

Light-Emitting Diode Electrical and Optical Characteristics: Theory and Practice

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ABSTRACT

Light-emitting diodes (LEDs) are now essential parts of contemporary optoelectronic systems, especially because of their excellent energy efficiency, durability, and small size. The electrical properties of LEDs are examined in detail in this work, with particular attention paid to the devices' power efficiency, threshold voltage, modulation capabilities, and current-voltage (V-I) behavior. The effects of changing injection current, temperature, and circuit design on performance are demonstrated by experimental data and theoretical models. To demonstrate LEDs's superiority over conventional light sources like incandescent and fluorescent lights, the report also cites important comparative metrics, including luminous efficiency and onset time. A brief discussion of applications in optical communication and signal systems emphasizes how crucial it is to optimize electrical characteristics for dependable, fast operation. The findings assist in designing LED-based electronics, where precise electrical behavior controls system integration and optical output quality.

Keywords— Light Emitting Diode (LED), V-I Characteristics, Forward Voltage, Efficiency, Electrical Behaviour, Modulation, Semiconductor

1. INTRODUCTION

In the field of optoelectronics, a light-emitting diode (LED) is a small component that generates light through the process of electroluminescence. Electroluminescence is a phenomenon that takes place when electrical energy is turned directly into photons. Electrons from the n-type region move to the p-type side when they are subjected to forward bias. Once there, they recombine with holes. This interaction releases light energy, which typically occurs within the active layer of the diode. [1] [2].

The semiconductor materials commonly used in light-emitting diodes (LEDs) possess direct bandgaps. Examples of such materials are gallium arsenide (GaAs) and gallium nitride (GaN), which enable efficient photon production. The bandgap of the material defines the color of the LED and corresponds to the energy of the emitted light, so the wavelength is the same. Direct and indirect band gap materials are the two types of semiconductors that can be classified according to the manner in which electrons flow between energy bands. In a material with a direct band gap, the minimum temperature of the conduction band coincides with the maximum temperature of the valence band in momentum space. This property allows for efficient photon emission through radiative recombination, which eliminates the requirement for additional energy carriers such as phonons. Because these extrema occur at distinct momentum levels in indirect band gap semiconductors, a phonon is required to mediate the transition through the semiconductor. Direct band gap semiconductors are useful for applications such as lasers and LEDs because they exhibit radiative recombination that is more efficient than other semiconductors.

In terms of electricity, the LED does not conduct significantly until the threshold voltage is achieved, which is normally between 1.8 and 3.3 volts. Once this voltage is reached, the current begins to increase exponentially. The V-I characteristics are similar to those of a normal diode, but they are accompanied by light emission [1] [3]. Up to the point that it reaches saturation, the light intensity will increase correspondingly as the forward current continues to increase. However, there is a correlation between excessive current and thermal effects, which can lead to a decrease in efficiency and possible degradation if heat management is not effectively managed [2]. The lightning-fast switching speed of LEDs is one of the most significant benefits that LEDs have over conventional light sources. Because their rise times are typically in the range of 10–20 nanoseconds, they are very well-suited for high-frequency modulation, which includes applications such as pulse-width modulation (PWM) and optical communication systems [1] [3].

2. Electrical Characteristics of LEDs

It is essential to have a solid comprehension of the electrical properties of light-emitting diodes (LEDs) in order to comprehend how they function and to ensure that they are utilized appropriately in circuits. Among the most

important electrical qualities are When an LED is forward biased (conducting current), the voltage drop across the LED is referred to as the forward voltage (V_f). The voltage of an LED can vary from approximately 1.8 V to 3.3 V, depending on the color and substance of the LED. For instance, the forward voltage of red LEDs is typically from 1.8 to 2.2 volts, whereas the forward voltage of blue and white LEDs can range anywhere from 3.0 to 3.3 volts.

