Volume 3, Issue 4, 2020 ISSN: 2664-0821
DOI: https://doi.org/10.31058/j.ap.2020.34004

Analysis of Band Diagram Design and Electronics Properties of II-VI Compound-Based Light Emitting Devices for Telecommunication Applications

Khaing Zin Nway[1*], Hla Myo Tun[2]

[1] Department of Electronic Engineering, Technological University (Myeik), Myeik, Myanmar
[2] Department of Electronic Engineering, Yangon Technological University, Yangon, Myanmar

Email Address

ecdepartment.ytu@gmail.com (Hla Myo Tun)
*Correspondence: ecdepartment.ytu@gmail.com

Received: 1 August 2020**; Accepted:** 25 September 2020**; Published:** 5 October 2020

Abstract:

The paper emphasizes on the ultimate concepts of semiconductor electronics for basic research purposes. There are two main analyses on II-VI compound-based light emitting devices for high speed telecommunication applications such as band diagram design and electronic properties in this research work. The numerical analysis and calculation for the development of efficient optoelectronic devices are vital role in computational electronics. The results confirm that the developed light emitting devices have high performance properties for fabrication process. The analyses are carried out based on the MATLAB language in this studies.

Keywords:

Band Diagram Design, Electronic Properties, II-VI compound, Light Emitting Devices, Telecommunication

1. Introduction

Light Emitting Devices (LEDs) lights are revolutionizing the lighting industry, they are often much more effective and durable than traditional incandescent lighting techniques. The typical consumer LED bulbs in use between 10% and 20% of the incandescent light bulb in the country with comparable brightness and more than 25,000 hours life of energy needed compared with only 1000 hours of incandescent bulbs [1]. LEDs are much more efficient than incandescent bulbs, because they work in a very different way. LED that produces light when electrons in the conduction in the entire transition band are a gap through the radiative recombination of holes in the valence band. Incandescent bulbs depend on resistant to heat a filament that emits light when it is hot enough to glow. It uses lots of energy for heating the filament and the lower part of the production of the energy goes to the production of light. The associated high temperature leads to a shorter life expectancy, such as burnt out filament also almost every cause of failure of the incandescent bulb.

The interest in II - VI group semiconductors has spread over the past two decades as the essential properties of materials offer advantages for optoelectronic components and high power devices in various applications. Zinc Sulphide (ZnS) and its associated alloys, has emerged as the semiconductor of promising sulfide for commercial applications [2]. Group II - VI materials do not have the technological development of other semiconductors like Silicon (the backbone of the semiconductor industry) because it still has many technological challenges. The complex properties of the material of the hardware system zinc sulfide must be well understood to fully reach the benefits offered by this semiconductor in devices. The theoretical based simulation of semiconductor devices passes in this cause by showing a quantitative relationship between the properties of the underlying material properties and device behavior. Device optimization in an experimental state is very costly and time consuming and should therefore also be complemented by simulations.

LEDs are more efficient than previous lighting technology, although still more design to develop some science and engineering to overcome the problem. In particular, greater driving currents reduce the efficiency of the LEDs. This event LED drop and at the same time as maintaining high efficiency achieved with increasing current density restriction according to increase total light emitted sub-linearly causes. As a result, to increase the total brightness increase or a light bulb typically device region instead of just adding additional LEDs a more updated application is required. This goes to the bulb and adds costs to the LED lights [3].

The paper is organized as follows. Section II presents the method and implementation of the research works. Section III mentions the results and discussions of the experimental studies. Finally, the conclusion is given for the whole works.

2. Methods and Implementation

The methods and implementation for the analyses are discussed in this section.

2.1. Theory

Like all other semiconductor devices, LEDs are sensitive to temperature. Increase in temperature, reduce the band gap of the semiconductor, thereby effecting most of the semiconductor materials parameters. The decrease in the band gap of a semiconductor with increasing temperature can be noticed as increasing the energy of the electrons in the material. The temperature dependence of the energy gap of a semiconductor can be expressed by the Varshni formula

$$E_g = E_g(0K) - \frac{\propto T^2}{T+\beta} \tag{1}$$

where Eg (0K) is band-gap energy at 0K, α and β are fitting parameters, frequently called the Varshni parameters. The Varshi parameters ($\propto$ and β) and bandgap energy (0K) of selected semiconductors are summarized in Table.1. Moreover, the variation in band-gap energy is the main aspect to determine the diode the diode voltage as a function of temperature.

