance	3
Total score (out of 35): 20	

Source: Future Markets.

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10.4 Industry and research developments 2013-2019

Table 46: Commercial development and research highlights in quantum dots in LED lighting 2013-2019.

Date	
April 2013	• Phillips announce a five-year, €3 million-funded “Advanced Sustainable Lighting Solutions” partnership with the Dutch government’s Technology Foundation STW. Those projects include an attempt to develop more efficient green emitters by incorporating aluminum gallium phosphide (AlGaP) nanowires into the semiconductor layer structure, another aimed at using cadmium-free quantum dots as phosphor downconverters, and the application of LED lighting to increase the vitamin C content in growing fruit.
July 2013	• Typical nanocrystals, though efficient at room temperature, contain the toxic element cadmium, and suffer from quenching of the fluorescence at high temperatures (>100°C) and/or at high optical excitation fluxes (>50 W/cm2). SUNY/Buffalo has made significant inroads in creating a viable replacement technology for conventional phosphors by forming indium phosphide-based nanocrystals having unique compositional structures. From a performance standpoint, the researchers have synthesized nanocrystals over the spectral emission range of green through red that have efficiencies in the mid-80 percent range, lose only 5 percent in efficiency at 150°C, and suffer minimal fluorescence loss at least up to excitation levels of 38,000 W/cm2.
May 2014	Quantum Materials Corporation option Los Alamos National Laboratory’s (LANL) Thick-Shell ‘Giant’ Quantum Dot patented technology which has the potential of 10 to 100-fold improvement in solid-state brightness compared conventional nanocrystal quantum dots (QD).

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June 2015	• Researchers at the University of Hiroshima fabricate a hybrid inorganic/organic LED that produces white-blue electroluminescence using quantum dots.[116] • Merck announces that it is acquiring the remaining stake in Qlight Nanotech Ltd., Jerusalem, Israel, and will hold 100% of the company.
October 2015	• Nanoco Group announce a further follow-on joint development agreement with lighting company Osram.
August 2017	Researchers at Lumileds use red QDs with tunable peak emission and narrow spectral width to demonstrate the first commercial production-ready white QD LEDs.

Source: Future Markets, Inc.

10.5 Global market for quantum dots in LED lighting

According to the DOE, LED lighting is projected to achieve a market share of 84% of lumen-hour sales in the general illumination market by 2030. QD-LEDs will compete with compact florescent lighting and LED lighting and offers significant advantages over these technologies, although cost at present is prohibitive beyond niche applications (e.g. high end retail). The current market for organic LED lighting is approximately $14.5 billion.

The UV lamp market is currently dominated by mercury lamps and is estimated to be worth approximately $500 million annually. There is likely to be an increased adoption of UV LEDs in the next few years as mercury lamps are phased out, and the market is estimated to be $>$500 million by 2020.[117]

Nanotechnology and nanomaterials will enable white LEDs to produce significantly better quality light at up to 30% higher efficiencies enabling faster market adoption of LED lighting at a lower overall cost to the end consumer due to their higher efficiencies.

Lighting is the most likely high penetration market for QDs after displays. The current market for QD LED lighting is small and they have yet to find commercial use in solid-state lighting, although a number of major solid-state manufacturers are conducting R&D and are engaged in commercial collaborations. They have identified QDs advantages over current technologies in terms of light quality, efficiency and potentially cost.

The potential addressable market for QDs in LED lighting is estimated to be $100-$200 million by 2020, with potential for greater returns with further R&D (up to $750 million by some industry estimates). The global lighting industry is estimated at >$80 billion annually, with LEDs market share estimated at approximately 22-28% in 2015 and growing. The white LED phosphor sector is estimated to be worth over $350 million per annum in sales and would benefit from the development of QD phosphors that offer warmer whites with greater energy efficiency. The total addressable market for nanomaterials in LED lighting is approximately $1.5 billion. In the UV-LED market, the addressable market is approximately $75-$100 million by 2020.

Table 47: Total QD LED lighting component revenues 2013-2030 ($M), conservative and optimistic estimates.

Year	Conservative estimate (M$)	Optimistic estimate (M$)
2013	1.5	4
2014	1.8	8.9
2015	2.2	11.4
2016	3	17
2017	4.9	30.7
2018	9.4	59.8

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Year	Conservative estimate (M$)	Optimistic estimate (M$)
2019	18.7	119.7
2020	30	173.5
2021	47.9	251.6
2022	79.1	364.9
2023	131	529
2024	189	767
2025	282	1036
2026	364	1346
2027	433	1616
2028	468	1810
2029	505	2027
2030	545	2270

Source: Future Markets, Inc.

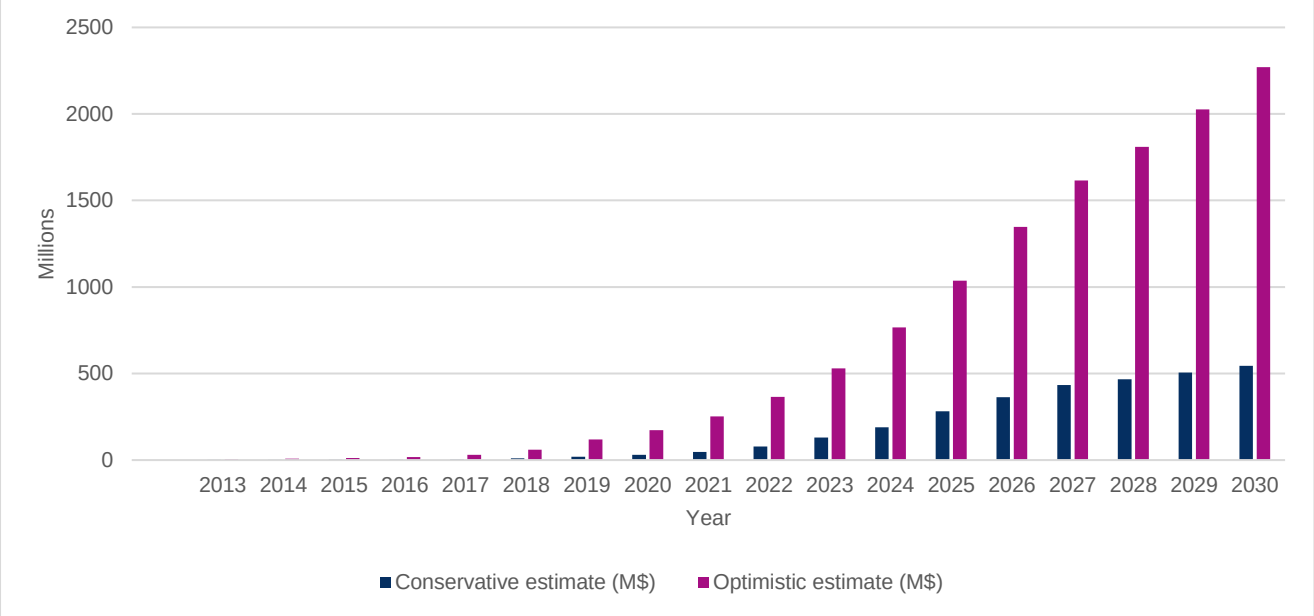

Figure 51: Total QD LED lighting component revenues 2013-2030 ($M), conservative and optimistic estimates.

Source: Future Markets, Inc.

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10.6 Quantum dot lighting companies

Table 48: Quantum dots product and application developers in lighting.

Company	Activity
Lumileds LLC	The company has demonstrated commercial production–ready white light-emitting diodes (LEDs) for the general illumination market with red colloidal quantum dots (QDs) applied in an on–chip configuration. Red QDs with tunable peak emission and narrow full width at half-maximum in combination with a conventional phosphor material can lead to LED conversion efficiency improvements of 5% to 15% over commercial phosphor based LEDs at correlated color temperatures (CCTs) ranging from 5000 to 2700 K.
Nanoco Lighting	The company's cadmium-free QDs can absorb a proportion of LED's light, convert it and re-emit it with the desired colour characteristics. The company partners with Marl International to produce QD based lighting products based on its CFQD® technology. The company has also developed a product for Horticultural lighting, the Nanoco Deep-Red CFQD® Quantum Dot Film.[118] Another focus area is cosmetic skin treatment.
NNCrystal US Corp.	NNCrystal is the owner of two patented and trademarked technology platforms for solid-state lighting applications-Qshift Lucid and Qshift Coral.
Osram	The company jointly develop cadmium free quantum dots from Nanoco for LED lighting
Pacific Light Technologies	The company produces quantum dot down converters for solid-state lighting. They are developing QDs for direct phosphor replacement in both lighting and display applications.
Pure Quantum	The company is a Cornell University start-up developing QDs for LED lighting applications.
Philips	Philips is exploring QDs for downlighting solutions.
QD Vision, Inc.	The company is a leading player in the QD displays and lighting markets. QD Vision's Quantum Light technology has been developed in collaboration with Nexxus Lighting backlights in high-colour-quality white LED SSL.
Quantum Materials Corporation	The company produces QDs for white light solid-state lighting (SSL) applications.
Revolution Lighting Technologies	The company produces Array™ Quantum LED R30 replacement light bulbs.
UbiQD, Inc.,	Produce a quantum dot (QD)-containing product, the UbiGro™ greenhouse film. In successful commercial pilot program, these films have demonstrated boosts in crop yields in excess of 10% for various plants, improvements in crop quality.

Source: Future Markets, Inc.

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11 QUANTUM DOTS IN BIOTECH AND MEDICINE

The exploitation of nanotechnology and nanomaterials in biomedicine and healthcare is on-going in:

- Disease diagnosis and monitoring
- Implants
- Tumour destruction via hyperthermia.
- Medical surfaces.
- Medical textiles.
- Medical devices.
- Regenerative medicine.
- Drug and gene delivery.
- Drug discovery.

Healthcare is the world's largest service sector, and in recent years there has been growth in the use of nanotechnology and nanomaterials in medical technology and improved treatments for patients.

Nanobiotechnology, integrating physical sciences, molecular engineering, biology, chemistry and biotechnology is leading to significant advances in pharmaceuticals and healthcare, especially in cancer therapy. Nanoparticles in the 1-10 nm size range are of considerable interest, not only because of their unique size-dependent properties but also their dimensional similarities with biological macromolecules (e.g., nucleic acids and proteins). Their use has been impacting the pharma and healthcare industries for a number of years, in molecular imaging and diagnostics, drug discovery and delivery (drugs, growth factors, DNA), prognostics, tissue scaffolds and implantable devices, biosensors and therapeutics.

Anti-bacterial nanocoating products have also been widely commercialized in life sciences & healthcare as antibacterial surfaces for medical catheters and wound dressings, in paints and lacquers used to coat operating tables, door knobs and door handles in hospitals and also as ultra-hard porous coatings for surgical and orthopaedic implants such as screws, plates or joint implants. In the medical coatings area, graphene is of particular interest in detection, inhibition and killing different types of pathogens.[119]

There is increasing interest in the unique biological and medical properties of graphene, and it is expected that biomaterials incorporating these materials will be developed for clinical use. Graphene is allowing for the manufacture of novel bio-devices, including biosensors, interfaces, tissue scaffolds, drug delivery and gene therapy vector systems. Quantum dots are intrinsically bright, are exceptionally photostable, and have a narrow emission spectra that reduces background staining and artifacts-all factors that make them useful in biotech and medical applications ranging from flow cytometry to imaging.

Table 49: Market snapshot for quantum dots in biotechnology and medicine market.

Category	Assessment	Trend
Market age	Market entry for imaging and biomarkers Development for other applications	Increasing
Revenues in 2015	<$5-$20 million	Increasing
Potential revenues by 2027	$650 million	Increasing

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Category	Assessment	Trend
Base year market growth rate (2015)	38.9%	Increasing
Forecast period market growth rate	40.8%	Increasing
Price sensitivity	Medium-High	Stable
Competitors (Active market competitors in base year)	~13 companies	Stable
Degree of competition (Low=1, High=10)	8	Stable
Degree of technical change	Medium-High	Increasing

Source: Future Markets.

11.1 Market drivers and trends

Table 50: Market drivers and trends for quantum dots in biotechnology and medicine.

Drivers	Trends
Modern healthcare demands for novel diagnostic tools	The sensitive monitoring of biological analytes, such as biomolecules (protein, lipid, DNA and RNA), and biological cells (blood cell, virus and bacteria), is essential to assess and avoid risks in healthcare. There is a growing need for medical sensors that enable quick, accurate, reliable, and cost-effective results so that appropriate treatments can be implemented in time, leading to improved clinical outcome. Early detection and diagnosis is crucial for cancer treatment; Stage 1 cancers have dramatically increased survival rates over those diagnosed at Stage 3 or 4. Traditional diagnostic tools are also of limited sensitivity: histology, X-ray or MRI imaging may also only detect tumours when they are well advanced. There is therefore a significant effort to find rapid, sensitive, low cost and preferably non-invasive cancer diagnostic tests.
Growth in the handheld point-of-care market	Point-of-care (POC) testing has traditionally been a manual, labor intensive process characterized by single use tests that do not readily interface with hospital and clinic information systems, and can only be carried out by trained medical staff. With increasing pressure on healthcare costs, hand-held POC molecular diagnostic devices, that are able to deliver instant diagnostics of our health status at home, at doctor's office, at bed side or at resource-limited settings are in great demand. As the number of drug-resistant superbug infections continues to rise, the development of POC devices that quickly identify bacteria and reduce the need to use unnecessary antibiotics is desirable. Antimicrobial resistance (AMR) is one the greatest healthcare challenges associated with infectious diseases and improved POC devices are needed to curtail this problem, in particular to determine if and which antibiotics are needed. POC devices enable rapid and accurate identification of infectious disease pathogens, even in remote areas and resource-poor settings. Threatening, potentially global epidemics by the Ebola, MERS, Zika, Dengue and Chikungunya viruses, and the emergence of multi-drug-resistant "superbugs" world-wide demand for simple rapid molecular tests that can help determine optimal treatment, curb the spread of infections, and assist with allocation of resources.

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Drivers	Trends
	Novel POC tests that are highly accurate, easy to use and equipped with data transmission capacities can be deployed across all healthcare settings. In the digital age and with the growth in the Internet of Things (IoT), linking data from diagnostic laboratories and POC testing sites can provide timely information on testing coverage, disease trends, and early warning of infectious disease outbreaks, thus increasing the efficiency of healthcare systems, and improving patient outcomes.
Universal to individualized medicine	There is an ongoing market transition from universal medicine to individualized medicine that involves new approaches for customized theranostics based on interpersonal variation to drug response.[120] Nanotechnology is a key component in diagnosing the state of diseases and offer patients with target-specific medications at the required dosage.
Growth in the wearable monitoring market	There is a growing need to support independent living in a globally aging population and support active and healthy living. Remote monitoring is desirable for enabling palliative care in the home and tracking treatment programmes for persons with intellectual or cognitive disabilities in the home. The remote monitoring of biomarkers is also useful for monitoring conditions such as diabetes and prenatal monitoring and diagnosis. Recently, human-machine interfaces as well as the healthcare system have experienced great advancement through the introduction of implanted and skin-mounted electronics.[121] However, the power supplying system has not kept pace with technological advances of such electronics.[122] [123] There is a need to develop new materials for power sources to meet these needs.
Need for improved medical imaging	Current clinical Gd^{3+}-based T_1 magnetic resonance imaging (MRI) contrast agents are suboptimal or unsuitable, especially at higher magnetic fields for advanced MRI applications such as blood pool, cellular and molecular imaging. Contrast agents used for MRI are not tumor selective, which leads to relatively poor contrast between tumors and non-tumor tissue. The risk of false positive findings (tumor findings that are not malignant) is therefore high. Although there are no currently approved non-magnetic nanoparticle MRI agents on the market, the use of nanomaterials is still expected to offer significant future benefits over traditional diagnostic probes and therapeutics. Nanomaterials can be tailored to enhance their site specificity, thereby ensuring an efficient diagnostic and therapeutic intervention.[124] [125] X-ray imaging is the most commonly used medical technique due to its high resolution capabilities and low cost. Improvements in X-ray imaging are reliant on the development of novel X-ray contrast agents with increased imaging capability. Currently used X-ray contrast agents can cause severe adverse effects (e.g. allergies, cardiovascular diseases and nephrotoxicity) in some patients owing to the large and repeated doses that are required to achieve good contrast. There is an increasing interest in the development of alternative X-ray contrast agents utilizing nanoparticles that have better imaging properties, longer blood circulation times and lower toxicity than conventional iodinated X-ray contrast agents. For traditional biological applications, QDs have already begun to replace traditional organic fluorophores to serve as simple fluorescent reporters in immunoassays, microarrays, fluorescent imaging applications, and other assay platforms. QD fluorescence resonance energy transfer sensors, quenching sensors, and barcoding systems are also under development for highly-sensitive genetic and epigenetic detection of diseases, multiplexed identification of infectious pathogens, and tracking of intracellular drug and gene delivery. When combined with microfluidics and confocal fluorescence spectroscopy, the detection limit is further enhanced to single molecule level.

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Drivers	Trends
Need for improved drug delivery	The trend in recent years is for medical therapies tailored to specific diseases and patients, especially for cancer treatment. The unique properties of nanomaterials when combined with special high loading and controlled release provide superior performance for drugs. The pharmaceutical industry faces a number of technological and market challenges in the coming years including: • Improving solubility.[126] • Enhancing product effectiveness and exclusivity in the face of generic competition.[127] • Need to reduce side effects of cancer therapies. • Active drug targeting. • Patient compliance. • Cost effectiveness (the cost of producing a new drug can be upwards of $800 million). • Product life extension. Therapeutic drug delivery is one of the main markets for nanomaterials-based applications, where the recent trend has been for medical therapies tailored to specific diseases and patients, especially in cancer therapy where, patients continue to suffer from the lack of selectivity of chemotherapy, which leads to severe side effects and has low therapeutic treatment efficacy. The unique properties of nanomaterials, such as large surface-to-volume ratio, small size, the ability to encapsulate various drugs, and tunable surface chemistry, give them many advantages over their bulk counterparts. This includes multivalent surface modification with targeting ligands, efficient navigation of the complex *in vivo* environment, increased intracellular trafficking, and sustained release of drug payload. These advantages make nanomaterials a mode of treatment potentially superior to conventional cancer therapies.
Limitations of conventional treatments	Nanotechnology and nanomaterials have been developed due to their ability to provide enhanced therapeutic and diagnostic (theranostic) approaches. They can overcome multi-drug resistance of cancer cells and the drawbacks of conventional cancer treatments such as the poor solubility of hydrophobic anti-cancer drugs, biocompatibility and the use of harmful radiations, temporary remission, systemic toxicity and lack of specificity.[128] High chemotherapeutic doses have side effects that patients find difficult to tolerate. The treatment of cancer involves different therapies based on alkylating agents, antimetabolites, biological agents, etc. with one of the principal problems the side effects due to difficulties in differentiating between cancerous and normal cells, which produces systemic toxicity. Additionally, the diagnosis and imaging of tumour evolution remain a challenge.
Increase in global cancer problem	The last World Cancer Report of the World Health Organization states that the incidence of cancer increased from 12.7 million in 2008 to 14.1 million in 2012. This trend is projected to continue with new cancer cases close to 25 million per year by 2035. Therefore, there is a significant need to develop new, more effective treatments.
Shortcomings of Chemotherapies	Chemotherapies and protein therapeutics have emerged as two common treatments for malignant tumours, but they have limited therapeutic efficacy due to the dose-dependent significant toxicity and inactivation of protein drugs stemming from their poor stabilities. To overcome the barriers and minimize dosing frequency the use of nanomaterials has been extensively studied.

