APPLICATIONS
Displays, photovoltaics, solid-state lighting, biomedicine, sensors and security.

QUANTUM DOTS
THE GLOBAL MARKET
Production volumes, prices, future projections and end user markets.

COMPANIES
All the leading companies profiled.

MARKETS
End user markets and products.

PRODUCTS
Main products and production.

APPLICATIONS
Displays, photovoltaics, solid-state lighting, biomedicine, sensors and security.
## EXECUTIVE SUMMARY
The global market for quantum dots (QD) will grow significantly in the next 18 months.

## INTRODUCTION
Quantum dots: materials, properties and production methods.

## APPLICATIONS
The main end user markets for quantum dots.

## REGULATIONS & SAFETY
Quantum dot global regulations and toxicity.

## GLOBAL REVENUES
Quantum dot global revenues, 2013-2024, regional markets and prices.

## ELECTRONICS
Market assessment in displays, including market drivers, commercialization, manufacturing and product development.

## ENERGY
Market assessment in energy, including market drivers, commercialization, manufacturing and product development.

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## SENSORS
Market assessment in sensors, including market drivers, commercialization, manufacturing and product development.

## COMPANIES
Producers, product developers and OEMs.

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**Companies**

Profiles of the leading quantum dots companies worldwide, including materials producers, product developers and OEMs.

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EXECUTIVE SUMMARY

Market expected to show strong growth in next few years.

The global market for quantum dots (QD) will grow significantly in the next 18 months. QD Vision and Nanosys have developed scalable solution production processes and are partnering with multi-national OEMs to use QDs in displays for consumer products. Products, such as tablets and high-end TVs incorporating QDs are already available and will be rolled-out into mass produced TVs by the middle of 2015. Light emitting diodes (LEDs) and displays utilizing QDs can be made ultra-thin, on flexible substrates and thus produced at a much lower cost.

APPLICATIONS

The current market for companies selling QDs is between $25 million (conservative) and $48 million (optimistic) in revenues, with the QD-enabled product market in excess of this. Revenues for QD-enhanced products are potentially upwards of $7 billion by 2024 across displays, solid-state lighting, solar, biomedical, anti-counterfeiting and sensors sectors.

QDs 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). Nanoco and other manufacturers have developed cadmium-free QDs, partially to circumvent restrictions on the use of cadmium in certain markets. Cadmium-based QD materials are subject to regulation limitations in a number of global regulatory environments, which may hinder their uptake in certain applications.

However, QDs are beginning to penetrate mainstream markets as optical down-converters and recent legislation will likely accelerate their marketability.

The market up to 2013 has 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.

Recent product launches featuring QDs have changed the commercial picture. Sony’s 2013 line of Triluminos liquid crystal display (LCD) televisions use edge-mounted red and green QDs from QD Vision to optically down-convert some of the television’s blue LED backlight.
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. Key partnerships include:
• Nanoco with Dow Electronic Materials for development of Cadmium-free Quantum Dots in consumer electronics. They also have partnerships with LG Electronic, Tokyo Electron (solar) and Osram (lighting).
• Nanophotonica with five leading display manufacturers.
• Nanosys with LG and Samsung.
• Qlight and Merck.
• Storedot with Samsung.

MARKETS
QD-enhanced applications are currently under development or are in limited production. The end user markets for QDs are potentially very lucrative. Lighting and displays each represent potentially $100 billion markets by 2020.
At the QD material and component level this is a potential $5-$10 billion revenue opportunity. Additional markets in solar, security, thermoelectrics and magnetics could double these potential revenues.

High volume applications
• Additives in displays
• Infrared imaging
• Quantum dot lighting
• Photovoltaics
• Contrast agents
• Drug delivery
• Biosensors
• Fluorescent reporters
• Security tags.

Low volume applications
• QD-lasers
• Photoelectrochemical sensors.
• Image sensors.

Novel applications
• Quantum switches
• Quantum computing
• Single electron devices.

Quantum dot TVs
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. According to Nanoco the proportion of quantum dots used in current LCD displays is:
• TVs: 2% of a Global Annual LCD Area (m²) of 157,333,925
• Monitors: 3% of a Global Annual LCD Area (m²) of 29,365,561
• Notebook/Ultrabooks: 7% of a Global Annual LCD Area (m²) of 22,819,763
• Tablets: 60% of a Global Annual LCD Area (m²) of 12,174,293
• Small displays (e.g. smartphone): 20% of a Global Annual LCD Area (m²) of 12,000,660.

Samsung has produced a full-colour QD panel as a potential replacement for LCD (although QDs are more likely to be easily incorporated into existing LCD design) and OLED (the main competition for QD-TVs). When compared to LCD, quantum dots use fifth of the power. In comparison to OLEDs, QDs are brighter, will eventually have a longer lifespan, and cost half as much to make. Samsung plans to launch a Quantum-dot LED TV (QLED-TV) in 2014–2015. They have cancelled plans for an OLED mass production facility due to production cost issues. The company released an OLED-TV onto the US market in 2013, but the large price tag ($14,700 for a 55-inch model) deterred consumers.

LG Electronics has partnered with QD Vision to develop a QLED-TV, and like Samsung are potentially set to begin mass production. In early 2013, 3M and Nanosys introduced a prototype of quantum dot enhancement film (QDEF) targeted at LCD manufacturers which has now been incorporated into commercially available products. Samsung and LG Display are currently the two largest global LCD panel providers. Sony and Panasonic are also developing QLED technology to be used in UHD TV, as is Taiwan LCD manufacturer AU Optronics. Apple has filed a number of QD display patents over the past year.

Competition from red phosphors
With the increased market pull and consumer demand for high colour gamut TV, producers are ramping up their activity to bring new UltraHD/4K sets to market this year. Although QD-TVs are coming to market they face competition from Mn 4+ red phosphor powder enabled products. These products consists of red phosphor and blue green phosphor powders combined with blue chips and are touted to reach 100% NTSC, and SRGB will also surpass 100%. General Electric possesses a Mn 4+ red phosphor patent, which they have authorized Nichia and Sharp to use.

MARKET DRIVERS
Displays
• Growth of the displays market in consumer electronics.
• QDs offer increased colour gamut, colour accuracy and power efficiency. Currently, LCDs can only reproduce about one third of the range of colours our eyes can detect.

Energy
• Improving solar conversion efficiencies. Demand for solar power is rising rapidly.
• Flexibility.
• 22% world electricity 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 color and use of mercury.
• Over 1/3 of the electricity for lighting could realistically be saved utilizing Solid-State Lighting (SSL): nearly 900 billion kWh (OSRAM).

Medical
• The need for automated and easy-to-handle techniques, which combine optimized sample preparation, analysis, and data evaluation
• The growing availability of molecular diagnostic tests for monitoring the therapeutic efficacy of expensive drugs
• The need for swift diagnoses techniques that diagnose disease condition and medical disorders quickly and offer a strong and consistent tool for quick therapy decisions.
• Current optical imaging markers have a short life. QDs are more resistant (can be up to 100 times) to photo chemical degradation than fluorescent dyes.
• Improving solubility, enhancing product effectiveness and exclusivity in the face of generic competition, active drug targeting, patient compliance, cost effectiveness (the cost of producing a new drug can be upwards of $800 million) and product life extension.

Security
• 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.

Sensors
• Up to 300-fold improvement in LF test strip sensitivity demonstrated.
• Unique and tunable photoluminescence, and physicochemical properties.

Regulations
• Driver for Cadmium-Free Quantum Dots is Regulation on Hazardous Substance RoHS Directive 2002/95/EC that restricts the use of Cd in EEE. However, the European Union has offered a temporary exemption for the use of cadmium-based Quantum Dots for display applications.
• In the European Union (EU), Cadmium-based QD materials are subject to the RoHS (Regulation on Hazardous Substances) Act and REACH. Sony TV’s Cadmium containment in their Triluminos TV range is compliant to RoHS, but recycling and disposal process is still a potential issue and has impacted its acceptance in U.S. and EU.
• Market restrictions are greater for cadmium-based products in Europe and Japan than in the United States.

Market Restraints
• The largest market challenges for QD technology are the use of cadmium, and its restriction on the level of it use on consumer electronics products in certain markets, and scalability for mass production. Dow and Nanoco claim to have solved these issues via their cadmium free QD technology. Current performance of cadmium free quantum achieve 95% to 96% of the Digital Cinema Initiative standard for TVs.
• High cost at present. Prices range from $3,000-$10,000 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.
• Low price of competing technologies. QD-enhanced TVs will be relatively high cost in comparison to existing technologies.

• 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. Companies are currently making relatively small quantities of QDs, not enough to meet market demands. However, production will increase considerably in 2014.

Regional Markets
The United States, Europe and Korea are the main current markets for QDs and products thereof at present. Japan, Taiwan and China are also significant markets. Main regional markets in displays and solid-state lighting are:

TVs and displays
1. North America (33-37%)
2. Europe (27-30%)
3. Asia-Pacific (20-24%)
4. Latin America (5-8%)
5. Rest of the world (2-3%).

Solid-State Lighting
1. Asia-Pacific (45-50%)
2. North America (23-25%)
3. Europe (19-22%)
4. Rest of the world (5-7%).

**TRENDS**

- There is a strong pull from the market and customers to introduce QD based high colour gamut LCD displays, as consumers seek improved visual experiences. A modified-LCD Triluminous TV is currently commercially available from Sony which utilizes QD Vision’s cadmium-based QD down converting technology.
- Most large consumer electronics companies are confident QD TVs will hit the mass market in the next 12-18 months. Some sources anticipate penetration of 20-50% in the LCD market in the next 3-5 years.
- The use of QDs in LCD displays is likely to grow significantly in smartphones (15-25% growth) and will likely outstrip TVs in terms of growth. Use in tablets will also increase greatly in the next five years (15-20% growth). Due to the size of these screens, the amount of QDs used is considerably smaller than TV displays. The Kindle Fire HDX 7 was first ever mobile device to feature a quantum-dot-enhanced display, produced by 3M in collaboration with Nanosys, Inc. Due to the size of these screens, the amount of QDs used is considerably smaller than TV displays.
- In solid-state lighting, while there is considerable commercial development, there are unlikely to be any product launches until 2015-2016.
- Main current market for QDs are (in order of market size):
  1. Display additives
  2. Diagnostics
  3. Academic & research
  4. Solid-state lighting
  5. Other biomedical applications (Drug delivery, biosensors)
  6. Other energy applications (Solar, batteries, thermoelectrics)
  7. Sensors
### Table 1: Quantum dot industry collaborations, partnerships and licence agreements

<table>
<thead>
<tr>
<th>QD Company</th>
<th>Partner/Collaborator/Licensee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evident</td>
<td>• LED patent agreement with Samsung</td>
</tr>
</tbody>
</table>
| Nanoco            | • Partnership with Dow Electronic Materials for development of Cadmium-free Quantum Dots in consumer electronics  
                     • LG Electronics  
                     • Tokyo Electron on developing products for solar  
                     • Osram for lighting applications.                                                                                                                   |
| Nanophotonica     | Five leading smartphone display-screen makers are conducting pilot programs using NanoPhotonica’s lighting technology.                                       |
| Nanosys, Inc.     | • LG Innotek  
                     • Samsung Electronics                                                                                                                                   |
| QD Vision         | • Nexxus  
                     • LG Display  
                     • Sony                                                                                                                                                    |
| Qlight Nanotech   | • Merck                                                                                                                                                     |
| StoreDot          | • Samsung                                                                                                                                                   |

