Analysis of LED Technologies for Solid State Lighting Markets

Cheng-Chih Hsieh

Electrical Engineering and Computer Sciences
University of California at Berkeley

Technical Report No. UCB/EECS-2012-156
http://www.eecs.berkeley.edu/Pubs/TechRpts/2012/EECS-2012-156.html

June 2, 2012

Acknowledgement

This work was supported by the Fung Institute for Engineering Leadership and Professor Connie Chang-Hasnain in the Electrical Engineering and Computer Sciences department. The author would also like to acknowledge his teammates Emmanuel Chao and Guannan Wang.

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By

Cheng-Chih Hsieh

A report submitted in partial satisfaction of the

requirements for the degree of

Master of Engineering

in

Engineering - Electrical Engineering and Computer Sciences

in

the Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Constance Chang-Hasnain

Professor Sayeef Salahuddin

Spring 2012

Abstract

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Cheng-Chih Hsieh

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University of California, Berkeley

Professor Constance Chang-Hasnain

This report focuses on the analysis of light emitting diode (LED) technology in the solid state lighting (SSL) market, that is, whether or not LED lighting products will replace incandescent bulbs and compact fluorescent lamps (CFLs). Today, the performance of LED bulbs is getting better and better, while the market share of LED bulbs in the SSL market is still much smaller than those of incandescent bulbs and CFLs. Hence, we analyze LEDs in terms of their fundamental technologies, such as color rendering, efficiency, and white light generation techniques, and in terms of social issues, policies, and market analysis. So far, our work has shown that for indoor lighting, the efficiency performance of LEDs is better than those of incandescent bulbs and CFLs. White light LED commercial products can surpass one hundred lumens per watt, which is much larger than the 60 lumens per watt of CFLs and the 12 lumens per watt of incandescent bulbs. The long-term costs of LED lighting are also competitive as compared with those of

other products. Therefore, LED technology will probably replace incandescent bulbs in the foreseeable future.

Table of Contents

Introduction

In the 21^{st} century, technology is leading us towards a more convenient life than we had in the 20^{th} century, but we have consumed enormous amounts of energy and resources to build modern society already. Now, our planet faces environmental crises: the greenhouse effect and pollution. Thus, it is important to find ways of saving energy and generating clean energy. A study from the department of energy (DOE) shows that lighting consumes 20% of the electricity used in the U.S. This is a tremendous amount. It is more electricity than computers and other electronics consume. Thus, reducing the electricity consumption from lighting is an important issue today, and since the first light-emitting diode (LED) was presented by Russian scientist Oleg Vladimirovich Losev[1], many studies have been done to address the possibility of using white light LEDs as residential lighting devices. Today, the white light LED has become a popular candidate to replace incandescent bulbs and compact fluorescent lamps (CFL), and the main issue in this report is to find out whether or not LEDs will replace traditional bulbs in the future.

In this report, I will examine all the considerations regarding using LED bulbs as indoor lighting devices. The analysis has two parts: technological analysis and business analysis. I will start with the technological analysis and then move on to the business analysis. To begin, we will compare LEDs with other alternatives in terms of technology. We will analyze the luminous efficacy of the commercial products now available in the market. Luminous efficacy is a very crucial index by which to judge the energy efficiency of a lighting device. We will talk more about luminous efficacy later in this report. Second, we discuss research related to the improvement of the luminous efficacy of LEDs and its potential impact on LED development. Third, we will focus on issues regarding the color performance of LEDs, the definition of the standard used to evaluate color performance in lighting devices, and the problems with the standard.

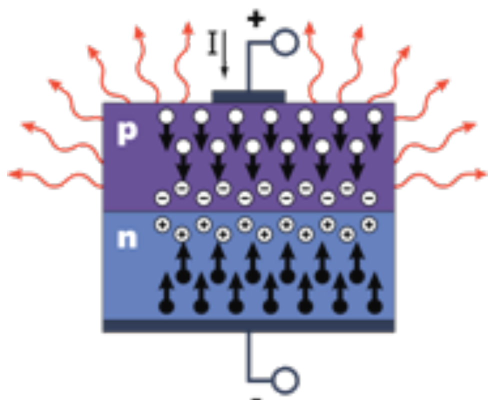
After the technological analysis is performed, we perform a business analysis. The business analysis is composed of the following elements: a comprehensive overview of the LED industry supply chain, which includes the position of each company in the supply chain, the cost structure breakdown, and the profiles of the major players in the market. Additionally, we will go deeper into the marketing strategies of LED companies and distribution channels. We also address future projects of these companies by evaluating the values of these projects based on technological availability. Finally, by combining the technology and business analyses, we can decide whether LEDs can dominate the solid-state lighting market in the near future or not.

