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Analysis on Heterostructure Band Diagram Designs and Electrical Characteristics of Light Emitting Diode (LED)

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Abstract

This paper presents the analysis on hetero-structure band diagram designs and electrical characteristics of light emitting diode (LED). This work is based on physical parameters of ZnCdSe, a ternary alloy semiconductor composed of Zinc (Zn), Cadmium (Cd), and Selenium (Se). In this work, the band diagram design results for n-ZnCdSe/p-Si heterojunction leds are approved by the parameters of the material such as such as effective masses of the materials, doing concentrations, electron and hole hall mobilities, bandgap bowing and so on. The electrical characteristics (energy dispersion with wave vector, intrinsic carrier concentration with temperature, intensity with wavelengths) of LED based on ZnCdSe material are also analyzed in this paper. This simulation curves are done by computer simulation. The band layer design for n-ZnCdSe/p-Si LED confirmed the high quality LED for real applications. This research gives information for the researchers who study in electronic and optoelectronic semiconductor devices.

A. Introduction

Zinc Cadmium Selenide Light-Emitting Diode, ZnCdSe LED is a type of semiconductor device that emits light when an electric current is passed through it. This LED is based on a compound semiconductor material composed of zinc (Zn), cadmium (Cd), and selenium (Se). ZnCdSe LEDs are known for their tunable bandgap, which allows them to emit light across a wide range of wavelengths, making them suitable for various applications in optoelectrnics.

The unique properties of ZnCdSe LEDs make them valuable in areas such as solid-state lighting, displays, optical communications, and sensing. By adjusting the composition of zinc, cadmium, and selenium in the material, the emission wavelength of ZnCdSe LEDs can be tailored to meet specific requirements. Additionally, these LEDs exhibit high efficiency, fast response times and low power comsumption, making them a promising technology for next-generation lighting and display applications.

Overall, ZnCdSe LEDs represent a versatile and efficient light-emitting technology with significant potential for advancements in various fields of electronics and photonics

B. Background Theory

A light emitting diode (LED) is a two-lead semiconductor light source. It is a p-n junction diode, which converts electrical signal into optical signal. When the junction is forward biased, electrons and holes are injected in opposite directions across the junction's depletion region. As these injected holes and electrons recombine with electrons and holes on the n and p sides of the juncitons, light is emitted from the diode in the form of photons [5].

LED is a p-n junction opto semiconductor that emits a monochromatic (single color) light when operated in a forward biased direction. When p-n diode is forward biased, annihilation of holes and electrons takes place close to the junction and some energy is released in the junction. In Ge, Si, this energy is in the form of heat. In GaAs (gallium arsenide), the energy is released in the form of radiation. This phenomenon is known as electro-luminescence and the diode based upon this phenomenon is called LED.

When a suitable voltage is applied to the leads, electron are able to recombine with electron holes within the devices, releasing energy in the form of photons. Electroluminescence can be defined as the emission of light from a semiconductor under the influence of an electric field. The colour of the light is determined by the energy band gap of the semiconductor. The wavelength of the light emitted, and thus its colour, depends on the band gap energy of the materials forming the p-n junction.

LED denotes high power, good efficiency and faster response time of 0.1 μs. LED technology has now developed to the point where there are several different types of LED. Light emitting diodes are one of the fastest growing sectors in the electronic component industry. Applications of light emitting diode are sensor applications, mobile applications, sign applications, LED signals, indicators, traffic light, barcode scanner, LED street lights, LED lamps, LED displays, LED car brake lights and so many other electronic things [6].