Table 1. *Varnish Parameters of Semiconductor Materials.*

Materials	$E_g(0K)$	$\alpha(10^{-4}eV/K)$	β (K)
ZnO	3.437	5.5	900

Volume 3, Issue 4, 2020 ISSN: 2664-0821
DOI: https://doi.org/10.31058/j.ap.2020.34004

The emission intensity of LEDs decreases as temperature increases. This decrease of the emission intensity is due to several temperature-dependent factors including:

a. non-radiative recombination via deep levels;

b. surface recombination;

c. carrier loss over heterostructure barriers.

At room temperature, the temperature dependence of the LED emission intensity is frequently described by the phenomenological equation:

$$I=I_{(300K)} \exp\left(-\frac{T-300K}{T_1}\right) \tag{2}$$

The temperature dependence of the LED can be described by the characteristic temperature which is shown in above equation. The characteristics temperature of UV LED is 497K.To get the weak temperature dependence, the high characteristic temperature is required. Interesting fact for both LEDs and semiconductor lasers is that they have a distinct temperature dependence of the emission intensity. Equation.2 is to show the decrease of the LEDs.

This equation is a very useful expression for the temperature coefficient of the forward voltage. Temperature dependence of forward diode voltage is defined by the following equation.

$$\frac{dV_f}{dT}=\frac{eV_f-E_g}{eT}+\frac{1}{e}\frac{dE_g}{dT}-\frac{3k}{e} \tag{3}$$

where, Vf is the forward voltage, Eg is the band gap energy, e is the unit charge, k is Boltzmann′ s constant and T is the junction temperature.

This equation provides the fundamental temperature dependence of the forward voltage. The first summand on the right-hand side of the equation is due to the temperature dependence of the intrinsic carrier concentration. The second term is due to bandgap energy, and third term is effective densities of states. LEDs are normally worked at forward voltages close to the built-in voltage, i.e. Vf ≈ Vbi.

When semiconductor devices are heated, there will be movement of carriers. The carriers add to the already moving carriers and align with them, i.e they possess more energy to move. This energy reduces the conduction band and valance band gaps. So, forward bias voltage reduces when the temperature increases [4,5,7,7,8,9,10].

2.2. Band Diagram Design of LED

By analyzing the band diagram design, the inspiration of turn-on voltage and depletion region can be found. An Energy band diagram design is considered by using the several basic energy level depended on some spatial dimension. In the band diagram, the vertical axis corresponds to the energy of an electron and horizontal axis represents position in space. All of the calculation values are considered at room temperature (300K).

VO is the total potential drop across the junction, whereas VOP is the portion of the voltage drop on the p-side and VON is the portion of the voltage drop on the N-side.

Volume 3, Issue 4, 2020 ISSN: 2664-0821
DOI: https://doi.org/10.31058/j.ap.2020.34004

The contact potential is evaluated using the bulks values of the Fermi levels Fp and FN measured from the valence of conduction band edges EVP and ECN, respectively.

$$V_0=\frac{F_N-F_P}{q} \tag{4}$$

$$V_0=\frac{E_{gp}+\Delta E_C-(F_P-E_{vp})-(E_{CN}-F_N)}{q} \tag{5}$$

For non-degenerated semiconductor,

$$E_{CN}-F_N\cong -k_B T\ln\left(\frac{N}{N_{CN}}\right) \tag{6}$$

Since the electron concentration on the p-side, p=N_a, the contact potential V_O can be evaluated from the above equations when the doping concentrations N_a and N_D are known.

