Economic and Environmental Costs of Polymer Optoelectronics

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Abstract

Polymer light-emitting diodes are desired for popular use by economists and environmentalists alike. They are much cheaper and easier to produce than conventional light-emitting diodes and are also more environmentally friendly because they contain a polymer active layer which is biodegradable. However, polymer light-emitting diodes are held back from popular use because they have much lower power, efficiency, and lifetimes, which prevent the use of full color polymer light-emitting diode screens. This project focuses on the economic and environmental costs of polymer light-emitting diodes compared to conventional light-emitting diodes, on determining which of their qualities need improvement and by what degree, and finding potential ways to make developments so that this new technology will be competitive in the consumer market.

1. Introduction

The lighting industry has seen major improvements in technology in recent years. Fluorescent lights with higher efficiency replaced incandescent light bulbs, and Light-Emitting Diodes, or LEDs, with less toxic materials replaced fluorescents. However, LEDs are far from perfect, and, in the near future, fluorescent Polymer Light-Emitting Diodes (PLEDs) may gain the potential to replace LEDs. PLEDs have a polymer active layer, as opposed to the metallic active layer of conventional LEDs. This makes PLEDs cheaper, more flexible, and much easier to produce than conventional LEDs. While the advantages PLEDs offer would have incredible impacts on the economy and the environment, the adoption of PLEDs for public use is made difficult because of the severe inefficiency of blue PLEDs. Compared to red and green, blue PLEDs have a much lower lifetime and are only one-third as efficient which prevents the use of full color PLED screens. Because of this, PLEDs are unable to compete with conventional LEDs as a common lighting technology.

Blue PLEDs must be efficient enough to contend with conventional blue LEDs in order for full color PLED lighting to be used by the public. This study involves comparing the economic costs and the environmental costs of four different PLED architectures to each other and to conventional blue LEDs. The main focus of this study is to research alternative methods and architectures for blue PLEDs to increase their efficiency so that they can be made marketable. If such technology were made equally or more efficient than existing lighting technology, the lighting industry would be much less environmentally damaging and much more economically friendly.[1]

2. Background

PLEDs consist of several layers of materials. Each colored PLED has an active layer that emits a specific color. Blue PLEDs, which have a poly(9,9-di-*n*-octylfluorenyl-2,7-diyl) (or PFO) active layer, are currently far less efficient, long-lasting, and practical than red and green PLEDs. In order to promote the marketability of polymer LEDs, blue PLEDs must be improved significantly.

2.1 PLED Structure

The bottom layer of a conventional bottom-emitting blue LED device is indium tin oxide (ITO) on a glass substrate, which acts as the anode. This ITO layer is followed by a poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (or PEDOT:PSS) hole transport layer , a PFO active layer, a lithium fluoride electron transport layer and is topped with an aluminum cathode.[1] A current passes through this device, creating holes (absences of electrons) at the anode and emitting electrons at the cathode. When the electrons and holes combine in the active layer, photons are released.

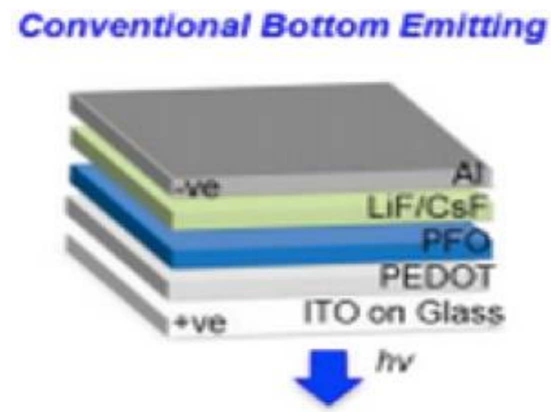

Figure 1. Architecture of a conventional bottom-emitting PLED[1]

ITO is chosen as the anode because it performs well at a large range of temperatures and is transparent, allowing light to be emitted. The PEDOT:PSS layer is used because of its low cost and high conductivity, which helps improve the efficiency of the device. PFO is a blue-conjugated polymer that is used due to its high efficiency. Finally, the lithium fluoride layer helps transport electrons, while aluminum is a common cathode (Figure 1).[2]

2.2 PLED Drawbacks and Advantages

Blue PLEDs are less efficient because of the difficulty of charge injection into blue emitting polymers, such as PFO, as their highest occupied molecular orbital is low in comparison to red and green LEDs.[3] This is a major roadblock in making polymer LEDs mainstream, as displays require red, green, and blue colors. If the blue colors continue to fade at the rate they currently do, the displays would begin losing their practicality relatively quickly.

