The Design and Manufacture of a Light Emitting Diode Package for General
Lighting

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By

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ABSTRACT

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Lighting technologies have evolved over the years to become higher quality, more efficient sources of light. LEDs are poised to become the market standard for general lighting because they are the most power efficient form of lighting and do not contain hazardous materials. Unfortunately, LEDs pose unique problems because advanced thermal management is required to remove the high heat fluxes generated by such relatively small devices. These problems have already been overcome with complex packaging and exotic materials, but high costs are preventing this technology from displacing current lighting technologies.

The purpose of this study is to develop a low-cost LED lighting package capable of successfully managing heat. Several designs were created and analyzed based on cost, thermal performance, ease of manufacturing, and reliability. A unique design was created which meet these requirements. This design was eventually assembled as a prototype and initial testing was conducted. This thesis reviews the design process and eventual results of the LED package design.

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Chapter 1: Introduction

One of the fundamental requirements for society is light. Since the first commercially viable incandescent light bulb was created by Thomas Edison, general lighting has evolved over the years. As energy costs have increased, there has been a growing need for more efficient light sources. Besides the cost of lighting, demand for better quality light has also increased. Better quality light sources provide various benefits; including better productivity, more architectural and marketing options, and even increased health [Figueiro, 2005]. High Brightness Light Emitting Diodes (HBLEDs) are capable of providing all these benefits.

Conventional lighting accounts for 11% of household energy costs [DOE, 2009b]. For schools, stores, and businesses, this number is closer to 40% [NEED, 2009]. Compared to fluorescent lighting, a HBLED lighting package does not contain mercury, a carcinogen. Another advantage of LED lighting is longevity. Many LED lighting packages are rated for 60,000 hours of use, which is 6.8 years of continuous lighting; 3 to 6 times more than a conventional fluorescent bulb. Some situations exist where the cost of replacing a light is much greater than the actual cost of the product, up to 16 times more [Philips Lumileds, 2008b]. In such cases, a longer-lasting light would be desired. Because LEDs are solid state devices, LED packages can be extremely durable compared to glass alternatives [L-Prize, 2008]. LEDs also have the advantage of being relatively small, providing the opportunity for more lighting options. As an example, the surface area of the LEDs used in this study is $.065 \text{ mm}^2$.

1.1 Current Lighting Technologies

The incandescent light bulb was the first commercially viable replacement for the standard candle, oil lantern, and gas lamp that dominated society until the invention of the standard incandescent light bulb by Thomas Edison in 1880. This design had remained as the standard light bulb in the United States for over 100 years because of its low cost, easy incorporation into electrical systems, and variety of applications and shapes [INVSEE, 2008]. Unfortunately only 8% of the energy used in incandescent lighting is converted to light; 73% of electrical energy is converted to IR radiant energy, and the remaining 19% of energy is lost as heat [DOE, 2009a]. This inefficient lighting has led many nations to require the discontinued use of incandescent light bulbs [Gajewski, 2007]. Brazil and Venezuela began the phase out in 2005, and many of the world's largest nations have continued the trend. By 2012; Argentina, Italy, Russia, the UK, Canada, the EU, and the US will have phased out almost all incandescent lighting [Gajewski, 2007]. The standard replacement for the incandescent light bulb is fluorescent and compact fluorescent technology.

Incandescent light bulbs and fluorescent light bulbs are both designed to emit light; however, the two technologies are much different. An incandescent light bulb is a filament within a vacuum surrounded by glasses. Fluorescent technology is more complex, but is a more energy efficient design. Fluorescent lighting's central element is a sealed glass tube. Inside this tube is mercury and an inert gas, sealed under low pressure. A phosphor powder is coated along the inside of the glass to provide white light. An alternating current is passed through the electrode within the device to force electrons to migrate from one end of the glass to the other. As electrons travel

through the tube, they collide with gaseous mercury atoms and are excited to a higher energy state. As the mercury atoms return to their original energy state, a photon of light is released.

Fluorescent lighting has evolved since the mid-1990s and has become increasingly popular. Fluorescent lighting produces more light, consumes less power, and lives a longer duration compared to incandescent lighting. Initially, there was resistance to fluorescent lighting due to the relatively large size, the distinct “humming” noise, unnatural colors, and delayed illumination when turned on. However, recent advances have solved or mitigated many of these problems. The advent of compact fluorescent lighting (CFLs) reduced the footprint of fluorescent lighting enough to replace the common incandescent light bulb. CFLs also include solid state ballasts, which produce little or no noise. CFLs have much better efficiency than incandescent light bulbs, with luminous efficiency reaching up to 100 lumens/watt [Durda, 2008]. CFLs still have the problem of containing mercury. Although CFL technology is much more efficient than incandescent technology, CFLs are not capable of the efficiency HBLEDs can deliver.

Many researchers believe HBLEDs will one day replace current conventional lighting [Grillot, 2006; Buso et al., 2008; NEMA, 2009]. Besides general lighting applications, HBLEDs can be found in architectural lighting, backlighting, decorative lighting, industrial and medical applications, mobile applications, traffic signals, and vehicle lighting. This is mainly due to the superior potential optical efficiency of LEDs in terms of lumens per watt. Currently, the maximum practical efficiency limit of an LED is 50% of electrical power absorbed converted to light [Philips Lumileds, 2008b]. A standard incandescent light bulb can only convert around 5-

8% of electrical power into light, and fluorescent tubes convert around 21% electrical power into light [Durda, 2008; DOE, 2009a].

1.2 LEDs in Developing Countries

Emerging technologies are usually reserved for developed countries. However, “leap-frog” technologies such as solar panels and LEDs are being considered and tested in developing countries to increase the standard of living of the poor. More than 2 billion people are without electricity and are forced to rely on fossil fuels for lighting and heat [Perry, 2006]. Kerosene “hurricane” lanterns are commonly found in developing countries for lighting. These lamps are very inexpensive; however, the kerosene fuel used is relatively expensive for those in extreme poverty. Kerosene is 2000 times more expensive when compared to the energy cost of LEDs for lighting purposes [Perry, 2006]. Transitioning from fuel based to electrical based lighting will require infrastructure updates, which is the natural progression of a developing country.

Figure 1 shows how much more efficient LED light is compared to the light output of a kerosene lantern. A relatively weak and inexpensive LED can produce similar light output, while delivering higher quality light. Higher quality light also results in a higher quality of living. More light allows extended work days, better safety, and better education [World Bank, 2008]. Bringing an affordable LED package can have a dramatic impact on the quality of life in developing countries.

Figure 1: Light Output and Efficiency of LED vs. Kerosene

Besides the cost, fossil fuels release pollution and carbon dioxide. Two-thirds of women with lung cancer in developing countries are non-smokers [Perry, 2006]. The World Bank estimates 780 million women and children are inhaling the equivalent of 2 packs of cigarettes per day in kerosene fumes. Figure 2 shows how much CO₂ is released by kerosene compared to CFL and LED technology. The Lawrence Berkeley National Laboratories stated the single greatest cause of greenhouse gases from lighting, 244 million tons per year, originates from developing countries burning fossil fuels for light [Perry, 2006].

Figure 2: Carbon Dioxide Emissions by Lighting Source, Source: Jones et al., 2005

1.3 LED Challenges

Although HBLED packages are beginning to be introduced into the market, several factors are preventing LED lighting from displacing alternatives. LED as a source of general illumination is still considered to be an emerging technology, and as such, the price of early adoption is relatively large. In most cases, a single high performance LED replacement bulb can range from \$40 to \$120. High prices are mainly attributed to the packaging of the device, which is due to the advanced thermal management needed to properly remove heat from the system [Arik, 2002].

Thermal management is uniquely challenging to LED lighting when compared to alternate lighting packages because of the method heat must be removed from the heat source. With incandescent lamps, heat and light are emitted through incandescence: materials heated to

temperatures greater than 750 °C to produce visible electromagnetic radiation [Schubert, 2006]. Conversely, LEDs emit nearly all energy either as electroluminescence or through conductive heat loss. Historically, light fixtures are designed to emit heat through radiation, not conduction. To design an LED lighting package that will replace current lighting solutions, special attention must be placed to safely conduct heat away from the package while still conforming to current lighting standards [NEMA, 2009].

Large amounts of heat through an LED die can produce several negative effects. Mainly, semiconductor degradation occurs more rapidly as junction temperature increases [Philips Lumileds, 2008a; Grillet, 2006]. LED degradation can lead to a significant reduction in LED useful life. In some cases, a reduction of LED temperature by a few degrees Celsius can increase the estimated lifetime of an LED by an order of 10,000s of hours [Philips Lumileds, 2008b]. At very high LED temperatures, catastrophic failure may occur due to component failure or semiconductor breakdown. With proper thermal management, LEDs are typically capable of surviving 60,000 hours of continuous use, but some manufacturers claim their LEDs can last longer than 100,000 hours [NEMA, 2009; Narendran et al., 2004].

The optical characteristics of an LED are also affected by temperature. As the temperature of an LED increases, optical material degradation begins to occur [Poppe & Lasance, 2009]. Optical degradation leads to a reduction in optical power and a change in color temperature. Generally this is due to a browning of encapsulant and the phosphor matrix materials [Poppe & Lasance, 2009]. Color temperature emitted by an LED is directly dependent on die temperature, and can be affected by small changes in temperature as small as 1-2 degrees Celsius [Philips Lumileds,

2008a; Xi et al., 2005]. As an example, the wavelength shift of red LEDs is 0.05 nm/°C [Philips Lumileds, 2008a].

1.4 L-Prize

Although LED lighting popularity is growing in the market, the US government has recently decided to accelerate the transition to less toxic, more energy efficient LED lighting. In 2007, Congress turned to the Department of Energy (DOE) to introduce a government-sponsored technology competition designed to spur lighting manufacturers to develop high-quality, high-efficiency solid-state lighting products to replace the common light bulb [L-Prize, 2008]. This competition is called the “L-Prize”, and the goal is to “... substantially accelerate America's shift from inefficient, dated lighting products to innovative, high-performance products” [L-Prize, 2008]. The primary objective of the L-Prize is to replace both the household standard 60W incandescent light bulb and the PAR38 halogen lamp. The first group or company to meet the requirements of the L-Prize will be awarded 20 million USD.

