

Components, Production Processes, and Recommendations for Future Research in
Organic Light Emitting Diodes

by

Lindsay Hunting

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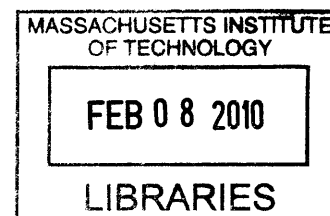
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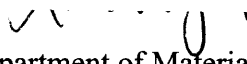
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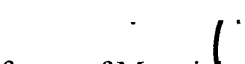


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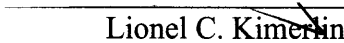
Signature of Author: _____

 Lindsay Hunting
Department of Materials Science and Engineering
May 15, 2009

Certified by: _____

 David Roylance
Associate Professor of Materials Science and Engineering
Thesis Supervisor

Accepted by: _____

 Lionel C. Kimerling
Professor of Materials Science and Engineering
Chair, Undergraduate Committee

ABSTRACT

Organic Light Emitting Diodes (OLEDs) are small, optoelectronic devices that can be used in the production of energy-efficient, high definition displays in cell phones, computers, and televisions. These devices have great potential to replace light emitting diodes (LEDs) completely because they are more environmentally friendly to produce, they are more efficient, and they can create displays much thinner than current LED displays. Moreover, OLEDs allow for the creation of brighter, flexible screens. While these devices have great potential, it has not been realized yet due to cost and difficulty in optimizing production processes. Many companies have been attempting to produce affordable OLED displays for years, but have not been successful due to lack of optimization of production processes. Work should continue to be done in economic optimization of the processes and also optimization of energy efficiency of the devices.

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I. Introduction

Organic Light Emitting Diodes, or OLEDs, are a relatively new technology with hope to be used in TV displays, computer monitors, and other products in the near future. An OLED is composed of two organic semiconducting layers sandwiched between an anode and a cathode. When a current is run through the device, energy is emitted in the form of light photons, thereby making these devices excellent candidates for new display technology. Current displays utilize technologies such as Light Emitting Diodes (LEDs) and Liquid Crystal Displays (LCDs), which are both much lighter and more energy efficient than previous technologies such as the Cathode Ray Tube. Even more promising though, OLEDs have a number of advantages over LED and LCD technologies, which is what makes it an attractive new technology for companies and consumers alike. For one, OLED technology is much “greener” than other technologies. Since it uses organic chemicals, it is much less toxic to the environment to produce or to dispose of. It is also much more energy-efficient than other technologies, as it does not require a backlight like LCD screens do. OLED screens and monitors are also very thin (on the order of millimeters)—much thinner than any other technologies in use. Another very attractive feature of OLED technology is that OLED materials can be painted onto bendable, thin materials like plastic, thus making it theoretically possible to turn an entire wall into a high quality TV screen that can be stored by simply rolling it up. Finally, OLEDs have

the possibility of producing much higher quality images than technologies currently in use.

OLEDs use organic chemicals that emit lights of different colors based on the electric current sent through them. They consist of a grid of rows and columns printed on some flat substrate. On top of this substrate are usually a layer of some polymer to promote adhesion to the substrate and then a layer of the chemicals themselves. While OLEDs are much better candidates for displays in terms of efficiency than the technology currently on the market, they go through a very complex manufacturing process, thus making the final product economically unfeasible for most consumers. Currently, the only affordable OLED screens being produced right now are, on average, only big enough to be used as cell phone screens. Companies such as Sony and Samsung are attempting to create bigger affordable displays out of OLEDs, but are having difficulty creating a product cheap enough for mass consumption. Without economic optimization of the production process, OLED displays may never succeed in the market. However, OLED technology is a very promising field, and could greatly reduce power usage in many everyday devices.

II. General Background

a. Light Emitting Diodes

LEDs are the primary technology currently being use in most color display products on the market. LEDs have many advantages over previously used CRTs, such as their low weight, higher brightness, and lower energy consumption. LEDs also have a

relatively long lifetime, they are durable, and they are very small (allowing high definition displays). When they first entered the market in television screens, they were very expensive, but now that processes have been improved and they are in full production, the cost has gone down significantly. LEDs have also started to replace regular incandescent light bulbs as a source of white light. LEDs have a much higher ratio of light output to energy input than incandescent bulbs, and are therefore much more energy efficient.