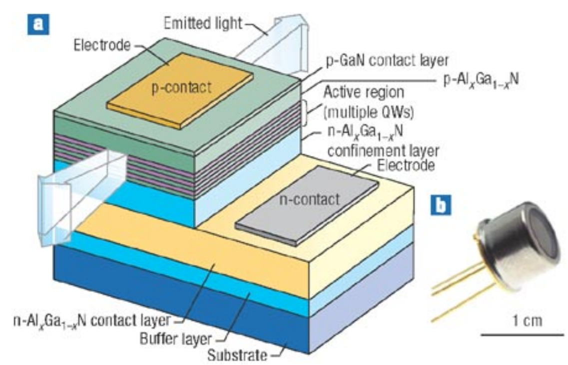
Literature review

Since the first LED was invented by Oleg Vladimirovich Losev[1], many studies have been performed in order to enhance the performance of the LED as a replacement for the traditional Edison lamp. In this section, I will review state-of-the-art LED technologies and the development of commercial LED products.

Fundamentally, the working principle of LEDs is simple: we apply a forward bias between the P-N junction, and there is a current in the junction. The carriers recombine near the interface and then generate light. **Fig.1**[3] shows the recombination of holes and electrons in the P-N junction. The studies on improving LEDs that have been done so far have included those on junction materials, the design of the semiconductor layer, how to extract light from the P-N junction, and heat dissipation during operation. **Fig.2**[3] shows the typical structure of an LED chip.

Fig.1 **Fig.2**





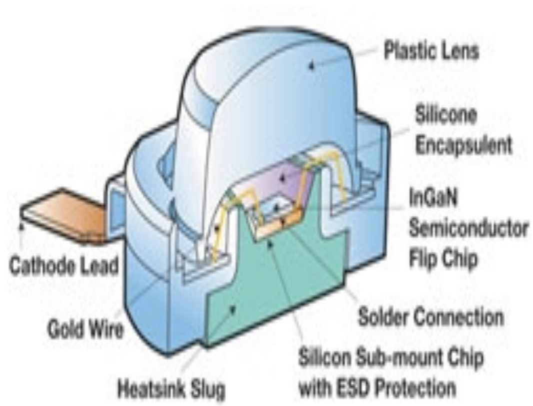


Fig.3[3] is the basic structure of an LED. The essential elements of LEDs includes an LED chip as a light source, encapsulant, a lens, bonding wire, and a heat sink. The design of an LED can be various in order to enhance the performance of the LED.

LEDs are favorable as light sources because of their lower levels of energy consumption and longer lifetimes as compared to incandescent bulbs and fluorescent lamps. We usually evaluate the performance of a light source by using the following three measures: luminous efficacy, lifetime, and color rendering index (CRI). Luminous efficacy, which is measured in lumens per watt, is defined as how bright a lighting source is given a certain amount of energy. Lifetime is defined by how long a lighting source can work normally. CRI is the most used quantitative metric of the ability of a light source to reproduce the colors of objects as compared to an ideal light source.

From the information on the commercial products of Cree Inc[2]. and the report of the U.S. Department Of Energy (DOE)[4], Table 1 shows the luminous efficacies, lifetimes, and CRIs of several light sources that are available today.

Light Type	Luminous efficacy (lm/W)	*Usable Luminous efficacy (lm/W)	Lifetime (hrs)	CRI
Incandescent	13-16	12-15	1.5-2k	100
T12 fluorescent[5]	60	40-50	20k	65-80
T8 fluorescent[5]	90	80-90	30-40k	78-85
T5 fluorescent[5]	90	75-85	30k	85
Halogen[6]	20	15-20	6k	100
Metal Halide[7]	65-70	30-40	10-20k	60-90
LED (cool white)[8]	150	100-120	50-80k	75
LED (warm white)[8]	100	65-75	50-80k	80-90

Table1: Luminous efficacy, lifetime, and CRI for commercial products

*Usable luminous efficacy is the expected luminous efficacy in real application.

From Table 1, it can be seen that both fluorescent lamps and LEDs are much more energy-efficient than incandescent bulbs. From the second column, it is clear that

LEDs have a higher luminous efficacy as compared with T-series fluorescent lamps, meaning LEDs are more energy-efficient. However, the luminous efficacy of warm-white LEDs for real applications is still lower as compared to that of fluorescent lamps.