Source: Future Markets.

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Table 51: Impact of market drivers for quantum dots in the biotech and medicine market.

Rank	Driver	1-2 years	3-4 years	5-8 years
1	Need for improved drug delivery	High	High	High
2	Increase in global cancer problem	High	High	High
3	Limitations of conventional treatments	High	High	High
4	Shortcomings of chemotherapies	High	High	High
5	Need for improved medical imaging	Medium	High	High
6	Demands for new diagnostic tools	Medium	High	High
7	Growth in the handheld point-of-care market	Medium	High	High
8	Growth in the wearable monitoring market	Medium	Medium	High
9	Universal to individualized medicine	Medium	Medium	Medium

Source: Future Markets.

11.2 Applications

The first commercial applications of QDs were used as in vitro fluorescent labels substituting for organic dyes due to their photo-oxidation robustness and singular excitation for the various emission wavelengths.[129] QDs are highly fluorescent and stable probes for cellular and molecular imaging. Most QDs are produced via organic methods, and hence require surface treatment to render them water-soluble for biological applications. Biocompatible QDs are typically generated through either an organic synthetic route requiring subsequent ligand exchange or encapsulation, or a more direct aqueous synthetic route where the nanocrystals are inherently water-soluble. QDs have potential applications in genotyping, DNA expression analysis, protein expression analysis, DNA sequencing, biological assays, imaging systems, research instrumentation, optical bar-coding of chemical and biological materials, tagging systems, and high-throughput screening.

They are excellent alternatives to organic dyes and fluorescent proteins for various cellular and biomedical imaging applications due to their high photoluminescent quantum efficiency, narrow emission spectral band, tunability, and photostability.[130] [131] [132] QDs also provide high quality deep tissue imaging using two-photon excitation microscopes. However, some drawbacks of QDs restrict their applicability for diagnosis and therapeutics. For instance, QDs dispersed in nonpolar solvents gradually aggregate and lose their fluorescence intensity, even in the dark. QDs enter cells very slowly and tend to become trapped in endosomes or other vesicles following cellular entry. Therefore, methods to improve QD solubility, cellular uptake, and biodelivery are under development.

11.2.1 Imaging and diagnostics

The main drawback for current optical imaging markers is their short life, and companies are developing QDs to supplant these markers. As a fluorescent label, QDs have been widely used in biomedicine. QDs have been developed for in vivo imaging at all levels of magnification and have been used as contrast agents for several years. Other applications in inmaging and diagnositcs include:

- High-resolution cellular imaging.[133]
- Long-term in vivo observation of cell trafficking.
- Photodynamic therapy.[134]
- Tumour targeting.

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- Blood monitoring.

11.2.1.1 Advantages

QDs can be excited by the same wavelength of light, making them ideal candidates for high-throughput screening of biological samples. They have a sharper spectrum, are more a stable over time and multiple dyes are excited simultaneously.

QDs are more resistant (can be up to 100 times) to photo chemical degradation than fluorescent dyes, which makes them useful for tracking cells and monitoring biological changes over extended periods of time. Advantages include:

- Increased brightness allows for sensitive detection.
- High photostability allowing for long-term monitoring and ease of use.
- Narrow emission peaks allow for simple multiplexing.
- Ease of illumination via multiple excitation sources.
- Easily conjugated to a variety of biomolecules.

11.2.1.2 Biomarkers

QDs are promising alternatives to traditional biomarkers. Advantages include:

- small size (5-10 nm)
- and high photoluminescence and photostability
- suitable for optical bar coding of targets, such as a particular analyte or cell type, since one wavelength could be directed at the sample that would give clear, distinct, and a characteristic set of signals.
- ideal probes for multiplexed analysis: a single light source can be used to simultaneously excite QDs of different colors
- emission spectra are clearly distinguishable.
- nearly 20 times brighter and thousands of times more stable to photobleaching than conventional organic dyes.
- have broad excitation spectra and narrow emission spectra with Stocks shifts larger than 100 nm.
- tailorable surface functionalities.

11.2.1.3 Photodynamic therapy

QDs can also be used in Photodynamic therapy (PDT) either as photosensitizers themselves or for activation of another photosensitizer by serving as energy donor to excite molecular oxygen into the singlet state. QDs can be tuned to emit in the near IR regions and thus can be suitable for use in PDT for deep tumours, to avoid light scattering by tissue.

11.2.1.4 Point-of-care

Researchers have developed magnetic nanoparticle/quantum dot-based immunoassays for the detection of pathogens responsible for waterborne and foodborne diseases (e.g., E. coli 0157:H7, Salmonella, etc.). Detection is achieved by labelling the captured bacteria with bioconjugated quantum dots which fluorescence.[135]

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11.2.2 Drug delivery

Therapeutic drug delivery is one of the main markets for nanomaterials based applications, where the trend in recent years is for medical therapies tailored to specific diseases and patients, especially for cancer treatment. QDs show excellent potential for drug delivery due to:

- their small size and versatile surface chemistry, allowing their incorporation within virtually any nanoparticle drug delivery vehicle with minimal effect on overall characteristics
- excellent optical properties for real-time monitoring of vehicle transport and drug release at both cellular and systemic levels.

Product developers are developing methods for QDs to be safely excreted from the body once they have delivered their payload. Though the direct use of cadmium based QDs for drug delivery remains questionable due to their potential long-term toxicity, the QD core can be easily replaced with other organic drug carriers or more biocompatible inorganic contrast agents (such as gold and magnetic nanoparticles) by their similar size and surface properties, facilitating translation of well characterized drug delivery vehicles to the clinic, maintaining drug delivery imaging capabilities, and potentially providing additional therapeutic functionalities such as photothermal therapy and magneto-transfection.

QDs can be functionalized to target specific cells or tissues by conjugating them with targeting ligands. Various colloidal core/shell usually synthesized are CdSe/ZnS, CdTe/CdSe, InP/ZnS and CdSe/CdS/ZnS. Advancement in making biocompatible QD formulations has made these nanocrystals suitable for in vivo.

11.2.3 Photodynamic therapy

Quantum Dots can be made into sheets of light emitting material with high intensity and precise wavelengths which activate certain otherwise inert compounds for treatment.

This could allow for non-invasive treatment for pre-cancerous lesions as well as rosacea, facial wrinkles, sun damage, and age spots. Specific cells would be targeted and surrounding tissue left unharmed.

Nanoco has supplied QDs to wearable light therapy company CareWear to a device that improves athletic performance by reducing physical pain and joint stiffness while accelerating recovery. Once applied to your skin the device uses miniature LED lights along with Nanoco Cadmium-free Quantum Dot film, producing a particular spectra that has been scientifically proven to aid athletic performance and bruise recovery. The device has already been trialed by professional sports teams.

11.3 Market challenges

Successfully translating nano-enabled drug delivery from pre-clinical proof of concept to product is challenging. The rate of failure of anti-cancer agents in clinical trials is high. Coupled with this failure rate, the technical and cost challenges in scale-up and manufacturing may be prohibitive.

Compliance with international regulatory industrial and healthcare guidelines before commercialization and translational medicine can take over 10 years and the cost of producing a new drug can be upwards of $800 million. Major challenges identified foe the use of nanotechnology and nanomaterials include:

- sufficiently high drug loading capability for practical uses
- suitable in vivo drug distribution and release profiles

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- proper chemical modifications of nanomaterials for cell membrane barrier penetration for drug delivery into the interior of a cell
- understanding of in vitro and in vivo toxicity profile, bio-distribution, bio-compatibility and bio-degradability of nanomaterials.

Table 52: Market challenges in imaging and diagnostics.

Nanomaterial	
Lack of current products	Apart from iron oxide nanoparticles which have been approved by U.S. FDA for clinical MRI, there are currently no other theranostic nanomaterials that have been approved for clinical use.[136] [137] [138]
Problems with delivery stability and toxicity	There is a need to develop nontoxic contrast agents that have optimal half-lives. Metal-based nanoparticles have not impacted in vivo imaging due to their prolonged elimination (slow wash-out), intracellular uptake (safety concerns) and organs accumulation (liver, spleen, skin). Poor intracellular delivery, stability, and toxicity of QDs in biological compartments have this far hindered their use in cellular imaging. Widespread uptake is also hindered by the use cadmium, a toxic heavy-metal that is unsafe for the human body. Steps are being undertaken to overcome this problem. Cadmium-free quantum dots are also a viable alternative.

Source: Future Markets.

Table 53: Market challenges rating for quantum dots in the medical imaging and diagnostics market.

Market acceptability	
Cost	2
Competition from other materials	3
Scalability	4
Industry pull	4
Market push	3
Regulatory	3-4
Consumer acceptance	3
Total score (out of 35): 22-23	

Source: Future Markets.

11.4 Global market for quantum dots in biotechnology and medicine

Increased interest in diagnosis and therapies for diseases have been a driving force for the utilization of QDs for in vivo and in vitro diagnostic methods as well as imaging techniques.[139] However, they have yet to achieve mass commercialization in biotech in medicine due to their cost and are mainly used in research labs for sample imaging.

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QDs are exploited for for research purposes in various biomedical applications, such as fluorescence microscopy, correlation spectroscopy, single-cell biochemistry, flow cytometry, DNA and protein arrays, immunoassays, cyto-and histochemistry, in situ hybridization, PCR, and drug screening in a high throughput setting. Cancer imaging, diagnostics and biosensors represents a significant future market opportunity for QDs. The global market for point-of-care diagnostics is expected to reach over $30 billion by 2020.

11.4.1 Imaging and diagnostics

The total medical diagnostics market was estimated to be worth >$50 billion in 2015. The USA and Europe account for >60% of the market. The global diagnostic imaging segment is estimated to be worth >$23 billion in 2015, with annual growth of 4-5%. The imaging segment is mainly comprised of ultrasound, X-Ray, CT and MRI. The global contrast media segment is worth >$6 billion.

Magnetic nanoparticle products have been approved for use; however, industry uptake is small at present (almost non-existent). Many products were dropped from the market due to long procedures, negative contrast and low usage. Five types of superparamagnetic iron oxide (SPIO), *i.e*. Ferumoxides (Feridex® IV, Berlex Laboratories), Ferucarbotran (Resovist®, Bayer Healthcare), Ferumoxtran-10 (AMI-227 or Code-7227, Combidex®, AMAG Pharma; Sinerem®, Guerbet), NC100150 (Clariscan®, Nycomed,) and (VSOP C184, Ferropharm) have been designed and clinically tested as magnetic resonance contrast agents. However, until now Resovist® is current available in only a few countries.

However, there are opportunities for biodegradable nanoparticles with biocompatible features. These include:

- Near Infrared Fluorescent (NIRF) contrast agents specifically targeted to relevant epitopes enabling minimally invasive surgery (e.g. nerve sparing, SLN detection, margin-free tissue resections etc.)
- Enzyme-activatable nanosensors for imaging and/or therapy (e.g. metalloproteases, caspases, cathepsins etc.)
- Optimized nanoprobes for Photoacoustic Imaging
- Targeted Luminescent nanophores for endoscopy based diagnostic procedures (OCT, FLTI, LIF, LDI etc.).

The global pharmaceuticals sector generated revenues of >$1.25 trillion in 2015, with North America accounting for >40% of the market. The biotechnology segment is worth approximately $300 billion, with growth rates of approximately 9% through to 2020. The global oral drug delivery market was valued at >$65 billion in 2015, with annual growth rates of 8-9%. The injectable drug delivery market is worth over $45 billion annually.

11.4.2 Drug delivery

A number of nano-based delivery systems are on the market, and many more are in the pipeline. The addressable market for nanomaterials based delivery systems is >$100 billion.

Table 54: Total QD revenues in biotechnology and medicine 2013-2030 ($M), conservative and optimistic estimates.

Year	Conservative estimate (M$)	Optimistic estimate (M$)
2013	3	7
2014	3.6	10.5
2015	5	15.2
2016	7.1	22.1
2017	10.2	32.6

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Year	Conservative estimate (M$)	Optimistic estimate (M$)
2018	14.8	48
2019	20.8	72
2020	29.1	108.1
2021	40.7	162.1
2022	58	235
2023	82.7	305.6
2024	107.5	366.7
2025	140	447
2026	168	546
2027	201	666
2028	215	732
2029	230	820
2030	246	919

Source: Future Markets, Inc.

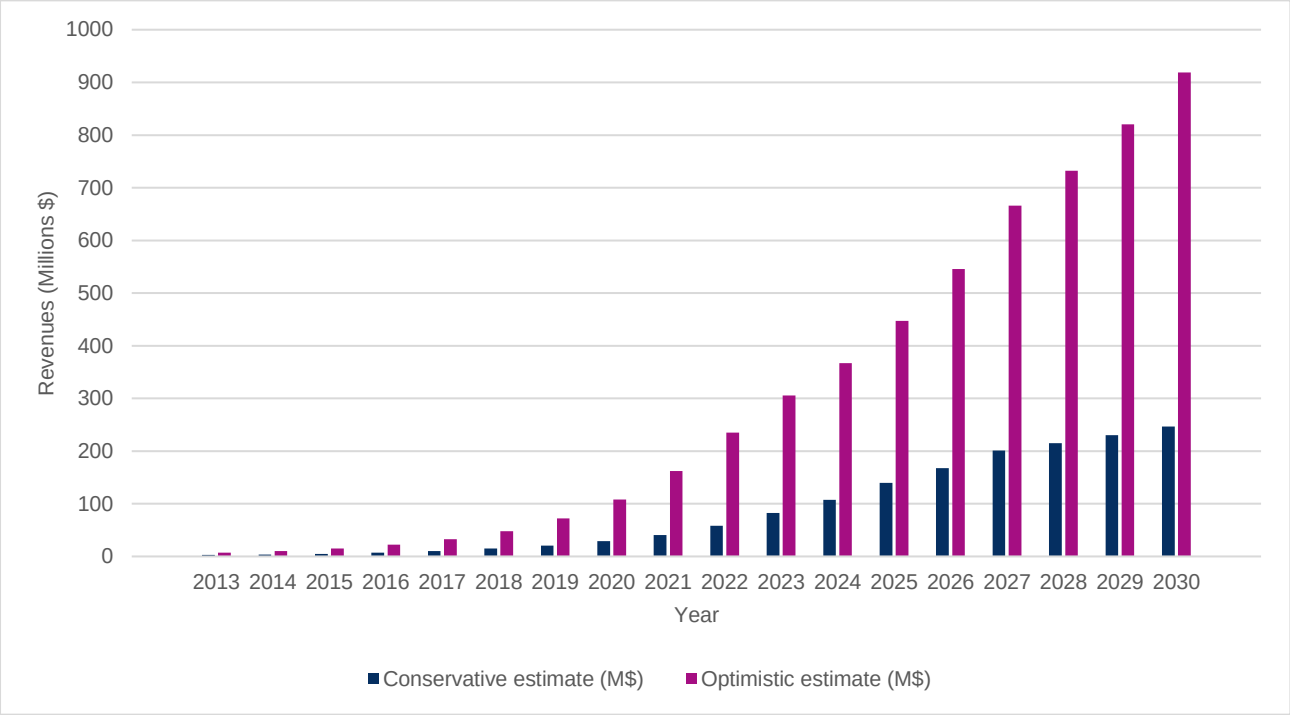

Figure 52: Total QD revenues in biotechnology and medicine revenues 2013-2030 ($M), conservative and optimistic estimates.

Source: Future Markets, Inc.

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11.5 Quantum dot biotechnology and medicine companies

Table 55: Quantum dots product and application developers in biotechnology and medicine.

Company	Activity
Affymetrix/eBioscience	eFluor Nanocrystals are high quantum yield nanocrystals that contain a heavy metal core particle surrounded by a patented surface coating enabling attachment to antibodies and other biomolecules.
Antibodies Incorporated	The company produces quantum-dot based anti-bodies.
Attonuclei	The company produces functionalized custom quantum dots.
Cromoz, inc.	The company is developing two proprietary technologies: water-soluble carbon nanotubes and water-soluble fluorescent carbon quantum dots mainly for the biomedical market.
Luminex Corporation	The company uses quantum dots as biomarkers.
NanoAxis	The company produces axicad quantum dots for pharma and diagnostics applications.
Nanoco	The company has received funding for developing cancer diagnostics using QDs. Nanoco's heavy-metal and cadmium-free quantum dots are a safe way to use fluorescent imaging to conduct cancer diagnostics, specifically related to Sentinel Lymph Node (SLN) Mapping. The company has a partnership with Charles River Labs partnership on in-vivo mouse models for pancreatic cancer
NNCrystal US Corp.	NNCrystal is the owner of two patented and trademarked technology platforms for solid-state lighting applications-Qshift Lucid and Qshift Coral.
Ocean Nanotech, LLC	Products include biocompatible quantum dots in visible and near IR range; biocompatible iron oxide nanocrystals; biocompatible gold nanocrystals and nanorods; quantum dot powders at electronic grade.
Quantum Materials Corp.	The company develops tetrapod QDs for application in medical diagnostic assays. Conventional organic dyes and other types of fluorophores are currently used for luminescence in assays by researchers, but they have limitations sometimes preventing clear distinctions in reading the data. Broad data sets can tend to obscure patterns that might become clear by removing these uncertainties. Tetrapod quantum dots address this issue well for biochemical detection and biomedical device application by providing a broad array of colours, which translates to increased number of pieces in the data set, and also precise tune-ability and stability for high contrast and distinctive identification certainty. The company is developing a suitable TQD film for medical devices.
Thermo FIsher Scientific	The company produces Qdot® nanocrystals mainly for life sciences applications. Qdot® Nanocrystal bioconjugates are coupled to proteins, oligonucleotides, small molecules, etc., which are used to direct binding of the quantum dots to targets of interest.
Unibiotest Co., Ltd.	The company provides a series of water soluble CdSe/ZnS core/shell quantum dots.

Source: Future Markets, Inc.

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12 QUANTUM DOTS IN SECURITY AND ANTI-COUNTERFEITING

Table 56: Market snapshot for quantum dots in security and anti-counterfeiting.

Category	Assessment	Trend
Market age	Development	Increasing
Revenues in 2015	<$5 million	Increasing
Potential revenues by 2027	>$300 billion	Increasing
Base year market growth rate (2015)	41%	Increasing
Forecast period market growth rate	34%	Increasing
Price sensitivity	High	Decreasing
Competitors (Active market competitors in base year)	~6 companies, mainly QD producers	Increasing
Degree of competition (Low=1, High=10)	8	Stable
Degree of technical change	High	Increasing

Source: Future Markets.

12.1 Market drivers and trends

Table 57: Market drivers and trends for quantum dots in security and anti-counterfeiting.

Drivers	Trends
Growth in counterfeiging and need for improved security	Counterfeiting is a major problem, causing the global economy billions of dollars per year. Sales of counterfeit products can greatly affect sales revenues, erode brand value and public trust, pose health risks for citizens, lead to product recalls and are a particular problem in the pharmaceuticals, airplane parts, auto parts, and designer clothing sectors, among others. Counterfeiters are at present able to counterfeit most anti-counterfeiting technologies within 18 months. In order to stay one step ahead of counterfeiters it is necessary to develop sophisticated new and forgery-proof marking systems. Incumbent technologies that need to be replaced are, for example, holograms. Due to the proliferation worldwide of holographic technologies they are now relatively straightforward to copy. The Dotmatrix equipment used to produce the technology is available off-the-shelf and is used to produce high quality counterfeits. Other weaknesses of holograms include the reliance only on visual perception and difficulty in authentication due to overcomplicated design. Other current anti-counterfeiting technologies such as tamper-evident closures, tags and markings and RFID labels can also eventually be copies. The use of luminescent inks has increased significantly in an attempt to prevent counterfeiting. Nanomaterials based applications are leading to new non-reproducible technological features that will lead to preventing illegal copying of intellectual property and products.