A Light Emitting Diode (LED) comprises two types of semiconductors bonded to one another and attached to positive and negative electrodes. A semiconductor is a material whose ability to conduct varies. Usually, semiconductors are poorly conducting materials that have been doped (impurities have been added) to allow electrons to flow more freely and thus increase the conduction capability of the material. There are two types of semiconductors: N-type and P-type. An N-type semiconductor is one with a surplus of negative particles (electrons), and a P-type semiconductor effectively has a surplus of positively charged particles. This means that a P-type semiconductor has “holes” in it, where any free electron can be caught. Electrons can jump from hole to hole, from a more negatively charged area to a more positively charged one, effectively moving the holes themselves from a more positively charged area to a more negatively charged area. Since the electrons move from the negative side to the positive side, electricity only flows in one direction.

When an N-type material and P-type material are bonded together, the extra electrons from the N-type jump across the interface into holes in the P-type material. This

creates a small area in the middle of the two materials called the “depletion zone.” This zone has a balance of positive and negative charges, effectively returning it to its insulating, un-doped state. To adjust this in order to promote the free flow of electrons (electricity), the two semiconducting materials must be attached to positive and negative electrodes. The negative electrode must be attached to the N-type material to repel the extra electrons into the P-type material, and the positive electrode must be attached to the P-type material to attract the electrons. Once the electrodes are attached, electrons may flow freely throughout the material. In other words, some electrons have enough energy to leave the valence electron shell of the atom/molecule they are in. When the circuit is complete and the electrons are flowing freely, the electrons have the possibility of falling into the holes and jumping from one hole to another. Falling into a hole means that the electron falls from the conducting band into a lower orbital, releasing energy in the form of a photon. If the photon’s wavelength is within the visible spectrum (the wavelength depends on the distance the electron has jumped, i.e. the width of the band gap), it produces a specific color light. Figure 1 shows the movement of electrons from the N-type material to the P-type material, resulting in the electron falling from the conduction band to the valence band of a molecule, releasing energy in the form of light.

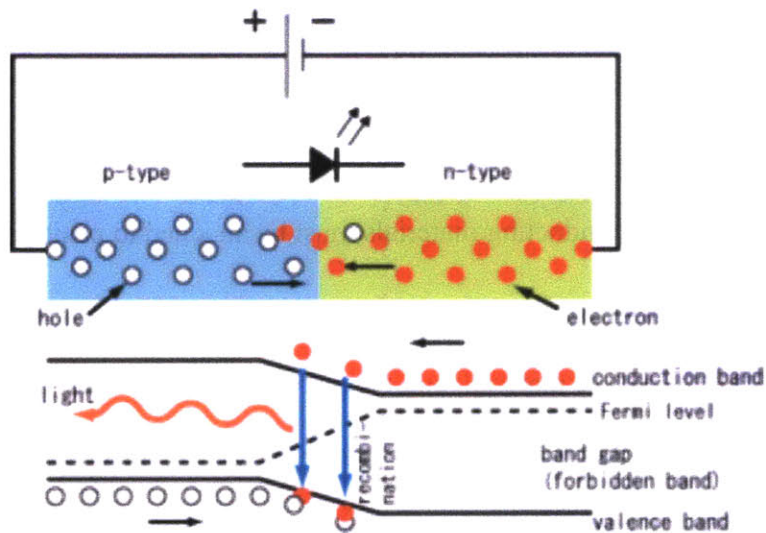


Figure 1. This shows the general process of an LED. When a current is applied, the electrons move from the N-type material to the P-type material, filling holes by falling from the conduction band to the valence band. When this happens, the electron sheds energy (whose exact amount is determined by the width of the band gap) in the form of light. <http://en.wikipedia.org/wiki/LED>.

The width of the band gap determines the amount of energy contained in the released photon, and ultimately determines the wavelength of the light emitted based on Equation 1:

$$E = h\nu \quad (\text{Equation 1})$$

where E is the energy contained in the photon (calculated), h is Planck's constant ($6.626 \times 10^{-34} \text{ Js} = 4.136 \times 10^{-15} \text{ eVs}$), and ν is the frequency of the light (measured). Using

Equation 2:

$$\nu = c/\lambda \quad (\text{Equation 2})$$

where c is the speed of light (2.998×10^8 m/s) and λ is the wavelength of the light. The wavelength of the emitted photon determines the color of the light, illustrated in Figure 2 below. Photons with a lower wavelength ($\sim 350\text{-}450\text{nm}$) lie in the purple-blue range of the spectrum, while photons with a higher wavelength ($\sim 650\text{-}700\text{nm}$) lie in the red range. Any photon with a wavelength lower than $\sim 350\text{nm}$ or higher than $\sim 700\text{nm}$ is outside of the visible spectrum, and cannot be seen with the naked eye. These types of photons lie in the ultraviolet range or the infrared range, and are not useful for creating an LED display. Instead, infrared and ultraviolet photons being emitted from an LED display decreases the efficiency of the device because some of the energy used to run it is being released as unusable energy. Because of this, when determining what materials to use for the semiconductors in the device, the width of the band gap must be taken into account so that the device emits photons in the visible range (thus creating a light display).

