Analysis of LED Technologies for Solid State Lighting Markets

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Abstract

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Light emitting diode (LED) technologies present significant advantages compared to today's lighting solutions: LEDs are favorable in terms of their electrical efficiency, economical value, and environmental impact. The question remains, when, if at all, will these technologies replace all the light bulbs and tubes in the world? We addressed this question by surveying both the technology and market landscape for solid state lighting. We found that solid state lighting technologies will become the dominant lighting solution within several years, as they steadily improve in color quality, brightness, and cost, and receive support from environmental and political policies.

Contents

Introduction

Light emitting diode (LED) technologies are currently growing in competitive presence within the worldwide lighting market. Compared to incandescent, fluorescent, and halogen lighting solutions, LED technologies present competitive advantages in terms of their electrical efficiency, economical value, and environmental impact. However, the question of when and how LED technologies may replace all the light bulbs and tubes in both the United States and the world remains open.

From the perspective of a stakeholder within the global lighting market, understanding the entire LED supply chain is valuable in making any investment decision. Therefore, our research group presents an analysis of LED technologies by fully investigating the entire LED supply chain. The results in this individual report focus on the lower-level segments of the LED supply chain, specifically the design and production of the actual white-light generating elements inside an LED bulb. The concerns for product lifetime, reliability, and cost of implementation are evaluated and compared for current state of the art technologies. To an investor, this indispensable information includes a cost breakdown of the current technologies, which may be used to weigh the advantages and disadvantages of choosing one technology option over another.

Additionally, we analyzed the different types of business models in the lighting market today, and evaluated which one may be a better solution for success. For example, companies like Philips, Osram, and Cree all have vertically integrated business models, meaning that they manage virtually all levels of the LED supply chain within the company, from low-level chip manufacturing and bulb assembly, all the way up to retail distribution. On the other hand, a pure-play company like Intematix focuses solely on phosphor manufacturing. Intematix is able to provide a wide range of versatile solutions for all phosphor consumers, including LED lighting companies. Both vertically integrated and horizontally integrated business models have advantages over each other.

Finally, we apply the trends of the technology adoption lifecycle to the LED lighting market. Since mass adoption of LED technologies has not yet been achieved, the goals for LED companies today are twofold. The first is to raise awareness through the marketing and advertisement of LED lighting. The second is to continue to improve LED color quality, efficacy (lumens brightness per watt of electricity), and the price. Once mass adoption is achieved, LED companies will then be able to focus on adding more functionality and value to the light bulb itself. Additional applications such as color tuning and integrated lighting control systems may then be developed.

Literature Review

Background

Light emitted by LEDs have different properties compared to the light emitted by incandescent bulbs. Incandescent bulbs emit light in a continuous spectrum, where the light is produced by heating a metal wire filament to generate blackbody radiation. However, LEDs emit light with a discrete spectrum, having only narrow and individual wavelengths of light[1]. LEDs are p-n junctions which emit different colors of light by using different active region semiconductor materials. For example, ternary compounds such as AlGaInP and AlGaAs are used to generate red light, GaN and AlGaP are used to generate green light, and InGaN used for blue light[1].

There are several approaches to generate white light using LEDs, three of which are described below. The first is to use individual LEDs with red, green and blue colors, together in one light bulb, to produce white light. The second is to use ultraviolet LEDs, which illuminate a red, green and blue phosphor. These phosphor materials convert the high energy UV light from the LED chip, down to lower energy wavelengths of red, green and blue light. The total light is combined to produce white light[1]. The third option is to use a blue LED to illuminate a yellow phosphor.

We believe that the third option is the best approach to generate white light at the time being. This design does not require the use of hazardous UV light, which causes deterioration of both the phosphor material and the internal packaging of the LED bulb. Additionally, the blue LED driven phosphor design does not require complex feedback control circuitry present in a 3-color mixed LED bulb. The feedback circuitry is required in a 3-color LED bulb because the individual colors need to be mixed and tuned precisely. Additionally, each individual color behaves differently, both over time, and over a range of operating temperatures, so that the control circuitry must be designed to take these effects into consideration as well[2].

Raw Materials

The primary ingredient within an LED's phosphor material is a crystal mineral host lattice doped with rare earth ions[3]. When the rare earth ions that reside within the host material are illuminated by light, they vibrate around and emit energy in the form of light of different wavelengths. Unfortunately, the mining of rare earth raw materials creates a lot of pollution and environmental harm. Thus, in the year 2010, China, as supplier of 97% of the world's rare earth demand, began imposing severe sanctions regarding rare earth mining, in order to control pollution. As a result, rare earth prices have alarmingly increased by ten-fold within the past two years[4]. In addition to controlling 97% of the world's rare earth oxide production since 2002, China is imposing new tariffs and mining regulations, while simultaneously reducing exports by up to 40%[5].

