NanoMarkets Report

Market Opportunities in Quantum Dots in Lighting and Displays

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SUMMARY

This new NanoMarkets report provides an in depth market analysis of the opportunities emerging within the field of quantum dots (QDs), examining the latest products, strategies and technical developments in electronics applications for these emerging materials. Within the report we assess how QDs are likely to penetrate addressable markets in lighting and display applications and along what time horizon. We also examine the technology hurdles facing QDs broader adoption and how the industry will resolve them. The report also evaluates the potential of QDs vs competing technologies and provides NanoMarkets opinions on how well QDs will fare.

The report also includes NanoMarkets' assessments of the strategies of leading firms active in the QD space with attention paid as to which are the companies to watch in the market. In addition, detailed and granular forecasts of QD shipments in volume and value terms and by application will be provided.

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Chapter One: Introduction

1.1 Quantum Dots: The Key Markets

NanoMarkets believes that Quantum Dots (QDs) have good potential to be a dominant large display format technology in the near term, but will take some more time to find commercial applications in the small display segment. In addition, NanoMarkets believes that in the near to mid-term, the lighting industry is likely to witness a good number of commercial launches, particularly in the solid-state lighting (SSL) segment, in which QDs have the potential to replace LED phosphor-based lighting solutions.

Downstream suppliers of QD raw materials are likely to expand their manufacturing facilities in order to meet the growing demand for QDs from consumer electronics producers, particularly TV manufacturers, as well as research facilities and some SSL-based lighting solution providers.

The QD market can be broadly classified into two segments:

- Displays employing QD technology in large (TVs) and small formats (smartphones, tablets, etc.) Although QD-based TVs have begun to emerge commercially, it will take some time for the market to realize their full potential. Meanwhile, small display formats are likely to test the commercial viability of QD-based solutions in their commercial products.

- Solid-state lighting solutions, where QDs have begun to find applicability in personal electronic devices, such as smartphones and tablets, and exterior signage. However, certain pitfalls with regard to tuning the color range, producing a true white color, and high costs have limited the application of QDs in home and commercial lighting setups.

NanoMarkets expects the U.S. to be at the forefront of QD-related research activities, as evident from the presence of a wide network of QD research-based start-ups and the number of collaborative deals that some of these start-ups have struck with established raw materials suppliers and OEMs, particularly in the consumer electronic display segment.

1.1.1 QD TVs Emerge, While QD-Based Smartphones and Laptops Have Yet to Gain Commercial Acceptance

Large display segment: QD-based solutions have made significant inroads in large format displays such as TVs, primarily because of the versatile applicability of QDs in a wide range of display devices combined with their better color production, color purity, and power efficiency.

Large format QD-based display solutions are mostly licensed to OEMs by a few innovative start-ups, such as QD Vision, Nanosys, Nano Photonica, and Nanoco Group.

An early entrant, QD Vision, is likely to lead the market. The company has strong collaborations with several leading TV manufacturers. Two of its patented technologies hold significant potential:

- Using currently available QD technology for displays that require a backlight source, Sony has incorporated QD Vision's proprietary Color IQ technology in its 55-inch Triluminous brand of LCD TVs. These QDs emit pure green and pure red light and have superior color reproduction capabilities compared to those found in most commercially available TVs.

- A quantum dot light emitting diode (QLED) is a direct-emissive display technology that is likely to do away with the requirement for an underlying substrate and backlight source. The technology is currently on the verge of commercialization and is likely to find application in next-generation electronic displays because of its proven superiority to organic light emitting diodes (OLEDs) in terms of reduced manufacturing costs, better power efficiency, and the ability to emit pure colors.

In addition to Sony, other notable consumer electronics players that are vying for a sizable share of the large format QD display segment include:

- Samsung, which is currently working in collaboration with Nano Photonica to incorporate the latter's proprietary S-QLED technology, which seems to promise low cost and versatility across all display sizes, into TVs that should reach the market in late 2014 or early 2015.

- LG, which has also been working with multiple entities that have patented QD technologies, such as Nanosys and QD Vision; however, there are uncertainties regarding the timeframe for commercial launch of any QD-based products.

- Sharp, which has reportedly been working on QD technology; however, nothing concrete has been officially confirmed by the company.