Total width of the depletion region x_w,

$$x_w=x_p+x_N \tag{7}$$

$$x_p=\frac{N_D}{N_a+N_D}x_w \tag{8}$$

$$x_N=\frac{N_a}{N_a+N_D}x_w \tag{9}$$

So, x_w to VO directly,

$$x_w=\left(\frac{2\varepsilon_p V_0}{qN_a N_D\left(N_D+\frac{\varepsilon_p}{\varepsilon_N}N_a\right)}\right)^{1/2}(N_a+N_D) \tag{10}$$

2.3. Band Diagram Design of p-ZnO/N-ZnO Homojunction LED

The energy band diagram of ZnO homojunction is evaluated by using suitable physical parameters. In ZnO homojunction LED, both p-type and N-type materials are assumed to use ZnO material. Unlike the heterojunction structure, there are no band edge discontinuities in homojunction. To obtain the energy band diagram, Table 2 shows the parameters that are needed to use in mathematical equations:

Table 2. *Parameter for band diagram design of ZnO homojunction LED.*

Parameters	p-type ZnO	N-type ZnO
χ(eV)	4.5	4.5
E_g(eV)	3.37	3.37
m_e^*	$0.13m_0$	$0.13m_0$
m_h^*	$0.78m_0$	$0.78m_0$
ε(F/cm)	$12\times8.85\times10^{-14}$	$12\times8.85\times10^{-14}$

2.4. Voltage-Current Characteristics

The standard equation for current through a diode is:

$$I=I_s\times\left(\exp^{\left(\frac{Vq}{n\times k\times T}\right)}-1\right) \quad (11)$$

Where:

I = current through the diode

I_S = the reverse saturation current

V =voltage across the diode

n = junction constant (typically around 2 for diodes, 1 for transistors)

k = Boltzmann's constant, (1.38×10^{-23} J/K)

T =temperature (K)

q = magnitude of an electron charge, (1.609×10^{-19} C)

In Equation (11) it would appear that the current should decrease as the temperature increases. The reverse saturation current, IS, is a strong positive function of temperature as discussed below. The increase in IS with temperature more than offsets the effect of T in the exponential above. The junction constant, n, is typically a constant at low currents and varies as the current becomes significant and may also vary somewhat with temperature. For this discussion, n will be taken as constant. The sub-expression, kT/q, has units of voltage and is referred to as the thermal voltage (VT = k*T/q) and is typically around 26 millivolts at room temperature.

If negative voltages are applied to the diode, the current becomes constant at –IS as the exponential term in Equation quickly approaches zero. That is why it is referred to as the reverse saturation current. The current is independent of applied voltage once a small voltage magnitude is exceeded. This current is very small and is typically in the low nano-ampere region. The following equation is a simplified model for the reverse saturation current and provides excellent results in normal operating regions.

$$I_s= eA\left[\sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_D}+\sqrt{\frac{D_n}{\tau_n}}\frac{n_i^2}{N_A}\right] \quad (12)$$

Where:

A =Cross-sectional area of diode

e = Magnitude of an electron charge, (1.609×10^{-19} C)

I_s = Reverse saturation current

Eg = Bandgap energy

n_i =Intrinsic carrier concentration

D_n =Electron diffusion constant

D_p =Hole diffusion constant

τ_n=Electron carrier lifetime

τ_p=Hole carrier lifetime

Volume 3, Issue 4, 2020 ISSN: 2664-0821
DOI: https://doi.org/10.31058/j.ap.2020.34004

N_D=Donor concentration

N_A=Acceptor concentration

The reverse saturation current should not be confused with an imperfection in diodes known as leakage current from a high value shunt resistance across the diode junction. Leakage current is often many times larger than IS. Thus, IS must be computed using data from the forward bias region.

The required parameters for LEDs based on ZnO materials are described in Table 3.

Table 3. *Required parameters for I-V characteristics.*

Required parameters of I_V curve	Required parameters of I_V curve		
	Symbols	p-ZnS	N-ZnO
Electron mobility	$\mu_n (cm^2 V^{-1} s^{-1})$	280	200
Hole mobility	$\mu_p (cm^2 V^{-1} s^{-1})$	800	50