To be awarded the winner of the L-Prize, winning design must conform to a rigorous evaluation process, which is performed by independent labs chosen by the DOE. This evaluation includes performance and lifetime testing, field assessments in collaboration with utilities and partners, stress testing, reliability requirements, and at least 150 lumen/watt efficiency [L-Prize, 2008].

1.5 Project Goals

The goal of this project was to develop a low-cost LED lighting package for general lighting capable of competing with market alternatives while conforming to the L-Prize requirements. To meet the goals of the L-Prize, several targets were specified for the design of the new package. With cost being the primary concern for the design, the target price for the final package is the L-Prize requirements: \$22 for an incandescent replacement and \$30 for a PAR 38 replacement. In order to achieve high reliability, the target LED die junction temperature was set as no more than 125 °C at steady state. The total lifetime rating of the package was again targeted at the L-Prize requirement of at least 25,000 hours as defined by $L_{70} / C_{95} / B_{10}$. L_{70} refers to 70% lumen maintenance. C_{95} refers to 95% statistical confidence interval for the rated lifetime. B_{10} refers to no more than 10% of products dropping below 70% of the initial LED lumen value. The final target of the design is to create a package capable of being adopted into current lighting form factors.

This thesis contributes to the design and development of a low-cost HBLED lighting package that is capable of displacing traditional lighting alternatives. The LED lighting package is designed with the goals of the L-Prize in consideration: low cost, high thermal performance, high reliability, and market adoptability. This thesis will discuss material and component selection, design considerations and limitations, prototype development, assembly, and testing. The possibilities of mass production will be discussed, and suggestions for reliability testing will be made.

Chapter 2: Literature Review

2.1 Electroluminescence – LED Light Generation

The unique form of light generation by a solid-state device is known as electroluminescence, which was discovered by Henry Joseph Round in 1907 by chance while trying to create a rectifying solid-state detector [Schubert, 2006]. Electroluminescence is an optical and electrical phenomenon in which a material emits light in response to an electric current passed through it, or to a strong electric field – J (A/cm^2). A schematic can be seen of the electroluminescence processes occurring in the LED active region in Figure 3. Electroluminescence in a P-N junction diode – contact between P-type and N-type semiconductor regions – occurs in semiconductors when electrons and electron holes recombine radiatively to produce a photon of light – B in Figure 3 [Schubert, 2006]. This electron/electron-hole recombination, known as radiative recombination, is the preferred method of generating light. However, recombination of electrons and holes within a semiconductor can occur as non-radiative recombination. The fraction of photons emitted to photons generated is known as extraction efficiency [Grillot, 2006].

The two major forms of non-radiative recombination are known as Shockley-Read-Hall and Auger Recombination. During Shockley-Read-Hall Recombination, electron energy is converted to vibrational energy of lattice atoms, known as phonons [Schubert, 2006] – A in Figure 3. This form of recombination results in heat within a semiconductor [Schubert, 2006]. When the Auger recombination process occurs during periods of high current, the energy which becomes available through electron-hole recombination is dissipated by the excitation of free

electrons – C in Figure 3. Both non-radiative recombination effects reduce the overall light extraction efficiency of the LED.

Other complex processes occur within an LED die which causes further reductions in extraction efficiency. Electron and electron-hole trapping mechanisms are inherent in LED design - c_n and c_p in Figure 3. There is also a leakage current out of the LED active region - J_L in Figure 3 [Grillot, 2006]. Some photons emitted by radiative recombination inside LEDs may be trapped inside the diode by Total Internal Reflection - TIR in Figure 3.

Figure 3: Electroluminescence Model, Source: Grillot, 2006

Although HBLEDs have the advantage of being longer lasting, smaller in size, and require less power; several challenges must be overcome. To generate the light necessary to displace other lighting solutions, relatively large amounts of electricity must be used to drive the LED. More power means more energy lost as heat. This leads to higher junction temperatures of an LED die, which can significantly reduce the reliability and key benefits of LEDs [Philips Lumileds, 2008b]. Keeping a low junction temperature is now a major consideration in the packaging of HBLEDs, with power densities as large as $(200-500 \text{ W/cm}^2)$ [Philips Lumileds, 2008b].

2.2 Common LED Package Types

Currently, there are two common types of LED packages in the market: low power LED packages and high power LED packages. An example of a low power LED package is shown in Figure 4. To be considered a low power LED package, the total power consumed by the device is less than 0.1 W. Generally, a low power LED package outputs 2-4 lumens. These packages are not designed as a source of general illumination; instead, low power LED packages are used as indicator lights. Low power LED packages come in 3mm, 5mm, and 8mm sizes. Due to the lower power needed for these LEDs, thermal management is not as important as for High Power LEDs [Arik, 2002].

Figure 4: Model of Conventional Low Power LED, Source: Nathan et al., 2007

High power LEDs (HPLEDs) are continually growing in its applications. An example of a HPLED can be seen in Figure 5. HPLEDs are generally considered as LEDs which consume at least 1 W of power. Generally HPLEDs fall between 1W – 3W each, with arrays of LEDs used for higher lumen output requirements. Common HPLEDs output between 40-80 lumens [Arik, 2002]. HPLEDs are found in many different package types and in multiple applications.

HPLEDs have been growing in the medical industry because of its high quality light and minimal weight. HPLEDs are also being found in high performance automotive lighting pioneered by Audi [Schubert, 2006]. Recently, HPLEDs have been used in various forms of artistic lighting such as the Stone Bridge across the Danube River in Regensburg, Germany.

Figure 5: Model of a High Power LED, Source: Philips Lumileds

One caveat of LED packaging is the optical requirement in which the LED active region must be exposed to emit light. Commonly in microelectronics packaging, high power devices are created as flip-chip packages. With flip-chip technology the bottom side of the package is used for electrical and power signals, while the top side is used to conduct heat away from the IC. The optical limitation of LEDs requires unique methods of transferring both heat and electrical signals through just one side of the package while leaving the optical side exposed [Zhao et al., 2006; Cheah et al., 2008].

2.3 Functions of Electronics Packaging

In order to successfully design and produce an electronic package, four major functions must be considered [Brown, 2006]:

- Heat Dissipation
- Power and Signal Distribution
- Circuit support and protection

2.3.1 Thermal Considerations

Thermal management has been a major consideration with electronics packaging since the rise of the electronics industry after World War II [Couvillion, 2006]. Just as is the case for this study, new thermal management techniques have been driven by constantly improving electronic components and systems. Improved thermal management is critical in electronics packaging by improving reliability, allowing increased power, and producing smaller packages.

In the case of an LED lighting package, heat is generated by several sources. Although LEDs are much more efficient than other lighting sources in converting energy into light, energy conversions heat losses exist and must be managed. LED efficiency is a product of electrical efficiency, internal quantum efficiency, die extraction efficiency, phosphor conversion efficiency, and phosphor extraction efficiency [Philips Lumileds, 2008b]. These are intrinsic properties of the LED and phosphor materials used. As LED efficiency increases, the amount of light generated by an LED will increase with the same power applied. More efficient LEDs will lead to better light and/or cooler devices.

Table 1: LED Energy Conversion

Efficiency	Current Status	Practical Limit
Electrical Efficiency	80%	90%
Internal Quantum Efficiency	60%	90%
Extraction Efficiency	80%	90%
Phosphor Efficiency	60%	70%
LED Efficiency Upper Limit	23%	51%

Source: Philips Lumileds, 2008b

In order to produce greater amounts of light, relatively high currents must be passed through a small die. A 1 mm² LED die using 3 Watts of power will pass 3 million W/m² through the die, and a majority of this power is wasted as heat. Heat fluxes have been known to be 5000 times higher than that of the sun's surface of 400 W/m² [Arik, 2002]. Figure 6 shows the challenges of managing heat in the microelectronics industry. This large amount of heat flux must be properly managed while satisfying other optical characteristics.

Figure 6: Heat Flux Challenges of Microelectronics, Source: CPS Technology Solutions

2.3.1.1 Approaches to Heat Removal

LEDs used for lighting applications pose a unique challenge for heat removal. As stated in the previous section, heat flux for a high power LED package can be as high as 500 W/cm^2 . This relatively high heat flux is due to the amount of power driven through such a small package, see Table 2 for a comparison of thermal parameters compared to other packages. In order to remove heat, various cooling methods can be used to keep die temperatures low enough to maintain high reliability and quality of packages.

Table 2: Packaging Thermal Parameters

	Handheld	Cost- Performance	High- Performance	Automobile	Memory	HPLED*
Power Dissipation (W)	2	75	129	14	1.5	1
Chip Size (mm ²)	59	430	430	59	560	0.06
Junction Temperature (°C)	115	100	100	180	100	150
Chip Heat Flux (W/cm ²)	3.4	17.4	30.0	23.7	0.3	500

Source: Couvillion, Ulrich (as of 2003, *2008)

The standard approach to removing heat from a die is to attach the die to a larger surface, thus increasing the area over which heat is distributed. By increasing the area, the heat flux is reduced. This effect is known as “heat spreading”. An example of this can be seen in Figure 7. Heat passes from the chip, to the heat spreader, and then to the heat sink. However, each level of spreading creates a contact resistance which hinders the ability to cool the die. A well-designed package allows heat flow along a path of low thermal resistance to an appropriate cooling source.

Figure 7: Standard Microelectronics Package, Source: Philips Lumileds, 2008b

Besides thermal conductivity, the coefficient of thermal expansion (CTE) must be considered when designing a package. The CTE describes how much a material will change in size when subjected to a change in temperature. A mismatch in the CTE of two bonded materials can cause stresses on a package during heating and cooling cycles. CTE mismatch can lead to strain on components and cause package failure [Raj et al., 2001].

Heat transfer occurs whenever a difference in temperature exists between two regions within a medium. Depending on the media, one or more of three modes of heat transfer can occur. The three modes of heat transfer are conduction, convection, and radiation. In each of the modes, the heat transfer rate increases as the temperature delta increases [Couvillion, 2006].

