The Basic Principles of Light Emitting Diodes with an Analysis of their History and Future

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Abstract:

The light emitting diode is a Nobel Prize winning invention that is hailed as one of the great achievements of the 20th and 21st century, and as such it is important to fully understand both the physical mechanics of the device as well as its history and current developments. This paper offers a brief overview of the physical theory behind the LED through the lens of semiconductor physics, a compendium of the history behind the invention, and an analysis of current trends and future potential of the LED.

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Section I: Introduction

Utilizing the optical phenomena of electroluminescence, the light emitting diode (LED) produces light via a direct source of current, rather than a heated filament or gas. In its simplest form the LED is a semiconductor that consist of conduction and valence bands which allow for free electrons to recombine and release photons. Although the first LEDs were created in the 1920's, useful applications were not invented until the 60's, and commercial applications were not available until as recently as the 1990s. Current research is still ongoing, and recent trends indicate that the future potential of LEDs far exceed that of all other current forms of light emission. [1][2]

Section II: Basic Principles of LEDs

The driving physical theory behind the LED is electroluminescence. Discovered in 1907, electroluminescence is the process of light emission through the recombination of electrons in an atomic lattice, typically semiconductors. When electrical current is passed through the material free electrons are forced into an excited state. With the right type of material, this process also creates a conduction band of electron holes. When a free electron transfers back to a lower energy state, the energy is typically released as a photon of light (although not always for larger systems). This is extremely useful for two reasons. First, due to the quantized nature of energy, it is known that the energy applied to any electron will release the same energy when it recombines. Second, the energy of any photon is a well-known result (Equation 1) and is related to the wavelength of the photon. Thus, the color of light can be predicted simply from the energy of the excited electrons. [1][4]

$$E = hc/\lambda \qquad \textit{Equation 1}$$

The basic design of an LED is such that electron recombination can occur frequently and in large abundance. The structure of the LED typically consists of Gallium Nitride (GaN), or some other type of crystal structure, doped with impurities. The two most common type of semiconductor doping techniques are p-type and n-type. The p-type technique uses impurities to create electron holes in the valence material (typically Boron is the injected impurity), and n-type is when the impurities cause an excess of free electrons in the conduction band (typically Phosphorus is used). For LED's, doping can be either n-type or p-type. The impurities added allow for more states closer to the band gap on both bands, thus allowing for easier electron travel across the band gap. When an external voltage is applied to the semiconductors, an electric field is produced and current is formed from the electron recombination. The recombination emits energy as photons. If the semiconductor has an indirect band gap, the energy is released as vibrations, if the semiconductor has a direct band gap, then the energy is released as light. GaN is a common semiconductor that can have a direct band gap, which is why it is heavily used in LEDs. See figure 1. [1]

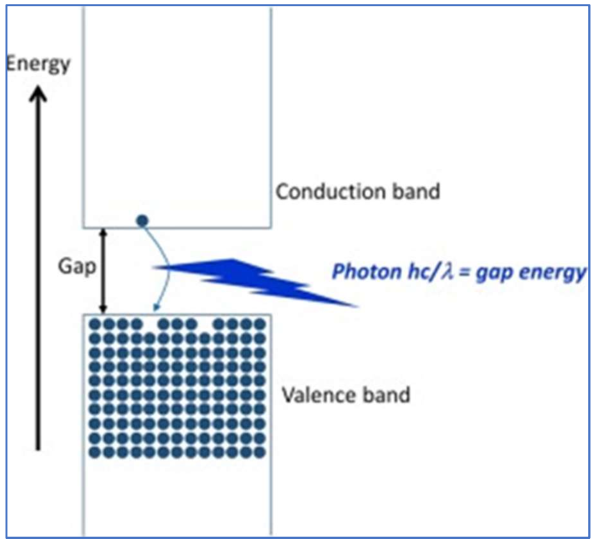

Figure 1

Demonstration of the basic setup of an LED. The conduction band consists of free electrons while the valence band consists of the electron holes. Electrons jump the energy gap by releasing energy in the form of photons. The amount of energy needed to jump is proportional to the wavelength of the photon, thus the band gap can be used to set the color of the LED. [1]