However, conventional LEDs also have drawbacks. While conventional LEDs are highly efficient and have significantly longer lifetimes, their disposal process is difficult. A major concern about the conventional LED is their potential to pose a problem in waste landfills as hazardous materials. Conventional LEDs contain mercury and a significant amount of aluminum in their heat sinks, while PLEDs are much more resourceful in their use of nonhazardous materials, omitting many of the toxic materials found in conventional LEDs.[4] PLEDs are more environmentally friendly than conventional LEDs.

Furthermore, the materials required to make PLEDs are more readily available and cheaper than those required for conventional LEDs. The manufacturing cost of PLEDs is also much lower than that of conventional LEDs, as PLEDs can be created using a solution-based process similar to inkjet printing. Conventional LEDs have to be grown on sapphire substrates and utilize a more complex process than that of PLEDs, with many inconvenient costly steps (Figure 2).

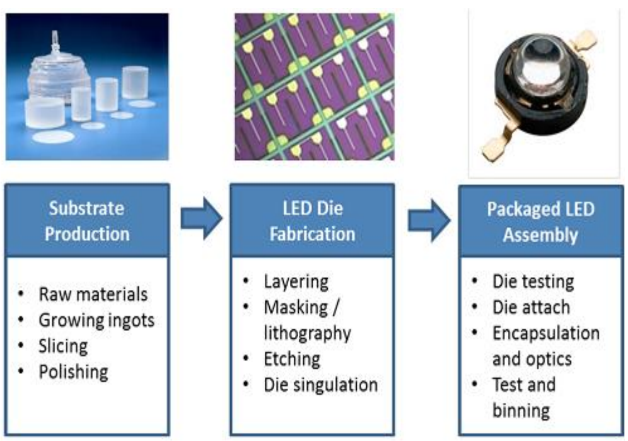

Figure 2. Fabrication process of a conventional LED[4]

Thus, while many improvements have been made to polymer LEDs and their manufacturing process, blue PLEDs will need to be improved upon if PLED displays want to stand a chance against conventional LEDs in the market.

3 Analysis Using Life-Cycle-Based Methodologies

New technologies face the challenge of competing with existing, much more mature technologies. Two important statistics to consider are economic and environmental costs. Polymer optoelectronics, regardless of their unique advantages, will be unable to compete in the solid-state lighting market if its technology is not economically viable. Emerging technology must also be environmentally-friendly in an age advocating clean energy.

3.1 Economic Assessment

3.1.1 Device Layer Costs

Polymer optoelectronics are composed of various materials forming layers that serve different purposes. Catrice M. Carter's manuscript reports a detailed analysis of four different PLED device architectures: conventional bottom-emitting, inverted bottom-emitting, conventional top-emitting, and inverted top-emitting (Figure 3). The architectures have different sets of materials, which determine the costs and direction of emission (Figure 4).

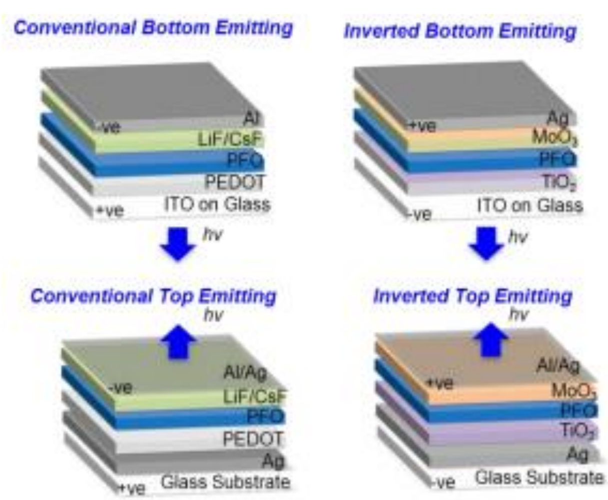

Figure 3. Orientation of the layers for the four PLED architectures[1]

