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Simulation and Analysis of III-V Characteristic and Bandgap Design for Heterojunction Laser Diode

Thu Rein Ye Yint Win, Tin Tin Hla

Department of Electronic Engineering, Mandalay Technological University, Mandalay, Myanmar

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ABSTRACT

This research is the analysis of computer-based simulation design for the semiconductor laser diode. The paper is emphasized by analyzing the band structure and voltage-current characteristics of AlGaAs/GaAs for the laser diode. In this paper, bandgap variation temperature dependence, voltage-current (V-I), band diagram of the p-n junction for laser diode are discussed briefly. On the other hand, this paper is emphasized band structure design and voltage-current calculation using the mathematical model. The AlGaAs/GaAs device technology is used for high-speed optical communication.

KEYWORDS: *Band structure design, Voltage Current, Bandgap, Temperature effect, Computer-based simulation*

I. INTRODUCTION

Semiconductor devices emit laser light when an electric current is applied to the P-N junction of a compound semiconductor. The semiconductor laser is a type of diode that combines the electrical properties of a diode with properties that produce laser light and are also called “laser diodes”. A laser diode is a semiconductor device similar to a light-emitting diode (LED). The term laser originated as an acronym: Light Amplification by Simulated Emission of Radiation. Laser diode uses p-n junction to emit coherent light in which all the waves are at the same frequency and phase [1].

The laser diodes are fabricated using direct band-gap semiconductors. The laser diode epitaxial structure is grown using one of the crystal grown techniques, usually starting from an N doped substrate, and growing the I doped active layer, followed by the P doped cladding, and a contact layer. The active layer most often consists of quantum wells, which provide lower threshold current and higher efficiency [2].

Optimization of the device design is usually done by computer simulation, and this must be based upon the physical processes which actually occur in the devices and have to use experimental results for material parameters. The band structures of semiconductors materials for p-GaAs/N-AlGaAs, and n-GaAs/N-AlGaAs are discussed with figures. The Fermi level will line up to be a constant across the junction under thermal equilibrium conditions without any voltage bias when the two crystals are in contact [3].

II. THEORETICAL CONCEPTS FOR BAND DESIGN

The density of the electrons (i.e., the numbers of electrons per unit volume) in an intrinsic semiconductor is evaluated in an incremental energy range. This density of the electrons dne with energy E distributed over the energy interval is comprised of the density of states and the distribution function, which defines the occupation of the electrons states

$$dn_e = N(E)\,f(E)\,dE \qquad (1)$$

The distribution function which satisfies electrons distribution conditions is the Fermi distribution

$$f(E) = \frac{1}{\exp\left(\frac{E-E_F}{kT}\right)+1}$$

Where, k is the Boltzmann constant, T is the absolute temperature in degrees Kelvin, and E_F is the energy of the Fermi level. For states with $E \ll E_F$, f(E) = 1,so that the states are completely occupied. Conversely, for f(E) = 0, states with $E \gg E_F$ are not occupied. Half of the states with $E=E_F$ are occupied.

In order to determine the density of states as a function of the electron energy, the relationship between momentum and energy must be known. In order that no current flows in the equilibrium state, an equal number of states must be occupied in any arbitrary direction at positive and negative momentum. Since the states are equidistant in momentum space, we conclude that the energy must be an even function of the momentum.

The number of states between E and E_C

$$N(E) = \frac{8\pi V\left(2m_e^*\right)^{3/2}}{3h^3}\left(E-E_C\right)^{3/2} \qquad (3)$$

Where E_C is the conduction band, h is the Planck constant $6.582\text{x}10^{-16}$eVs and m_e* is called the effective mass of the electrons.

The number of electrons in the conduction band per unit volume of the crystal, n is given by

$$n = N_C e^{(E_F - E_C)/kT} \qquad (4)$$

Where N_C is a constant at fixed T known as the effective density of states in the conduction band.

Similarly, the total number of holes in the valence band per unit volume of the crystal, p is given by

$$p = N_V e^{(E_V - E_F)/kT} \tag{5}$$

Where N_V is the effective density of states in the valence band

III. NUMERICAL MODEL

In this research, two regions of p- and n-type semiconductor materials are analyzed by changing the doping concentration. The band-edge discontinuities of types are varied with the type of semiconductor materials. The following block diagram is the procedure of band structure analysis.

Firstly, the effective masses of electron and hole are set to find the effective density of states of conduction and valence band of different materials depending on the various temperature. In order to determine the density of states as a function of the electron energy, we need the relationship between momentum and energy which for electrons in a crystal might be quite different from that for a free electron.