Heat is transferred through the conduction mode when a temperature gradient exists within a continuous solid or liquid medium [Couvillion, 2006]. With all electronic devices, heat must be conducted from within the device to the surface. This is the case with LEDs more than any other current form of lighting because of the solid-state nature of the technology. After heat is conducted to the surface it may be removed via convection or radiation. Fourier's law for one-dimensional heat transfer via conduction through a solid is

$$q = -kA_c \frac{dT}{dx} \quad (2.1)$$

Where

q = rate of heat transfer (W)

A_c = Cross-sectional area of the solid in the direction of heat flow (m^2)

K = Thermal conductivity of the solid in the direction of heat flow (W/m K)

$\frac{dT}{dx}$ = Thermal gradient within a solid (°C/m)

Thermal conductivity can be likened to Ohm's law for electrical current, electrical potential, and resistance. Heat flow is analogous to current, the temperature differential analogous to electrical potential, and the thermal conductivity constant with the dimensional properties analogous to the electrical resistance. Thermal conductivity therefore can be written as

$$q = \frac{T_1 - T_2}{L/kA_c} \quad (2.2)$$

Convection occurs between a surface and a fluid moving over that surface when at different temperatures [Couvillion, 2006]. There are two major types of heat convection: forced and natural. Forced convection occurs when fluid motion is created outside the source of heat surface. An example of forced convection is a fan moving air within a computer case. Forced convection generally results in higher rates of heat transfer than natural convection. Natural convection occurs when airflow results from the buoyant forces created by a temperature difference between the heated surface and the ambient air. Newton's law of cooling describes convection processes as:

$$q = hA_s(T_s - T_\infty) \quad (2.3)$$

Where

q = rate of heat transfer (W)

A_s = Surface area (m^2)

T_s = Surface temperature ($^{\circ}C$)

T_x = Fluid temperature ($^{\circ}C$)

h = Convection heat transfer coefficient ($W/m^2\ ^{\circ}C$)

Again, thermal convection can be written in a form analogous to Ohm's Law, with convective resistance $R_{conv} = 1/h A_s$ analogous to electrical resistance.

$$q = \frac{T_s - T_{\infty}}{1/hA_s} \quad (2.4)$$

Radiation is the third mode of heat transfer. Any matter in an environment above absolute zero emits thermal radiation at its surface. Radiation can occur in a vacuum; no medium is necessary. Radiation is often difficult to characterize, because it is dependent on the wavelength of the electromagnetic radiation emitted from the body. The heat emission from an ideal radiating surface is given by:

$$q_{RAD} = \varepsilon \sigma A_s (T_s^4 - T_{\infty}^4) \quad (2.5)$$

Where

ε = Material emissivity

σ = Stephan-Boltzmann Constant ($5.6703 \cdot 10^{-8} W/m^2 K^4$)

A = Area of emitting body

T_s = Surface temperature of emitting body

T_{∞} = Ambient air temperature

It can be seen that Equation 2.5 is dependent on the area of the radiating surface, as well as the temperature delta. Since the heat sink temperatures used in this study are so small compared to ambient temperature, the thermal radiation given by the LED package in this study is considered to be negligible compared to the other modes of heat transfer.

2.3.1.2 Contact Resistance

As stated in the previous section, often heat must be distributed via conduction across increasing areas of surface in order to allow proper heat convection into the environment. This involves mating two surfaces of differing solids. However, two joined surfaces cannot make perfect thermal contact because surface roughness creates small voids between the mating surfaces, thus inhibiting heat flow. This effect is known as contact resistance. Often, a thermal interface material (TIM) is introduced to fill the voids between joining surfaces, but these interface materials generally have a much lower thermal conductivity than the solids being joined, e.g. copper's thermal conductivity is 381 W/m °K vs 1-10 W/m °K for standard TIM. Conduction thermal resistance can be used to characterize TIM thermal resistance as:

$$R_{cond} = \frac{L}{kA_c} \quad (2.6)$$

Where

k = Thermal conductivity of TIM (W/m °K)

A_c = Cross-sectional area of layer at interface (m²)

2.3.1.3 Advanced Cooling

Often, natural convection is insufficient to cool devices with high heat flux. Most commonly, a fan is used to improve thermal management. Fans in conjunction with heat sinks commonly remove chip-level fluxes of 25 W/cm^2 [Couvillion, 2006]. Fans are considered a cost-effective and relatively simple method of removing heat. This method has been developed for use with LED lighting as shown in Figure 8. However, using a fan to cool a lighting source brings multiple issues. First the lifetime of a ball-bearing fan is around 20,000 to 50,000 hours, but this requires some maintenance and cooling effectiveness lowers over time [Philips Lumileds, 2008b]. Adding another source of potential failure to the device will ultimately lower the reliability of the package. Another issue with using a fan to cool an LED device is the noise concerns associated with turbulent air and faulty fans. Adding a cooling fan will decrease the power efficiency of the package by consuming more power to drive the fan. Finally, fans generally require a relatively large amount of space to function and will increase the size of an LED package. This will limit the versatility of an LED lighting package. In this particular study, fans were not considered when designing the LED package.

XLED, fan cooling

Figure 8: XLED Lighting Package with Internal Fan, Source: XLED

More advanced cooling methods exist outside air cooling. Liquid cooling is used to cool devices beyond air cooling, see Figure 9. This method of cooling was not considered for this study due to cost and complexity.

Enfis, Liquid cooling

Figure 9: Enfis Liquid Cooling System, Source: Enfis

Heat pipes are becoming an increasingly popular form of heat removal in the electronics industry. Heat pipes are tubes filled with a two-phase mixture used as a heat transfer medium, and a capillary material. Heat pipes are a promising technology because they can transfer heat at

a rate hundreds of times higher than solid copper and over large distances [Couvillion, 2006]. However, heat pipes are generally used in conjunction with a fan and fins. This method of cooling was not considered for this study due to cost and complexity.

Other forms of cooling LEDs in the market are synthetic jet cooling and Peltier cooling, see Figure 10. Both cooling technologies are considered exotic cooling methods. These cooling methods were not considered for this study.

Figure 10: Nuventix Synjet Cooling System, Source: Nuventix

2.3.1.4 Thermal Modeling

Besides using basic thermodynamic mathematics to estimate the heat transfer of the LED packages, computer-aided modeling was used to simulate each prototype. The software used to model each prototype is FloEFD, a powerful 3D computational fluid dynamics (CFD) software made by Mentor Graphics. FloEFD uses CFD techniques to predict airflow, temperature, and heat transfer in electronic systems. FloEFD is integrated into SolidWorks to easily analyze the thermal properties of a solid model prototype designed in SolidWorks.

2.3.1.5 Measuring Junction Temperature

Junction temperature, which refers to the temperature of an LED device, can significantly affect the reliability and optical characteristics of an LED. Rising junction temperatures have been known to decrease luminous efficacy and shift the color spectrum [Philips Lumileds, 2008a]. Long periods of high temperature can result in the degradation of ohmic contacts, decayed phosphor materials, and premature failures [Philips Lumileds, 2008a]. Knowing the value of the LED junction temperature is crucial to predicting LED reliability.

The most popular method of measuring the junction temperature of an LED is the forward-voltage based method [Hong & Narendran, 2004; Philips Lumileds, 2008a, Xi et al., 2005; Xi & Schubert, 2004]. The forward voltage method is a means of measuring a diode's junction temperature by utilizing the linear relationship between the diode forward voltage and diode temperature. Another popular method is IR thermography [Grauby and Forget et al., 1999, Cheng et al., 2005]. Less popular methods of measuring the die temperature are based on wavelength shifts or liquid crystal coatings [Philips Lumileds, 2008a, Gu & Narendran, 2004; Lee & Park, 2004].

Thermal resistances are widely used to characterize heat transfer between semiconductors and their packages. These characterizations, which are tested using a temperature measurement method described above, are used to report the heat extraction efficiency of HBLED packages. However, according to L. Zhang and T. Treurniet at Philips Lumileds, there is ambiguity in terms of environmental conditions and/or reference temperatures [Philips Lumileds, 2008a]. The authors conjecture there is an urgent need to standardize thermal resistance measurements for

reporting LEDs [Philips Lumileds, 2008a]. If standardization occurs, this should benefit both consumers and companies because data reported can be equally compared.

Zhang and Treurniet describe the complications of each method of measuring the junction temperature [Philips Lumileds, 2008a]. The forward voltage method can only represent one value, so LEDs with temperature gradients cannot be correctly measured. Also, forward voltage measurements are different between each LED of the same wafer.

IR thermography can measure temperature gradients, but only the surface temperature can be accurately measured. The LED junction is just below the surface. Normally this is not a problem for standard electronics packaging, but several issues exist using a thermal camera with LEDs. Due to the small size of LEDs, accurate measurements by a thermal camera can be very difficult. IR cameras capable of measuring such small LED junctions are very expensive, costing \$100,000 for an appropriate camera.

Even if a capable thermal camera is used to measure the package, accurate measurements may still be impossible. Many LED packages use a phosphor coating, which results in greater thermal dissipation; causing difficulties in measuring the actual junction temperature, the area where LED degradation occurs. Another complication of IR thermography is the LED die material can be transparent to the wavelength of the IR camera, so black-body radiation is impossible to measure.

Spectral-based methods used to compare peak wavelength shift to junction temperature is very difficult to implement in practice because of the small magnitude of the effect. Relatively broad LED emission peaks make it very difficult to measure the wavelength shift accurately enough to derive an accurate temperature measurement.

After testing both the IR method and forward voltage method, the Zhang et al. found each method yielded a different thermal resistance measurement. The forward voltage method matched more closely with the peak IR temperature measurement than the mean IR measurement across the die.

Zhang et al. concluded by recommending that both forward voltage methods and IR thermography can be used to measure junction temperatures, with IR thermography being complimentary to the forward voltage method with large thermal gradients. To ensure accuracy, it is recommended to perform thermal resistance measurements at multiple current/heat sink conditions to account for optical characterization dependencies.

2.3.2 Power and Signal Distribution

Power distribution is another major function of electronics packaging. In order for the package to function, power must be delivered to the LEDs at the designed current and voltage. Before designing the package, decisions were needed to be made regarding the total number of LEDs; whether to place them in series, parallel, or a combination of the two; and how the power would be carried to and out of the devices.

Fortunately, LED lamps are relatively simple devices to integrate into a circuit. LEDs require no ignition voltage to start the light, and no voltage spikes or power surges occur with LEDs [Cooper, 2008]. LEDs have a polarity, and will only produce light when current flows from anode to the cathode. It is important not to put too much current and voltage into an LED, which may damage the device. Too little current and voltage will result in no or dim light. Generally white HPLEDs require a forward voltage of 3.3-3.5V, and a forward current between 350 – 800 mA.

