Tripping the light fantastic #3

Quantum dots – all the colours of the rainbow

This report is the last in a series of three examining key growth areas in the global photonics market. It looks at quantum dots (QDs), engineered semiconductor particles which emit light of precisely controlled colours when stimulated by either light or electricity. QDs are used in a growing range of applications including displays, infra-red sensors, horticultural lighting, photovoltaic generation and biological probes. Mordor Intelligence expects demand from these applications to drive market growth at a CAGR of 40.9% between 2021 and 2026 to reach US$4.4bn by 2026.

Displays: Brighter reds, richer greens

QDs have been used in high-end TV displays since 2013 when Sony used them to extend the colour range of its KDL-W900A model. Since then, QDs have been used in tens of millions of TV displays, with **Samsung (005930:KRW)** becoming the dominant supplier, supported by QD manufacturers **Hansol Chemical (014680:KRX**) and Nanosys. According to Bloomberg, Nanosys is in talks to go public through a merger with **SPAC GigInternational1 (GIW:US).**

Sensors: Improving the sensitivity of silicon

Applications such as 3D sensing are migrating from the visible to the near infra-red (NIR) and short wave infra-red (SWIR) regions of the spectrum. OEMs are adopting longer wavelengths for light detection and ranging (LiDAR) to be eye-safe and, in the case of mobile phones, able to be located under the OLED (organic LED) screen rather than in a cutaway. Cost-effective silicon sensors are widely used in mobile devices at present but are not sufficiently sensitive at these longer NIR and SWIR wavelengths. Semiconductor manufacturer STMicroelectronics (**STM:EPA**), Belgian research institute IMEC and camera manufacturer SWIR Vision Systems are developing silicon sensor architectures which include QDs for improved sensitivity. We have previously inferred that ST is using nanomaterials from **Nanoco (NANO:LN).**

Horticultural lighting, photovoltaics and bioprobes

QDs are beginning to be used for other applications as well. QD specialists UbiQD are deploying QDs in a film for greenhouses that converts sunlight to wavelengths used for photosynthesis, thus improving crop yield. Both UbiQD and Polish photovoltaic specialist ML System **(MLS:WSE)** are adding QDs to construction glass to generate light from incident sunlight. QDs have also been proposed for use in cancer diagnosis, image-guided surgery and targeted therapy.

Transition to non-toxic materials

Initially most QDs used in commercial applications were based on cadmium selenide (CdSe) because of the efficiency with which the material converts light colours. However, cadmium is known to be toxic so various families of materials have been developed as alternatives. These include copper indium sulphide (UbiQD), indium phosphide (Nanosys/NN Crystal), indium alloy (Nanoco), lead selenide (Quantum Solutions) and perovskite (Avantama).

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Edison themes

Edison themes

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Companies mentioned in this report

Applied Quantum Materials
Hansol Chemical
ML System
Nanoco*
NanoPhotonica
Nanosys
Samsung
Sony
Samsung *
SPAC GigInternational1
STMicroelectronics
SWIR Vision Systems
UbiQD

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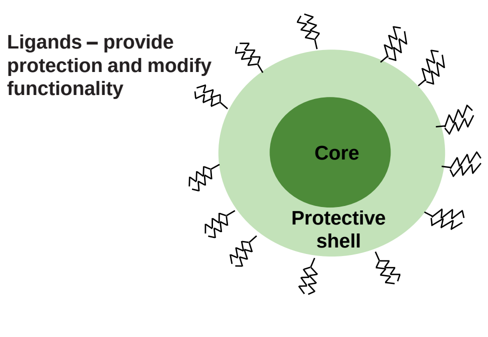
Quantum dot overview

Introduction

Quantum dots are very small semiconductor particles, typically 10–100 atoms in diameter, which is one thousandth the width of a human hair. When one of these particles is energised by an external light or electrical source, it converts the incoming energy to light of a specific colour with a high degree of efficiency. The colour (wavelength) of the light emitted is determined by the size of the particle. The smaller the dot is, the shorter the wavelength. By closely controlling the size of the particles as they are formed, so all the particles are a very similar size, it is possible to produce a material that emits a very pure coloured light (ie with a very narrow band of wavelengths). Stopping particle growth at a specific point gives control over particle size, enabling the production of materials that can emit any colour of light from the spectrum. Critically, unlike fluorescent dyes or doped phosphors, many colours can be achieved from the same material by changing the particle size. Colours that are not on the spectrum, such as brown, can be produced by combining QDs of two or three different sizes.

