RESEARCH ARTICLE OPEN ACCESS

LED: Revolutionizing lighting

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ABSTRACT
LED lighting technology has proven to be a worthwhile product offering efficiency. Its features, advantages and disadvantages were described to provide a perspective of the changes since it was invented. The latest developments in LED technology were provided in the light of these features, advantages and disadvantages. Improvement in functionality and usefulness has been the thrust for LED technologies. As more and more technologies are developed, the integration of LED technologies into their design has been established to be useful. Various applications of its use have been developed even considering the psychological well-being of consumers. Sustainability issues have also impacted the development of LEDs and the products where LEDs have proven to contribute to sustainable designs.
Keywords: LED technology, lighting

Date of Submission: 03-11-2017 Date of acceptance: 16-11-2017

I. INTRODUCTION

Illumination has taken on modern steps in its development. Developers and researchers have found novel ways of producing light and have even in fact went to explore unique applications of lighting technologies. One of these lighting inventions is the light emitting diode (LED). LED have been in use for years. In the earlier periods, they were utilized often to light buttons and meters in electronic appliances. However, in the past ten years, LEDs have been improved to produce white light equal or better than incandescent light bulbs. In 2010, unlike the other types of lighting – CFLs, fluorescents, halogens and incandescents – LED was carried by stores in a smaller proportion (Allen, 2010). But then, at that time, this scenario was expected to change since a less expensive LED bulb producing as much light as a 40-watt

incandescent bulb was made. Its maker, the Lighting Science Group, a small Florida company, indicated that the new LED bulb was to change the world. The new LED bulb only consumes 80 percent less energy as well as lasts about 20 times longer (Allen, 2010). Moreover, the digital trend in products such as in communications, entertainment and information is taking place in lighting technology. Lighting products have also become more sensitive and reactive to the environment. Semiconductors were introduced into the light which has made the product smart, like appliances. A move from analog light bulbs to LED lights was anticipated. LED bulbs with enhanced features were projected to be produced. Due to this, the LED manufacturing company expected that about half of light bulb sales in the United States were estimated. Other light manufacturing companies like General Electric and Philips raced to produce its own line of LED products. A considerable shift to commercial use due to the benefits of LED can be observed. These are just a few of the development trends and efforts which can be observed in LED technology. A wide range of development efforts can also be noted in the field. It is of interest to look into the developments in lighting technology as new uses and applications have been discovered. Lighting has proven to provide very practical uses for people's lives. The latest trends in LED technology further surprises people in their newfound applications.

From the inception of LED bulbs, the product has evolved into a state-of-the- art item. LEDs have found its way into many products which have become salient features of products' designs and functionality. This evolution and development in LED lighting technology is examined in this paper. Features, advantages and disadvantages are described. Innovations in and with LED technology are also presented. Tracing along the history of LED lights allows the illustration of its development over the years. This also presents a brief comparison of LED lights with other types of lighting technologies to depict the shifting preferences of users towards LED lighting technology. Some of the latest developments are also outlined here to identify the direction the technology is taking. Moreover, the effects of its evolution to the life of people today, consumers and sectors alike, are also identified.

II. OBJECTIVES

This paper primarily describes the features, advantages, disadvantages and latest developments in LED lighting technology. This research aims to achieve the following obejctives:

• To present the features, advantages and disadvantages of LED bulbs
• To illustrate the development of LED technology through time to depict the changes and discovered uses for LED
• To compare LED technology with other lighting technology
• To identify and describe the latest trends in LED technology

III. FEATURES OF LED LIGHT BULBS

A description of the inner workings of LED lights is first presented which should give way to understand the direction of the trends in its innovation. The light-emitting diode (LED) is a light source using a two- lead semiconductor which is a p-n junction diode. The diode produces light when turned on. When the leads receive the correct voltage, photons are released as energy which were made possible by the recombination of the electrons with electron holes within the device. Electroluminescence is the effect produced. This process is described by the release of light from a semiconductor through an electric field. Electrons crossing the N- region to the P-region emit energy in the form of light and heat. Current flow is in the reverse direction. LED emits light when 2 or more volts are used. The color of the light which matches up with the energy of the photon is established by the semiconductor's energy band gap. Figure 1 illustrates the working principle of LED lights.

