Analysis of LED Technologies for Solid State Lighting Markets

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Abstract

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Energy saving or emission reduction is crucial for sustainable development. Lighting emitting diode (LED) has been proven to be the most promising lighting technology because of its potential to save a large amount of electricity. However, the market share of LED is limited by its high initial purchase price and poor performance in color rendering. This paper discusses basic concepts of color science and color rendering. Different methods of measuring color rendering and the new standard under development by the International Illumination Committee and several industry leading companies are introduced. Furthermore, the current situation of the LED market and the different roles of leading companies are discussed. Finally, a forecast of the future of LED and its market pattern will be given based on an analysis of the market.

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Introduction

According to a report from the U.S. Energy Information Administration, national primary electricity consumption was about 40 quadrillion BTU in 2010. The Department of Energy (DOE) estimates that lighting for residential, commercial, industrial, and outdoor uses were responsible for nearly 25% of that figure. If Solid State Lighting (SSL) technology replaces the current low-efficiency lighting bulbs for general illumination, 16 quadrillion BTU would be saved in the next 20 years [1]. No other lighting technology has as much potential to save energy as SSL, and it is regarded as an ideal lighting technology to meet the requirements of President Obama's energy and environment agenda, which is calling for the development of "the Cheapest, Cleanest, and Fastest Energy Source – Energy Efficiency. [1]"

The worldwide lighting market is estimated at about USD 110 billion [1]; it has shown a distinct transition from the low-efficiency incandescent bulbs to the relatively high-efficiency fluorescent lighting bulbs in residential and commercial markets over the past ten years. However, the lighting market is facing some challenges in shifting to an even more efficient lighting technology. The high initial cost, general lack of awareness, and relatively poor color rendering of Light Emitting Diodes (LEDs) hinder the further development of SSL. We know that when fluorescent lamps were initially introduced, most customers did not show a positive attitude towards them; however, due to the outstanding performance of fluorescent bulbs, the resistance decreased. Though many experts hold the opinion that LED will be the most promising technology for the next few decades, it still needs improvement.

Color rendering is one of the most important factors to consider when we evaluate the overall performance of LED bulbs. It is the ability of a light source to reproduce the color of an object that is lit by that particular light source. Unlike incandescent bulbs, which have a continuous spectrum that contains all the visible light human beings can perceive, the spectrum of LEDs is discrete. If an object's color happens to be in the spectrum range that LEDs are missing, the color our eyes detect is absolutely wrong. Different occasions have different requirements for color rendering; for example, we do not necessarily need a high-accuracy color reproducing light source in the bathroom, but we do need one for a display of paintings or jewelry. In the latter case, the color will directly affect the feelings of buyers, which is why color rendering is sometimes the most important aspect for commercial use of lighting.

In this paper, we will explore both the technical and business side of LEDs, especially in color rendering. We will start from the basic science of color and how human beings perceive light. After that, several concepts related to color rendering, such as color space, tristimulus values, and color matching functions, will be introduced. How to measure color rendering and the standard by which to evaluate the color rendering index will follow. Even though the standard of color rendering set by the International Illumination Committee (CIE) is widely accepted, it is still not enough for an accurate evaluation. A new standard is under development by the CIE together with many big players in the market such as Osram and Philips. How they will balance the interests of different companies and what effects this new standard will have on the market will be predicted based on expert interviews.

Then, the supply chain of the LED lighting market will be discussed and different companies’ positions in the market will be analyzed. Philips, Osram and Cree will be investigated in detail. Finally, a full view of the LED market and its future will be shown.

Literature Review

A good understanding of basic color science is necessary to understand color rendering and the method of evaluating the color rendering index of a particular lighting source. Most information about color science comes from the color matching experiments conducted by Maxwell in the 1850s. These experiments were based on Young-Helmholtz trichromatic theory and Maxwell's trichromatic measurements, which suggest that any color of light can be matched by properly combining just three primaries; the three primaries refer to scarlet light (650 nm wavelength), green light (510 nm wavelength), and blue light (480 nm wavelength) [2].