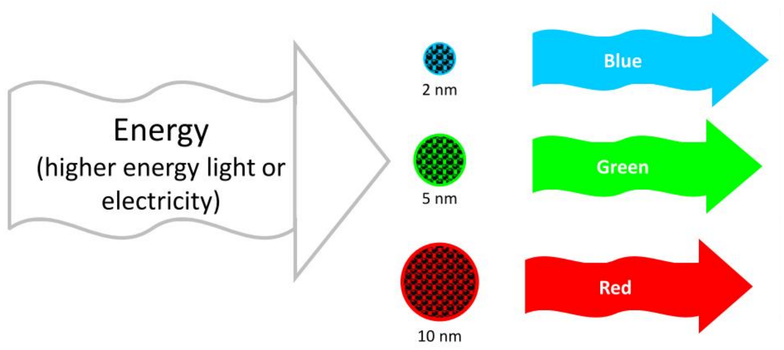
These properties mean that QDs can be applied to a number of different applications, including TV and other electronic displays, enhancing the efficiency of silicon sensors and photovoltaic cells, specialist lighting for horticultural applications and medical imaging. These applications are discussed later in the note.

Exhibit 1: Quantum dot structure



Source: Edison Investment Research

Exhibit 2: Different colours emitted depending on size



Source: Nanoco Group

A high growth market

Market analysts Mordor Intelligence notes that the global quantum dots market was valued at US$652.2m in 2020 and predicts that it will reach US$4.4bn by 2026. This represents a CAGR of 40.9% between 2021 and 2026. Demand is being driven primarily by consumer appetite for high-quality TV displays.

M&A activity secures critical IP

Smaller companies with significant IP in QD technology have been purchased by larger ones seeking to gain a competitive advantage. In November 2016, Samsung acquired the entire IP (c 250 patents) of QD Vision for US$70m, preventing competitors from gaining access to the technology. In 2017 Apple acquired start-up InVisage Technologies which has developed a photosensitive material containing QDs for improving the sensitivity of silicon sensors. In February 2018, Osram acquired Pacific Light Technologies, which had previously supplied QDs to competitor Lumileds for the world's first commercially available LED chip with built-in QDs. In 2019 Osram launched its own high colour rendering index LEDs using these QDs instead of phosphors.