Figure 1. LED inner workings

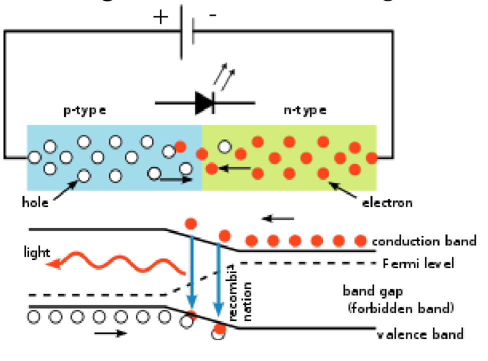


Figure 2 shows an I-V diagram for a diode in a LED light. In the reverse bias region, a different vertical scale is applied from the forward bias region. This depicts that the leakage current is almost steady with voltage up until a breakdown takes place. Photons are released and tumbles into a lower energy when an electron and a hole meet.

Figure 2. LED I-V diagram for a diode.

LEDs are commonly made on n-type substrate. An electrode is attached to the p- type layer placed on its surface. However, there are also p-type substrates which are not as common. Sapphire substrate are most frequently found in commercial LEDs.

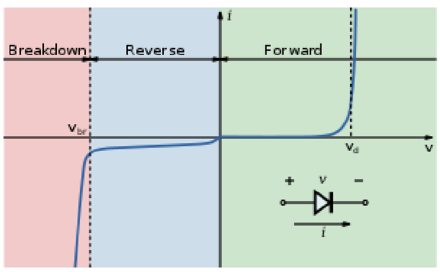
In the earlier stages of its existence in the market, LEDs appeared as a practice electronic component (Okon & Board, 2015). The first LEDs radiated low-intensity infrared light. They are still often used to transmit elements in remote-control circuits like those found in consumer electronic products. The initial visible-light LEDs were also made with low intensity and restricted to red since these made the indicators bright enough yet subdued enough not to light up an area. An image of the red LED is presented in Figure 3.

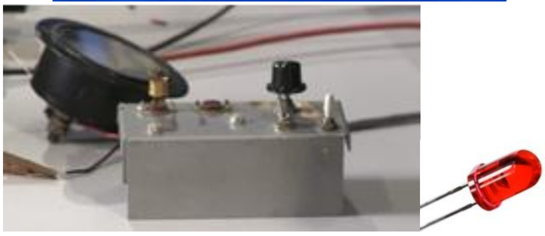
Figure 3. Red LED bulb

Far along, other colors were added and used in different appliances and equipment. In 1972, Blue LEDs were developed using gallium nitride (GaN) on a sapphire substrate (Patel, 2014). But, these first productions did not make very bright lights. In 1994, brighter blue LED lights, based on InGaN, appeared (Nakamura, Mukai & Senoh, 1994). In the following year, high-brightness LEDs were tested which led into the development of a transparent-contact LED with indium tin oxide. In 2001 and 2002, gallium nitride (GaN) were successfully used on LEDs on silicon (Dadgar, Alam, Riemann, Blasing et al, 2002). The blue LEDs proved to be of high efficiency. Figure 4 shows pictures of the current and first blue LED light.

Figure 4. The current and first blue LED light.

The blue light was swiftly trailed by white LED. The use of Yttrium Aluminium Garnet (YAG) phosphor coating on the emitter produced a whitish light due to the combination of the yellow light through fluorescence and blue emission. Though the initial white LEDs were costly and inefficient, LED light output had improved considerably. They have proven to produce more than 300 lumens per watt of electricity. Some white LEDs have lasted up to 100,000 hours (Nobel Prize, 2014). The trend was





due to the corresponding progress of semiconductor technologies and developments in optics (Nature Photonics, 2007). Due to this, the white lights have increasingly replaced incandescent and fluorescent lights (Nick, 2006), as they have also proven to be cheaper per bulb through the years (EIA, 2014). Figure 3 shows a comparison of the LED bulb efficiency as against compact fluorescent lamps (CFL) and incandescent bulbs. It can be observed in this graph that LED lumen watts performance has exceeded both CFL and incandescent bulbs. Although at the onset LED bulbs had higher costs, the cost per bulb has drastically gone down to meet the prices of CFLs and incandescent bulbs. Despite the almost equivalent prices, LED's longevity prove that these lights are more efficient.