These experiments are quite easy to understand. First, choose a target color. This target color can be any single-wavelength light or a mixture of lights with different wavelengths. Next, try to match this color by mixing three RGB real (visible) primaries, typically at wavelengths around 645 nm (Red), 526 nm (Green), and 444 nm (Blue). For moderately saturated and near-white colors, this method results in a direct color match. However, many target colors are more saturated, so they are not able to be matched by any mixture of three primary lights. In these cases, the third primary is mixed with the target color itself to desaturate the target color until it can be matched by a mixture of the remaining two primaries. Maxwell proposed the theory of imaginary primary colors, but he did not take individuals' differences in perceiving colors into consideration.

In the late 1920s, W. David Wright [3] and John Guild [4] worked independently to determine how people perceive colors, and their work was used to define the Standard Observer (how the average person sees color). Real color matching functions and CIE color spaces are derived from experimental data in their work. A brief review of how to calculate the CRI is shown below.

In Fig. 1, the y-axis represents the tristimulus values or proportional quantities of each Red, Green, or Blue primary color in the combination that matches the target color with a particular wavelength. The negative tristimulus values mean that the primary must be added to the target color as in Maxwell's experiments. The x-axis indicates the wavelength of a single-wavelength light. For example, for a yellow color of a single wavelength at 580 nm, 2.8 parts of the R primary light (read from the $r(\lambda)$ curve), 0.6 parts of the G primary light (read from the $g(\lambda)$ curve), and zero parts of the B primary light (read from the $b(\lambda)$ curve) will produce an exact color match for a "yellow" hue. If the light is actually a mixture of many different wavelengths, then the tristimulus values for each wavelength are multiplied by the intensity of light at that wavelength, and the products are summed across all wavelengths to determine the three tristimulus values [5].

By the above-mentioned method, we can determine the tristimulus values of all the visible colors. However, further adjustment must be applied since negative values are inconvenient in practical use. We transfer real color matching functions to XYZ color matching functions by the following manipulation [6]:

$$x_{10}(\lambda) = 0.341*r_{10}(\lambda) + 0.189*g_{10}(\lambda) + 0.388*b_{10}(\lambda)$$

$$y_{10}(\lambda) = 0.139*r_{10}(\lambda) + 0.837*g_{10}(\lambda) + 0.073*b_{10}(\lambda)$$

$$z_{10}(\lambda) = 0.000*r_{10}(\lambda) + 0.040*g_{10}(\lambda) + 2.026*b_{10}(\lambda)$$

As before, λ denotes a specific wavelength.

This is a pure mathematics transformation and it is not related to the color matching experiments even though we get three new parameters—x, y, and z. The new color matching functions are shown in Fig. 3. Therefore, the new three primaries (XYZ) are outside the gamut of all real colors, which means they are invisible. No color of light can reproduce them. However, the triangle built by the three imaginary primaries completely contains the chromaticity space of all visible colors, which can be described as the positive mixture of the XYZ imaginary lights. As can be seen in Fig. 1, the black triangle inside the color space is built by real RGB primaries; all the colors within the triangle can be produced by properly mixing these primaries. The colors outside of the triangle have to be described using some negative RGB values. After the transformation, the new primaries are located outside of the color space, and therefore, all visible colors are enclosed in the new triangle formed by the XYZ primaries.

It is clear that we need three values to describe a color, which indicates that the color space should be three dimensional (3D). Fig. 2 is a two dimensional (2D) color space that is commonly called a chromaticity diagram. In order to get coordinates for a 2D chromaticity diagram, the effect of luminance on the tristimulus values is made constant by normalizing the values. That is, the X and Y (the $x_{10}(\lambda)$ and $y_{10}(\lambda)$ values summed across all wavelengths) are divided by the sum of all three tristimulus values [5].