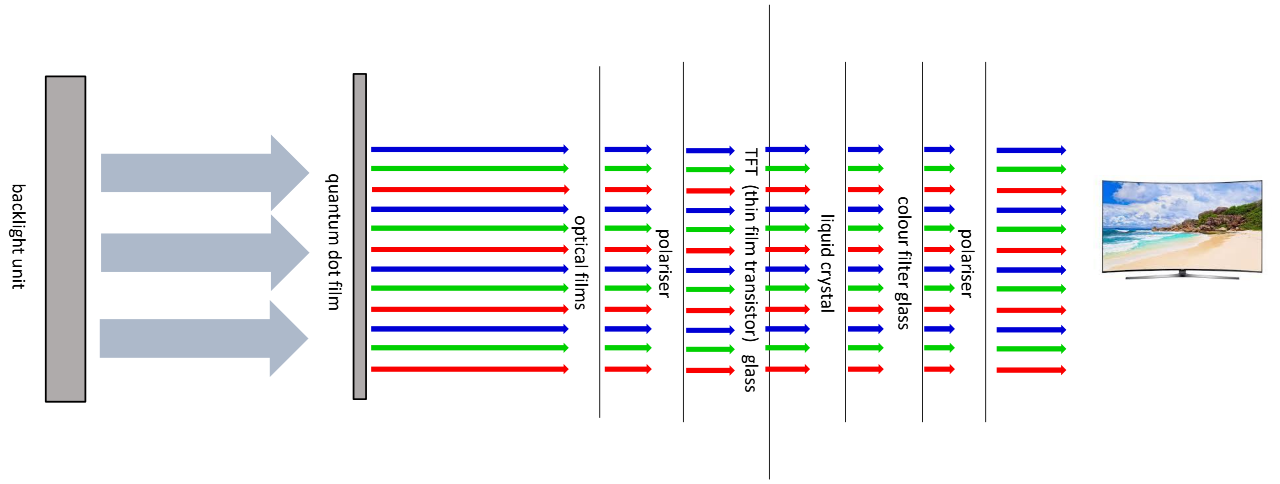
Display: Richer reds, brighter greens

Although Sony was the first manufacturer to launch a QD-enhanced TV display back in 2013, Samsung Electronics is now the dominant provider of QD-enhanced TVs with a 75% share of the global market in Q121. Around 5% of all TVs sold in the quarter contained QDs, 12% of Samsung's contain QDs. According to market experts Omdia, Samsung sold 7.8m QD TVs in 2020 compared with 5.4m in 2019 and is aiming to exceed 10m units this year. LG, Hisense, Sony, TCL and Vizio also make QD-enhanced TVs, but their individual market shares are insignificant compared to Samsung's.

First-generation QD displays incorporate QD film

LCD (liquid crystal displays) are commonplace in electronic devices varying in size from smartphones to large screen televisions. In an LCD television the LED backlight provides a source of white light (a mix of red, blue and green light), which is passed through several optical filters before reaching the LCD panel which has thousands of pixels that individually block or let through light. Light from the LCD panel then passes through a layer of red, green and blue pixelated filters to add colour. The colour range (colour gamut) of traditional LCD displays is limited by the backlight, which does not provide adequate emission of red and green light.

Exhibit 3: First-generation QD display



Source: Edison Investment Research

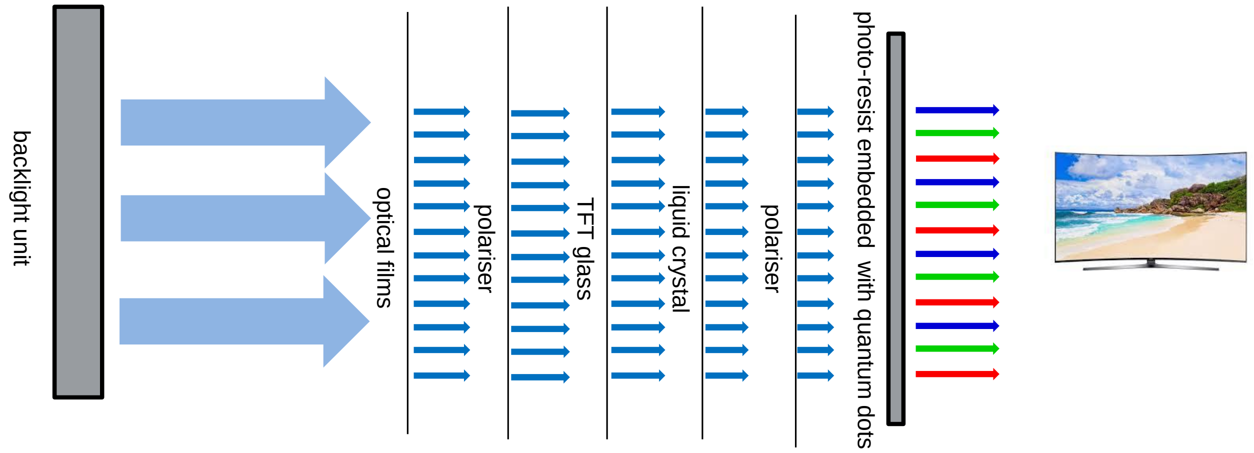
In a QDLCD television (Exhibit 3), the filters between the backlight and LCD panel are replaced by a film incorporating QDs and the backlight only emits blue light The QDs are excited by this blue light, transforming some of it into very pure green and red light, while the remaining blue passes through. As a result, the LCD panel receives a richer white light made up of three narrow bands of red, green and blue. This expands the range or gamut of colour that the display can reproduce. Crucially the technique uses a similar display architecture to conventional LCDs, thus minimising disruption and investment into a well-established supply chain.

