White Light Emitting Diodes

EE 332 Research Paper

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Table of Contents

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Abstract

This article is a simple review of white light emitting diodes LEDs. In section one we start with a brief discussion of what a light emitting diode is and its importance to the continued development of optical devices. Next, in section two we cover the device physics of how it works, including the physics concept of double heterostructures and the different approaches of designing a white LED. In section three, we make mention of a specific phosphors material used in designing the white LEDs. In section four, we discuss the main manufacturing techniques for this technology including chemical vapor deposition. Section four also includes the latest advances and technology in producing white light. Section five looks at the future direction of LEDs such as advancements in lighting and communication, as well as the future improvements in creating LEDs.

1. Introduction

The first commercially valuable light bulb was invented in the late 1800s by Thomas Edison. A light generated by heating a filament was basic idea of this invention, which is very inefficient. Less than 5% of the energy going into the bulb gets turned into light, and the rest gets turned into heat. A much more efficient source of light is a light emitting diode or LED. This new light source is consisted of two specialized semiconductors that are stuck together. Once a sufficient voltage is applied across these two semiconductors, they emit light through an optical phenomenon called electroluminescence. Although there is still some energy converted to heat in the LEDs, the overall process is a lot more efficient than that of the incandescent light bulbs. A wide variety of devices that we are using in a daily basis are exploiting LEDs. Visible LED has a multitude of applications as an informational link between electronic and users. White light LEDs devices are important in technology development because of the wide range of application such as in building integrated electronic circuit, general lighting, medical devices ,traffic signal, and cell phones as well.

2. Device Physics:

Several decades ago, light emitting diodes (LEDs) were used as indicators in many electrical devices since they were made in the early 1960s. Researchers have strived to boost this new technology in order to improve the stability and efficiency of this technology. Due to their much better characteristics, LEDs have been replacing previous generations of light sources on almost all fields around us **[1]**. In comparison to the highly inefficient incandescent lamps, and to the fluorescent lamps that contain toxic chemical, LEDs are very high efficient, can last for very long periods of time, very robust, and have very little UV and IR emissions in addition to no mercury was involved to make them. To begin our discussion of white LEDs, I would like to first start with a review of the basic physics through which the white LEDs are being designed. The two main physics concepts involved in making the LEDs are the heterostructure p-n junctions and the common high level approaches in designing them.

2.1 Double Heterostructure LEDs:

The double heterostructure today is the basis technology for optical communications, and it is used in a wide variety of electronic devices that we are using in a daily basis including the light emitting diodes, lasers, and solar cells. A heterostructure in general is a structure where you grow a semiconductor of a different type on a substrate. A double heterostructure is basically a heterostructure that has two heterojunctions, which is made by having a low band semiconductor that is sandwiched between two high band gap semiconductors, as shown in **Figure 1**.

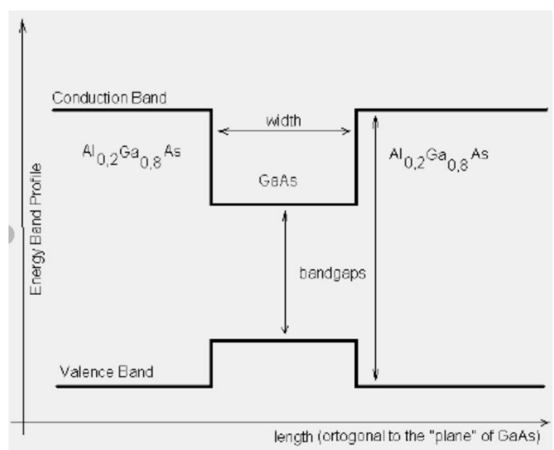

Figure 1. Sketch of Semiconductor Heterostructure of Quantum Well Type. (Adopted from Ref. [2]).

The layers used to make the double heterostructure need to have a nearly perfect covalent bonds and that is done by exploiting semiconductor with the same lattice layers. A high chemical yield of perfect covalent bonds is important in order to minimize the possibility of the defects in the junction, which are so detrimental to the optoelectronic devices. The chart shown in **Figure 2.** shows all the materials that are lattice matched. This chart covers everything from visible light emitting diodes and beyond. For visible light emitting diodes, we should be wise in choosing the material that have energy band gap that emits photons with energy within the visible light spectrum. We can use the chart in **Figure 2.** to determine which materials are lattice matched and have different band gaps. Most of the commercial devices use gallium arsenide 'GaAs' and aluminum gallium arsenide 'AlGaAs', and we can see why form the same chart. We can see that the lattice constant of two of these materials is almost the same, which is about 5.6A. These materials are thus used to make the double heterostructure for LEDs.