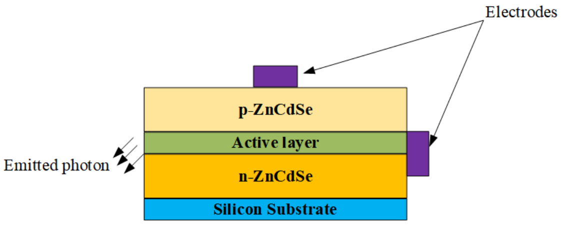

Figure 1. Proposed Structure of ZnCdSe based LED

The main goal of this research work is to develop the band layer and characteristics of the LEDs used the wide band gap material, ZnCdSe before the experiments. Fig. 1 illustrates the proposed structure of ZnCdSe LED

C. Materials and Research Methods

Energy band diagram of n-ZnCdSe/p-Si Material

In the band diagram design of n-ZnCdSe/p-Si heterojunction, $N_a=1\times10^{17}cm^{-3}$ and $N_d=1\times10^{18}cm^{-3}$ for n-region and $N_a=3\times10^{15}cm^{-3}$ and $N_d=1\times10^{16}cm^{-3}$ p-region are used as doping concentrations. The required parameters of ZnCdSe and Si are shown in Table 1 [8].

Table 1. Input Parameters for ZnCdSe Semiconductor

Parameters	Symbol	ZnSe	CdSe	Si
Bandgap	Eg	2.67 eV	1.74eV	1.12 eV
Permittivity (free space)	ε_0	8.854×10^{-12}	8.854×10^{-12}	8.854×10^{-12}
permittivity	ε	$8.5\varepsilon_0$	$10\varepsilon_0$	$11.7\varepsilon_0$
Electron Hall mobility at 300K	μ_e	$1500 cm^2 V^{-1} s^{-1}$	$900\ cm^2 V^{-1} s^{-1}$	$1500\ cm^2 V^{-1} s^{-1}$
Hole Hall mobility at 300K	μ_h	$355\ cm^2 V^{-1} s^{-1}$	$50\ cm^2 V^{-1} s^{-1}$	$450\ cm^2 V^{-1} s^{-1}$
Rest mass of electron and hole	m_o	$9.1 \times 10^{-31} kg$	$9.1 \times 10^{-31} kg$	$9.1 \times 10^{-31} kg$
Donor concentration	N_d	$1 \times 10^{18}\ cm^{-3}$	$1 \times 10^{18}\ cm^{-3}$	$1 \times 10^{16}\ cm^{-3}$
Acceptor concentration	N_a	$1 \times 10^{17}\ cm^{-3}$	$1 \times 10^{17}\ cm^{-3}$	$3 \times 10^{15}\ cm^{-3}$
Electron effective mass	m_e^*	$0.16m_0$	$0.13m_0$	$0.98m_0$
Hole effective mass	m_h^*	$0.6m_0$	$0.45m_0$	$0.49m_0$
Bandgap bowing	b	0.301	0.301	-
Electron Affinity	χ	4.16 eV	4.74 eV	4.01 eV
Threshold Voltage	V_T	25.85 mV	25.85 mV	25.85 mV

The energy band structures for n-ZnCdSe/p-Si heterojunction are analysed by using the physical parameters and following equations. [1-4]

Hole effective mass $(0 \le x \le 1)$ is (1)

$$m_p^{AB} = m_p^A.x + m_p^B.(1-x)$$

Electron effective mass ($0 \leq x \leq 1$) is,

$$m_n^{AB} = m_n^A.x + m_n^B.(1-x) \quad (2)$$

Energy bandgap ($0 \leq x \leq 1$) is,

$$E_g^{AB} = E_g^A.x + E_g^B(1-x) + C_g.(1-x).x \quad (3)$$

Relative permittivity for ($0 \leq x \leq 1$) is,

$$\varepsilon_\Gamma^{AB} = x\varepsilon_\Gamma^A + (1-x.)\varepsilon_\Gamma^B \quad (4)$$

The density of states in the conduction band and valence equations [5-6].

$$N_C = 2\left(\frac{2\pi\, m_e^* kT}{h^2}\right)^{3/2} \quad (5)$$

$$N_V = 2\left(\frac{2\pi\, m_h^* kT}{h^2}\right)^{3/2} \quad (6)$$

where m_e* and m_h* are the effective masses of the electrons and holes, k is the Boltzmann's constant (1.38 x 10^{-23} J/K), temperature in degrees Kelvin, respectively. For ZnCdSe material at 300K, the density of states, N_c and N_v in the conduction band and valence band of ZnCdSe material are 4 x10^{18} cm^{-3} and 1.3 x10^{18} cm^{-3}, respectively.