2.5. Light-Current Characteristics

As a light-emitting diode that is pumped by current injection, a very important property of an LED is its output optical power as function of the injection current. The plot of optical output (L) as a function of current (I) characterizes an electrical to optical converter. The modulation capability of a LED is described with optical power and electrical current (L-I). There following ideal power-current relation for an LED is

$$P_{out}=\eta_e \frac{h\nu}{e} I \tag{13}$$

$$\nu=\frac{c}{\lambda} \tag{14}$$

P_{out} is output power of an LED, η_e is external quantum efficiency, h is Planck's constant $(4.1356 \times 10^{-15} eVs)$, c is speed of light $(3 \times 10^{8} ms^{-1})$, λ is wavelength, e is electric charge $(1.6 \times 10^{-19} C)$ and I is injection current. These characteristics have several important features that distinguish an LED from laser. There is no threshold current in L-I characteristics of an LED so the LED's optical output power can be linearly modulated with the small input voltage signal that is biased above turn-on voltage. The L-I curve of an LED is certainly quite linear, particularly at moderate current levels as indicate by equation (13). This linearity is useful for analog modulation of an LED. The efficiency starts at low injection levels, increases sharply with an increasing injection current, but saturates or even decreases at high injection levels.

3. Results and Discussions

The results and discussions on the implementation for the II-VI compound-based LEDs are described in the following section.

3.1. Temperature Dependence Band-Gap Energy

The selected semiconductor materials such as ZnO (Zinc Oxide) is calculated for the temperature dependence band-gap energy. The results of the temperature dependence band-gap energy of ZnO is shown in Figure 1.

As a result, the energy gap of semiconductors tends to decreased as the temperature is increased. An increase in temperature, changes the chemical bonding because electrons are encouraged from valence band to conduction band. The lattice phonons have relatively small energies and are excited in large numbers at reasonable temperatures. They influence the bonding through various orders of electron-phonon interaction. The major contribution to the temperature dependence of the energy gap of semiconductors comes from a shift in the relative position of the valence and conduction bands because of a temperature dependent electron-lattice interaction. It has been shown through theoretical calculations, that the effect linearly with the temperature at high temperatures. This mechanism makes a fraction (1/4) of the total variation in this region the energy gap temperature. In the field of low temperature, this mechanism leads to a temperature dependence of non-linear, the energy gap because of the thermal expansion coefficient varied together with temperature.

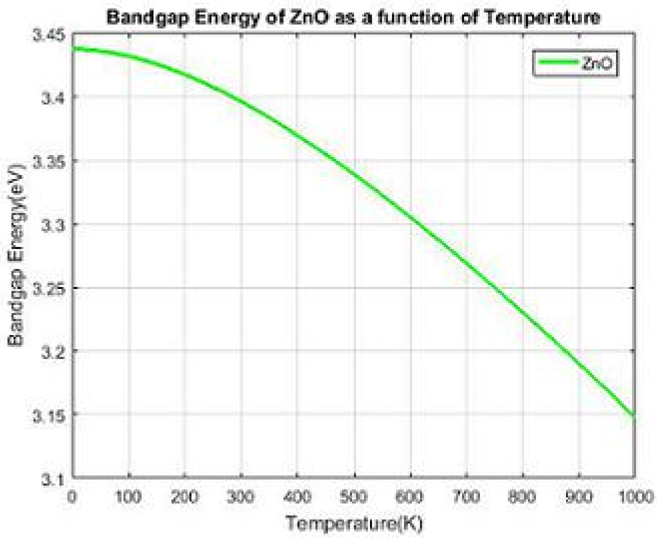

Figure 1. *Temperature dependence band-gap energy of ZnO material.*

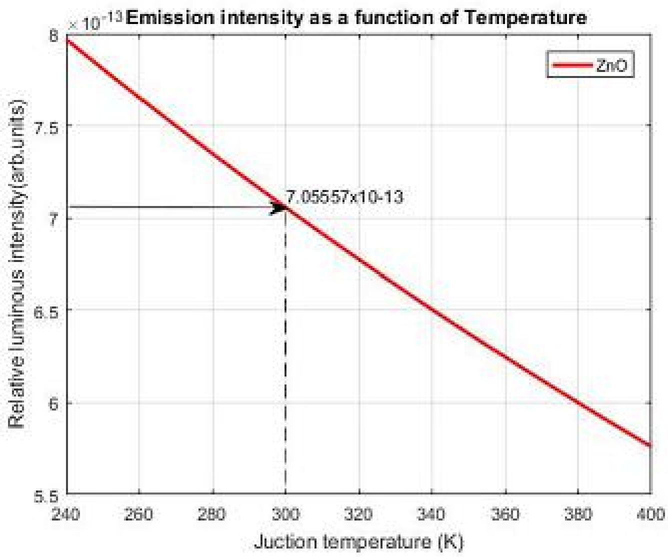

Figure 2. *Emission intensity of ZnO as a function of junction temperature.*

3.2. Junction Temperature and Emission Intensity of LED

The intensity of the light emitted by an LED depends on the junction temperature of the LED. The investigation of the figure shows that emission intensity is directly proportional to the temperature value. When increasing the temperature, the constant current is decreasing in this analysis. (Figure 2)