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Drivers	Trends
Combating counterfeiting in 3D Printing	3D printing represents an exciting new opportunity for manufacturers.[140] However, it also presents a significant opportunity for Intellectual Property theft. Integration of QDs within the printing process allows for 3D printed objects with unique, unrepeatable signatures.[141]
Threat detection and prevention	Defence against biological and chemical agents and environmental security are viewed as key priority areas for global security. Chemical and biological threats pose a significant concern not only to military personnel but also to individuals and groups. Nanomaterials and nanotechnology can play a vital role in the detection and decontamination of chemical and biological threat agents. Nanosensors are allowing for improved detection, decontamination and protection against chemical, bio-agents and explosive threats. Current decontamination processes for biological agents are complex, cumbersome and costly. To circumvent this process, nanocoatings have been developed with the continuous ability to decontaminate a surface exposed to biological agents including spores.
Increased use of electronic devices in military and security	There is a need condense the size of electronic devices while increasing their capability, features, and speed to save space, weight, and mass, while allowing for more digital signal paths in applications ranging from unmanned aerial vehicles (UAVs) to handheld devices deployed in the military, homeland security, and law enforcement. Their increased need for greater power and energy requirements for a range of military applications, such as weapons systems, combat vehicles, ships, data centres, and military micro-grid applications.

Source: Future Markets, Inc.

Table 58: Impact of market drivers for quantum dots in the security and anti-counterfeiting market.

Rank	Driver	1-2 years	3-4 years	5-8 years
1	Growth in counterfeiting and need for improved security	High	High	High
2	Threat detection and prevention	Medium	High	High
3	Combating counterfeiting in 3D printing	Medium	Medium	High

Source: Future Markets, Inc.

12.2 Applications

The novel optical properties of QDs make them ideal fluorophores for ultra-sensitive, multicolour, and multiplexing applications in anti-counterfeiting label and security identification such as passports and ID cards. They offer superior optical properties and enhanced photochemical and thermal stabilities. As a cryptoprotection system, they are used to create a larger quantity of the various combinations (coding marks) for application to various substrates. A set of QDs having six different particles sizes and ten different QD concentrations can form one million unique fluorescent codes.

QDs have been developed for use as photo luminescent inks in security documents, banknote paper, packaging paper and labels in both single colour and full colour characters and images. QD-based inks may be applied via conventional screen, flexography, offset, gravure, and ink jet printing processes while the paints are designed to be sprayed onto any surface.

QDs offer the ability to specifically control absorption and emission spectra to produce unique validation signatures. They are almost impossible to mimic with traditional semiconductors. By adjusting the particles size and concentration

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of QDs, a QD ink forms a unique fluorescent marker. They emit different wavelengths of visible light under UV excitation; the different spectra act as the anti-counterfeit code.[142] CdSe/ZnS core-shell QDs have mainly been utilized for anti-counterfeiting inks. Similar optical and stability properties in some cadmium-free nanocrystals, such as ZnCuInSe CQDs, have also been reported.

12.3 Global market size for quantum dots in security and anti-counterfeiting

There is a significant market need to improve anti-counterfeiting techniques and tools in order to effectively prevent counterfeiting of money, goods, pharmaceuticals, agro products and improve security.

The worldwide counterfeit goods trade, excluding counterfeit money, is believed to be on the order of $1.8 trillion annually-up to 10% of global trade-and growing by over 15% per annum.[143] The U.N. estimates counterfeit drug sales alone were over $300 billion in 2008, while the World Customs Organization believes that other counterfeit goods sold for more than $600 billion. According to U.S. Immigration and Customs Enforcement, these losses cost American industry and trade between $200 billion and $250 billion each year and equate to 750,000 American jobs lost.[144] [145]

Quantum dot-based anti-counterfeiting is at a relatively early stage of development. The security and authentication sector is very competitive and there is a wide range of technologies available. However, there is a significant market opportunity in security inks and anti-counterfeiting technology due to both the scale of the market and the inadequacies of current products. The security ink market is worth >$22.5 billon per annum.

Table 59: Total QD revenues in security and anti-counterfeiting 2013-2030 ($M), conservative and optimistic estimates.

Year	Conservative estimate (M$)	Optimistic estimate (M$)
2013	1	2
2014	1.2	3
2015	1.7	4.4
2016	2.4	6.3
2017	3.4	9.3
2018	4.9	13.7
2019	6.9	20.6
2020	9.7	31.9
2021	13.6	49.5
2022	19.3	76.7
2023	25.1	118.8
2024	32.7	154.5
2025	42.5	200.8
2026	51	261
2027	62.7	339.3
2028	67.1	371.5
2029	71.8	406.8
2030	76.8	445.5

Source: Future Markets, Inc.

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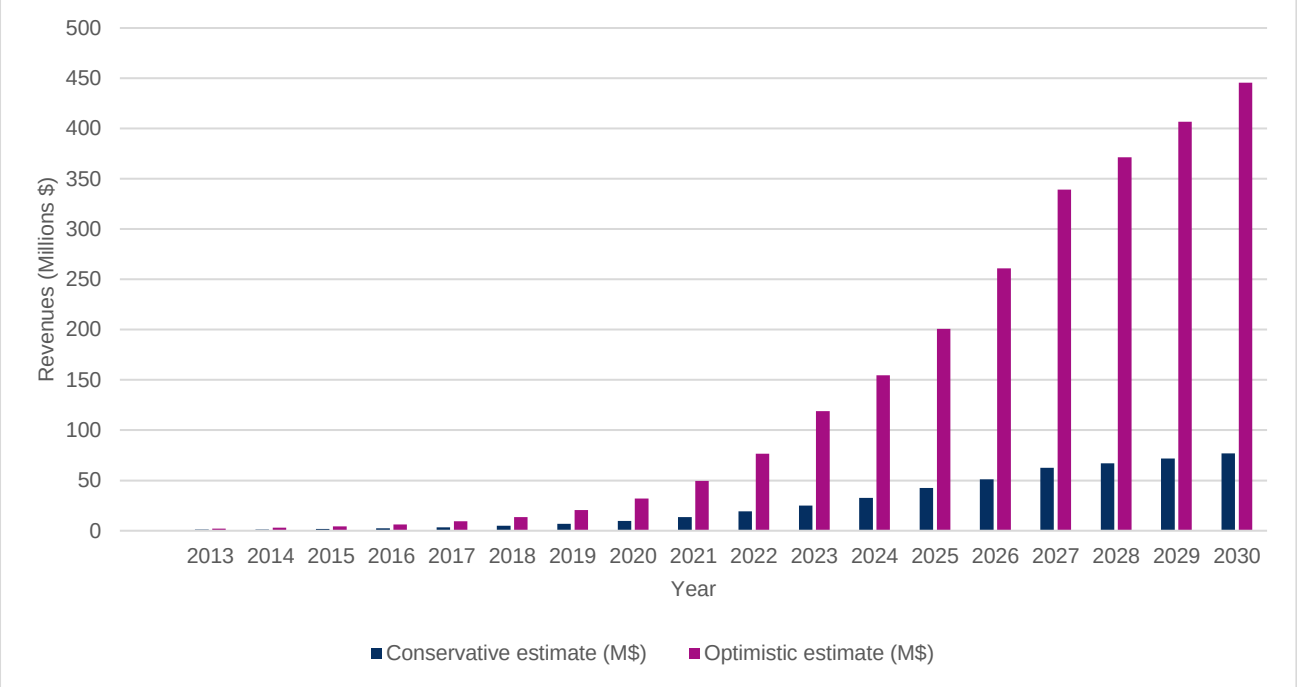

Figure 53: Total QD revenues in in anti-counterfeiting and security 2013-2030 ($M), conservative and optimistic estimates.

Source: Future Markets, Inc.

12.4 Quantum dot security and anti-counterfeiting Companies

Table 60: Quantum dots product and application developers in security.

Company	Activity
IQDEMY Quantum Technology SA	The company produces QD inks for anti-counterfeit tags.
Nanoco	The company's QDs have been utilized for anti-counterfeiting ID-tags (CD's, packaging, fabric, documents currency, etc).
Nanosys	The company is collaborating with Life Technologies in anti-counterfeiting applications of QDs. According to the company the QDs will allow manufacturers to trace the source of their materials and manage and track product shipments, helping stop counterfeit material use in pharmaceutical and diagnostic products, food and beverages (and their agricultural and environmental sources), and electronic goods, reducing counterfeiting of currency, documents, fine art, and luxury goods.
Quantum Materials Corporation	The company has a 3D printing and additive manufacturing anti-counterfeiting quantum dot detection technology developed at the Institute for Critical Technology and Applied Science and the Design, Research, and Education for Additive Manufacturing Systems (DREAMS) Laboratory at Virginia Tech.
UbiQD	The company has a US patent on the use of its quantum dot technology in anti-counterfeit inks.

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Source: Future Markets, Inc.

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13 QUANTUM DOTS IN SENSORS

Table 61: Overall market assessment for the quantum dots in the sensors market.

Category	Assessment	Trend
Market age	Development	Increasing
Revenues in 2015	<$5 million	Increasing
Potential revenues by 2027	>$400 million	Increasing
Base year market growth rate (2015)	27%	Increasing
Forecast period market growth rate	45%	Increasing
Price sensitivity	High	Decreasing
Competitors (Active market competitors in base year)	<5	Increasing
Degree of competition (Low=1, High=10)	7	Increasing
Degree of technical change	High	Increasing

Source: Future Markets.

13.1 Market drivers and trends

As well as biomedical sensing, QDs also find application in photoelectrochemical sensors for the detection of chemicals and biochemical molecules. The luminescence of core QDs can be extremely sensitive to the surrounding chemical environment. The sensors typically consist of QDs immobilized by a linking molecule (linker) to an electrode, so that upon their illumination, a photocurrent is generated which depends on the type and concentration of the respective analyte in the immediate environment of the electrode.

Table 62: Market drivers and trends for quantum dots in sensors.

Drivers	Trends
Increased demand for chemical and biosensors	In the last decade, increasing demand for chemical and bio-sensors with improved performance from industries such as environmental control, process industry, security, biodefense and food safety, has been driving interest in nanotechnology and nanomaterials. Technolgies that nanomaterials enable such as low power and low cost CO_2 gas sensors are in high demand in both industrial and domestic applications, and there is a consistent market need to make sensors smaller, more responsive and cheaper. Main growth markets for sensors are in consumer and mobile electronics. Automotive, healthcare and environmental monitoring markets are also important. There is a drive towards sensor fusion, creating intelligent, complex and integrated systems with enhanced power and performance while reducing cost. There is also an increasing

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Drivers	Trends
	demand for biosensors based on simple electrical/optical transducing schemes able to achieve cost efficient detection.
Enhanced sensitivity	High sensitivity and selectivity of the response are crucial for applications in diagnostics. Due to the fact that the analytes to be detected in clinical, environmental or food samples are in very low concentrations, the need for biosensing systems that can detect with high sensitivity and selectivity that include very low detection limits along with high reproducibility, is an important challenge. To meet growing accomplishing requirements, most research efforts are focused on signal amplification and noise reduction of biosensors via the incorporation of nanomaterials. The development of new and enhanced nanosensors is allowing for the detection of biological and chemical contaminants at very low concentration levels in the environment, including water. The sensitivity and performance of biosensors are improved by using nanomaterials for their construction. Nanosensor technology can significantly out-perform current commercial detection devices by up to a 1,000 fold. Nanosensors could allow for rapid and precise process control and environmental monitoring, leading to remote, in-situ, real-time and continuous measurement of species at trace (ppt) concentrations.
Growth in the home diagnostics and point of care market	Increasing personal health awareness has resulted in the growth of the home diagnostics and point of care (POC) markets. First generation POC diagnostics are not regarded as being of sufficient standard and effectiveness due to limited sensitivity capabilities, slow response and poor accuracy. Printed biosensors for the point of care (POC) market are a future and key development opportunity. POC devices and systems offer lower cost routes towards continuous monitoring of patients and reduce dependency on primary health systems.

Source: Future Markets.

Table 63: Impact of market drivers for quantum dots in the sensors market.

Rank	Driver	1-2 years	3-4 years	5-8 years
1	Increased demand for chemical and biosensors	High	High	High
2	Growth in medical sensors market	Medium	High	High

Source: Future Markets, Inc.

13.2 Applications

Nanomaterials employed in sensors construction are mainly metal oxide nanoparticles, quantum dots, carbon nanomaterials such as graphene and carbon nanotubes and polymers like dendrimers. Carbon-based materials display exceptional promise for the development of highly sensitive, inexpensive and low-power devices that offer an alternative to conventional silicon-based devices. Properties that are attractive for sensing applications include:

- exceptional electrical properties (e.g., extremely high carrier mobility and capacitance)
- electrochemical properties (e.g., high electron transfer rate)
- optical properties (e.g., excellent ability to quench fluorescence)
- structural characteristics.

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Table 64: Quantum dot sensors and applications.

Sensor types	Types of quantum dots	Applications
Gas and chemical sensors	• CdS QDs. • PbS QDs. • (In)GaN QDs. • Graphene QDs.	• Water monitoring • Leak detection • Fluid monitoring
Food sensors	• CdSe–ZnS. • Carbon QDs.[146] • Mn-ZnS.	• Food safety detection.[147] • Pesticide detection.[148]
Biosensors	• CdSe–ZnS. • CdTe. • Carbon QDs. • InN.	• DNA Biosensing. • Blood sampling. • Biological imaging. • Immunoassays. • Glucose biosensors. • Detection of pathogens. • Drug discovery.
Image sensors	• CdSe.	• Cameras. • Smartphones.

Source: Future Markets, Inc.

13.2.1 Food sensors

Lateral flow (LF) or immunochromatographic (IC) test strips are commonly used to detect pregnancy, drugs, and provide food safety assessments as the are easy to use, results are almost instantaneous, accurate and relatively inexpensive. However, for food safety applications, standard colloidal gold or latex particle immuno-LF test strip sensitivity is limited to approximately 2,000 pathogenic E. coli cells per millilitre and the food safety testing industry demands more extensive screening capabilities. Therefore, there is a demand in the industry for more sensitive testing.

Fluorescent tags are under development for improving LF sensitivity including fluorescent nanoparticles and QDs, which result in up to 300-fold improvement in LF test strip sensitivity demonstrated.[149] Desirable properties of QDs for use in LF test strips include: size-adjustable, bright fluorescence, strong resistance against photo bleaching, narrow band-edge luminescence and excellent compatibility with biological molecules.[150]

13.2.2 Chemical and gas sensors

Detection of environmental gases is becoming increasingly important for applications such as global warming, monitoring and control of environmental pollution, advanced diagnostics in medical applications, destruction of the ozone layer, etc. High sensitivity and selectivity are important for explosive gas leakage detection and for a real-time detection of toxic, combustible or pathogenic gases in industrial applications. Other applications include:

- Agriculture: detecting concentrations of pesticides
- Homeland security: Warning systems for bio-terrorism
- Military: detecting chemical warfare agents.

Highly sensitive CdS and PbS colloidal quantum dots have been developed by a number of research groups for application in gas and chemical sensors.[151] Graphene quantum dots are also promising for gas sensor application due to their unique and tunable photoluminescence, and physicochemical properties. [152] [153]

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13.2.3 Biosensors

The use of nanomaterials in bioanalytics is growing rapidly. Their novel physical and/or chemical properties allow for improved analysis, and the highly fluorescent properties of QDs are of particular interest for sensing and invivo imaging. The availability of a large range of emission wavelengths of QDs with different sizes enables efficient multiplexed analysis. QDs are typically composited with other semiconductor materials with a wider band gap range to overcome surface defect issues.

Properties that are desirable for application in biosensors include:

- Excellent optical and electronic properties compared to the routinely employed fluorescent organic dyes.
- Size-tunable light emission over a wide range of energies.
- High photoluminescence quantum yield (PL QY).
- Narrow emission line width.
- Good solution processability.
- Physicochemical stability.
- Extremely large surface area.
- Possibility of functionalizing their surface by conjugation with appropriate molecules.

Applications include:

- Ultrasensitive sensors with the possibility of multiplex (bio)chemical detection.
- DNA Biosensing.
- Blood sampling.
- Biological imaging.
- Immunoassays.
- Glucose biosensors.
- Detection of pathogens.
- Drug discovery.

13.2.4 Image sensors

QDs are utilized as highly efficient photodiodes and allows thinner films than the active depth in conventional silicon photodiodes.

13.3 Global market size for quantum dots in sensors

The value of the global sensor market is $70 billion plus per annum.[154] Revenues for target markets for QD-enabled-based sensors include:

- Biosensors: $21 billion by 2020[155]
- The global In-vitro-diagnostics (IVD) market is currently worth $50 billion per year and the printed biosensor market for glucose monitoring is currently worth $6.4 billion [156]
- The annual chemical sensors market exceeds $15 billion per annum.

The addressable market size for QDs in the gas and chemicals sensors market is approximately $100 million-$250 million. In biosensors, the addressable market is $250million-$500 million. However, this market is a long-term bet as QD sensors are currently not applied commercially in these markets to a great extent. The most promising near-term market is in image sensors.

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In November 2015, Invisage launched a 13-megapixel smartphone camera sensor utilising the company's QuantumFilm platform. The global volume of the 13-megapixel camera sensor market is projected to increase from over 400 million units in 2015 to approximately 1000 million units in 2020.

Table 65: Total QD revenues in sensors 2013-2030 ($M), conservative and optimistic estimates.

Year	Conservative estimate (M$)	Optimistic estimate (M$)
2013	1	1.5
2014	1.1	2.1
2015	1.4	3
2016	3	6.4
2017	5.7	12.1
2018	8.3	18.2
2019	12.4	27.3
2020	18.6	46.5
2021	26.1	79
2022	39.1	118.5
2023	58.6	154.1
2024	70.4	200.3
2025	84.4	260.4
2026	101.3	338.5
2027	121.6	440
2028	136	506
2029	153	582
2030	171	669

Source: Future Markets, Inc.

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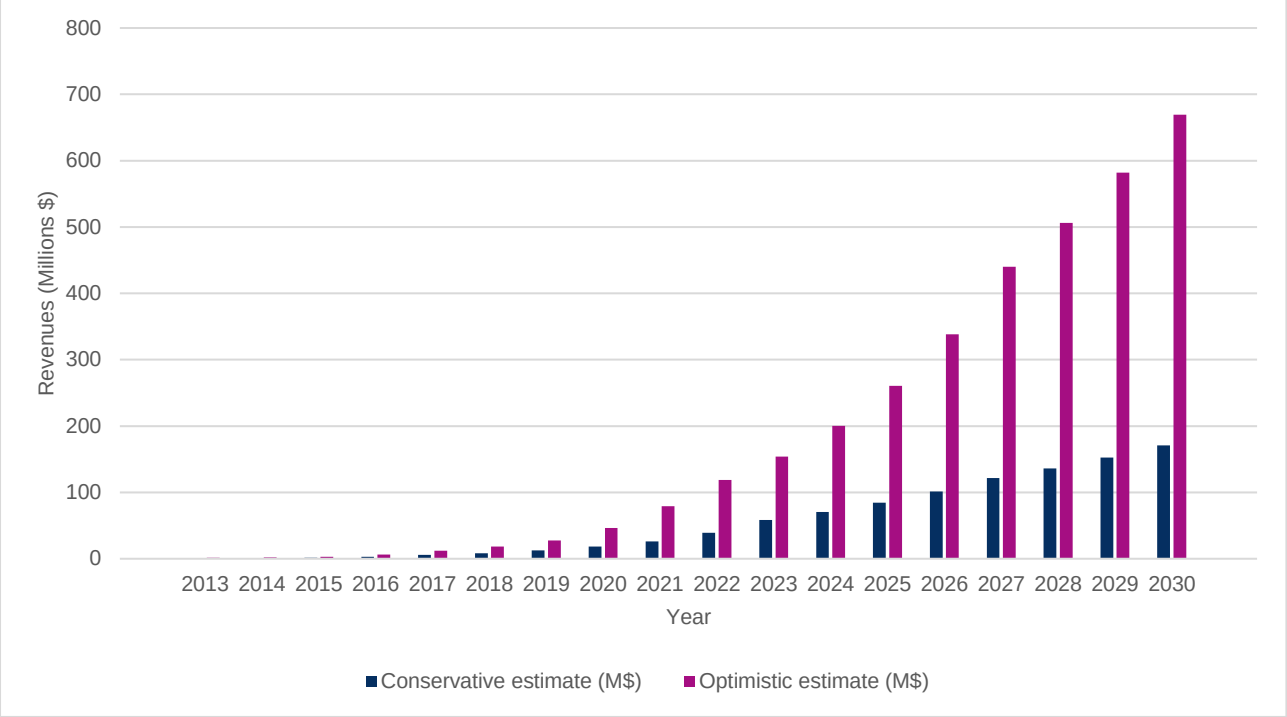

Figure 54: Total QD revenues in in sensors 2013-2030 ($M), conservative and optimistic estimates.