The basic LED structure described can produce the primary colors red, blue, and green, with only some technical modifications to the design. The red LED is the simplest to produce as it requires the least amount of energy to emit red light. The GaN semiconductor doped with Phosphorus is also one of the trivial semiconductors to construct, adding to the simplicity of the red LED. Along similar lines, a green LED can be created through GaN doped with Indium, although this is slightly more difficult to do, due to the higher energy gap and doping process. The most difficult primary color LED to create is blue. This is partly due to blue having the shortest wavelength and the difficultly of creating materials with the proper band gap for blue light emission to occur. However, doping materials such as Silicon, Indium Tin Oxide, and Gallium Nitride have all been viable ways of producing blue LEDs. Commercially, sapphire is the most commonly used as it resembles the structure of Gallium Nitride and has less of an economic impact. [1][3]

More complex LEDs can be created using more involved designs. For example, the white LED can be produced in two main ways, each with their own advantages and disadvantages. The first way is to simply combine the red, blue, and green LEDs output to produce what humans perceive as white light. This method is the simplest way to produce a white LED, however it is limited in two major ways. The first is by the lowest optical power of the RGB system, that is, the total optical power has a limiting factor which is the lowest optical power of one of the three LEDs. Second by the discrete wavelengths emitted by each LED. This means the emission of white light is fixed by only three wavelengths, and thus doesn't cover the spectrum of light that is typically encapsulated by white light. The second method for producing white LEDs is to produce monochromatic light from Phosphorus. In this method, Phosphorous materials are shined with low spectrum light (typically blue) which then produces yellow light. The blue and yellow light mix to form white, but some residual blue and yellow light are leftover, which is a downside to this method. Another downside is the technical challenge of phosphorus shining rather than combing three separate LEDs. Besides the white LED, many different types are currently in development, from high power, alternating current, or even dual color. [3][5]

The theory of electroluminescence through the recombination of electrons in atomic lattices allowed for a consistent way of producing light emission. Through the development of doped semiconductors, the ability to reliably use this process allowed for the creation of the light emitting diode. The LED is able to produce varying colors of light emission, based on the electron gap energy and the type of semiconductive material used. The creation of white light and more complex LEDs is achieved through more advanced methods of LED construction, and are still being developed to this day.

Section III: History of LEDs

The first known demonstration of electroluminescence occurred in 1907 by H.J. Round, who made a crude example of the phenomena by placing electrodes on different parts of silicon carbide. He saw different colors emit from his setup but made no attempt to describe the phenomena. It was not until 1929 that Oleg Losev, a junior scientist, managed to create the first light emitting diode. Using the same material as Round, he created a more refined version of the setup and was even able to patent his design. However, most scientists still did not understand electroluminescence and the study of semiconductors was still in its infancy. [1]

It was not until a deeper understanding of semiconductive properties were obtained that progress on the LED would continue. With the invention of p-n junctions and transistors, this method of producing light was finally able to output reliable and more powerful signals. Specifically, the development of gallium semiconductors allowed for the red LED to be created. Invented in 1962 by Biard and Pittman, the first true LED was a GaAs based red LED. It was patented the same year and the parent company, Texas Instruments, began plans to commercially produce the product. The initial uses of the red LED were limited to mainly scientific laboratories and select industries due the high initial cost. [1][6]

After 1962, many other types of LEDs were quickly invented, due to the similar structure for producing different colors of light from GaN. However, it was nearly a decade before the blue LED was finally shown to be possible. The major difficulty surrounding the creation of the blue LED had to do with the band gap required to generate photons near the blue end of the visible light spectrum. The first successful attempts at the blue LED did not occur until the early 1970's, almost a decade after the red LED. These first blue LEDs managed to use the similar GaN structure with a bandgap of 3.4 eV (365 nm emission) but managed only 0.12% efficiency. The difficulties surrounding this production led many scientists to assume that the blue LED could not be created using the GaN semiconductors, certainly not to a usable efficiency. [1]