In the event that the LED is forward biased, the current that flows through it is referred to as the forward current (I_f). For the most part, standard indicator LEDs operate at 10–20 milliamperes. Doing more than the maximum forward current can cause the LED to become damaged. The highest voltage that an LED is able to withstand in a reverse-biased condition before it fails to function properly is referred to as the reverse voltage (V_r). As a result of this being relatively low, often somewhere around 5 V, LEDs are not intended to be utilized in reverse bias. Pd, which stands for power dissipation, refers to the amount of power that an LED is able to safely dissipate. We derive this value by multiplying V_f with I_f . In excess of this, it is possible to cause damage and overheating. Junction Capacitance: The LED's p-n junction capacitance influences the switching speed and performance at high frequencies.

Temperature Coefficients: The forward voltage drops as the temperature rises, typically by approximately -2 millivolts per degree Celsius. These parameters are typically included in the datasheet of the LED to guide the construction of the circuit in an appropriate manner and to ensure that it operates reliably.

One way to explain the relationship between the voltage that is applied and the current that is produced by LEDs is through their V-I characteristics, which stand for voltage-current characteristics. With a non-linear increase in current as voltage increases, the LED exhibits behavior that is comparable to that of a typical diode when it is operating under the forward bias condition. The light-emitting diode (LED) is distinguished by the fact that it creates light whenever electricity is sent through it.

In the case of a light-emitting diode (LED), the threshold voltage is the minimal voltage that must be present to overcome the inherent potential of the p-n junction, hence triggering the flow of current and the emission of light. The voltage can normally range anywhere from 1.8 to 3.3 V, depending on the substance and the wavelength of the emitted light. As an illustration, light-emitting diodes (LEDs) that are based on gallium arsenide (GaAs) often have a lower threshold voltage in comparison to LEDs that are based on gallium nitride (GaN), which are utilized for blue and white light.

Following the behavior described in the Shockley diode model, the LED current increases dramatically as the voltage increases beyond the threshold once it has passed through. This connection provides a mathematical expression of the exponential increase in forward current that occurs as a result of the voltage and temperature conditions observed at the junction. If we consider the equation

$$I = I_0 \{ \exp (qV/nKT - 1) \} - - - (1)$$

We can see that I_0 represents the reverse saturation current, q represents the electron charge, V represents the applied voltage, n represents the ideality factor, K represents Boltzmann's constant, and T represents the temperature in Kelvin.

The light output of the LED grows proportionally with the amount of current that is flowing through it. Having said that, its expansion is not without limits. Reverse bias causes the LED's current to remain extremely low until it achieves the reverse breakdown voltage. This condition occurs when the LED reaches a certain point beyond which it begins to undergo efficiency droop, which is characterized by the emission of light that is less efficient and the possibility of overheating. The use of reverse bias is often avoided in practical applications due to the fact that LEDs are only meant to function in the forward direction.

3. Thermal Management and Efficiency Droop in LEDs

Thermal management and efficiency droop are critical factors affecting the performance and reliability of Light Emitting Diodes (LEDs). Here's an overview of both aspects:

A. Thermal Management in LEDs

- i. **Importance:** LEDs convert electrical energy into light, but some energy is inevitably lost as heat. Excessive heat can degrade LED materials, reduce light output, shift color characteristics, and shorten device lifespan.
- ii. **Heat Generation Sources:** Resistive losses in the LED chip, non-radiative recombination, and losses in packaging and driving circuitry.
- iii. **Thermal Path:** Heat generated in the LED junction must be efficiently transferred away through the LED package, substrate, and heat sink to the ambient environment.

iv. Thermal Management Techniques:

It is common practice to make use of substrates with high thermal conductivity, such as silicon carbide and sapphire. An increase in heat dissipation is achieved by the utilization of cutting-edge packaging materials and designs. The LED drive currents have been tuned to achieve a balance between the amount of light output and the amount of thermal generation. This goal has been accomplished by the incorporation of heat sinks or active cooling devices.

v. Impact of Effective Thermal Management: Maintains LED junction temperature within safe limits, ensuring stable performance, color consistency, and device longevity.