An important characteristic of LEDs to note is as LEDs heat up, the forward voltage drops and the current increases through the device [Cooper, 2008]. An increase in current results in the heating of the die. This can cause what is known as thermal runaway. The preferred method of preventing this phenomenon is to use a constant-current power supply. Constant current power supplies can be expensive and bulky. Another option is to use a current-limiting resistor; a less expensive alternative. However, resistors generate heat and lead to wasted power.

2.3.3 Circuit Support and Protection

Circuit support and protection is the final major component of a package design. Often with LED packages, the sensitive components of the package are protected with an encapsulant. LED encapsulants usually provides the purpose of protecting the sensitive components while directing light output. Other manufacturers choose to use a separate plastic lens over the encapsulant. For general illumination applications, the light extracted from an LED must be converted from blue light to white light by the use of phosphor matrix materials mixed within the encapsulant [Philips Lumileds, 2008b].

2.4 LED Package Degradation and Reliability Studies

Much research has focused on LED degradation and reliability. Grillot et al. studied light output degradation of LEDs up to 60,000 hours in order to understand degradation mechanisms [Grillot, 2006]. Findings were consistent with other research in that junction temperature and current density affect LED reliability. Epoxy degradation was also found to cause failures at higher temperatures. Buso et al. found that besides thermal management, the electrical driving is important to LED lifetime [Buso et al., 2008].

LED die size also plays a role in the thermal management [Yang et al., 2008]. As the chip surface area increases, more heat can conduct through the package. Yang et al. suggested larger LED die to reduce the number of packages and thus improve package reliability.

Studies have shown LED performance is directly dependent on forward voltage, current, temperature, and dissipated power [Poppe & Lasance, 2009]. Each of these properties is also dependent on the other. Due to this dependency, many of the light output properties of an LED die are a direct result of die junction temperature. Since voltage and current can be easily adjusted when designing a package, junction temperature becomes a key metric in both thermal and optical performance [Poppe & Lasance, 2009].

2.4.1 LED Package Prototype Reliability Goals

The reliability goal of this study is 25,000 hours as defined by $L_{70} / C_{95} / B_{10}$. This requirement entails multitudes of testing and design requirements. In order to meet the reliability requirements of this study, several factors of package reliability should be considered. Failure mechanisms must be determined for each component of the package.

Industry reliability standards for measuring LED lifetime is defined as the probability a specific package will be operational after a given amount of time; considering a device has failed if the lumen maintenance falls below 70%. This assumes all packages studied for reliability are functioning after production. Reliability can be expressed mathematically as:

$$\begin{aligned} R(0) &= 1 \\ \frac{dR(t)}{dt} &\leq 0 \end{aligned} \tag{2.7}$$

Often it is the case the probability of failure mechanisms are not known for a package design. However, testing a group of prototypes through the lifetime of the package is infeasible for a package designed to last a minimum of 3 years of continuous use. Therefore a method of accelerated testing must be established in a method that will yield valid and ostensible results.

2.4.2 LED Lifetime Analysis Standards

As stated in Chapter 1, L_{70} refers to 70% lumen maintenance. Unlike incandescent lighting in which the lamp will maintain relatively consistent levels of light output until catastrophic failure,

LED lights tend to gradually degrade over time. The Alliance for Solid-State Illumination Systems and Technologies (ASSIST) found that 70% lumen maintenance is the threshold at which an observer can perceive diminished lighting. An example of light output reduction over time can be seen in Figure 11.

Figure 11: Philips Lumileds K2 LED Light Output over Time, Source: Philips Lumileds

Light output from an LED will continually diminish during use as time passes. However, the rate at which LED light output will decay is based on several factors [Philips Lumileds, 2007]. The amount of current chosen to drive an LED will affect its lifetime, see Figure 12. By driving a LED below its rated forward current, the life of an LED can be extended. This should be considered when designing an LED to perform based on light output and longevity.

Figure 12: The Effect of Current on Philips Lumileds K2 LED Lifetime, Source: Philips Lumileds, 2007

Lowering the LED junction temperature by a few degrees can extend its useful life by thousands of hours, see Figure 13. As mentioned in a Section 2.3.1.5, several methods exist for measuring junction temperature. The forward-voltage method is the most common method of measuring junction temperature. This method is recommended for measuring junction temperature so the package can more easily be compared to other LED package studies.

Figure 13: The Effect of Junction Temperature on Philips Lumileds K2 LED Lifetime, Source: Philips Lumileds, 2007

B_{10} refers to the point in time which 10% of packages drop below 70% of the initial LED lumen value. This metric must be included when determining the lifetime rating of an LED package. Both the B-lifetime value and the L-lifetime values can be presented graphically to easily reference performance characteristics to apply to a package in order to achieve a desired result, see Figure 14. Creating a graph similar to Figure 14 for the prototype package can be used to determine which solution would be used when determining the desired requirements using junction temperature and forward current. This allows a package designer to determine which operating conditions the LEDs should operate; e.g. a package operating below the specified junction temperature can be driven with more current to produce a higher performing package and still meet minimum lifetime requirements.

Figure 14: The Effect of Junction Temperature and Current on Philips Lumileds K2 LED Lifetime at B50, L70, Source: Philips Lumileds, 2007

When developing LED packaging lifetime analysis, both ASSIST and Philips Lumileds recommend publishing several design parameters. The purpose of publishing these parameters is to establish better standardization and study replication. The following design parameters should be published when the prototype package begins extensive reliability testing:

- Number of samples used
- Description of heat sink used
- Ambient temperature during testing
- Thermal resistance of package and leads
- Voltage and current applied to device

2.4.3 Accelerated Lifetime Testing

Due to the long lifetimes of LEDs, methods of expediting the failure mechanism of the package prototype are necessary. In order to reduce the times needed to accelerate lifetime testing, the prototypes must be exposed to exaggerated environmental conditions. However, it is important these conditions do not cause failure mechanisms unique to the exaggerated testing environment. Accelerated testing will allow the determination of failure mechanism in the prototype, as well as estimate the overall lifetime.

Accelerated testing can be tailored to different failure mechanisms. Environmental tests involve subjecting a package to high temperatures and high humidity to test corrosion of materials. Mechanical testing involves cycling temperatures to understand the effects of CTE mismatches on a package. Electrical testing involves subjecting the package to high voltages, high currents, or pulsed discharges. Some or all of these tests should be used to determine the failure mechanisms of the prototype.

2.4.4 Predicting LED Lifetime/ Weibull distribution analysis

The Weibull distribution is a well-known statistical distribution often used for reliability analysis. The Weibull distribution is used to extrapolate recorded data to predict behavior over a longer period than measured [Meeker & Escobar, 1998]. The Weibull distribution, a two-parameter model, can be written as:

$$f(x; k, \lambda) = \frac{k}{\lambda} \left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^k} \quad (2.8)$$

Where:

λ = The lifetime parameter, which is a measure of the average time until failure.

k = The shape parameter, a measure of how the failure frequency is distributed around the average lifetime

x= Time

Data collected of LED lumen maintenance can be used to calculate the values of x, k, and λ .

With this information, more data can be extrapolated beyond testing to predict future failures.

The size of the dataset is an important factor when using the Weibull distribution. More data allows for better prediction of future failures.

2.5 Package Design Research

Although solid state lighting was first discovered in 1907, the LED technology known today gained traction during the 1960s [Nathan et al., 2007]. Until the late 1990's and early 2000's, LEDs were not capable of providing general illumination because white light could not be produced by LEDs. As white LEDs grew in capabilities, more applications emerged. Major applications for LEDs today are traffic signals, flashlights, general illumination, TV/monitor backlighting, and automobile headlights [Schubert, 2006; Nathan et al., 2007]. Another emerging LED application is its use in pico projectors, which allow handheld devices to project images on a surface [Keuper et al., 2004].

Much research has been conducted on LEDs as a source of general illumination. In some cases, a direct application approach was utilized by designing a complete package and testing the

results. Two studies published by Philips and Luo et al. analyze the use of LEDs for street lamp lighting in place of current incandescent fixtures, respectively [Luo et al., 2007]. Philips designed a demonstration lamp using 50 Luxeon Rebel LEDs arranged in different rows and angles across the lamp face. This produced a more uniform light over an area to reduce glare problems with current lighting solutions. Luo et al. performed a similar study by packing LED packages across an aluminum heat sink street lamp. Both studies found the performance and efficiency of the LED solution is a preferred solution if thermal requirements can be sufficiently managed.

Jang et al. proposed a novel solution for cooling automotive LED head lamps by drawing air through inlets in the head lamp housing [Jang & Shin, 2008]. Again, thermal management was the focus of this study. Thermal performance was evaluated using commercial thermal modeling software to estimate performance. The package design assumed the LED dies are soldered to a MCPCB.

Other researchers have focused on improving the most common thermal bottleneck of an LED package, the LED itself. HBLEDs are composed of sapphire or GaAs, which are both thermal insulators [Schubert]. Chen et al. proposed a package design in which electroless and electroplating techniques are applied to the bottom of the LED to add nickel, gold, then copper [Chen et al., 2006]. This package could then be attached to a MCPCB for improved thermal performance. Tan et al. proposed creating an array of micro grooves in the structure of the LED itself to reduce thermal expansion problems [Tan et al., 2008]. The study found an improvement

in thermal capabilities due to easing of CTE requirements and has the added benefit of increased light extraction.

2.5.1 Current Market High Power LED Lighting Packages

Many different solutions exist for LED lighting. There are several differences and similarities between manufacturers. Some of the largest LED package manufacturers are Nichia (Japan), Lite-On (Taiwan), Cree (US), Philips Lumileds (Netherlands), and Osram (Germany). Many other LED manufacturers exist across the world. As of this study, there is limited standardization among LED manufacturers. The most noticeable difference between packages is the overall shape and footprint.

Several published solutions exist for creating a HPLED package. A straightforward approach involves directly attaching the LED to a substrate, as seen in Figure 15. This method requires advanced substrate materials to sufficiently conduct heat from the LED. A more thermally optimized LED package can also be seen in Figure 15. In this package an LED is attached to a heat sink, which is then attached to a substrate for power and signal distribution. Variations of this package can be seen in Figure 16 by which the anode and cathode are vertically separated from the substrate. The “recessed die” LED packaging method is created by attaching the LED to a recess in the package. This allows for light to be directed by the package recess itself. Figure 16 also shows a “dome die”, in which an epoxy dome lens is placed over the LED to direct light and protect the LED.