The normalized z value is redundant since the normalized weights sum to 1.0, so z can be recovered by subtraction:

$$z = 1.0 - x - y.$$

The x and y values are used to indicate the chromaticity of the color, as shown in Fig. 2. From this chromaticity diagram, we can reach two conclusions: 1) the outer edge of the tongue-shaped region represents monochromatic light (each point representing a pure hue of a single wavelength), and 2) colors on the straight line between any two points of color on the chromaticity diagram can be formed by mixing these two colors [2].

Now it is time to discuss how to measure the CRI. The procedure for the calculation is first to calculate the color differences (ΔE_i) of 14 selected Munsell samples when illuminated by a reference illuminant and when illuminated by a given illumination. The first eight samples are medium saturated colors, and the last six are highly saturated colors (red, yellow, green, and blue), complexion, and leaf green. The reference illuminant is the Planckian radiation for test sources having a correlated color temperature (CCT) < 5000 K, or a phase of daylight for test sources having CCT ≥ 5000 K. The process incorporates the von Kries chromatic adaptation transformation. The special color rendering indices (R_i) for each color sample is obtained by

$$R_i = 100 - 4.6\Delta E_{i;}\ (i = 1\ldots\ 14).$$

This gives the evaluation of color rendering for each color. The general Color Rendering Index (Ra) is given as the average of the first eight color samples. The score for perfect color rendering is 100. Note that the CRI is often used to refer to the Ra, but the CRI actually consists of 15 numbers [7].

Though the CRI is the only standard accepted worldwide, it has many drawbacks, especially when it is used for evaluating white LEDs [8]. The CIE is developing a new standard that works well with white LEDs, but before it becomes available, experts have reported that considering the CRI together with the gamut area index (GAI) will be a better way to rate the performance of LEDs [9][10].

The CRI is a gateway to understanding the LED industry from a technical side. Another two team members will work on two additional technical topics. Based on the understanding of LED technology, we will discuss the market and value chain.

Methodology

Information on the global LED market is based on a combination of scientific and business research. Scientific research includes three major points regarding LEDs: color rendering, efficacy, and phosphor-related issues. Business research covers supply chain analysis, global/regional market analysis, market strategies of big players and their positions in the supply chain, and sensitivity analysis of the LED industry. This paper is mainly focused on the analysis of color rendering, supply chain analysis, and 360 degree analysis of major companies.

First, color rendering is investigated. We started from classic and basic materials about color science. Then, regarding LED lighting technology, the fundamental methods of testing the color rendering index and analyzing color quality are investigated in depth by reading reports from the standard setter, CIE. In addition, the latest papers from prestigious national laboratories, companies, and universities are crucial for determining the current status of this technology, including what challenges people have and what methods they are using to solve problems. Potential alternative technologies, such as laser diodes, and the influence these will have on the current market are also researched. Talking with professors and experts in this area also helps deepen our understanding of the latest trends.

Second, supply chain and three major companies' roles in the market are investigated. This business research involves in-depth interviews with experts to obtain information on the trends, market, distribution, and technological breakthroughs in LED market. Experts from both industry and academia are chosen in order to obtain different perspectives. Data is gathered from relevant sources, including consumer and industry publications, newspapers, government reports, company literature, and corporate annual reports. The DOE's annual reports, industry forecasts from consulting groups such as McKinsey, white papers from different governments, and magazines on lighting are reviewed.

Some companies and research institutions have their own supply chain models of the LED market, but they are basically the same with each other with slight differences. In this project, we mainly analyze the supply chain based on the Philips' five-level model, which will be discussed later. Several companies reside in each level of the supply chain. The manufacturing equipment supplier and chip maker are at the bottom, and companies that supply lighting solutions and energy management systems are at the top. Companies like Osram and Philips which are at the top of the supply chain will be discussed since that part is the closest to customers and it generates a large profit. Moreover, the top of the supply chain is the most competitive part of the market. Philips and Osram are the most prominent players in the lighting market, and share similar marketing strategies. For example, both acquired specialty companies to integrate the supply chain.