B. Efficiency Droop in LEDs

i. Definition: Efficiency droop refers to the reduction in the internal quantum efficiency (IQE) of LEDs at high current densities.

ii. Phenomenon: As the injection current increases, the light output does not scale linearly and eventually decreases in efficiency.

iii. Causes:

a. Auger Recombination: As current density rises, non-radiative three-carrier interactions become more probable. These processes, involving two carriers and a third energy-absorbing particle, dissipate energy as heat instead of light, lowering luminous efficiency.

b. Carrier Overflow: At high currents, carriers may recombine outside the active region, leading to a reduction in the number of carriers available for radiative recombination, thus reducing light output.

c. Poor Carrier Injection or Distribution: Non-uniform carrier distribution can increase non-radiative recombination.

d. Consequences: Limits the brightness and power efficiency of LEDs, particularly in high-power applications.

e. Mitigation Strategies: To improve carrier confinement, engineering quantum well architectures is possible. Reducing the defect densities responsible for non-radiative recombination is important. Optimizing the device's geometry and the materials used can reduce auger recombination. To achieve a balance between production and efficiency, operating at optimal current densities is essential.

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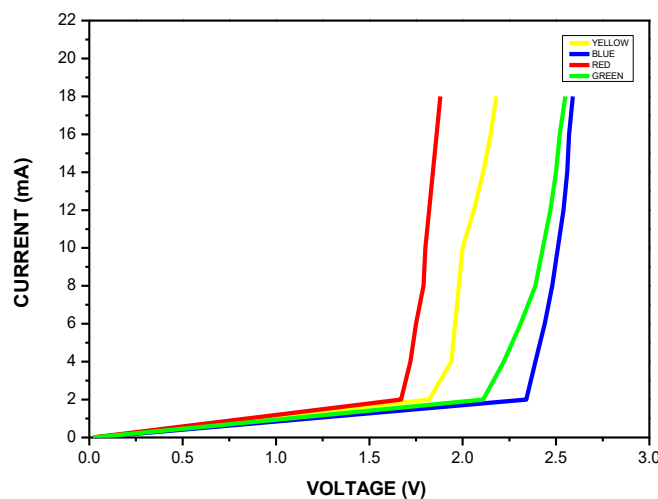
Effective thermal management is essential to dissipate heat generated in LEDs, thus preserving performance and lifetime. Efficiency droop limits LED efficiency at high currents due to non-radiative processes such as Auger recombination. The junction temperature of the LED is an important factor that affects its efficiency. With an increase in junction temperature, there is a corresponding decrease in the bandgap energy of the semiconductor material. This decrease leads to a shift in the emission wavelength and a decline in efficiency. Therefore, it is essential to keep the junction temperature low to reduce efficiency droop. Addressing both thermal issues and efficiency droop is key to advancing LED technology for brighter, more reliable and energy-efficient lighting solutions.

4. Experimental Data: V-I Characteristics of LEDs

In the following table, the V-I characteristics of red, yellow, blue, and green LEDs are presented. These characteristics were derived from a variety of studies that were published. It is crucial to have a comprehensive grasp of the performance of LEDs in a variety of applications, and the data presented here indicates typical forward voltage levels at several different currents.

Current (mA)	Yellow Voltage (V)	Red Voltage (V)	Green Voltage (V)	Blue Voltage (V)
0	2.05	1.9	2.2	3.1
2	2.06	1.91	2.22	3.12
4	2.08	1.93	2.24	3.14
6	2.09	1.94	2.26	3.16
8	2.11	1.96	2.28	3.18
10	2.12	1.97	2.3	3.2
12	2.14	1.99	2.32	3.22
14	2.16	2	2.34	3.24
16	2.18	2.02	2.36	3.26
18	2.2	2.03	2.38	3.28

The typical voltage-current relationship of LEDs is as follows



5. Applications of LEDs

The energy efficiency, extended lifespan, and tiny size of LEDs have caused them to revolutionize a variety of diverse industries. Lighting, displays, and communication systems are just some of the many applications that now incorporate them as essential components. LEDs are utilized in a variety of most important fields, including the following:

i. General Lighting

As a result of their greater energy economy and extended operating life, LEDs have become increasingly integrated into the illumination of everyday environments. Light-emitting diode (LED) sources are superior to incandescent or fluorescent sources in terms of their ability to convert electricity into light. As a result, LEDs have lower power consumption and require less maintenance.

Due to their improved luminous effectiveness and the capacity to deliver high-quality light while consuming less energy, LED bulbs are now widely utilized in residential, commercial, and industrial lighting. This is because LED bulbs are the most energy-efficient light bulbs available.