In heterojunction structure, the two semiconductors are assumed to have different energy bandgaps E_g, different dielectric permittivity ε_s, different work function $q\varphi_s$, and different electron affinities $q\chi$. The difference in energy of the conduction band edges in the two semiconductors is represented by ΔE_c, and the difference in energy in the valence band edges is represented by ΔE_V, can be expressed by [2]:

$$\Delta E_C = q(\chi_{ZnCdSe} - \chi_{Si}) \quad (8)$$

$$\Delta E_V = \Delta E_g - \Delta E_C \quad (7)$$

The different band gap energy is

$$\Delta E_g = E_{g2} - E_{g1} \quad (9)$$

The electrostatic potentials (ϕ_n and ϕ_p) at the depletion layer edge of the n-region and p-region and the built-in potential of a p-n junction,

$$\phi_n = V_T \ln\frac{N_d}{n_i} \quad (10)$$

$$\phi_p = -V_T \ln\frac{N_a}{n_i} \quad (11)$$

The built-in potential of a p-n junction,

$$V_{bi} = \phi_n - \phi_p = V_T \ln \frac{N_d N_a}{n_i^2} \tag{12}$$

Using the depletion approximation, V_{b1} and V_{b2} in the N-ZnCdSe and p-Si regions can be expressed by,

$$V_{b1} = V_{bZnCdSe} = \frac{\varepsilon_{Si}\varepsilon_0 N_a}{\varepsilon_{ZnCdSe}\varepsilon_0 N_d + \varepsilon_{Si}\varepsilon_0 N_a} V_{bi} \tag{13}$$

$$V_{b2} = V_{bSi} = \frac{\varepsilon_{ZnCdSe}\varepsilon_0 N_d}{\varepsilon_{ZnCdSe}\varepsilon_0 N_d + \varepsilon_{Si}\varepsilon_0 N_a} V_{bi} \tag{14}$$

Under thermal equilibrium condition, the depletion layer widths on either side of the n-ZnCdSe and p-Si heterojunction are given by [10]:

$$x_n = \left[\left(\frac{2\varepsilon_{ZnCdSe}\varepsilon_0 V_{bi}}{q}\right)\left(\frac{N_d + N_a}{N_d}\right)\right]^{1/2} \tag{15}$$

$$x_p = \left[\left(\frac{2\varepsilon_{Si}\varepsilon_0 V_{bi}}{q}\right)\left(\frac{N_d + N_a}{N_a}\right)\right]^{1/2} \tag{16}$$

$$x_T = x_n + x_p = \left[\left(\frac{2\varepsilon_s\varepsilon_0 V_{bi}}{q}\right)\left(\frac{N_d + N_a}{N_d N_a}\right)\right]^{1/2} \tag{17}$$

Under forward bias condition, the depletion layer widths on either side of the n-ZnCdSe/p-Si heterojunction are given by [9]:

$$x_n = \left[\left(\frac{2\varepsilon_{ZnCdSe}\varepsilon_0 (N_a + N_d)}{qN_d}\right)(V_{bi} - V)\right]^{1/2} \tag{18}$$

$$x_p = \left[\left(\frac{2\varepsilon_{Si}\varepsilon_0 (N_a + N_d)}{qN_a}\right)(V_{bi} - V)\right]^{1/2} \tag{19}$$

where χ_1 is the electron affinity for ZnCdSe material and χ_2 is the electron affinity for silicon material, V_{bSi} and $V_{bZnCdSe}$ are built-in potentials for silicon material and zinc oxide material, ε_{ZnCdSe} and ε_{Si} are permittivities for ZnCdSe material and silicon material and N_d is the donar concentration for ZnCdSe material and N_a is the acceptor concentration for silicon material [10].