Source: Future Markets, Inc.

13.4 Market challenges

Table 66: Market challenges rating for quantum dots in the sensors market.

Market acceptability	
Cost	2-3
Competition from other materials	3
Scalability	2-3
Industry pull	4
Market push	3
Regulatory	4
Consumer acceptance	4
Total score (out of 35): 22-24	

Source: Future Markets.

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13.5 Quantum dot sensor companies

Table 67: Quantum dots product and application developers in sensors.

Company	Activity
StoreDot	The company produces QDs for application in image sensors.
SWIR Vision Systems	The company manufacutures high-resolution short-wave infrared cameras based around a sensor utilizing colloidal quantum dots (CQDs).

Source: Future Markets, Inc.

14 OTHER MARKETS

14.1 Batteries

14.1.1 Properties

QDs of various materials have been incorporated into anodes, cathodes and electrolytes in Li-ion (LIB) batteries to improve cycling and storage capacities. [157] [158] [159]

14.1.2 Companies

Nanosys and StoreDot are developing QDs for battery applications. The companies claim that QD batteries charge much faster than current batteries, and will withstand thousands of charge/discharge cycles, prolonging battery life expectancy considerably.

Figure 55: StoreDot battery charger.

Table 68: Quantum dots product and application developers in batteries.

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Company	Activity
Advano	The company is producing Functionalized Silicon Nanoparticles/Quantum Dots for applications in batteries.
Nanosys, Inc.	The company is developing battery storage additives based on quantum dots.
StoreDot	The company has developed a battery utilizing QDs for smartphone applications. The company claim that the technology can charge a phone battery in 30 seconds.

Source: Future Markets, Inc.

14.2 Thermoelectrics

14.2.1 Properties

QDs are promising candidates for the inter-conversion of heat and electrical energy in applications to cooling and waste heat recovery as they achieve a significantly higher figure of merit (ZT) than traditional thermoelectric (TE) bulk polycrystalline materials. They can potentially boost energy conversion efficiency to 20-30% depending on temperatures.

Due to QDs delta-like density of states, they exhibit high Seebeck coefficient, nearly zero electronic thermal conductance and ultra-low photonic thermal conductance if embedded in an oxide matrix. PbSeTe-based QD superlattices have been shown to exhibit thermoelectric figure of merit ZT as high as 1.6.[160] [161] [162]

QDs small size offers the possibility of converting heat into electrical energy on the nano- and meso-scales and they may also be easily manipulated and integrated within larger processing units, offering flexible design and greater efficiency.[163]

14.2.2 Companies

Table 69: Quantum dots product and application developers in thermoelectrics.

Company	Activity
Evident Thermoelectrics	The company is developing QDs for applications in thermoelectrics.

Source: Future Markets, Inc.

14.3 QD Lasers

A quantum dot laser (QDL) is a semiconductor laser utilizing quantum dot crystals as an active layer to produce optical gain. QDLs utilizes index coupling grating on GaAs material systems.[164] In May 2018 Ranovus launched its 200G On-Board Optics and CFP2 optical transceiver solutions for 5G mobility and data centre interconnect (DCI) applications. These are based on the company's multi-wavelength Quantum Dot Laser (QDL), ring resonator based silicon photonic (SiP) modulators, driver ICs as well as receiver building blocks. The Quantum Dot Multi-Wavelength Laser (QD MWL) is a semiconductor laser that uses self-assembled quantum dots to generate multiple wavelengths simultaneously from a single device. A single QD MWL device can provide up to 96 wavelengths in the C-band alone, allowing for the replacement of 96 individual lasers in an equivalent system.

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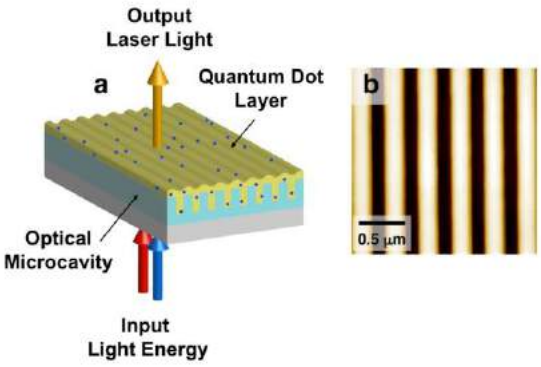

Figure 56: Schematic of QD laser device.

14.3.1 Companies

Table 70: Quantum dots product and application developers in lasers.

Company	Activity
Innolume GmbH	The company produces QD laser diodes. www.innolume.com/technology/quantum_dots.htm
QD Laser	The company produces lasers incorporating quantum dots. The company is a spin-off from Fujitsu Laboratories. www.qdlaser.com
QD Vision, Inc.	The company's QDs are utilized in photonic components. http://coloriq.com
Ranovus, Inc.	The company has developed optical transceivers based on QD lasers. http://ranovus.com

Source: Future Markets, Inc.

14.4 Photocatalysts

The degradation and removal of harmful compounds utilizing semiconductor photocatalysts is increasingly used in waste water treatment. Properties of quantum dots (QDs) that are useful in photocatalysis include:

- high photostability
- tunable optoelectronic properties
- large extinction coefficients (>106)
- high PL quantum yields
- tunable surface chemistry.[165]

Carbon QDS are under investigation for photocatalytic applications.[166]

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14.5 Spectrometers

Current microspectrometer designs mainly utilize interference filters and interferometric optics that limit photon efficiency, resolution and spectral range. Researchers have overcome these problems by replacing interferometric optics with a two-dimensional absorptive filter array composed of QDs.

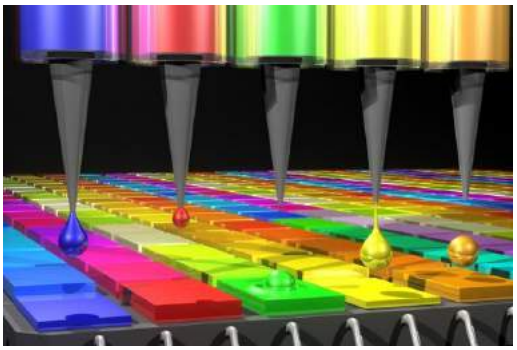

Figure 57: Quantum dot spectrometer.

In this illustration, the Quantum Dot (QD) spectrometer device is printing QD filters.

Image: Mary O'Reilly.

14.6 Computing

Silicon-based quantum-dot qubits are promising candidates for constructing large-scale architectures in quantum computing. In December 2015, researchers from the Technical University of Munich, the Los Alamos National Laboratory and Stanford University evaporated indium gallium arsenide onto a gallium arsenide substrate to form their nanostructure. As a result of the different lattice spacing of the two semiconductor materials strain is produced at the interface between the crystal grids. The system thus forms quantum dots "hills".

When the quantum dots are cooled down to liquid helium temperatures and optically excited, a single electron can be trapped in each of the quantum dots. The spin states of the electrons can then be used as information stores. Laser pulses can read and alter the states optically from outside. This makes the system ideal as a building block for future quantum computers.[167]

Other applications that have identified for QDs in electronics include:

- Human machine interface.[168]
- Facial recognition.
- Motion control.

14.7 Hydrogen production

Photoelectrochemical (PEC) water splitting using QDs as sensitizers is a promising approach for hydrogen (H2) generation, due to the QD's size-tunable optical properties. QDs are used as photosensitizers for molecular (or metallic) co-catalysts to drive chemical transformations. Examples include hole transfer to a water oxidation catalyst or electron transfer to proton reduction catalyst to make molecular hydrogen as a solar fuel.

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14.8 Autonomous vehicles

Quantum Dots have been identified as viable technology for use in self-vehicles for application in:

- LIDAR.
- Infra-red sensing.
- Human – car interface.[169]

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15 QUANTUM DOT PRODUCER AND PRODUCT DEVELOPER PROFILES

15.1 Acer, Inc.

Taiwan

Company profile	
Company description	Acer is one of the world's top ICT companies and has a presence in over 160 countries.
Founded	1976
Products	The company has incorporated quantum dots into the Predator range of monitors. The Predator X27 supports NVIDIA® G-SYNC™ HDR at 4K resolution while the Predator Z271UV sports an immersive 1800R curved panel. both monitors offer a significantly wider, brighter and more accurate colour range, with the Predator X27 supporting 99% of the Adobe RGB colour space, and Predator Z271UV covering 130% of the sRGB colour space. QDs are also used in the Iconia 10 Tab Tablet.
QD applications	• Consumer electronics.
Address	Acer Incorporated 9F, 88 Hsin Tai Wu Rd., Sec 1 Hsichih, Taipei 221 Taiwan T: +886-2-696-1234
Web	www.acer.com

15.2 Applied Quantum Materials, Inc.

Canada

Company profile	
Company description	AQM is a spin-off from the University of Alberta.
Founded	2016
Products	**Silicon quantum dots (SiQDs)** AQM is involved in the research, development and synthesis of biocompatible silicon quantum dots (SiQDs) and Group IV semiconductor nanoparticles. (SiQDs) have been developed to address the issues of other quantum dot technologies that contain either toxic or scarce heavy-metals such as cadmium, lead and indium. AQM also sells a polymer resist for extreme UV, electron-beam and helium-ion semiconductor lithography and nanoimprint lithography to nanofabrication research centers around the world.
QD applications	Main target markets are displays, solar windows, sensors and medical imaging reagents..

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	Tires AQM is active in the development of silicon nanostructured materials for improved tire performance. A prototype silica nanofiber that can be easily manufactured at low temperatures has been developed as a replacement for precipitated silica. AQM is looking to demonstrate the technology with tire manufacturers and as a reinforcement for polymers. **Optical films for displays** AQM designs and has developed several nanocomposite polymers with unique physical properties. One nanocomposite is being evaluated as an optical film for displays. Another is being integrated into a security application. AQM is looking for partners in the solid-state lighting and display sectors. **Photovoltaics** The materials also have applications as luminescent solar concentrators for building integrated photovoltaics (BIPV). AQM is undertaking a developmental project to optimize the parameters and scale the process. **Bio imaging** AQM is developing in vivo bio imaging agents that incorporate our silicon quantum dots AQM has also developed graphene/silicon aerogels and is exploring partnerships with advanced materials companies or Lithium-ion battery manufacturers.
Address	Applied Quantum Materials Inc. 4-152 Centennial Centre for Interdisciplinary Sciences Edmonton, AB T6G 2G2 Canada T: +1 780-554-7398
Web	https://www.aqmaterials.com/

15.3 Attonuclei

France

Company profile	
Company description	Spin-out from the University of Nantes
Founded	2005
Employees	13
Products	The company offers functionalized custom quantum dots.
QD applications	• Bio imaging agents.
Address	Attonuclei 25 Boulevard Albert Einstein, 44300 Nantes, Fance Tel: +33 2 51 77 54 71
Web	www.attonuclei.com

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15.4 AUO Optronics

Taiwan

Company profile	
Company description	AU Optronics Corp., incorporated on August 12, 1996, is a thin-film-transistor liquid-crystal display (TFT-LCD) panel provider. The Company operates in two business segments: display business and solar business. It was formed in September 2001 by the merger of Acer Display Technology, Inc and Unipac Optoelectronics Corporation.
QD History	August 2015: AUO produces QD-TVs using 3M's QDEF technology. August 2018: AU unveil 85-inch 8K4K bezel-less ALCD Quantum Dot TV display. May 2019: AU unveil 32-inch UHD 4K display with direct-lit mini LED backlight incorporating QDs.
Products	AUO line of 8k and 4k TVs are equipped with Nanoco CFQD Fine Colour Film. The film is produced by Nanoco and coated onto film by Wah Hong in Taiwan.[170] Figure 58. AU 85" bezel-less quantum dot TV. Image credit: AU Optronics.
QD Applications	• Displays for TVs and monitors.
Collaborations/licences	• Nanosys
Address	AU Optronics Corp No.1 Li-Hsin Road 2, Hsinchu Science HSINCHU 300 Taiwan

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	P: +88 635 008800
Web	https://auo.com/zh-TW

15.5 Avantama AG

Switzerland

Company profile	
Company description	Avantama AG (previously known as Nanograde) is a producer of nanoparticles and dispersions. The company is specialized in the development and supply of printable and coatable materials for the manufacturing of optical or electronic thin films. Avantama's materials are based on liquid formulations and inks containing semiconducting metal oxides or luminescent perovskite quantum dots
Founded	2008
Products	The company produces Perovskite-based QD films and Cadmium free quantum dot display materials. Quantum yield is close to 100%, FWHM around 20nm. Materials are reliable to be used in displays. The materials exhibit high absorbance for thin QD film applications for mobile, notebook and tablet applications. The high absorbance also enables thin pixels for QD color filter applications. According to the company their QDs show several differences when compared to other commercial QDs (CdSe and InP), for example; • The chemical composition is based on metal halide perovskites such as e.g. CsPbBr3 • The QD color is mainly controlled by the chemical composition and not by the QD size. • No additional inorganic shell is needed for high quantum efficiency and stability. • The absorbance per gram of QDs is at least 3 times higher than CdSe or InP, which is crucial for the second generation of QD TVs (QD color pixels). **Performance of Perovskite-based QDs** – QY > 95% – FWHM: • < 25 nm (530 nm) • < 40 nm (630 nm) – 12x higher extinction than InP – Cost advantage The company's metal halide perovskite QDs yield the highest possible quantum efficiencies of > 95% which will result in best peak brightness of LCD displays. **Green Perovskite QD Film product** *Optical performance* – QY 90% – Emission 525 nm – FWHM 23 nm *Color gamut coverage*

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	– NTSC 120% – DCI-P3 99.5% – Rec-2020 90.5% The company has installed a production line with an annual capacity of QDs sufficient for 2 Million m^2 of QD films per year. **Synthesis and production** QDs can be synthesized in a Proprietary 1-step-process at ambient conditions. This is possible because no inorganic shell needs to be deposited on the QDs nor is the QD size control critical. The company have a pilot scale production capacity of Perovskite QDs of 1kg QDs/day in suspension form.
QD Applications	• TVs. • Lighting. • Solar.
Address	Avantama AG Laubisrutistrasse 50 CH-8712 Stafa Switzerland Phone: +41 (44) 927 13 91
Web	http://avantama.com/

15.6 Bio Square, Inc.

South Korea

Company profile	
Company description	Start-up developing technology for detecting multiple diseases with a single kit at a molecular level. The company has licensed technology from Seoul National University and Kunkook University.
Founded	2018
Products	**Quantum PACK™ technology** The company has applied the technology for in vitro diagnostic assays in need of an improvement in assay stability, sensitivity and multiplexing. Q-PACK technology has a 10-log linear dynamic range, zeta-molar sensitivity and room-temperature stability. Bio Square has two products based on the Quantum PACK™ (Q-PACK) platform – Quantum PACKTM Easy & Pro.
QD applications	• Life sciences and healthcare.
Address	Bio Square, Inc. 3F, Institut Pasteur Korea, 16, Daewangpangyo-ro 712-gil, Bundang-gu, Seongnam-si, Gyeonggi-do, 13209, South Korea T; +82-31-5182-9715
Web	http://www.bio-square.com/en/index.html

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15.7 BOE Technology Group Co., Ltd.

China

Company profile	
Company description	BOE Technology Group Co. Ltd. is a supplier of Internet of Things technologies, products and services. BOE focuses on three core businesses: display devices (including panels, modules and sets), smart systems and healthcare servicesThe company is developing QLED displays using an ink-jet printing process and soluble QDs.
Founded	1993
Products	**Active Matrix Quantum Dot LED (AMQLED)** Full color Active Matrix Quantum Dot LED (AMQLED) displays are being applied in computer monitors and 5-inch cellphone-like displays. AMQLED is a self-luminous display technology without a backlight source.
QD applications	• Consumer electronics.
Address	BOE Technology Group Co., Ltd. No.10 Jiuxianqiao Road, Chaoyang District Beijing BEJ 100176 China P: +86 106 431 8888
Web	www.boe.com

15.8 China Beijing Beida Jubang Science & Technology Co., Ltd.

China

Company profile	
Company description	The company is a producer of quantum dots.
Products	**Water soluble quantum dots** • CdTe quantum dots with –COOH • CdTe/CdS/ZnS Core-shell quantum dots • CdTe quantum dots with -NH2 • ZnS/Mn Core-shell **Oil soluble quantum dots** • Oil soluble CdTe quantum dots • CdZnSe/ZnS Core-shell quantum dots • CdSe/CdS Core-shell quantum dots

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	Carbon quantum dots
QD applications	• Biological medicine, chemical analysis, lighting and display, solar cell etc.
Address	China Beijing Beida Jubang Science & Technology Co., Ltd. No.505 Tower A, Millennium Plaza, 72 North Xisanhuan Avenue, Haidian District Beijing,100048, P.R.China T: +86 010-51799741
Web	www.pkuchemgd.com

15.9 Creative Diagnostics

USA

Company profile

Company description	Creative Diagnostics develops and produce highly uniform nanoparticles for R&D.
Founded	2005
Products	The company supplies DiagNano™ semiconductor quantum dots with different chemical compositions and surface functionalization.
QD applications	• Imaging • Biosensors • Photovoltaic devices • Solar cells • Light emitting devices • Catalysis
Address	Creative Diagnostics 45-1 Ramsey Road, Shirley, NY 11967, USA Tel: **+**1-631-624-4882
Web	www.cd-bioparticles.com/l/Quantum-Dots_258_264_0.html

15.10 CrystalPlex Corporation

USA

Company profile

Company description	Crystalplex is a biochemistry and diagnostics laboratory, specializing in nanotechnology for the life sciences industry. In 2009, the company directed its research to optoelectronics and developed high-performance nanocrystals for photoluminescent, electroluminescent and photovoltaic applications.