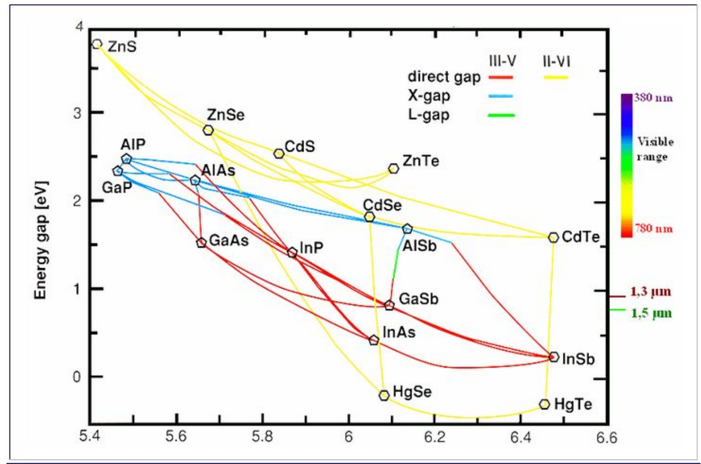

Figure 2. Lattice matched material plot. Adopted from [3]

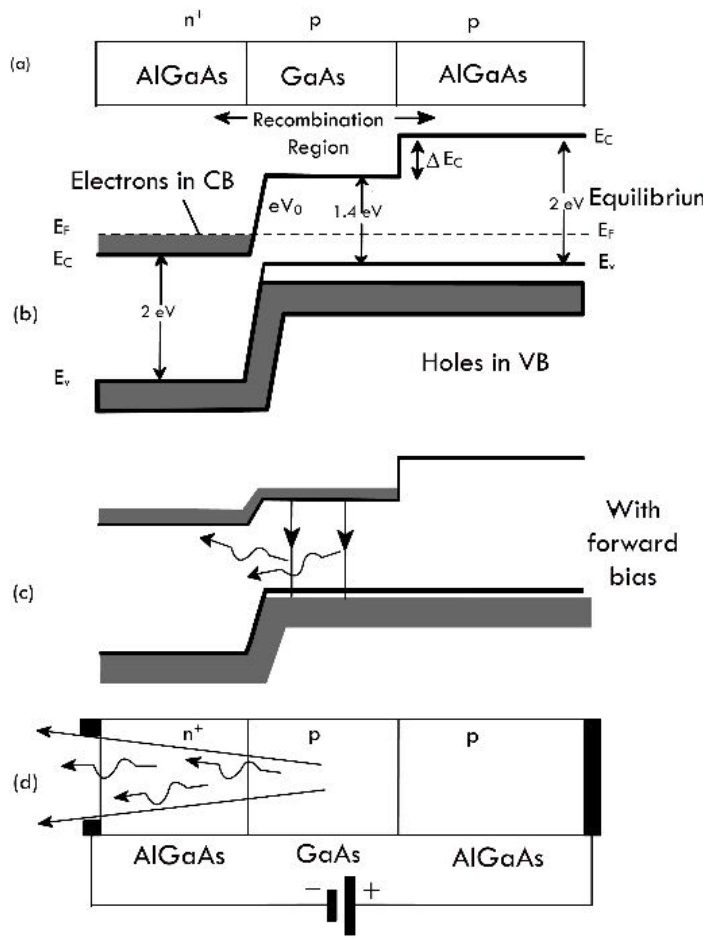

Figure 3. Double heterostructure based LED. (a) Device structure. (b) Equilibrium band diagram. (c) In forward bias electrons and holes are injected in GaAs. (d) Visible light emission.