The density of state in the conduction band is

$$N_C = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \tag{6}$$

Where, N_C is the density of state in the conduction band, m_e^* is the effective mass of electrons,

k is the Boltzmann's constant=8.854$\times 10^{-14}\ As/V_{cm}$and h is the Plank's constant=6.582$\times 10^{-16} eVs$. T=300K (room temperature)

$$N_C = 2.51\times10^{19}\left(\frac{m_e^*}{m_0}\frac{T}{300}\right)^{3/2} \tag{7}$$

The density of state in the valence band is

$$N_V = 2.51\times10^{19}\left(\frac{m_h^*}{m_0}\frac{T}{300}\right)^{3/2} \tag{8}$$

In heterojunction structure, the two semiconductors are assumed to have different energy bandgap, different dielectric permittivity ε_s, different work function $q\varphi_s$, and different electron affinities $q\chi$. The work function is defined as the energy is required to remove an electron from Fermi level EF to a position just outside the material (the vacuum level). The electron affinity is the energy required to remove an electron from the bottom of the conduction band E to the vacuum level. 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. [4]

From Fig.1, ΔE_C, and ΔE_V can be expressed by

$$\Delta E_C = q(\chi_1 - \chi_2) \tag{9}$$

$$\Delta E_V = E_{g2} + q\chi_2 - (E_{g1} + q\chi_1) \tag{10}$$

The different bandgap energy is

$$\Delta E_g = E_{g2} - E_{g1} \tag{11}$$

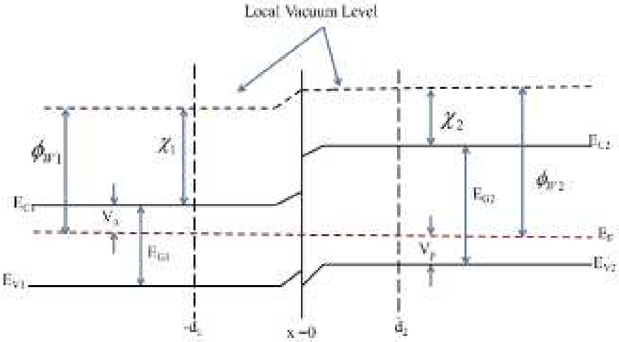

Figure1. Energy band diagram of two isolated semiconductors

The Fermi level for both p-type and n-type materials is given by

$$E_C - E_F = -kT\ln\left(\frac{N_D}{N_C}\right) \tag{12}$$

Where N_D is donor concentration.

$$E_F - E_V = -kT\ln\left(\frac{N_A}{N_V}\right) \tag{13}$$

Where N_A is acceptor concentration.

The intrinsic-carrier concentration is

$$n_i = \sqrt{N_C \times N_V}\ e^{-\frac{E_g}{2KT}} \tag{14}$$

The barrier potential is

$$V_b = \frac{KT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) \tag{15}$$

The width of the depletion region is

$$W_d = x_p + x_n \tag{16}$$

$$x_p = \left(\frac{2\varepsilon_p\varepsilon_0}{q}\frac{N_D}{N_A(N_A+N_D)}V_b\right)^{1/2} \tag{17}$$

$$x_n = \left(\frac{2\varepsilon_n\varepsilon_0}{q}\frac{N_A}{N_A(N_A+N_D)}V_b\right)^{1/2} \tag{18}$$

Minority carriers diffusion coefficients, carrier lifetimes

$$D_{n,p} = \frac{kT}{q}\mu_{n,p} \tag{19}$$

$$\tau_{n,p} = \frac{1}{BN_{A,D}} \tag{20}$$

Electron and hole diffusion lengths

$$L_{n,p} = \sqrt{D_{n,p}\tau_{n,p}} \tag{21}$$

Saturation current density

$$I_s = eA\left(\frac{D_p n_i^2}{L_p N_D} + \frac{D_n n_i^2}{L_n N_A}\right) \tag{22}$$