Figure 15: Standard Chip-On-Board LED Packages, Source: Bergquist

Figure 16: Recessed and Dome Dies, Source: Bergquist

Other proposed solutions for packaging LEDs have been suggested to improve thermal performance. Figure 17 shows an LED attached to a multi core printed circuit board (MCPCB) using a thermally conductive resin [Chen et al., 2008]. Wire bonds can then be attached to separated electrodes. Another solution proposed by Chen et al. involves using electroless and electroplating techniques to create a thermally conductive substrate as seen in Figure 18.

Figure 17: Die Bonding to MCPCB Using Resin, Source: Chen et al.

Figure 18: HPLEDs Attached using Electroless and Electroplating Techniques, Source: Chen et al.

Figure 19 shows a model of Philips LUXEON Rebel Package. This package uses some of the previous techniques discussed by attaching an LED to a metal interconnect layer to transfer heat to an electrically isolated thermal pad. An epoxy dome lens is placed over the package.

Figure 19: Philips LUXEON Rebel Package, Source: Philips Lumileds

Many commercial LED packages can be found in the market. Some packages, such as the Cree Xlamp seen in Figure 20 and Figure 21, simply feature a packaged LED mounted to the center of a small printed circuit board. A similar example by Philips can be seen in Figure 22. An optical lens is placed over the LED packaging. These packages can be mounted to a larger substrate or PCB which can be used in LED lighting systems. Other designs feature what is known in the industry as a “heat slug”. This slug is a heat sink embedded in the package. Using a heat slug allows manufacturers to separate the thermal pad from the electrical portions of the packaging. Examples can be seen in Figure 23 and Figure 24.

Figure 20: Illuminated Cree Xlamp LED Package,
Source: Cree

Figure 21: Cree Xlamp LED Packages on substrate, Source:
Cree

Lumileds Rebel

Figure 22: Philips Lumileds Rebel LED Package, Source:
Philips Lumileds

Lumileds Luxeon K2

Figure 23: Philips Lumileds Luxeon K2 LED Package,
Source: Philips Lumileds

Major LED package manufacturers also sell packages embedded on heat spreaders, as seen in Figure 25, Figure 26, and Figure 27. These heat spreaders can be attached to larger systems as

self-contained functioning packages. Although these packages have good thermal performance, it comes with a higher cost.

OSRAM Golden Dragon

Figure 24: OSRAM Golden Dragon LED Package, Source: Osram

OSRAM Ostar

Figure 25: OSRAM Ostar LED Package,
Source: Osram

Lumileds
Luxeon K2 Star

Figure 26: Philips Lumileds Luxeon K2 Star LED
Package, Source: Philips Lumileds

Lamina Titan

Figure 27: Lamina Titan LED Package, Source: Lamina

The packages designed by the LED package manufacturers are designed to be embedded in a mechanical package. Philips, along with several other vendors, packages their products into a standard light bulb replacement by using the light bulb body as a large heat sink, see Figure 28. This is a commercial product found in many hardware stores, and sells for a relatively large amount of money compared to CFL alternatives.

Figure 28: Philips LED Light Bulb Replacement, Source: Philips Lumileds

Chapter 3: Prototype Design

3.1 Design Requirements

Before the design of the first prototype could begin, several modeling assumptions were made and design requirements were set. The LED package prototype was designed to meet the requirements of the L-Prize, see Table 3 below.

Table 3: L-Prize Requirements with Relative Importance

	Target	Relative Importance
Cost	\$22-\$30 per package	Highest
Thermal Performance	Avg. Junction Temperature < 125 °C	High
Reliability	25,000 hours @ L70, C95, B10	Medium
Manufacturability	Capable of mass production	Medium
Market Readiness	Easily adaptable design	Low
Color Quality	Consistent color quality	low

Note low cost is the highest importance for the prototype. However, the prototype is still designed to perform consistently and competitively with other LED lighting products. To compete with other products, cost-effective thermal management was considered the most important factor when designing the package.

Reliability issues were considered during each prototype design iteration. This was accomplished by considering material selection, component placement, and design for

manufacturability. Again thermal management was of the greatest importance for reliability. However, other failure mechanisms such as mechanical failure and electrical failure were considered.

In order to meet the requirements of the L-Prize, the LED package prototype is designed to be easily manufacturable. Specifically, mass production techniques were kept in mind to keep costs low and allow high volume processing.

Color quality is an important issue for many consumers, and is another requirement of the L-Prize. LEDs for lighting purposes are blue LEDs with a phosphor coating to create a white light. Even with phosphor coating, the light output from LEDs can often look blue or synthetic to a consumer. Color quality is mainly attributed to two factors: LED material properties and LED junction temperature [Poppe & Lasance, 2009]. The LED prototype is designed to have low, stable temperatures. A stable temperature across the LED die contributes to a consistent color quality. In this study, LED material properties were not analyzed.

For the LED prototype to be successful in a commercial arena, it must be easily adaptable into current lighting solutions. LEDs are designed to use low-voltage and constant DC current to generate light. As such, many commercial options exist to take a basic LED package and provide constant and correct power.

3.2 Material Selection

Material selection is a critical factor when designing a package for high thermal performance. Often in this study, a tradeoff had to be made between cost and performance. Materials were selected based on the properties desired for high thermal conductivity and manufacturability. CTE concerns were also considered when selecting materials.

There are many different LEDs on the market designed for high power applications. These designs have different electrical, optical, and physical properties. For the purpose of the study, the LEDs used were kept constant because it was assumed the thermal performances between LEDs would be negligible compared to the method of packaging. The LEDs used in this study were provided by General LED, see Figure 29 for more details. These LEDs have the anode and cathode pad on top of the LED die. Other LED dies are designed with the anode pad on top, and the cathode on the bottom of the die. When designing the prototype package, both types of LEDs were considered.

Figure 29: Dimensions of LEDs Used for Prototype

A heat sink was designed to conduct the heat away from the LED package, as well as act as housing for the components. To keep costs down and thermal performance high, three different materials were considered for the heat sink: copper, aluminum, and CuW. Copper has a thermal conductivity of $381\ \text{W/m } ^\circ\text{C}$, while aluminum and CuW has a thermal conductivity of approximately $200\ \text{W/m } ^\circ\text{C}$ as seen in Table 4. However, copper is over 3 times more expensive than aluminum. Aluminum is still a good conductor of heat, but it has the highest CTE of the three materials studied. CuW is common in electronics packaging because its low CTE closely matches that of FR-4, but is much more expensive than copper or aluminum. Aluminum was selected as the heat sink material because of a high thermal performance to cost ratio and its ease of machining and shaping. With aluminum, CTE issues must be overcome through use of TIM/epoxy materials.

Table 4: Thermal Conductivities of Common Materials

Material	Electrical Conductivity	Thermal Conductivity	CTE	Young's Modulus	Tensile Strength (ksi)	Density	Cost
		(W/mK)	(PPM/C)	(Gpa)	(Mpa)	(kg/m ³)	(USD/kg)
Cu	Good Conductor	381	18	148	400	8940	6.29
*CuW	Good Conductor	200	6.8	367	1172	1640	>30
Al	Good Conductor	200	24	82	550	2900	2.86

Source: CES EduPack 2007 unless otherwise specified.

* Source: A New Substrate for Electronics Packaging: Aluminum-Silicon Carbide Composites, Table 1

To adhere the LED die to the heat spreader and mitigate CTE issues, thermally conductive epoxy TIMs were tested on the prototype. Several important characteristics of the epoxy are considered in this study. A well performing epoxy will have high thermal conductivity, low curing temperatures, and sufficient bonds to the heat sink and die. Multiple epoxies were tested and will be discussed in further detail in the Section 3.4.

To keep costs down and ease of manufacturability high, standard FR-4 PCBs were designed for power distribution functions. The PCBs designed are simple circuits to carry power to the LEDs and contain a current limiting resistor in the package. The PCBs can also be electrically joined to other PCBs to string multiple packages together. The unique design and function of the PCB will be discussed in the Sections 3.3 and 3.4.

The dominant method of electrically connecting LEDs to its packaging is through the use of wire bonding. This technique involves bonding extremely thin 25 μ m-75 μ m diameter gold or

aluminum wires between the chip pads and the package pads [Railkar & Warren, 2006]. There are two common types of wire bonding used in microelectronics packaging: thermosonic bonding, also known as ball bonding, and ultrasonic wedge bonding, also known as wedge bonding. Both methods of wire bonding cost similarly, but wedge bonding is slightly less expensive because aluminum wire is used instead of gold. Ball bonding allows for higher bond reliability and has the ability to turn the wire in different directions. Gold ball bonding accounts for 95% of all wire bonds in electrical packaging industry because wedge bonding is a slower process than ball bonding [Pan & Fraud, 2004]. Although wire bonding is an established technology, multiple factors must be considered before using the method. The wire, substrate, and bond process variables must be considered when wire bonding. Both methods of bonding were successfully used to create package prototypes.

In order to protect the LEDs after bonding, encapsulant is normally placed on the package. Encapsulant for LED lighting packages contains a phosphor material which is used to change the color temperature. LED encapsulant was not analyzed in this study.

3.3 Prototype Design Approach

Several factors were taken into consideration when designing package prototypes. It was established that building a low cost LED lighting package is an important endeavor based on environmental aspects such as containing no hazardous substances, efficiency and power savings, and government support through the L-Prize. Current LED lighting package designs were studied and compared to understand current packaging methods. Finally, previous studies on packaging and reliability were reviewed.

As stated in a previous section, creating a low cost solution to a high performance LED package was the goal of this study. Current LED package designs shown in Chapter 2 display leading designs of LED lighting packages.

The most common design can be seen in Figure 30. This design involves an LED die attached to a substrate or chip carrier. This substrate is bonded to a heat spreader, a MCPCB, which is then attached to a housing or heat sink by use of a mechanical fastener. Heat is then convected to the ambient air from the heat sink. Other electronics can be integrated into the MCPCB. The use of the metal core PCB serves the major requirements of electronics packaging for signal distribution and component protection, and also acts as a heat spreader. MCPCBs are high performance components, but result in a high cost to produce.