The reason why we need a double heterostructure to make LEDs is to keep the carriers away from the exterior surfaces because we want the energy to go into light rather that heat. The structure of this device is shown in **Figure 3.** The figure shown in **Figure 3.a** illustrates a lightly doped p-type GaAs sandwiched between two highly doped AlGaAs of different type. At both of the junctions, there is a potential energy variation because of charge migration. This typical p-p-n junction will have a constant fermi level at thermal equilibrium as shown in **Figure 3.b**. Under forward bias, the energy levels of the n-type band will rise because the majority carriers (electrons) will get additional negative potential as shown in **Figure 3.c.d.** The depletion region will then have large number of both electron and holes which will recombine radiatively to from the current [4].

2.2 LEDs design options:

In order to design LEDs that emit white light, there are usually three viable approaches. One approach is by combining the primary colors by using three individual monochromatic LEDs with red, green, and blue colors, which will generate a white light. Second more common approach is by making violet LED coated with a phosphorous material. The third approach is by using a blue LED to pump yellow or green and red phosphorous.

First approach is by producing mixed-color white light. By mixing the light from several colored LEDs, mainely red, green and blue LEDs, the resulting light is white in appearance. Depending on the wavelength of the wave transmitted in the air, we see different colors. Humans cannot see any wavelength shorter than infrared (~3900 Å) or greater than ultraviolet (~7800 Å) as our eyes are not sensitive to wavelengths beyond this range; however, mixing all the colors together, our brains will tell us that we are seeing white light. This scheme about colors has been worked out in some details in the late 17th- late 18th century when the primary

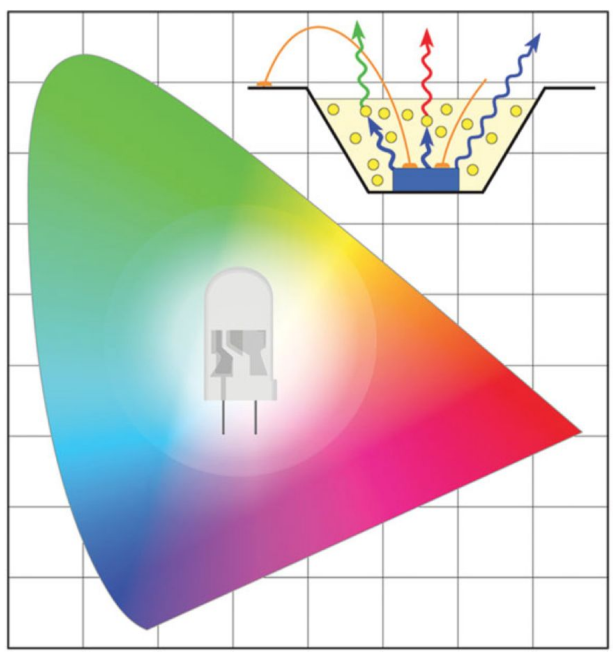

Figure 4. Light spectrum of colors

colors are discovered. It was discovered that when you mix light, which is called additive mixing, the three primary colors are green, red, and violet. The idea behind having a white light, is that if we mix these primary colors in the right proportion, we can get the desired radiation color [5]. The color triangle shown in **Figure-4** above illustrates the recipe of how to mix the colors to make the white light. This color triangle has three corners with primary colors (green, red, violet). Giving the right intensity of these three mixed colored lights, we can generate a white light, as shown in **Figure.5.** [6].