$$I = I_s\left(e^{V/V_T} - 1\right) \tag{23}$$

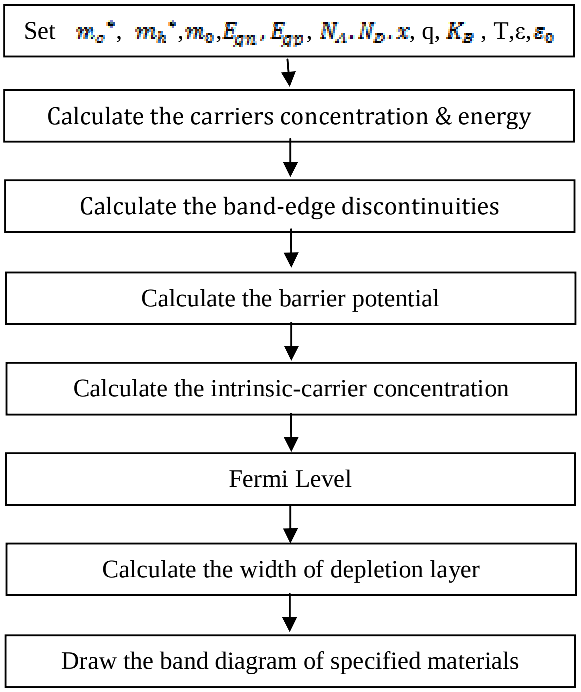

Figure2. The Procedure of band diagram design

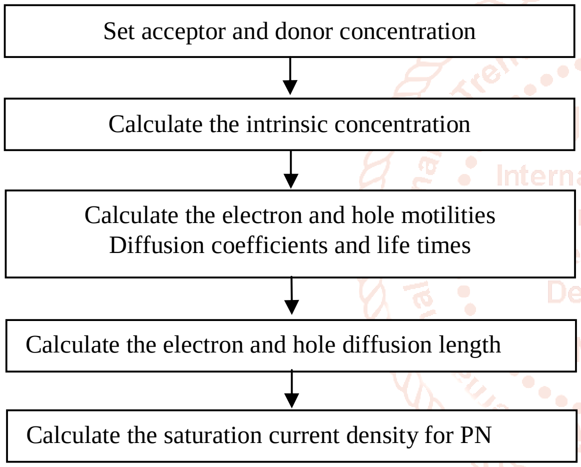

Figure3. The Determination of V-I Characteristics

IV. MATERIAL PARAMETER FOR ALGAAS/GAAS CELL

A. The band structure of p-GaAs/ N- $Al_xGa_{1-x}As$

TABLE 1

PARAMETERS FOR P-GAAS / N-AL_XGA_{1-X}ASSTRUCTURE

	p-GaAs	N-AlGaAs
Electron effective mass, m_e^*	$0.665 m_0$ at x=0.3	$0..914 m_0$ at x=0.3
Hole effective mass, m_h^*	$0.5 m_0$ at x=0.3	$0.587 m_0$ at x=0.3
Energy Bandgap, E_g	1.424 eV at 300K	1.798 eV at 300K
Dielectric constant, ε	$13.1\varepsilon_0$ At x=0.3	$12.2\varepsilon_0$ At x=0.3
Acceptor & donor concentration,	$N_a = 1x10^{18}$ cm^{-3}	$N_D = 2x10^{17}$ cm^{-3}
Intrinsic-Carrier Concentration , n_i	2.13×10^6 cm^{-3}	2.2×10^3 cm^{-3}
Barrier potential, V_b	1.53V	
Width of depletion	$0.11 \mu m$	

B. The band structure of n-GaAs / P- AlxGa1-xAs

TABLE 2

PARAMETERS FOR n-GAAS / P-AL_XGA_{1-X}AS STRUCTURE

	n-GaAs	P-AlGaAs
Electron effective mass, m_e^*	$0.665 m_0$ at x=0.3	$0.914 m_0$ at x=0.3
Hole effective mass, m_h^*	$0.5 m_0$ at x=0.3	$0.587 m_0$ at x=0.3
Energy Bandgap, E_g	1.424Ev at 300K	1.798 eV at 300K
Dielectric constant, ε	$13.1\varepsilon_0$ At x=0.3	$12.2\varepsilon_0$ At x=0.3
Acceptor & donor concentration,	$N_d = 4x10^{18}$ cm^{-3}	$N_A = 2x10^{17}$ cm^{-3}
Intrinsic-Carrier Concentration , n_i	2.13×10^6 cm^{-3}	2.2×10^3 cm^{-3}
Barrier potential, V_b	1.44V	
Width of depletion ,	$0.238 \mu m$	