With many scientists focusing research on other types of semiconductors, Dr. Akasaki and his team still pursued the production on the blue LED using a GaN based semiconductor. Akasaki, along with his student Amano, developed a new method for creating a layer of GaN on sapphire. Although complex, the method utilized different temperatures to manipulate the growth rate of sapphire on a GaN crystal and applying electron radiation to allow for p-type doping of the material. This method was the first to create a good quality blue LED from GaN, but still was to inefficient to be widely used. In 1989, an engineer named Nakamura was able to improve the methods developed by Akasaki and Amano and produce high brightness blue LEDs and pave the way for more efficient LEDs. Akasaki, Amano, and Nakamura were awarded the Nobel Prize in 2014 for their contributions to the development of the blue LED. [1][7]

The development of the LED to its current state took close to a century. Although the physics was known as early as the 1900's, the technology required to create LEDs was simply not available. Through the course of the century, countless teams of scientists and engineers contributed small yet essential parts to the theory, creation, and production of LEDs. Although the scientific community tends to honor only a few in the community, it is important to respect the work of all those involved. The development of the LED from its initial conception to its current state is one of the most relevant examples of the power of modern scientific collaboration. The development was never achieved by one experiment or one person, but rather the collective effort of the scientific community.

Section IV: Current and Future Potential of LEDs

Recently the production cost of LED finally reached a suitable level for large scale productions. Coupled with this, trends indicate that the efficiently of any given LED has risen drastically as well. This relationship can best be represented in figure 2, where we see a logarithmic trend in both regimes. The most basic implication of this relationship is that efficient light sources can be made in large scales and within reasonable costs. The colloquial name given to this effect is Haitz's law, named after Roland Haitz, who initially noticed the trend. The reasons behind the increased efficiency trend stem mainly from the process optimization of semiconductors that has been occurring exponentially over the past few decades. Better semiconductors allow for more powerful emissions with less operating voltage required. The efficiency of an LED can be modeled by equation 2. Here in this simplified form the efficiency of an LED lamp η is equivalent to the optical output power φ_V divided by the LED operating voltage V_f and current I_f. The decrease in the cost per unit production is mostly in part due to the industrial scaling of production. Whereas before LED's were only capable of being created in scientific labs or small-scale productions, they are now being produced at scales concurrent with other typical light industries. [1][3][7]

$$\eta = \frac{\varphi_V}{V_f I_f} \qquad \textit{Equation 2}$$

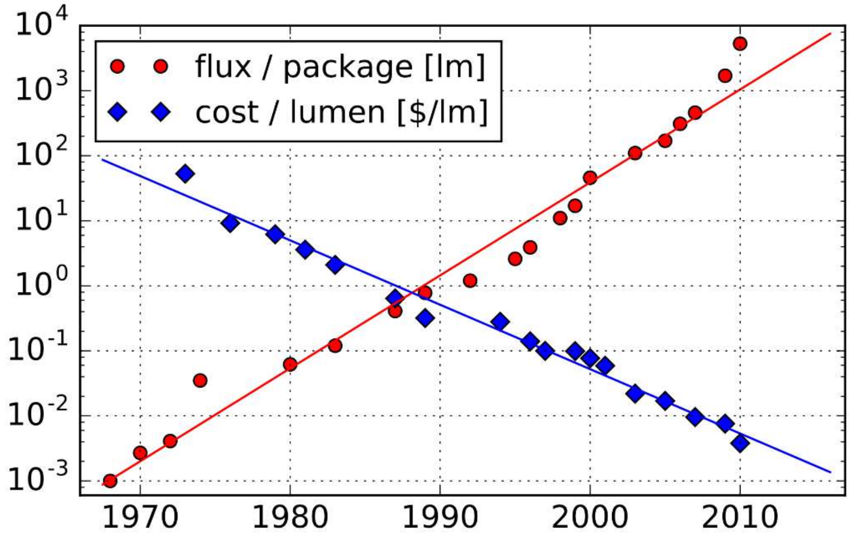

Figure 2

Data points fitted with logarithmic relationship over the past five decades. The red represents the optical output of a typical LED lamp while the blue represents the typical cost per optical output. The data follows nearly perfectly what Haitz's law predicts. [7]

