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Electrical Characteristics of PN Junction Structure for GaAs, InP and InSb based III-V Compounds

Tin Tin Hla [1], Kyawt Khin[2], Hnin Ngwe Yee Pwint [3]
tintinhla99a1@gmail.com[1], kyawtkhin@gmail.com[2], hninngweyeepwint12@gmail.com[3]
[1,3] Department of Electronic Engineering, Mandalay Technological University, Myanmar
[2] Department of Electronic Engineering, Technological University (Maubin), Myanmar

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Abstract

The electrical properties of the pn junction structure for GaAs, InP and InSb based III-V compounds using the numerical equation are provided by a computer-aided simulation method. *The band model predicts the electrical properties of III-V compound semiconductors.* The analytical description of the immobile space charge layer (ISPL) related to immobile charge concentration, the amount of electric field intensity and the barrier potential height under unbiased, forward-biased and reverse-biased conditions has been investigated. And then the specific explanation of electron and hole distributions in the bulk region due to the majority carrier injection under forward biasing has been evaluated by using boundary conditions. *The J-V characteristics of Group III-V compounds are observed using mathematical computation based on diffusion current density and recombination current density of the pn junction structure.*

A. Introduction

Optical devices are strongly influenced by electrical to-light conversion and vice versa. III-V compounds are concerned with the direct band gap semiconductors and high emission and absorption of light mechanisms. The electrical behaviours of the pn junction structure are also crucial for photonic devices like light-emitting devices and solar cells. GaAs, InP and InSb are direct band gap III-V compound semiconductors that have electron and photon emission and absorption characteristics and are specially used in infrared and visible light-emitting diodes (LEDs). [1] The band structure is important for semiconductor materials. In-band theory, the electron with sufficient energy from the lower energy level, the valence band is excited to the higher energy level, the conduction band and an unoccupied state, a hole is left in the lower energy level. The electron at the higher energy level becomes free and the conduction takes place in the material. The electrical conductivity of the materials is determined by the gap between the conduction band and valence band. [2,3]Then, the electrical nature of the space charge layer under no voltage biasing, forward-biasing and reverse-biasing is determined by space charge width, immobile charge carrier concentration, electric field intensity and potential barrier. [4] Moreover, when the pn junction is forward-biased, the electrical characteristics are evaluated by the current density of the majority carrier injection and carrier recombination under a carrier transport mechanism. The electron and hole diffusion current density, which is concerned to the carrier diffusion coefficient, carrier diffusion length, thermal equilibrium minority carrier concentration, and intrinsic carrier concentration, then determines the electrical behaviors of the pn junction structure. [5,6,7]

B. Electrical Behaviours of PN Junction Structure for GaAs, InP, InSb

Band Model

GaAs, InP and InSb are group III-V compound semiconductor materials and they have direct bandgaps. GaAs has the band gap, Eg = 1.424 eV at 300K. The band structure of GaAs includes the energy band of Γ, L, and X valleys and split-off band. It has E_{Γ} = 1.42eV, E_L = 1.71 eV, E_X =1.90eV and E_{SO}=0.34eV at 300K. [8] InP has an energy gap, Eg =1.344eV at 300K. InP occupies the energy band of Γ valley (E_{Γ}) = 1.34eV, L valley (E_L) =1.93eV, X valley (E_X)= 2.19eV and split-off band (E_{so}) = 0.11 eV. [9] In InSb, Eg is equal to 0.17eV. In the InSb band structure, Γ valley band energy (E_{Γ}) = 0.17eV, L valley band energy(E_L) = 0.68eV, X valley band energy (E_X)= 1.0eV and split-off band energy (E_{so}) = 0.8 eV. [10]

The general form of band structure of the semiconductor, the equation of the higher energy level, conduction band energy and the lower energy level, valence band energy with wave vector are as followed.

$$E_c(k) = E_g + \frac{\hbar^2 k^2}{2m_n^*} \tag{1}$$

where k is the wave vector of momentum and m_n^* is the electron's effective mass.

$$E_v(k) = -\frac{\hbar^2 k^2}{2m_p^*} \tag{2}$$

where m_p^* is the unoccoupied state, hole's effective mass. [11]

Electrical Behaviors of Space Charge Layer

The majority of carrier diffusion occurs due to the carrier concentration gradient across the pn junction structure under no-bias conditions, and recombination occurs at the metallurgical junction. The immobile positive charges have appeared at the interface of the carrier depleted layer in n region and immobile negative charges have appeared at the interface of the carrier depleted layer in p region. The carrier depletion width known as immobile space charge width (ISPW) is produced at the internation of each region. At the metallurgical junction, there is a step junction for charge concentration. [12] So the built-in potential in terms of charge concentration is

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_a N_d}{n_i^2}\right) \tag{3}$$

where V_{bi}= built-in potential

N_a = immobile negative charge density in carrier depleted layer of p region

N_d = immobile positive charge density in carrier depleted layer of n region

k= Boltzmann's constant (1.38e-23)

T= 300K

q = the magnitude of electron and hole charge (1.6e-19)

Using Poisson's equation, the space charge induced field and potential height can be calculated from the charge concentration of the ISPW. [13]

