AL_{0.3}GA_{0.7}AS/GAAS HETEROJUNCTION DIODE ANALYSIS

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Abstract: Theoretical treatment by analysis the Al_{0.3}Ga_{0.7}As/GaAs for long and short heterojunction diode is presented. The analysis is started by obtaining the built-in potential from the structure of diode, then the electric field and potential distribution are attained using different concentrations. In case of equal concentration, the maximum field is (4.32×10⁴ V/cm) and potential with maximum peak at (1.2V), the depletion layer capacitance was also defined at applied voltage (VR) with value about (11.6×10¹⁵ F/cm²). According to the type of doping in (P-n) heterojunction the injected minority carrier and current densities analysis are achieved when applying voltage (+0.8 V) for forward bias and (-0.8 V) for reverse bias for both long and short diode, respectively. The value of minority carriers in n-side for both short and long diode is about (10.8×10⁹cm⁻³) at forward bias. The (I-V) characteristics for two diodes (long and short) is executed using the Drift-diffusion model. The resulting for the (I-V) characteristics show typical exponential relationship between the applied voltage and output current in Cartesian and semi-log plots. The complete modeling of the device is achieved by MATLAB software.

1. Introduction

Semiconductor heterojunction produced by utilising two different semiconductor materials to

build the junction, but when the same semiconductor materials utilised to build the junction the homojunction is obtained. The energy band of heterojunction will have a discontinuity at the junction interface due to the different materials that utilised to build the junction, this will cause an abrupt junction in which the semiconductor changes abruptly from wide-bandgap material to narrow-bandgap material or vice versa. In the case of the lattice constant of the two materials are perfectly matched, a useful heterojunction will have resulted. Since any mismatch in the lattice gives dislocations resulting in interface states. Gallium arsenide-aluminum gallium arsenide (GaAs/Al_{0.3}Ga_{0.7}As) junction have a lattice constant which vary by no more than 0.14 percent, therefore; the GaAs and Al_{0.3}Ga_{0.7}As system have been investigated quite thoroughly [1].

Heterojunction research was taken up intensively after 1957, when Kroemer suggested that anisotype heterojunctions might exhibit extremely high injection efficiencies in comparison with homojunctions. Since that time,

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additional characteristic advantages of heterojunctions have been suggested. Actual heterojunctions of both types were realized first by Anderson, in 1960. He also presented more detailed models for the arrangement of the energy bands near the interface between the two semiconductors and for current transport through the interface [2].

One combining the a-Si and c-Si as a heterojunction solar cell gives the opportunity to have a high potential of maintaining the current collection advantages offered by the crystalline silicon, while at the same time, offering a low temperature-processing scheme via the heterojunction formation, thereby avoiding the high thermal budget of p-n homojunction formation [3].

The heterojunction can be used in spectral response in optical applications. Spectral response (SR) is a key performance parameter of heterojunction phototransistors (HPTs). The performance of HPTs is supported by their internal current gain.

These advantages, along with their process and layer compatibility to heterojunction bipolar transistors, make them highly attractive in the manufacture of monolithic integrated single-chip optical receivers [4].

The heterojunction offers a larger set of device configurations and has become the basis for the so-called field of bandgap engineering. The principle of operation of an HBT is identical to that of the BJT, except that the bandgap of the emitter region exceeds that of the base region by ΔE_g , where ΔE_g is the forbidden energy gap [5].

Semiconductor heterojunctions play an important role in numerous devices, including heterojunction bipolar transistors (HBTs), high electron mobility transistors (HEMTs), photodiodes and laser diodes. These devices utilise heterojunctions to direct and confine carriers, resulting in improved performance [6].

2. Diode Structure

Heterojunction has four basic types, anisotype when the dopant type at the junction is changing, Pn or Np junction can be formed. And isotype when the dopant type at the junction is the same, nN and pP junction can be formed, where the capital letter refers to the larger-bandgap material. Figure 1. show the energy-band diagram of isolated P-type and n-type materials, the vacuum level is used as a reference. The difference between the two conduction band energies is denoted by ΔE_c , and the difference between the two valance band energies is denoted by ΔE_v [7], [8]. From figure.1. we can obtain

$$\Delta E_c = e(X_n - X_p) \quad (1)$$

$$\Delta E_c + \Delta E_v = E_{gp} - E_{gn} = \Delta E_g \quad (2)$$

Figure 1. Energy band diagram of the two isolated semiconductors (P – n) type.

