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LED Phosphor Markets – 2014

SUMMARY

This new NanoMarkets report provides a thorough analysis of the latest opportunities in the LED phosphor markets. It builds on NanoMarkets' successful 2012 phosphor report and shows how the phosphor market is shifting in response to latest developments in both display backlighting and general illumination markets.

In this years' report, we are placing special attention on some of the newer phosphor chemistries such as nanophosphors, glass phosphors and QDs. And we also ask and answer the question as to how new phosphor materials can build market share in a market crowded in new materials.

We identify how performance improvements are likely to help grow addressable markets for phosphors, with an especial focus on general illumination, outdoor/street lighting and backlighting and how money will be made in the LED phosphor market.

The report also includes NanoMarkets' assessments of the product/market strategies of leading firms active in the LED phosphors space. And, as always with our reports, this report contains granular eight-year forecasts of the LED phosphors shipments in volume and value terms, with breakouts by type of phosphor and type of application. This report is required reading, not just for strategy planners at phosphor firms, but for those throughout the solid-state lighting and display industries.

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Chapter One: Introduction

1.1 Background to the Report

Increasing demand for luminous efficacy, a high color rendering index, and cost-effectiveness is fueling the lighting industry. NanoMarkets believes that LED phosphors, will therefore enjoy an expanding market.

Phosphors are the critical luminescent materials for LEDs. In a white LED, for example, the phosphor emits up to 95 percent of the visible lumens. Existing phosphors have been able to provide LEDs with 100 percent greater increase in LED efficacy and a 50 to 200 percent decline in price. The use of phosphors has also helped drive down the price of high-quality LEDs by a dramatic amount.

As a result, NanoMarkets believes that LED phosphors will continue to play a major role in the development of the LED phosphor market. In particular, we think that the use of phosphors in applications such as traffic lights and exit signs will become key drivers for the phosphor market.

More generally, we expect in LED applications where a lower cost per lumen, a high CRI, and a lower cost of ownership can be demonstrated, phosphor penetration will continue to grow. We also think that phosphor choice may help reduce consumer perception of LED lamps as being cold, dull, and above all, unaffordable.

Also, and, as we discuss throughout this report, another critical factor is who owns the IP in the phosphor space; a factor that has shaped—and clearly will continue to shape—the market. Other factors that seem likely to continue and which NanoMarkets will also determine the structure of the phosphor sector are the "division of labor" based on both supplier size and geography.

What we have in mind here is that our analysis indicates that large phosphor players will continue to improve their products through the deployment of efficient production lines while smaller players will seek novel phosphor solutions. There is also something of a divide between Asian and European/U.S. firms with regard to product development. This is portrayed in Exhibit 1-1.