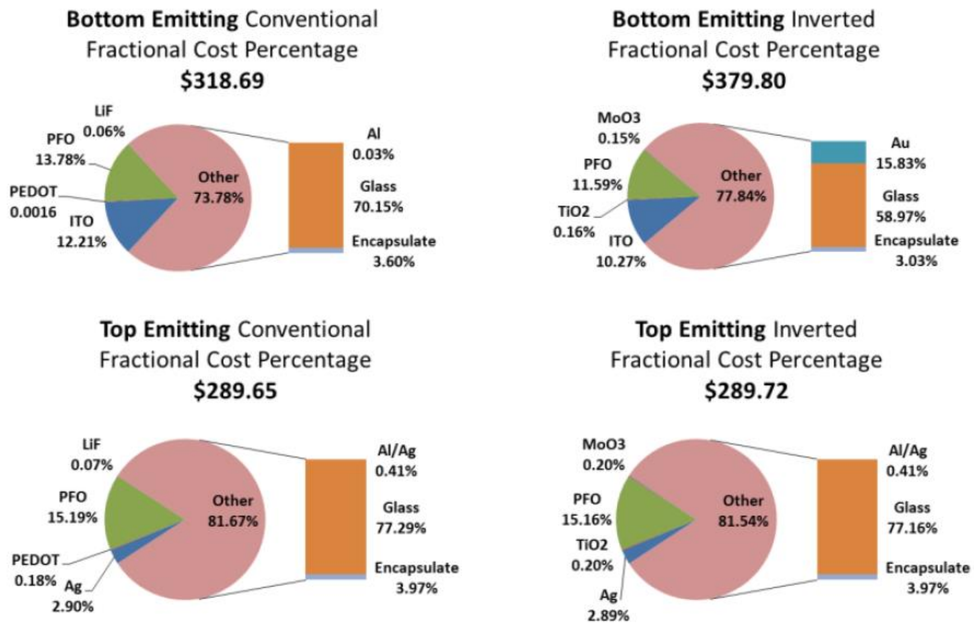

Figure 4. Each layer's contribution to the total cost for the four PLED architectures for 1m^2 display screens[1]

Conventional LEDs are also made up of multiple layers (Figure 5).

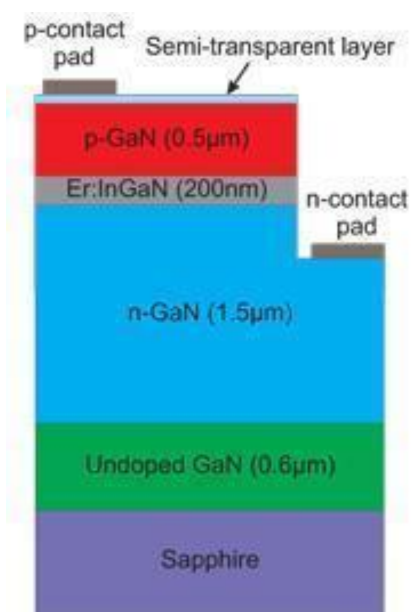

Figure 5. Orientation and thickness of each layer in a blue conventional LED[5]

Sigma-Aldrich sells Gallium Nitride (GaN) at a price of $17.55 per gram.[6] Indium Gallium Nitride (InGaN) is a semiconductor mix of Indium Nitride (InN) and Gallium Nitride (GaN). Sigma-Aldrich sells InN at a price of $188 per gram. The price of a 1m^2 layer is calculated using the equation:

$$Cost = Area \cdot Thickness$$

$$\cdot\ Density \cdot Price\ per\ gram$$

Sapphire wafers are sold at $2.0558 per cubic centimeter at University Wafer[7]. The thickness of the sapphire substrate was determined to be 100 microns[8]. The cost of each layer is determined separately and then added to obtain the total cost of the device.

3.1.2 Life Cycle Costs[1]

The total life cost savings, in $/yr, was calculated by:

$$C_{yr} = (C_{tot}/L) \cdot 24 \cdot 365$$

where L is the lifetime and C_{tot} is the total cost defined as:

$$C_{tot} = C_{mat} + C_{man} + C_{phase}$$

C_{mat} is the materials cost, C_{man} is the manufacturing cost, and C_{phase} is the use phase cost which is defined as:

$$C_{phase} = \frac{P \cdot L}{1000} C_{elec}$$

where C_{elec} is the cost of electricity in \$/kWh.[9]

3.2 Device Qualities

It is also vital to compare blue PLEDs to blue conventional LEDs based on their lifetime, power, luminance, and power efficiency. Catrice M. Carter's manuscript reports these values for the four different architectures (Table 1) based on New Jersey's energy statistics.