It is a general concern among manufacturers to alter existing processes in order to accommodate commercial production of any product based on a new technology. The same applies to the adoption of QD technology.

In order to address such manufacturing concerns, Nanosys, in collaboration with 3M's Optical Systems Division, has developed proprietary Quantum Dot Enhancement Film (QDEF) technology that is designed to replace the traditional LCD backlighting unit. This technology therefore offers TV manufactures a readymade solution for incorporating QDs into their existing manufacturing facilities with minimal incremental cost.

Despite rumors of a significant extended product development time, 3M has indicated that it expects to commercially roll out the QDEF-based solutions for OEMs offering TVs, smartphones, and tablets by the end of 2013. Due to the adaptive nature of the technology within the existing LCD manufacturing framework, QDEF could potentially replace other competing phosphor-based technologies and OLEDs in the next generation of TVs.

Small display segment: The flexibility and high energy efficiency of ultra-thin film QDs make these nanomaterials potentially valuable for small displays. However, despite this strong potential (including that of technologies such as QDEF (patented by Nanosys)), only a few commercial QD-based products have been developed for this segment. Some of the barriers to entry to this segment, which limit the participation in this industry, include the dominance of OLED technology in the market, the longer time required for commercialization of these products, and lack of initiatives to set up large-scale manufacturing facilities.

A few notable players pursuing the small display strategy include:

- Osram, which is one of the few suppliers of QD backlighting solutions (through its MicroSideled brand) that offer minimal color loss and high power efficiency for personal electronic devices, such as tablets, ultra-books, and smartphones.

- Sony, which is one of the few electronic OEMs that currently offers its proprietary QD-based display (Triluminous) in its Xperia range of smartphones and Vaio range of laptops.

The entry of established players in the small display segment will likely spur additional research efforts and increase the scope of possible commercial launches.

Key concerns in the display industry: QDs are likely to face stiff competition from OLEDs, a technology in which some of the leading OEMs, such as Samsung, have already invested heavily. It is expected that Samsung and other OEMs will require some time to recoup their investments before shifting to a new technology such as QDs.

Some of the key business concerns in the display industry regarding QD-based solutions are:

- The role of start-ups and their IP positions,

- The race among OEMs to secure licensing deals, and

- The verified performance improvements that QDs provide compared to OLEDs.

The QD supplier community is typically comprised of technology start-ups with IP rights that either license their products to OEMs or directly sell to research facilities. Consumer electronics OEMs are likely to generate the maximum demand for QDs in the coming years. Thus, it makes sense for QD providers holding IP positions to work in collaboration with established raw material suppliers to the electronic display industry or directly with the OEMs, which typically have large distribution networks and marketing prowess.

Clearly, companies that hold IP positions in QD materials are likely to depend heavily on OEMs and other big raw material suppliers to gain market visibility. However, firms such as QD Vision and Nanosys will have a significant advantage over other players because of their innovative product lines, which are flexible enough to serve different display segments.

Moreover, with the commercial success of QD technology, established electronic display manufacturers are likely to select such strong suppliers in order to secure their QD raw material base. OEMs will, in fact, compete with one another to strike exclusive deals with leading QD material suppliers. Although product profiles are likely to expand over time, the competitive pressure will lead to some level of consolidation, with only the financially strong players emerging as successful suppliers of QD materials to the display industry.

While compared to OLEDS, QDs offer the manufacturing advantage of fitting into the existing backlighting units of LCD TVs; QDs must also offer dramatic performance enhancements over OLEDs in order to attract investment. Long product lifetimes and cost-effective large-scale manufacturing are likely the key factors that will make QD technology successful in the display industry in the near future.

Future outlook for the display industry: In the next two-three years, QDs are likely to dominate the LCD backlighting TV segment, while it will take four-five years to witness the commercial entry of

large display products based on direct-emissive (pure QD) technologies, such as the QLED technology developed by QD Vision, that can be applied across a wide range of display formats, including ultra-thin products.

Although OLEDs are to some extent comparable to QDs in terms of their versatility, smart customization moves from QD material suppliers, such as those made by Nanosys with its QDEF technology, have the potential to place QDs at the forefront of next-generation large display products that are likely to hit the market in the mid-term.