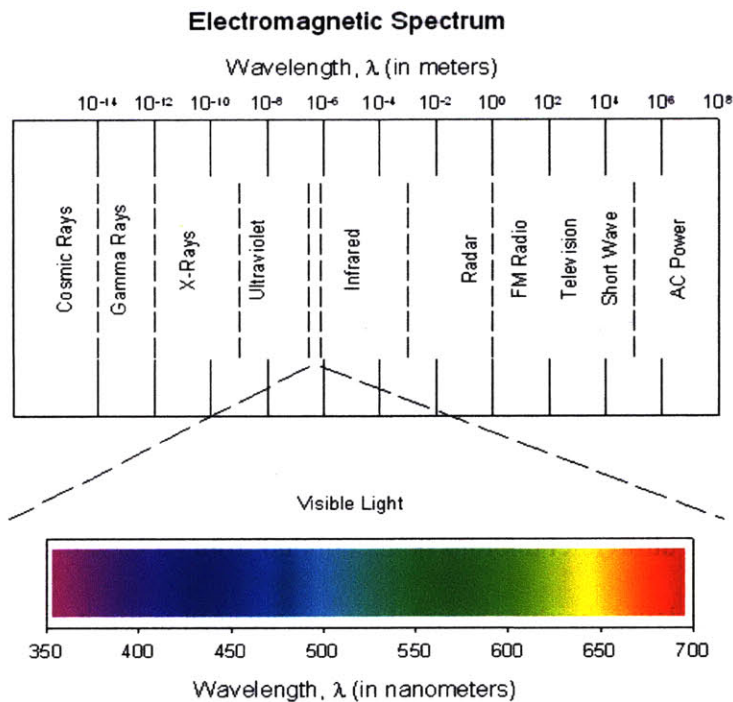


Figure 2. This is the electromagnetic spectrum. Visible light photons have wavelengths ranging from $\sim 350\text{nm}$ to $\sim 700\text{nm}$. The wavelength of the photon determines the color of light. <http://www.psych.ndsu.nodak.edu/mccourt/Psy460/Light%20as%20a%20stimulus%20for%20vision/electromagnetic%20spectrum.JPG>.

Since the color of the light emitted is determined by the wavelength, which is determined by the band gap of the semiconductors, it can be concluded that the material composition of the semiconductors determines the color of light produced. Therefore choosing the right materials to be used as semiconductors is important in creating a device with a large range of visible colors emitted. A variety of inorganic materials are used as semiconductors in light emitting diodes, and the wavelength and color of light emitted from them is listed in Table 1:

MATERIAL	WAVELENGTH (nm)	COLOR
Gallium Arsenide (GaAs) Aluminum Gallium Arsenide (AlGaAs)	$\lambda > 760$	Infrared
AlGaAs Gallium Arsenide Phosphide (GaAsP) Aluminum Gallium Indium Phosphide (AlGaInP) Gallium (III) Phosphide (GaP)	$610 < \lambda < 760$	Red
GaAsP AlGaInP GaP	$590 < \lambda < 610$	Orange
GaAsP AlGaInP GaP	$570 < \lambda < 590$	Yellow
GaP AlGaInP Indium Gallium Nitride (InGaN) Gallium (III) Nitride (GaN) Aluminum Gallium Phosphide (AlGaP)	$500 < \lambda < 570$	Green
InGaN Zinc Selenide (ZnSe) Silicon Carbide (SiC)—substrate Silicon (Si)—substrate	$450 < \lambda < 500$	Blue
InGaN	$400 < \lambda < 450$	Violet
Dual blue+red LEDs Blue LED with red phosphor White LED with purple casing	Various types	Purple
AlGaN Diamond (C) Aluminum Nitride (AlN) Aluminum Gallium Indium Nitride (AlGaInN)	$\lambda < 400$	Ultraviolet
Blue or UV diode with yellow phosphor	Entire spectrum	White

Table 1. This is a table of inorganic materials used in LEDs and the wavelength/color of light they emit when used in the devices. <http://en.wikipedia.org/wiki/LED>.

Some white LED displays, instead of using phosphor to convert blue or UV light into white light, use RGB systems, or “Red Green Blue” systems. In these systems, various materials are used to produce red, green, and blue light. Then, the colors are mixed together to produce the full range of wavelengths, emitting white light. Since this system requires a precise mixing of color photons, it is not used as often as the blue/UV light and yellow phosphor system. In the phosphor system, a blue/UV LED is coated with yellow phosphor. When the blue/UV waves pass through the yellow phosphor they undergo a Stokes shift, increasing their wavelengths to lengths in the visible spectrum. While this system is used more than the RGB LED, it is not as energy-efficient because energy is lost in the form of heat during the shift.