3.3. Junction Temperature and Diode Forward Voltage

With a constant current, the forward voltage drop of a diode has a very linear negative slope with temperature. (Figure 3)

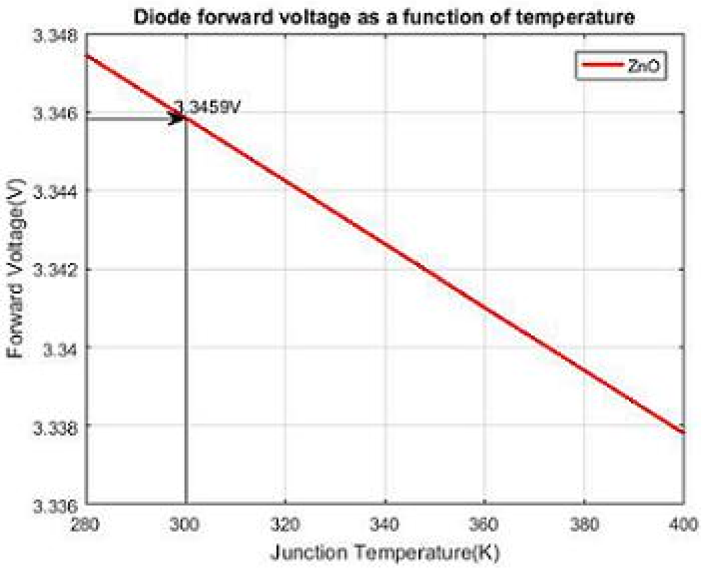

Figure 3. *Diode forward voltage of ZnO as a function of junction temperature.*

The investigation of results show that the temperature decreases, diode forward voltage increases. Basically, as the temperature increase, the intrinsic carrier concentration increase. This pushes the Fermi level closer to the intrinsic Fermi level (middle of the band gap).Since the built-in voltage of the diode is determined by the difference in fermi-levels in the p-type and n-type regions, the Fermi level in each region mover closer to the middle of the gap, and the built-in potential is decreased. So, the band-gap energy is one of the essential points in the temperature dependence of diode forward voltage. As the temperature increases, the diode voltage of ZnO decrease.

3.4. Band Diagram Design of p-ZnO/N-ZnO Homojunction LED

In the band diagram design of p-ZnO/N-ZnO homojunction, $\mathrm{N_a} = 4 \times 10^{17}\mathrm{cm}^{-3}$ and $\mathrm{N_D} = 2 \times 10^{19}\mathrm{cm}^{-3}$ are used as doping concentration for p-region and N-region as shown in Figure 4.

Under thermal equilibrium conditions (i.e.no biasing voltage), when the two materials are joining, the Fermi level will be a constant line across the junction. These materials have equal band gap but typically have different doping. Different doping level will happen band banding and depletion region will be formed. Although the process of homojunction structure is similar to that of heterojunction structure, there are no band edge discontinuities in homojunction. From the design of the band

Volume 3, Issue 4, 2020 ISSN: 2664-0821
DOI: https://doi.org/10.31058/j.ap.2020.34004

diagram, the consequence of the built-in voltage or forward voltage and the effect of depletion region can be found.