### Table 2: Market summary for quantum dots

| Selling grade particle diameter | • Typical dimensions: 1 – 10 nm, usually on the order of 3-7nm in size.  
|                                | • Can be as large as several μm.  
|                                | • Different shapes (cubes, spheres, pyramids, etc.)                                                                                                         |
| Usage                         | • Quantum dots are included into an LCD by incorporating a small amount of quantum dots (typically 3-5ug/cm²) into a polymeric film that is inserted into the back light unit (BLU).  
|                                | • In biomedicine, a water-phase method is used for dispersion in a solution.                                                                                     |
| Advantages                    | • Size-tuneable bandgap/fluorescence  
|                                | • Narrow & bright emission  
|                                | • Broadband & efficient absorption  
|                                | • Low-cost/scalable synthesis  
|                                | • Solution processible  
|                                | • High quality: Low polydispersity & single-crystalline.                                                                                                           |
| Market challenges             | • Performance in high-temperature environments.                                                                                                                  |
|                                | • Prohibitions against Cadmium in some regulatory environments.                                                                                                     |
|                                | • Price.                                                                                                                                                        |
|                                | • Scalability.                                                                                                                                                   |
| Average price/kg              | • $3,000-$10,000 depending on the grade.                                                                                                                        |
Table 2: Market summary for quantum dots

<table>
<thead>
<tr>
<th>Market estimates</th>
<th>BCC Research</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$67 million in 2010</td>
</tr>
<tr>
<td>Markets and Markets</td>
<td>$108.41 million in 2013 to $3,414.54 million in 2020.</td>
</tr>
<tr>
<td>IndustryARC</td>
<td>$2.85bn in 2013 to around $2.85bn by 2018.</td>
</tr>
</tbody>
</table>

Future markets estimates based on interviews:
- 2014 market for QDs: $24.85 million (conservative estimate) to $47.95 million (optimistic)
- 2020: $146 million (conservative estimate), $360 million (optimistic)
- 2024: $563 million (conservative estimate), $1595 million (optimistic)

<table>
<thead>
<tr>
<th>Main applications</th>
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</thead>
<tbody>
<tr>
<td>• LEDs.</td>
</tr>
<tr>
<td>• Solar cells.</td>
</tr>
<tr>
<td>• Solid-state lighting.</td>
</tr>
<tr>
<td>• Bioindicators.</td>
</tr>
<tr>
<td>• Lateral flow assays.</td>
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<tr>
<td>• DNA/gene identification, gene chips.</td>
</tr>
<tr>
<td>• Cancer diagnostics.</td>
</tr>
<tr>
<td>• Biological Labeling Agent.</td>
</tr>
<tr>
<td>• Sensors.</td>
</tr>
<tr>
<td>• Anti-counterfeiting.</td>
</tr>
<tr>
<td>• Battery additives.</td>
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</tbody>
</table>
The report covers the main quantum dots suppliers and product developers. The market is forecasted from 2013 through to 2024, in terms of revenues. Revenues are based on current quantum dot company incomes and future penetration and growth estimates. End user markets and applications are also outlined and forecast. The following methodology was utilized:

1. Identification of companies in the quantum dots sector and companies developing products thereof. This was mainly be accrued from Future Markets, Inc. existing information database and proprietary information on nanomaterials companies. This was also supplemented with a search of the literature on companies producing relevant nanomaterials. 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.

2. A series of interviews was conducted via email with relevant quantum dots company representatives to gauge production volumes and end users markets sold to.

3. Market estimates and industrial intelligence based on information accrued from nanomaterials company representatives, Future Markets, Inc.'s in-house data and market reports.
Quantum dots (QD) were first characterized in 1983 by Brus as small semiconductor spheres in a colloidal suspension. 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. 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).

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 photoluminescent 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. 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.

Since the aforementioned directed QD synthesis over 30 years ago, QDs have featured in a range of optoelectronic devices, including light-emitting devices (LEDs), solar cells, photodiodes, thermoelectrics, photoconductors and field-effect transistors, while QD solutions have been used in a number of in vivo and in vitro imaging, sensing and labelling techniques.

**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. Cadmium free quantum dots are produced by Nanoco. 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 color gamut sizes from 70% NTSC to 100% NTSC).

Graphene QDs are promising materials as substitutes for Cd, Ir, Ga, S, Se and P quantum dots. Properties include excellent quantum yield and potentially sharp emission wavelength.

**PRODUCTION METHODS**

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

| Table 3: Comparison of graphene QDs and semiconductor QDs (KRI, Inc.) |
|-----------------|-----------------|---------------|-------------|---|
| **Types**       | **Optical properties** | **Stability** | **Toxicity** | **Cost** |
|                 | **Quantum yield** | **Emission** | **Half-height** |               |
| Graphene QDs    | 90+ %            | 380-570nm     | >40nm (ca. 70nm) | Yes           | No | Low    |
| Semiconductor QDs | CdSe 10-25% | 480-640nm     | 40nm>          | No            | Yes | High   |
| ZnSe/CdSe       | 30-50%           |               |               |               |     |        |
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 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 have solved these issues. They are confident the technology will be commercially adopted in the near future and will be widely accepted as a breakthrough for the LCD display industry.

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 4: Chemical synthesis of quantum dots

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Organic phase method</strong></td>
<td></td>
</tr>
</tbody>
</table>
| 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.  
• 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. |
Applications

Main applications for quantum dots are in biomedicine, solid-state lighting and consumer electronics (Televisions and other display applications). Other applications at varying stage of development include photovoltaics, laser applications, fluorescent probes, memory devices, photodetectors, and multiplexing sensors. Main current market for QDs are (in order of market size):

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

High volume applications
- Additives in displays
- Infrared imaging
- QD-lasers

Low volume applications
- Security tags.

Novel applications
- Quantum switches
- Quantum computing.

- Quantum dot lighting
- Photovoltaics
- Contrast agents
- Drug delivery
- Biosensors
- Fluorescent reporters
- Photoelectrochemical sensors
- Biosensors
- Image sensors.
## Table 5: Main quantum dots applications

<table>
<thead>
<tr>
<th>Market</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displays</td>
<td>• Active and white LCD-backlighting additives</td>
</tr>
<tr>
<td>Energy</td>
<td>• Dye-sensitised solar cells films.</td>
</tr>
<tr>
<td></td>
<td>• Thermoelectric superlattices.</td>
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<tr>
<td></td>
<td>• Battery additives for mobile electronics.</td>
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<tr>
<td>Security</td>
<td>• Anti-counterfeiting inks.</td>
</tr>
<tr>
<td>Medicine</td>
<td>• Drug carriers.</td>
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<td>• Drug taggants.</td>
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<td></td>
<td>• Bimodal molecular imaging.</td>
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<td></td>
<td>• Detecting Cell Death.</td>
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<td></td>
<td>• In-vivo imaging.</td>
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<td></td>
<td>• Tumor Cell Markers.</td>
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<td></td>
<td>• Immunoassays.</td>
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<td></td>
<td>• Pathogen and toxin detection.</td>
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<td></td>
<td>• Gene Therapy.</td>
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<tr>
<td></td>
<td>• Contrast agents.</td>
</tr>
<tr>
<td></td>
<td>• Fluorescent probes for imaging.</td>
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</tbody>
</table>
Regulations

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. 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. The exemption has been extended until 2017 and only applies to QDs for display applications (http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/20140422_RoHS2_Evaluation_Ex_Requests_2013-1-5_final.pdf). The QD film in an LCD application contains up to 20 μg of Cadmium per cm² of screen area, which is contained within a physical device. Therefore disposal, according to some companies, 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.

In the US Cadmium-based QDs are regulation under the EPA Toxic Substances Control Act.

Safety

The main shortcoming of QDs is their toxicity. Cadmium has a toxicity (LD50) of 100 – 300 mg/kg (rats and mice, oral). Therefore it 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 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.
Revenues

Global production
Revenues for quantum dots are based on estimated current income from quantum dot producers and product developers. Current revenues are between $24.85 million (conservative estimate) and $49.95 million (optimistic estimate). Most of the main quantum dot players will witness growth in the next few years, especially in consumer electronics and solid-state lighting applications. Some market estimates put compound annual growth rate CAGR at over 50%, however a conservative estimate of 29.7%, mainly driven by the demand from the aforementioned sectors represents a $500 million plus market by 2024. In an optimistic scenario, CAGR is around 34%.

Regional markets
The United States, Europe and Korea are the main current markets for QDs and products thereof at present. Japan, Taiwan and China are also significant markets. Main regional markets in displays and solid-state lighting are:
TVs and displays
1. North America (33-37%)
2. Europe (27-30%)
3. Asia-Pacific (20-24%)
4. Latin America (5-8%)
5. Rest of the world (2-3%).
Solid-State Lighting
1. Asia-Pacific (45-50%)
2. North America (23-25%)
3. Europe (19-22%)
4. Rest of the world (5-7%).

Prices
Prices range from $3,000-$10,000 kg. However mass production is predicted to drive prices down to >$500 kg and a number of companies have announced mass production techniques in the last 18 months:
• Nanoco: 400 kg/year.
• Quantum Materials Corp.: 250 kg/year.
• Nanosys, Inc: 1,000 kg/month.

Table 6: Quantum dots revenues estimates, conservative and optimistic, 2013-2024

<table>
<thead>
<tr>
<th>Year</th>
<th>US Dollars (Conservative)</th>
<th>US Dollars (Optimistic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>24,850,000</td>
<td>47,950,000</td>
</tr>
<tr>
<td>2014</td>
<td>28,577,500</td>
<td>57,540,000</td>
</tr>
<tr>
<td>2015</td>
<td>32,864,125</td>
<td>69,048,000</td>
</tr>
<tr>
<td>2016</td>
<td>41,080,156</td>
<td>95,286,240</td>
</tr>
<tr>
<td>2017</td>
<td>55,458,211</td>
<td>131,495,011</td>
</tr>
<tr>
<td>2018</td>
<td>74,868,585</td>
<td>184,093,016</td>
</tr>
<tr>
<td>2019</td>
<td>104,816,019</td>
<td>257,730,222</td>
</tr>
<tr>
<td>2020</td>
<td>146,742,426</td>
<td>360,822,311</td>
</tr>
<tr>
<td>2021</td>
<td>205,439,397</td>
<td>523,192,351</td>
</tr>
<tr>
<td>2022</td>
<td>287,615,155</td>
<td>758,628,908</td>
</tr>
<tr>
<td>2023</td>
<td>402,661,217</td>
<td>1,100,011,917</td>
</tr>
<tr>
<td>2024</td>
<td>563,725,704</td>
<td>1,595,017,280</td>
</tr>
</tbody>
</table>
Electronics

Quantum dots (QD) are already incorporated into consumer electronics products including the Amazon Kindle HDX and other Sony Xperia devices. Most major companies are developing QD technology that can achieve a significantly larger range of colours (60% - 100% improvement) over LCD displays as well as using significantly less energy. Mass produced displays incorporating QDs are set to hit the market in 2014/2015. Modified LCD-TVs from Sony (using QD Vision’s QDs) have been commercially available since 2013.