Discussion

More and more countries are in the process of phasing out incandescent bulbs because of their low efficiency. Compact fluorescent lamps (CFL) and LEDs are better choices for general illumination since they are both far more efficient than traditional incandescent bulbs. CFLs currently have more market share than LEDs as a result of their lower price. However, the advantages of LEDs over CFLs, such as longer lifetime, better color rendering, and even higher efficiency, have convinced experts and lighting companies that they are a better choice going forward. Therefore, the continued fall in costs is set to accelerate the growth of the LED segment, leading to the greatest changes ever seen in the lighting market[11].

Over the past four years, LED component consumption was dominated by mobile phone and other backlighting applications. According to Strategies Unlimited, LEDs for general lighting were 5% of the lighting market in 2009, and it forecasts 32% growth with a 44% compound annual growth rate over next five years. Veeco, the global leader in process equipment solutions for LEDs, expects 48% compound annual growth through 2013, and expects that general lighting will account for around 25% of the total demand. Regarding the cost, Cree, a market-leading innovator of LED components, reports that lumens per watt (a key measure of efficiency) has doubled every 18–24 months over the past 20 years due to better design; this will be a major factor of continually reducing cost [11]. In high CRI (76–90) SSL, the DOE expects efficiency to be 147 lumens per watt in 2020, rising to 176 lumens per watt in 2030 [1]. The price for a kilo lumen is also expected to drop from $170 to $5 by 2030 for high CRI products [1]. The DOE also expects SSL to completely displace all other technologies in commercial, residential, industrial, and outdoor segments by 2030.

Based on our research, we identify four levels in the LED value chain.

Level 1	LED chips & materials: Philips Lumileds, Nichia, Cree, Osram, Toyoda Gosei
Level 2	LED modules & components: Toyoda Gosei, Cree, Osram, Nichia, Philips
Level 3	LED lamps: Philips, GE, Osram, Cree
Level 4	Applications & solutions: Acuity Brands, Zumtobel, Osram, Philips, GE

LED chip manufacturing has been developed on the basis of traditional semiconductor production, which requires highly automated plants and high capital intensity. Metal organic chemical vapor deposition (MOCVD) is one of the most important processes in the manufacturing of LEDs. Veeco and Aixtron are the two major suppliers of MOCVD equipment, which represents over 50% of an LED fab's capital expenditure [12]. Veeco reported a full-year 2011 revenue of a record 979 million dollars, which is up 5% over 931 million in 2010 [13]. Three years ago, Veeco reported they had a 200% rise in orders and the LED market was responsible for 69% of that [11]. This figure indicates that major LED manufacturers were expanding their capacity at that time, which is also the main reason to anticipate the upcoming growth of LEDs in general illumination.

In the higher levels of the value chain, Philips believes that the key to success is to build a strong position in applications and solutions, such as luminaires and lighting solutions [14]. However, the difficulties for companies to penetrate this area include the lack of channel to end users and the high level of customized solutions. Philips, Siemens

(Osram), and Cree will be discussed in detail. Philips and Osram are number one and number two, respectively, in terms of market share in the lighting industry as well as LED lighting. Cree is a U.S. company that is leading the development of LED chips due to its consistent innovation as well as support from the government. Cree is a typical example of a company benefitting from preferential policies from the government.