The main allure of LED lighting comes from this newfound efficiency. Traditional lighting techniques, such as incandescent bulbs or fluorescent lamps, generate light emission through non-direct processes. In the case of incandescent, a metal must be heated to a certain temperature threshold, which gives off energy in the form of light through restabilization of the metal. However, in this process nearly all the electric input is applied to heating the metal, a process that returns only around 5% efficiency. Fluorescent lamps offer a more efficient process through an ionization of a gas, but the process is not as direct, and therefore not as efficient, as the LED. The LED has a theoretical efficiency of 100% due to the direct interactions of photon emissions through electron recombination. This translates into direct savings in both the domestic and industrial settings, as seen in figures 3 and 4. [1][3]

Although the LED has many intriguing prospects for modern lighting, there are still some downsides that must be considered when discussing the practically of the LED. The first major issue that is known is that the optical output of an LED is related to the ambient temperature. If the temperature surrounding an LED lamp exceeds a certain threshold it can cause overheating of the lamp. The second is that LEDs require a specific voltage to operate correctly (the band gap for emission). If this voltage cannot be applied or transformed correctly, then the output of the LED is severely reduced. Both issues and many more are being investigated as part of ongoing research, with the goal of being able to cheaply and consistently create more efficient and reliable LEDs. [1][3]

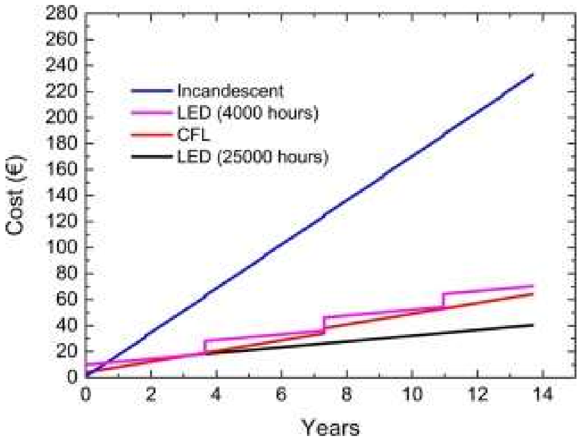

Figure 3

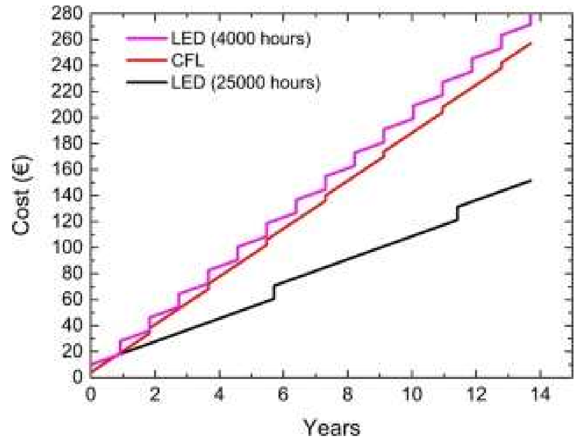

Figure 4

Figure 3 shows four main lighting sources cost over years used for domestic purposes. Figure 4 shows four main lighting sources cost over years for industrial purposes. In both cases, LED lighting preforms better over longer periods [1].

The recent trends indicate that the availability and efficiency of LEDs and LED lamps have allowed for the LED to become a mainstream source of light emission both in domestic and industrial cases. The relationship between optical power and operating voltage and current can be described in a trivial way to show efficiency of a LED. The efficiently of an LED has been rising logarithmically while the cost of production is dropping logarithmically over the past few decades. Even though LEDs have a great potential to both save on costs and emissions, there are still technical challenges that are actively being solved with current research. [1]

Section V: Conclusions

The light emitting diode has proven to be one of the most impactful inventions of the past century. Understanding the mechanics that govern the nature of this light emission has created many new opportunities within the realm of physics. The research on semiconductive properties has had a great benefit to mankind, not just within the scope of the LED. The history shows how both induvial and collaborative contributes contribute to the scientific process. The future prospects of the LED are promising and are likely to have far reaching impacts both economically and environmentally.

Section VI: References

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