Market drivers
As well as enabling novel approaches to display designs, nanomaterials are also incorporated into display components, such as transparent electrodes, thin film transistors and coatings, sensors, transparent conductors, and infrared and visible photodetectors. Multi-national companies Toshiba, Motorola, Hitachi and Samsung are all developing nanomaterial-based display technologies utilizing a variety of nanomaterials including graphene, carbon nanotubes, silver nanowires and quantum dots (QD).

Liquid Crystal Displays
Traditional Liquid Crystal Displays (LCD) offer only a fraction of the colours that are visible to the human eye. In the current display market LCDs are both inefficient and do not produce the vibrant colors of organic light-emitting diodes (OLEDs).

Organic light-emitting diodes (OLEDs) are thinner, have a clearer picture and utilize significantly less power. However, they also suffer from a number of drawbacks. QD films used in displays are regarded as superior to both technologies (although QDs are easily integrated into the existing LCD displays). QD films 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. They 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, LCDs are relatively inexpensive to produce in large screen sizes, and consumers will generally choose the right price over the right colour. The traditional LCD market is mature and very competitive, with revenues falling after high capital spending. Therefore the incorporation of QD films into devices is of increasing importance. QD films are also easily integrated into existing LCD supply chain, with white LEDs replaced by blue LEDs.

Organic light-emitting diodes (OLEDs)
A number of OLED manufacturers have stated that larger size OLEDs can be built that will provide a comparable colour gamut to quantum dot films, but the energy consumption of an OLED display is significantly higher than quantum dot film LEDs (as high as three times that of a cadmium-based QD LCD). It has been demonstrated that the cadmium generated in waste from the additional electricity generation required to operate OLEDs far exceeds the amount of cadmium
present in an equivalent quantum dot film. A number of companies claim OLEDs cannot currently be made in acceptable yields except in small sizes and cannot be made in larger sizes in sufficient quantities to meet a fraction of the current world wide display needs due to limited capacity. Main current applications are in smartphones, tablets, digital cameras, electric razors, car stereos and monitors. OLEDs have been consistently facing mass production issues for applications on large-size displays and is expected to have high production costs for at least a few more years. Yields and capital spending requirements will keep costs high. The aforementioned technical issues will also limit the ability to bring OLED costs down, limiting the technology to niche/high end applications. However, the technology is improving with energy usage likely to reduce significantly in the next few years. In terms of the scale of the displays, 55” panels are currently available in Asia, the UK and US. Although many feel they are only likely to be of significance for Suitable for thin, lightweight, small displays, according to industry sources, TVs will represent 17% of the OLED market by 2014. A leading OLED manufacturer plans to commercialise a 60” flexible, ultrahigh definition TV by 2017.

Due to drawbacks with the aforementioned technologies, display developers have been seeking alternative solutions to providing high contrast and more energy-efficient products to their TV and possibly even tablet, smartphone and notebook customers, which has lead to the development of QD displays. QDs are able to meet both the performance and lifetime requirements for LCD applications.

Table 7: Approaches for integrating QDs into displays

<table>
<thead>
<tr>
<th>QD Integration</th>
<th>ON-CHIP</th>
<th>ON-EDGE</th>
<th>ON-SURFACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>QDs placed directly within LED package (directly on the blue LED dye), which is coupled to light guide.</td>
<td>QDs placed between LED package and light guide.</td>
<td>QDs placed in thin film on top of the light guide plate, covering entire display surface.</td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>High (~150°C)</td>
<td>Moderate (between that of on-surface and on-chip).</td>
<td>Near room temperature (Resulting in Improved system lifetime).</td>
</tr>
<tr>
<td>QDs usage</td>
<td>Low (Small surface area). In the single pass configuration a higher concentration of quantum dots are required.</td>
<td>Moderate (Medium surface area). In the single pass configuration a higher concentration of QDs are also required.</td>
<td>High (Largest surface area). Significantly lower concentration of quantum dots needed due to multiple light reflection.</td>
</tr>
<tr>
<td>Pros &amp; cons</td>
<td>• 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.</td>
<td>• 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.</td>
<td>• Ease of mass production • Lower optical flux and heat • Easy to incorporate into an existing device same assembly</td>
</tr>
</tbody>
</table>
**QD-LEDs**

Current applications of QD luminescence harness the optically induced emission (photoluminescence) of colloidal QDs for use in the backlighting of liquid-crystal displays. 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 process
- and compatibility with flexible substrates.

QD films are already incorporated in products such as TVs, monitors, tablets, notebooks and smartphones. According to Nanoco the proportion of quantum dots used in current LCD displays is:

- TVs: 2% of a Global Annual LCD Area (m²) of 157,333,925
- Monitors: 3% of a Global Annual LCD Area (m²) of 29,365,561
- Notebook/Ultrabooks: 7% of a Global Annual LCD Area (m²) of 22,819,763
- Tablets: 60% of a Global Annual LCD Area (m²) of 12,174,293
- Small displays (e.g. smartphone): 20% of a Global Annual LCD Area (m²) of 12,000,660.

The lifetimes of QD-LEDs (mainly type IV) at present operated at initial video brightness (100 cd m²) are of the order of 100–1,000 hours (>10,000 hours is required for displays). They turn on instantly, and can be tuned to produce any shade of white light (or any colour). The lifetimes of state-of-the-art OLEDs are in the range of 103–106 hours. QD Vision has reported a QD-LED with a half-life of >10,000 hours when operated at an initial brightness of 100 cd m². Advantages of QLEDs over OLEDs include:

- Power consumption: more energy efficient than OLEDs (> 2 times) at the same colour purity.
- Brightness: 30 - 40% luminance (brightness) efficiency advantage at the same colour quality.
- Cost: ability to print large-area of QLEDs on ultra-thin flexible substrates, which will reduce manufacturing costs.

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 re-
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 color 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 and they are planning on rolling out Cd-free QDs for application in LCD displays in the next 12 months. They signed a licence agreement in 2013 and small-scale manufacture is currently undertaken in the UK and large scale manufacture is scheduled to be online by mid-2014, with Dow building a $400 million plant in Asia. 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).

PRODUCT INTEGRATION
There are three methods to integrate quantum dots into conventional LCD BLUs:
• on-chip;
• on-edge;
• and on-surface.

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 quantum dots 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 color filters in the panel.

The concentration of quantum dots, and therefore, the concentration of cadmium in QD film depend on these factors and the total thickness of the film. However, no more than 20 μg of cadmium/cm² of screen area should be used for any application. Typically, only 3 – 5 μg of cadmium/cm² of screen area would be used.

COMMERCIALIZATION
The commercialization of QD-LEDs is expanding to high-volume applications. There are a large number of start-up companies and major corporations developing colloidal QD-enhanced LCD displays such as QD Vision,
Nanosys, LG Innotek, Samsung, Philips Lumileds Lighting Company and Avago. Most of these are based on CdSe/ZnS quantum dots. In January 2013, Dow Electronic Materials entered into a global licensing agreement with Nanoco to manufacture, market and sell CFQD™ cadmium-free quantum dots. A pilot launch of the first TVs using CFQD™ cadmium-free quantum dots is planned for the first half of 2014, with full commercial production expected within the following 12 months.

MANUFACTURING
The synthesis of colloidal QDs is scalable, with the key technical challenge being 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 benefited 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. The growth of OLED markets demonstrates that these materials costs should not be prohibitive to the commercialization of QD-LEDs.

PRODUCT DEVELOPERS
3M
www.3m.com
The company has an agreement with Nanosys to produce QD films for displays. They have produced quantum dot enhancement film (http://solutions.3m.com/3MContentRetrievalAPI/BlobServlet?lmd=1383547134000&locale=en_US&assetType=MMM_Image&assetId=1361748701374&blobAttribute=ImageFile). The Asus Zenbook NX500 laptop has a 4K UHD 3M Quantum Dot Enhancement Film (QDEF) touchscreen display. Asus claims that not only does this increase resolution, but it enables an ultra-wide colour gamut of 100 per cent NTSC, 108 per cent Adobe RGB and 146 per cent sRGB.

LG DISPLAY
www.lgdisplay.com
The company has agreements with QD Vision and Nanosys to develop QD displays. They are expected to bring a QD-TV to market within the next 12 months.

NANCO GROUP PLC
www.nanocotechnologies.com
The company has an agreement with Dow Chemical for cadmium-free quantum dots in LCD displays. They have agreements with a number of other OEMs in a variety of industries.

Figure 4: The light-blue curve represents a typical spectrum from a conventional white-LED LCD TV. With quantum dots, the spectrum is tunable to any colors of red, green, and blue, and each color is limited to a narrow band. (Courtesy SMPTE and QD Vision)
markets. The company CFQD® quantum dot technology is expected in TVs in 2014 and in solid-state lighting applications in 2015.

NANOSYS, INC.
www.nanosysinc.com
QDEF™ and QuantumRail™ are composed of Nanosys’ proprietary, high efficiency quantum dot phosphors. Currently, Nanosys is focused on commercializing its quantum dot and silicon composite anode materials for the LED LCD and lithium ion battery industries and has agreements with a number of display manufacturers.

QD VISION
www.qdvision.com
The company’s Quantum Light™ product platform was used in Sony’s 2013 Triluminos TVs. The 2014 version no longer uses the company’s QDs.

SAMSUNG
www.samsung.com
The company has a number of agreements with QD manufacturers. It is anticipated that they will bring out a QD-TV in late 2014, early 2015.

SONY
www.sony.com
The company’s 2013 range of Triluminos TVs incorporate QD Vision’s quantum dots. According to industry sources, the product’s high cost and use of Cadmium (Cd) impacted the product’s acceptance in the European and U.S. market.

INDUSTRY DEVELOPMENTS 2013-2014
January 2013
Sony demonstrates QD Vision’s quantum dots in its high-end Bravia television at the Consumer Electronics

Table 8: Quantum dots in displays: Product developers and market size

<table>
<thead>
<tr>
<th>Intermediate developers</th>
<th>Product developers</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Evident Technologies</td>
<td>• LG Display</td>
</tr>
<tr>
<td>• Nanoco</td>
<td>• Samsung</td>
</tr>
<tr>
<td>• Nanosys, Inc.</td>
<td>• Samsung</td>
</tr>
<tr>
<td>• N-N Labs</td>
<td>• Sony</td>
</tr>
<tr>
<td>• Quantum Materials Corp</td>
<td></td>
</tr>
<tr>
<td>• QD Vision.</td>
<td></td>
</tr>
</tbody>
</table>

Target markets size according to industry estimates

- Consumer Electronics Association (CEA)
  Revenues for the consumer electronics (CE) industry are projected to reach a record-high of $209.6 billion in 2013

- University of Sheffield
  Global electronics coatings and films market, in 2010 is estimated to be $3 billion.

- Engineer live
  The electronic displays market, in 2010 is estimated to be $100 billion. Touchscreens account for approximately 13% of this total.

- Lux Research
  • Current market is $100 billion plus.
  • OLED market of nearly $11 billion in 2017.
Show.

January 2013
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

April 2013
QD Vision reports achieving 18 percent External Quantum Efficiency, which puts QLEDs near the fundamental efficiency limit of the technology.

April 2013
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 3M\textsuperscript{TM} Quantum Dot Enhancement Film (QDEF).

June 2014
Quantum Materials Corp. announces producing 250 kilograms of quantum dots per annum.

June 2014
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 IQ\textsuperscript{TM} optics and ShineOn’s LED backlight solution.