Philips lighting is the global leader in LED components, applications, and solutions with a strong global presence across the LED value chain. It holds 70% of all patents on LED applications [11]. In 2011, the total sales amounted to EUR 7.6 billion and LED-based products grew to over 16% of the total sales, up from 13% in 2010 [15]. Sales in growth geographies increased to over 40% [15] of the total lighting sales, driven by China and India. In North America and other mature geographies, the growth is very low due to the lower demand. Regarding the trends of the industry, Philips said it is witnessing the transition from bulbs and components as the point of value creation to end-user-driven applications and solutions. This point leads us to believe that the key for a lighting supplier to succeed will be having the innovative strength to create systems and solutions that are truly customer-centric and highly customized, while leveraging the supply chain scale. Philips has been more competitive than before in integrating the supply chain by acquiring specialty companies. From 2005 to 2010, Philips acquired 12 companies [14] specializing in lighting chips and components (e.g., Lumileds in 2005, Lighting Technologies International in 2007), applications and solutions (e.g., Color Kinetics in 2007, Dynalite in 2009, and Amplex in 2010). These acquisitions together with Philips' strong customer base and brand franchise help Philips Lighting span the entire lighting value chain, from light sources, electronics, and controls to full applications and solutions.

Philips' other advantages include strong value chain partnerships, strong distribution partnerships, especially in Original Equipment Manufacturer (OEM), leading the industry in standard setting initiatives, a strong intellectual property position, and a platform approach to drive scale and cost down.

Osram is one of the two leading light manufacturers in the world after Philips. It is also a wholly owned subsidiary of Siemens and is in the process of an IPO. In the 2011 financial year, the sales of Osram were EUR five billion with LED-based products responsible for 20% of the total sales [16]. Osram also says that it has a strong presence across the entire lighting value chain with an extraordinary strength in supplying automotive lamps, LED for vehicles, and electronic control gear for lamps. Osram Opto Semiconductors announces it is the number two in LED chips manufacturing, behind Nichia and ahead of Cree. Osram holds important intellectual property rights together with Nichia and has licensed the rights to other companies. In order to reduce manufacturing costs, Osram purchases 40% of its external volume and 80% of its merchandize from Low Cost Countries (LCC), and the headcount in LLC is representing over 60% of total employees [17]. For a better integration of the upper levels of the value chain, Osram acquired Traxon in 2008, which enhanced its ability to provide highly customized LED lighting solutions and lighting management systems. Osram sees the acquisition of Traxon as a success that has brought in over 200 projects and a strong revenue growth in the next year of the acquisition. Similar to Philips, Osram sees its tight relationship with customers as an important advantage over other companies. Other advantages of Osram include setting standards for LED headlights, a strong LED IP position, and producing the first fully qualified Organic LED.

Cree is a U.S. leading innovator of lighting-class LEDs. Cree is focused primarily on LED chips, LED components, and LED lighting products. It considers Nichia to be the competitor with the largest market share for LEDs, based on industry information [18]. Cree's net revenue of the financial year 2011 was USD 987 million, of which LED products represented 90%; this is double the revenue of 2008 [18]. Clearly, Cree is not a company like Philips or Osram who have a global presence across the entire value chain. However, this company is chosen for discussion because it has strong support from the U.S. government and plays an important role in President Obama's energy plan, the DOE's multiyear program plan for SSL, and Obama's jobs plan. Cree benefits from U.S. federal funding, financial backing, and a platform for partnerships provided by the DOE and the North Carolina state government's preferential policies. Unfortunately, because of the high upfront cost and low consumer awareness, Cree has reported persistent market barriers to the wider adoption of LEDs in the U.S [19]. In contrast, in China, Cree benefits from the Chinese central government's policy in reducing emission, the booming construction industry, and the top-down approach to strategy execution. For example, in the 2008 Beijing Olympics, the Bird's Nest stadium and Water Cube aquatic center were lit by 750,000 red, blue, and green LED chips manufactured in Durham by Cree [20]. It is also reported that over 40% of Cree's sales are generated in China [11]. Even though Cree's focus is shifting to emerging markets like China and India, it is still committed to the U.S. market, with its focus on innovation, using U.S.-based suppliers, and creating more jobs. Cree is trying to achieve higher rates of adoption through its LED awareness programs in the U.S., and is one of the most innovative LED companies worldwide based on the fact that it holds exclusive rights under 721 issued U.S. patents and approximately

1228 foreign patents with various expiration dates extending up to 2036 [18]. Due to its continuous innovation, its number of employees has quadrupled in the past ten years. Cree’s example illustrates the importance of consistent innovation and R&D, especially in the post-financial-crisis period.