Luminous efficacy can be broken up into several elements[5]:

$$\eta_L = \frac{\eta_{ext} \times \eta_{int}}{V_f} \times \eta_{phos} \times \eta_{pkg} \times hv$$

$where\ \eta_L$ = luminous efficacy, η_{ext} = extraction efficiency, η_{int} = internal efficiency, η_{phos} = phosphor efficiency, η_{pkg} = package efficiency, V_f = operating voltage, and hv = energy of light. I will now discuss the studies that have been performed in order to improve each term in the above equation.

First, to enhance the internal efficiency of LEDs, the prevailing approach is to use a quantum well active region, a double heterostructure (DH-structure)[9], and a current-spreading layer[10]. The quantum well and DH-structure enhance light generation from the LED chip, and the current-spreading layers reduce the current crowding effect, especially at high input currents, so that the input electrical power can be used more efficiently. The reason[9] quantum wells work so well is that the electrons in the quantum well have a higher density of states, which means that the probability of light generation will be higher with quantum well active region.

Additionally, a DH-structure confines electrons[9], so the electrons have a lower probability of leaking out of the active region. Moreover, a current-spreading layer increases two-dimensional electron gas (2DES) in the LED die, so the current from the electrode can spread more widely into the active region. Thus, the electrical power can be used more efficiently. Now, many companies have already achieved internal efficiencies of over 86%; however, LED dies confront heat-dissipation issues at high input currents.

Second, extraction efficiency is defined as how much light can escape from the LED die and go into the epoxy. There are many ways of improving extraction efficiency[11], such as performing surface roughening by using indium tin oxide (ITO) electrodes and coating a reflective layer on the substrate. By using the proper solutions to etch the surface of an LED die, the surface is roughened, and the light generated in the active region can escape from the surface much more than from a surface without roughening. In addition, ITO is transparent, colorless, and conducting, so ITO does not absorb visible light and is suitable to be an electrode in an LED. A part of the light emitted from the active region is reflected back into the chip at the interface of the chip surface and the epoxy. The chip itself absorbs the backscattered light, and this causese the extraction efficiency to deteriorate. To solve this problem, coating a thin reflective layer on the substrate can reflect the backscattered light back into the interface of the surface and the epoxy. Thus, it increases the chance for light to escape from the LED chip. Thus far, there are still some problems for commercial products attempting to reach high extraction efficiencies because of the cost. However, some academic papers have reported high extraction efficiencies that are over 75%.

Third, regarding package efficiency and phosphor efficiency, it has been proven that phosphor efficiency can reach nearly 98%. However, for package efficiency, different LED chip sizes and the shapes of LED bulbs affect package design dramatically, as does package efficiency. Nevertheless, a group from OSRAM[12] has reported that by using their patented package design, their LED bulbs have package efficiencies of over 80%. Usually, a lens package has a better performance than a flat package, and the different shapes of LED bulbs require different package designs. Moreover, high-power LEDs need package material that can endure high photon energies, such as blue light, without any deterioration and keep the refractive index desirable. Usually, for commercial products, the packaging efficiency is lower than 70%[11].

Also, the operating voltage affects the efficiency of LEDs, especially high-power LEDs, because high-power LEDs require high electrical input currents. Reducing the operating voltage of LEDs is also an important issue to manufacturers, and this can be achieved by increasing the chip size, improving crystal growth quality, and using a current-spreading layer. A current-spreading layer, as mentioned in the previous paragraph, can make the current go more widely through the active region, and increasing the chip size can also reduce both current crowding and the electrode obscuring the current from going through the chip.

Methodology

When can LEDs replace incandescent bulbs and fluorescent lamps as the dominant technology in the residential lighting market? It will occur when the LEDs outperform their competitors and the prices are competitive. My teammates and I decided to split this question into three parts: efficiency, color, and cost. These three factors are the key factors LEDs taking over the market. I am responsible for covering the issue of efficiency, and my two teammates investigated color and cost issues.

To start my research regarding the efficiency issues of LEDs, I studied some review papers about the development of LED techniques and the improvements that have been made. After picking up some basic knowledge about LEDs, I studied recent papers in the LED field to discover the state-of-the-art LED techniques and what the challenges to improve efficiency are. I collected the useful data regarding energy efficiency. The details of the literature review appear in the previous section. By understanding the state-of-the-art LED techniques, our team can start working on a business analysis of LEDs.