June 2014
Nanosys, Inc. announces LMS Co., Ltd. as the second major supplier of optical films based on its proprietary Quantum Dot Enhancement Film (QDEF) light emitting technology. LMS, based in South Korea and one of the world’s leading producers of optical films for displays, has been qualified by Nanosys to utilize QDEF technology for its Quantum Light Accumulation Sheet (QLAS).

Figure 5: QDEF integration into a standard LCD display.
Energy

Application 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.

MARKET POTENTIAL

MARKET POTENTIAL

SOLAR

Market drivers

Demand for solar power is rising rapidly. According to IHS, Inc., global solar photovoltaic (PV) market-installations are approximately 46 GW in 2014 with annual double digit growth expected over the next five years. US, Asian and German 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, with a wide range of innovative and promising materials and designs. 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 nanoparticles and carbon nanotubes are at the forefront of new photovoltaics applications via low cost, low temperature fabrication. With improvements in efficiency and lifetime, nanomaterials will potentially provide improved photovoltaic devices at a price substantially lower than that offered by 1st and 2nd generation technologies, opening up new markets for solar.

Quantum dots in photovoltaics

Steady progress has been made in laboratory efficiencies for devices based on CdS/CdTe, Cu (In,Ga) Se2 (CIGS), and amorphous Si nanoparticles. The most commonly used and investigated QD-sensitized solar cells (QDSSCs) is 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.

Figure 6: Schematic of QD Solar Cell (Image: 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 ef-
ficiency, 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%. The solar-power conversion efficiencies of colloidal quantum dot solar cells have advanced from sub-1% reported in 2005 to a record value of over 9% in 2014. There are a number of companies developing quantum dot based solar cell technologies.

INDUSTRY DEVELOPMENTS 2013-2014

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). (http://www.nature.com/nphoton/journal/v8/n5/full/nphoton.2014.54.html).

May 2014
Researchers at MIT set a new record for the most efficient quantum-dot cells, with 9% efficiency (http://www.nature.com/nmat/journal/vaop/ncurrent/full/nmat3984.html).

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 (www.nature.com/nmat/journal/vaop/ncurrent/full/nmat4007.html).

Figure 7: Doped quantum dot LSC developed by Nova Solar Technologies

PRODUCT DEVELOPERS

DUPONT
Produces Innovalight™ Silicon inks incorporating QDs for improving PV module performance. The company acquired the technology from Innovalight.

KOPIN CORPORATION
www.kopin.com
The company has developed Indium Nitride-Based
Quantum-Dot Solar Cells.

**KRI, INC.**  
www.kri-inc.jp  
The company design and fabricate silicon quantum dots solar cells. They are also developing graphene quantum dots.

**NANOCO TECHNOLOGIES**  
www.nanocotechnologies.com  
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**  
www.natcoresolar.com  
The company fabricates multilayer quantum dot films for solar cells in collaboration with Rice University.

**NOVA SOLAR TECHNOLOGIES**  
www.novasolartech.com  
The company is developing QD films for solar power window panels. The transparent luminescent solar concentrators are based on doped QDs. A luminescent solar concentrator (LSC) is a device that contains a thin sheet of material (usually a polymer such as polymethylmethacrylate (PMMA), doped with luminescent species such as organic dyes, quantum dots or rare-earth complexes) that absorbs sunlight over a large area. The sheet then re-emits the absorbed light (at a different wavelength) and directs it to photovoltaic cells mounted on the edges of the material layer. These cells convert the directed light into electricity (http://pubs.acs.org/doi/abs/10.1021/nn406360w).

**OCEAN NANOTECH**  
http://oceannanotech.com  
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.

**SOLterra RENEWABLE TECHNOLOGIES, INC.**  
www.solterrasolarcells.com  
The company focuses on the use of tetrapod quantum dots to produce solar cells. Quantum Materials is their parent company.

**SOLID-STATE LIGHTING**  
Market drivers  
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 (Department of Energy: SSL MYPP report 2013). Therefore from an environmental and economic perspective, the benefits of developing low-cost, environmentally friendly QDs are apparent. The industry is seeking to develop energy efficient lighting with a high quality colour spectrum.

The DOE plan to develop, by 2025, 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.

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). However, 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. SSL is currently based on blue light-emitting diodes combined with wavelength down conversion via phosphors. Current red phosphors do not satisfy all of the criteria for SSL, which is why QDs are under commercial development in this sector. Red
phosphors suffer from severe efficiency loss as the temperature increases. QDs have numerous long-term and fundamental advantages over rare-earth phosphors, including:

- a broad and a five-orders-of-magnitude-greater blue absorbance;
- a 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.

Quantum dots in solid-state lighting (SSL)
Red-emitting CdTe-based QD heterostructures meet several criteria for SSL performance including:

- Precise peak emission placement (~2 nm)
- Very narrow emission peaks (< 35 nm)
- Broad blue absorption
- 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 improved CRI: >90 easily obtained
- Fewer LEDs required in a luminaire
- 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°C. QD Vision and Nexxus Lighting announced in 2010 the first commercially available QLED light bulb with a 60-lm/W white-light output.

INDUSTRY DEVELOPMENTS 2013-2014
April 2013
Philips 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). Quantum Materials plans to integrate the LANL thick-shell technology into the company’s quantum dot product line.

PRODUCT DEVELOPERS
NNCRYSTAL US CORP.
www.nncrystal.com
NNCrystal is the owner of two patented and trade-marked technology platforms for solid-state lighting applications-Qshift Lucid and Qshift Coral.

PACIFIC LIGHT TECHNOLOGIES
www.pacificlighttech.com
The company produces quantum dot down converters for solid-state lighting.

PHILIPS
www.phillips.com
Philips, a leader in the lighting industry, is already exploring QDs for downlighting solutions and would definitely like to explore commercial QD manufacturing techniques.

QD VISION, INC.
www.qdvision.com
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 Light-
ing backlights in high-colour-quality white LED SSL.

QUANTUM MATERIALS CORPORATION
www.qmcdots.com
The company produces QDs for white light solid-state lighting (SSL) applications.

REVOLUTION LIGHTING TECHNOLOGIES
www.rvlti.com
The company produces Array™ Quantum LED R30 replacement light bulbs.

BATTERIES
Properties
Nanosys and StoreDot are two companies 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.

PRODUCT DEVELOPERS
NANOSYS INC.
www.nanosysinc.com
The company is developing battery storage additives based on quantum dots.

STOREDOT
www.store-dot.com
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. The company has received over $16 million in investment 2013-2014.

THERMOELECTRICS
Properties
The efficiency of the energy conversion devices depends in many ways on the materials used and various emerging cost-effective nanomaterials have promised huge potentials in highly efficient energy conversion. Due to QDs delta-like density of states, they exhibit high Seebeck coefficient, nearly zero electronic thermal conductance and ultra-low phononic thermal conductance if embedded in an oxide matrix. PbSeTe-based Quantum Dot (QD) superlattices have been shown to exhibit thermoelectric figure of merit ZT as high as 1.6 (Harman T C, Taylor P J, Walsh M P, and LaForge B E 2002 Science 297 2229-2232).

PRODUCT DEVELOPERS
EVIDENT TECHNOLOGIES
www.evidenttech.com
Produces quantum dots for various markets including life sciences, solid-state lighting, energy, security, telecommunications and emergent nanotechnology markets. They are also exploring applications in thermoelectrics.

Table 9: Quantum dots in Energy-Product developers and market size

| Intermediate developers | • Evident Technologies  
| | • Nanosys Inc.  
| | • Pacific Light Technologies  
| | • StoreDot  
| | • Quantum Materials Corporation  
| | • QD Vision, Inc.  
| | • Kopin Corporation  
| | • KRI, Inc.  
| | • Nanoco Technologies Ltd  
| | • Natcore Technology  
| | • Nova Solar Technologies  
| | • Ocean NanoTech  
| | • Solterra Renewable Technologies, Inc.  


| Product developers                          | • Dupont           |
|                                           | • Phillips          |
|                                           | • Revolution Lighting Technologies |
|                                           | • Sharp Corporation |
| Target markets size                       | Markets and Markets |
| according to industry estimates            | Global solar energy market will grow from $39.6 billion in 2011 to $75.2 billion in 2016 |
|                                           | SEMI                |
|                                           | Global lighting industry worth $4 billion in 2010. |
|                                           | Phillips            |
|                                           | By 2015 LEDs will account for 45% of a lighting market expected to be worth between €75 billion and €80 billion (excluding automotive lighting). |
Biomedicine

Increased interest in diagnosis and therapies of diseases have been a driving force for the utilization of QDs for in vivo and in vitro diagnostic methods as well as imaging techniques. Quantum dots are exploited for 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.

APPLICATIONS AND ESTIMATED TIME TO MARKET
- Diagnostics-Biological screening and imaging (Commercialized)
- DNA Labeling (5 years+)
- Drug delivery systems for cancer (3-7 years+)

MARKET POTENTIAL

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.

DIAGNOSTICS
Market drivers
The development of fast, portable point-of-care diagnostics will address the diagnostic problems that many doctors and hospitals are facing today. Rather than taking multiple blood samples, sending them to test labs and then waiting for the results, point-of-care diagnostic devices are decentralized diagnostic tools that allow doctors a fast and often multiparametric analysis. Such devices would be especially valuable for the quick detection of various infectious diseases. The molecular diagnostics market is driven by:
- the need for automated and easy-to-handle techniques, which combine optimized sample preparation, analysis, and data evaluation
- the growing availability of molecular diagnostic tests for monitoring the therapeutic efficacy of expensive drugs
- the need for fast diagnoses techniques that diagnose disease condition and medical disorders quickly and offer a strong and consistent tool for quick therapy decisions.

Medical imaging reagents allow clinicians and healthcare providers to determine whether a tumor 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.

Nanomaterials
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 intra-
cellular drug and gene delivery. When combined with microfluidics and confocal fluorescence spectroscopy, the detection limit is further enhanced to single molecule level.

Quantum dots in diagnostics
The drawback for current optical imaging markers is their short life. Companies are now developing QDs to supplant these markers. Quantum dots have been developed for in vivo imaging at all levels of magnification and have been used as contrast agents for a decade. Other applications include:

- high-resolution cellular imaging
- long-term in vivo observation of cell trafficking
- photodynamic therapy
- tumour targeting.

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 stable over time and multiple dyes are excited simultaneously.

QD labels are 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. The multiplexing potential of QDs can enable obtaining information on the location, abundance, and distribution of multiple proteins in living cells. It would also allow multicolor encoding of cells or beads and thus obtaining data on differential response of cell types to common stimuli. This multiplexing potential would be particularly significant for cancer diagnostics and research, where multiple cancer biomarkers can be simultaneously detected, which would help untangle the associated complex gene expression patterns.

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.

Widespread uptake is 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.

Advantages
QDs are more resistant (can be up to 100 times) to photodegradation 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.

However, poor intracellular delivery, stability, and toxicity of QDs in biological compartments have thus far hindered their use in cellular imaging.

DRUG DELIVERY
Market drivers
The pharmaceutical industry faces a number of technological and market challenges in the coming years including improving solubility, enhancing product effectiveness and exclusivity in the face of generic competition, active drug targeting, patient compliance, cost effectiveness (the cost of producing a new drug can be upwards of $800 million) and product life extension. To meet these challenges the industry has turned to nanomaterials.