LEDs in televisions are essentially tiny light bulbs. The diode is attached to a positive and negative terminal and encased in a transparent plastic case to focus the

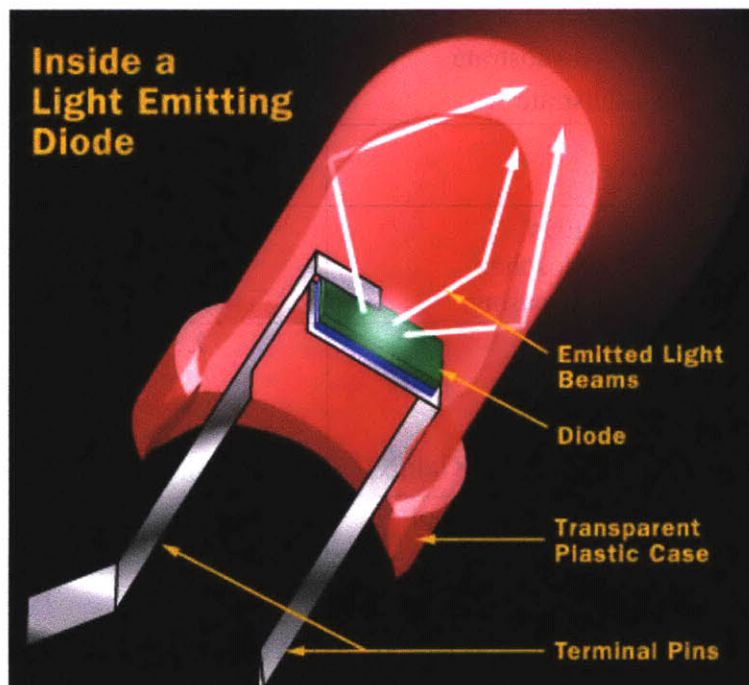


Figure 3. This is the structure of an LED. The diode is encased in a transparent case used to focus the emitted light in one direction and maintain efficiency. <http://electronics.howstuffworks.com/led3.htm>.

emitted light in the forward direction (Figure 3). This focusing is important in the conservation of energy, as less light is reflected back into the device as wasted energy.

b. Organic Light Emitting Diodes

Organic Light Emitting Diodes (OLEDs) work very much like LEDs, except that the emissive (N-type material) and conductive (P-type material) layers are made from organic materials. The fact that the materials are organic is important in the safe production and disposal of the devices. A typical emissive layer is made from a polymer such as polyfluorene (Figure 4), whereas a typical conducting layer is made from polymers such as polyaniline (Figure 5). These two chemicals are prime candidates for the semiconductors because the phenyl groups on each of them stabilize the radicals. This is because the pi orbitals in the double bonds align parallel to one another, and resonance between different conformations allows the electron clouds to mesh together. Thus, when the N-type material gives up an electron and becomes unstable because there is a free radical present in the molecule, the pi bonds are able to stabilize the free radical by distributing the extra negative charge over all of the pi bonds that have been meshed together. The same goes for the P-type material receiving electrons. When an electron is received as a free radical, the pi bonds in the phenyl groups are able to stabilize it.

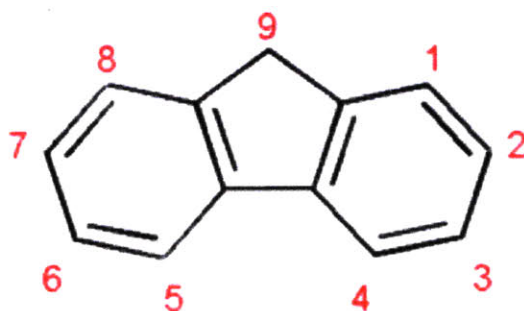


Figure 4. This is the structure of polyfluorene. The fluorine molecules in polyfluorene are connected at the 2 and 7 positions. <http://en.wikipedia.org/wiki/Polyfluorene>.

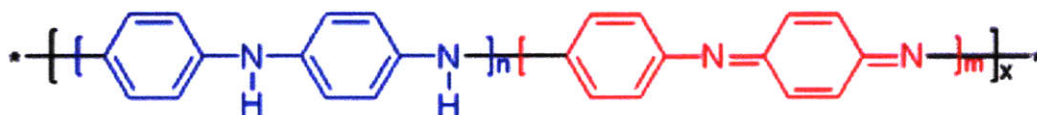


Figure 5. This is the structure of polyaniline. In this diagram, $n+m=1$, and x is the number of units in the chain (degree of polymerization). <http://en.wikipedia.org/wiki/Polyaniline>.