	Bottom-emitting Conventional	Bottom-emitting Inverted	Top-emitting Conventional	Top-emitting Inverted
Lifetime (hr)	16,787	25,675	16,787	25,675
Power (W)	21,407.38	10,993.17	20,047.79	8,815.85
Luminance (cd/m²)	1,180	1,257	1,640	2,930
Efficiency (lm/W)	0.255	0.528	0.3779	1.53548

Table 1. Device qualities of the four PLED architectures[1]

The values for blue conventional LEDs were determined through various methods. The lifetime was determined from Philips White Paper "Understanding Power LED Lifetime Analysis" (Figure 6). 350mA is the minimum current necessary to power general LEDs, and the corresponding lifetime is 60,000 hours.

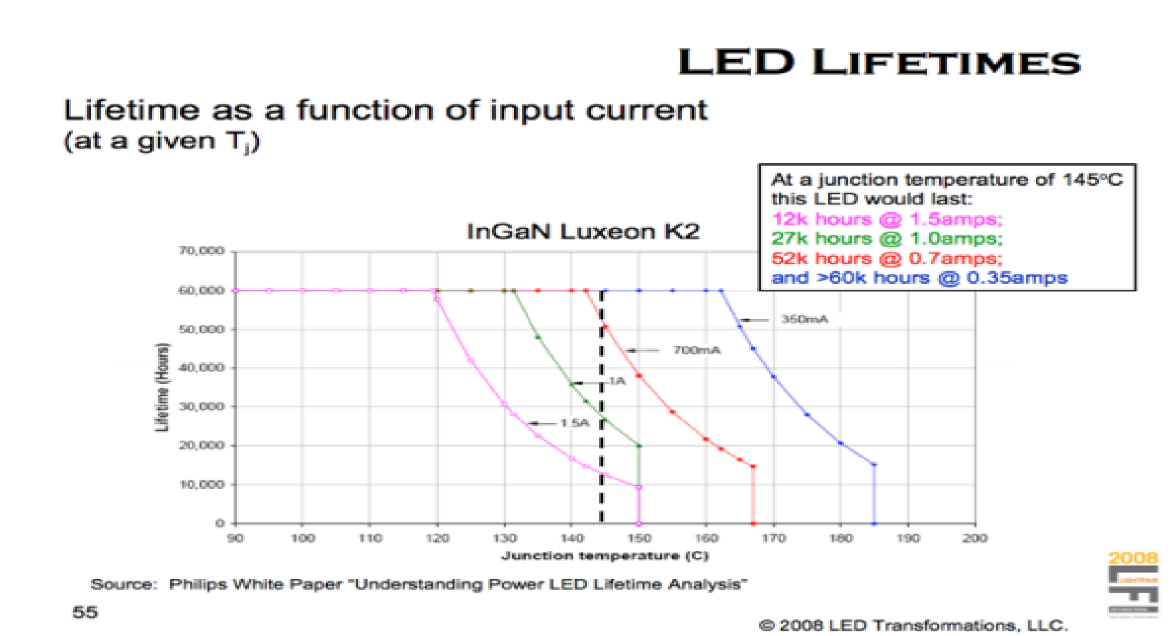

Figure 6. LED lifetimes as a function of input current at a given temperatuer[10]

The luminance is given to be 5000 cd/m^2 for blue conventional LEDs.[11] The power efficiency calculations are based on a 5mm Blue LED sold on the market.[12] Its specifications state 0.3 lumen and 0.07 watts. The power efficiency is calculated using the equation:

$$P_e = \frac{Lumens}{Total\ power\ consumption}$$

giving 4.2857 lm/W. The power values of the four PLED architectures were calculated according to:

$$P = \frac{E_f \cdot \pi}{P_e} k$$

where E_f is efficacy in cd/m^2, P_e is power efficiency in lm/W, and k is 1/PR(performance ratio) for display devices. The PR is given to be 68%. This equation was used to calculate the power of blue conventional LEDs.

The operating energy consumption per unit area, in cd/Wm^2, was calculated by:

$$E_{op} = \frac{E_f}{p}$$

where E_f is efficacy and p is power.

3.3 Environmental Assessment

3.3.1 Global Warming Potential

Electricity generation involves the production of carbon dioxide gas. Therefore, powering polymer optoelectronics is inevitably tied to greenhouse gas emissions. The Global Warming Potential of the devices over their lifetime was calculated for the four different blue PLED architectures and blue conventional LEDs by:

$$Mass\ of\ CO_2 = Power \cdot Lifetime \cdot [(\%oil \cdot CO2\ for\ oil)+(\%coal \cdot CO2\ for\ coal)+(\%natural\ gas \cdot CO2\ for\ natural\ gas)]$$

The devices' power and lifetime values are taken from Table 1. The U.S. Energy Information Administration reports the percentages of oil, natural gas, and coal New Jersey uses to generate electricity (Figure 7). Petroleum makes up 0.825%, natural gas makes up 38.357%, and coal makes up 4.760% of New Jersey's electricity generation.