Nanomaterials
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. The unique properties of nanomaterials when combined with special high loading and controlled release provide superior performance for drugs. Nanomaterials are being utilized for treating cancer, inflammatory disorders, infectious disease and cardiovascular disease as they help drugs reach diseased tissues and release their payload in a controlled way. Most drugs have primary targets within cells and tissues; ideally, these agents may be preferentially delivered to these sites of action within the cell. Selective subcellular delivery is likely to have greater therapeutic benefits, and this is where nanomaterials are useful due to their enhanced targeting and diffusion capability. Nanomaterials used in for drug delivery are mainly the following types:
• Nanoparticles, including inorganic, polymer-based and solid lipid nanoparticles
• Nanocrystals (quantum dots)
• Liposomes.

Quantum dots in drug delivery
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 applications.

PRODUCT DEVELOPERS
ANTIBODIES INCORPORATED
www.antibodiesinc.com
The company produces quantum-dot based anti-bodies.

ATTONUCLEI
www.attonuclei.com
The company offers flexible custom manufacturing services to produce high quality “functionlized custom quantum dots”. The use of quantum dots for biological imaging provides researchers and clinicians new and versatile approaches to a range of biomedical challenges.

CROMOZ INC.
www.cromoz.com
The company is developing two proprietary technologies: water-soluble carbon nanotubes and water-soluble fluorescent carbon quantum dots mainly for the biomedical market.

DIAGNANO
http://nanohc.com
DiagNano’s platform is based on a “non-stick” surface coating that allows quantum dots and other metal
nanoparticles to be used for biological applications, including in vitro diagnostics, without nonspecific binding and agglomeration. DiagNano can develop optically active quantum dots capable of imaging at the molecular level.

**EVIDENT TECHNOLOGIES**
www.evidenttech.com
EviTag are fluorescent markers used in life sciences imaging.

**HELCOS BIOSCIENCES CORPORATION**
www.helicosbio.com
True Single Molecule Sequencing (tSMS) technology enables rapid analysis of large quantities of genetic material by directly sequencing single molecules of deoxyribonucleic acid (DNA) or single DNA copies of ribonucleic acid (RNA) (cDNA) and its approach of direct sequencing of RNA. The company uses quantum dots as biomarkers.

**INVITROGEN CORPORATION**
www.invitrogen.com
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.

**LUMINEX CORPORATION**
www.luminexcorp.com
The company uses quantum dots as biomarkers.

**NANOAXIS**
www.nanoaxisllc.com
Produce axicad quantum for pharma and diagnostics applications.

**NANOCO GROUP PLC**
www.nanocogroup.com
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.

**OCEAN NANOTECH, LLC.**
www.oceananotech.com
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.**
www.QMCdots.com
The company develop tetrapod QDs for application 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 colors, 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.

**SELAH TECHNOLOGIES, LLC**
www.selahtechologies.com
Selah Dots™ are patent-pending photoluminescent carbon-based nanoparticles. Selah Tubes™ are enriched single-walled nanotubes with precisely engineered electronic properties.

**UNIBIOTEST CO., LTD.**
www.unibiotest.com
The company provides a series of water soluble CdSe/ZnS core/shell quantum dots.
| Intermediate developers | Antibodies Incorporated  
| Attonuclei  
| Cromoz Inc.  
| DiagNano  
| Evident Technologies  
| Helicos BioSciences Corporation  
| Invitrogen Corporation  
| Luminex Corporation  
| Nanoco Group plc  
| Quantum Materials Corp. |

| Target markets size according to industry estimates | Cientifica  
Global drug delivery market 2011: $33 billion.  
| FDA  
Oral drug delivery market 2010: $49 billion  
2017: $97 billion  
| BCC Research  
Drug delivery market 2011: $137.9 billion  
2016: $175.6 billion  
| HRI  
Medical diagnostics market 2012: $380 billion  
| LSI  
The global medical devices and diagnostics (MD&D) market was $345 billion in 2011.  
| Grand View Research  
Global market for molecular diagnostics is expected to reach USD $8,020.1 million by 2020. |
Security

Miniaturization of electronic and photonic devices is a demanding trend in current and future technologies including consumer products, military, biomedical, and space applications. Nanomaterials are being widely applied in the electronics and computing industry, primarily arising from the need to create smaller, faster microchips and memory devices, as well as offering improved performance for displays and sensors.

Market drivers
Counterfeiting is a major problem, causing the global economy billions of dollars per year, and affecting people in all walks of life as well as industry. 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. The worldwide counterfeit goods trade, excluding counterfeit money, is believed to be on the order of $1 trillion annually. 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.
Counterfeitors 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 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 be eventually be copied. The use of luminescent inks, has increased significantly in an attempt to prevent fraud and counterfeiting of materials and goods. Obvious applications of these inks include banknotes, branded goods, drug packaging and food security. Security inks can either show up overtly or be covert, with the latter driving the luminescence further from the visible spectral region into the ultraviolet (UV) and near infrared (NIR) regions.

Nanomaterials
Nanotechnology-enabled applications are leading to new non-reproducible technological features that will lead to preventing illegal copying of intellectual property and products. Methods utilizing nanomaterials such as nanotubes, quantum dots, nanofibers, and metal oxide nanoparticles are being employed.

MARKET POTENTIAL

MARKET POTENTIAL

APPLICATIONS AND ESTIMATED TIME TO MARKET
- Security printing (Commercialized)
- Bar coding (5-10 years)
in holograms, laser surface authentication, physically unclonable functionality, magnetic fingerprints and nanobarcodes and taggants. Advantages of utilizing nanomaterials in anti-counterfeiting 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.

Quantum dots in security and anti-counterfeiting

The novel optical properties of QDs make them ideal fluorophores for ultrasensitive, multicolor, and multiplexing applications in anti-fake label and security identification. 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.

They have been developed for use as photoluminescent 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 semi-conductors (http://nanotech-dubna.com/research-and-development/marking). By adjusting the particles size and concentration 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. CdSe/ZnS core-shell QDs exhibit stable and size-tunable fluorescence with a quantum yield up to 95%. By tailoring the QD size between 2-10nm, the luminescence emission is tunable over the entire visible and part of the near-infrared spectrum (450-700nm) with a very long lifetime (~10 years).

These features illustrate why QDs appealing printable inks for a variety of applications, including advertising posters, anti-counterfeiting labels, and security identification. Similar optical and stability properties in some cadmium-free nanocrystals, such as ZnCuInSe CQDs, have also been reported.

PRODUCT DEVELOPERS
NANOCO
www.nanocotechnologies.com

The company’s QDs have been utilized for anti-counterfeiting ID-tags (CD’s, packaging, fabric, documents currency, etc).

**NANOSYS**
www.nanosysinc.com
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.

**QDLIGHT**
www.qdlight.ru
The company produces QD fluorescent ink for intaglio printing. The product of the company is a nanocomposite mixture possessing unique optical properties. The fluorescence of the complex composition is observed when exposed with UV, violet, blue, green light. Distinctive feature of the mark is combination of the original colour of the mark itself and the fluorescence colour when exposed with UV or visible light source (including narrow- and broadband). Apart from visual control the fluorescent code can be read with a portable device.

**QD VISION**
www.qdvision.com
The company has received funding from the U.S. Department of Defense to develop QDs for military applications.

**QUANTUM MATERIALS CORPORATION**
www.qmcdots.com
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.

**VOXTEL**
http://voxtel-inc.com
The company develops QD security ink, NightMarks, via a subsidiary, Nanovox.
| Intermediate developers | Nanoco  
|-------------------------|---------
|                         | QDLight 
|                         | QD Vision 
|                         | Quantum Materials Corporation 
|                         | Voxtel |
| Target markets size according to industry estimates | Global Anti-Counterfeit Packaging market is projected to reach about US$82.2 billion by the year 2015. 
| | 2008: Counterfeiting accounted for $700 billion in sales, or 8-10% of all global trade 
| | Global smart packaging market 2011: $4.8 billion 
| | Global smart packaging market 2013: $14.1 billion 
| | Global anti-counterfeiting packaging market is expected to be worth $79.3 billion by 2014, growing at an estimated CAGR of 8.6% from 2009-2014. 
| | Bar code forms the largest market segment and is expected to reach $26 billion by 2014. 
| | Value of counterfeit and pirated goods in international trade totaled more than $250 billion in 2007, up significantly from about $100 billion in 2000. 
| | The world market for pharmaceutical anti-counterfeiting technology will reach around $1.2bn in 2015. 
| | Allied Market Research 
| | The “Global anti-counterfeit packaging market accounted for $57.4 billion in 2013, which is forecast to generate revenue of $142.7 billion by 2020 at 13.9% CAGR from 2013-2020. 
| | Global Industry Analysts 
| | The global market for anti-counterfeiting technologies could reach $82.2B by 2015. |
Sensors

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 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.

MARKET POTENTIAL

Due to their scale, the optical properties of QDs are quite sensitive to changes in the surface chemistry that occur when new molecules or ions bind to the surface. This sensitivity makes them excellent candidates as fluorescent sensors.

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 milliliter 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 quantum dots, which up to 300-fold improvement in LF test strip sensitivity demonstrated.

Gas sensors

APPLICATIONS AND ESTIMATED TIME TO MARKET
- Chemical sensors (3-5 years)
- Gas sensors (5 years plus)

COMPANIES

INVISAGE
www.invisage.com
The company produces QuantumFilm image sensors for use in cameras. They are also under development for smartphones.

STOREDOT
www.store-dot.com
The company produces QDs for application in image sensors.
<table>
<thead>
<tr>
<th>Table 12: Quantum dots in sensors—Product developers and market size</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intermediate developers</strong></td>
</tr>
<tr>
<td>• Nanosys</td>
</tr>
<tr>
<td>• StoreDot</td>
</tr>
<tr>
<td><strong>Product developers</strong></td>
</tr>
<tr>
<td>• InVisage</td>
</tr>
<tr>
<td>• 3M</td>
</tr>
<tr>
<td><strong>Target markets size according to industry estimates</strong></td>
</tr>
<tr>
<td>• GIA</td>
</tr>
<tr>
<td>Global chemical sensors market 2015: $17.28 billion</td>
</tr>
<tr>
<td>Caneus</td>
</tr>
<tr>
<td>Chemical sensors market 2016: £40 billion</td>
</tr>
<tr>
<td>BCC Research</td>
</tr>
<tr>
<td>Global sensors market 2010: $56.3 billion</td>
</tr>
<tr>
<td>Catalyst Corporate Finance</td>
</tr>
<tr>
<td>Image sensor market 2011: $18 billion</td>
</tr>
<tr>
<td>2016: $27 billion</td>
</tr>
<tr>
<td>Industry experts</td>
</tr>
<tr>
<td>Global market for biosensors in 2012 is estimated to touch $8.5 billion and projected to reach $16.8 billion by 2018.</td>
</tr>
<tr>
<td>Nanomarkets</td>
</tr>
<tr>
<td>Radiation detection market 2016: $2.7 billion</td>
</tr>
</tbody>
</table>
Table 13: Quantum dot producers-Types of dots produced, target markets and estimated revenues