The United States has responded to rare earth export sanctions imposed by China by passing several legislations of its own. Legislation has been passed to permit the re-opening of rare earth mines within the United States, as well as promote rare-earth stockpiling and rare-earth recycling measures[5]. Recently, this has spurred the restarting of rare earth mining in the United States, such as the action taken by Colorado based Molycorp Minerals LLC in 2008. Molycorp purchased the previously closed-down Mountain Pass mine in southern California[4]. Overall, however, the imbalance in rare earth supply should settle within the next few years, as global mining companies reopen, and a more balanced distribution of rare earths is achieved worldwide.

Environmental Impact

Rare earth mining creates a lot of environmental pollution. However, the amount of rare earth materials used in fluorescent lighting bulbs and tubes today is much more significant compared to the amount present in LED bulbs. Fluorescent tubes are fully coated internally with phosphorescent material, while LED bulbs can simply illuminate a local patch of phosphor material. Fluorescent tubes and bulbs also contain mercury vapor, while LED bulbs are mercury free. When comparing the relative environmental footprint of both fluorescent lighting and LED lighting technologies, LEDs are more environmentally friendly in terms of raw resource consumption and waste generation. Additionally, LEDs are much more energy efficient- a typical incandescent lamp produces 10 lumens of brightness per watt of electricity, a fluorescent lamp 60 lumens per watt, but an LED more than 150 lumens per watt. Additionally, the luminous efficacy of LEDs is still growing steadily each year[2]!

Phosphor Manufacturing

In terms of phosphor manufacturability, rare earth doping of crystal garnet host materials is easily achieved. Prevalent host lattices (such as YAG- Yttrium Aluminum Garnet)[6] crystallize in the cubic system, and can be easily doped through the ubiquitous Czochralski crystal growth pulling process [7]. Czochralski crystal pulling is common, because it serves as the standard process used for the fabrication of the silicon wafer substrates found in every computer chip in the world. Multiple phosphors, each with different rare earth dopants, can be used in one bulb to produce more colors and increase color rendering capability. For example, Neodymium doped YAG emits green wavelengths when stimulated, and Europium doped YAG emits red wavelengths when stimulated[3].

Phosphors are also very flexible and versatile when used inside an LED bulb. Yu has shown that by changing the dimensions of phosphor volume, dimensions of phosphor particles, or the placement of the phosphor material relative to the LED chip, the output light colors will vary[8]. Specifically, Yu has quantified results for varied densities of phosphor particulate mediums, in terms of their absorption and emission properties. Additionally, Wenzl has shown that mixing or stacking layers of phosphor reveals improved color conversion efficiency and color rendering[9]. Also, Xie has demonstrated that the incorporation of oxynitride and nitride into phosphor materials can tune light generation properties as well[10].

Competing Technologies

Although blue LED driven yellow phosphors are the most widely used technology in the mainstream LED lighting industry today, there are definitely other technologies being investigated for white light generation. New materials besides phosphors have been confirmed to generate light, such as those from Cadmium Selenide and Zinc Selenide nanoparticles[11]. These nanoparticles are also illuminated by a blue LED chip, but suffer more from quality and performance degradation over time and at higher operating temperatures compared to phosphors. However, one advantage they have is that the color of light emitted by nanoparticles can be precisely tuned, by varying the size of the particle itself[11]. On the other hand, lasers have also been investigated for generating white light. Nichia has demonstrated a high brightness, white light source, using a blue laser diode driving a phosphor material[12]. Additionally, Sandia National Laboratory has demonstrated a four color laser illuminant system that achieves high color rendering quality, without the need to use phosphor materials at all[13]!

In terms of their market share today, these alternative technologies are less popular compared to phosphor illumination by LED chips. However, they are all viable technologies in the solid state lighting roadmap. Eventually, the quality, reliability, and actual product price will be the principle differentiators between choosing one white light generation technology over another.

Methodology

Motivation for Experiment

Our capstone project focuses on answering the question of when LED technologies will penetrate the entire lighting industry. We approach to the answer this question from two primary perspectives- the market perspective, and the technology perspective.