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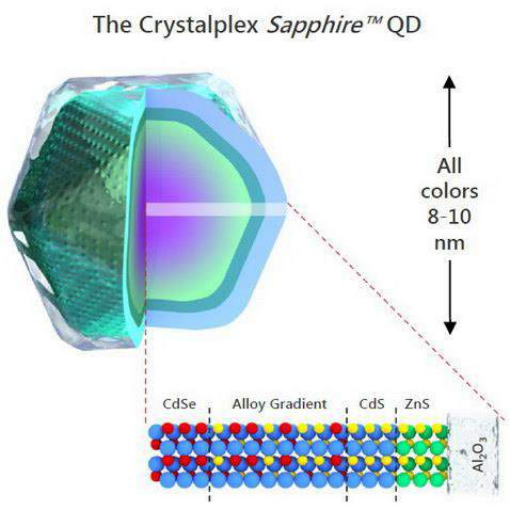
Founded	2004
Products	**Sapphire**™ Crystalplex has developed cadmium-free alloy gradient Sapphire™ quantum dots (QDs) for the optoelectronics industry. The proprietary technology produces stable QDs adaptable to an array of polymer matrix applications that meet demanding performance requirements for high-end consumer electronics such as LCD TVs, displays and high CRI architectural lighting.  **Properties** 1. All colors the same size – no differential aging by color 2. Sapphire™ shell – protects each QD from H2O and O2 3. Liquid Ion's custom polymer – optimizes dispersion – stabilizes QD environment – enables thermoplastics – enables thermosets Sapphire™ quantum dots are available: • in solution • in polymer inks • as solvent cast films, or • in thermoplastic pellets
QD applications	• Biomedical. • Displays. • Lighting.
Address	Crystalplex Headquarters 2403 Sidney Street, Suite 270 Pittsburgh, PA 15203 USA Tel: +1 412 246 2044

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Web	www.crystalplex.com

15.11 Cytodiagnostics, Inc.

Canada

Company profile

Company description	The company provides a range of nanomaterials for biotechnology applications.
Founded	1987
Products	The company offers a range of quantum dots. They also provide nanocrystals by emission and optimization kits. Alkyl Nanocrystals CdSxSe1-x/ZnS core/shell fluorescent nanocrystals with alkyl ligand surface. Available with emission from 450nm to 665nm (custom emission also available). Carboxyl Nanocrystals CdSxSe1-x/ZnS core/shell fluorescent nanocrystals functionalized with carboxyl(-COOH) ligands. Amine Nanocrystals CdSxSe1-x/ZnS core/shell fluorescent nanocrystals functionalized with amine(-NH3) ligands. Hydroxyl Nanocrystals CdSxSe1-x/ZnS core/shell fluorescent nanocrystals functionalized with hydroxyl(-OH) ligands. Quantum dots are available both in organic soluble (oleic acid surface) and water soluble (carboxyl, amine & hydroxyl surfaces) formats.
QD applications	• Photovoltaics (light capturing materials), solid state LED lighting, biodiagnostics (lab-on a chip), laser applications, fluorescent probes, memory devices, photodetectors, and multiplexing sensors.
Address	Cytodiagnostics, Inc. 919 Fraser Drive, Unit 11 Burlington, Ontario L7L 4X8 Canada Tel: +1-866-344-3954
Web	www.cytodiagnostics.com/fluorescent-nanocrystals.php

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15.12 E. I. du Pont de Nemours and Company (DuPont)

USA

Company profile	
Company description	E. I. du Pont de Nemours and Company, commonly known as DuPont, is an American company formed by the merger of Dow Chemical and DuPont in 2017.
Products	**TREVISTA™** Dupont and and Nanoco Group plc global have a licensing agreement for Nanoco's cadmium-free quantum dot technology for TREVISTA™ QD films. The company has built a CFQD® quantum dot facility for mass production of cadmium-free quantum dots under the TREVISTA™ brand in Cheonan, South Korea. The facility has a capacity of >2million QDTVs per annum. Dupont also acquired Innovalight, a developer of quantum-dot inks for improving PV module performance in 2011.
Collabortions/licences	Nanoco. The company has non-exclusive worldwide rights for the sale, marketing and manufacture of Nanoco's cadmium-free quantum dots for use in electronic displays.
QD applications	• Displays (TV, monitor, PCs, home appliances)
Address	DuPont Electronic & Communications Tech 14 TW Alexander Dr, Research Triangle, NC 27709, USA Phone: +1 919-248-5000
Web	https://www.dupont.com/

15.13 Dai Nippon Toryo Co., Ltd.

USA

Company profile	
Company description	Dai Nippon Toryo Company, Limited manufactures and sells coatings and jet inks in Japan, China, and Southeast Asia.
Products	The company is producing gold quantum dots.
QD applications	• Diagnostic agents, sensing, and security.
Address	Dai Nippon Toryo Company, Limited 6-1-124, Nishikujo Konohana-ku Osaka, 554-0012 Japan Phone: +81 6 6466 6690
Web	www.dnt.co.jp

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15.14 Dotz Nano Ltd.

Israel

Company profile	
Company description	The company develops, manufactures, and commercializes graphene quantum dots (GQDs) in Australia and Israel. The products are used in the development and marketing of novel advanced materials used for tracing, anti-counterfeiting and product-liability solutions.
Founded	2014
Products	Products are ValiDotz ™, Fluorensic™, InSpec™ and BioDotz™ **ValiDotz™ security markers** When Dotz Nano's material is exposed to ultraviolet light, it emits energy in a color that changes according to the size, which makes it useful in detecting forgeries. The material is combined as a marker within a product providing a unique signature indicating that the product is not a fake. Dotz's ValiDotz molecular non-toxic markers feature multiple layers of security and can be verified in real-time with the company's InSpec detectors. By adding ValiDotz™ marker to a product line, a specific spectral signature is formed that is: • Based on a novel technology, unknown to counterfeiters; • Non-toxic with infinite number of encoding combinations; • Cost effective due to low effective concentrations required; • Does not affect the properties and appearance of the tagged products; • Stable over time even in harsh conditions; and • Extremely challenging to reverse engineer.
QD applications	• Displays • Solar cells • Biomedical imaging • Anti-counterfeiting tags. • Batteries. • Lubricants. • Crude Oil & Gas • Agro-Chemicals Tagging • Polymers Tagging • DEF (AD Blue) • Tracing Frac Fluid
Collaborations/licences	Dotz Nano Limited has signed an exclusive three-year distribution and sales agreement to sell $15 million of its graphene quantum dots to joint venture China Israel (hengqin) Science Technology Innovation Center (CisticPoly). Dotz Nano also signed a purchasing agreement for the sale of GQDs with Colorplastic, who have agreed to purchase $300,000 of GQDs per annum and a memorandum of understanding (MoU) with Recochem Inc. regarding the distribution of graphene quantum dots (GQDs). The company has also has also signed a Joint Collaboration Agreement with UltraCharge to integrate graphene quantum dots (GQDs) in its anode technology for lithium-ion batteries. Other collaborations include China Tobacco Company, an international lubricant manufacturer and Kecai Printing Company (a subsidiary of Brilliant Circle Holding International Limited, the industry leader in China's cigarette packaging industry).[171]

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Address	Dotz IL 2 Granit Street Petah Tikva, Israel, 4951623 Phone: +972-3-7755235
Web	https://www.dotz.tech/

15.15 Efun Technology Co., Ltd.

China

Company profile	
Company description	EFUN Technology Co., Ltd. develops, manufactures, and sells LCD optical films in Taiwan and internationally. The company's products are used in liquid crystal displays, such as smart phones/tablets, digital cameras/cameras, desktop computers/monitors, LCD TVs, etc. It also provides ITO touch transparent conductive films, cured films, and explosion-proof films, as well as photovoltaic film related products, such as roll-type touch modules, which are used in various consumer electronic products.
Founded	1996
Products	The company produces cadmium selenide (CdSe)-free quantum dot enhancement film. Efun has initially shipped the film to digital gaming, public signage and medical care sectors.
QD applications	• Consumer electronics. • Digital gaming • Public signage • Medical care
Address	Efun Technology Co., Ltd. No. 391, Honda Road Section 2 Annan District Tainan, Taiwan Phone: +1 886 6 3841313
Web	www.efun.com.tw

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15.16 Emfutur Technologies

Spain

Company profile	
Company description	EMFUTUR Technologies is a nanomaterials supplier, offering nanoparticles, nanopowders, micron powders, and CNTs (carbon nanotubes) in small quantity for researchers and in bulk order for industry groups
Products	The company is a supplier of Quantum dots CdTe, CdSe/ZnS (core/shell), ZnCdSe/ZnS (core/shell).
QD applications	• Displays.
Address	Emfutur Technologies Industrial Park - cmno. Betxi s/n Castellón de la Plana, 12540 Spain Tel: +34 (644) 341 200
Web	www.emfutur.com

15.17 Fraunhofer Institute for Applied Polymer Research IAP/CAN GmbH

Germany

Company profile	
Company description	CAN GmbH was founded as a joint venture by the Free and Hansestadt Hamburg (24.8%), the University of Hamburg (10%) and well-known industrial enterprises (65.2%) which have combined to form a sponsor association. Since January 1, 2018, the Hamburg Center for Applied Nanotechnology CAN has been a research division of the Fraunhofer Institute for Applied Polymer Research IAP in Potsdam-Golm.
Founded	2005
Products	The company produce CANdots® for various applications. Products include: • CANdots® Series A - Quantum Dots with emission in the visible range • CANdots® Series A plus - Superbright Quantum Dots • CANdots® Series C - Lead sulfide Quantum Dots with emission in the IR • CANdots® Series G - Plasmonic nanoparticles for biological use. The company develop ready-to use reagents and custom kit solutions easing biochemical lab routines based on gold-nanoparticles.
QD applications	• Electronics • Lighting • Solar • Life Sciences.
Address	Center for Applied Nanotechnology (CAN) GmbH Grindelallee 117

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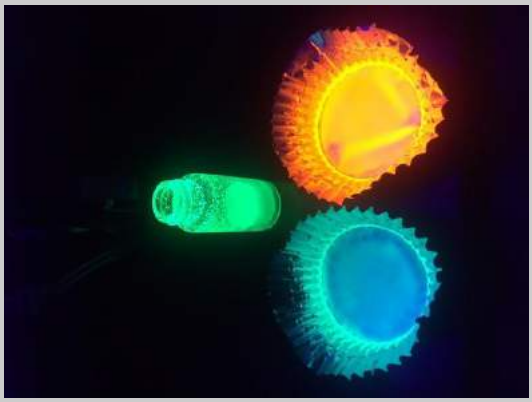
	D-20146 Hamburg Germany Tel: +49 - 40 42 83 83 983
Web	http://www.can-hamburg.de/

15.18 Green Science Alliance Co., Ltd.

Japan

Company profile

Company description	The company produces a range of nanomaterials including CNTs, quantum dots and cellulose nanofibers. The company is a subsidiary of Fuji Pigment. Fuji Pigment Co., Ltd. was founded in 1944. The Company's line of business includes the manufacturing of cyclic organic crudes, intermediates, organic dyes, and pigments.
Founded	2007
Products	The company produces: • InP/ZnS quantum dots • Perovskite quantum dots composite materials. • ZnS, InP/ZnS, CdS, CuInS2(CIS), CuInSe2, CuInS2/ZnS, PbS, and AgInS2 quantum dots • Silicon quantum dots • Graphene quantum dots.  Figure 59: InP/ZnS, perovskite quantum dots and silicon resin composite under UV illumination. **Perovskite quantum dots composite materials** Green Science Alliance Co. Ltd. has developed a quantum dot (QD) resin composite. The composite is a mixture of perovskite QDs with polyethylene (PE). GS Alliance supply the composite for sheets and molding. **Quantum dot inkjet ink** Prepared graphene quantum dot inkjet ink can be printed on various types of substrates including normal paper and films. It is invisible under normal room light

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	although it becomes visible and emission spectra peak will be different depending on the different wavelength of illuminated light so that they can be good anti-counterfeiting inkjet ink because normal fluorescent dye based anti-counterfeiting ink emits only certain spectrum with same peaks no matter what wavelength of light is illuminated. **Production** GS Alliance can manufacture up to 1–2 kilograms per day of Perovskite quantum dots.
QD applications	• Displays • Bioimaging • Counterfeit prevention • Silicon resins for LED sealants.
Address	Green Science Alliance Co., Ltd. 2-22-11 Obana Kawanishi-city, Hyogo prefecture 666-0015 Japan T: +81-72-7598543
Web	www.gsalliance.co.jp/en/

15.19 Hansol Chemical Co., Ltd.

South Korea

Company profile

Company description	Hansol Chemical Co., Ltd. manufactures and sells various chemicals primarily in South Korea.
Founded	1980
Products	The company supplies cadmium free quantum dots films to Samsung for its range of QD-TVs. Samsung developed the IP for the films.
Address	Hansol Chemical Co., Ltd., 7~8th Fl., K-Tower 513, Teheran-ro, Gangnam-gu, Seoul, Korea 06169, T:+82-2-2152-2399
Web	www.hansolchemical.com/front/contents/contents.do?menuCd=1030206

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15.20 HP Inc.

USA

Company profile	
Company description	HP Inc. is an American multinational information technology company headquartered in Palo Alto, California, United States. It develops personal computers (PCs), printers and related supplies, as well as 3D printing solutions.
Founded	2015
Products	In 2019 the company unviled the HP Pavilion 27 Quantum Dot Display that is based on Quantum Dot on Glass. This is the first Quantum Dot on Glass product, which is also expected to be unveiled by TV manufacturers in 2019.
Address	HP Inc, Building 3 1501 Page Mill Rd, Palo Alto, CA 94304, USA Phone: +1 650-857-1501
Web	https://www8.hp.com/uk/en/home.html

15.21 HiSense

China

Company profile	
Company description	Hisense Co., Ltd. is a Chinese multinational white goods and electronics manufacturer headquartered in Qingdao, Shandong province, China. It is a state-owned enterprise with publicly traded subsidiaries.
Products	The company produces QLED-TVs utilizing Nanosys QDs. Hisense has two Quantum Dot series – the edge-lit series 8 and the full backlit series 9.
QD applications	Consumer electronics.
Collaborations/licences	Nanosys
Address	HiSense 17 Donghai W Rd, DongBu ShangQuan, Shinan Qu, Qingdao Shi, Shandong Sheng, China, 266000
Web	http://global.hisense.com

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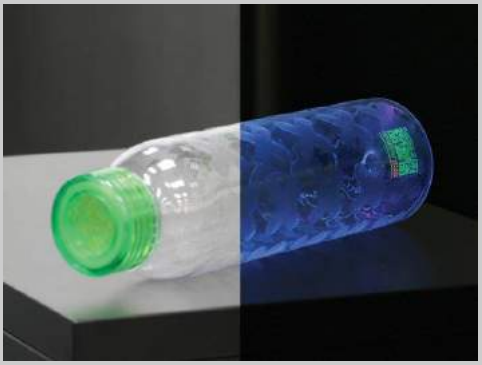
15.22 IQDEMY Quantum Technology SA

Switzerland

Company profile	
Company description	The company is a subsidiary of Russian chemicals producer IQDEMY Holding. IQDEMY SA synthesizes quantum dots, develops different fluids and powders, and builds customized printing machines.
Founded	1998
Products	**Quantum Dots Ink** The ink is available for water-based and UV, UV-LED printing processes whereby each ink set is tamper-evident and contains a code that cannot be broken. Adaptive custom solutions enable only the brand owner to reproduce the code. The company develop a QR-code expanded version with several colours. It allows to increase code capacity several mes. By mixing shades, it produces a unique colour code, which, when using only 4 colours, produces 4.3 billion variants.  Figure 60: Quantum dots tag on plastic bottle. Image credit: IQDEMY.
Collaborations/licences	• Mantel Digital
QD applications	• Anti-counterfeiting. • Displays.
Address	IQDEMY Quantum Technology SA 3960, Techno-Pole 4, Sierre, Switzerland T: +41 79 198 20 82
Web	http://iqdemy.ch/en/

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15.23 Innolux Corporation

Taiwan

Company profile	
Company description	Innolux is Taiwan's leading display panel manufacturer, with assets totaling over $15 billion. It is the world's third-largest flat-panel maker after South Korea's Samsung and LG.
Products	The company produces QD displays. The company has integrated quantum dots into LED allowing for 90% BT2020 coverage and 120% high color saturation. The company plans to produce QLED panels for notebooks in 2019.
QD applications	• Consumer electronics.
Address	Innolux Corporation No. 160 Kesyue Road, Hsinchu Science Park, Miaoli, 35053, Taiwan Phone: +886.37.58.6600
Web	www.innolux.com

15.24 Kateeva

USA

Company profile	
Company description	Spin-out from MIT developing OLED ink-jet deposition processes.
Founded	2008
Products	The company has innovative inkjet printing equipment, branded as YIELDJet printers. Kateeva inkjet printing platform is used for both OLED and QD depositions. The company's equipment is used by Samsung to deposit QDs for its QD-OLED TVs.
QD applications	Consumer electronics.
Address	Silicon Valley Headquarters 7015 Gateway Blvd. Newark, California 94560 USA Tel: 800.385.7802 (toll free)
Web	http://kateeva.com

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15.25 KRI, Inc.

Japan

Company profile

Company description	Spin-out from Osaka Gas Co., Ltd.
Founded	1987
Products	The company is a producer of graphene quantum dots and has developed proprietary synthesis methods.
QD applications	• Electronics.
Address	KRI, Inc. Kyoto Research Park, 134, Chudoji Minami-machi, Shimogyo-ku, Kyoto 600-8813 Japan
Web	www.kri-inc.jp/index_e.html

15.26 Merck KGa

Germany

Company profile

Company description	The Merck Group is a German multinational pharmaceutical, chemical and life sciences company headquartered in Darmstadt, with around 50,000 employees in around 70 countries.
Products	The company signed a non-exclusive material supply and licence agreement with Nanoco for supply of cadmium-free quantum dots in August 2017. **Quantum rods** The company also QLight Nanotech in June 2015. The company are developing technology based on quantum rods which can be used within LCD backlight units, or as display layers to increase light throughput and extend the colour gamut (e.g. QD pixel colour converter). The company is also leading a joint project to explore the use of quantum dots and other quantum materials in organic LED (OLED) displays and other light sources. The project "Exploration of quantum materials – New paths to realizing innovative optoelectronic components (ELQ-LED)," will receive total funding of € 5.5 million from the German Federal Ministry of Education and Research (BMBF). The total budget of the project is € 9.1 million and it is scheduled to finish in 2020.
QD applications	• Displays. • Automotive.
Collaborations/licences	Nanoco

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Address	Merck Frankfurter Straße 250. Darmstadt, 64293, Germany T: +496151720
Web	www.merckgroup.com

15.27 LG Display Co., Ltd.

South Korea

Company profile

Company description	LG Display Co., Ltd. is LG's panel-manufacturing and R&D subsidiary and a leading manufacturer and supplier of thin-film transistor liquid crystal display (TFT-LCD) panels, OLEDs and flexible displays. The company provides TFT-LCD panels in a wide range of sizes and specifications for use in TVs, monitors, notebook PCs, mobile products and other various applications. LG Display currently operates eight fabrication facilities and five back-end assembly facilities in Korea, China and Poland.
QD history	January 2015: LG signs a partnering agreement with Dow Chemical Company in for the supply of cadmium-free quantum dots from Nanoco. September 2018: LG Display purchased a $10m stake in Nanosys.
Products	There are no current QD product offerings, with the company incorporating Nanocell technology into OLED TV products. Nanocell LCD display technology is positioned as a direct competitor to the Samsung QLED line.
Collaborations/licences	• Nanosys
QD applications	• Displays.
Address	LG Display Co., Ltd. West Tower, LG Twin Towers, 17th Fl., 20 Yoido-dong, Youngdungpo-gu Seoul 150-721 South Korea Tel: +82-2-3777-1010
Web	www.lgdisplay.com

15.28 LMS Co., Ltd.

South Korea

Company profile

Company description	LMS Co., Ltd. is mainly engaged in the manufacture of prism sheets for back light units (BLUs) used in liquid crystal displays (LCDs).