Moreover, the intent of big raw material suppliers, such as Dow Electronic Materials (DEM) and 3M, to serve the display segment with QD products in a big way should be considered a positive move by other OEMs and suppliers. Other players are likely to follow suit, given the likely commercial launch of QD-based solutions from DEM (in collaboration with Nanoco Group) in the first half of 2014 and 3M (in collaboration with Nanosys) by the end of 2013.

NanoMarkets believes that the large display manufacturers, such as Sony and Samsung, will play a significant role in the commercialization of QD products, although they are likely to make smaller investments in the QD space compared to those made in OLED technology. Even so, NanoMarkets expects that commercialization in the large display segment will progress at a faster rate than that in the small display segment, in which manufacturers are likely to carefully gauge the market potential of QDs and follow policies similar to those adopted by the established players, such as Sony and Samsung.

1.1.2 QD-Based Solid State Lighting on the Verge of Commercialization, but Little Impact in Other Lighting Categories

Solid-state lighting (SSL) segment: In the solid-state lighting (SSL) segment, QLEDs hold significant promise in terms of commercial success, because QLED-based lighting solutions can be applied on flexible surfaces and offer better efficiency, a wider color range, and better color saturation than other competitive products, such as LED phosphors. In addition, the high costs associated with OLED manufacturing have kept this technology out of the reach of residential and commercial consumers, a fact that can actually play in favor of QLEDs in the near future.

Energy-saving cost benefits, low toxicity, and the ability to provide true incandescent light make QD-based SSLs a strong contender for new SSL solutions and potential replacements for existing LED phosphor-based SSLs.

As in the display segment, QD Vision has a significant first-mover advantage in the SSL segment. As early as 2009, the company demonstrated its patented ‘Quantum Light’ QD–based SSL technology in collaboration with Nexxus Lighting Inc., which incorporated the technology in its commercially available ‘Array’ series of lamps. QD Vision’s ‘Quantum Light’ technology, which offers better energy savings and a longer shelf-life than conventional halogen lamps, is ideal for downlight solutions typically used in commercial and residential settings.

While QD Vision heads the pack of QD solution providers, there are others that are likely to make their presence felt in the SSL domain with proprietary QD-based solutions:

- Using NN Crystal’s proprietary QShift Coral technology, Renaissance Lighting has commercially launched downlight solutions that can be precisely controlled to emit pure light of a particular color.

- Pacific Light Technologies, which is solely focused on developing toxic material-free QDs for the SSL industry, is likely to attract consumer attention once it is commercially launched.
- Wisys Technology Foundation, working in collaboration with the University of Wisconsin, has also developed a proprietary QD-based SSL solution that is ready for market testing.

These early advances should ideally incentivize other developers of QD-based SSL solutions to push their products from the research lab into consumers' hands. An increase in the number of QD-based offerings is critical for the success of the technology in the lighting sector, given that currently there are only a handful of organizations offering commercially available QD-based SSL products.

It must be noted, however, that successful commercial launches of QD-based lighting solutions also depend heavily on the extent of the financial support received by the research organizations developing QD-based solutions. Recognizing this fact, the U.S. government, through the Department of Energy (DOE), is providing financial grants to QD-based projects in order to move laboratory products to the commercial launch stage. Some grant receivers include:

- The University of Buffalo, which is developing high-efficiency colloidal QD phosphors, and
- The University of California, which is developing QD phosphors for SSL applications.

Other lighting segments: QD technology also has significant advantages over currently available LCD and OLED technologies in terms of better image performance and power efficiency in applications such as projectors, video walls, and digital signage. Trenton Systems is one firm that sees potential for QDs in such applications. The company is planning for the possible introduction of a QD-based video wall.

However, there are uncertainties with respect to the adoption rate of QD technology in these niche lighting segments, primarily due to the high product costs and the need to change existing manufacturing processes.

Key concerns in the lighting industry: Although some QD material suppliers have achieved a head start in the SSL segment, there are reasons why a majority of the QD-based research activities have shied away from this segment. The display industry has two key concerns about QD-based solutions:

- The expensive manufacturing processes for commercial products and
- The attractiveness of the business segment.