Similar to semiconductors in an LED, the polymers used as semiconductors for OLEDs must be doped to enable easier electron transport. There are two methods of doping a polymer. In the first method, a polymer is exposed to either an oxidant or a reduction agent. This will either add extra electrons to create an N-type doped polymer or remove electrons to create a p-type doped polymer. The second method of doping polymers involves an electrochemical reaction. In this process, an electrode coated with polymer is placed in a solution with electrolytes in which the polymer is not soluble. The

solution should also contain other reference electrodes. When current is run through the solution, a charge is created along with ions from the electrolytes, and the extra charge either adds extra electrons to the polymer for an n-type doped polymer or removes electrons for a p-type doped polymer.

A typical OLED's structure begins with the substrate, or the material used to support the system. This material is usually something along the lines of a silicon or glass slide. On top of this is the anode layer, which removes electrons from the P-type material when a current flows. Next in the OLED are the conductive layer, and then the emissive layer. Finally, the cathode is layered on top (Figure 6).

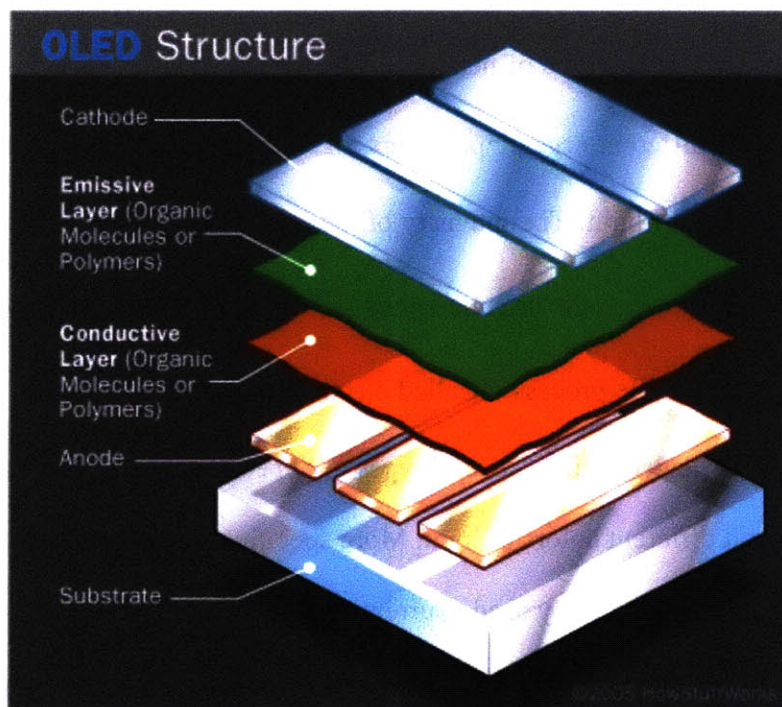


Figure 6. This figure shows the general structure of an OLED: substrate, anode, conductive layer, emissive layer, cathode. <http://electronics.howstuffworks.com/oled1.htm>.

Different voltages applied to the different areas cause current to flow from the anode to the cathode through the two organic layers. When this happens, electrons are removed from the conductive layer (leaving behind holes) and taken to the emissive layer. This leaves behind many holes that need to be filled, so the holes jump to the emissive layer to recombine with the surplus of electrons. The holes and electrons recombine at the interface of the two layers when a free electron falls back into an energy state in an atom that is missing an electron. When the electrons fall back into the holes, they release energy in the form of photons in the visible spectrum. The wavelength of the photon depends on the difference in the energy of the free electron and that of the energy level the electron has just filled. More generally, the color of the light emitted depends on the type of material in the emissive layer. In industry today, manufacturers layer different organic polymers together to form the emissive layer and create different colors of light. The intensity of the light is based on the amount of current being passed through the organic layers—the greater the current, the brighter the light emitted is. This whole process is called electrophosphorescence.

Most OLED devices utilize several types of doped polymers that create different band gaps and emit different colors of light. More specifically, polymers that emit red, blue, and green light are primarily used. Currently, most devices pattern the red, blue, and green emitting diodes on the same plane. When they are patterned on the same plane, however, the gap between pixels is still large and the definition of the display is not as

clear as it could be. Layering the red, blue, and green emitting diodes on top of each other in a “Stacked OLED” has the potential to increase display definition and color depth.

While this is the typical structure and process of an OLED, there are different types of OLEDs being researched today. These include the Passive-matrix OLED, Active-matrix OLED, Transparent OLED, Top-emitting OLED, Foldable OLED, and White OLED. Passive Matrix OLEDs are distinct in that they have strips of anode and strips of cathode aligned 90 degrees perpendicular to one another. This makes a grid of crossings, or “pixels,” where different amounts of current can be sent, determining whether the pixel remains off, turns on, and the intensity of the light emitted. The Passive Matrix OLED requires external circuitry, which makes it more energy-intensive and harder to manufacture than other types of OLEDs. Because of this, Passive Matrix OLEDs are most suited for small displays, such as a cell phone or PDA display. However, though they are more energy intensive than other types of OLEDs, they still consume less power than LCDs in use today.