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Products	The company utilize Nanosys QDEF technology for Quantum Light Accumulation Sheet (QLAS). QLAS makes LCDs more vibrant and lifelike by improving brightness and color gamut by over 50%.
QD applications	• Displays.
Address	LMS Co., Ltd. 53-73, Jinwisandan-ro, Jinwi-mye PYEONGTAEK 17709 South Korea P: +8231.4212345
Web	http://www.lmsglobal.com/

15.29 Lumileds Holding B.V.

Netherlands

Company profile

Company description	The company develops, manufactures and distributes LEDs and automotive products.
Founded	1999
Products	The company has used red QDs with tunable peak emission and narrow spectral width to produce white QD LEDs for the general illumination market. The company uses QDs supplied by Pacific Light Technologies.
QD applications	• Lighting.
Address	Lumileds Evert van de Beekstraat 1 Schiphol, 1118 CL Netherlands Phone: +31 85 043 4900
Web	https://www.lumileds.com/

15.30 Luminit LLC

USA

Company profile

Company description	The company develops light diffuser films and holographic components. The company is privately held, with 80+ employees.
Founded	2006
Products	The company is developing quantum dost for lighting applications.
QD applications	• Lighting. • Displays. • Automotive.

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Address	Luminit LLC 1850 W 205th St. Torrance, CA 90501 USA T: +1 310-320-1066
Web	http://www.luminitco.com

15.31 ML System S.A Zaczernie

Poland

Company profile	
Company description	Polish producer of building-integrated photovoltaics (BIPV) for the construction industry.
Founded	2007. R&D centre founded in 2012.
Products	The company plans to start mass production of a transparent photovoltaic glass based on QD coatings, that converts ultraviolet and infrared radiation into electricity. Commercialization is expected by 2020. The company has a patent for “Encapsulation of active layers in third generation photovoltaic cells”. This patent encompasses tight closure of third generation cells in the glass laminate and their isolation from external factors. The company holds 5 patents. The company also has another patent application for their QD coated glass mass production technology. Figure 61. QDSSC Module. Image: ML System S.A. Laboratory
QD applications	• Construction • Transport.
Address	ML SYSTEM Spółka Akcyjna Zaczernie 190 G,

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	36-062 Zaczernie, Poland Tel. (17) 7788266
Web	http://mlsystem.pl

15.32 Najing Technology Co.,Ltd

China

Company profile

Company description	The company produces a range of cadmium-based QD materials and devices.
Founded	2009
Products	The company produces QDs, QD polymers and QD devices. Products include Color In™, QLEDNanoGen™ and LEDISUN.
QD applications	• Displays.
Address	Najing Technology Co.,Ltd Building 3 No. 428, Qiuyi Road Binjiang District Hangzhou, 310052 China Phone: +86 571 5605 8866
Web	www.najingtech.com

15.33 Nano Elements Source, LLC

USA

Company profile

Company description	The company has an exclusive license to a patented process to manufacture heavy metal-free quantum dot material (QDM) at 10x less cost.
Founded	
Products	The company's bacterial fermentation of QDs has been demonstrated at pilot scale (~50kg/year), and produces a narrow, tunable distribution of crystallite sizes. The photoluminescence and purity of the QDs is comparable to the commercially-available alternatives. Similar to the process of fermenting alcohol, sugar is fed to single-celled organisms. As these cells grow, they produce the QD cores extracellularly. They have licensed the rights to this proprietary NanoFermentation technology from Oak Ridge National Laboratory to create low-cost quantum dots. NanoFermentation of ZnS quantum dots costs $0.067 per gram.
QD applications	• Solid state lighting and display markets. • Biomedical.

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Address	Nano Elements Source, LLC 10607 Lee Hwy McDonald, TN 37353 USA P: +1 (423)557-6159
Web	www.nanoelso.com

15.34 Nano Chem Tech, Inc.

Korea

Company profile

Company description	Nano Chem Tech Inc. develops, manufactures, and sells organic conducting polymers and related products in Korea.
Products	The company offers conducting sheets for thermoforming package, and electrical/electronic/telecommunication part applications; conducting coating solutions; advanced materials including quantum dots; anti-static films for mobile LCD and keypad process applications; and metal PCB and T-preg for MCCL, inverter, converter, rectifier, and power supply, as well as TV PDP, LED, and regulator applications.
Address	Nano Chem Tech, Inc. 112, Yangseong-ro, Yangseong-myeon, Anseong-si, Gyeonggi-do Korea T: 031-671-9466
Web	www.nanosbiz.com/boxi/eindex.php

15.35 Nanoco Group Plc

UK

Company profile

Company description	The company is as a spinout company from Manchester University's Chemistry Department. The company currently operates facilities in the UK and Japan. The company has 94 employees.
Founded	2001
QD history	July 2016: Signed a 7-Year Supply and Licensing Agreement with Wah Hong Industrial Corporation. August 2016: Sign worldwide material supply and licensing agreement with Merck.

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	January 2019: Partnership with Plessey Semiconductors to shrink the pixel size of monolithic microLED displays using Nanoco's cadmium free quantum dot (CFQD® quantum dots). June 2019: Apple cancels contract with Nanoco for supply of QDs for image sensors for Iphone camera. The contracts was valued at £17 million.
Products	The company produces Cadmium-Free Quantum Dots, IR quantum dots and 2D materials. Nanoco manufactures and supplies smaller quantities to the market and licensees. **Products include:** • CFQD quantum dots. • CFQD quantum dots and resin. • CFQD quantum dots/resin in device. The company has over 730 patents and patent applications. IP covers 4 key areas: • Quantum dot materials, including CFQD® quantum dots • Process for quantum dot mass production • Surface chemistry • QD devices. VIVODOTS™ nanoparticles have been developed for life sciences applications. Projects include the for detection, resection and management of pancreatic cancers. Vivodots cadmium-free quantum dots can be tuned to emit any wavelength of light using a wide range of excitation sources.
QD applications	**CFQD® quantum dots** • Displays. • Lighting. • Solar. • Life sciences. **Infrared quantum dots** • Drones • Consumer electronics • Automotive **2D Materials** • Catalysis • Display • Sensing
Collaborations & agreements	Merck: Licence fee on royalties from Merck produced products. Merck then supplies to Display OEMs. Dupont: Focused on large volume opportunities Wah Hong: Supply of CFQD® resin. Carewear: Photo-Dynamic Therapy. Osram and Marl International Limited: QDs for lighting applications. Charles River Labs: Life sciences. Plessey: Micro-LEDs Kyulux: Hybrid OLED / QLED displays.
Address	Nanoco Group PLC Global Headquarters

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	46 Grafton Street Manchester, M13 9NT UK Tel: +44 (0)161 603 7900
Web	www.nanocotechnologies.com

15.36 Nano-Lit Technologies

Canada

Company profile

Company description	Nano-Lit Technologies design and create Smart Lights that significantly reduce energy consumption, and improve health and well-being in humans and the environment. The product allows for tunable, full-spectrum Circadian Rhythm Lighting, which assists humans in realigning with their natural biological rhythms.
Founded	2013
Products	**Nano-Lit Smart Diffuser™** Smart Diffuser™ is a lighting retro-fit and stand-alone product that tunes white lighting for office environments. Use of QDs allows for high quality color purity, high efficiency, manufacturing versatility, flexibility and lowered costs. The Smart Diffuser™ shifts light temperature from 2400K to 7000K in response to real time changes detected through a sensor system that captures real time data from both the user and the room itself.
QD applications	• Lighting.
Address	Nano-Lit Technologies 1055 West Hastings Street Suite 1700 The Guinness Tower Vancouver, BC V6E 2E9 Canada T: +1 (250) 327-2745
Web	https://www.nano-lit.com/

15.37 Nanooptical Materials, Inc.

USA

Company profile

Company description	NanoOptical Materials Inc (NOM) is a spin off from Intelligent Optical Systems.
Products	The company supplies chalconide (S, Se, and/or Te) core/shell quantum dots as well as PbS quantum dots that are available in organic solvents or in water-soluble form. The company also supplied cadmium free QDs.
QD applications	• Displays.

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	• Lighting.
Address	Nanooptical Materials, Inc. 1330 E 223rd St, Suite 511 Carson, CA 90745-4343 USA T: +1 (424) 262-4666
Web	http://nomcorp.com

15.38 NanoPhotonica, Inc.

USA

Company profile	
Company description	The company has a portfolio of electroluminescent QD materials
Founded	2011
QD history	October 2018: Sign contract with Lockheed Martin to develop Quantum Dot Light Emitting Diode (QLED. May 2019: NanoPhotonica receive $3.5 million investment from Samsung Ventures and DeepWork Capital.
Products	**S-QLED®** For display applications, the company's patented, all-solution-processable quantum dot light-emitting diodes technique (S-QLED®) allows fabrication of displays using ink-jet printing methods. **Electroluminescent quantum dot (EL-QD)** The company is also developing EL-QD for displays.
QD applications	• Displays.
Collaborations/licences	• Lockheed Martin • Samsung
Address	NanoPhotonica Inc. Corporate Headquarters 7025 CR 46A Suite 1071 #322 Lake Mary, Florida 32746 USA T: +1 (407) 718-7940
Web	http://nanophotonica.net/

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15.39 Nanosquare Co., Ltd.

South Korea

Company profile

Company description	The company is a spin-out from Seoul National University.
Founded	2006
Products	The company is a manufacturer of quantum dots, which they can mass-produce.
QD applications	• Displays. • Biomedical.
Address	Nanosquare Co., Ltd. Engineering Building 39–122 Seoul National University San 56-1, Sillim-Dong, Kwanak-Gu Seoul 151-744 South Korea T: +82-2-872-0801
Web	www.nanosquare.co.kr

15.40 Nanosys, Inc.

USA

Company profile

Company description	The company technology, products, and processes are covered by over 750 patents and patent applications that address a wide range of industries including LED backlighting, LED general lighting, power (batteries and fuel cells), medical applications, next generation NAND Flash memories, Solar, Flat Panel Display driver transistors, and specialized nano-surface coatings (super-hydrophobic, super-adhesive, super-hydrophilic, super-hemostatic). The company has approximately 100 employees. Currently, Nanosys is focused on commercializing its quantum dot and silicon composite anode materials for the LED LCD and lithium ion battery industries. Major funders of the company include Venrock Associates, Samsung, Arch Venture Partners, Intel, El Dorado Ventures, Polaris Venture Partners, Prospect Ventures, Harris & Harris Group, Lux Capital, Kodak, and Wasatch Advisors.
Founded	2001
QD history	January 2010: Nanosys, Inc. signs agreement with LG Innotek to develop quantum dot phosphors for use in displays. March 2017: Strategically partnered with Exciton Technology for the development of optical Quantum Dot Enhancement Films (QDEF®). December 2017: The company announced collaboration with DIC to develop inkjet-printed quantum dot color filters (QDCFs) for displays.[172]

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	January 2019: HP unveil the HP Pavilion monitor using Nanosys Quantum Dot on Glass or QDOG™ display.
Products	Nanosys offers three lines of Quantum Dots products for use in LCD backlight applications such as Quantum Dot Enhancement Film (QDEF) or Quantum Dot on Glass (QDOG): • Heavy Metal Free Quantum • Hyperion™ Quantum Dots • Cadmium-Selenide Quantum Dot **Production** The company is manufacturing cadmium and cadmium free QDs. Nanosys operates a 60,000 sq. ft. state-of-the-art nano-material fab with installed capacity to service more than 6 million 60" class TVs. Nanosys has production capabilities for 25+ tons of QD material, which is available to customers that do not wish to produce internally.
QD applications	• Displays.
Collaborations/licences	**TVs** • Hisense • JVC • Philips • Samsung • TCL • Vizio **Computer monitors** • Acer • ASUS • HP • Philips.
Address	Nanosys, Inc. 2625 Hanover Street Palo Alto, CA 94304 USA Tel: +1 650 331 2100
Web	www.nanosysinc.com

15.41 Natcore Technology, Inc.

USA

Company profile	
Company description	Natcore Technology Inc., formerly Syracuse Capital Corp., controls a process for thin film growth with applications in solar energy, semiconductors, fiber optics and other industries. The Company's products are focused for the silicon solar cell manufacturing industry. Natcore's liquid phase deposition (LPD) process enables the growth of thin oxide films on silicon substrates in a mild chemical bath at ambient

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	temperatures and pressures, eliminating the need for the high-temperature, vacuum furnaces, which is necessary for the production of these films.
Products	The company is developing an all quantum dot tandem solar cell.[173]
QD applications	• Solar.
Address	Natcore Technology, Inc. 87 Maple Avenue Red Bank, NJ 07701 USA Tel: +1 8777006262
Web	www.natcoresolar.com

15.42 Navillum Nanotechnolgies, LLC

USA

Company profile	
Company description	The company is a producer of QDs, spun-out from the University of Utah. The company has patented a method for fabricating quantum dots on a commercial scale. The company's process uses significantly lower temperatures than conventional methods. It allows greater control over the size of quantum dots. The lower temperature gradient also allows more uniform cooling of the solution. This provides narrower quantum dot size distribution resulting to high quality batches.
Founded	2012
Products	• Cadmium Selenide Quantum Dots (CdSe) • Cadmium Selenide/Zinc Sulfide Quantum Dots (CdSe/ZnS) • Indium Phosphide/Zinc Sulfide Quantum Dots (InP/ZnS) • Quantum dot Instructional kits • Near-infrared and Infrared Quantum Dots available as custom orders.
QD applications	• Displays • Solid-State Lighting (SSL)
Address	Navillum Nanotechnologies, LLC 2500 S. State St. G246 South Salt Lake, UT 84115 USA T: +1 (385) 646-4022
Web	www.navillum.com

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15.43 Nexdot SAS

France

Company profile

Company description	The company was incorporated in 2010 and is spin-out from Ecole Supérieure de Physique et de Chimie Industrielles de la ville de Paris (ESPCI).
Founded	2010
Products	The company produces 2D nanosheet Quantum Dots “Quantum Plates”. The company has filed 46 patents.
QD applications	• Displays
Address	Nexdot SAS 102 Avenue Gaston Roussel, 93230 Romainville, France T: + 33 8 92 97 65 01.
Web	www.nexdot.fr/en/home/

15.44 Nippon Chemical Industrial Co., Ltd.

Japan

Company profile

Company description	Nippon Chemical Industrial Co., Ltd. manufactures and sells various chemical products in Japan.
Products	The company offer industrially commercialized hi-pure TMSP made from core technology, Phosphine.[174] TMSP is a typical P source for Cd free Q.D.
Address	Nippon Chemical Industrial Co., Ltd. 1-1, 9-chome, Kameido, Koto-ku, Tokyo, 136-8515
Web	www.nippon-chem.co.jp

15.45 NN-Labs, LLC

USA

Company profile

Company description	NN-Labs LLC is a developer of advanced functional materials including semiconductor, noble metal and magnetic metal oxide nanocrystals.

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Founded	2001
Products	**CdTe** Cadmium telluride (CdTe) nanocrystals for solar photovoltaic (PV) applications. **InP/ZnS** Produces indium phosphide-based quantum dots as a environmentally-friendly, heavy metal-free, high performance alternative to cadmium selenide-based (CdSe) quantum dots. **D-dots™** Doped semiconductor nanocrystals without the presence of any heavy metal ions, such as cadmium (Cd), mercury (Hg), or lead (Pb). **Quantum Dot Microspheres** Cadmium selenide zinc sulfide (CdSe/ZnS) quantum dot microspheres with carboxylic acid (QDM) or streptavidin (QDMS) stabilizing ligands.
QD applications	• Photovoltaics. • Lighting. • Displays.
Address	NN-Labs PO Box 2168 Fayetteville, AR 72702-2168 USA Tel: +1 479-595-0662
Web	www.nn-labs.com

15.46 NS Materials, Inc.

Japan

Company profile

Founded	2006
Company description	The company develops technology from the National Institute of Advanced Industrial Science and Technology (AIST). As well as quantum dots the company also produces compound semiconductor nanoparticles, oxide nanoparticles and metal nanoparticles.
Products	The company produces quantum dot (QD) sheets, which are used to improve colour reproduction in LCD screens. The company has changed the structure of the QD's core shell itself to improve both heat resistance and reliability. The company is also developing technology to lower the cadmium concentration of QD sheets. Through improvements to QD arrangement technology, the company has succeeded in maintaining sheet performance while using less QDs, making it possible to come in below the concentration limit of 100 parts per million imposed by the EU's Restriction of Hazardous Substances (RoHS) directive. The company is targeting film manufacturers. These companies are unable to clear the technological hurdle of dispersing QDs throughout coating materials, and as a result the company is seeking to collaborate with film and coatings companies.

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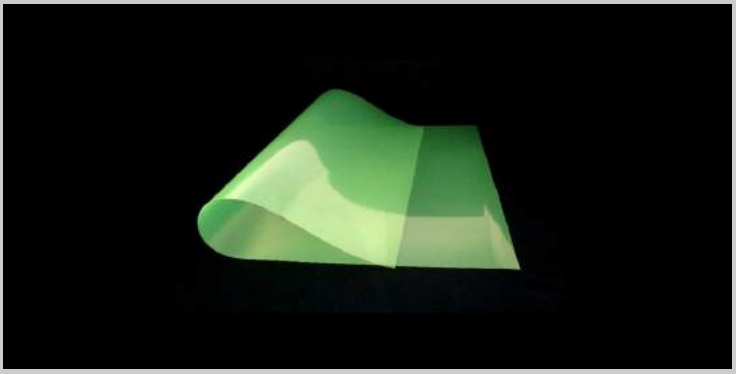
	The company is developing mass-production technology for QD sheets that need no barrier film, and will bring this to mass production in conjunction with domestic coating makers. The first sample shipments have already been sent out, targeting major television OEMs. Plans are to begin mass production next year, with NS Materials aiming to support a monthly production of 10,000 square meters of the product by mid-2020.  Figure 62: Quantum dot sheet. Image: NS Materials, Inc.
Address	NS Materials Corporation (NS Materials Inc.) 818-0042 Fukuoka Prefecture Chikushino City Shichi-ji Temple 511-1 Japan
Web	www.ns-materials.com

15.47 Ocean Nanotech LLC

USA

Company profile	
Company description	Ocean NanoTech, LLC engages in the synthesis and production of dispersible quantum dots and magnetic nanoparticles in the United States. It offers quantum dot powders, and quantum dots in organic solvents and water, as well as NIR quantum dots in water; metal nanocrystal powders and metal nanocrystals in water; and iron oxide magnetic nanoparticles in organic solvents and water. The company provides custom synthesis, contract research, and joint product development services.
Founded	2004
Products	Core competences are: • Preparation of quantum dots, magnetic nanoparticles and metal nanocrystals • Conversion of hydrophobic nanomaterials to water soluble and biocompatible nanocrystals

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	• Bioconjugation of quantum dots and magnetic nanocrystals to proteins, DNA, and other molecules The company's product line includes quantum dots, core shell quantum dots in organic solvents, nanocrystals for LEDs and solar cells, water soluble biocompatible nanocrystals, reaction buffers for conjugating nanocrystals to biomolecules, conjugation kits.
QD applications	• Fluorescent biolabeling • Optoelectronics and displays
Address	Ocean NanoTech LLC 2143 Worth Lane Springdale, Arkansas 72764 USA Tel: +1 4797515500
Web	http://oceannanotech.com

15.48 Osram Opto Semiconductors

Germany

Company profile

Company description	OSRAM Licht AG is a multinational lighting manufacturer headquartered in Munich, Germany. Osram Opto Semiconductors acquired Quantum Dot technology, assets and know-how from Pacific Light Technologies (PLT) in 2018.
Products	Osram Opto Semiconductors produce lighting products with significantly improved efficacy incorporating CdSe based Quantum Dots. Quantum Colors is based on a green quantum converter which is combined with red phosphor on a blue chip. The technology was developed in part in the SSL4EU and Hi-Q-LED projects funded by the EU and the German Ministry of Education and Research (BMBF) and does not require any cadmium. **Osconiq S 3030** QD mid-power LEDs that yse quantum dots to deliver a narrow energy peak in the red spectral region. The quantum dot technology enables the LEDs to deliver 173-lm/W efficacy in warm-white CCT with 90-CRI color rendering, whereas typical warm-white LEDs in the same class might deliver efficacy in the 140–150 lm/W range.
QD applications	• Lighting • Displays and projections.
Address	Osram Opto Semiconductors GmbH Leibnizstraße 4, 93055 Regensburg, Germany Phone: +49 941 8505
Web	www.osram.com

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15.49 Particle Works

UK

Company profile

Company description	Particle Works manufactures high-performance nano- and microstructured materials.
Founded	2015
Products	Particle Works uses state-of-the-art, automated continuous flow microfluidic techniques and successive ionic layer adsorption and reaction (SILAR) to fabricate highly monodisperse and batch-to-batch consistent quantum dots (CV values as low as 1% and 0.5% respectively).
QD applications	• Diagnostic, biomedical and optoelectronic applications.
Address	Particle Works 27 Jarman Way, Royston, Herts, SG8 5HW, United Kingdom Telephone: +44 (0) 1763 252103
Web	http://www.particle-works.com/

15.50 PhosphorTech Corporation

USA

Company profile

Company description	PhosphorTech Corporation was formed with the support of the Advanced Technology Development Center at the Georgia Institute of Technology.
Founded	1998
Products	The company offers a wide range of material and optoelectronic technologies, including LED phosphors, nanocrystals, colour conversion films, as well as specialized LED devices and lamp fixtures. Product development areas include QDs for solid-state lighting.
QD applications	• Displays. • Lighting.
Address	PhosphorTech Corporation 3645 Kennesaw North Industrial Parkway Kennesaw Georgia 30144 USA T: +1 770-745-5693
Web	https://phosphortech.com/

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15.51 Pixel Display, Inc.