Figure 30: LED Heat Spreader, Source: Philips Lumileds, 2008a

The other standard option for creating an LED package is similar to that in Figure 30, but between the LED die and the heat spreader is standard FR-4 PCB. This is a lower cost solution because FR-4 PCB is a well-established means of packaging. However, this adds additional complexity to the entire package. FR-4 is a very poor conductor of heat, so thermal vias must be created to transfer heat from the substrate to the heat sink. This method still requires an additional heat spreader and the use of a TIM on the underside of the FR-4 substrate. In order for this type of package to achieve good performance, complex handling is required. Even then heat must travel through the PCB to reach the heat sink, adding a large amount of thermal resistance to the thermal path.

Both of the two major LED package designs incorporate several layers of heat spreaders and TIMs between the LED die and the main heat sink. Each layer adds a level of manufacturing complexity. Another important consideration is the distance heat must travel from the source to

the heat sink. Each layer can cause a potential bottleneck for heat flow. More complexity leads to higher costs and more opportunities for failure.

In this study, a new approach was considered to simplify a standard LED lighting package. Two very important design characteristics were set in order to increase thermal management performance and potentially lower manufacturing costs. The basic package design was based on the patent pending design of Ratcliffe and Pan, and all prototype designs that ensued followed two major design deviations from a common LED lighting package [Ratcliffe & Pan, 2010]. The package design created for this study can be seen in comparison to a conventional LED package in Figure 31.

Figure 31: Conventional LED Package Design vs. Prototype LED Package Design

The first major design differentiation was minimizing the distance and complexity of heat transfer from the LED package to the heat sink. The prototype design features an LED die

directly attached to the heat sink via a silver-filled epoxy TIM material. This is a very important characteristic because the only potential bottleneck for heat propagation is the TIM material used to attach the die to the heat sink. Heat travels directly from the heat source, the LED, to the heat sink. This prototype design also drives the cost of production down by minimizing the processing steps, materials, and complexity.

The second major design differentiation, which is necessitated by the first design differentiation, is separating the electronics from the LED thermal path. Fortunately, this design differentiation is beneficial to the overall robustness of the package. By separating the electronics from the LED, standard FR-4 board can be used to increase manufacturability and also lower production costs. Another major advantage to separating the electronics is the thermal isolation of the electronics from the LED dies. More heat generated by the LEDs will not affect the FR-4, and vice versa. The package simplicity allows easy design changes to different components of the entire package. This design adds a small amount of complexity by requiring wire bonds to cross from the LED die to the FR-4 substrate; however wire bonding is a common practice in microelectronics packaging industry.

3.4 Material Selection

After determining the basic design structure of the LED package, creating a bill of materials was necessary to begin thermal modeling of the prototype. Thermal modeling calculations were needed to confirm the effectiveness of the LED package before actual prototype production would begin. A bill of materials for the final prototype design can be seen in Table 5.

Table 5: Prototype Bill of Materials

Quantity	Description	Material	UOM
1	PCB	FR-4	Ea
1	Heat sink	Al 6061	Ea
7	LED		Ea
1	51 ohm SMT Resistor		Ea
-	Bond wire	Au/Al	ft
20	Epoxy		mg
10	TIM		mg

Materials needed to design the prototype can be broken into the two major functions of the prototype design. The first function is the lighting itself, which includes the LED die, the epoxy TIM material, and the heat sink. The second function is the electronics, which includes the FR-4, the wirebond material, and the resistor.

In this study, an array of 7 LED dies in series on a package is considered. A standard 24V DC source can be applied to drive the LEDs. It is common practice for multiple LEDs to be used in a single package because a single LED normally cannot output sufficient light using a safe amount of power. By placing 7 LEDs in series, a standard 24V source will be sufficient to meet the 3.4V forward voltage requirement of each LED.

Figure 32: 3D Model of LED Used for Prototype

The LED used in this study had both the anode and cathode pad on top of the die. This requires wire bonds to be connected to the die from a nearby PCB. Unfortunately, pads on top of an LED die leads to a small reduction in light output because the metal pads cause light to reflect back into the die.

Aluminum was decided upon to be used for the heat sink. After aluminum was selected for the heat sink, the specific alloy needed to be selected. A table of properties for different aluminum alloys can be seen in Appendix A. The most important properties of the desired aluminum alloy are cost, thermal performance, and ease of manufacturing. Both Al-6061 and Al-2024 alloys have the best overall thermal conductivity at 180 W/m K and 193 W/m K, respectively. However, Al-6061 is a much more common alloy, less expensive, and more easily machined. For these reasons, the 6061 alloy was chosen as the heat sink material.

The thermal interface material is a critical component of the package design. First, the TIM must be able to reliably bond the LED die to the aluminum heat sink. While doing so, it must be able to successfully conduct heat from the die to the heat sink. Finally, the TIM must be able to handle the CTE mismatch between the die and the heat sink without causing stress on the die. Not all TIM materials have bonding capabilities, but all TIMs used in this study were thermally cured epoxy adhesives.

When determining which TIM material would be used for the device prototype, several epoxy characteristics must be considered. The thermal conductivity of a TIM is very important, because often the TIM is a thermal bottleneck. Most standard thermally conductive epoxies have coefficients of thermal conductivity less than 10 W/m K. Compared to solder at 60 W/m K, TIM materials have a very high thermal resistance. Selecting the TIM material with the highest thermal conductivity rating may not be the best performing. Equation 2.6 shows the importance of TIM thickness. Both the thermal conductivity and cross-sectional area cannot be changed for a given TIM and LED interface, so minimizing the interface thickness is crucial to thermal performance. It is very difficult to characterize how easily a TIM can be applied both consistently and evenly. Therefore, several epoxies were tested during the prototype creation. The TIMs used in this study can be seen in Table 6.

Table 6: Table of TIM Materials Tested

Manufacturer	MFG Model	Thermal Conductivity (W/mK)	Viscosity (cp)	Max Operating Temp (°C)
AiT	ME8630-RC	8.6	15,000	150
AiT	ME8650-RC	7.9	15,000	150
AiT	ME7655-RC	0.86	50,000	150
Lord	MT-315	11.3	85,000	125
Lord	MD-140	12	40,000	150
Ablestik	84-1LMI	2.4	30,000	not specified

All electronics and power for the prototype package are routed through a PCB designed for the prototype's requirements. The PCB is a standard 62 mil thick FR-4 board. The PCB has four 80 x 170 mil solder pads designed to connect to a 24 Volt source and ground. There are also fourteen 15 x 15 mil wirebond pads designed to be connected in series to the prototype's LED pads. In the middle of the PCB are pads for a 51 ohm resistor. The overall dimensions for the PCB is 0.75" L x 0.25" W. A layout of the PCB can be seen in Figure 33.

Figure 33: Prototype PCB Layout

To successfully wirebond to the wirebond pads of the PCB, an electroless gold metallization was required. The electroless gold is plated over electroless nickel. This adds cost to a standard FR-

4 board. However if the PCB produced in high quantities, manufacturing costs would remain relatively low.

A 51 ohm SMT resistor was used as a current limiting device for the prototype. During the prototype assembly process, the resistor was bonded to the PCB by soldering with lead-free solder.

3.5 Thermal Modeling

Before beginning the prototype design and manufacturing process, it was necessary to develop a thermal model. Thermal modeling allows the estimation of operating temperatures, heat sink size, and airflow requirements. However, the primary purpose of thermal modeling of LED packages is to predict the junction temperature within the semiconductor die. This is where heat is generated within the die. Each LED purchased from a manufacturer has a data sheet which lists the maximum junction temperature so a package can be designed to meet these requirements.

3.6 Design Iterations

3.6.1 Design Iteration 1

The first prototype design was a very straightforward implementation of the two fundamental traits described in the previous section, see Figure 34. This package was designed to be a flat stamped piece of aluminum. This package had recesses for the LEDs and the PCB for easier mounting. There is also a hole in the package for mechanical fastening.

Figure 34: First Design Prototype, "Simple" LED Package

This design was focused on low cost manufacturing processes. Stamping is a well-known and mature forming process in which a machine press is used to produce a desired form from sheet metal. Stamping would require few fabrication steps, and the fastening hole could be punched out. Since tight tolerances are not needed for a flat heat sink, the low-precision manufacturing process seemed acceptable for mass production purposes.

After the prototype design was created in SolidWorks, it was analyzed using FloEFD to determine if the heat sink was sufficient for thermal considerations. The design was modeling using the materials specified in Table 5. The design was modeled as being attached to two different environments with an ambient temperature of 20 °C: a wooden pine backboard and a backboard with no heat transfer. Both environments have little heat transfer to best estimate the overall performance of the package design. Figure 35 and Figure 36 show a visual representation of the heat output from the package after steady state.

Figure 35: “Simple” Package with Backboard Heat Transfer

Figure 36: “Simple” Package without Backboard Heat Transfer

Figure 37 shows the actual steady state temperatures simulated by FloEFD in the two environments. It can be seen that the LED temperature is only slightly higher than the substrate temperature. This shows the design can successfully transfer heat directly from the LED die to the heat sink via a TIM. Note that even though the wooden pine backboard is an insulator, it still had a large effect on the thermal dissipation of the prototype. Also note in Table 7 that temperatures can be 60 degrees higher than ambient in certain conditions. This limits the viability of this design because warm, enclosed environments can quickly reach the thermal limits of the LEDs.

Figure 37: Steady State Temperatures of "Simple" Prototype

Table 7: "Simple" Prototype Temperatures over Ambient

	ΔT over Ambient	
	Backboard Heat Transfer	No Heat Transfer
Avg LED Temp (°C)	37.9	59.9
Avg PCB Temp (°C)	35.8	57.4
Avg Substrate Temp (°C)	35.39	57.3

3.6.2 Design Iteration 2

After the first design iteration, FloEFD simulations indicated the heat sink design could not sufficiently convect heat from the surface of the heat sink. Equations 2.3 and 2.4 both show that increasing the surface area of the heat sink will improve heat convection. The prototype design needed greater surface area, but needed to maintain a similar footprint. Fins were added to the

design and were bent in to keep the footprint similar, see Figure 38. It was quickly determined this design was not feasible. It can be seen from the figure below that there is no way to fasten the package to a surface without covering the LEDs.