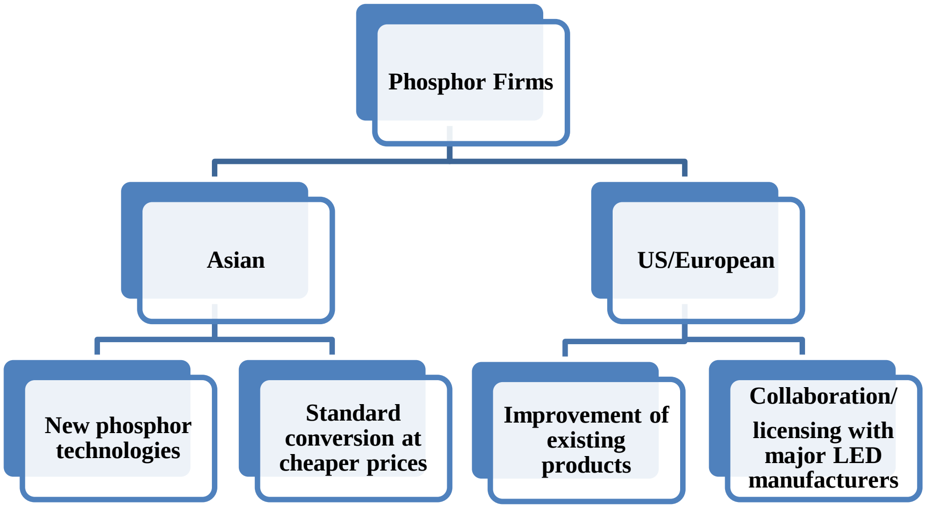

Exhibit 1-1: Phosphor Product Development Strategies by Geography

1.1.1 Emerging Requirements for LED Phosphors

For now the standard, blue chip Ce:YAG combination is the most popular on the market, green and red phosphors are steadily growing their market share, particularly for applications that require a high CRI and good color reproducibility, such as general lighting and liquid crystal display (LCD) backlights in cell phones and flat-panel displays.

What NanoMarkets is seeing though is intensified competition for new green/red phosphors. What this means in practical terms is that certain companies—like Intematix (U.S.) and Mitsubishi Chemical Group Science—are actively working in this area and strengthening their IP. Where we believe the thrust of the important R&D work in phosphors needs to be in the next few years is in the areas discussed below.

Color-mixed solutions: In NanoMarkets' opinion, there is considerable room in the market for color-mixed solutions. The workhorse for current lighting products is phosphor-converted blue light, and there is still potential for energy improvement and cost reduction in that technology.

Color rendering indices: For high-quality LED solutions, the key factor is to increase the CRI at various color temperatures while maintaining high efficiency.

NanoMarkets believes that new phosphors that have broad emission spectra (except for the red phosphors, where a small bandwidth is needed to avoid NIR-losses), or emit at various wavelengths with minimized re-absorption are needed.

Color consistency over time must also be guaranteed. Color conversion requires temperature-stable phosphor solutions, while RGB (red, green, blue) solutions require color controls that compensate for the divergent aging properties of LEDs of different colors.

To take advantage of these opportunities, we believe that an understanding of the color mixing mechanism at the molecular level is needed to be able to maintain the same color impression during the lifetime of a single lamp and between individual lamps. This goal is difficult to achieve, however, because the temperature and aging behavior of red, amber, and blue LEDs is different.

1.1.2 Materials Trends: Novel Products and New IP

All commercially available phosphors are heavily patent-protected items and have become the basis for much of the IP litigation in the industry today. In NanoMarkets' view, however, an active search for novel phosphors is beginning, and we also believe there is plenty of opportunity for entrepreneurs and businesses to enter this area and create novel IP.

NanoMarkets believes that the materials that will be key to the technical development of new phosphors are garnets, silicates, aluminates, sulfides, selenides, nitrides, and oxynitrides. There are interesting trends occurring with many of these materials, particularly with respect to intellectual property issues.

Garnet: The IP related to Ce^{3+} doped yttrium aluminum garnet (Ce:YAG), or yellow phosphors, is mainly controlled by Nichia (Japan). Compositional modifications give CRIs of approximately 70-80. This color quality is acceptable for applications such as backlights for portable displays and indicators; applications which currently dominate the LED market and result in garnets dominating the phosphor market.

NanoMarkets expects that the important role of garnets in the LED phosphor market will continue. However, we think that there will be growing opportunities for new players to enter the market with improved phosphor solutions in lieu of licensing technology from Nichia.

Silicates: *We also expect something similar to occur in the silicate sector. Because Nichia's critical IP is set to expire in the next few years, an increasing number of phosphor manufacturers are offering YAG compositions as well.*

Sulfides and selenides: Sulfides and selenides are mainly patent-protected by Lumileds. However, in addition to any limitations that IP places on the use of these materials, NanoMarkets notes that this class of material has not been popular because it is sensitive to moisture and has poor stability and a low QE (quantum efficiency). There are also some regulatory issues due to the presence of sulfur compounds.

Despite all these negatives, we are seeing opportunities in this space, because when combined with YAG:Ce, however, warm white light LEDs are produced.

Nitrides and oxynitrides: A new approach is to add red and/or green phosphors to nitrides or oxynitrides to improve performance. This technology is currently controlled by Denka (Japan) and Mitsubishi Chemicals (Japan) through with strong IP.