<table>
<thead>
<tr>
<th>Company</th>
<th>Type of dots</th>
<th>Target markets</th>
<th>Estimated QD revenues range (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affymetrix/Ebioscience</td>
<td>• CdSe/CdS</td>
<td>• Biomedical</td>
<td>$2-$5 million</td>
</tr>
<tr>
<td>American Elements</td>
<td>• CdTe • CdSe • CdSe/ZnS • PbSe • ZnCdSe/ZnS • ZnCuInS/ZnS • ZnCdSeS • ZnO • InP/ZnS • Mn doped ZnO • Mn/ZnSe • Graphene</td>
<td>• Various</td>
<td>$0.5-$1 million</td>
</tr>
<tr>
<td>Attonuclei</td>
<td>• CdSe/CdS</td>
<td>• Various</td>
<td>$0.25-$0.5 million</td>
</tr>
<tr>
<td>CAN GMBH</td>
<td>• CdSe • CdSe/CdS Core/Shell • Electronics • Lighting • Solar • Life Sciences</td>
<td></td>
<td>$2-$2.5 million</td>
</tr>
<tr>
<td>Cromoz, Inc.</td>
<td>• Carbon dots • Biomedical</td>
<td></td>
<td>$0.1-$0.25 million</td>
</tr>
<tr>
<td>CrystalPlex</td>
<td>• CdSe</td>
<td>• Biomedical</td>
<td>$0.5-$1 million</td>
</tr>
<tr>
<td>Cytodiagnostics</td>
<td>• CdSeS</td>
<td>• LEDs</td>
<td>$0.5-$1 million</td>
</tr>
<tr>
<td>Evident Technologies</td>
<td>• CdTe, CdSe, CdSe/Zns • Various</td>
<td></td>
<td>$1-$1.5 million</td>
</tr>
<tr>
<td>Irilliant</td>
<td>• CdSe • CdTe • CdSe/ZnS • CdS</td>
<td>• Various</td>
<td>$0.1-$0.5 million</td>
</tr>
<tr>
<td>Lab 21</td>
<td>• CdSe/CdS</td>
<td>• Biomedical</td>
<td>$1.5-2.5 million</td>
</tr>
<tr>
<td>Life Technologies Corporation</td>
<td>• CdSe</td>
<td>• Biomedical</td>
<td>$2-$5 million</td>
</tr>
<tr>
<td>NanoAxis</td>
<td>• CdSe • Cadmium-Free</td>
<td>• Biomedical</td>
<td>$0.1-$0.5 million</td>
</tr>
<tr>
<td>Nanoco</td>
<td>• Cadmium-Free</td>
<td>• Various</td>
<td>$2-$3.5 million</td>
</tr>
<tr>
<td>Nanooptical Materials, Inc.</td>
<td>• Blue CdS/ZnS &amp; CdSSe • Visible CdSe/ZnS • Visible CdSe/ZnS • Near Infrared CdSeTe/ZnS • Near Infrared CdSeTe/ZnS • Longer NIR PbS/CdS • Longer NIR PbS/CdS</td>
<td>• Various</td>
<td>$0.5-$1 million</td>
</tr>
<tr>
<td>COMPANY</td>
<td>MATERIALS</td>
<td>APPLICATIONS</td>
<td>FUNDING</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-----------------------------------------------</td>
<td>---------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>NanoPhotonica, Inc.</td>
<td>ZnCdSSe/ZnS</td>
<td>LEDs, Photovoltaics, Electronics</td>
<td>$0.5-$1 million</td>
</tr>
<tr>
<td>Nanosquare, Inc.</td>
<td>CdSe/ZnS</td>
<td>Various</td>
<td>$0.5-$1 million</td>
</tr>
<tr>
<td>Nanosys, Inc.</td>
<td>CdSe/ZnS</td>
<td>Various</td>
<td>$2.5-$5 million</td>
</tr>
<tr>
<td>Navillum Nanotechnologies</td>
<td>Cadmium-Free</td>
<td>Various</td>
<td>$0.1-$0.5 million</td>
</tr>
<tr>
<td>NN-Labs LLC</td>
<td>CdTe, CdSe, CdSe/ZnS</td>
<td>Various</td>
<td>$0.1-$0.5 million</td>
</tr>
<tr>
<td>NNCrystal US Corp.</td>
<td>CdSe, CdTe</td>
<td>LEDs, Photovoltaics, Electronics</td>
<td>$0.5-$1 million</td>
</tr>
<tr>
<td>NovaSolar Technologies</td>
<td>CdTe</td>
<td>Photovoltaics</td>
<td>$0.1-$0.5 million</td>
</tr>
<tr>
<td>Ocean Nanotech LLC</td>
<td>CdSSe/ZnS or CdSe/ZnS, Cadmium-Free</td>
<td>Various</td>
<td>$0.5-$1 million</td>
</tr>
<tr>
<td>Pacific Light Technologies</td>
<td>CdSSe/ZnS or CdSe/ZnS, Cadmium-Free</td>
<td>LEDs</td>
<td>$2-$3.5 million</td>
</tr>
<tr>
<td>PlasmaChem GmbH</td>
<td>CdTe, ZnCdSe/ZnS, low cadmium, Zn-Cu-In-S/ZnS, cadmium-free</td>
<td>Various</td>
<td>$0.1-$0.5 million</td>
</tr>
<tr>
<td>QD Solution</td>
<td>CdSe</td>
<td>LEDs</td>
<td>$0.1-$0.5 million</td>
</tr>
<tr>
<td>QD Vision, Inc.</td>
<td>CdSe</td>
<td>LEDs</td>
<td>$2-$3.5 million</td>
</tr>
<tr>
<td>QLight Nanotech</td>
<td>CdSe</td>
<td>LEDs</td>
<td>$2-$3.5 million</td>
</tr>
<tr>
<td>Quantum Materials Corporation, Inc.</td>
<td>CdSe, Cadmium-free (Tetrapod QDs)</td>
<td>Various</td>
<td>$0.1-$0.5 million</td>
</tr>
<tr>
<td>Sigma-Aldrich</td>
<td>CdSe, CdS</td>
<td>Various</td>
<td>$0.1-$0.5 million</td>
</tr>
<tr>
<td>StoreDot Ltd.</td>
<td>Cadmium-free</td>
<td>Batteries, Electronics, Sensors</td>
<td>$0.1-$0.5 million</td>
</tr>
<tr>
<td>Sun Innovations</td>
<td>Phosphor-based lanthanide</td>
<td>LEDs</td>
<td>$0.1-$0.5 million</td>
</tr>
</tbody>
</table>
Affymetrix/eBioscience

COMPANY DESCRIPTION
eBioscience produces high-quality antibodies, ELISA kits, dyes and reagents for life science researchers and clinicians.

PRODUCTS
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. Nanocrystals 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 applications ranging from flow cytometry to imaging.

ADDRESS
eBioscience, Inc.
Headquarters
10255 Science Center Drive
San Diego, CA 92121
USA
Tel: +1 8889991371

WEB
www.ebioscience.com
American Elements

COMPANY DESCRIPTION
Founded in 1995, the company manufactures laser dyes, near infrared absorption dyes, polymeric dyes, conjugated polymers, light emitting polymers, hole transport materials and laser imaging materials based on fullerenes, quantum dots and nanoparticles.

PRODUCTS
The company offers the following quantum dots:
• CdTe Green Emission Quantum Dot Aqueous Solution
• Red Emission Quantum Dot Aqueous Solution
• CdHgTe Near Infrared Emission Quantum Dot Aqueous Solution.

ADDRESS
American Dye Source, Inc.,
555 Morgan Blvd., Baie D’Urfé
Quebec, H9X 3T6
Canada
Tel: +1 5144570070

WEB
www.adsdyes.com
Antibodies Incorporated

COMPANY DESCRIPTION
Manufacturer of polyclonal & monoclonal antibodies & immunochemistry products. Products include antigens, antisera, serums, immuno chemicals, peptides, proteins, hybridomas, quantum dots, conjugates, immunoglobulin & in-vitro diagnostic test kits. Capabilities include contract manufacturing, blending, mixing, filling, packaging, labeling, filtration, research & development, lyophilizing, design, assembly & testing.

PRODUCTS
The company produces quantum-dot based antibodies, Streptavidin, Protein A and Protein G conjugates as well as a custom quantum dot conjugation service. Using EviTags(R) from Evident Technologies, Inc., these conjugates are made ready-to-use for researchers in biology, life-sciences, drug discovery, disease diagnostics, proteomics, and genomics.

ADDRESS
Antibodies Incorporated
Davis, CA 95617-1560
USA
Tel: +1 800-824-8540

WEB
www.antibodiesinc.com
Attonuclei

COMPANY DESCRIPTION
Attonuclei™ was founded in 2005 by polytechnic research scientist Han Athalin in order to progress the research and development of custom quantum dot technology.

PRODUCTS
The company offers flexible custom manufacturing services to produce high quality “functionalized custom quantum dots”.

ADDRESS
Attonuclei - QuantaDots Laboratory
Faculte de Sciences - Universite de Nantes
2 rue de la Houssiniere
44322 Nantes
France

WEB
www.attonuclei.com
CAN GmbH

COMPANY DESCRIPTION
CAN GmbH was founded in November 2005 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.

PRODUCTS
The company produce CANdots® for various applications.
Inorganic Nanoparticles
• Nanoparticles consists of an inorganic core (metal, semiconductor, insulator, magnetic)
• Particle synthesis in colloidal solution (2-150 nm)
• In a 5 nm particle ~ 20% of the atoms are at the surface!
• (Post-synthetic) surface modification allows various applications

Sales are approximately 1.5 million Euros per annum. A full list of their products is available at http://www.can-hamburg.com/english/menu/products/candots-series-a.html.

ADDRESS
Center for Applied Nanotechnology (CAN) GmbH
Grindelallee 117
D-20146 Hamburg
Germany
Tel: +49 - 40 42 83 83 983

WEB
www.can-hamburg.com/english/home.html
Cromoz, Inc.

COMPANY DESCRIPTION
The company was founded in 2005.

PRODUCTS
The company produce non toxic water soluble carbon nano tubes 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. Initial in vitro studies on certain cancer cell lines at Johns Hopkins have shown no cytotoxicity.

ADDRESS
Cromoz Inc,
2 Davis Drive, Research Triangle Park,
North Carolina 27709-3169
USA
Tel:+1 919-522-1390

WEB
www.cromoz.com
CrystalPlex Nanotech

DESCRIPTION
The company develops tools to aid in drug discovery and clinical diagnosis.

PRODUCTS
The company produces the following range of CdSeS quantum dots:
• Carboxyl Quantum Dots
• Amine Quantum Dots
• Hydroxyl Quantum Dots
• Alkyl Quantum Dots.

ADDRESS
Crystalplex Headquarters
2403 Sidney Street, Suite 270
Pittsburgh, PA 15203
USA
Tel: +1 412.246.2044

WEB
www.crystalplex.com
Cytodiagnostics

DESCRIPTION
The company provides a range of nanomaterials for biotechnology applications.

PRODUCTS
The company offers a range of CdSeS 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.

ADDRESS
Cytodiagnostics
919 Fraser Drive, Unit 11
Burlington, Ontario L7L 4X8
Canada
Tel: +1-866-344-3954

WEB
www.cytodiagnostics.com/fluorescent-nanocrystals.php
Dow Chemical Company

DESCRIPTION
Dow Electronic Materials, a global supplier of materials and technologies to the electronics industry, brings innovative leadership to the semiconductor, interconnect, finishing, photovoltaic, display, LED and optics markets. From advanced technology centers worldwide, teams of talented Dow research scientists and application experts work closely with customers, providing solutions, products and technical service necessary for next-generation electronics.