Commercial manufacturing processes for QD-based solid-state lighting solutions remain expensive and it will be some time before economies of scale can be achieved. This should prompt the development of cost-effective techniques for manufacturing general purpose lighting products. In addition, the incremental performance benefits that QDs provide compared to conventional lighting solutions, such as CFLs and LEDs, will also be important factors deterring the rate of adoption of QDs by the lighting industry at large.

The competition for research dollars with other segments, particularly the lucrative display industry, is another major factor affecting the development of QD-based lighting solutions. Hence, a successful foray into SSL and other residential and commercial lighting solutions will depend

significantly on several key factors, including the development of cost-effective mass production capabilities and favorable government mandates for the adoption of energy efficient measures, such as the U.S. government's emphasis on replacing 100 watt and 75 watt incandescent bulbs with 60 watt and 40 watt bulbs.

Future outlook for the lighting industry: NanoMarkets believes that, in the lighting segment, SSL is likely to provide the maximum number of innovative opportunities for start-ups such as QD Vision and other QD materials producers. It will be necessary, however, for major lighting industry OEMs to make such products commercially available. NanoMarkets is also of the opinion that some of the U.S. government-assisted QD-based SSL research projects are likely to gain commercial significance in the near to mid-term; however, other lighting segments are likely to wait and watch for radical innovations that will offer potential manufacturers a viable route to break into commercial markets.

At the same time, NanoMarkets thinks that QD materials firms should also look beyond traditional business segments and target niche lighting categories, such as projectors, video walls, and digital signage – business segments in which QD solutions can address the significant issue of high energy consumption.

1.1.3 QD Material Suppliers Likely to Benefit in the Mid-Term

QD materials form the fundamental building blocks of any QD device. These materials primarily consist of either heavy metal (HM)-based semiconductor materials or non-heavy metal (NHM)-based semiconductor materials.

Typically, NHM-based QDs find use in biomedical applications, while HM-based QDs have been traditionally used in all other applications. However, growing concerns over the use of cadmium have led researchers to shift their focus on NHM-based QDs.

HM-based QD materials: QDs have been traditionally based on HM semiconductor materials, such as cadmium telluride, zinc sulfide, lead selenide, and zinc cadmium selenide. The supplier base remains fragmented, with OEMs having the option to choose from several patented QD materials.

The success of material suppliers is likely to be determined by their ability to mass produce QDs of consistently high quality. Therefore, traditional suppliers, such as American Elements and M K Impex Corporation, will need to not only continue to differentiate themselves on the basis of their product variety, but also look to acquire mass production capabilities.

NanoMarkets believes that companies such as Nanoco Group and Quantum Materials Corporation, which hold IP positions related to QD materials and novel large-scale QD manufacturing techniques, are likely to have an edge over others because they will be in a position to strike bulk HM-based QD manufacturing deals with OEMs in the near to mid-term.

NHM-based QD materials: Addressing growing environmental concerns over the use of certain heavy metals, such as cadmium and lead, has led to the emergence of NHM-based QDs. NHM-based products have begun to emerge only recently, however, and the supplier base with large-scale production capabilities is limited at this time. Some of the companies with patented mass production manufacturing techniques include:

- U.K.-based Nanoco Corporation, which has modified its existing HM-based QD manufacturing techniques in order to produce NHM-based QDs with optical properties identical to the well-accepted properties of HM-based QDs. Nanoco has patented this mass production technique in order to cater to the growing demands of the electronic display industry.

- U.S.-based Quantum Materials Corporation, which by the end of 2013 will be mass producing an entire range of HM-based and NHM-based quantum dots using its patented continuous flow process. The company's range of QD materials is likely to find applicability in various industries including display and lighting, but the firm's focus has been on developing QD materials suited for the biomedical and solar energy segments.

NanoMarkets believes that QD material providers in this highly specialized material segment are likely to ensure business viability through continuous IP-related research activities, which will enable these manufacturers to receive a steady stream of licensing revenues from OEMs in the mid-term. However, NanoMarkets expects significant development efforts will also be directed towards the implementation of cost-effective large-scale manufacturing techniques, which will be the key to the commercialization of cost-effective and high-performance QDs.

1.1.4 Technology Gaps in Current-Generation QD Materials

It must be noted that despite their proven potential, QDs have yet to become the material of choice for the display and lighting industries. Although this trend can be partly explained by the fact that OEMs are hesitant to dramatically shift towards a new technology such as QDs before recouping their investments in other similar and promising technologies (OLEDs), there are also several technological barriers that QDs must overcome in order to prove their superiority over other rival technologies.