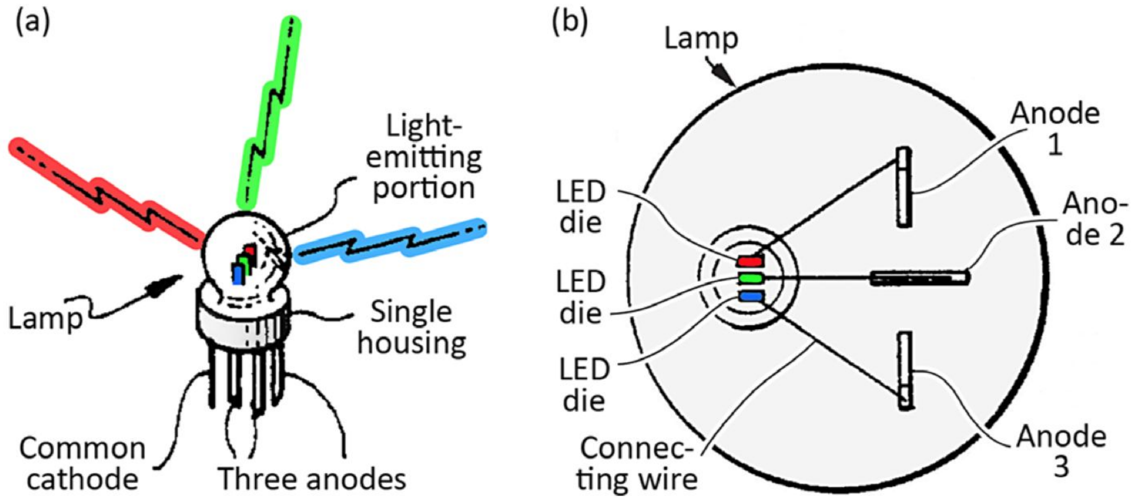

Figure 5. (a) Perspective view and (b) top view of multi-LED-chip white LED consisting of a red (R), green (G), and blue (B) LED chip (or die). Optical mixing of the RGB emission components results in white light (adapted from Ref. [6]).

Another approach to design an LED that emits white light is by making a near ultra-violet or violet LED coated with a layer of phosphorous material. The phosphor layer emits a wide spectrum of visible light ranging from blue to red upon receiving the near UV or violet light radiated from the LED chip. **Figure. 6** illustrates the design that consists of LED chip and the phosphor layer. The light coming from the

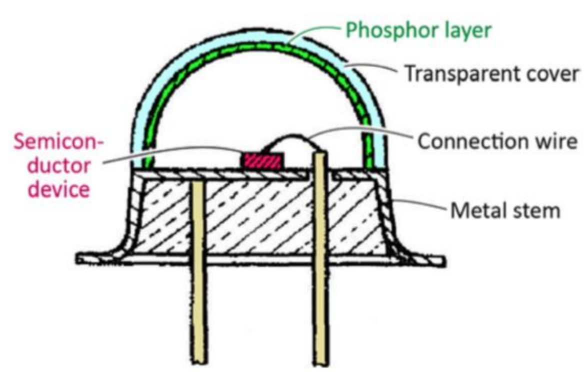

Figure 6. LED structure having an LED chip exciting a phosphor that is coated on the inside of transparent cover. The arrangement of the phosphor is reminiscent of a fluorescent lamp that has the inside of a glass tube coated with a phosphor (adopted from Ref. [6]).

LED is fully or partially absorbed by the coated phosphor layer depending on the design. In a full absorption of this light, the phosphor layer will emit all three primary colors resulting in a white light. In a partial absorption, however, a blue LED is used instead, and the phosphor layer emission is limited to the red and yellow lights. The remaining non-absorbed blue light from the LED for this later design is then mixed with the two generated lights to form a white light. This partial conversion method has higher efficiency as it only requires converting wavelengths of two colors (red and yellow) [6].

In the later two options for designing LEDs emitting white light, an appropriate phosphors layers are used to absorb the violet or blue LED light. The phosphorus material used in LEDs should have a high absorption to be excited and to generate the white light using one of the later two approaches aforementioned. In the next section, we will review the principles and properties of the materials used in this technology.

3. Common Phosphors Technology for White LEDs:

The most common phosphors material used in LEDs today is the aluminate phosphors, specifically Yttrium aluminium garnet “$Y_3Al_5O_{12}$” (YAG:Ce), and that goes back to its excellent radiation conversion efficiency, high stability against chemicals, and to its low cost. Due to its wide band gap that approximates to the energy of ultraviolet light, the pure material of $Y_3Al_5O_{12}$ cannot be excited to emit visible light, nor can it absorb visible light. When doped with cerium “$Y_3Al_5O_{12}:Ce^{3+}$”, however, it emits a yellow-green broadband upon excitation with blue light of wavelength 430~480 nm [7]. The combination of these yellow, red, and green lights will form a white light.

On the other hand, however, white LEDs that uses (YAG:Ce) has disadvantages including high temperature quenching of luminescence. Moreover, it is impossible to create light with a high temperature using this material. Therefore, studies that involved a developed yellowish orange phosphor was conducted. The material “Ca-α-SiAlON” doped with europium Eu^{+2} was used and combined with blue LED chip. For a specific experiment

$Ca_{0.925}Eu_{0.075}Si_9Al_3ON_{15}$ was used. **Figure 7.** shows the excitation and emission spectra of the synthesized SiAlON phosphor. The peak excitation wavelength is about 450 nm and an emission monitoring wavelength of 581 nm, which is suitable for excitation by a blue LED chip. α-SiAlON is a high-temperature structural material and has excellent thermal stability compared to YAG:Ce^{+3} as shown in **Figure 8.** It is clear from this plot that the low thermal quenching of α-SiAlON:Eu^{+2} leads to a small variation of chromaticity in white LEDs [8].