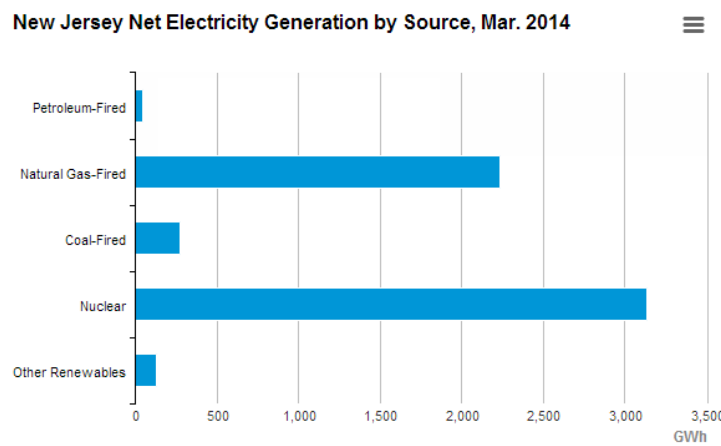

Figure 7. Use distribution of energy sources for New Jersey's electricity generation in 2014[13]

The EIA also reports the amount of carbon dioxide produced per unit of energy for each of the fossil fuels (Table 2). Coal was averaged to produce 2.14 lbs/kWh and oil was averaged to produce 1.745 lbs/kWh.

Fuel	Lbs CO_2 per kWh
Coal	
Bituminous	2.08
Sub-bituminous	2.16
Lignite	2.18
Natural gas	1.22
Distillate Oil (No. 2)	1.68
Residual Oil (No. 6)	1.81

Table 2. Pounds of CO_2 produced per kWh of different fuels[14]

3.3.2 Recyclability and Toxicity

The environmental impact of PLEDs and LEDs after their lifetime was also studied and compared. Relevant data were collected for each layer separately. The recyclability factors include recovery, reusability, efficiency, and cost of the recycling process. The viability of recycling was determined through judgment of payback time, costs, and ease. The toxicity of each material was also considered in the case of failure to recycle. Factors include biodegradability and specific environmental hazards.

4 Results and Discussion

4.1 Economic Cost

The operational energy and lifetime of blue PLEDs, as recorded in Catrice M. Carter's report (Table 3), are much lower than those of conventional blue LEDs. Inverted design PLEDs, which have 50% longer lifetime than conventional design PLEDs, still have half the lifetime of LEDs. Their low efficiency is a result of high power usage coupled with low luminance. The severe lack of efficiency and low lifetimes of blue PLEDs are the reason why full color PLED screens are not possible with the existing blue PLED architectures. However, any of the four blue PLED architectures are, on average, cheaper than LEDs over their lifetimes (Table 5). This is huge motivation for the lighting industry to find new ways to improve PLED technology.

	Bottom-emitting Conventional	Bottom-emitting Inverted	Top-emitting Conventional	Top-emitting Inverted	Blue Conventional LED
Lifetime (hr)	16,787	25,675	16,787	25,675	60,000
Power (W)	21,407.38	10,993.17	20,047.79	8,815.85	5,000
Luminance (cd/m^2)	1,180	1,257	1,640	2,930	5,390
Efficiency (lm/W)	0.255	0.528	0.3779	1.53548	4.2857

Table 3. Device Qualities of the four PLED architectures and blue conventional LED[1, 10, 11, 12]

		Price ($/g)	Mass (g)	Total Cost ($)
Gallium Nitride (GaN)		17.55	15.99	280.62
Indium Gallium Nitride (InGaN)	Gallium Nitride (GaN)	17.55	0.8610	15.11
	Indium Nitride (InN)	188.00	0.4086	76.82
Sapphire Wafer		0.5165	398.0	205.57
Total Cost				578.12

Table 4. Price of layers in blue conventional LEDs for 1 m² devices[5, 6, 7, 8]

	Bottom-emitting Conventional	Bottom-emitting Inverted	Top-emitting Conventional	Top-emitting Inverted	Blue Conventional LED
Operational Energy (cd/Wm^2)	0.0551	0.1143	0.0818	0.3324	0.9276
Cost per year ($/yr)	30,040	15,470	27,179	12,401	18,829
Life Cost ($)	2.689	4.125	2.598	4.123	23.93