USA

Company profile	
Company description	The company has developed patented and patent pending display technology.
Products	NanoBright™, is a nanoparticle material for nano-patterning in micron and sub-micron sized photo-emissive and electro-emissive structures. According to the company the product has all the enhanced properties of QDs and phosphors combined into one material with none of the drawbacks.
QD applications	• Displays.
Address	pixeldisplay inc 2880 Zanker Rd, San Jose, CA 95134, USA Phone: +1 408-954-7328
Web	https://www.pixeldisplay.com/

15.52 Plasmachem GmbH

USA

Company profile	
Company description	The company typically buys nanomaterials and then functionalizes.
Products	• CdTe Quantum Dots, hydrophilic • Zn-Cu-In-S/ZnS Quantum Dots, cd free, hydrophobic • ZnCdSeS alloyed, hydrophobic • ZnCdSe/ZnS hydrophobic • CdSe/ZnS hydrophobic • Perovskite Quantum Dots, cadmium free, hydrophobic.
Address	PlasmaChem GmbH Schwarzschildstr. 10 12489 Berlin Germany Phone: +49 30 6392 6313
Web	www.plasmachem.com

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15.53 Plessey Semiconductors

UK

Company profile	
	Plessey is an embedded technologies developer at the forefront of microLED technology for the AR and display markets. Plessey operates leading-edge 150mm and 200mm wafer processing facilities to undertake design, test and assembly of LED products, and a comprehensive suite of photonic characterization and applications laboratories.
Products	Plessey uses QDs to generate their red and green sub-pixels for microdisplays. Plessey have been able to reduce pixel size by up to 87% utilising Nanoco's cadmium free quantum dots (CFQD®) semiconductor nanoparticle technology to convert Plessey's native Blue to Red and Green.
Collaborations/Licencing	Nanoco
QD applications	microLED displays in applications such as AR/VR devices, watches, and mobile devices.
Address	Plessey Semiconductors Ltd Tamerton Road Roborough Plymouth Devon PL6 7BQ United Kingdom Tel: +44 1752 693000
Web	http://www.plesseysemiconductors.com/

15.54 QD Laser, Inc.

Japan

Company profile	
Company description	QD Laser, Inc. was founded by Fujitsu and Mitsui Ventures, to commercialise semiconductor lasers and amplifiers using Quantum Dot and Quantum Well structures. The company has 22 employees.
Founded	2006
Products	Quantum dot technologies were developed through an academic-industrial research collaboration by Fujitsu Limited, Fujitsu Laboratories, and Professor Yasuhiko Arakawa's laboratory at the University of Tokyo, supported by a grant from NEDO Japan. QDL's Quantum Well laser products encompass Fabry-Perot diodes in the 640nm to 905nm range with outputs of up to 120mW and operating temperatures of up to 70°C. These devices are offered in TO-56 packages with integrated monitor photodiodes in both common-Anode and common-Cathode configurations.

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	QD Laser also offer a range of Distributed Feedback (DFB) laser diodes from 1030nm to 1180nm (Quantum Well) and a 1240nm Quantum Dot DFB device. These lasers offer users extremely tight wavelength control by virtue of their precise e-beam grating structures and are suitable for operation in gain-switched modes with pulse lengths from 30ps to 1000ps and can also be directly modulated for pulse lengths in the 1-20ns regime. The lasers are offered in a variety of packages including 14-pin Butterfly with integrated TEC, thermistor, monitor photodiode, isolator and polarisation maintaining fibre pigtail. They are ideally suited for use as seeds in fibre laser products. QDL also offer a combined DFB/SOA (Semiconductor Optical Amplifier) laser in 14-pin Butterfly package which is rated at 100mW CW. QDL's Compact Visible Modules (CVMs) combine an NIR DFB/SOA device with Waveguide Periodically-Poled Lithium Niobate (PPLN) frequency doubling to produce up to 50mW CW at 532nm, 561nm and 594nm in an extremely compact (<4x6x22mm) package. These lasers exhibit extremely fast stabilisation times (effectively zero) along with excellent stability in CW mode and can be modulated at up to 100MHz with extinction ratios of up to 40dB.
QD applications	• Telecoms and consumer electronics.
Address	QD Laser, Inc. Keihin Bldg. 1F, 1-1 Minamiwataridacho, Kanagawa-ku, Kawasaki, Kanagawa 210-0855 Japan Tel: +81 44 333 3338.
Web	www.qdlaser.com

15.55 QD Solar

Canada

Company profile

Company description	The company is using QDs for next generation solar cells, developed in the Nanomaterials for Energy Laboratory, part of the Department of Electrical and Computer Engineering at the University of Toronto.
Founded	2014
Products	The company's QD Solar product, an insert into conventional silicon solar panels, has potential to increase energy output of solar panels by 20%.
QD applications	• Photovoltaics.
Address	661 University Avenue MaRS Centre West Tower Suite 465 Toronto, ON M5G 1M1 Canada

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	Telephone: 1-416-272-5115
Web	http://www.qdsolarinc.com

15.56 QNA Technology

Poland

Company profile

Company description	Small-scale production, including design, manufacturing and modification of colloidal surfaces in semiconductor nanostructures.
Founded	2016
Products	QNA Technology specialize in the design and manufacture of semiconductor colloidal nanostructures and their surface modification. The company offer both quantum dots (QNA.dots) as well as quantum-based inks (QNA.ink).
Address	QNA Technology Duńska 9, Bud. Delta Wrocław, 54-427 Poland T: +48 882 760 674
Web	https://qnatechnology.com/

15.57 Quantag

Turkey

Company profile

Company description	Quantag was founded as a spin-off company from Opet Petroleum.
Founded	2014
Products	Quantag has developed “Quantum Tagging” technology, a novel method to identify and authenticate products. Quantum Tagging employs quantum dots to generate highly secure and unique quantum tags that cannot be duplicated.
QD applications	• Liquid Tagging • Security Ink • Solar Energy • Display Technologies • Bioimaging
Address	Quantag Barbaros Mah. Gelincik Sokak No: 4/A Ataşehir 34746 İstanbul T: +90 549 7873435

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Web	http://quantagnano.com/quantum-tagging/

15.58 Quantum Materials Corporation

USA

Company profile

Company description	Quantum Materials Corporation, together with its wholly owned subsidiary, Solterra Renewable Technologies Inc., manufactures and commercializes tetrapod quantum dots. The company, using a proprietary quantum dot synthesis method adapted to continuous flow chemistry, produces printed thin-film PV quantum dot solar cells, printed electronics, and colloidal tetrapod quantum dots. It focuses on adapting the R2R quantum dot printing presses for printed electronics via precise high-speed printing processes based on technology similar to screen printing.
Founded	2007
Products	Quantum Materials Corp. has increased capacity equipment has a capability of producing 2.25 metric tons of QDs per annum. Price is $200/g. Products include: • QDX™ Heat-Resistant QDs • Tetrapod QDs • Large Stokes Shift QDs.
QD applications	Target markets include televisions and displays, solid state lighting, biotech, anti-counterfeiting, batteries and capacitors, sensors, solar panels, paint and coatings, inks, hydrogen conversion, glass, and lasers. QMC is also developing TQD-infused films for medical devices, solid state lighting applications, electronic displays and quantum dot solar cells.
Collaborations/licences	Indian company Amtronics CC has paid cadmium-free quantum dot producer Quantum Materials Corp an initial $500,000 as part of an agreement securing the right to manufacture quantum dots and thin-film quantum dot solar cells based on QMC technology for commercial supply in India. Construction has already started on a manufacturing facility in the state of Assam. Amtronics will develop, manufacture and commercialize quantum dots through joint venture Qamronics India, formed by Amtronics and the state-owned Assam Electronics Development Corp Ltd (AMTRON). Construction has started on a 120,000 sq ft facility for large-scale, low-cost quantum dot production in Assam. The factory will also develop thin-film quantum dot solar cells, solid-state LED lighting and displays.
Address	Quantum Materials Corporation 12326 Scott Drive Kingston OK 73439 United States Tel: +1 214-701-8779
Web	www.qmcdots.com

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15.59 Quantum Solutions LLC

Saudi Arabia

Company profile

Company description	The company is a spin-out from the King Abdullah University of Science and Technology (KAUST),
Products	• Perovskite Single Crystals • PbS Quantum Dots • Zero-Dimensional Perovskite Cs4PbBr6 • Perovskite Quantum Dots • Thermostable Perovskite QDs • Ink for CsPbBr3 thin film
QD applications	• LCD Display • QD LEDs • UV sensors • Quantum Dot Photodetectors • NIR Photodetectors
Address	Quantum Solutions LLC Office 3-470, Building 24, KAUST, Thuwal, Saudi Arabia T: +966 56 302 3423
Web	https://quantum-solutions.com

15.60 Ranovus Inc.

Canada

Company profile

Company description	Ranovus is a start-up providing multi-terabit interconnects.
Founded	2012
Products	Data Centers and Mobile networks have surpassed the CO2 footprint of the airline industry. Their traffic is forecasted to triples in the next five years. Ranovus core photonic technologies reduce the power consumption of the networking equipment in DC and Mobile networks by 50% Ranovus provides high capacity photonic connectivity for DC and Mobile networks using its proprietary Quantum Dot Laser and Silicon Photonics technologies. A Quantum Dot Laser generates multiple streams of light simultaneously from a single laser hence replacing 10s of today's lasers at significantly lower power consumption per Gigabit per second than traditional Quantum Well laser technologies.
QD applications	• Photonics.
Address	Ranovus Inc. 16 Fitzgerald Road, Suite 100

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	Ottawa Ontario K2H 8R6 Canada Phone/Fax: 647 522 0762
Web	http://ranovus.com/

15.61 Raytheon Company

USA

Company profile	
Company description	The Raytheon Company is a major American defense contractor and industrial corporation with core manufacturing concentrations in weapons and military and commercial electronics.
Products	Raytheon is developing quantum dot applications in collaboration with Prof. Moungi Bawendi's Group at the Massachusetts Institute of Technology (MIT) for imaging systems in military and defence sectors.
QD applications	• Imaging.
Address	Raytheon Company 870 Winter Street Waltham, MA, USA Tel: +1 (781) 933-3564
Web	www.raytheon.com

15.62 Revolution Lighting Technologies

USA

Company profile	
Company description	Revolution Lighting Technologies, Inc., together with its subsidiaries, designs, manufactures, markets, and sells light emitting diode (LED) replacement lamps and fixtures; and LED-based signage, channel-letter, and contour lighting products.
Products	The company produces Array™ Quantum LED R30 replacement light bulbs. Developed in conjunction with QD Vision, this is the first commercially available LED lamp that utilizes quantum dots to deliver true 2700° Kelvin, high-colour rendering (91 CRI) incandescent warm white light at an industry leading 60 lumens per watt.
QD applications	• Lighting.
Address	Array Lighting A Revolution Lighting Technologies Company 124 Floyd Smith Drive, Suite 300

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	Charlotte, NC 28262 USA Tel: +1 704 4050416
Web	www.rvlti.com

15.63 Samsung

South Korea

Company profile	
Company description	Samsung Electronics is part of one of the largest multi-billion dollar corporations in the world.
QD history	December 2016: Samsung purchases QD Vision's IP for $70 million. May 2017: Samsung, Hisense, and TCL form the QLED Alliance. January 2019: Samsung Display demonstrate 65-inch QD-OLED prototype.
Products	The company licences QD technology from Nanosys to produce QD films in-house. They use Hansol (using Samsung developed IP) as the primary supplier of quantum dots. They are the largest producer of QD-TVs. Initially they produced a SUHD TV range. Current product offerings are the QLED TV and monitor range. Product range • Q9F • Q8C • Q7F • CF791 quantum dot monitors. The company adopted the QLED name for its highest level 2017 TVs in place of its previous SUHD sub-brand. According to industry reports the company plans to produce QD-OLED TVs. Trial production may commence end 2020, with mass production on a new 10-Gen line in 2023.The company is also actively involved in development of EL-QD displays.
QD applications	• Displays.
Address	Samsung Headquarters Maetandong 416 Suwon Gyeonggi-do Samsung Medison Bldg., 42, Teheran-ro 108 gil
Web	www.samsung.com

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15.64 Saphlux Inc.

USA

Company profile

Company description	Saphlux develops, manufactures, and supplies the innovative semi-polar gallium-nitride (semi-polar GaN) materials for customers in display and lighting.
Founded	2014
Products	**Nanopores for Quantum Dots (NPQD)** NPQD technology utilizes a nano-structure that can be formed inside LEDs to hold quantum dots. Because of its strong internal scattering effect, the effective path of light traveling inside nanopores can be greatly extended to boost the conversion efficiency of quantum dots. Thus, high efficiency RGB micro-LED can be achieved with just a 3μm NPQD with either the photo lithography method or the inkjet printing method. The company are offering the NPQD color conversion services to Micro-LED manufacturers.
QD applications	• Displays. • Lighting.
Address	Saphlux Inc. 4 Pin Oak Drive Branford CONNECTICUT 06405 USA
Web	http://www.saphlux.com/

15.65 Shanghai Simbatt Energy Technology Co., Ltd.

China

Company profile

Company description	The company is a graphene producer.
Products	Shanghai SIMBATT Energy Technology Co., Ltd. engages in the research and development, production, sales, and service of graphene powder. It provides graphene-related products, including graphene powder and its solution, graphene oxide and solution, graphite oxide, doped graphene, graphene quantum dots (GQD) and solution, graphite microflakes, ultra-thin graphite nanosheets, nano-graphite, etc. The company produces GQD powder and in solution.
Address	Shanghai Simbatt Energy Technology Co., Ltd. Building A2 #1180 Xingxian Road Jiading District Shanghai, 201821 China Phone: +86 21 3953 8630

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Web	www.simbatt.com

15.66 Shenzhen China Star Optoelectronics Technology Co., Ltd

China

Company profile

Company description	Shenzhen China Star Optoelectronics Semiconductor Display Technology Co., Ltd. manufactures and sells thin film transistor liquid crystal display devices and Organic Light-Emitting Diode (OLED) related products.
Founded	2009
Products	The company is developing Novel QD-OLED Structures. They have demonstrated a 6.6" QD-OLED display that features a relatively low resolution (384x300) and brightness (50 nits). The backplane of this prototype is an Oxide-TFT. The QD-OLED is made from blue OLED emitters with a quantum-dots color conversion layer.
Address	Shenzhen China Star Optoelectronics Semiconductor Display Technology Co., Ltd. No. 9-2, Tangming Road Gongming Street Guangming New District Shenzhen, 518132 China
Web	http://www.szcsot.com/

15.67 Shenzhen Jufei Optoelectronics Co., Ltd.

China

Company profile

Company description	The company specializes in the R&D, production and sales of SMD LED devices. The company produces QD-LED backlighting displays. Jufei Optoelectronics was officially listed on the Shenzhen Stock Exchange on March 19, 2012 and is a key High-Tech Enterprise of the National Torch Program.
Founded	2005
Products	In collaboration with Tianjin Zhonghuan Quantum and Southern University of Science and Technology the company has developed an On-Chip type packaging method (encapsulating red and green quantum dots in LED lamp beads). The product has high color saturation (gamut value > NTSC 98%), excellent reliability (using a new packaging process and QD materials), high luminous efficiency, fast response time etc.
QD applications	Backlight LED, lighting LED, light bar products, small pitch display LED and automotive LED for mobile communications and displays.
Address	Jufei Optoelectronics Co., Ltd.