C. V-I Characteristics of p-GaAs / N- AlxGa1-xAs

TABLE 3

PARAMETERS FOR p-GAAS / N-AL_XGA_{1-X}AS STRUCTURE

Intinsic concentration, n_i^2	$5.05 \times 10^{12} cm^{-6}$(GaAs) $5.56 \times 10^{12} cm^{-6}$(AlGaAs)
Hole and elecron mobilities	$\mu_n = 9400 \, cm^2/vs$ $\mu_p = 145.6 \, cm^2/vs$
Diffusion coefficient	$D_n = 243.46 \, cm^2/vs$ $D_p - 3.77 \, cm^2/vs$
Carrier life time	$\tau_n = 1.39$ ns $\tau_p = 27.78$ ns
Hole and elecron diffusion length	$L_n = 5.82 \times 10^{-4} cm$ $L_p = 3.24 \times 10^{-4} cm$
Saturation current	$I_s = 9.42\times 10^{-24}$A

D. V-I Characteristics of n-GaAs / P- AlxGa1-xAs

TABLE 4

PARAMETERS FOR n-GAAS / P-AL_XGA_{1-X}AS STRUCTURE

Intinsic concentration, n_i^2	$5.05 \times 10^{12} cm^{-6}$(GaAs) $5.56 \times 10^{12} cm^{-6}$(AlGaAs)
Hole and elecron mobilities	$\mu_n = 2300 \, cm^2/vs$ $\mu_p = 9400 \, cm^2/vs$
Diffusion coefficient	$D_n = 59.57 \, cm^2/vs$ $D_p = 10.36 \, cm^2/vs$
Carrier life time	$\tau_n = 27$ ns $\tau_p = 34.72$ ns
Hole and elecron diffusion length	$L_n = 12.7 \times 10^{-4} cm$ $L_p = 6 \times 10^{-4} cm$
Saturation current	$I_s = 6.98\times 10^{-23}$A

V. TEST AND RESULTS

A. Band-gap energy as a function of Temperature

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

Where E_g = band-gap energy, T = temperature (K)

and β = fitting parameters (frequently called the Varshni parameters)

Figure4. shows the width of the bandgap for GaAs, InP, Si and Ge as the function of temperature.

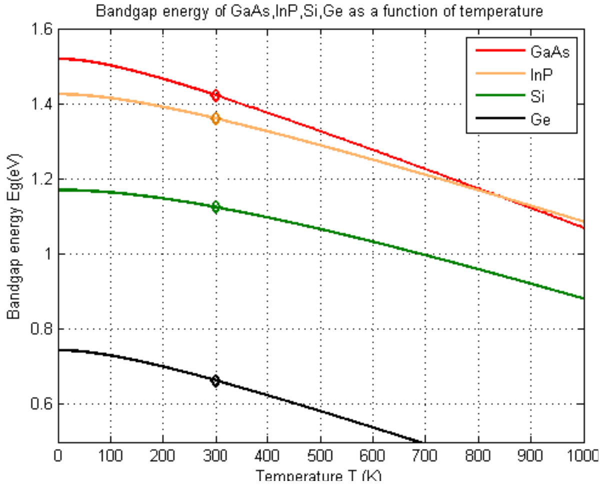

Figure4. The energy gap with temperature

B. The band structure of p-GaAs / N- AlxGa1-xAs

Figure 5 shows the band diagram of P- and N-type semiconductor materials that are doped

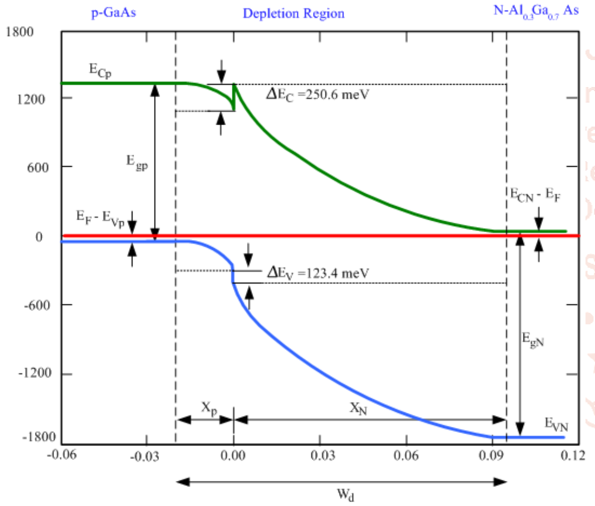

Figure5. Band structure of p-GaAs/N-AlGaAs

C. The band structure of n-GaAs/ P- AlxGa1-xAs

Figure 6 shows the PN junction band diagram that used for GaAs as n-type material and AlGaAs as P-type material.