Conclusion

Regarding CRI, a new standard is under development by the CIE and major companies in the lighting industry. However, the reaction of companies to this new standard is not as big as it was supposed to be according to our expert interviews. In fact, most of the major companies have their own methods and standards for evaluating and improving color quality, which is also why those companies cannot reach an agreement on the new standard easily. Therefore, the new standard is likely to have a limited impact on the current industry.

Philips, GE, and Siemens/Osram are key players in the highly consolidated conventional lighting industry; these companies consider LEDs to be the driving force for further growth of the lighting market and the differentiator for the market dynamic of the big three. However, the LED industry is in its infancy, with a variety of competitors entering the marketplace. Generally speaking, the LED lighting industry is currently fragmented with different competitors in different regions and segments. For this reason, it is difficult to come to a conclusion on who will be the real winners in the new world of lighting. However, it is plausible that suppliers closer to the customers, who are able to offer highly customized solutions and energy management systems focusing on lighting quality, reliability, and energy efficiency, will be in a stronger position.

Figures

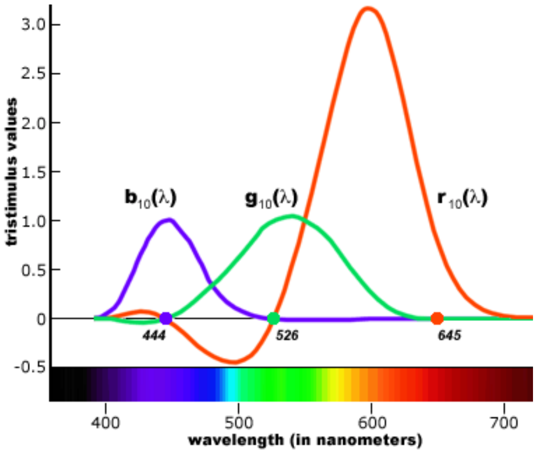

Fig.1 Real color matching functions

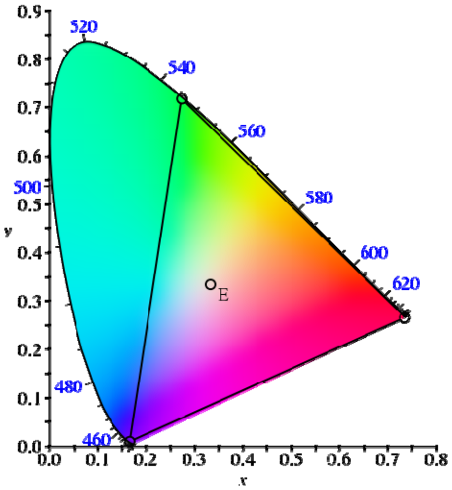

Fig.2 CIE color space (chromaticity diagram)

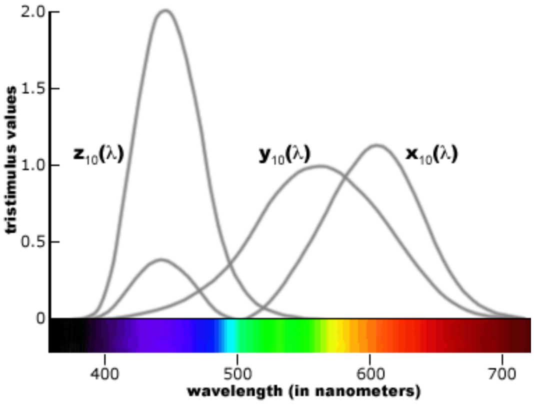

Fig.3 Color matching functions

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