LG uses OLED technology for its high-end displays. OLEDs give better contrast than either conventional LCD displays or LCD displays enhanced with QDs. This is because an LCD pixel still lets some light through when it is switched off, while an OLED pixel does not emit any light when switched off. However, OLED TVs (2% global TV market Q121) are more expensive than QD-enhanced displays, partly because they deploy a different display architecture from LCDs, necessitating substantial infrastructure investment (see below).

Second-generation technology gives brighter, more efficient displays

In October 2019 Samsung announced that it was planning an $11bn investment in the world's first dedicated QD display manufacturing facility which will be used to produce second-generation displays. This second-generation QD technology for displays dispenses with the colour filter. The colour filter creates red light by blocking out the blue and green colour in white light (and similarly for extracting blue or green light from white light) thus substantially reducing the efficiency of the system. In a second-generation display, instead of a colour filter, blue light emitted from the backlight unit excites red and green QDs. The backlight unit can be a conventional LED unit or made from OLEDs. Eliminating the colour filter therefore improves the efficiency and brightness of displays. According to an article in The Korea Economic Daily in July 2021, Samsung is developing 55-inch and 65-inch quantum dot organic light emitting diode (QD-OLED) TVs for market launch in the first half of 2022.

Exhibit 4: Second-generation QD display



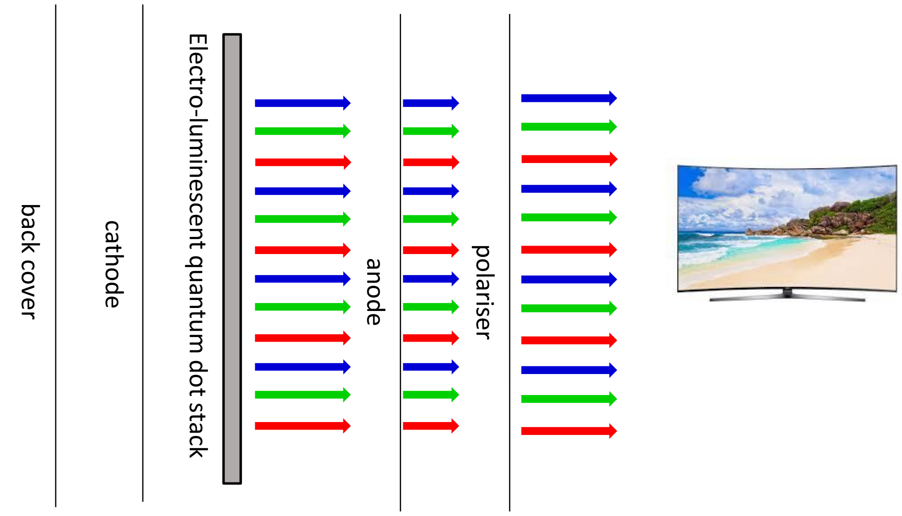
Source: Edison Investment Research

A variant of this technique is being developed for microLED displays used in applications such as augmented reality (AR) smart glasses, head-up and head-mounted displays (HUDs/HMDs), mobiles and wearable devices. It will enhance both colour rendition and energy efficiency, thus extending battery life in portable devices. Please refer to our thematic research on micro-LEDs for more detail.