Table 5. Operational energy, cost per year, and life costs of the four PLED architectures and blue conventional LED for Samsung Galaxy S4 dimensions[1]

4.2 Environmental Cost

The environmental costs of PLEDs are approximately equal to that of LEDs. The conventional design PLEDs are slightly more costly in terms of energy while the inverted design PLEDs are slightly less costly, with the top inverted architecture having the lowest energy cost (Table 6). These results, however, are deceiving as they are calculated based on the power output of the LEDs for the duration of their lifetimes. The semiconductor based LEDs have much longer lifetimes with much lower power outputs. If the devices' energies were measured over just the PLED's lifetimes, the LEDs would have used much less energy in that time.

The global warming potential of each PLED architecture and the blue conventional LED architecture is calculated in terms of its energy cost over its lifetime and the amount of CO_2 released by different fossil fuels. The total energy consumption is proportional to the CO_2 emission. The conventional PLED architectures use more energy and therefore produce more carbon dioxide than blue conventional LEDs while the inverted PLED architectures use much less energy and therefore produce less carbon dioxide than blue conventional LEDs. These values still may be misleading because conventional LEDs have a much greater lifetime. The rate of CO_2 released over time for conventional LEDs is much lower than the rate of emission for each PLED structure and therefore LEDs have a much lower global warming potential over time. Because PLEDs have a much shorter lifetime, over the duration of each LED's lifetime they will release an approximately equal amount of CO_2 (Table 6).

	Total Energy Consumption (J)	Global Warming Potential (kg of CO_2)
Bottom-emitting Conventional	1.294×10^{12}	95130
Bottom-emitting Inverted	1.016×10^{12}	74690
Top-emitting Conventional	1.212×10^{12}	89100
Top-emitting Inverted	8.148×10^{11}	59900
Blue Conventional LED	1.080×10^{12}	79400

Table 6. Lifetime energy use and CO_2 emission of the four PLED architectures[1, 13, 14]

4.3 Post-life Assessment

Another major point to consider between LEDs and PLEDs is their environmental impacts after they have been used as in when recycled or thrown away. In terms of recyclability, conventional LEDs have a great advantage. Gallium and indium, LEDs' two most abundant metals, can be recovered from the semiconductor with almost perfect purity.[15] It is estimated that over 95% of the semiconductor in an LED is reusable.[16] For PLEDs, indium in its ITO layer, its most expensive layer, is 60-65% recyclable after 30 days. In addition, the glass layer can also be removed and reused with almost no difference in efficiency.[17] The metal cathode, aluminum or silver, could also be reused, but the polymer layers cannot. While recyclable, the costs of recycling each layer may be too high to be worth reusing. While the costs are difficult to ascertain, it is known that PLEDs have very high energy payback, and it may be easiest to discard them after use rather than using energy to recycle them.

Recyclability is not the only concern; the majority of people are more likely to throw away LEDs at the first sign of failure rather than recycle them, thus the toxicity of each layer must be taken into account as well. PLEDs have an advantage in this case, as all polymer layers are biodegradable and will cause no damage to the environment. For the conventional PLEDs, Ag, Al, and LiF are all not environmental hazards, however, LiF may create damaging long-term products. The inverted PLED designs use TiO_2 which is harmless' but also contain MoO_3 which creates toxic products when biodegrading. ITO is also extremely hazardous to water, but its biodegradability is unknown. LEDs on the other hand, are entirely metal with no biodegradable layers. Neither indium nitride nor gallium nitride are biodegradable, and, while dangerous to touch, their long-term toxicity is unknown. Overall, assuming humans are more likely to throw out used lights than to recycle them, PLEDs are more environmentally friendly in this aspect.

4.4 PLED Improvements

Until the lifetime and power efficiency of PLEDs are improved, they will neither be economically nor environmentally viable for public use compared to conventional LEDs, despite their advantages. However, there are many potential improvements to PLEDs that, while still in experimentation, have much greater recorded efficiencies and lifetimes than those recorded in Dr. O'Caroll's study.[1]

4.4.1 Improving Electron Recombination

One of the causes of inefficiency in blue PLEDs is the difference in barrier voltage between the polymer layer and active layer. The barrier voltage between the cathode and PFO layer is 0.6ev while between the PFO layer and PEDOT:PSS layer it is a slightly greater 0.8ev. Because of this, a greater proportion of electron recombination occurs more towards the cathode than the active layer, creating less light for a given voltage. Solutions to this are either using a low work function cathode such as barium, or to use a buffer layer between the cathode and active layer to reduce the electron imbalance. A buffer layer, NaOH in this particular study, reduces the driving voltage for the device and improves its efficiency.[18] Only a small enough amount so the device will not be damaged.