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	No. 4, E Ling Industrial Area, E Gong Ling Community, Ping Hu Street, Long Gang District, Shenzhen, China T: 0755-29632290/0755-89236514
Web	http://www.jfled.com.cn/en

15.68 Shoei Chemical, Inc.

Japan

Company profile

Company description	Shoei Chemical Inc. engages in the manufacture, sale, and import/export of electronic materials for electronic devices and components. It offers conductive pastes which are used in thick film hybrid integrated circuits, network resistors, chip resistors, variable resistors, and potentiometers; and dielectric pastes that are used in thick film hybrid integrated circuits, resistors, and display devices.
Founded	1956
Products	The company is producing Cd-free quantum dots and has several patents covering QD production.[175]
Address	Shoei Chemical, Inc. Shinjuku Mitsui Building 1-1 Nishi Shinjuku 2-chome Shinjuku-ku Tokyo, 163-0443 Japan Phone: +81 3 3344 6662
Web	www.shoeichem.co.jp

15.69 Sigma-Aldrich

USA

Company profile

Company description	The company is one of the world's chemicals and materials suppliers.
Products	The company supplies QDs from several producers: • CdSeS/ZnS alloyed quantum dots • CdS Type Quantum Dots • CdTe core-type quantum dots • Core-Shell Type Quantum Dots

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	• PbS core-type quantum dots • Non-cadmium quantum dots.
Address	Sigma-Aldrich 3050 Spruce St St Louis, MO 63103 United States Tel: +1 800-521-8956
Web	www.sigmaaldrich.com

15.70 Sinon Therapeutics

USA

Company profile	
Company description	The company was founded in 2005 as Cromoz, Inc.
Products	The company produces non-toxic water soluble carbon nanotubes and carbon quantum dots for drug delivery and as fluorescent probes for imaging. Water-soluble carbon nano-materials are introduced as a nontoxic, fluorescent reagent; enabling a living species to be imaged alive. This extends the possibility of tagging drug molecules so that they can be delivered to the proper site guided by image movement of the fluorescent tag. The water soluble fluorescent multi-walled Carbon Dots (C. Dots) are produced by functionalization of the surfaces and with no external passivation of surfaces with any organic wrappers. These carbon nano materials are produced from simple natural organic resources on pyrolysis and not from the commonly used laser ablation techniques on graphitic carbon. They have successfully conjugated these water-soluble functionalized C.Dots with Paclitaxel and Gemcitabine
QD applications	• Biomedicine.
Address	SiNON Therapeutics, 2 Davis Drive, Research Triangle Park, North Carolina USA T: +1 27709-3169
Web	http://sinontp.com/research.html

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15.71 Solvay SA

Belgium

Company profile

Company description	Solvay SA manufactures chemicals and plastics. The Company produces soda ash, hydrogen peroxide, functional polymers, silica, surfactants, food and fragrance flavors, and other specialty polymers.
Products	Solvay's CYTOP® family comprises a wide range of phosphine derivatives owing its name to the chemistry behind them. In the television display space, CYTOP® 380HP and CYTOP® 250 are two key products used to commercially make quantum dots, the former as a solvent and ligand, the latter as the very core of the dot. These liquids play a significant role in the formation of the nanocrystals. Solvay sells its CYTOP® products to quantum dot manufacturers, who sell the quantum dots often on a film to display manufacturers, who in turn sell the displays to electronics manufacturers.
Address	Solvay SA Rue de Ransbeek 310 Bruxelles, 1120 Belgium T: +32-2-264-21-11
Web	www.solvay.com

15.72 SpectriS-dot BV

The Netherlands

Company profile

Company description	SpectriS-Dot is a spin-off of the University of Amsterdam and works in close collaboration with the research department of the University of Twente.
Products	SpectriS-Dot has developed light emitting quantum dots (QDs) covering the full-colour spectrum, based on an abundant and non-toxic material silicon (Si). Compared to competitive solutions, these C:Si QDs provide similar optical qualities, improved stability, ease of preparation and increased functionality. These C:Si QDs have the potential to replace all currently employed toxic and/or scarce materials used in LEDs and displays, as well as in a variety of other applications.

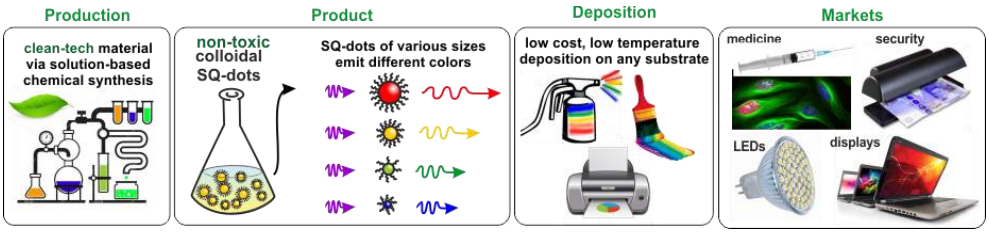

Figure 63. SQ dots production process.

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QD applications	• Security and surveillance • UV-coatings • Bio-functional coatings for sensing • Medical imaging • Drug delivery. • Renewable energy • Quantum optics and photonics • LEDs • Colour-displays for portable devices, large screen TVs or advertisement panels.
Address	SpectriS-dot BV Science Park 904, 1098 XH Amsterdam The Netherlands
Web	http://www.spectris-dot.com/

15.73 StoreDot Ltd.

Israel

Company profile	
Company description	StoreDot was established to commercialize bio-organic quantum dots, based on a process developed at Tel Aviv University, for application in mobile displays and energy storage devices. The company has raised >$145 million in investment funding to date. The company has 31 granted patents and ~50 pending.
Founded	2012
Employees	~85
QD history	2014: StoreDot develops battery prototype that can fully charge a mobile phone in 30 seconds 2014: Company closes $42 million Series B funding round. September 2017: Daimler leads $60 million funding round. May 2018: BP Ventures invests $20 million. May 2018: TDK invest in and signs a joint development contract with StoreDot. December 2018: The company sign agreement with EVE Energy Co.. The company will start mass production of StoreDot's FlashBattery technology for consumer electronics applications in the China market. June 2019: StoreDot and its strategic partner BP demonstrate a live, full-charge of a two-wheel electric vehicle (EV) in just five minutes
Products	**Technology** StoreDot has developed a proprietary Li-ion capacitor (LiC) technology-a hybrid of lithium batteries and supercapacitors. The company's technology is based on an electrode structure containing proprietary electrolyte and chemically synthesized organic quantum dots with metal oxide compounds. By adding organic compounds to traditional Li-ion batteries, this new architecture enables ions to flow from a modified anode to a modified cathode at a speed that is much faster than existing technologies, resulting in enhanced energy density and high storage ability with the rapid-charging rate capability of capacitors. **Product** StoreDot's FlashBattery™ technology is a fast charge battery with applications

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	in the consumer electronic market. The company is also developing electric-car batteries. According to the company a StoreDot Flash Battery can be filled to capacity in five minutes, providing a range of up to 300 miles under optimal conditions for EV batteries.
QD Applications	• Batteries for consumer electronics (e.g. smartphones). • Organic displays. • Electric vehicles (EV) batteries.
Collaborations/licences	• TDK • Daimler (EV batteries) • Samsung • BP • EVE Energy Co. Ltd.
Address	StoreDot Ltd. 3 Shenkar St. Herzeliya 4672503 Israel Tel: +972 3 5097710
Web	www.store-dot.com

15.74 Suzhou Xingshuo Nanotech Co., Ltd (Mesolight)

China

Company profile	
Company description	The company was founded at Nanopolis in 2012 by Wang Yunjun.
Founded	2012
Products	The company produces InP/ZnS QDs and CdSe/ZnS QDs. Mesolight mainly supply to the China market.
QD applications	• QD-LEDs • QD-LCD • QD Lighting • Bio-Labeling
Address	Suzhou Xingshuo Nanotech Co., Ltd. Bldg NW06-403, 99Jinji Lake Rd, Suzhou Industrial Park, China, 215123 T: +86 -512 6292 3025
Web	http://www.mesolight.cc/ www.mesolight.com

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15.75 SWIR Vision Systems

USA

Company profile	
Company description	SWIR Vision Systems Inc. is a startup company launched by RTI International (https://www.rti.org/), developing and commercializing an image sensor technology, for infrared imaging cameras with full HD resolution. RTI's patented infrared (IR) camera technology is based on novel IR image sensor materials.
Founded	2018
Employees	<10
Products	The company has developed a shortwave infrared camera based on quantum dot sensor technology.

Figure 64. Infrared QD sensor company.

The Acuros™ family of high definition cameras feature CQD™ sensor technology. d CQD-SWIR, a SWIR imaging sensor platform that provides low noise and broad spectral sensitivity in a low-cost architecture. CQD-SWIR is a monolithic device fabricated by building a colloidal quantum dot photodiode structure directly on the surface of silicon (Si) CMOS circuitry, bypassing the hybridization process required by conventional SWIR sensors. The techniques used in the fabrication of CQD-SWIR sensors are standard highthroughput processes found in the commercial CMOS industry. The use of these high-throughput processes, coupled with the low-cost materials employed in the diode structure, enables the fabrication of CQD-SWIR sensors that are more than an order of magnitude lower cost than existing SWIR sensors.

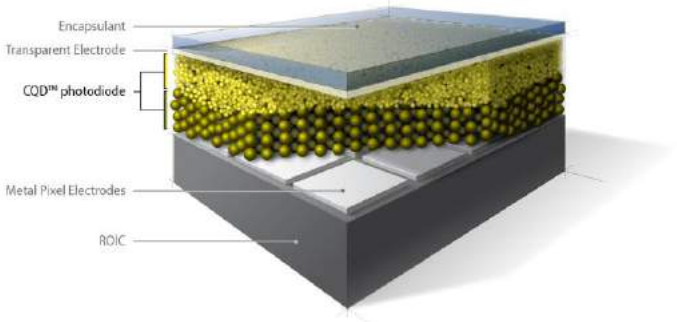

Figure 65. CQD™ photodiode schematic

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	Image: SWIR Vision Systems
QD applications	• Industrial machine vision. • Security • Agricultural imaging.
Address	SWIR Vision Systems 3021 E Cornwallis Rd, Durham, NC 27709, USA Tel: +1 (919) 248-4107
Web	https://www.swirvisionsystems.com/

15.76 TCL Corporation

China

Company profile	
Company description	The company are the third largest TV manufacturer globally. The company manufactures and sells LCD panel-backlight module, QLED, Android, smart, and ATVs; mobile phones; and semiconductor displays and materials. It is also involved in the venture capital and investment businesses. In addition, the company offers Internet applications, logistics, and financial services. It sells its products approximately in 160 countries and regions worldwide under the TCL, Thomson, and Alcatel brands. The company was founded in 1981 and is based in Huizhou, China.
QD history	January 2015: TCL introduces a 55'' Ultra HD television incorporating Quantum Dots. January 2019: TCL announces plans to 8K 8 series models QLED TVs. January 2019: TCL demonstrates 31 inch hybrid H-QLED TV developed with China Star Optoelectronics Technology (CSOT)
Products	The company use a proprietary NBP (nano band phosphor) photon display technology in 8 series quantum dot TVs. In 2019 the company plans to launch 8K 8 series models that will feature the Roku OS, quantum-dot display technology, and screen sizes of at least 75 inches. The company will launch QD-TVs into the North America market in 2019. The X10 is the first Quantum Dot television TCL has launched globally. The company is also developing hybrid Quantum Dot OLED displays using a blue OLED emitter coupled with red and green Quantum Dot emitters. TCL is branding the technology H-QLED based on inkjet printing from 'Guangdong Zhuhua', an open R&D platform.

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	 Figure 66. TCL QLED TVs.
Target markets	• TVs.
Collaborations/licences	China Star Optoelectronics Technology (CSOT)
Address	TCL Corporation 22/F,TCL Technology Building, 17 Huifeng 3rd Road, Zhongkai Hi-tech Development District, Huizhou,Guangdong, 516006 P.R.China
Web	http://news.tcl.com

15.77 Thermo Fisher Scientific

USA

Company profile	
Company description	Thermo Fisher Scientific is an American biotechnology product development company located in Waltham, Massachusetts, and was created in 2006 by the merger of Thermo Electron and Fisher Scientific.
Products	The company produces Invitrogen QDdot probes for medical imaging. Qdot nanocrystals and bioconjugates are high quantum yield nanocrystals that contain a heavy metal core particle surrounded by a patented surface coating enabling attachment to antibodies and other biomolecules.
QD applications	• Biomedicine.
Address	Thermo Fisher Scientific 168 Third Avenue Waltham, MA USA 02451 Phone:+ 1 781-622-1000
Web	https://www.thermofisher.com/uk/en/home/brands/molecular-probes/key-molecular-probes-products/qdot.html

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15.78 Tianjin Central Electronic Lighting Technology Co., Ltd. (Zhonghuan Quantum)

China

Company profile

Company description	The company has a number of QLMS, QD-ALEF, HB-QLED, etc. products based on Quantum Dot Microspheres (QLuMiS) technology.
Founded	2013
Products	The company has established three core businesses including advanced packaging materials based on quantum dot material preparation, LED packaging devices based on composite quantum fluorescent materials, and high-quality and high-color rendering quantum dot lighting products. The company has produced QLEDs (QLuMiS) and Quantum dot backlight devices and the first QLED high-colored lighting table lamp that uses QD packaging devices. The quantum dot LED package device has a wide color gamut, low power consumption, and low cost. The QD lighting device has a core advantage of high color rendering index (Ra>95, R9>95), achieving a balance of red, green, and blue light. At the same time, the product has improved the accurate interpretation of different colors, enhanced the recognition of edge contours, and essentially improved the lighting effect of the lamp from the light source.
QD applications	• The company has developed QLEDs (QLuMiS) and Quantum dot backlight devices and the first QLED high-colored lighting table lamp that uses QD packaging devices. QLuMiS is suitable for multiple types of packaging (e.g., on-chip, remote, and others).
Address	Tianjin Central Electronic Lighting Technology Co., Ltd. No 51 Tianxiang Road, Tianxiang Industry Area Liqixhuang Street Xiqing District Tianjin China Phone: 4000773669
Web	www.zhonghuanlighting.com

15.79 Tianma Microelectronics Co., Ltd.

China

Company profile

Company description	Tianma Microelectronics Co., Ltd. designs, manufactures, and supplies LCD and LCM products worldwide. Its products include TN-LCD, STN-LCD, TFT-LCD, CF, and LTPS AM-OLED products for various applications, such as mobile phone, tablet PC, PDVD and DPF, DSC and DVC, smart wearable, automotive, and home automation

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	applications, as well as industrial, medical, and monochrome displays. The company was founded in 1983 and is based in Shenzhen, China.
Products	The company has developed a RoHS compliant QD solution for application in the medical diagnostic display market.[176] [177] The company's display products utilize non-cadmium quantum dot technology combined with an optimised colour filter.
QD applications	• Displays.
Address	Tianma Microelectronics Co., Ltd. No.88, Daxin Road, Tianma Building, Nanshan District, Shenzhen, China Tel: 86-755-36351000
Web	http://en.tianma.com/

15.80 TPV-Vision

Hong Kong

Company profile	
Company description	In April 2011, TPV Technology and Philips agreed to form a Netherlands-based television manufacturing joint venture comprising all of Philips' television operations, and owned 70% by TPV Technology and 30% by Philips. Creation of the joint venture, named TP Vision, was completed in April 2012. In January 2014, TPV Technology announced an agreement with Philips to transfer the remaining 30% shares to TPV, which was completed in May 2014, making TP Vision a wholly owned subsidiary of TPV Technology.
Products	The company use CFQD® Fine Color Film™, the cadmium-free quantum dot film produced through Nanoco's commercial relationship with Taiwan's Wah Hong Industrial Corp.
QD applications	Consumer electronics.
Address	Suite 1023, 10th Floor 5Canton Road, Tsim Sha Tsui Wan Chai Hong Kong (SAR) Phone: +1 852-2858-5736
Web	http://www.tpvision.com/

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15.81 UbiQD, LLC

USA

Company profile

Company description	The company is headquartered in Los Alamos, New Mexico. The company completed its latest round of financing totalling $330,000, with more than $700,000 raised since its inception in 2014. Its technology was developed at M.I.T. and Los Alamos National Laboratory.
Founded	2014
Products	The company is commercializing a new class of quantum dots composed of I-III-VI2 semiconductors, with a focus on CuInSeS. The company's QDs are low-toxicity and low-cost.
QD applications	Security inks for currency and brand protection, luminescent pigments for personal care products and design, and luminescent solar concentrator windows for net zero buildings. While the company's primary focus is in enabling windows to generate electricity, UbiQD also currently sells its materials for R&D purposes and provides materials technology development services.
Address	UbiQD, LLC Santa Fe National Forest, 100 Entrada Drive, Los Alamos, NM 87544, USA Phone: +1 505-310-6767
Web	http://www.ubiqd.com

15.82 Unique Materials

Taiwan

Company profile

Company description	The company has nvested NT$70 million (US$2.346 million) to set up a plant in the Central Taiwan Science Park (CTSP) to develop and produce quantum dot materials for the display and lighting industries.
QD applications	Displays and lighting.
Address	Unique Materials No.2, Jhongke Rd., Situn District, Taichung City 40763, Taiwan (R.O.C.) T: +886-4-25658588
Web	NA

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15.83 VueReal, Inc.

Canada

Company profile	
Company description	The company is developing innovative micro-LED technologies. In 2018 the company received $8.5 million in funding from Sustainable Development Technology Canada (SDTC) to support a total project investment of over $26.0 million.
Products	The company are developing Quantum dots for application in Micro-LEDs.
QD applications	Smartphones, TVs, laptops, virtual/augmented reality systems, heads-up-displays, instrument panels, infotainment systems, and wearables.
Address	VueReal, Inc. 440 Phillip Street, Unit 100, Waterloo, ON N2L 5R9 Canada
Web	https://www.vuereal.com/

15.84 Wah Hong Industrial Corporation

Taiwan

Company profile	
Company description	Wah Hong is a manufacturer and supplier of optical films and sheets for the display Taiwanese and Chinese display industry. Based in Taiwan, Wah Hong serves global customers in the display industry from five factories in China, one in Malaysia and one in Indonesia. Its LCD product range includes all types of optical film including diffusion, reflection, prismatic and multi-function films along with light guide sheets and other products.
Products	The company is manufacturing films under Nanoco's CFQD® Fine Color film brand. Nanoco's cadmium-free quantum dots (CFQD®) resins are converted into films by Wah Hong and supplied to an Original Equipment Manufacturer (OEM) for usage in TV and monitor products. The Cadmium Free QD films offer improved colour gamut performance for LCD displays with blue LED backlights.
QD applications	• Displays.
Collaborations/licences	Nanoco
Address	Wah Hong Industrial Corporation 11/F, 235 Chung-Cheng 4th Road Chienchin District Kaohsiung Taiwan Phone: +1 886-7-971-7777
Web	http://www.wahhong.com.tw/

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15.85 Wuhan Jiayuan Quantum Dots Co., Ltd.

China

Company profile	
Company description	The company was as a spin-out from Wuhan University.
Founded	2005
Products	The company produces Avidin-QDs (CdSe/ZnS core–shell structure with a diameter about 10 nm).
QD applications	• Biomedical imaging and biodiagnostics.
Address	Wuhan Jiayuan Quantum Dot Technological Development Co., Ltd. Rm.1201, Wuhan University Tech. Enterprise Incubator,129 Luoyu Rd., Hongshan Wuhan, Hubei, China Tel: +86-27-87158543
Web	www.qds.net.cn

15.86 XF Nano Materials Tech Co., Ltd

China

Company profile	
Company description	Nanjing XianFeng Nano Material Technology Co.,Ltd. is based at the National University Science Park of Nanjing University. The company is focused on producing graphene, molecular sieves, catalysts, supercapacitors and the bio-fuel cells.
Founded	2009
Products	The company produces graphene oxide quantum dots in solution.[178]
QD applications	• Displays.
Address	Nanjing XFNANO Materials Tech Co., Ltd Nanjing City Jiangsu Province China 210046 Tel: +86 025-58595385
Web	www.xfnano.com

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15.87 Zhijing Nanotech Co., Ltd.

China

Company profile	
Company description	The company produces low-cost Perovskite Quantum Dots (pQDs) and colour conversion films for LCD displays based on these pQDs. The company business office is located in Beijing and the R&D base is located in Zhangjiagang.
Founded	2016
Products	**Perovskite Quantum Dots** • Organometal halide perovskites quantum dots • All-inorganic colloidal perovskites quantum dots • Organometal halide perovskites monocrystalline **Other** • Cadmium selenide quantum dots • Zinc oxide quantum dots **Optical film** Using patented technology, the company has developed a PQD/polymer based optical film (PQDF). LCD displays equipped with PQDF reportedly exhibit a colour gamut of 110% NTSC and brightness of 600 nits. Zhijing Nanotech is working with industrial partners to integrate its PQDF product into various commercial display products. **Coatings** The company can also produce patented PQD coating materials in large quantity. PQDF samples made from PQD coating material are being tested by end customers. Zhijing Nanotech is able to offer PQDF samples with size range from A4 to 65 inch (16:9).
QD applications	• Displays. • Lighting. • Seperator membrane for Li ion battery. • UV converter for Si solar cell.
Address	Zhijing Nanotech Co., Ltd. 1 Xingyuan Road Nanfeng Town Zhangjiagang Jiangsu Sheng China
Web	http://finestnano.com/

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