Third-generation technology brighter still

In the third-generation technology, the QDs form a light-emitting layer that is excited by electricity. This could potentially give a highly energy efficient, bright display with very pure colours and high contrast because, as in OLED TVs, pixels are completely dark when off. The third-generation technology is therefore being proposed as an alternative to OLED displays because OLEDs require investment in vacuum deposition equipment while QD-LED displays could potentially be manufactured using printing or photolithographic techniques which are less capital intensive.

Exhibit 5: Third-generation QD display



Source: Edison Investment Research

Companies manufacturing quantum dots for displays

Hansol Chemical and Nanosys are key suppliers to market leader Samsung

Hansol Chemical is a Korean manufacturer of fine chemicals and electronics materials with annual revenues of c US$500m. In 2015 Samsung named Hansol as its primary supplier of QDs for high-end TVs. Nanosys, based in Milpitas, California, was the first QD supplier to ship in volume and holds over 1,000 patents. Since 2013 the company's QDs have been used in more than 600 products from OEMs such as Samsung, Hisense, Visio, TCL, Acer and Asus. As of August 2021, more than 35m devices incorporating its material had been shipped, collectively requiring over 50,000kg of QD materials. Nanosys has recently acquired micro-LED firm glō, expanding its technology portfolio of display applications. LG Display currently has a stake in Nanosys, having invested $10m in the company in 2018. Samsung took a $15m stake in 2010, at which point it announced a multi-year patent licence with Nanosys. This IP was used in the QD-enhanced TVs Samsung launched in 2017.

Nanoco initially developed QDs with Samsung and is now seeking damages

Nanoco and Samsung initially worked together to develop cadmium-free QDs based on Nanoco's IP. However, Samsung ended the collaboration and launched its QD-based televisions without entering into a supply or licensing agreement with Nanoco. In February 2020 Nanoco announced that it had filed a patent infringement lawsuit against Samsung. The lawsuit alleges that Samsung has wilfully infringed the patents relating to Nanoco's unique synthesis and resin capabilities for QDs. Nanoco is seeking a permanent injunction from further acts of infringement and unspecified but significant monetary damages (Please click here for Edison's research on Nanoco.)

Avantama's materials recently qualified for use in displays

Avantama is based in Switzerland. It manufactures a range of nanoparticles which it supplies in easy-to-use formulations. These include cadmium-free QDs. In October 2020 Avantama announced that a large OEM has qualified its perovskite QDs which would be deployed in displays starting in 2021.

NanoPhotonica working on technology for third-generation displays

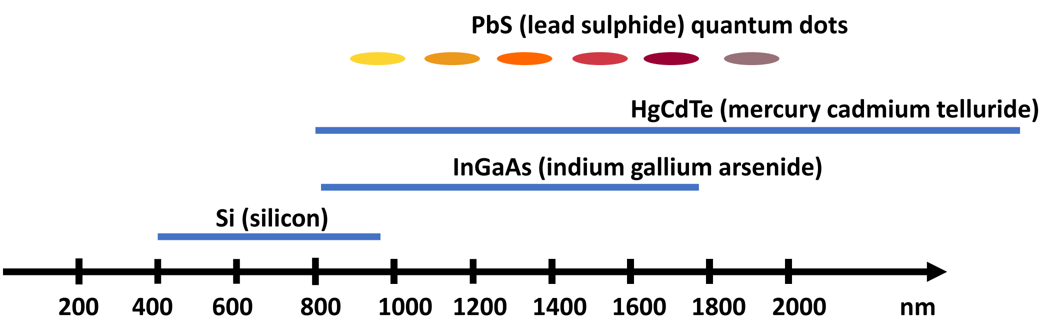
In May 2019, US-based NanoPhotonica announced that it had secured a $3.5m investment from Samsung Ventures and DeepWork Capital to help it further develop and commercialise its electroluminescent QD technology for potential use in third-generation displays. The company is engaged in a number of joint development agreements with vehicle lighting providers and other leading display manufacturers.