PRODUCTS
Dow Electronic Materials, a business unit of The Dow Chemical Company and Nanoco Group plc global have a licensing agreement for Nanoco's cadmium-free quantum dot technology. Under the terms of the agreement, Dow Electronic Material have exclusive worldwide rights for the sale, marketing and manufacture of Nanoco's cadmium-free quantum dots for use in electronic displays. Dow intends to build production capacity in Asia where it has extensive manufacturing capabilities to supply high-performance materials to its customers in the display and semiconductor-related segments. Full commercial production is expected to begin in the first half of 2014. Dow revenues were $2.1bn in 2013 for electronic materials in 2013, and is market leader in OLED (organic light-emitting diodes) emitters.

ADDRESS
Dow Electronic Materials
451 Bellevue Rd,
Newark, DE 19713,
United States
Tel: +1 800-258-2436

WEB
www.dowelectronicmaterials.com
DESCRIPTION
E.I. Dupont De Nemours and Company (DuPont) was the world’s third largest chemical company based on market capitalization and ninth based on revenue in 2012.

PRODUCTS

ADDRESS
Head Office
1007 Market St., Wilmington,
Delaware,
USA
Tel: +1-302-774-1000

WEB
Emfutur Technologies

COMPANY DESCRIPTION
The company produces a wide range of nanomaterials.

PRODUCTS
The company is a supplier of Quantum dots CdTe, CdSe/ZnS (core/shell), ZnCdSe/ZnS (core/shell).

ADDRESS
Industrial Park - cmno.
Betxi s/n
Castellón de la Plana, 12540
Spain
Tel: +34 (644) 341 200

WEB
www.emfutur.com
Evident Technologies

COMPANY DESCRIPTION
Evident Technologies produces quantum dots for various markets including life sciences, solid state lighting, energy, security, telecommunications and emergent nanotechnology markets.

PRODUCTS
Evident’s proprietary EviDots™ are high performance semiconductor nanocrystals active throughout the visible spectrum and into the near–infrared. The company’s technology is licensed by Samsung for LED production.

ADDRESS
Evident Technologies
65 First Street
Troy, New York 12180
USA
Tel: +1 518.273.6266

WEB
www.evidenttech.com
InVisage Technologies, Inc.

COMPANY DESCRIPTION
The company is a fabless semiconductor company known for producing a technology called Quantum-Film, an image sensor technology that improves the quality of digital photographs taken with a cell phone camera.

PRODUCTS
The company produces QuantumFilm, QD based image sensors. The product enables the high-resolution images from handheld devices, such as camera phones and PDAs. Its products are used in security and surveillance, automotive imaging, military, and medical imaging applications, as well as mobile phone cameras, Webcams, and digital still cameras.

ADDRESS
InVisage Technologies, Inc.
990 Hamilton Avenue
Menlo Park, CA 94025
USA
Tel: +1 408–916–5560

WEB
www.invisage.com
Irilliant, Inc.

COMPANY DESCRIPTION
Utilizing the company’s patented CAFS technology, Irilliant can manufacture large quantities of a variety of nearly monodisperse colloidal solutions of nanomaterials (including CdSe, CdTe, CdSe/ZnS, CdS Quantum Dots, nanometals, and nano-oxides) at low cost.

PRODUCTS
In Irilliant’s CAFS process, liquid containing the precursors for the synthesis flows continuously through a sprayer, which in turn generates micron-sized droplets. These droplets serve as microreactors, and facilitate the creation of narrow-size distributed nanoparticles. Spraying large amounts of liquid in the reactor, facilitates manufacture of high-quality, surface-stabilized nanoparticles in large quantities. Ultrasonic or large scale industrial sprayers can be used to further enhance throughput. This configuration permits production of a higher quality product with a greater yield compared to previous methods.

ADDRESS
Irilliant, Inc.
Marketing Department
67 East Evelyn Avenue
Suite 5
Mountain View, CA 94041
USA
Tel: +1 (650) 575-4450

WEB
http://irilliant.com
KRI, Inc.

COMPANY DESCRIPTION
Spin-out from Osaka Gas Co., Ltd..

PRODUCTS
The company is a producer of graphene quantum dots. The Nano-Materials Research Laboratory has a high tech specialty in sol-gel, organic-inorganic hybrid, advanced analysis/measurements and MEMS.

ADDRESS
Kyoto Research Park,
134, Chudoji Minami-machi,
Shimogyo-ku,
Kyoto 600-8813
Japan

WEB
www.kri-inc.jp/index_e.html
Lab21 Ltd.

**COMPANY DESCRIPTION**
The company purchased nanomaterials company Selah Technologies in 2009.

**PRODUCTS**
Selah Dots™ are patent-pending brightly photoluminescent carbon-based nanoparticles targeted to revolutionize the cellular imaging markets by replacing fluorescent dyes and other contrast agents both in vitro and in vivo critical to early disease detection and rapid screening.

Selah Dots™ are built around a core of ordinary inert carbon that can be covalently passivated with biocompatible moieties. Selah’s highly innovative and scalable manufacturing process is compatible with standard process equipment. The robustness of the process produces highly consistent nanoparticles which are readily water soluble. Selah Dots™ promise the following performance benefits over competing imaging products:

- Improved signal sensitivity
- Improved detection specificity
- Improved biocompatibility
- Physicochemical and photochemical stability.

**ADDRESS**
Lab21 Limited
184 Cambridge Science Park
Cambridge
CB4 0GA
UK
Tel: +44 (0)1223 395450

**WEB**
www.lab21.com
Life Technologies Corporation

COMPANY DESCRIPTION
Quantum Dot Corporation was acquired by Invitrogen Corporation (now known as Life Technologies Corporation) in October 2005.

PRODUCTS
The company produces QDdot probes for medical imaging. Qdots 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.

ADDRESS
Life Technologies
Attn: EvoQuest™ Laboratory Services
3175 Staley Rd. Grand Island, NY 14072
USA
Tel: +1 8009556288

WEB
www.lifetechnologies.com
LG Display Co., Ltd.

COMPANY DESCRIPTION
LG Display Co., Ltd. is 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. The company has a total of 35,000 employees operating worldwide.

PRODUCTS
LG Display and QD Vision have joint development agreement focused on creating highly-efficient, high-performance active matrix displays based on electroluminescent quantum dot LED (QLED) nanotechnology.

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
NanoAxis LLC

COMPANY DESCRIPTION
A biotech start-up that develops bio-conjugated quantum dots and applications thereof in the medical and biological markets.

PRODUCTS
NanoAxis produces AxiCad™ QDs. AxiCad brand quantum dots come in wavelengths ranging from 530 nm to 740 nm. The company collaborated with NanoAxis LLC in 2011 to develop tetrapod quantum dot-based cancer diagnostic kits and theranostic applications, including Alzheimer’s, Type 1 and Type 2 diabetes, breast cancer and major depression.

ADDRESS
NanoAxis LLC
9845 Main Street #299
Clarence, New York 14031
USA
Tel: +1 716-908-2349

WEB
http://nanoaxisllc.com
Nanoco Group PLC

COMPANY DESCRIPTION
Nanoco was founded in 2001 as a spinout company from Manchester University’s Chemistry Department. The company currently operates facilities in the UK and Japan. Nanoco partners major R&D and blue-chip industrial organizations in the development of applications incorporating quantum dots.

PRODUCTS
The company produces Cadmium-Free Quantum Dots for Display and Lighting applications. According to the company CFQD® quantum dots offer performance benefits for display and solid-state lighting technologies:
- Improved colour performance
- Improved efficiency
- Improved efficacy with high colour rendering

Launch of CFQD® quantum dot solid-state lighting is expected in 2015.

ADDRESS
Nanoco Group PLC
Global Headquarters
46 Grafton Street
Manchester, M13 9NT
UK
Tel: +44 (0)161 603 7900

WEB
www.nanocotechnologies.com
Nanooptical Materials, Inc.

COMPANY DESCRIPTION
NanoOptical Materials Inc (NOM) is a spin off business launched from Intelligent Optical Systems. Now completely independent, NOM has advanced technology originally developed via SBIR funding to manufacture nanocrystals for optical applications.

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.

ADDRESS
Nanooptical Materials, Inc.
1330 E 223rd St, Suite 511
Carson, CA 90745-4343
USA
Tel: +1 (424) 262-4666

WEB
http://nanoopticalmaterials.com
NanoPhotonica, Inc.

COMPANY DESCRIPTION
Founded in 2011.

PRODUCTS
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.

ADDRESS
NanoPhotonica, Inc.
5036 Dr. Phillips Blvd.
Suite 319
Orlando, FL 32819
USA

WEB
www.nanophotonica.com
Nanoshel LLC

COMPANY DESCRIPTION
The company manufactures more than 50 nanomaterials. The main products are non-metallic single-walled, multi-walled, and functionalized carbon nanotubes.

PRODUCTS
The company produces:
• Cadmium Selenide Nano Powder (CdSe Nanopowder, Purity: >99%, 40-80nm)
• Cadmium Teluride Nano Powder (CdTe, Purity: >99%, APS: <100nm)
• Lead Selenide Nanopowder (PbSe, Purity: 99%, <100nm) Metal Base
• Lead Sulphide Nanopowder (PbS, Purity: 99%, <100nm) Metal Base
• CdSe/ZnS (core/shell) Quantum Dots, Average Particle Size: 600-700nm
• Cadmium Sulfide Nanopowder, (CdS), Purity: 99%, 3N, 60nm

ADDRESS
Nanoshel LLC
3422 Old Capitol Suit 1305
Willmington DE – 19808
United States
Tel: +1 302 652 3464

WEB
www.nanoshel.com
Nanosquare, Inc.

COMPANY DESCRIPTION
The company is a spin-out from Seoul National University.

PRODUCTS
The company is a manufacturer of quantum dots, which they can mass-produce.

ADDRESS
Nanosquare, Inc.
Engineering Building 39–122
Seoul National University
San 56-1, Sillim-Dong, Kwanak-Gu
Seoul 151-744
South Korea
Tel: +82-2-872-0801

WEB
www.nanosquare.co.kr
Nanosys, Inc.

COMPANY DESCRIPTION
Nanosys, Inc designs products based on a technology platform that incorporates high performance inorganic nanostructures. Its 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).

PRODUCTS
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.

QDEF™ and QuantumRail™ are composed of Nanosys’ proprietary, high efficiency quantum dot phosphors. They find application in LED displays. Nanosys Quantum Dot Enhancement Film, or QDEF, is an optical film component for LED driven LCD displays. Based on Nanosys’ proprietary high efficiency Quantum Dot Phosphors, QDEF enables a new level of LCD display performance by providing a high quality, tri-color white light from a standard blue LED light source. Larger than a water molecule, but smaller than a virus, these tiny phosphors convert blue light from a standard Gallium Nitride (GaN) LED into different wavelengths based upon their size. Larger dots emit longer wavelengths (red), while smaller dots emit shorter wavelengths (green). Blending together a mix of dot colors allows Nanosys to precisely engineer a new spectrum of light to customer specifications.

The quantum rail is a glass capillary optical component containing red and green quantum dots that is inserted between the LEDs and the light guide panel (LGP) of an LED LCD display in manufacturing to improve color gamut.