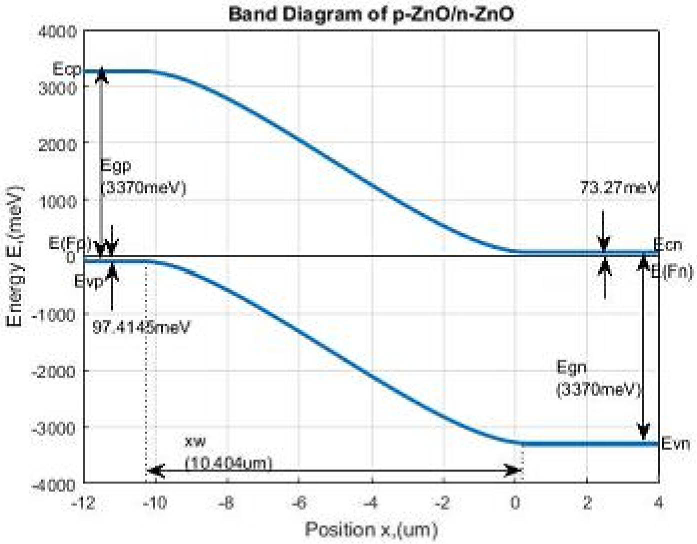

Figure 4. *Band diagram design of p-ZnO/N-ZnO homjunction.*

According to the result, built-in potential of this structure is 3.2V and the total width of the depletion region is 104.2μm. And then, the valance band is slightly far from Fermi level than the conduction band. Depletion in p-region is wider than in N-region. It can be observed that the energy barrier in the depletion region is reduced with the increase in the applied potential. Thus, the electrons and holes can easily move into p and n layers respectively under forward bias.

3.5. Results of Voltage-Current Characteristics

The V-I curves of p-ZnO/N-ZnO is shown in Figure 5. When the forward voltage exceeds the diodes P-N junctions' internal barrier voltage, which for ZnO homojunction LED is about 3.37V, avalanche occurs and the forward current increases rapidly for a very small increase in voltage producing a non-linear curve.

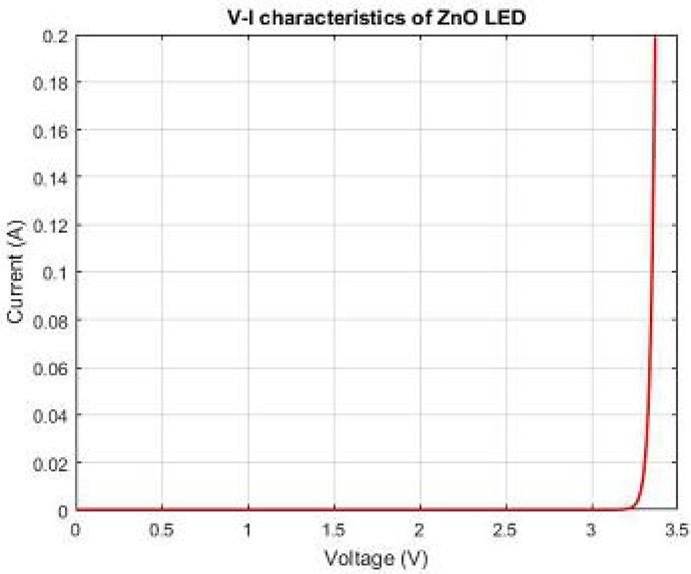

Figure 5. *V-I characteristic curve of p-ZnO/N-ZnO LED.*

It is clearly shows a good rectification behaviour with forward current rising on varying forward bias of ZnO homojunction LED from 0 to 3.37V. The built-in voltages of these device is1.85V, and then turn-on voltages is 3.29V at 20mA. So, these two devices of turn-on voltage and the built-in voltage are too far to complete the recombination process.

3.6. Results of Light-Current Characteristics

The light-current curve characterizes the emission properties of a semiconductors LED as it shows the current that needs to be applied to obtain a certain amount of power. According to the result, the output power of p-ZnO/N-ZnO LED has 0.873nW at maximum injection current (20mA). Figure 6 illustrates the Light-current characteristics p-ZnO/N-ZnO LED.