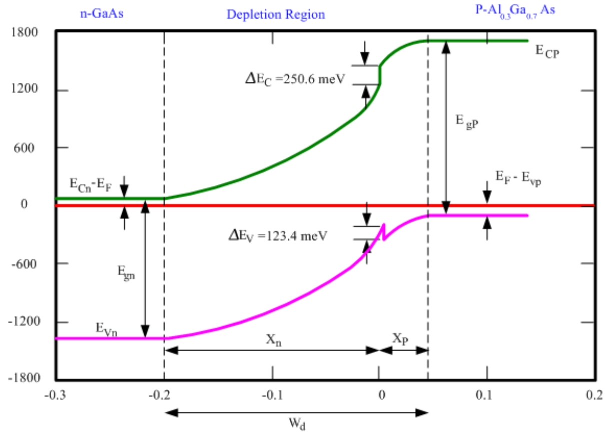

Figure6. Band structure of n-GaAs/P-AlGaAs

D. V-I Characteristics of p-GaAs / N- AlxGa1-xAs

Figure 7 shows the V-I characteristics curve and the the current equation is I=

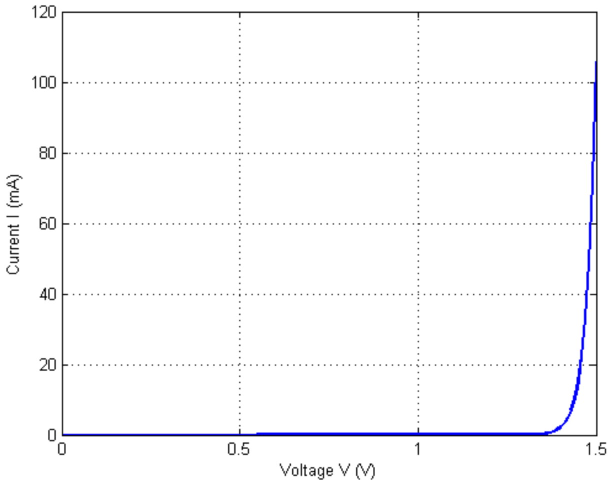

Figure7. V-I Characteristics of p-GaAs/N-AlGaAs

E. V-I Characteristics of n-GaAs / P- AlxGa1-xAs

Figure 8 shows the V-I characteristics curve and the the current equation is I=

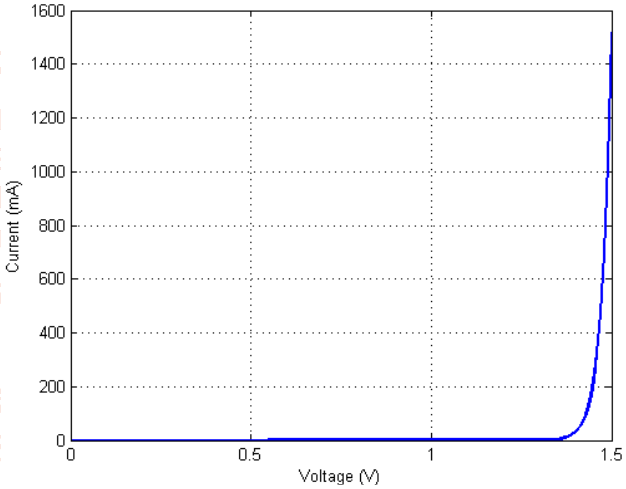

Figure8. V-I Characteristics of n-GaAs/P-AlGaAs

VI. CONCLUSION

The above process is band structure design analysis of AlGaAs/GaAs materials and is based on mathematical equations of semiconductor theory. Figure 4 shows the width of bandgap for GaAs, InP,Si and Ge as the function of temperature. GaAs decrease from 1.424 eV at 300K to the 1.06 eV at 1000K. InP is slightly decrease from 1.36 eV at 300K to 1.08 eV at 1000K. The bandgap energy can vary to different values as the changing of temperature. the energy band structures of (n-GaAs/P-AlGaAs) and (p-GaAs/N-AlGaAs) for laser diode have been drawn in figure 5 and 6. For the energy band of heterostructure, the conduction band is 61.4meV (n-GaAs/P-AlGaAs), 32.2meV (p-GaAs/N-AlGaAs) close to the Fermi level than the valence band. When using a laser diode it is essential to know its performance characteristics. The laser diode specification for the forward voltage across the diode is required in a number of areas of the design. From figure 7 and 8, it can be seen that the voltage across the laser diode in around 1.5 volts. A laser diode is normally operated by applying fixed voltage because the flow of current could depend on that voltage and affected by device temperature. The development of the device with the help of computerized analysis will be observed the physical properties and characteristics of the AlGaAs/GaAs that are used in semiconductor laser diodes.

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