The expression of the built-in potential V_{bi} can be obtained as the difference between Fermi level at both sides of the junction

$$V_{bi} = E_{fn} - E_{fp} \quad (3a)$$

As illustrated from Figure.1.

$$eV_{bi} = (E_{cn} + kT \ln \frac{n_{no}}{N_{cn}}) - (E_{vp} - kT \ln \frac{p_{po}}{N_{vp}}) \quad (3b)$$

which can be written in terms of valance band energy as

$$eV_{bi} = \Delta E_v + kT \ln \left(\frac{p_{po} N_{vn}}{n_{no} N_{vp}} \right) \quad (4)$$

Also, it can be written in terms of conduction band energy as

$$eV_{bi} = -\Delta E_c + kT \ln\left(\frac{n_{no}N_{cp}}{n_{po}N_{cn}}\right) \quad (5)$$

where k is Boltzman constant, T is the absolute temperature in Kelvin, p_{no} and n_{po} are the hole and electron concentrations in n and P side, respectively, and N_{vp} and N_{vn} are the effective density of state function in P and n side, respectively.

3. Electric Field and Potential Distribution

The electrostatic potential Ψ can be given by Poisson's equation:

$$\begin{aligned} \frac{d^2\Psi}{dx^2} &= -\frac{d\xi}{dx} = -\frac{\rho_s}{\epsilon_s} \\ &= -\frac{q}{\epsilon_s} (N_D - N_A + p + n) \end{aligned} \quad (6)$$

For completely depleted region $p = n = 0$, Eq. (6) becomes

$$\frac{d^2\Psi}{dx^2} = \frac{q}{\epsilon_s} (N_A - N_D) \quad (6a)$$

By utilising the integration for the Poisson's equation, the electric field is obtained, as follows:

$$\begin{aligned} \xi_1(x) &= -q \frac{N_A}{\epsilon_1} (x + x_p) \\ \text{for } -x_p \leq x < 0 \end{aligned} \quad (7a)$$

$$\begin{aligned} \xi_2(x) &= q \frac{N_D}{\epsilon_2} (x - x_n) \\ \text{for } 0 < x \leq x_n \end{aligned} \quad (7b)$$

The second integration for Poisson's equation gives the potential distribution, as follows:

$$\begin{aligned} \phi_1(x) &= q \frac{N_A}{2\epsilon_1} (x + x_p)^2 \\ \text{for } -x_p \leq x < 0 \end{aligned} \quad (8a)$$

$$\begin{aligned} \phi_2(x) &= q \frac{N_A}{2\epsilon_1} x_p^2 + q \frac{N_D}{2\epsilon_2} (x x_n + \frac{x^2}{2}) \\ \text{for } 0 < x \leq x_n \end{aligned} \quad (8b)$$

where N_A and N_D are acceptor and donor concentrations, respectively, x_n as x_p are the depletion layer width in n , and p side, respectively, ϵ_1 and ϵ_2 are the permittivities of p and n side, respectively. The depletion layer width in p -side is given by:

$$x_p = \sqrt{\frac{2\epsilon_1 \epsilon_2 N_D vbi}{q N_A (\epsilon_2 N_D + \epsilon_1 N_A)}} \quad (9)$$

For n -side

$$x_n = \sqrt{\frac{2\epsilon_1 \epsilon_2 N_A vbi}{q N_D (\epsilon_2 N_D + \epsilon_1 N_A)}} \quad (10)$$

Depletion layer width depends on the type of biasing, and it reduces at forward bias and increases at reverse bias.

Figure 2. Electric field distribution at difference concentrations.

Figure 3. Potential distribution at difference concentration.

The Depletion capacitance is given by:

$$C_j = \sqrt{\frac{qN_A N_D \epsilon_1 \epsilon_2}{2(\epsilon_2 N_D + \epsilon_1 N_A)(V_{bi} - VR)}} \quad (11)$$

By utilizing the MATLAB software, the electric field, potential distribution, and depletion capacitance are depicted in Figures 2-4, respectively.

Figure 4. Depletion capacitance versus reverse voltage (VR).