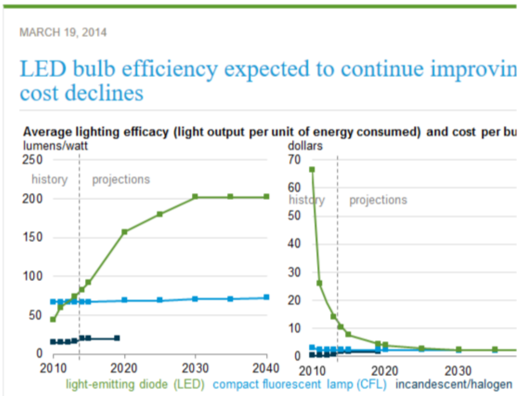
Figure 5. LED efficiency in terms of lumens/watt and costs

more expensive. Appendix 1 presents the available colors with wavelength range, voltage drop and material of LEDs.

LEDs early uses were usually as indicator lamps for electronic devices substituting the small incandescent lights and neon indicators (Rotsky, 1997). They were then found in expensive equipment in laboratories and electronics test equipment. Later, they were promoted into numeric readouts in the appearance of 7-segment displays and were ordinarily observed in digital clocks. However, these readouts were made more visible by incorporating small plastic lenses on each of the digits on the calculator to make them more readable. They were later integrated in consumer electronics such as televisions, radios, calculators and telephones.

From the 1950s until 1968, they were very expensive at $200 each and consequently had little practical use (Schubert, 2003). Its commercial introduction was made possible by using compound semiconductor chips manufactured with the planar process and an innovative packaging method (US Patent, 1962). The new design reduced the cost of the light bulb (Bausch, 2011) and then were introduced as indicators for various products which led to the visible LED's mass production.

For indicators, majority of the LEDs come in 2 mm to 8 mm sizes and in through- hole and surface mount packages. Packages are in 5 mm T1⁄4 and 3 mm T1 suites. Packaging can either be round or rectangular with a domed or flat top or triangular or square with a flat top. The enclosure may be clear or colored. Since power output increased, the need to get rid of excess heat was considered so that the lighting can be preserved reliably (Lunaraccents, n.d.). To make this possible, complex packages were designed to allow more efficient heat



All other colors in the spectrum are also now produced with nitrides containing aluminum. Through these nitrides, shorter wavelengths were produced which have provided the ultraviolet LEDs. Multicolor LEDs are used to create white light, permitting precise dynamic color control (Schubert & Kim, 2005); but these colors are also available in their individual hues. However, the shorter wavelength diodes are release. Materials now have very high refractive indices such as silicon with bare uncoated semiconductors. Light is bounced back into the material and directed to the material or surface interface. The photon's passage at sharp angles is prevented which creates the light-emission and light-absorption efficiencies. This light extraction is a significant feature in LED production.

IV. COMPARISON OF LED LIGHTS WITH OTHER TYPES OF LIGHTS

There are three main differences of LEDs over other types of lights - light source, direction and heat. Generally, LEDs are better than incandescent bulbs due to the following features. LEDs consume lower energy. They also last longer. They have better physical robustness. They are smaller and have faster switching. They are also directional light sources as they radiate light in a particular direction as against incandescent and CFL lights which spread light and heat in all directions. Heat emission is also far less than CFL or incandescent bulbs which emit heat at 90% and 80% respectively (Energy Star, n.d.). This allows for more efficient lighting systems. Unlike the other types of light, they also come in various colors which could be suited for various applications more particularly as indicators.

V. ADVANTAGES OF LED LIGHTS

LED lights are beneficial for several reasons. First, LED lights are more efficient as they consume less energy. There are greater lumens per watt than incandescent bulbs (U. S. Department of Energy, 2013). Regardless of the shape and size, its efficiency remains unchanged. Second, a variety of colors may be emitted by a LED light. There is no need to use color filters which puts down the initial cost and thus is more efficient. Third, LED lights can be as small as 2mm2 (Avago Technologies, 2008).

With this size, they can be easily affixed to printed circuit boards. Fourth, warm up time is shorter compared to other light bulbs which allows faster response times especially in communication devices. Fifth, the cycling time is better than other light bulbs which makes LEDs ideal in on-off cycling. Sixth, these lights can also be easily dimmed such as those for car headlights and on cameras. Seventh, little heat is also radiated unlike other types of light. Damage to sensitive objects or material is reduced. Thus, it is considered a cool light. Eight, LED bulbs exhibit slow failure as bulbs fail by dimming over time. Ninth, they have long lasting hours estimating from 35,000 to 50,000 hours (U.S. Department of Energy, 2006). This extended lifetime is the chief reason for its short payback period (LT-governors, n.d.). Tenth, LEDs are less prone to damage due to external shock. Lastly, the solid packaging allows the focus of light.