In addition to conventional lighting, LED-based streetlights and outdoor lighting have become the norm in many places. These products offer brilliant and uniform illumination while simultaneously lowering the amount of money spent on electricity and the frequency with which maintenance is required. Shows and graphical displays. The use of light-emitting diodes (LEDs) has become an essential component of contemporary display technology. Televisions, cellphones, computer monitors, and billboards for advertisements all use LED displays. LEDs are able to achieve outstanding resolution, color accuracy, and brightness, which make them an excellent choice for displays that are used both indoors and outdoors. There is a specific subgroup of LEDs known as organic light-emitting diodes (OLEDs), which are utilized in flexible displays due to their capability of emitting light directly without the need for a backlight. When compared to traditional fluorescent backlit displays, the use of LED backlighting in LCD panels has also helped in the creation of displays that are slimmer, more energy-efficient, and offer improved contrast ratios and control over the brightness of the display.

ii. Optical Communication

In the realm of optical communication systems, LEDs are of utmost importance, particularly in the context of fiber optic networks. Light-emitting diodes (LEDs) are utilized as light sources in communication systems because of their high modulation speed. These systems send signals through the usage of fiber optics. Infrared light-emitting diodes (LEDs) are frequently utilized in short-range communication systems, such as local area networks (LANs) and cloud computing facilities. The use of light-emitting diodes (LEDs) in optical communication allows for the transfer of data at fast speeds while consuming a low amount of power, making them an indispensable component of the current telecommunications infrastructure.

iii. Automotive Applications

As a result of their capacity to generate light that is both high-intensity and energy-efficient, LEDs have found widespread application in the lighting of automobiles. LED-based systems have led to the changeover of headlights, taillights, indicators, and interior illumination in vehicles. This has resulted in an improvement in the aesthetic appeal of vehicles as well as an increase in their safety. Adaptive headlights and dynamic turn signals,

both of which make use of LEDs, are ubiquitous in contemporary automobiles. These features offer enhanced visibility and more functional capabilities.

Moreover, LEDs are perfect for use in electric vehicles (EVs), where decreasing power consumption is a priority, due to their energy efficiency and long lifespan when compared to other light sources. The Applications of Medicine

Light-emitting diodes (LEDs) are finding more and more uses in the medical field, particularly in the fields of medical illumination, phototherapy, and diagnostic equipment. LEDs make it possible to achieve brilliant, high-quality illumination in endoscopy, surgical lights, and examination lamps while simultaneously reducing the amount of heat that is produced.

LEDs are also utilized in the field of biophotonics for the purpose of administering wound-healing therapies and skin therapy. In these applications, particular wavelengths of light are utilized to stimulate the regeneration of tissue. In addition, near-infrared light-emitting diodes (LEDs) are utilized in diagnostic imaging systems, which offer non-invasive approaches for the diagnosis of medical conditions.

6. Conclusion

✓ In general, red LEDs have a lower forward voltage, ranging from 1.90 V to 2.03 V for the same current range. This implies that red LEDs require less voltage due to their lower bandgap. Yellow LEDs, on the other hand, often exhibit a forward voltage that falls somewhere in the range of 2.05 V to 2.20 V when the current is between 0 and 18 mA.

✓ In general, the forward voltage of green LEDs is slightly greater than that of yellow LEDs, often ranging from 2.20 V to 2.38 V. Blue LEDs, on the other hand, have the greatest forward voltage, typically ranging from 3.10 V to 3.28 V. The large bandgap of materials used for blue LEDs, such as gallium nitride (GaN), is the reason for the increased voltage need. This discovery is in line with the findings that were published in Schubert.

✓ The electroluminescent qualities of LEDs are often reflected by these voltage values, which can change depending on various parameters, including temperature, the composition of the material, and the design of the LED.

The behavior of light-emitting diodes (LEDs) is dictated by the physics of semiconductors, which are well-defined. For the purpose of optimizing performance in real systems, it is vital to have a comprehensive understanding of their electrical behavior. This is especially true in situations where speed, efficiency, and control are of particular importance.

7. References

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