4. Long Diode (Infinite Length)

4.1. Minority Carrier Distribution

When the junction has been formed, we have injected minority carrier, holes are injected into the n-side, and electrons are injected into p- side. For long diode where the layer width is too large about $10L_p$ or $10L_n$ for both sides, where L_p and L_n are the hole and current diffusion lengths, respectively. The minority carriers are recombining with the majority carrier as it moves away from the boundaries. For the neutral n-region the steady-state continuity equation is

$$\frac{d^2 p_n}{dx^2} - \frac{p_n - p_{n0}}{D_p \tau_p} = 0 \quad (12)$$

The solution of Equation (12) with the boundary conditions

$$p_n(x = \infty) = p_{n0}$$

and

$$p_n(x = x_n) = p_{n0} e^{qv/kT} \text{ gives}$$

$$p_n(x) = p_{n0} + p_{n0}(e^{qv/kT} - 1) e^{-(x-x_n)/L_p} \quad (13)$$

similarly, we obtain for neutral p-region

$$n_p(x) = n_{p0} + n_{p0}(e^{qv/kT} - 1) e^{(x+x_p)/L_n} \quad (14)$$

where p_{n0} and n_{p0} are hole and electron minority carriers densities at thermal equilibrium, respectively. The applied voltage V is $+V$ for forward bias and $-V$, for reverse bias. The minority carrier distribution is depicted in Figure 5.

(a) Hole minority carrier in n-side for forward bias

(b) Hole minority carrier in n-side for reverse bias

(c) Electron minority carrier in p -side for forward bias (d) Electron minority carrier in p -side for reverse bias (b) Hole current in n -side for reverse bias**Figure 5.** The minority carrier distribution for pn and np

4.2. Current Density

The hole and electron current density can be obtained as follows; For neutral n -region

$$J_p(x) = -qD_p \frac{dp_n}{dx} = \frac{qD_p P_{n0}}{L_p} (e^{qv/kT} - 1) e^{-(x-x_n)/L_p} \quad (15)$$

and for neutral p -region

$$J_n(x) = qD_n \frac{dn_p}{dx} = \frac{qD_n n_{p0}}{L_n} (e^{qv/kT} - 1) e^{(x+x_p)/L_n} \quad (16)$$

Where D_p and D_n are hole and electron diffusion constants. The electron and hole diffusion current will decay exponentially in each side with diffusion length L_n and L_p , respectively, as illustrated in Figure 6.

(a) Hole current in n -side for forward bias (c) Electron current in p -side for forward bias (d) Electron current in p -side for reverse bias**Figure 6.** The electron and hole diffusion current

4.3. Current-Voltage Characteristics

The I/V characteristics can be obtained as the sum of Equations (15) and (16) at $x = x_n$ in the

n-side and $x = -x_p$ in the p-side, respectively, the total current

$$J_t(x) = J_p(x_n) + J_n(-x_p) = J_s(e^{qv/kT} - 1) \quad (17)$$

$$J_s = \left(\frac{qD_p P_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right)$$

Where J_s is the saturation current density. The I/V characteristics of long diode is depicted in Figure 7.

Figure 7. I/V characteristics of long diode

The difference between homojunction and heterojunction diodes is the permittivities, which is the same value in case of homojunction according to the same materials that used to form the junction, and a difference value in case of heterojunction due to difference materials used to form the junction.

5. Short Diode (Finite Length)

5.1. Minority Carrier Distribution

For short diode the length of layer width will be very small as compare to diffusion length, about $(0.1L_p$ or $0.1L_n$) for both sides of the junction.

The steady-state continuity equation is the same as (12) but the boundary will change, for neutral n-region with boundary condition

$$p_n(x = x_n) = p_{n0} e^{qv/kT}$$

and

$$p_n(x = w_1) = p_{n0} \text{ gives}$$

$$P_n(x) = P_{n0} + P_{n0} (e^{qv/kT} - 1) \frac{\sinh(\frac{w_1 - x}{L_p})}{\sinh(\frac{w_1 - x_n}{L_p})} \quad (18)$$

where $w_1 = x_n + w_n$, w_n is the length of neutral n-region and it taken to be $0.1L_p$.

similarly, for neutral p-region with boundary condition

$$n_p(x = -x_p) = n_{p0} e^{qv/kT}$$

and

$n_p(x = -w_2) = n_{p0}$ gives

$$n_p(x) = n_{p0} + n_{p0} \left(e^{qv/KT} - 1 \right) \frac{\sinh\left(\frac{w_2+x}{L_n}\right)}{\sinh\left(\frac{w_2-x_p}{L_n}\right)} \quad (19)$$

where $-w_2 = -x_p - w_p$, w_p is the length of neutral p-region and it taken to be $0.1L_n$. In this case the minority carrier and majority carrier recombination will take space at small neutral region, and again using MATLAB program the distribution is shown in Figure 8.

(a) Hole minority carrier in n -side for forward bias

(b) Hole minority carrier in n -side for reverse bias

(c) Electron minority carrier in p -side for forward bias

(d) Electron minority carrier in p -side for reverse bias

Figure 8. The minority carrier distribution for pn and np for short diode.

As shown before we obtain the minority carrier for long and short diode. Now we can find the minority carrier in different diffusion lengths, where the depletion layer width ranges from $0.1L_p$ to $10L_p$ (taken different values between them).