The problem here is that the price of these materials is, however, five- to ten-fold higher than that of yellow phosphors. Thus, what we are seeing is that many research groups are scrambling to develop better and cheaper converters, and a large number of patents have been filed in the last two years.

One important example is Intematix's (U.S.) latest U.S. patents (numbers 8,529,791 and 8,475,683), which describe green aluminate (GAL) technology for rendering high CRI solid-state lighting (SSL). Companies are also investigating tungstates, molybdates, and carbidonitrides as alternative candidates.

The focus on new materials development and patent protection here has mostly shifted toward red and green converters. This is prmarily because current display and residential/ retail lighting applications demand LEDs with warm colors and saturated reds. There are also some new approaches emerging that involve the addition of a red/green phosphor to a yellow phosphor to increase the white light quality.

Other technologies: We also think that there are various other phosphor technologies that have what it takes to emerge as a winners. In NanoMarkets' opinion, the most promising include:

- Nanophosphors, synthesized from phosphor nanoparticles. These are already gaining in popularity.
- Mn^{2+} (manganese)-doped red phosphors. These were developed by GE (U.S.), and have the advantage of not contain rare earth doping agents.
- Hybrid phosphors prepared by functionalizing quantum dots (QDs) using glass phosphors or by tuning the desired emission quality. Proof of concept has already been demonstrated for these phosphore and we expected in-field testing to follow.
- Non complex phosphors. For example, scientists from the University of Georgia have created what is thought to be the world's first LED that emits a warm white light using a single light-emitting phosphor with a single emitting center for illumination.

1.1.3 Manufacturing Technology Challenges and Opportunities

Improving production efficiency for phosphors, NanoMarkets believes, is a major challenge that phosphor firms must overcome. LED phosphors are currently made in small batches mostly using manual processes, but volumes are doubling almost every year, and many of the manufacturing steps must now be automated. Various new kinds of phosphors are emerging that have demanding requirements and present a number of manufacturing challenges. These are reviewed in Exhibit 1-2.

As we see it, such automation will also address to some degree the current lack of consistency between phosphor batches, which can be significant and leads to the required testing of all incoming materials. And in the future, NanoMarkets expects that finer phosphor production technologies, such as spray pyrolysis, could also improve particle size control. A better understanding of particle morphology and the mechanisms of formation would also lead to improvements in both production and performance.

New phosphor deposition technologies, including thin film, multi-chip array, chip-on-board (CoB), package-free (phosphor on die—PoD), embedded LED chip (ELC), and flip chip, are being sought that improve emission uniformity and cost effectiveness. For remote phosphor application processes, the availability of more uniform and reproducible phosphor materials would eliminate the need for such matching processes and reduce costs. Thus, increased optical stability is needed to meet the requirements for longevity and performance, particularly for remote phosphor technology.

Exhibit 1-2: Phosphor Requirements and Challenges associated with Existing and New deposition Technologies		
Technology	**Phosphor requirements**	**Challenges**
Direct contact	High efficacy; high CRI; heat dissipation.	Increase in CRI at various color temperatures while maintaining high efficiency without generating heat.
Remote phosphor	Intelligent phosphor color engineering; high CRI and efficacy.	Difficult to achieve high CRI and warmness. Need for new types of phosphors, including solutions that optimize the ratio of phosphor mixing and new phosphors that have broad emission spectra (except for the red phosphors where a small bandwidth is needed to avoid NIR-losses) or emit at various wavelengths with minimized re-absorption. Color consistency over time has to be guaranteed.
Thin film	Nanophosphors; ink-printable phosphors; well-mixed phosphor slurries.	Need for new phosphor synthesis techniques with high quantum efficiencies.
Modular light engines/CoB	Remote phosphors; integration with encapsulants; uniform phosphor layering.	Need to develop highly efficient phosphors/ phosphor formulations and phosphors printed on plastic sheets. Thermal stability, no color loss.
Package-free/PoD	Uniform phosphor layering; high efficiency; novel polymer-phosphor slurry solutions.	New phosphor technology. Compatibility with new types of components. Controlled application of phosphor to the die.
ELC/Flip chip	Hybrid phosphors; RGB solutions.	Functionalized phosphors, color engineering, and no thermal quenching.