Figure 38: First “Bent Fin” Design

A new design was created to retain the concept of the bent fin design so the stamping manufacturing process could remain. The new design wraps over itself and features less fins and two surfaces, see Figure 39. This allows the package to be mounted to a wall, while keeping the footprint the same. This new heat sink design manages to more than triple the surface area exposed to air, going from 1.01 in² to 3.53 in².

Figure 39: Final “Bent Fin” Design

This new design was modeled using FloEFD to determine how much the thermal properties would improve from the original design. The “Bent Fin” design was modeled using the same conditions as the original prototype. Figure 40 and Figure 41 show a much cooler design. The increased surface area and open design allows for enhanced cooling.

Figure 40: “Bent Fin” Package with Backboard Heat
Transfer

Figure 41: “Bent Fin” Package without Backboard Heat
Transfer

Figure 42 shows the actual steady state temperatures simulated by FloEFD in the two environments. Just like the “simple” prototype, it can be seen that the LED temperature is only slightly higher than the substrate temperature. In this case, the difference between environments is much less pronounced than before. Temperatures have dropped from 80 °C to around 55 °C for the worst case at 20 °C ambient. Table 8 shows a ΔT in the low 30s. This is a very reasonable number and suggests thermal conditions may be sufficient for an LED package in any reasonable environment.

Figure 42: Steady State Temperatures of "Bent Fin" Prototype

Table 8: "Bent Fin" Prototype Temperatures over Ambient

	ΔT over Ambient	
	Backboard Heat Transfer	No Heat Transfer
Avg LED Temp (°C)	27.7	35.7
Avg PCB Temp (°C)	22.6	30.7
Avg Substrate Temp (°C)	23.2	31.2

After spending time analyzing the manufacturing processes required to form the “Bent Fin” prototype package, it was deemed too difficult to manufacture. Note in Figure 39 the package heat sink has a square shape with three 90 degree bends. An example of how this process would be created can be seen in Figure 43. This process would require intricate tooling to perform this

feat with such a small package. Even then, tolerances would be difficult to hold and a relatively high scrap rate would occur. A new manufacturing route was decided because complex shapes are not suitable for this situation and requirements.

Figure 43: Bending Process for "Bent Fin" Prototype Heat Sink

3.6.3 Design Iteration 3

Extrusion is a common method of creating heat sinks. Extrusion is a process in which a large hydraulic ram forces a heated aluminum column against a die which deforms the aluminum column into the cross-sectional shape of the die. The aluminum shape is then cooled and cut into lengths of at least 3 feet. Extrusion is well suited for high-volume production, and

manufacturing costs are low. The extruded aluminum keeps tight tolerances and has the added benefit of a high surface finish. This allows easier mounting of LED dies.

A decision was made to remove the constraint requiring the option of a mechanical fastener on the package. This simple design decision allowed heat sink to be completely redesigned while maintaining the positive aspects of the previous packages. The new heat sink design would consist of a single extruded piece of aluminum 6061 alloy with three fins tapering upwards on each side, and a trough for the top of the PCB to sit flush with the LEDs when mounted, see Figure 44.

Figure 44: Extrusion Design Side View

After the design was set, the package was modeled in FloEFD to determine the effectiveness of the new design. One difference in the modeling compared to the previous models is the thermal conductivity of the TIM. Between the design the first package and the extrusion package, a TIM

with a thermal conductivity of 11.3 W/mK was purchased for use with the prototype. This thermal conductivity was used for the FloEFD model.

Figure 45 shows the thermal model for the extrusion prototype. This package was modeled in an environment with no heat transfer between the package and the mounting surface. Table 9 shows the steady state temperatures of the extrusion package prototype. Note the ambient temperature was modeled at 26.9 °C. The new design of the prototype, along with the higher thermal conductivity TIM, leads to a much better ΔT than previous designs.

Table 9: "Extrusion" Prototype Steady State Temperatures

	Steady State Temperature	ΔT over Ambient
Avg LED Temp (°C)	37.1	10.2
Avg Substrate Temp (°C)	34.9	8.0

Figure 45: "Extrusion" Package without Backboard Heat Transfer

Thermal modeling was also able to show the benefits of separating the electronics from the optics in the package, see Figure 46. By thermally isolating the resistor in the package, a primary source of heat was separated from the LED dies. This will further increase the lifetime of the LEDs and may prove to be a viable alternative to a constant current driver.

Figure 46: Isometric View of "Extrusion" Package

After the feasibility of both the manufacturability and thermal analysis was confirmed, the prototype was ready to be created. Parts and materials were purchased from several vendors, and several dozen packages were assembled in California Polytechnic State University's electronic manufacturing and packaging laboratory. A rendered drawing of an assembled package can be seen in Figure 47.

Figure 47: Rendering of Assembled LED Package

3.7 Prototype Assembly

The assembly process for creating the designed LED prototype can be split into three portions, see Figure 48. First, a resistor is soldered to the PCB. Afterwards, wires are soldered to the PCB to easily power the device after final assembly. The PCB is then cleaned with alcohol to remove contaminants.

The next portion of the assembly process is the heat sink fabrication. The extruded aluminum heat sink arrived from the supplier in 6 foot lengths. Each length of heat sink is then cut to 1.1” using a saw. These cut heat sinks have sharp burrs, so there a sanding process to deburr the aluminum. Finally, the heat sink is cleaned to remove particles.

After the heat sink and PCB are prepared, the packaging process is ready to begin. To attach the PCB to the heat sink, an adhesive epoxy is placed in the trough and the PCB is set on top. Since the epoxy is thermally cured, it is then placed in an oven until the epoxy cures. A scribe line is then etched into the heat sink so the LEDs can be placed at a consistent distance from the PCB. The TIM material is then placed on the scribe line between the PCB wirebond pads. It is important that not too much TIM is applied because it is electrically conductive and can short the package. The LEDs are then placed on top of the TIM in the correct orientation using a manual die attach tool. The package is placed in the oven again to cure the TIM and set the LEDs. Next, wire bonds are made from the LED pad to the PCB pads to create the electrical connections. The package is then tested using a 24V power supply. If the package works, it can finally be encapsulated to protect the wire bonds.

Figure 48: Operations Process Chart of LED Prototype

3.8 Mass Production

The process for producing the designed package would be very similar if the production increased. The resistor can be mounted to the PCB using a SMT process. The TIM can be laid consistently using a stencil printing process. Finally, the LED dies can be automatically placed and wire bonded. The processes used in this study are cost-effective processes and can easily scale based on demand.

3.9 Minor Changes to Assembly Process

By physically creating prototypes, small improvements were made to the assembly process after encountering problems. Originally the PCB was mounted to the heat sink using a simple cyanoacrylate, Krazy Glue. Soon after being placed in the oven to cure the TIM, delamination between the PCB and heat sink would occur. The design was changed to use a stronger bonding, thermally cured epoxy.

Several issues were also found during the wire bonding process. Originally, the wire bonds, both wedge and ball, were not bonding to the PCB pads. After examination with a microscope, it was determined the PCBs were being contaminated during handling. A process was added to the assembly to clean the pads before wire bonding to resolve the problem.

Two improvements were also made to increase reliability. First, the ultrasonic time and power of the wirebond tools were well calibrated to ensure strong and consistent bonds. The second improvement involved the orientation of the LED dies during assembly. By orienting the LED pads as close to the PCB pads as possible, wire bonding became easier because the chance of

shorting the wires was minimized and the bond angles were reduced, see Figure 49 and Figure 50.

Figure 49: Original LED Orientation

Figure 50: Improved LED Orientation

Chapter 4: Prototype Performance Measurements

4.1 Current Prototype Reliability Analysis

Testing the reliability of the prototype after its production is a very important requirement. Reliability testing will validate the models created during the design phase, as well as introduce any failure mechanisms of long term use. Multiple prototypes were assembled using different materials so future research can determine which material combination will be optimal for an LED lighting package.

Six different TIM materials were used to attach the LED dies to the heat sink. Both aluminum wedge bonding and gold ball bonding were used for electrical connections. Each combination of these factors should be considered during lifetime testing.

Accurate measurements of different components are critical to understanding future failure mechanisms. The forward current and voltage used to power the LEDs is simple to measure using a power supply. However, the junction temperature of the LEDs involves a slightly more complex process. Another important factor is the thickness of the TIM used, because this information is critical to accurately measure the package thermal resistance.

4.2 Measuring Prototype Temperatures using IR Thermography

The forward voltage method is the preferred method for measuring junction temperature, but was unavailable during the writing of this thesis; see Chapter 2 for more details on the forward voltage method. Another method of measuring junction temperature, IR thermography, is

simply photographing the heat output from the LED dies. This method provides a less accurate measurement, but is useful for quickly determining thermal performance of a package. A FLIR thermal imaging camera was used to capture thermal measurements of a working prototype, see Figure 51.

Figure 51: FLIR T200 Thermal Infrared Camera, Source: FLIR

Before using the infrared camera, a working prototype was powered at the designated operating conditions until reaching steady state temperatures. The camera was used to focus on different parts of the package to determine the temperature of different components. Unfortunately, the camera used was not designed for macro images, so focusing the camera on an individual LED could only occur with the entire package in the image. This further reduced the accuracy of the camera, but the results are still valid enough for reference.

The first set of thermal measurements taken was of LEDs on the prototype. Each measurement was within a degree of the others, further validating the results. Figure 52 and Figure 53 show

the steady state temperature of the LEDs at 28.8 °C and 28.5 °C, respectively. Note the ambient temperature during testing was 23 °C. These results are consistent with the thermal models found in the previous section. IR imaging shows the LEDs are well below the LED junction temperature requirement of 125 °C. This will allow future designs of the package to either reduce the footprint, or increase the operating power.

Figure 52: 1st Point Temperature Measurement of LED

Figure 53: 2nd Point Temperature Measurement of LED

The second thermal measurements were of the resistor. The thermal modeling suggested the resistor would be the hottest component of the package, and the PCB would be thermally isolated from the package. This is confirmed in Figure 54, with the resistor showing a temperature of 42.2 °C.

Figure 55 shows the overall maximum temperature of the package. The picture seems to suggest the hottest component of the package is the resistor at 40.6 °C.

Figure 54: Point Measurement of Resistor

Figure 55: Overall Maximum Temperature of Prototype
Package

4.3 Measuring TIM Thickness

The TIM thickness can be measured by encasing the package in plastic and cutting the package in two parts to expose the desired cross section. The cross section is then polished to clearly expose the face of the cut. A microscope can then be used to accurately measure the TIM thickness. The materials engineering department at California Polytechnic State University has these capabilities.