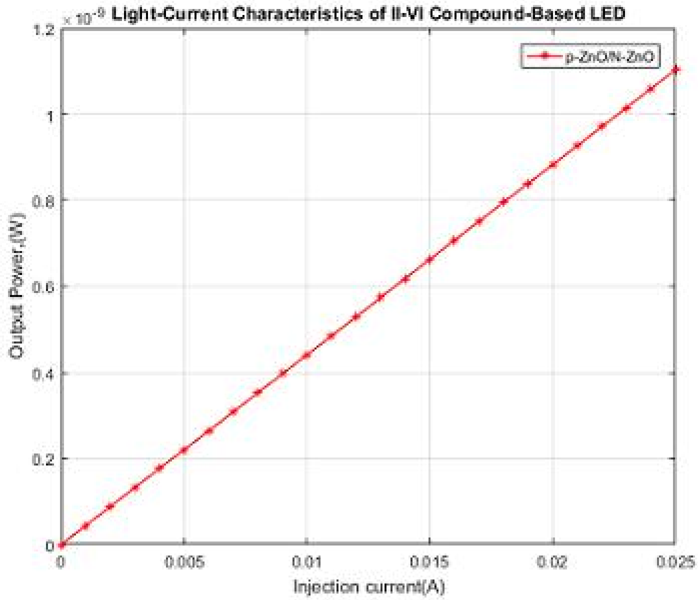

Figure 6. *Light-current characteristics p-ZnO/N-ZnO LED.*

4. Conclusion

The selected materials are calculated for thermal properties such as the temperature dependence band-gap energy, diode forward voltage and emission intensity. Among them, band gap energy as a function of temperature has the major contribution to the temperature dependence of the energy gap of semiconductors comes from a shift in the relative position of the valence and conduction bands because of a temperature dependent electron-lattice interaction. As a result, the results curvature of ZnO materials are not much far-away. So, these two materials can do work together at room temperature. Also, diode forward voltage due to temperature for the materials such as ZnO is discussed. As a result, the operating voltage of LED is related to the diode's built-in voltage. The forward voltage method provides the most accurate values of the junction temperature. When a LED gets hot, the voltage is reduced, and therefore the power output is also reduced. Then, emission intensity as a function of temperature for these two materials is calculated. In this analysis, increasing the temperature, the constant current is decreasing. With the rapid increase in the computational tools, numerical simulation techniques are becoming more efficient and accurate in the development of optoelectronic devices. Numerical simulations help shorten the development cycle of products and also tend to reduce huge costs that experience during analysis with complicated experimental setups.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgement

The author wish to would like to acknowledge colleagues from the Semiconductor Electronics Research Group of the Department of Electronic Engineering at the Yangon Technological University directly or indirectly involved in the successful completion of this journal.

Funding

This work is partially supported by Government Research Funds Grant No of GB/D(4)/2019/1.

References

[1] Syms, R.R.A.; Cozens, J.R. Optical Guided Waves and Devices, chap.12.

[2] Donald, A. N. Semiconductor Physics and Devices, part III, chap.14.

[3] Maria, C.T. II-VI Semiconductor Materials and Their Applications, chap.12.

[4] Shadia, J.I. Advances in the II-VI Compounds Suitable for Solar Cell Applications, 2014, ISBN: 978-81-308-0533-7.

[5] Zhores, I.A. The Double Heterostructure: The Concept and its Applications in Physics, Electronics, and Technology (Nobel Lecture). *CHEMPHYSCHEM,* 2001, 2, 500-513

[6] Shen, B.; Shi, H.T.; Zhang, R.; Chen, Z.Z.; Zheng, Y.D. Electrical and Optical Properties of InGaN/AlGaN Double Heterostructure Blue Light-emitting Diodes. *Chinese Physical Society and IOP Publishing Ltd,* 2001, 18(2), 283.

[7] Liu, J.M. Photonic devices part2, Cambridge University Press, 2009, chap. 12.

[8] Ma´rtil, I.; Redondo, E.; Ojeda, A. Influence of defects on the electrical and optical characteristics of blue light-emitting diodes based on III–V nitrides. *Journal of Appl. Phys.* 1997, 81(5), 2442-2444.

[9] Fischer, F.; Laubender, J.; Lugauer, H.J.; Litz, T.; Weinggrtner, A.; Zehnder, U.; Gerhard, T.; Ossau, W.; Schi.ill, K.; Waag, A.; Landwehr, G. Electrical properties of light-emitting devices based on the II-VI compounds BeTe and BeMgZnSe. *Materials Science and Engineering,* 1997, B43, 92-96.

[10] Priyanka, K.; Subhash, C.; Jozef, O. Current–voltage characteristics of Schottky diode simulated using semiconductor device equations. *International Journal of Electronics,* 2003, 100(5), 686-698.