Infra-red sensing devices

Emitters need matching sensors

The second report in this series, which focuses on laser diodes, discusses applications such as 3D sensing which are driving demand for laser diodes emitting in the NIR and SWIR regions of the spectrum, that is the section from 900nm out to 1,800nm. OEMs are shifting to longer wavelengths in order for LiDAR to be eye-safe and, in the case of mobile phones, able to be located under the OLED screen rather than in a cutaway. These applications require cost-effective sensors that can detect light at these wavelengths if they are to be widely adopted. Silicon sensors have adequate sensitivity in the visible part of the spectrum, but not in the IR part. Sensitivity is particularly important for mobile device users because higher sensitivity results in lower power consumption and thus a longer time between charges. Sensors based on the compound semiconductor indium gallium arsenide (InGaAs) are sufficiently sensitive but substantially more expensive than silicon to manufacture. Moreover, a silicon sensor can readily be integrated with a silicon-based readout circuit, further reducing cost while a compound semiconductor one cannot. Depositing a layer of QDs tuned to the IR frequency of interest on the sensor potentially provides a cost-effective route for improving the range and sensitivity of sensors, though it has yet to be commercialised.

Exhibit 6: Infra-red absorbers by wavelength



Source: Edison Investment Research

ST Microelectronics ready to commercialise QD photodetector platform technology

In May 2021, ST presented a paper at the Society for Information Display's annual symposium. This announced that the company was ready to commercialise its QD photodetector platform technology and intended to have 940nm engineering samples ready for release to early adopters during calendar H221 and SWIR (<1,400nm) samples ready during calendar 2022. The paper noted that the technology held great promise for enabling lower cost (100–1,000 times lower), high-performance, high-resolution, large spectral response image sensors, which would potentially drive large SWIR imaging growth. It identified initial opportunities in mobile devices, miniature spectrometers and hyperspectral imaging, machine vision and advanced driver assistance, noting that the variant currently at R&D scale was likely to surpass the required performance specifications including sensor speed for time-of-flight applications in future. Belgian research institute IMEC and camera manufacturer SWIR Vision Systems also presented papers on the use of QDs in infra-red imaging at the same event.

We have previously inferred elsewhere that ST is deploying QDs from Nanoco for this application. If successful, this programme could lead to production scale-up and eventual volume production in calendar 2023 at Nanoco's proven production facility in Runcorn. Nanoco is also working with a 'very significant' Asian chemical company on the development of QDs or infra-red sensing applications. The Asian customer intends to incorporate Nanoco's nanomaterials in its own materials, which it will sell globally to companies making electronic devices (ie companies at a similar level in the supply chain to ST). Volume production for the Asian customer is likely to commence one year to 18 months after any potential volume ramp-up for ST.

Apple and QDs

3D sensors are used in front-facing cameras deployed in some iPhone and iPad models to power a facial recognition system called Face ID and in world-facing cameras to support AR and gaming applications Current models use silicon-on-insulator sensors from Sony, Panasonic and Infineon, but nanomaterials could potentially be used in future generations of sensors to improve their sensitivity. According to TechCrunch, at an undisclosed date between November 2016 and November 2017, Apple acquired photosensor technology company InVisage. InVisage used nanomaterials dispersed on a grid and coated on a substrate to create image sensors that it claimed could absorb the same amount of visible and IR light as a conventional sensor, but on a layer that is one-tenth the thickness and can perform better in low-light situation.

Emerging applications

QDs are beginning to be used for other applications as well. Three of these: horticulture, photovoltaic (PV) electricity generation and medical probes are discussed in this section. We note that all three are in the early stages of commercialisation.