Design of Experiment

The methodology by which we executed our project is threefold. First, we investigated the brightness specifications of the lighting market in terms of lumens output. Second, we investigated the power efficiency requirements of solid state lighting technologies. Third, we investigated color rendering quality requirements, from both a market and technology viewpoint.

Additionally, we sought to determine what feedback loop continues to reinforce the LED value chain. Could any new and disruptive technologies build a competitive advantage against the currently standing value chain? To answer this question, we designed our experiment to investigate the sensitivity of the solid state lighting market to new challenges, opportunities, and solutions. We evaluated the current solid state lighting market status, its capacity for further technological improvement, and the impact of various feedback loops on the entire lighting industry.

Collection of Data

The information we acquired to answer these questions were gathered from market reports and technical research papers. Using results from technical reports, we evaluated new technologies and designs for the LED lamp. We also evaluated the trends and implications of the continued drive towards high volume manufacturing, and how it would serve to lower LED lamp costs.

On the other hand, we generated our market perspective from data taken from market reports, in order to analyze the entire solid state lighting supply chain. We break down the supply chain into five primary levels. Ranging from lowest to highest, these five levels are the raw materials suppliers, LED bulb component manufacturers, product assemblers and designers, distributors, and finally, the end users. We analyzed one or two companies at each level of the supply chain to understand their value net- their relationships between their customers, competitors, complementors, and suppliers. This information serves to identify which company, if any, will be dominant in the entire LED supply chain.

Details of Data Analysis

The technical portion of this research report begins with a focus on the extraction of raw materials for the production of LED phosphors, including the mining of both rare earth metals and crystal garnet host minerals. The significance of environmental concerns is evaluated, according to our analysis of environmental impact based on a literature review of environmental reports, such as those provided by the United States Geological Survey (USGS). The significance of political concerns is evaluated, based on a review of current government policies, incentives, and legislation surrounding solid-state lighting technologies. The implications of manufacturing the LED phosphor materials is first analyzed by understanding the method of growing rare-earth doped crystals. A comparison between the environmental footprint of the manufacturing of compact fluorescent lamps (CFLs) versus LEDs are calculated directly from the dimensions of a single light bulb to determine the amount of raw materials that go into an individual bulb.

Proximate phosphor versus remote phosphor technologies are compared to each other, with respect to their total phosphor volume, light extraction properties, and the color quality degradation due to chip heating over time. The benefits of multi-layer and multi-phosphor patterning are compared against single layer, single phosphor LED bulb designs, with respect to color control, quality, and efficiency.

We also investigate the advantages of potential disruptive technologies in the solid state lighting market space. To do so, we analyze how sensitive current phosphor technologies are to advancements and improvements of other competing lighting technologies on the market horizon. We consider three potential disruptive technologies- the first being a blue laser driven phosphor; second, replacing phosphor with quantum dots or nanocrystalline particles; and third, using multiple color LEDs instead of phosphors. We predict how each level in the supply chain may change as these potential disruptive technologies continue to improve.

Lastly, we predict when mass adoption for solid state lighting may occur, by analyzing the factors which drive the lowering of solid state lighting costs. These factors include the lowering of raw material cost, increasing product shipment volume, and improving high volume manufacturing.

Minimizing Effect of Anticipated Problems

Some problems we anticipated before conducting the research was the lack of data for technologies currently being researched. We minimized this problem by taking both the trend lines and lighting roadmap predictions into consideration, to make educated guesses as to the performance metrics and numbers we could foresee as reachable in the near term future. Thus, we attempted to minimize our prediction error by making reasonable assumptions.

We believe our research report has enough information to make a conclusion about the imminent success of solid state lighting technologies for the general lighting market. However, it remains unknown how the lighting market will change after solid state lighting achieves full market penetration.

Our research report has strived to show how the interplay between different market and technology variables will affect the market landscape. As solid state lighting technologies eventually exceed market needs for brightness, color, and cost, the lighting industry may then shift focus towards adding new functionality to lighting applications, instead of searching for another better alternative to solid state lighting technology.

Discussion of Results

Government Driving Force

The government has been, in a subtle way, one of the earliest adopters and proponents for solid state lighting technologies. The government is a key supporter of green energy and technology, and has taken the first steps to replace public lighting, such as those of streets and government buildings, with LED lighting products. As we investigated the market adoption lifecycle, LEDs are currently sitting at the brink of the edge of mass adoption. However, the push to really drive the purchasing of LED bulbs depends on having the market realize the value of LED products.