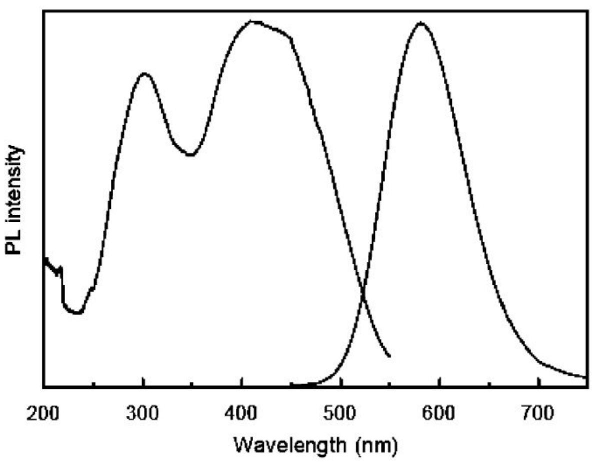

Figure 7. Excitation and emission spectra of $Ca_{0.925}Eu_{0.075}Si_9Al_3ON_{15}$. The excitation and monitoring wavelengths are 420 and 581 nm, respectively. (Adopted from Ref. [8]).

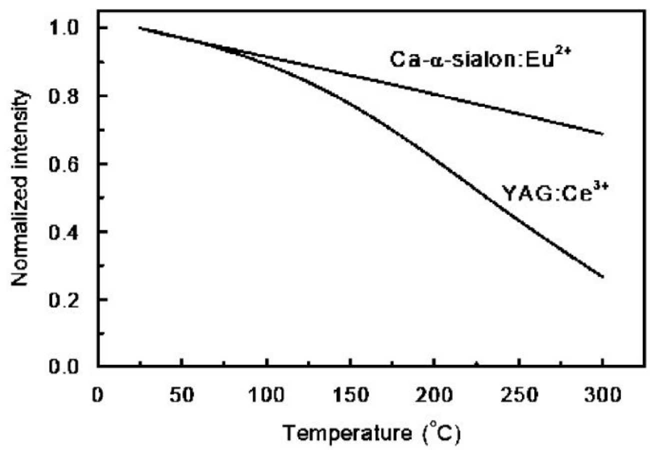

Figure 8. Temperature dependence of emission intensities of Ca-a-silalon:Eu^{2+} and YAG:Ce^{3+}. (Adopted from Ref. [8]).

4. Technology:

In the 1970's, several research teams began working to grow GaN using newly developed crystal growth techniques. Isamu Akasaki and Hiroshi Amano were successful in producing high quality GaN by including a buffer of polycrystalline on sapphire. Also in more recent years, the development of GaN-on-GaN has increased and many believe that it is the future of LEDs. Some advantages that GaN-on-GaN LEDs include its substrate level and efficiency level. Below is a diagram **(Figure 9)** comparing the process of a traditional Silicon or Sapphire substrate to that of a GaN-on-GaN LED. As you can see, there are much less steps to the GaN-on-GaN process which would reduce the manufacturing cost and time. Although it would be less expensive to create, GaN substrates are much more expensive than sapphire or silicon which is why most of the world has yet to switch over to this new process [9].