Modifying sunlight to improve crop yield

Plants only absorb certain portions of the visible spectrum, so tuning the spectrum of light a plant receives can affect how quickly a plant grows, when it flowers and, most importantly, crop yield. For several years growers have been using magenta (blue and red) LEDs in indoor farming applications as there is no point in generating green light which will not be absorbed by plants. QDs have been proposed as a mechanism for enhancing these benefits by absorbing some of the light emitted by the LEDs and re-emitting it at the wavelength required to improve chlorophyll absorption peaks in specific varieties of plants without materially affecting the efficiency of electricity to light conversion. While there have been numerous studies showing the benefit of modifying the LED light in this way, the technique does not appear to have been adopted commercially in meaningful volumes.

Venture capital-backed UbiQD has taken this concept one stage further by creating a film containing QDs that is applied to the glass in greenhouses and converts the incident sunlight to light of the desired frequency. During 2019 and 2020 various pilot customers and technology institutes tested UbiQD's UbiGro film, validating its ability to achieve 10–20% higher yields with faster cycle times, reduced waste and improved crop quality. Management estimates that the greenhouse cover film market is more than 50bn square feet globally or 20x greater than the display industry. UbiQD has developed its own copper indium sulphide QDs but is partnering with Nanosys for this application because Nanosys has the manufacturing scale required to address the market.

Next generation solar cells

QDs are also starting to be deployed as a mechanism for absorbing light energy from the sun and converting it to electrical energy, replacing bulk materials such as silicon, copper indium gallium selenide or cadmium telluride in solar cells with QDs. One key advantage of this approach is that a significant proportion of the light energy incident on a conventional solar cell is wasted because the photosensitive layer is tuned to a specific wavelength and light with a longer wavelength (and thus less energy per light particle) cannot be converted to electricity while light with a shorter wavelength is only partly converted to electricity, the remainder is wasted as heat. It is possible to manufacture solar cells with several photosensitive layers, each tuned a different wavelength, but this adds complexity and cost. In contrast, QDs tuned to multiple wavelengths may be incorporated into the same photosensitive layer, simultaneously extracting energy from different wavelengths of sunlight. In addition, QD solar cells can be manufactured using variations of print processes, which are substantially less capital and energy intensive than the semiconductor manufacturing processes required for conventional solar cells.

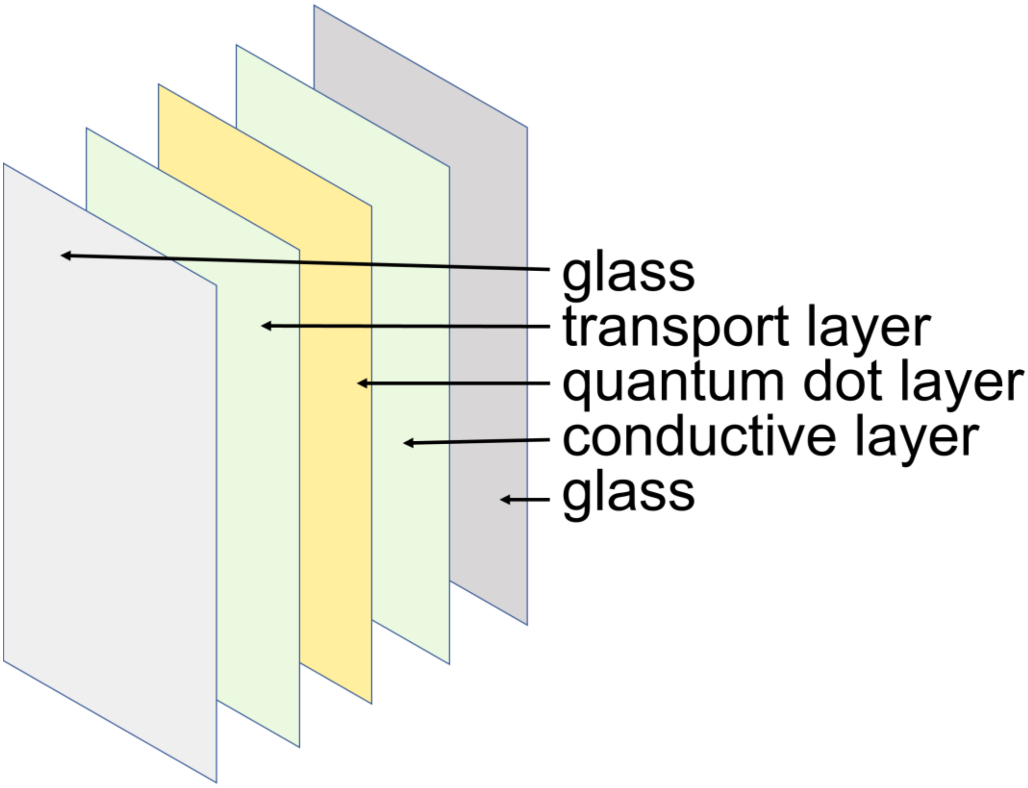
Exhibit 7: Video showing demonstration of QD solar cell