Largely, LEDs are used in a variety of applications. They are found in advertising, aviation lighting, camera flashes, general lighting, motorized headlamps, traffic signs and even lighted wallpaper. Disposal of LEDs has less environmental impact (Carlessi, Oliveira, Neto, Spacek et al., 2013).

VI . DISADVANTAGES

LED lights also have a list of disadvantages. Its initial price is higher than other types of light. Another disadvantage is that lighting performance relies on ambient temperatures. With high ambient temperatures, overheating may result which leads to device failure. Thus, there is a need for adequate heat sink. Voltage sensitivity is one issue. There should be voltage supply more than their threshold voltage and a current beneath their rating. Thus, a current-regulated supply is necessary. Moreover, the phenomenon of metamerism produces colors to be perceived different from their original hues especially with cool-white LEDs (Worthey, 2006). LED lights also give a lambertian distribution of light instead of a spherical distribution of light since LEDs cannot offer divergence below a few degrees. Being so, its uses are limited to those that require lambertian lighting distribution. LED lights also function only with correct electrical polarity. Rectifiers are used to correspond to the source polarities of LED devices. LED lights also produce blue- light hazard as these lights can surpass safe limits for the eyes, particularly with the blue and cool-white LEDs (Raloff, 2006). As there is increased effects to human health and the environment, LED lights contribute to light pollution particularly those with high color temperature as they radiate more short wavelengths (Raloff, 2006). Additionally, when the electric current surges above tens of milliamperes, LED's efficiency drops. This occurrence is referred to as the efficiency droop – a lowering of the luminous efficiency. . However, this droop is observed to be less pronounced at elevated temperatures (Stevenson, 2009). The increased heat also shortens the LED life span (Stevenson, 2009). As a result, industry standard is placed at only 350 mA to balance light output, efficiency and longevity features. Meanwhile, insects are also attracted to LED lights (Pawson & Bader, 2014). A final disadvantage is that in winter conditions, LED lights do not give off much heat and can be covered by snow, making it unproductive for traffic control during these seasons (Leamy & Weber, 2010).

VII. INNOVATIONS IN AND WITH LED TECHNOLOGY

Considering the features, advantages and disadvantages of LED lights. Advancements in lighting have been based on these which led to the modifications on

LEDs to address particularly its disadvantages. Among the more significant problems of LED is its efficiency droop phenomenon especially as the first red LEDs were noted for their short life span. Since these higher-powered LEDs are exposed to higher junction temperatures and increased current densities, combining several LED bulbs in one packaging has resolved this issue. The use of ceramic aluminum nitride (AIN) substrates, which have higher thermal conductivity, rather than sapphires was introduced (Cooke, 2014). Consumers realize a reduction in household costs as they would only need fewer LEDs.

LEDs now usually come in smaller than 1 mm2 sizes. They are combined with optical mechanisms used to form the radiation pattern (Moreno & Sun, 2008). Newer LEDs come in infrared, ultraviolet and visible infrared wavelengths, emitting very high brightness. They have become appropriate lighting for the environment and task use. There are now new displays and sensors. They have also proven to be practical in advanced communications technology. State-of-the-art packaging has evolved for LED lights for more efficient functioning. How it looks now is far from how it was earlier designed. Careful thermal designs are considered to be a significant feature to improve thermal resistance particularly for high-power LEDs.

LED light bulbs have also been turned into broadband data transmitters. A research in German organization, Fraunhofer Heinrich Hertz Institute, was able to manipulate the light flicker rate of LED light bulbs to transmit data. At a single frequency, 1 Gpbs was transmitted at a fast pace (Tenningas (d), 2013). Thus, LED bulbs at three frequencies can have 3Gbps as bandwidth capability. However, sending data is not possible except for streaming data. As the need for data transmission grows, the research has shown that LED lights can be used at a bandwidth of 30 MHz. This breakthrough is seen promising for receiving devices and cars and in areas where radio communication is hard or in large spaces. Future developments along this line are seen in terms of the integration of image replication and rendering for video conferencing.

The red LED light was naturally produced a result of the chemical make-up and the production process of the first LEDs. “Several layers of semiconductor crystals are built upon a wafer and as these layers are built, certain dopants are added. The first mixture used for LEDs consisted of gallium arsenide phosphide, consisting of the placement of a wafer into a molten liquid solution combined with the main metal contacts and leads.” (Tenningas (e), 2013). The red also explains why this color is preferred for most indicator lights, and especially those that are based on LED technology.