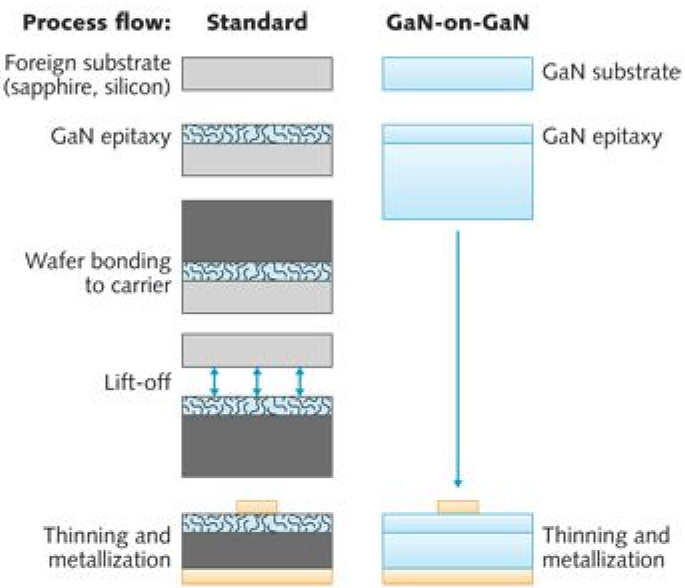

Figure 9. A semiconductor manufacturing flow chart for LEDs. (Adopted from Ref. [9]).

At the same time Shuji Nakamura was working on a new process called MOCVD (Metalorganic Chemical Vapor Deposition) to produce high quality GaN, with much lower background n-doping. This process is done by taking atoms that will be in the crystal and combining it with complex organic gas molecules and then passing it over a hot semiconductor wafer. The atoms are then deposited layer by layer onto the surface [10]. Using this process, we can specify the thickness of the layer to the millionth of a millimeter to grow high quality semiconductor layers. This method is still widely used for volume production because there is no need to change material. Below **(Figure 10)** is the MOCVD process; as you can see, the atoms are being mixed with a gas and then deposited on the surface.

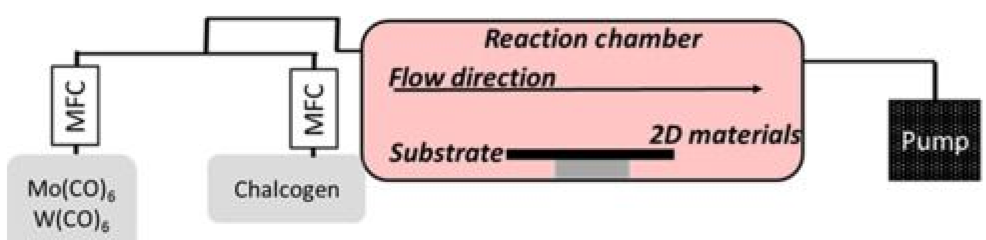

Figure 10. The schematic of an MOCVD reactor for TMD synthesis. (Adopted from Ref. [10]).

5. Future Direction:

LED technology and applications have increased rapidly ever since the development of high-brightness GaN LEDs in the 1990's. Today, LEDs play a pivotal role in our society and continue to become more advanced. These advancements are leading to new opportunities that we previously thought were not plausible. LEDs have can transform our society through a variety of applications in lighting, communications, and other areas.

With the advancements of LEDs, future lighting systems will become much more advanced as well as more efficient. From his book, <u>Thermal Management for LED Applications</u>, Dr. Robert F. Karlicek Jr.says, "Future lighting systems will harness the ability to control spectral content, autonomously adjust the distribution of illuminance, transmit digital information, and interface with other energy management systems in power distribution grids and building controls" [11]. It is evident that LED lighting will eventually take over incandescent and fluorescent lighting systems, and with these upcoming advancements, it is likely to happen sooner rather than later. As you can see below in **Figure-11**, the wall plug efficiency of GaN-based LED devices has steadily been improving and now can reach as high as 70%. Not only are these lights more efficient, but they are also producing better light quality.