Energy Dispersion with Wave Vector of ZnCdSe LED

Energy dispersion is the energy difference between the conduction band and the valence band, also known as the band gap energy. It is described as E-k diagram. E-k diagram is used to describe the electrical and optical properties of semiconductor. This diagram is the same for free electrons, nearly free electrons, as well as the bound electrons as shown in Fig.2. It is a continuous curve only for free electrons. For nearly free electrons as well as bound electrons, confinement of the electron results in only specific values of k to be permitted and therefore only the corresponding values of energy to be permitted. The allowed values of k are nπ/L for nearly free electrons and nπ/a for bound electrons [3].

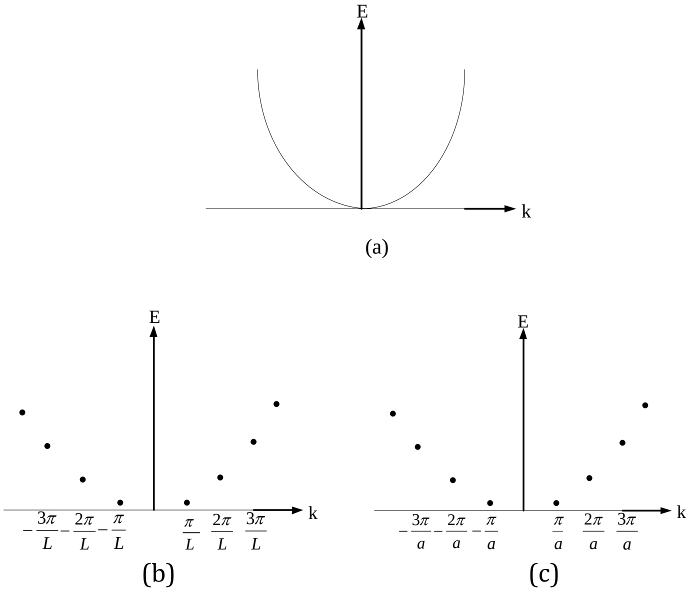

Figure 2. E-k Diagram of (a) Free Electron (b) Nearly Free Electron (c) Bound Electron [3]

E-k diagram is periodic because potential is periodic. If the values of −π/a to π/a had been known, every value of would have been recognized because it is periodic.

The energies for the conduction and valence band are

$$E_c = E_g q + \frac{\hbar^2 k^2}{2m^*_{ec}} \tag{20}$$

$$E_v = -\frac{\hbar^2 k^2}{2m^*_{ev}} \tag{21}$$

where E_c, E_v and E_g are conduction and valence band energy and energy band at k = 0, q is the electric charge (1.602×10^{-19}C), ħ is the Planck's constant (1.054×10^{-34}) and m^*_{ec} and m^*_{ev} effective mass of conduction and valence band [4]

Intrinsic Carrier Concentration of ZnCdSe Dependent on Temperature

Intrinsic carrier concentration of any semiconductor materials can be obtained using the following equations. Intrinsic semiconductors are usually non-degenerate so that the expression for the electron and hole concentrations in non-degenerate semiconductors can be applied [5].

$$n_i = \sqrt{N_C N_V} \exp\left(\frac{-E_g}{2K_B T}\right) \tag{22}$$

where N_c and N_v are the effective density of states in conduction and valence band, E_g is the band gap energy and T is the temperature (K).

Intensity Characteristic Curve of Light Emitting Diode

The intensity of light emitted by an LED as a function of wavelength and width can be described using the Gaussian distribution. The intensity profile of an LED can be approximated by a Gaussian function, which is given by: [1]

$$I(\lambda) = e^{\left(-\frac{(\lambda-\lambda-peak)^2}{(2\sigma)^2}\right)} \tag{23}$$

where I(λ) is the intensity of the LED emission at a given wavelength, λ-peak is the peak wavelength of the LED emission, σ is the standard deviation, which is related to the width of the LED emission.