Source: NanoMarkets LC

There are also some opportunities in the area of novel substrates. Specifically, phosphors printed on plastic sheets that serve as diffusers of downlights are desirable. Some companies are also working on fabricating phosphors in injection-molded plastic domes that are designed to sit on top of an array of blue LEDs.

Thin films: In this technique, chips are packed tightly together to create multi-chip packages with high luminance, and nanophosphors are preferred. Spray pyrolysis could be an enabling technology here, since it provides for the formation of finer particles with a narrow particle size distribution that is suitable for formulating inks.

In addition, NanoMarkets believes that the use of nanoparticles will reduce the sintering temperature and allows the formation of thick layers at much lower temperatures. Nanoparticles are also better at minimizing optical scattering.

Multi-chip arrays: Packaged multi-chip arrays (or modules) offer two main benefits. First, they generate a high light output, but allow the heat to disperse, and will thus find use in spotlight sources in which multiple chips are densely packed on small-scale substrates that require a light output of

5,000 lumens or more. Second, these multi-chip arrays enable the high color rendering required for high-quality white light and color adjustment.

Two types of LEDS are currently prepared with these modules: phosphor-converted white LEDs and modules with blue-pump LEDs and remote-phosphor optics. In addition, we think that manufacturers should be able to develop custom red, green, and blue emitters for SSL that are not restricted to atomic transitions. Integration with encapsulants is another option.

NanoMarkets also believes that it may also be possible to mix phosphors directly into epoxy resins to create package domes, thus setting the phosphor apart from the chip, which would reduce its temperature and make the light source less point-like and more distributed. This approach will be extremely useful for CoB and similar techniques.

Phosphor on die technology: PoD technology was first launched in 2012. Manufacturers including Philips Lumileds (U.S.), Toshiba (Japan), TSMS Solid State Lighting (Taiwan), and Epistar (Taiwan) are promoting package-free chip products in which the phosphor layer encapsulates the die without additional packaging to create the emitting device. In this technique, controlled application of the phosphor to the die is very critical.

PoD package-free chip products have an increased luminosity rate of 200 ml/W and a beam angle of 300 degrees. In addition, because the use of secondary optics is not required, power consumption and costs are reduced. NanoMarkets believes that compatible, phosphor slurries, coated phosphors, and nanocrystalline phosphors will be needed for this technology.

Another package-free chip technology: LUXEON Q package-free chip technology has been, not surprisingly, the focal point of the industry in 2013. Philips Lumileds' first application of flip-chip technology for high powered LEDs involves pasting the phosphor mixed with glue onto the flip chip for cutting.

NanoMarkets believes there is significant potential here to develop phosphor sheets, and Epistar is already working on this technology. Compared to conventional dispensing and spraying methods, the phosphor sheets have higher uniformity, including optimized color uniformity and brightness. Nonetheless, manufacturers will have to investigate novel and more environmentally friendly synthesis methods that maintain high quantum efficiencies and lumen performance over the lifetime of the LED.

1.1.2 Two "Threats" to Traditional Phosphors: Quantum Dots and Rare Earth Shortages

Summing up the phosphor sector's prospects, we believe that we have illustrated above that there are many significant opportunities. But there are also some potential threats, although, as discussed below, these are in no sense immediate.

Quantum dots: QDs are not phosphors at all, but NanoMarkets sees them increasingly as a credible alternative to traditional phosphors in some applications. We think in particular, they are already competitive with red nitride in terms of cost of ownership for a system level solution but only used in remote phosphor configuration due to temperature sensitivity.

Nonetheless, there can be little doubt the high cost remains a major factor retarding the use of QDs as an alternative to phosphors. This largely is due to the complex wet chemistry associated with QDs and the relatively small batch size it implies.