Active-matrix OLEDs have complete layers of everything (not strips), but there is a thin-film transistor (TFT) grid overlaid by the anode. This is the grid that determines which pixels get turned on and off, and the intensity of the light emitted. Active Matrix OLEDs are less energy-intensive than Passive Matrix OLEDs because the TFT array requires less power than the external circuitry of the Passive Matrix OLED, so Active Matrix OLEDs are more suitable for large displays such as TV and computer

screens. Active Matrix OLEDs may even be used for things as big as electronic billboards. The next type of OLED is the Transparent OLED. A Transparent OLED can be either an Active Matrix OLED or Passive Matrix OLED, but the difference is that all of the components of the structure (anode, cathode, emissive layer, and conducting layer) are all composed of transparent materials. Because of this, light can be passed in either direction. This type of OLEDs, therefore, would be especially suited for alert systems on the front or rear windshield of a car.

A Top-emitting OLED, usually an Active Matrix OLED, and has emissive and conducting layers that either reflect light or are opaque (transmitting very little light). This type of OLED has the potential to work well in products like “smart cards,” which are cards much resembling a credit card but have a microprocessor instead of a magnetic strip. A foldable OLED can be any of the above types, but is built on a foldable substrate (such as plastic), and has potential uses in many things like clothing. Finally, a White OLED simply emits white light that requires much less energy than even fluorescent lights. The light emitted is also a much brighter, more uniform light. White OLEDs have the potential to replace all fluorescent lights and reduce energy costs drastically in buildings currently using fluorescent lights.

III. Production of Organic Light Emitting Diodes

In the production of OLEDs, layering the substrate, anode, and cathode is simple. However, layering the organic materials is not. Currently there are three types of production techniques in use for layering the organic polymers: Vacuum Deposition or Vacuum Thermal Evaporation, Organic Vapor Phase Deposition, and Inkjet Printing. Inkjet printing uses regular inkjet technology, and the organic molecules are sprayed onto the substrate. Inkjet printing lets there be very large substrates (like for a big-screen television) at a much-reduced cost from other methods of manufacturing. In Organic Vapor Phase Deposition, the organic polymer is heated and evaporated. It is then mixed with an inert gas and transported, in gaseous form, to a cold substrate. At this point, the polymer cools down enough to condense on the substrate and form a uniform layer. The inert gas remains gaseous and is not deposited on the film. This process has excellent resolution over large areas. Vacuum Thermal Evaporation is a process of depositing polymer on a substrate, and can create very thin (<100nm), uniform layers. In Vacuum Thermal Evaporation, the organic polymer is heated and evaporated and allowed to condense on the substrate (without the aid of a gas). The resolution from this process is exceptionally good, and can create OLED displays with an excellent resolution. However, the process itself is very expensive and inefficient. Another method of producing OLEDs is very similar to Organic Vapor Phase

Deposition, but rather than mix the gaseous organic polymer with an inert gas, the organic polymer is mixed with an inert gas jet. This allows for much more precise deposition of the molecules onto the substrate.

IV. Uses

a. White OLEDs

As stated earlier, White OLEDs have the potential to be much more efficient than regular LEDs and incandescent bulbs currently being used. However, the biggest problem with White OLEDs right now is that the photons being emitted in the form of light are not reaching the eye of the observer. In other words, the White OLED emits enough photons to theoretically be much more efficient than regular LEDs and incandescent bulbs, but not enough of the photons are leaving the OLED in the right direction. As a result, the extra photons that could be increasing the efficiency and intensity of light from the device are being wasted. This is because the substrates with which most OLEDs are being made (plastic and glass) usually have a high index of refraction, but open air has a low index of refraction. Therefore, the emitted photons can easily pass through the OLED device, but once they hit the air interface most of them are scattered and never reach the eye of the observer.

Efforts are being made to increase the efficiency of the White OLED by reducing photon scattering at the interface. However, most methods, such as creating gratings on the surface or coating the surface with a low-index of refraction substance, cause the light emitted to either blur or change color when viewed from different angles. The most promising method being tested right now is imprinting a grid of lens shapes on the OLED (Figure 7) using imprint lithography. In this process, a pattern of hemispheres is stamped into the polymer immediately after it has been layered onto the device but while it is still liquid. The polymer then solidifies in this hexagonal array of lenses. This research is being conducted at the University of Michigan under Stephen Forrest. While the process has not yet been optimized, imprint lithography can be used to create a grid of mounds in the organic substance that focus the light emitted in one direction, rather than having it scatter in multiple directions and decrease the efficiency. It is claimed that this process increases the amount of light put out by the device by a full 70%. While the process has not yet been perfected, it is estimated that mass-producing this technology will optimize the process and greatly decrease the overall cost.