Source: UbiQD

Conversion efficiency still low for standalone PV cells

QD solar cell technology is still under development. During 2020 UbiQD carried out test installations involving 1m^2 QD solar panels that were indistinguishable from regular window glass in buildings in the United States and the Netherlands. The panels had a power conversion efficiency of 3.6% which compares unfavourably with conventional solar panels which exhibit efficiencies of 15–20%. However, laboratory trials using perovskite QDs (eg $CsPbI_3$ and $CsPbI_2Br$) have reported substantially higher efficiencies. In 2020 the Nanomaterials Center at the University of Queensland in Australia reached a conversion efficiency of 16.6% with a postage stamp-sized solar cell. While the efficiency of a QD solar panel compared to a conventional solar panel may be low at present, the amount of electricity generated is more than that from standard glass (ie zero), with the added benefit that the QD panel reduces the amount of UV and IR light entering a building. ML System, a company based in Poland specialising in the design, engineering and production of building-integrated photovoltaic cell systems is currently offering ‘quantum glass’, where a conventional metal oxide coating on glass is replaced by a coating of QDs. ML Systems does not provide data on the relative cost of this glass or the payback period.

Exhibit 8: Construction glass enhanced with QDs



Source: Edison Investment Research

QDs can improve efficiency of conventional PV cells

While solar panels relying entirely on QDs for energy conversion may be some time off, QDs are being used to improve the efficiency of conventional solar cells. For example, Quantum Solutions is currently offering PbS (lead sulphide) QDs which absorb light in the NIR spectrum for adding to silicon solar cells to improve total power efficiency by up to 5%.

Using QDs as biological probes

Creating non-toxic QDs

First QDs based on toxic heavy metals

Initially, most QDs used in commercial applications (ie in lighting and TV displays), were based on cadmium selenide (CdSe) because of the efficiency with which the material converts colours. However, cadmium is known to be toxic. It is one of six substances regulated by the European Union's Restrictions on Hazardous Substances (RoHS), which came into force in July 2011, though displays are still subject to an exemption from this directive.

Cadmium-free alternatives now widely used

Various families of materials have been developed as cadmium-free alternatives including copper indium sulphide (UbiQD), indium phosphide inside a zinc sulphide shell (Nanosys/NN Crystal) and lead selenide (Quantum Solutions). Nanoco's patented CFQD (cadmium-free QD) technology is based on an alloy of indium and other elements. Indium phosphide is the most widely deployed cadmium-free material as it is deployed in Samsung's QLED range of TVs and the Vizio P Series and Hisense U9A and NU9700 ranges. While there are toxicity concerns surrounding indium phosphide QDs as well, the material is not on the RoHS restricted list.

Perovskites are a promising alternative

More recently the performance of perovskite QDs (Avantama/Quantum Solutions) has improved to such an extent that the material has been successfully qualified by a TV major for use in displays. Perovskites contain lead, which is also on the RoHS restricted list, but the default limit is at a level where the green-only QD film-based perovskite technologies being offered are likely to contain lead at permitted concentrations. This may not be the case for future applications of perovskites such as QD colour filters or colour converters used in QD-OLED displays.

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