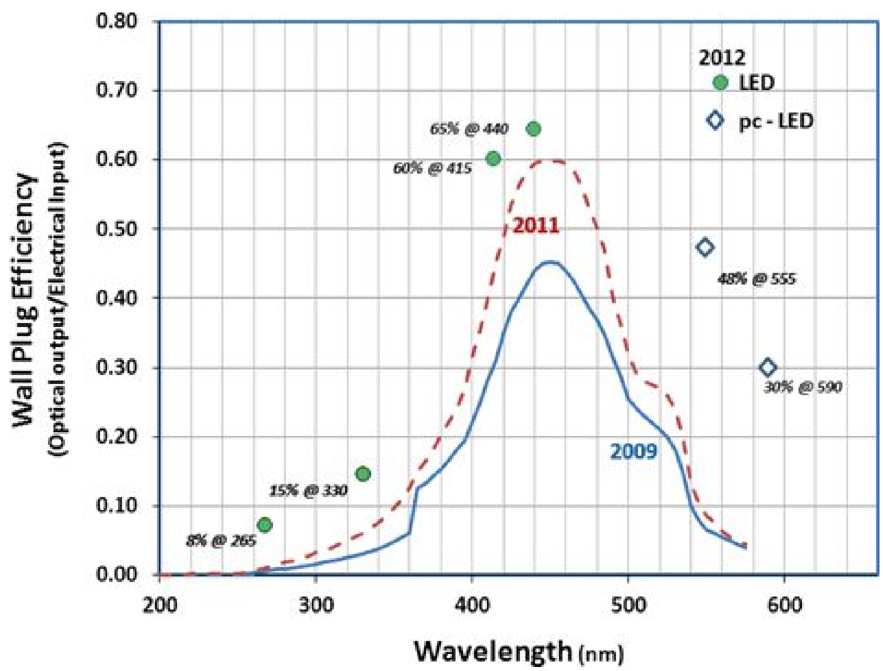

Figure 11. Efficiency vs emission wavelength for GaN-based LED devices showing progress between 2009 and 2012. (Adopted from Ref. [11]).

Communication is also an area which is affected greatly by the future of LEDs. One functionality that has been under work for some time now is the concept of light fidelity (LiFi). LiFi is a wireless communication technology that uses visible and infrared light for high speed data communication. Since LED bulbs are semiconductors, the brightness can be changed at extremely high speeds.[12] This allows us to send a signal by modulating the light at different rates. These signals can then be picked up by a receiver which interprets these signals as data. As you can see below **(Figure 12)**, data can be effectively transmitted using Li-Fi.

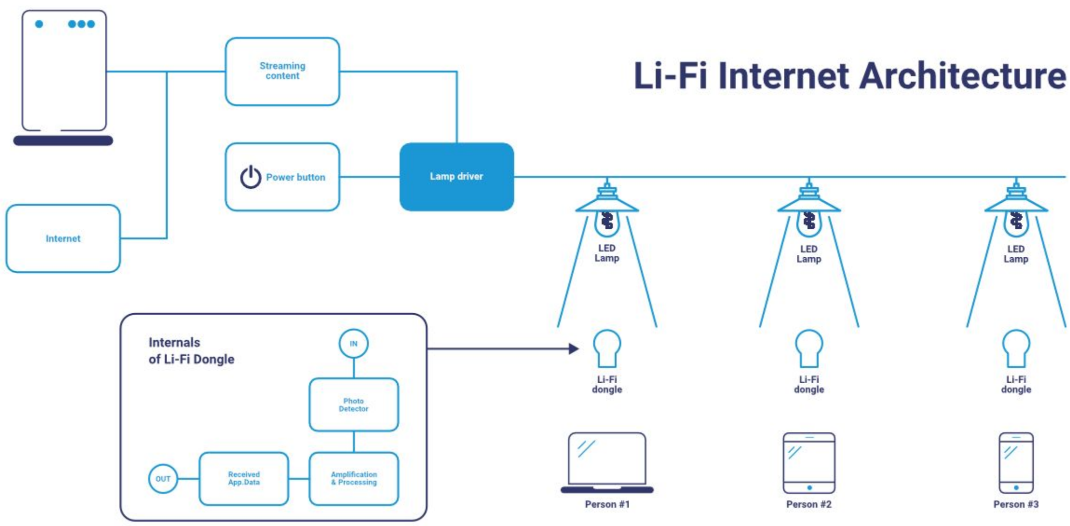

Figure 12. Li-Fi Internet Architecture.
(Adopted from Ref. [12]).

While this process hasn't been perfected yet, it already provides a great alternative to WiFi. One problem with WiFi is that it is uses radio waves to transmit data, and different signals can interfere with each other. This problem is most evident in hospitals and on airplanes. To avoid having devices interfere with equipment, they often avoid the use of unnecessary devices. Also, since walls block light, unlike radio waves, LiFi also provides a more secure data transfer which would make it better for schools and workplaces.