The standard deviation, σ is related to the full width at half maximum (FWHM) of the LED emission by the eqution:

$$\text{FWHM} = 2\sqrt{(2\ln(2))}.\sigma \tag{24}$$

where FWHM is the width of the emission at half of the maximum intensity.

By controlling the width parameter, the spectral width of the LED emission can be effectively controlled. A narrower width will result in a more monochromatic (single wavelength) emission, while a wider width will result in a broader emission spectrum [1-3].

D. Results and Discussion

This section includes results and discussions on band diagram designs for a n-ZnCdSe/p-Si heterojunction under thermal and forward conditions and electrical characteristics ZnCdSe-Based LED.

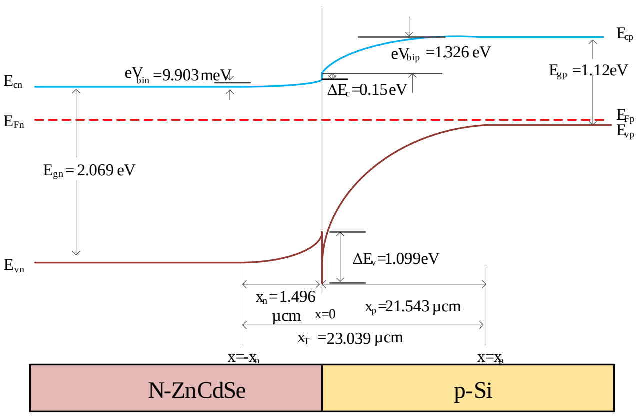

Figure.3. Energy band diagram of n-ZnCdSe and p-Si Heterojunction under thermal Equilibrium

Figure.3 shows the energy-band diagram of N-ZnCdSe and p-Si heterojunction under thermal equilibrium which shows that the position of the N-type semiconductor is smaller than the p-type semiconductor. As a result, the total width of the depletion region is 23.039 µcm and the value of the barrier height is 1.326 eV. The valence band is closer to the Fermi level than the conduction band. The valence band edge for the p-type is obtained from the difference in the energy gap and the fermi level of the p-type material. Then, the band decreases according to the potential drop and finally close to the Fermi level. A similar configuration can occur for the conduction band. From the design of the band diagram, the conditions of the drift current or diffusion current flowing across the heterojunction can be observed.

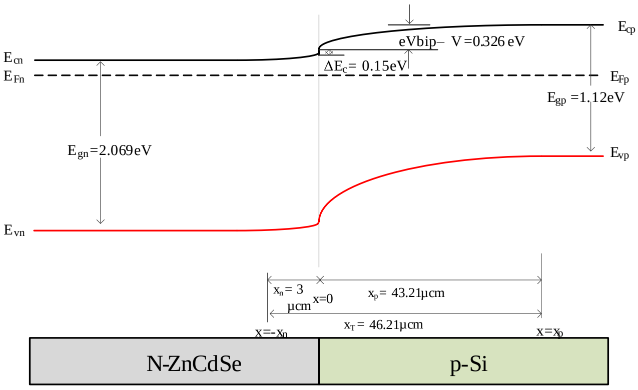

Figure 4. Energy band diagram of n-ZnCdSe and p-Si Heterojunction under forward bias condition

Figure 4 demonstrates the energy-band diagram of N-ZnCdSe and p-Si heterojunction under forward bias conditions. In Fig., when the forward voltage is applied, the conduction band edge of p-type silicon is close to the Fermi level as compared to under thermal equilibrium conditions without any voltage bias.

The forward bias will reduce the barrier height (0.326 eV) unbalancing the electron current flow, resulting in a huge forward current that increases exponentially with applied voltage. Reduction in depletion layer due to forward bias represents low resistance path through pn junction allowing very large currents with only a small increase in bias voltage. Consequently, the majority carrier, electrons from the N-ZnCdSe to the p-Si side can easily flow over the barrier. This junction is an Ohmic contact.