Another design to improve charge balance is through a multilayer polymer structured PLED separated by an electron blocking layer. This blocking layer is applied during the spin coating process of the polymer layers and is later boiled away. 1,2-polymer glycol is used in the reported study since it has a high viscosity, easy application, and low boiling point. Using this design, a this study has shown that the lifetime of the PLED is increased threefold and its luminance is significantly increased from 5,633 cd/m^2 to 21,180 cd/m^2.[19]

4.4.2 Alternative Substrates

A commonly used anode/substrate for PLEDs is ITO because it is transparent, reasonably efficient, and works at all temperatures; however, it is very expensive and has been shown in some research to actually have a reduced efficiency and lifetime because indium from ITO has a tendency to diffuse into the polymer layer, and block electron flow. There are many alternative substrates being studied, but they also have drawbacks.

One such alternative is fluorine tin oxide (FTO) which is far cheaper than ITO. In one study, FTO based PLEDs were found have a much lower work function than ITO based PLEDs, and thus a greater efficiency.[20] FTO is also less affected by cleaning chemicals in the lab while ITO can be degraded during its cleaning procedure. FTO is not perfect though: it has a very high current leakage which significantly lowers its lifetime. This problem makes FTO less likely to replace ITO as the common PLED substrate, even though indium based substrates are much more expensive.

One particular research group proposes that PLEDs would function more efficiently without ITO at all. This group experimented with a PLED using a transparent polymer anode.[21] A polymer anode/substrate would not only be cheaper and potentially more efficient, but also biodegradable. This particular experiment tests polyaniline and polyethylenedioxythiophene electrodes that have been doped with different organic solvents. These polymer anodes act as oxygen barriers, inhibit short-circuiting, and most importantly, have much slower degradation rates than ITO, thus improving the lifetime of the device. Their study shows that even their best ITO based PLEDs have lower lifetimes and efficiencies than PLEDs with a polymer anode. Replacing the ITO layer with a transparent polymer anode would be a good place to continue research in as this would make PLEDs much more economically and even more environmentally viable. More research is still needed in order to find the most effective polymer anode.

4.4.3 Light Extraction

Another major problem with the structure of a PLED is that, due to the refraction of the glass, some of the light is reflected internally and trapped within the glass. According to a study done in the journal "Organic Electronics,"[22] the fraction of emitted photons can be as low as

20%. Because of this huge luminance loss, many studies are being done in finding a glass structure for PLEDs that reduce internal reflectance; small changes in shape are generally easy to implement and are a simple way to improve PLEDs. This particular study involves the use of a micro-lens array structure to increase light extraction which found a significant increase in light intensity.

5. Conclusion

5.1 Summary

Upon comparing the statistics of the conventional and polymer LEDs, we found that conventional LEDs are more advantageous in terms of efficiency and lifetime, while PLEDs are cheaper and more environmentally friendly. Conventional LEDs have 50% longer lifetime than PLEDs, a greater efficiency, and a significantly larger luminance. Furthermore, conventional LEDs are more easily recyclable and have a rate of CO_2 emission than PLEDs. However, PLEDs are far less harmful in waste landfills than conventional LEDs, which utilize harmful materials in their structure. In order to increase PLEDs' effectiveness and give them a competitive edge in the market, the efficiency and lifetime of the device must be improved significantly.

5.2 Analysis

Conventional LEDs' better lifetime, efficiency, luminance, and recyclability are a result of the years of research that went into them. Research on polymer LEDs is a fairly recent endeavor and as such, PLEDs have the potential to meet or surpass their conventional counterparts with years of research. However, PLEDs' strength is in their biodegradability and potential to pose a far smaller threat to the environment than conventional LEDs. Despite the relatively insignificant amount of research that has gone into PLEDs as compared to conventional LEDs, they surpass LEDs in their ability to break down in waste landfills, where normal LEDs would regularly cause harm to the environment. Due to their biodegradability and far lower cost, PLEDs are an important field to explore, as they could significantly lower humans' negative impact on the environment.