Also there have been specific advancements in semiconductor processes using GaN which will lead to brighter output LEDs and power devices. One example of this is Bridgelux Inc., a developer of LED light sources, has created an LED with light output 135 lm/W by growing GaN on a silicon wafer [13]. They believe that the utilization of this process can improve manufacturing costs by up to 75%. One of the main disadvantages of LEDs is that initially they are more expensive than traditional fluorescent or incandescent light bulbs; but if costs are reduced by that much, it would greatly accelerate the transition to LED lighting systems. Also, scientists at North Carolina State University have developed a new process to boost high-power potentials for GaN devices so that they are able to handle higher voltage levels. During a test of the LED, they were able to achieve a breakdown voltage of 1650V or almost 7 times higher than normal [13]. By improving this breakdown voltage, we will be able to greatly reduce the electrical resistance of the LED which will lead to more powerful and efficient devices. As mentioned before GaN-on-GaN LEDs could be the future or LEDs and if we are able to find less expensive ways to create GaN substrates, it could replace traditional methods very quickly.

6. Conclusion:

The invention of the light bulb revolutionized our society and shed possibility to many things that had previously seemed impossible. With the more recent development of the LED, we have once again solved a great need and opened the door for further technological advancements. In the short 50 years since the first development of the LED, we have already seen major advancements in efficiency and brightness and are still continuing to improve at a rapid pace. With all the recent advancements, it would appear that the future of the LED is bright. The crucial developments of white LEDs have played an important role in technology advancements. From being used as detectors in electronic circuits to their exploitation as light sources in many vital devices, white LEDs nowadays are very important designs as they are being used in a wide variety of daily basis devices.

7. References

[1] Nadarajah Narendran, (2005), Improved Performance White LED, Retrieved from https://www.lightingassociates.org/i/u/2127806/f/tech_sheets/Improved_performance_white_LEDs.pdf

[2] Jorge Pirolla, (2009, Jan),*Quantum well width as an uncertainty source in electronic transitions* Retrieved from https://www.researchgate.net/figure/Sketch-of-a-semiconductor-heterostructure-of-quantum-well-type-There-is-a-100-A-quantum_fig1_237502623

[3] Christian Albrechts, (2019, Feb 22). III-V Semiconductors, Retrieved from https://www.tf.uni-kiel.de/matwis/amat/semitech_en/kap_2/backbone/r2_3_1.html

[4] Parasuraman.Swaminathan, (2014, Sep 22), *Light Emitting Diodes*, Retrieved from, https://nptel.ac.in/courses/113106062/Lec16.pdf

[5] Joseph N. Tawil, (2019, Aug 25), "Color Theory", Retrieved from http://www.gamonline.com/catalog/colortheory/language.php

[6] John.Wen, (2017), *White Light-Emitting Diodes,* Retrieved from https://www.ecse.rpi.edu/~schubert/Reprints/2017-Cho-J-(L&PR)-White-light-emitting-diodes--History-progress-and-future.pdf

[7] Yuanhong Liu et al. (2015), Research on Trend of Worldwide White LED Phosphors Technologies and Market Development, Retrieved from https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7360684

[8] Rong-Jun Xie (2007 Oct), Silicon-Based Oxynitride and Nitride Phosphors for White LEDs-A Review, Retrieved from https://www.researchgate.net/publication/222703912_Silicon-Based_Oxynitride_and_Nitride_Phosphors_for_White_LEDs-A_Review

[9] Mike Krames, (2013, Sep 16). *light -emitting diodes : GaN-on-GaN platform removes cost/performance tradeoffs in LED lighting, Retrieved from* https://www.laserfocusworld.com/articles/print/volume-49/issue-09/features/light-emitting-diodes-gan-on-gan-platform-removes-cost-performance-tradeoffs-in-led-lighting.html

[10] K. Zhang, .and J.A. Robinson (2001),*metal-organic chemical vapor deposition*,Retrieved from https://www.sciencedirect.com/topics/chemistry/metal-organic-chemical-vapor-deposition

[11] Robert F. Karlicek,(2017, Sep 17). *future directions in led applications,Retrieved from* https://link.springer.com/chapter/10.1007/978-1-4614-5091-7_16

[12] Youssouf Ould Cheikh Mouhamedou, (2017, Nov 21), *What is Light Fidelity* (LiFi),Retrieved from https://www.grandmetric.com/2017/11/21/light-fidelity-lifi/

[13] Roger Allan, (2011, Apr 7)Expect GaN To Play A Role in Future LEDs and Power Devices, Retrieved from https://www.electronicdesign.com/energy/expect-gan-play-role-future-leds-and-power-devices