Other developments in laser technology which uses LED are found in its features such as size, power outputs and power source. The thinnest LEDs have also been developed. These new versions are 10 to 20 times slimmer as they come in two-dimensional flexible materials unlike the 3- D LEDs. They are also 10,000 times thinner than the human hair (Ma, 2014; Nature Nanotechnology, 2014). Meanwhile, there are LEDs capable of radiating more than one thousand lumens (Luminus, 2017). To avoid overheating, a heat sink is provided to allow heat dissipation. LEDs can also now operate on AC power without a DC converter using a simple controlling circuit. These have become more flexible as dissipation of power is low (International Dark Sky Association, 2010).

Still other breakthroughs include wireless LED light bulbs. The unit has a wireless transmitter and is connected to the
internet. This allows adjustment of up to 50 light bulbs which can be conducted through the mobile phone or the web browser (Daniel, 2012). The units 11 colors can be fined tuned and controlled. More interestingly, colors can now be replicated from the area of photos selected like famous settings or sceneries.

A huge retail chain, Target, has installed lighting-based navigation systems in its stores. The LED ceiling lights can send signals to shoppers’ smartphones to help them navigate through the aisles and find specific items. Shoppers are also provided information about products and promotions. The system is made possible by visible light communication (VLC). LED light waves are used instead of radio frequencies to transmit the data (Halper, 2017). The next move along this line for Target is towards providing indoor positioning systems (IPS). In the meantime, IPS has transformed lighting infrastructures using LED as intelligent data networks. Major airports have also considered to install these navigational programs. Maps are called up on passengers’ phones to steer them to shops and terminals.

Osram, a lighting company, is developing clothes weaved with smart lighting. Workwear is designed to have LED lights intended as interactive apparel (Halper (b), 2017). Examples of these workwear include a cycling jacket and safety vests. For better visibility at the work site, these workwear are intended to light up when the rider hits on the brakes and lights that flash when the rate pulses are shooting up. Unlike reflector strips on clothing, smart lighting on clothes provide active illumination which provide for increased work safety. The company’s initial tests were on hockey players and their sticks and pucks during an outdoor night game.

To trace the use of LED light bulbs over time, LED was incorporated in the various products – LED pocket calculators, the LED watch, the flat panel TV screen, the optical LED mouse and as light sources. LED flashlights proved to consume less power and the light diodes appeared to last by a long way. These products are found in motion sensors such as those in optical computer mice and pulse oximeters (Dietz, Yeraunis & Leigh, 2003`) and LED screens. LED screens are growing more popularly particularly during events as they provide more capabilities and affordability (Begley, Jr, 2017). Television screens have improved watching experiences because of the higher ratio and better color scale. Meanwhile, OLED has also found its way in television screens. Significant features of OLED in TVs is that it does not consume additional backlight, it is low weight and size and it has a richer color scheme and contrast ratio (Tenningas (e), 2013).

Other product innovations for LED include insulating LED blankets for newborns as well as face-wearable gadgets with LED technology. The production of T8 LED tube lights has also provided for a very reliable, energy-efficient and affordable substitute for fluorescent bulbs. Consumers have reaped the benefits of lowering their electric bills with this technology.

Considering the increased efficacy at lower temperatures, LED lights are well in use for freezers specifically at supermarkets. These are able to contribute to lower refrigeration expenses. Since they are also predisposed to frost and snow buildup compared to incandescent bulbs, an extra heating circuit was introduced. Moreover, the development of heat sink technologies allowed the transfer of heat to the correct areas of the light bulb (Schubert, 2006).

Certain innovations in LED technology have come about specifically concerning about sustainability issues and providing for consumers' savings method. Lighting pollution in cities have been reduced because of LED street lamps. The reduction of CO2 emissions has also been provided for by this technology where Audi, for instance, has integrated in its car design full-LED headlights. More than one gram of CO2 emissions were proven to have been reduced per kilometer unlike those produced by halogen lights (Tenningas (c), 2013). For consumers, LED prices have been reduced by as much as 30 percent since 2011 (Tenningas, (b), 2013).