Therefore we believe that the government plays a key role in increasing general awareness of LED technologies, as more and more people begin to hear about and notice the LED products surrounding them, while the government continues promoting green energy. Legislation around the world, such as that in China, the European Union, and the United States, have already set schedules to phase out, and eventually ban, the production of incandescent light bulbs. This serves to both increase awareness of new lighting options and force the world to move to a new lighting technology.

Lighting Technology Comparisons

In order to compare incandescent, compact fluorescent lamp (CFL), and solid state lighting technologies, I constructed **Table 1** below. This table compares the performance and operating specifications for each kind of bulb. It also shows the total cost to own and operate each kind of bulb for 50,000 hours, where each bulb is rated to produce 1700 lumens of perceived brightness.

Table 1- Performance comparison of Incandescent, CFL, and LED bulbs

	Incandescent Bulb	Compact Fluorescent Lamp	Phosphor Driven by Blue LED
Input Electrical Power to Output Optical Power Conversion Efficiency	~5%	~10%	~25%
Luminous Efficacy (lumens per Watt)	17	75	90 (Warm White LED)
Lifetime (Hours)	1200	10000	50000
Bulb Cost	$1.25	$3.50	$20-40
Bulbs needed for 50k hours of use	42	5	1
Electrical Operating Cost (for 50k hours of use)	$750	$170	$142
Total Cost of Ownership	$802.50	$187.50	$180

The first row shows the electrical power input to optical power output conversion efficiency, for the three different kinds of lighting options. An incandescent bulb converts approximately 95% of the input electrical power to heat, such that only 5% of the input electricity is eventually converted into usable light. A compact fluorescent lamp performs about twice as well with a conversion efficiency of around 10%. Phosphor driven by a blue LED light source performs the best of all three with 25% conversion efficiency. However, the total brightness (lumens output) is not simply a function of the total output optical power.

Several steps are required to convert from output optical power (i.e. watts) to lumens. The first is to measure the total radiant flux. Then, the luminous flux is calculated based on the amount of radiant flux collected by one steradian of solid angle, multiplied by the sensitivity function of the human eye to different wavelengths of visible light. Incandescent bulbs, CFLs, and LED bulbs on the market today are, on the average, rated with luminous efficacies of approximately 17, 75, and 90 lumens per electrical watt. This means that for one watt of electricity, each light source produces that many lumens of perceived brightness. Keep in mind that this perceived brightness will vary from person to person because everyone's eyes have different sensitivities.

In addition to luminous efficacy, I also consider both the lifetime and cost of an individual bulb. I then use this data to calculate the total cost to own and operate incandescent, CFL, or LED bulbs, in order to produce 1700 lumens of output brightness for 50,000 hours of consecutive operation. The operating lifetimes for incandescent bulbs and CFLs are well known, while LED bulbs are claimed to be able to reach several tens of thousands of hours of operation. As an estimate, I chose 50,000 hours to be the operating lifetime of a phosphor driven LED bulb. The total electricity cost to power a bulb for 50,000 hours is then calculated as follows:

$$Total\ Electrical\ Operating\ Cost = \frac{1700\ lumens}{luminous\ efficacy} * (50{,}000\ hours) * \frac{\$0.15}{kiloWattHour} * \frac{1\ kiloWatt}{1000\ Watts}$$

The total cost of ownership is then calculated as the sum of the total electrical operating cost and the total cost to purchase N number of light bulbs (to keep the lights running for 50,000 consecutive hours). The bulb costs for each respective bulb category are estimated from the average household bulb market prices today. Finally, in comparison to incandescent and CFL lighting, the blue LED driven phosphor bulb is found to cost the least to own and operate, over the total assumed time period of 50,000 hours.

Conclusion

We analyzed how solid state technologies will disrupt the global lighting market, and how different players at different levels of the solid state lighting supply chain will interact with each other. Our analysis predicts that unlike the semiconductor integrated circuit industry, there will currently not be a dominant player throughout the entire LED supply chain. The levels of the LED bulb supply chain are relatively evenly distributed in terms of technology complexity. However, we do expect key players to exist within each level of the supply chain.

As we addressed the complex interdependencies and tradeoffs between different stages throughout the LED bulb manufacturing process, we found reason to believe that the phosphor driven LED technology has the ability to dominate the solid state lighting market for the near term future. New, novel technologies that propose improved light emission efficiency, directionality, and color stability, are also expected to mature over time. These technologies will definitely compete against the phosphor driven LED technologies, and play a role in the future roadmap of solid state lighting.

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