Another method available for measuring TIM thickness is using an automatic general purpose dimensional measurement tool, such as the SmartScope Flash 250 in use at California Polytechnic State University. This tool is capable of measuring in the XYZ using a laser, touch probe, or optical imaging.

Chapter 5: Cost Analysis

5.1 Prototype Costs

Lowering the cost of LED packages for lighting is a major factor in displacing other forms of lighting. This consideration is the driving force behind the L-prize in hopes of energy efficient LEDs becoming a ubiquitous form of illumination. This requirement translated into this study by selecting the components and packaging methods to minimize the packaging costs while maintaining sufficient reliability. Unfortunately, a full cost analysis of the prototype is not possible because insufficient prototype testing has occurred. In time, the package will continue to be finalized and supplier quotes can be offered.

Cost estimates for the package can be applied using the current R&D costs. Table 10 shows the prototype BOM with cost estimates for high volume production. Note the cost of materials is approximately \$6. Factoring labor and manufacturing would marginally increase the cost of the package. However, these costs consider the manufacturer has access to high volume microelectronics packaging tools, such as a ball bonder tool capable of mass production and a die pick and place tool able to handle the small LED dies. Each of these tools can cost hundreds of thousands of dollars [Lau, 2000]. The total end cost per the designed package will estimated as \$20 for this section.

Table 10: Estimated Package Costs at High Volume Production

Quantity	Description	Material	UOM	Unit Cost (High Volume)	Total Cost (High Volume)
1	PCB	FR-4	Ea	\$ 0.50	\$ 0.50
1	Aluminum heat sink	Al 6061	Ea	\$ 0.18	\$ 0.18
7	LED		Ea	\$ 0.43	\$ 3.00
1	51 ohm SMT Resistor		Ea	\$ 0.01	\$ 0.01
-	bond wire	Au/Al	ft	\$ 0.10	\$ 0.10
20	Epoxy		mg	\$ 0.03	\$ 0.50
10	TIM		mg	\$ 0.20	\$ 2.03
				Total	\$ 6.32

5.2 Lighting Technology Cost Comparison

This section will compare the cost of LED lighting to other lighting technologies to better understand the cost requirements needed to displace CFL as a standard lighting method. For a basic cost comparison, pricing for a standard PAR38 bulb of different technologies were compared to the estimated prototype LED package, see Table 11. Due to the thermal performance results of the prototype, the lifetime of the prototype will be estimated as 60,000 hours. The LED PAR38 lamp chosen for the study is a high performance LED light bulb found in a general hardware store.

Excluding the prototype, the results of the cost comparison shows CFL is the most inexpensive form of lighting over 25k hours of use. The current market LED light bulb studied, a Sylvania Ultra LED PAR38 lamp, is an order of magnitude higher cost than its CFL alternative; its longer life and better efficiency are not enough to return better savings. However, the prototype package shows much better returns than the other alternatives due to its lowered cost and extended life. Incandescent light bulbs are inferior to both CFL and LED. After 25,000 hours of

use, the total household savings by switching from incandescent bulbs to more efficient forms of lighting will result in several thousand dollars in savings.

Table 11: PAR 38 Lighting Cost Comparison

PAR38 Lighting Comparison				
	Incandescent	CFL	LED	Prototype
Life Span (hrs)	1500	8000	25000	60000
Watts	90	23	16	16
End Cost of Item	\$ 1.35	\$ 6.49	\$ 68.98	\$ 20.00
KWh of electricity used over 25k hours	2250	575	400	400
Electricity Cost @ \$0.151 per KWh*	\$ 339.75	\$ 86.83	\$ 60.40	\$ 60.40
Bulbs needed for 25k hours	17	4	1	1
Cost of bulbs over 25k hours	\$ 22.95	\$ 25.94	\$ 68.98	\$ 8.33
Total Cost	\$ 362.70	\$ 112.77	\$ 129.38	\$ 68.73

* http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_b.html

Although the total cost of the current market LED solution is higher than that of the CFL, several factors must be considered besides overall cost. When purchasing lighting solutions total illumination, minimum light output, mortality rate, re-lamping interval, color quality, and operating conditions are all important factors [Philips Lumileds, 2008b]. Mortality rate is a very important factor given the high cost of a package. The re-lamping interval is an important factor for businesses where administrative costs and location outweigh the cost of the package.

Initial cost remains a major factor when purchasing lighting as an individual consumer. By using the data in Table 11, the payback period was calculated assuming an LED package is purchased

instead of a CFL. This results in a negative value at year 0. The payback period calculation takes into account package replacement costs, energy costs based on average California utility costs in 2008, and package lifetime. The payback period calculation also assumes light will run continuously.

Figure 56 confirms the findings in Table 11 which shows the energy savings of current LED lighting products is not enough to displace the alternative CFL technology. In order to pay back the cost of upgrading from CFL to LED within 3 years, the price of the LED package must fall to \$42.29. Even after adjusting the cost and lifetime performance to match the L-Prize requirements of \$30 per package, the payback period is shortly over 2 years of continuous use. However, the prototype package's low initial cost allows the payback period to be less than 1 year.

Energy costs are another important factor when considering a more efficient technology. As the price of energy increases, the efficiency improvements of an LED will make the option more viable. However, even a 20% increase in energy costs is not enough to displace CFL technology based on current technology, as seen in Figure 56. If the L-prize standards are set along with a 20% increase in energy costs, the payback period is very close to 1 year.

Instead of changing the initial cost of the lamp, changes in the LED lifetime were analyzed. Since some LEDs have been shown to reach 60,000 hours of continuous operation, this number was used to calculate the payback period for both the current market LED package and the prototype LED package. Figure 57 shows the payback period between years 2 and 3 for the

current market package. Doubling the lifetime rating of the LED lamp results in a very similar payback period to reducing the cost of the package in half. Notice the prototype LED package results in substantial savings over its lifetime. A scenario such as this would make LEDs much more competitive in the marketplace.

Figure 56: Simple Payback Period of LED vs. CFL 25k Hour Scenarios

Figure 57: Simple Payback Period of LED vs. CFL 60k Hour Scenarios

Chapter 6: Conclusions and Future Research

The LED package designed in this study was shown to be capable of successfully providing general lighting with sufficient thermal management at a relatively low packaging and assembly cost. The design created is unique because the LEDs are directly mounted to the heat sink, and the electronics are separated from the thermal path. This led to the creation of a functioning package with simulated die junction temperatures only 10 °C above ambient temperatures. Thermal imaging results confirmed the thermal performance of the package.

Several design iterations were carried out to improve the manufacturability of the LED package based on the DOE's L-Prize requirements. One major requirement, keeping the LED junction temperature below 125 °C, was successful. Also, the package remained capable of mass production. Costs were kept as low as possible, but an exact cost of production is yet to be determined. At its current state, the cost of the prototype is within the L-Prize cost requirement. Market ready design, long-term reliability analysis, and LED color quality requirements of the L-Prize were not analyzed as of writing this thesis.

It is recommended that future research of the package prototype continues to strive towards meeting the requirements of the L-Prize to become a viable product. Future package research should include encapsulant characterization and evaluation, TIM characterization and evaluation, an evaluation of an integrated lens, and implementation of the prototype into standard fixtures. The market ready prototype should include an integrated AC transformer. After the prototype reaches a market ready state, it should be tested in a variety of applications to determine its overall effectiveness.

Reliability testing should be conducted by future researchers to determine the long-term reliability and feasibility of the package design. This will likely require accelerated lifetime testing. The prototype should be stress tested using high ambient temperatures, voltage and current fluctuations, and high humidity environments to better understand the prototype's ability to operate in multiple environments.

The results of the study seem promising, but the design must be directly compared to market leaders to determine the true success of the design. It is left to future researchers to conduct these tests in hopes of providing a safe and efficient source of lighting in an affordable package.

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Appendix A: Aluminum Alloy Material Properties

Aluminum (Al) Specification Sheet

	Al 5052-O	Al 6061-O	Al 2024-O	Al 7075-O
Physical Properties	Metric	Metric	Metric	Metric
Density	2.68 g/cc	2.7 g/cc	2.78 g/cc	2.81 g/cc
Mechanical Properties				
Hardness, Brinell	47	30	47	60
Ultimate Tensile Strength	193 MPa	124 MPa	186 MPa	80
Tensile Yield Strength	89.6 MPa	55.2 MPa	75.8 MPa	68
Elongation at Break	25 %	25 %	20 %	228 MPa
Elongation at Break	30 %	30 %	22 %	103 MPa
Modulus of Elasticity	70.3 GPa	68.9 GPa	73.1 GPa	16 %
Ultimate Bearing Strength	345 MPa	228 MPa	345 MPa	17 %
Bearing Yield Strength	131 MPa	103 MPa	131 MPa	71.7 GPa
Poisson's Ratio	0.33	0.33	0.33	0.33
Fatigue Strength	110 MPa	62.1 MPa	89.6 MPa	*
Machinability	30 %	30 %	30 %	*
Shear Modulus	25.9 GPa	26 GPa	28 GPa	26.9 GPa
Shear Strength	124 MPa	82.7 MPa	124 MPa	152 MPa
Electrical Properties				
Electrical Resistivity	4.9e-06 ohm-cm	3.6e-00 ohm-cm	3.5e-06 ohm-cm	3.8e-06 ohm-cm
Thermal Properties				
CTE, linear 68°F	23.8 µm/m-°C	23.6 µm/m-°C	23.2 µm/m-°C	23.6 µm/m-°C
CTE, linear 250°C	25.7 µm/m-°C	25.2 µm/m-°C	24.7 µm/m-°C	25.2 µm/m-°C
Specific Heat Capacity	0.88 J/g-°C	0.896 J/g-°C	0.875 J/g-°C	0.96 J/g-°C
Thermal Conductivity	138 W/m-K	180 W/m-K	193 W/m-K	173 W/m-K
Melting Point	607 - 649 °C	582 - 652 °C	502 - 638 °C	477 - 635 °C
Solidus	607 °C	582 °C	502 °C	477 °C
Liquidus	649 °C	652 °C	638 °C	635 °C
Processing Properties				
Annealing Temperature	343 °C	*	413 °C	413 °C