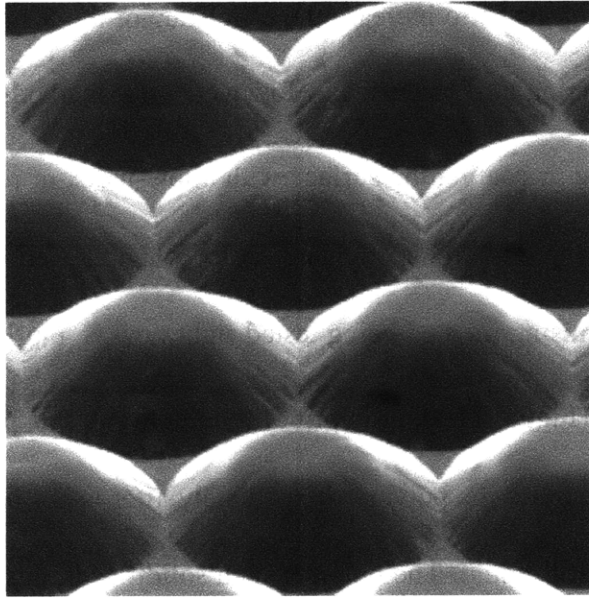


Figure 7. The pattern imprinted on the White OLED to increase efficiency by focusing all emitted light in one direction.
<http://www.technologyreview.com/energy/17808/>

b. Foldable OLEDs

Foldable OLED displays are created by producing the devices on flexible substrates. Because the layers are so thin, bending the devices is easy. Flexible OLED displays could vastly change technology in use today, and would make storing and transporting high-definition displays feasible. They would also erase the need for certain other technologies by condensing multiple technologies into one. For instance, projectors would no longer be needed because the large screen that projectors shine images on now would be able to produce the images itself and then roll up for easy storage. Technology transportation would also be much easier, as the flexibility of the OLED displays would be much more resilient than current rigid technology. Flexible OLED displays could

potentially be used in many other applications, from moving advertisements or flags to clothing. In short, flexible OLED displays could change the very way we think of technology. The possibilities are vast.

V. Company Research and Products Already on the Market

Various companies have begun exploring the uses of OLED technology as well. In January of 2005, Samsung released the largest OLED television to date (21 inches). Since then Samsung has introduced larger and larger OLED display televisions, and most recently released a 40-inch OLED television. All of these televisions are high definition displays, and are all very thin (much thinner than any displays currently on the market, such as LCDs and LEDs). In October of 2008, Samsung introduced the thinnest OLED display to date, 0.05mm thick. This display was also bendable. Samsung has been predicting the use of OLED technology in everyday life as early as 2010, but the production is still too expensive for the prices to compete with existing LED technology.

Sony has also been experimenting with OLED technology in their products. This was the first company to introduce an OLED screen to the public in 2004. Since then, Sony has tried to incorporate OLED technology in more and more of their products, and released research done with the Max Planck Institute in 2008 discussing the feasibility of mass producing thin OLED bendable screens. In this research, they also discussed

the possibility of layering several OLED screens on top of one another to produce 3-D images. These ideas are still in their beginning stages, and the company has not yet produced anything that could create 3-D images. Sony has, however, begun to produce OLED televisions on a regular basis. They use small molecule OLED technology as opposed to polymer OLED technology, and they are marketing their 11-inch OLED Digital Television for \$2499.99 online.

Sony is also advertising on their website “What’s Next for OLED?” In this section, Sony describes what they plan to do with OLED technology in the future. Most of the plans include making television displays even bigger and thinner, but Sony also plans to focus on developing an offshoot technology from OLEDs—Organic Thin Film Transistors. These organic TFTs can be layered onto flexible plastic substrates, creating displays that can bend. Displays such as these would be able to display regular, full-color, high definition, moving images while the display itself is bent. Looking even further into the future, this technology could be used to create very large, very thin televisions that can be rolled up for storage.

OLED technology has also been used in the production of the Optimus Maximus keyboard, developed by the Russian Art. Lebedev Studio, led by Artemy Lebedev. This keyboard uses small OLED displays in each of the keys, so the keyboard can change depending on what the user is doing. In other words, the function of the key can change depending on what is happening on the screen. This allows for rapid switching between

languages, and even shows small changes like showing all of the letters in upper case or lower-case depending on whether or not the Shift key is being pressed. This product was only on the market for a short period of time from 2007-2008, but is still being researched. In fact, a patent application filed in early 2008 indicates that the company Apple is also working on a similar product.