The energy dispersion of semiconductor material says the energy dispersion from the valence band to the conduction band with the gap of energy from stage to stage. Fig. 5 illustrates the energy dispersion of zinc cadmium selenide (ZnCdSe) semiconductor material. Otherwise, this figure shows that the energy band gap of ZnCdSe is 2.069 eV.

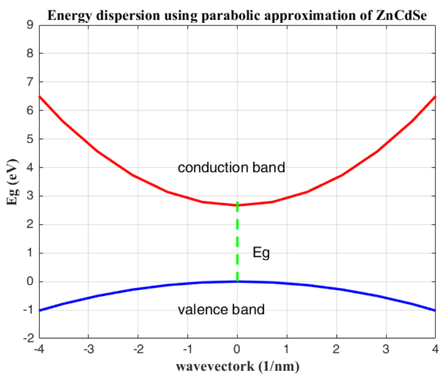

Figure 5. Energy Dispersion Using Parabolic Approximation of ZnCdSe

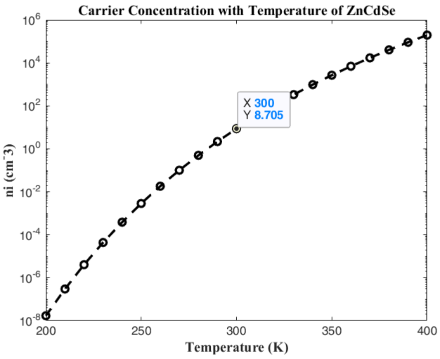

Figure 6. Intrinsic Carrier Concentration Using ZnCdSe Material

The intrinsic carrier concentration of ZnCdSe varied with temperature is shown in Fig. 6. The response shows that the value of intrinsic concentration has been changed with respect to temperature values of 300K. At room temperature, the concentration is achieved 8.705 cm^{-3} and it is used as a common value of concentrations for zinc cadmium selenide material junction.

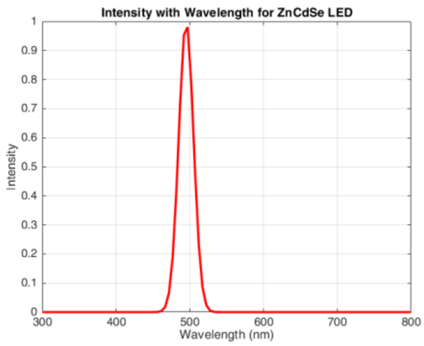

Figure 7. Light Output Characteristic for blue ZnCdSe LED

Figure 7 shows the plot of light emission with wavelength for blue LED. The wavelength range for ZnCdSe typically falls within the ultraviolet to near-infrared region, approximately 300 nm to 800 nm. But, the wavelength range for blue ZnCdSe is approximately 450 nm to 485 nm. The maximum wavelength value for ZnCdSe for producing a brightest blue colour is around 495 nm. The light output from the ZnCdSe blue LED is sharply peaked at 495 nm with a FWHM of 72 meV.

E. Conclusion

In this research paper, the band diagram of n-ZnCdSe/p-Si heterojunction structure of proposed design are plotted and the energy dispersion characteristics curve with various wave vector, intrinsic carrier concentration with temperatures, intensity with respect to wavelengths based ZnCdSe semiconductor material are furthermore analyzed and discussed. The proposed pn junction band structures are evaluated and designed as bands that can be used for light-emitting diode. And then the high performance of light-emitting diode is determined depending on the pn band design. This proposed band design in this paper is n-Zn CdSe/p-Si heterostructure for electronic and optical applications. The electrical properties such as the energy dispersion characteristics curve with various wave vector, intrinsic carrier concentration with temperatures, intensity with respect to wavelengths based on ZnCdSe material would be carried by computer simulation. The physical parameters of ZnCdSe material confirmed that the electrical properties of LED design would be matched with the specific application in real world. Therefore, it is hoped that this research paper will be good support researchers who study in electronics and photonics device applications.

F. Acknowledgment

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