Some of the current material-related issues faced by QDs include:

- The suitability of current fabrication techniques to facilitate cost-effective mass production;
- The ease of manufacturing blue QDs; and
- Blinking issues with QDs.

Despite the emergence of several fabrication techniques for the effective manufacture of QDs, the majority of currently available fabrication techniques do not provide significant room for cost reduction in large-scale production. Research efforts to develop new fabrication techniques or modify existing techniques are highly desired. Until a cost-effective fabrication technique is developed, QDs may not be able to make the leap to commercial success.

With respect to display solutions, the majority of current-generation QDs is likely to find initial applicability in the LED backlighting space. However, the difficulty in producing blue QDs on a consistent basis is a major cause of concern for LED and LCD TV manufacturers. In addition, because blue QDs are likely to be smaller than red QDs, blue and green variants of blue QDs require manufacturing techniques that make them visible to the human eye. Thus, QD materials manufacturers must develop an optimal manufacturing process for blue QDs – an effort that is likely to require strong collaborations between the materials suppliers and OEMs.

Furthermore, QD manufacturers have in general been struggling to simultaneously ensure uniform size and narrow emission peaks in order to prevent the QDs from blinking on and off. Although a potential solution to this problem has been achieved by MIT researchers, the suitability of the new technique at commercial scale has yet to be verified.

Additional advances in technology are likely to solve some of the other existing problems with QDs in the coming years, leading to increased applicability of the technology.

In the immediate future, the QD industry is likely to focus primarily on the large display market, in which QDs are expected to be extensively incorporated in the backlighting units of LCD and LED-based TVs. Moreover, NanoMarkets believes that the development of cost-effective mass production techniques will surely attract established OEMs that would like to harness the benefits of QDs in a variety of other applications ranging from direct-emissive QD TVs and smartphones to solid-state lighting.

However, NanoMarkets also expects that the potential for QD technology to replace OLEDs (in the large display segment) and LEDs and CFLs (in the lighting segment) will largely depend on demonstration of the long-term performance enhancements offered by QDs compared to these rival technologies, particularly in terms of their reduced manufacturing cost, enhanced power efficiency and color production, longer lifetimes, and flexibility.

1.2 Opportunities and Scope of this Report

This report is the latest NanoMarkets report on opportunities in the QD materials markets.

NanoMarkets has been providing industry analysis of the QD community for over six years and is the leading supplier of analysis in the QD display and lighting space. The goal of this report is to analyze and forecast the prospects for QD materials in the coming eight years.

Specifically, the objective is to examine the QD materials sector and analyze what we see as the different opportunities that are emerging in this space for materials in both the QD display and QD lighting sectors. The report contains detailed forecasts in both revenue and volume terms for all of the major materials used in QDs.

1.3 Methodology and Information Sources for this Report

This report is based on NanoMarkets' ongoing industry research in the area of QDs and QD materials, and on ongoing discussions with key players throughout the QD community. We also draw on extensive secondary research, including an analysis of the relevant applications markets within the QD display and lighting space.

Additional research for this report was drawn from the Internet, commercial databases, trade press articles, press releases, SEC filings, and other corporate literature in order to further elucidate what is occurring in this sector. The forecasting approach taken and the assumptions made when preparing the forecasts in this report are explained in more detail in Chapter Four.

This report is entirely international in scope. The forecasts are worldwide forecasts and we have not been geographically selective in the firms that we have covered in the report or interviewed in order to collect information.

1.4 Plan of this Report

Chapter Two reviews the various applications for QDs and contains our panel area forecasts for those applications, which form the basis of the materials forecasts later in Chapter Four of the report.

Chapter Three examines the QD materials supply chain, with a focus on recent developments in IP, acquisitions, and consolidation. We also analyze the strategies of some of the major players in this space.

In Chapter Four, we provide detailed forecasts for the QD materials sector with breakouts by application. The display segment is divided into QD-backlit LCD televisions, other QD-backlit displays, direct-emission QD displays, and other types of QD displays. Lighting applications include energy-efficient lighting, mood-, health-, and performance-enhancing lighting, and other types of lighting.