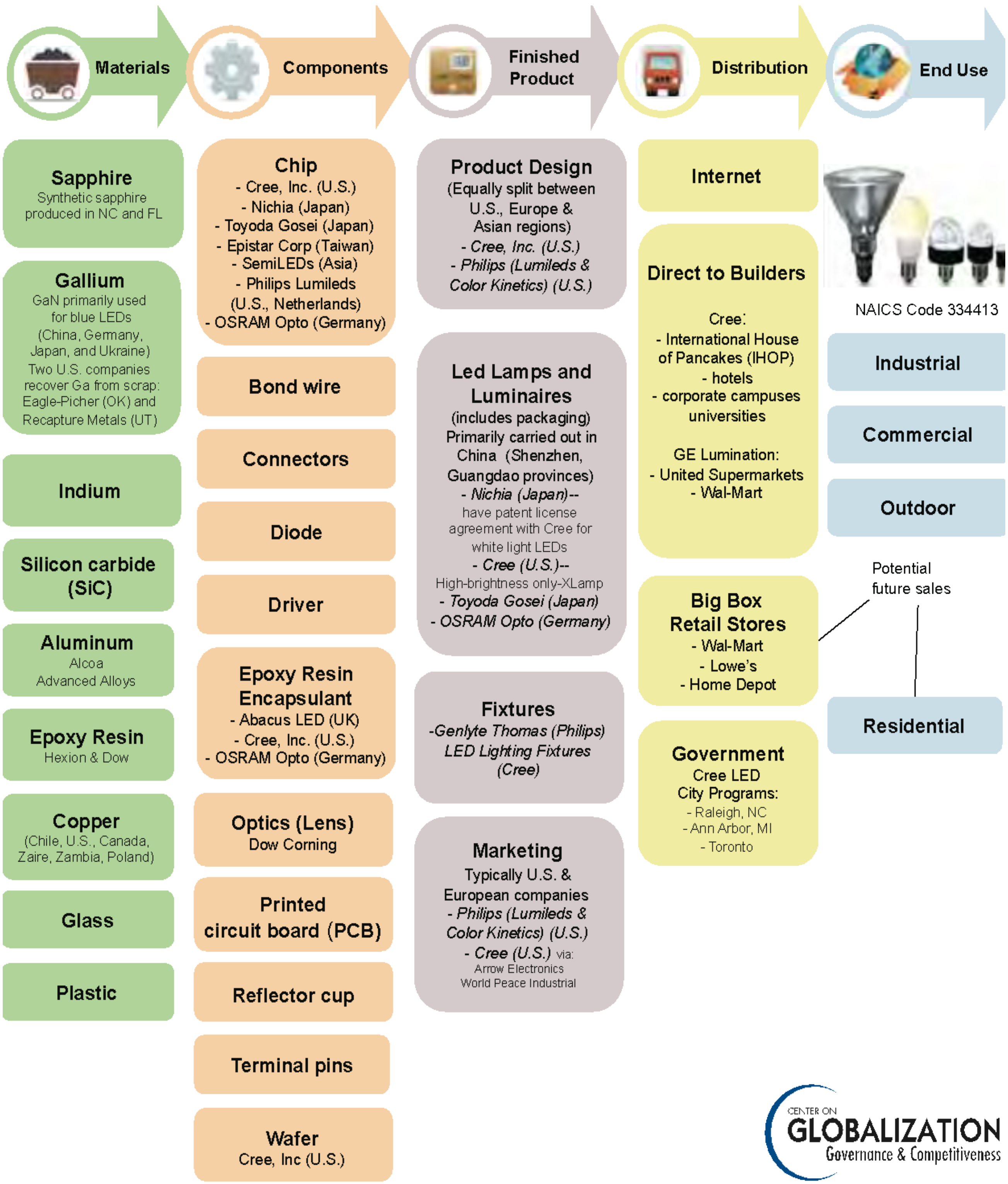
For the business analysis, the topic can be separated into three parts: industry profile, marketing issues, and potentially disruptive technologies. The industry profile includes the supply chain of LED products and company profiles. The industry profile helps us to understand each stakeholder in the market, their goals, and their methods of achieving these goals. Marketing issues include the technology adoption challenges, political concerns, and cost breakdown. To start this analysis, I referred to market reports from Frost & Sullivan[13], SBI Energy[14], and the multi-year program plan report from the U.S. Department of Energy[4] and arranged interviews with experts in LED marketing to ask them about the adjustments of the distribution channels in different regions, potential market segments, political concerns, and technology development.

After considering all the items mentioned above, the following question can be answered: Will LEDs fully replace incandescent bulbs or not?