ADDRESS
Nanosys, Inc.
2625 Hanover Street
Palo Alto, CA 94304
USA
Tel: +1 650 331 2100

WEB
www.nanosysinc.com
Nanotech-Dubna LLC

COMPANY DESCRIPTION
Founded in 2008.

PRODUCTS
Nanotech-Dubna LLC produces QDlight™ quantum dots in quantities of 20 kg per year. The technology is scaled up to 100 kg as appropriate.

ADDRESS
Nanotech-Dubna LLC
4/4 Programmistiv str., Dubna
Russian Federation.
Tel: + 7 (496) 219-06-50

WEB
http://nanotech-dubna.com
Natcore Technology, Inc.

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 temperatures and pressures, eliminating the need for the high-temperature, vacuum furnaces, which is necessary for the production of these films.

PRODUCTS

ADDRESS
Natcore Technology, Inc.
87 Maple Avenue
Red Bank, NJ 07701
USA
Tel: +1 8777006262

WEB
www.natcoresolar.com
Navillum Nanotechnologies, LLC

COMPANY DESCRIPTION
The company is a producer of QDs, spun-out from the University of Utah.

PRODUCTS
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 in high quality batches.

ADDRESS
Navillum Nanotechnologies, LLC
2500 S. State St. G246
South Salt Lake,
UT 84115
USA
Tel: +1 (385) 646-4022

WEB
www.navillum.com
NN-Labs LLC

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

PRODUCTS
CdTe
NN-Labs have developed high-quality cadmium telluride (CdTe) nanocrystals for solar photovoltaic (PV) applications.

InP/ZnS
NN-Labs, LLC produces indium phosphide-based quantum dots as a new 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).

ADDRESS
NN-Labs
PO Box 2168
Fayetteville, AR 72702-2168
USA
Tel: +1 479-595-0662

WEB
www.nn-labs.com
NNCrystal US Corp.

COMPANY DESCRIPTION
Arkansas-based NNCrystal US Corp. is a wholly owned subsidiary of Hangzhou Nanjing Technology Ltd. and an exclusive licensee of advanced materials synthesis technology from NN-Labs LLC.

PRODUCTS
NNCrystal is the owner of two patented and trademarked technology platforms for solid-state lighting applications-Qshift Lucid and Qshift Coral. NNCrystal is focused on leveraging its advanced materials capabilities to deliver breakthrough, differentiated and sustainable solutions to the global lighting industry.

ADDRESS
NNCrystal US Corp.
534 West Research Center Blvd
Suite 254
Fayetteville
USA
Tel: +1 5854908833

WEB
www.nncrystal.com
NovaSolar Technologies

COMPANY DESCRIPTION
Spin-out from Western Washington University.

PRODUCTS
The company is developing QD films for solar power window panels. Further information is available at http://pubs.acs.org/doi/abs/10.1021/nn406360w, “Zero-Reabsorption Doped-Nanocrystal Luminescent Solar Concentrators”.

WEB
www.novasolartech.com
Ocean Nanotech LLC

COMPANY DESCRIPTION
Ocean NanoTech was founded in 2004. Core competences are:
• Preparation of quantum dots, magnetic nanoparticles and metal nanocrystals
• Conversion of hydrophobic nanomaterials to water soluble and biocompatible nanocrystals
• Bioconjugation of quantum dots and magnetic nanocrystals to proteins, DNA, and other molecules

PRODUCTS
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.

ADDRESS
Ocean NanoTech
2143 Worth Lane
Springdale, Arkansas 72764
USA
Tel: +1 4797515500

WEB
http://oceannanotech.com
Pacific Light Technologies

COMPANY DESCRIPTION
PLT was founded in early 2011 by researchers formerly with SpectraWatt, an Intel spin-off which attempted to develop quantum-dot-enhanced solar cells prior to closing in 2011. In late 2011 PLT acquired the intellectual property of SpectraWatt.

PRODUCTS
The company produces PLT Quantum Dots for solid-state lighting.

ADDRESS
Pacific Light Technologies
2828 SW Corbett Avenue, Suite 3
Portland, OR 97201
USA
Tel: +1 (503) 802-0529

WEB
www.pacificlighttech.com
PlasmaChem GmbH

COMPANY DESCRIPTION

PRODUCTS
The company is a manufacturer of a wide range of nanomaterials including quantum dots.

ADDRESS
PlasmaChem GmbH
Rudower Chaussee 29
D-12489 Berlin
Germany
Tel: +49 3063926313

WEB
www.plasmachem.com
QD Laser, Inc.

COMPANY DESCRIPTION
QD Laser, Inc. was launched by Fujitsu and Mitsui Ventures, to commercialise semiconductor lasers and amplifiers using Quantum Dot and Quantum Well structures.

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.

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.

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
QD Solution Co., Ltd.

COMPANY DESCRIPTION
The company has developed a mass production technology for QDs.

PRODUCTS
The company manufactures CdSe quantum dots, mainly for LED applications.

ADDRESS
QD Solution
59-303 Hanbat National University
125, Dongseo-daero
Yuseong-gu
Daejon
Korea

WEB
www.qdsnano.com
QD Vision, Inc.

COMPANY DESCRIPTION
The company is focused solely on QDs for displays and lighting.

PRODUCTS
QD Vision’s Color IQ™ platform enables step-change advances in current generation solutions, such as LCDs, LEDs and even OLEDs, and ultimately a significant leap over these technologies. Leveraging a first-tier patent position in nanotechnology originating at MIT, QD Vision is a privately held company based in Watertown, Mass. QD Vision’s Color IQ™ product platform exploits the unique light-emitting properties of semiconductor nanocrystals for application in LED-based products, with enhanced color quality, high power efficiency, manufacturing versatility, and design flexibility.

ADDRESS
QD Vision Corporate Headquarters
313 Pleasant Street
Watertown, MA 02472-2491
USA
Tel: +1 6176079700

WEB
www.qdvision.com
QLight Nanotech

COMPANY DESCRIPTION
QLight Nanotech was founded in 2009 by Professor Uri Banin as a spin-off of Yissum, the technology transfer company of Hebrew University of Jerusalem.

PRODUCTS
QLight Nanotech is developing quantum dot semiconductor nanoparticles for energy-efficient light sources and displays. The technology can nearly double the battery run time in mobile devices, and reduce by almost half the energy consumption of TV sets. Qlight Nanotech’s film also improves the color quality of the display, thus dramatically upgrading the user’s viewing experience.

ADDRESS
Hi-Tech Park
Givat Ram
Jerusalem, 91390
Israel
Tel: +972-2-6584253

WEB
http://qlightnano.com
Quantum Materials Corporation, Inc.

COMPANY DESCRIPTION
Quantum Materials Corporation, Inc. was founded in 2007 and is based in Kingston, Oklahoma.

PRODUCTS
Quantum Materials Corporation, Inc., 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. Quantum Materials Corp. has increased capacity equipment and is launching mass production of 250 kilograms of quantum dots per annum. In addition to manufacturing Tetrapod Quantum Dots (TQD) engineered to specific lighting, display and medical applications for leading manufacturers worldwide, QMC is also developing TQD-infused films for medical devices, solid state lighting applications, electronic displays and quantum dot solar cells.

ADDRESS
Quantum Materials Corporation, Inc.
12326 Scott Drive Kingston
OK 73439
United States
Tel: +1 214-701-8779

WEB
www.qmcdots.com
Raytheon Company

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.

ADDRESS
Raytheon Company
870 Winter Street
Waltham, MA,
USA
Tel: +1 (781) 933-3564

WEB
www.raytheon.com/newsroom/technology_today/2012_i1/quantum.html
Reade Advanced Materials

COMPANY DESCRIPTION
READE is a manufacturer, value add custom processor and global distributor of higher technology specialty chemical solids with three customer care and distribution facilities in the Americas.

PRODUCTS
The company produces a wide range of quantum dots.

ADDRESS
Reade International Corporation.
P.O. Drawer 15039
850 Waterman Avenue
Providence, Rhode Island 02915-0039
USA
Tel: +1 401-433-7000

WEB
www.reade.com
Reinste Nanoventures Pvt., Ltd.

COMPANY DESCRIPTION
The company produces a wide range of nanomaterials.

PRODUCTS
REINSTE is a supplier of Carbon Nanotubes, Nanodiamonds, Nanoceramics, Quantum Dots, Nanometals, Fullerene, Nanowires, Nano- and Micro- Salts, Tectomers, PEG Derivatives, Phosphonic Acid Derivatives

ADDRESS
Reinste Nanoventures Pvt., Ltd
A-105, Sector 63, Noida,
Uttar Pradesh 201301,
India
T: +91 98 10 662669

WEB
http://reinste.com
Revolution Lighting Technologies

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-color rendering (91 CRI) incandescent warm white light at an industry leading 60 lumens per watt.

ADDRESS
Array Lighting
A Revolution Lighting Technologies Company
124 Floyd Smith Drive, Suite 300
Charlotte, NC 28262
USA
Tel: +1 704 4050416

WEB
www.rvltx.com
Samsung

COMPANY DESCRIPTION
Samsung Electronics is part of one of the largest multi-billion dollar corporations in the world.

PRODUCTS
The company is working with a number of quantum dots companies to produce displays for televisions.

ADDRESS
Samsung Headquarters
Maetandong 416 Suwon
Gyeonggi-do Samsung Medison Bldg., 42,
Teheran-ro 108 gil

WEB
www.samsung.com
 Sigma-Aldrich

COMPANY DESCRIPTION
The company is one of the world’s chemicals and materials producers.

PRODUCTS
The company produces:
• Alloyed Quantum Dots
• CdS Type Quantum Dots
• CdSe Type Quantum Dots
• Core-Shell Type Quantum Dots

ADDRESS
3050 Spruce St
St Louis, MO 63103
United States
Tel: +1 800-521-8956

WEB
www.sigmaaldrich.com
StoreDot Ltd.

COMPANY DESCRIPTION
StoreDot Ltd. is a privately owned nanotechnology startup, incorporated in Israel in 2012, which develops technologies that apply bio-organic Nanodots to mobile displays and energy storage devices.

PRODUCTS
StoreDot Ltd. produces bio-organic Nanodots. Manufacturing Nanodots is relatively inexpensive as they originate naturally, and utilize a basic biological mechanism of self-assembly. They can be made from a vast range of bio-organic raw materials that are readily available and environmentally friendly. StoreDot develops batteries and displays for smartphones and tablets, designed to replace current technology with more efficient power consumption and better color vividness. StoreDot batteries will be charged much faster than current batteries, and will withstand thousands of charge/discharge cycles, prolonging battery life expectancy considerably. Furthermore, StoreDot paper-thin displays can be designed to be flexible and transparent.

ADDRESS
StoreDot Ltd.
16 Menachem Begin St.
Gamma Building, 4th floor
Ramat-Gan Israel 5270003
Tel: +972-3-5097710

WEB
www.store-dot.com
Sun Innovations

COMPANY DESCRIPTION
Sun Innovation’s Nanomaterial Store synthesizes and supplies functional nanomaterials.

PRODUCTS
The company produces PhosphorDots™, phosphor-based lanthanide nanomaterials that can be used in a variety of quantum dot-type applications, and are particularly suitable for medical and pharmaceutical research.

ADDRESS
Sun Innovations, Inc.
43241 Osgood Road, Fremont,
CA 94539
USA
Tel: +1 (510) 651-1329

WEB
www.nanomaterialstore.com
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