NanoMarkets is confident that these issues around QDs are going to become increasingly resolved. What we are seeing is that leading QD manufacturers like QD Vision (U.S.) and Nanosys (U.S.) appear ready to tackle the challenge of large volume manufacturing for QDs that would result from a design win in a consumer display application. Also, we believe that once QDs achieve precise tuning to deliver only the needed/desired emission colors, this technology will pose a long-term threat to conventional phosphors.

Supply of rare earth metals: All phosphors are currently doped with rare earth metals, and previously, supply tightness and upward spiraling costs were feared.

Fortunately these fears were not realized, and the LED phosphor market is actually benefiting from a glut of new manufacturing capacity and a near-collapse in rare earth metal prices. New recycling technologies are also lowering the pressure on rare earth prices. All of this is driving down the cost, and hence, encouraging the rapid take-up of novel concepts for the development of novel phosphor technologies and the improvement of existing materials.

1.2 Objectives and Scope of this Report

The objective of this new NanoMarkets report is to provide an in-depth analysis and forecast of the LED phosphor market over the next eight years. It builds on the extensive experience that NanoMarkets has in the area of solid-state lighting and related materials. The in-depth analysis of market trends and major industry segments found in this report will help readers make informed business decisions.

This report examines the latest market strategies, products, and technical developments in the area of LED phosphors. We identify how performance improvements are likely to help grow addressable markets for phosphors, with an emphasis on general illumination, outdoor/street lighting, and backlighting, and where the potential opportunities can be found to make money in the LED phosphor market.

In this report, the various LED manufacturing technologies are evaluated and compared, assessments of the strategies of leading firms active in the LED phosphors space, and a forward looking perspective on the major factors driving and restraining market growth in the LED phosphor market are provided. In addition, this report presents a technological growth map over time and explains its impact on the market.

The report is written with a focus on emerging technologies that have recently been or have just been commercialized. Less space and effort is devoted to LED phosphor technologies that exist only on laboratory benches.

A broader objective of this report is to provide a detailed picture of the patent landscape for LED phosphors. The aim is to understand who owns what and identify key patents by composition or assignees. The report provides an overview of the phosphor-related IP litigation and licensing that has shaped the industry since the mid-90s, as well as the key players with the most relevant IP.

This report also includes a special focus on the emerging LED phosphor market in China and a demand/supply case study of rare earth metals. And, as always with NanoMarkets reports, this report contains a granular assessment of emerging down converters, like quantum dot LEDs, nano LEDs, and glass LEDS, highlighting their importance in this growing and dynamic technology segment.

1.3 Methodology of this Report

The information for this report is derived from a variety of sources, but principally comes from primary sources, including NanoMarkets' ongoing interview program with insiders in the field of LED phosphors, including entrepreneurs, business development and marketing managers, and technologists involved with solid-state lighting and emerging electronics of all kinds.

Secondary research has come from a variety of sources, such as company and industry organization Internet sites, technical journals, press releases, trade association articles, company literature, and SEC filings.

The basic forecasting approach involved identification and quantification of the underlying markets for LED phosphors, along with their materials needs, and the technological and market pressures that will affect the growth prospects for white LEDs produced using phosphors. We also assessed the competitive landscape to determine the suitability and likely volume of LEDs that will be produced over the next eight years, and we considered broader economic developments that may impact LED phosphor development and commercialization.

This report is international in scope. That said, due to the nature of the research, much of the work on LED phosphors is taking place in the developed world. The forecasts given are worldwide, with the selection of relevant data based on importance, not on the location of the firms and research discussed.

1.4 Plan of this Report

Chapter Two is an overview of the emerging material and research trends across LED phosphor technologies. It covers work done in the private sector at both large and small companies across the globe. Where applicable to commercialization, university research is also discussed. A special focus is placed on the value proposition of LED phosphors.

Chapter Three discusses the state of the LED phosphor market and its future development and opportunities. In addition, this chapter is separated by application, and the emphasis is on the largest opportunities, which are not necessarily the largest markets.

Chapter Four provides our eight-year forecast for the LED phosphor technologies and applications that are discussed in the report.