Discussion

Industry profile:

Fig. 4[15] shows the LED lighting supply chain, which has five main segments: materials, components, finished products, distribution, and final sales. To date, LED residential lighting products have been sold in retail stores, but only on a small scale. Instead, LED distribution has occurred primarily through Internet sales and direct sales to businesses and builders. Three large players have traditionally dominated the general lighting market: Philips (the Netherlands), OSRAM (Germany), and General Electric (the United States). Philips, for instance, has a large facility, Lumileds, in California and is a major manufacturer of LED chips for use in the company's own packaged LED lighting products; it also sells packaged chips to other firms. OSRAM is a top manufacturer of LED components, as is General Electric, under its Ohio-based subsidiary, Lumination (formerly Gelcore). These traditional lighting giants must face competition from new LED lighting firms, especially in Japan, Taiwan, Korea, and other Asian countries. In the future, more players from Asian companies will join the supply chain, especially in parts of LED components and finished products. In conclusion, it is predicted that the value chain will become more complicated and more focused on residential sales through large retail stores.



Source: CGGC, based on company websites, interviews, industry sources, and Sanderson et al., 2008.

eFig.4

Marketing issues:

Regarding technology adoption, LED lighting is a mature technology, and it is interesting to discuss which factors will affect the timing of LEDs replacing incandescent lighting. There are three main factors: reducing manufacturing cost, increasing the awareness of LED benefits, and developing associated products.

Table.2[4] shows the profile of different lighting products in terms of energy efficiency, lifetime, and cost. It is obvious that the cost per kilolumen of LEDs, which represents the cost of lighting by different techniques, is one hundred times larger than that of incandescent bulbs. This indicates that although LED lighting is energy-efficient, its manufacturing costs are still much higher than those of CFLs and incandescent bulbs. From a technology adoption model, increasing the awareness of a new product is crucial to creating a bridge between early innovators and adopters. Now, in addition to governments, there are few efforts to enhance the awareness of LED lighting by private companies. A difference between an LED luminaire and an Edison bulb is that the LED luminaire can be designed for customizable applications in terms of the geometry of the lamp, the panel, the driver, and even the light spectrum. These associated products create value for LED lighting, making LEDs more functional in terms of different lighting requirements.

Table. 2

Product Type	Luminous Efficacy	Wattage	Color Rendering Index	Lifetime	Cost per kilolumen
60W Incandescent bulb	17 lm/W	60	100	1k hours	$0.5
CFL	71 lm/W	15	82	12k hours	$2
HID	120 lm/W	341	90	12k hours	$60
Cool White LED	130 lm/W	18	70	50k hours	$50
Warm White LED	60 lm/W	20	88	50k hours	$50

The policies intended to promote energy-efficient technologies also play an important role in the LED lighting market. For example, in Europe, the European Union (EU) has introduced a plan with a timeline to replace incandescent lighting with energy-efficient lighting. This is expected to benefit LED products directly. While other options, such as CFLs, are also expected to take over for incandescent lighting, the potential of this market phenomenon is expected to be so high as to benefit all the EEL technologies. This will be the prime driver for the market in both the short term and the long term. Another policy promoting LEDs is the Restriction of Hazardous Substances (RoHS), which prescribes regulations on the use of toxic substances in electrical products. In this respect, the use of mercury, which is not present in LEDs, in CFLs makes the market more favorable to LED lighting.

Potential competitor:

LEDs have been considered to be a more energy-efficient lighting source and a disruptive technology for a long time. However, laser lighting also possesses the same benefits that LEDs do and is even more energy-efficient. Though BMW has used blue laser light with phosphor in the headlight systems in its new cars, laser lighting is still an unaffordable option for residential lighting due to its high cost, low power, and poor color rendering ability. As a disruptive technology, laser lighting still has a long way to go in order to penetrate into the residential lighting market, but because of the directional lighting abilities of lasers, they have been used with optic fibers to illuminate environments such as museums and hotels.

Conclusion

There is a general expectation that over the next 10 years, the prices of conventional energy sources, such as crude oil and natural gas, will continue to increase and lead to a rise in the prices of electricity. This will increase the demand for energy-efficient lighting. LED lights will benefit from this, especially for large-scale commercial and industrial projects. Additionally, regulations promoting energy-efficient lighting are foreseeable in the near-term future, which will also impact the demand for LEDs.

Based on our analysis, the energy efficiency and color performance of LEDs will continue to improve. R&D and innovation are still required to enhance performance and reduce manufacturing costs. The increasing demand will form large economies of scale, which will lead to the large-scale production of LEDs and help to cut down on manufacturing costs. According to the technology adoption model, once the price of LEDs becomes competitive with existing lighting products, market awareness of LED lighting will increase. LEDs will then become favored and take over the entire lighting market share.

Acknowledgement

This work was supported by the Fung Institute for Engineering Leadership and Professor Connie Chang-Hasnain in the Electrical Engineering and Computer Sciences department. The author would also like to acknowledge his teammates Emmanuel Chao and Guannan Wang.

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