5.3 Future Work

In order to make PLEDs viable for public use, their efficiency and lifetime must be improved by factors of 9.76 and 2.96, respectively. In order to accomplish this, more research should be done concerning the poor light extraction of the device caused by the structure of the glass substrate, which can be improved with different shaped glass or specific nanostructures. Alternative substrates can also be researched to lower the cost of the expensive ITO glass layer, which is the most costly aspect of the PLED. To improve the efficiency of the device, research can be done about electron recombination in the active layer, which can be improved by using a sodium hydroxide buffer layer or introducing a polymer electron blocking layer within the active layer. The advantages PLEDs have over conventional LEDs will make it more favorable for others to attempt to find improvements for PLEDs in the future.

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References

[1]C.M. Carter, *Economic and Environmental Assessment of Organic Polymer Light Emitting Diodes*, Catrice Carter Manuscript Rutgers University (Unpublished).

[2]S. Siva, *Fabrication and Lifetime Testing of Organic Polymer-Based Polymer Light Emitting Diodes*, Dr. Deirdre O'Carroll Progress Update (Unpublished).

[3]X.Y. Deng, *Light Emitting Devices with Conjugated Polymers,* WWW Document, (http://www.mdpi.com/1422-0067/12/3/1575).

[4]M.J. Scholand and H. E. Dillon, *Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products*, US Department of Energy, (2012).

[5]Semiconductor Today, (http://www.semiconductor-today.com/news_items/2010/OCT/DAHAL_181010.htm)

[6]Sigma-Aldrich, (https://www.sigmaaldrich.com/united-states.html).

[7]Chris Baker, University Wafer Inc, https://order.universitywafer.com/

[8]D. Steigerwald, *III-V Nitride Semiconductors for High-Performance Blue and Green Light-Emitting Devices*, JOM (1997).

[9]U.S Department of Energy, *The DOE Simple Modular LED Cost Model*, WWW Document, (http://www1.eere.energy.gov/buildings/ssl/ledcom_cost_model.html).

[10]Philips White Paper, *Understanding Power LED Lifetime Analysis*, LED Transformations, LLC, (2008).

[11]Sino-Colour, (http://www.sino-colour.com/service/faq/how-to-calculate-brightness-of-each-lamp.html)

[12]Super Bright LEDs, (http://www.superbrightleds.com/moreinfo/component-leds/5mm-blue-led-15-degree-viewing-angle-5500-mcd/269/#/tab/Specifications)

[13]*New Jersey Net Electricity Generation by Source*, U.S. Energy Information Administration, (2014).

[14]*Pounds of CO_2 Produced by a Steam-Electric Generator for Different Fuels*, U.S. Energy Information Administration (2014).

[15]SMG Indium Resources LTD, *The Indium Market*, WWW Document, (http://www.smg-indium.com/Market.html).

[16]M.H. Chang, *Light-emitting Diode Reliability Review*, WWW Document, (http://www.sciencedirect.com/science/article/pii/S0026271411003283).

[17]S. J. Hong, *Characteristics of IndiumTinOxide (ITO) Glass Re-Used from Old TFT-LCD Panel*, WWW Document, (https://www.jim.or.jp/journal/e/pdf3/53/05/968.pdf).

[18]M. Liang *et al*, *An Improved Blue Polymer Light-emitting Diode by using Sodium Hydroxide/Ca/Al Cathode*, WWW Document, (http://iopscience.iop.org/0256-307X/22/12/057/pdf/0256-307X_22_12_057.pdf).

[19]S.R. Tseng *et al*, *High-efficiency Blue Multilayer Polymer Light-emitting Diode Fabricated by General Liquid Buffer Method*, WWW Document, (http://web.it.nctu.edu.tw/~polymer/Research/SM_158_130.pdf).

[20]A. Anderson *et al*, *Fluorine Tin Oxide as an Alternative to Indium Tin Oxide in Polymer LEDs*, WWW Document, (http://onlinelibrary.wiley.com/doi/10.1002/(SICI)1521-4095(199808)10:11%3C859::AID-ADMA859%3E3.0.CO;2-1/pdf).

[21]S.A Carter *et al*, *Polymeric anodes for improved polymer light-emitting diode*

performance, WWW Document, (http://maxwell.ucsc.edu/~sacarter/sue_497.pdf).
[22]F. Galeotti *et al*, *Microlens arrays for light extraction enhancement in organic light-emitting diodes: A facile approach,* WWW Document, (http://www.sciencedirect.com/science/article/pii/S1566119912005009).