Figure.9. Minority carrier distribution in n -side at different diffusion lengths.

As presented from Figure.9, the minority carrier will be moves away from boundaries in several steps until it completely diffused.

5.2. Current Density

The current of short diode can be obtained as the same way that used in long diode. The hole and electron current can be obtained as follows:

for neutral n-region

$$J_p(x) = -qD_p \frac{dp_n}{dx} \quad (20)$$

$$= \frac{qD_p P_{n0}(e^{qv/KT} - 1)}{L_p} \frac{\cosh(\frac{w_1 - x}{L_p})}{\sinh(\frac{w_1 - x_n}{L_p})}$$

and for neutral p-region

$$J_n(x) = qD_n \frac{dn_p}{dx} \quad (21)$$

$$= \frac{qD_n n_{p0}(e^{qv/KT} - 1)}{L_n} \frac{\cosh(\frac{w_2 + x}{L_n})}{\sinh(\frac{w_2 - x_p}{L_n})}$$

The current density for the n -side takes an exponentially curve, as illustrated in Figure 10.

(a) Hole current in n -side for forward bias

(b) Hole current in n -side reverse bias

(c) Electron current in p -side for bias

(d) Electron current in p -side for reverse bias

Figure 10. Electron as well as hole current density in the n -side and in p -side

5.3. Current-Voltage Characteristics

Similarly as in the long diode the I/V characteristic of short diode, at $x = x_n$ in n -side and $x = -x_p$ in p -side .

$$J_p(x) = \frac{qD_p P_{n0}(e^{qv/KT} - 1)}{L_p} \coth(\frac{w_1 - x_n}{L_p}) \quad (22)$$

$$J_n(x) = \frac{qD_n n_{p0}(e^{qv/KT} - 1)}{L_n} \coth(\frac{w_2 - x_p}{L_n}) \quad (23)$$

The total current is given by:

$$J_t(x) = J_p(x_n) + J_n(-x_p) = J_s(e^{qv/KT} - 1) \quad (24)$$

Using the properties of the hyperbolic functions, since $\coth(y) = \frac{1}{y}$ the saturation current will be

$$J_s = (\frac{qD_p P_{n0}}{w_n} + \frac{qD_n n_{p0}}{w_p}) \quad (24a)$$

Figure 11, illustrated the I/V characteristic for short diode.

(a) Forward I/V in Cartesian

(b) Forward I/V in semi-log

(c) Reverse I/V in Cartesian

(d) Reverse I/V in semi-log

Figure 11. I/V characteristic for short diode.

6. Comparison of I/V Characteristics between Long and Short Diode

Using Equations (17) and (24); also with MATLAB, a comparison between the I/V characteristic for both long as well as short diode is done and it is shown in Figure 12.

(a) I/V characteristic for both long and short diodes in Cartesian plot

(b) I/V characteristic for both long and short diodes in semi-log plot

Figure 12. Comparison between the I/V characteristic for both long and short diodes

Table 1 shows all the constants that used in our calculations [9-12].

Table (1): values of constant

quantity	symbol	GaAs	Al _{0.3} Ga _{0.7} As	unit
Band-gap energy	E_g	1.42	1.7981	eV
Intrinsic carrier concentration	n_i	2×10^6	2.1×10^3	cm ⁻³
Effective DOS at CB	N_c	4.4×10^{14}	6.256×10^{17}	cm ⁻³
Effective DOS at VB	N_v	7.7×10^{18}	1.12×10^{19}	cm ⁻³
Electron affinity	X	4.07	3.74	V
Relative dielectric constant	ϵ_r	13.1	12.048	/

Figure.13. shows the flow chart that employed in the modeling process of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ heterojunction diode.

Figure 13. Flow chart used in analysis.

7. Discussion

As previously demonstrated the distribution of electric field is more negative in p -side and it is positive slop in n -side, it means increasing with x . The potential distribution with a peak equals the built-in potential. Injected minority carriers and it distribution in the neutral region, take exponentially curve in long diode and straight line in short diode because the distance is much smaller than the diffusion length for both n and p sides. Also a comparison of I/V characteristic shows that the current in long diode is higher than that of short diode in case of forward bias.

8. Conclusion

In this paper, a comprehensive investigation, analysis, and modelling for different aspects for the heterojunction diode have been discussed. Two types of the heterojunction were studied (i.e. long and short diode) with their properties such the minority carrier distribution, current density, and current-voltage characteristic utilising the drift-diffusion model, also the depletion capacitance was analysed.

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9. References

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