VI. Experimentation

To determine the efficiency of an OLED sample, a device allowing the input of a known voltage must be used in order to measure the wavelength and intensity of emitted light. Such an instrument is the Model PM100 Optical Power Meter System, available from ThorLabs at MIT. This model has an S120uv sensor and has a range from 200nm-1100nm. This allows for the measurement of wavelengths from the ultraviolet range to the fiber optic range, which includes the visible spectrum.

Therefore, inputting a voltage would allow measurement of the wavelength of light. The intensity of the light can also be measured. The energy efficiency of the sample can also be determined by measuring the inputted energy and comparing it to the outputted energy. Scanning electron microscopy can be used to determine the thickness and uniformity of the layers.

VII. Costs

The costs for creating OLEDs are currently very high because the processes have not yet been optimized and the market is still small. The materials being used are not expensive themselves; instead, the production of the devices is the expensive aspect. Starting at the first step of the process, synthesizing polyaniline and polyfluorene requires time, energy, and special safety measures. Polyaniline is synthesized by exposing the monomer (described earlier) to a strong oxidizing agent while dissolved in hydrochloric acid. Strong safety measures must be taken with the oxidizing agent (usually ammonium persulfate) and the hydrochloric acid. Also, the reaction is very exothermic, and must be moderated closely. In the next step of production, if an electrochemical reaction is used to dope the polymers, it requires energy input in the form of a current run through the solution. While this would not require much energy or time for small samples, larger samples require a voltage to be applied for a much longer period of time.

Next, the production processes such as Inkjet Printing, Organic Vapor Phase Deposition, and Vacuum Thermal Evaporation have not yet been optimized, and are still expensive. Vacuum Thermal Evaporation, especially, is very inefficient and expensive in the production of OLEDs. This process technique requires a lot of energy input to heat the polymers to their gaseous states and to keep the substrate at a cool temperature. Similarly, Organic Vapor Phase Deposition (with and without the inert gas jet) requires a substantial amount of energy input to heat the polymers to their gaseous states. It requires even more energy to transport the gases to the substrate and to keep the substrate cool. While inkjet printing requires that the polymers only be heated to their liquid phase, it

requires energy to keep the polymers at that liquid stage for a long enough period of time to get them into the printer and stay liquid until they are deposited on the substrate.

Another problem with all of these processes is that they are not optimal for creating large OLED displays. These techniques are only really useful for small samples, and larger ones cannot be made without creating small sections one at a time. This requires a lot of precision in moving from section to section and can end up in non-uniform layers across the substrate.

Producing OLED displays will inevitably get cheaper as more and more companies start to produce them. Right now a major factor in the cost is economies of size—since the market is still small

VIII. Recommendations for Future Research

Future research should aim at optimizing two things: the energy efficiency of the devices and the cost of producing them. More research should be done in looking at new materials to use, possibly with lower melting and evaporation temperatures so the production processes not as energy-intensive. The melting and evaporation temperatures, however, should not be so low that the material cannot be used at room temperature. These materials should be polymers that can be doped and that have phenyl groups to stabilize free radicals.

Producing affordable OLED displays for consumption has been a long and expensive process thus far, but continuing to produce these devices will most likely decrease production costs. Once companies get past the high fixed costs of starting to

produce OLEDs, they will move into faster and cheaper production, resulting in a cheaper final product. Because the best method of production is still unknown, fixed costs have not yet come down. Finding the best way to produce the most efficient products is very important in bringing down cost.

The most important thing to optimize, though, is the efficiency of these devices. In a market with rising energy prices and depleting natural resources, it will soon be important to save energy whenever possible, no matter what the cost, and these devices could help immensely. More work should be done in optimizing the imprint lithography process in creating more efficient white OLEDs. Laser etching may also be a possible route of research in creating patterns on the OLEDs to make them more efficient.

IX. References

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Images

Figure 1: <<http://en.wikipedia.org/wiki/LED>>.

Figure 2:
<<http://www.psych.ndsu.nodak.edu/mccourt/Psy460/Light%20as%20a%20stimulus%20for%20vision/electromagnetic%20spectrum.JPG>>.

Figure 3: <<http://electronics.howstuffworks.com/led3.htm>>.

Figure 4: <<http://en.wikipedia.org/wiki/Polyfluorene>>.

Figure 5: <<http://en.wikipedia.org/wiki/Polyaniline>>.

Figure 6: <<http://electronics.howstuffworks.com/oled1.htm>>.

Figure 7: <<http://www.technologyreview.com/energy/17808/>>.

Table 1: <<http://en.wikipedia.org/wiki/LED>>.