LED technology has contributed to health benefits as well as increased well- being and mood (Daniel, 2013). This contribution was supported in the field of human centric lighting (HCL) and mood lighting. Research indicated causal relationships between human well-being and LED lighting, more so that green lighting technology has been developed. This was brought about as a response to sustainability issues and the need for more efficient energy sources. Also, LED lighting has provided for a non-invasive and effective treatment for people in the northern hemisphere as natural daylight is inadequate. However, people who also stay indoors mostly also benefit from the LED illumination. They benefit from LED lighting as the scarcity of natural lighting brings about mood disorders, anxieties and work inefficiencies. The consideration of human-centric lighting in LED production has allowed the stimulation of the cognitive performance and improved emotional well-being. In similar use, mood and ambient lighting were developed with the use of LED. These lights can be seen at airplanes where the light intensity is dimmed or increased to adapt to the sleeping patterns of passengers during transcontinental flights (Daniel, 2012).

LED lighting has expanded its application in urban settings. Aside from lighting public spaces and public transportation, LED lighting is also now being used for urban farming. LED lights are being used as light sources for indoor cultivation of plants and vegetables. These grow lights are designed for increasing photosynthesis in plants (Goins, Yorio, Sanwo & Brown, 1997). Moreover, bacteria and viruses can be eliminated from water and other substances as UV LEDs are used for sterilization (Mori, Hamamoto, Takahashi, Nakano et al, 2007).

OLED Technology, organic light emitting diodes, is regarded an emerging trend. Figure 6 on the right shows a picture of an OLED bulb. This technology offers less energy consumption, brighter displays and capability to produce increased brightness. OLED is made up of thin films, the electroluminescent material, of organic molecules. These films are capable of producing light when electricity is employed. This organic material is considered to be electrically conductive and functions as a semiconductor (Burroughes, Bradley, Brown, Marks et al, 1990).

OLEDs are thin and relatively low cost. They have a low driving voltage, wide viewing angel and high contrast and color spectrum (Bardsley, 2004). They are found to be useful for visual displays in electronic devices like cellphones and digital cameras.

OLED technology may have appeared to threaten the future of LED technology but this was regarded unlikely. LED technology is still more affordable than OLED Technology since prices of LEDs are continuously decreasing. OLED is more expensive because of its encapsulation layer and integrated substrates (Tenningas, 2013). LED is also more energy-efficient. It has an extended life and it is also eco-friendly. Meanwhile, OLED's efficiency is less at 20- 501m per watt and life expectancy is shorter at 5,000 to 15,000 hours only (Tenningas, 2013. Functionally, LED technology does not seem to be disadvantaged by OLED technology; however, the latter's design may prove to be unfavorable for LEDs.

Another development in LEDs is the

Quantum Dot LEDs (QD LEDs). These are semiconductor nanocrystals comprising of optical properties that allow their emission color to be adjusted from the visible hue to the infrared spectrum (Massachusetts Institute of Technology, 2002; Neidhardt, Wilhelm, & Zagrebnov, 2015). They make possible the creation of almost any color on the CIE (Commission Internationale de l'Eclairage) diagram. There are now more color options and better color rendering compared to white LEDs. More importantly, the adjustability of emission wavelength and narrow bandwidth is valuable for fluorescence imaging. QD LEDs can now produce 300 lumens of visible light per watt of radiation and warm- light emission through the use of nanocrystals (Inman, 2008)l; thus producing better luminous efficacy.
LED lights have also been used on a large scale. Rural and urban areas have

adapted LED illumination because of its economic, environmental and financial benefits. With global warming issues, these lights have been considered as an environmentally-friendly approach in lighting cities. Figure 7, on the left, shows an example of LED use in major walkways in public spaces. LED lights are also in traffic lights.

VIII. CONCLUSION

From its introduction in lighting, LED technologies have come a long way into its developments and applications. Although basically intended for lighting, LED has been integrated in many commercial, industrial and public uses. Technological breakthroughs have introduced and integrated LED lighting even in urban farming, navigational systems and interactive workwear. With its features of efficiency and longevity, LED technology has proven to contribute to economic, environmental concerns as well as the improvement of systems, life and health of populations. As it now contributes to sustainability, LED appears to promise wide scale use in various commercial and public sectors. Also with the continuing development efforts, LED lights are expected to be applied in many novel ways from how it has begun as a simple illuminating device.

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[55]. Wavelength [nm]

[56]. $\lambda > 760$ $610 < \lambda < 760$

[57]. Voltage drop [ΔV]

[58]. $\Delta V < 1.63$ $< \Delta V < 2.03$

[59]. Semiconductor material

[60]. Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)

[61]. Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP)

Hadeel Sami A. Rajab LED: Revolutionizing lighting.” International Journal of Engineering Research and Applications (IJERA), vol. 7, no. 11, 2017, pp. 86-95.