Poisson's equation for one-dimensional analysis is

$$\frac{d^2\emptyset(x)}{dx^2} = \frac{-\rho}{\epsilon_s} = -\frac{dE(x)}{dx} \tag{4}$$

The space charge width of the n-type region is

$$x_n = \sqrt{\frac{2\varepsilon_r V_{bi}(N_A)}{qN_D(N_A+N_D)}} \tag{5}$$

The space charge width of the p-type region is

$$x_p = \sqrt{\frac{2\varepsilon_r V_{bi}(N_D)}{qN_A(N_A+N_D)}} \tag{6}$$

The ISPW of pn junction is

$$W = (x_n + x_p) = \sqrt{\frac{2\varepsilon_r V_{bi}(N_A+N_D)}{q(N_A N_D)}} \tag{7}$$

where W= the amount of ISPW

$\varepsilon_r = \varepsilon_0\varepsilon_s$ and ε_0=8.85e-14

The space chargre-induced electric field intensity for the n-region, $0 \le x \le x_n$ is

$$\epsilon_n = \frac{-qN_D}{\varepsilon_r}(x_n - x) \tag{8}$$

The space charge-induced electric field intensity for the p-region, $-x_p \le x \le 0$ is

$$\epsilon_p = \frac{-qN_A}{\varepsilon_r}(x_p + x) \tag{9}$$

The barrier potential height in n-region ISPW is

$$\varphi_n(x) = \frac{q}{2\varepsilon_r}(N_D x_n^2) \tag{10}$$

The barrier potential height in p-region ISPW is

$$\varphi_p(x) = \frac{q}{2\varepsilon_r}(N_A x_p^2) \tag{11}$$

Under forward biasing across the pn junction, the amount of electric field strength is reduced and the potential height is dropped in the carrier depleted layer and ISPW is narrowed. According to the electron hole concentration gradient,

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the majority carriers are injected via the immobile space charge region. Under forward bias, the total barrier voltage of the pn junction is

$$V_f = V_{bi} - V_a \tag{12}$$

where V_a is the forward bias voltage. [7] Under reverse biasing across the pn junction, the space charge induced electric field is strengthened, the potential height is raised and the ISPW becomes larger. The minority carriers of each region are drifted by the induced field due to immobile charges within the ISPL under reverse applied voltage. Due to the reverse biasing, the total barrier height of the pn junction is

$$V_{total} = V_{bi} + V_r \tag{13}$$

where V_r is the reverse applied voltage.

Carrier Concentration of Bulk Region

Due to the forward biasing, the majority carriers, electron in the bulk n region and hole in the bulk p region are injected in opposite directions. Under the carrier dynamic mechanism, the carriers pass through the ISPL. The injection of carriers into each region becomes the minority carriers: holes in n region and electrons in p region have the following boundary conditions: [5]

$$p_n(x_n) = p_{n0} exp\left(\frac{eV_a}{KT}\right) \tag{14}$$

$$n_p(-x_p) = n_{p0} exp\left(\frac{eV_a}{KT}\right) \tag{15}$$

$$p_n(x \to \infty) = p_{n0} \tag{16}$$

$$n_p(x \to -\infty) = n_{p0} \tag{17}$$

where $p_n(x_n)$ = injection of hole distribution at the margin of ISPW in n region, (x_n), under forward biasing

p_{n0} = hole concentration in n region under no biasing

$n_p(-x_p)$ = injection of electron distribution at the margin of ISPW in p region, $(-x_p)$, under forward biasing

n_{p0} = electron concentration in p region under no biasing

Assuming a long diode pn junction structure, the carrier, electron and hole distributions are continuous. According to the boundary equation, the hole distribution is exponentially increased in the neutral n region $(x \geq x_n)$ and the electron distribution is also increased exponentially in the neutral p region $(x \leq -x_p)$. The differential change for excess hole distribution in the n neutral region with respect to +x direction $(x \geq x_n)$ is

$$\partial p_n(x) = p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_n - x}{L_p}\right) \tag{18}$$

The differential change for excess electron distribution in the p neutral regionwith respect to -x direction $(x \leq -x_p)$ is

$$\partial n_p(x) = n_{p0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_p + x}{L_n}\right) \tag{19}$$

where L_p and L_n are the diffusion length of hole and electron.

Diffusion Current Density of PN Junction

Due to the forward bias, injection of hole current density, $J_p(x_n)$ is the change of excess hole distribution in the neutral n region and injection of electron current density, $J_n(-x_p)$ is the change of excess electron distribution in the neutral p region.

$$J_p(x_n) = \frac{eD_h p_{n0}}{L_p}\left(exp\left(\frac{eV_a}{KT}\right) - 1\right) \tag{20}$$

$$J_n(-x_p) = \frac{eD_n n_{p0}}{L_n}\left(exp\left(\frac{eV_a}{KT}\right) - 1\right) \tag{21}$$

The whole current density for the pn junction structure is the addition of the electron injection current density in the p bulk region, and hole injection current density in the bulk n region,

$$J_D = J_s\left(exp\left(\frac{eV_a}{KT}\right) - 1\right) \tag{22}$$

where $J_s = \frac{eD_h p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}$, the reversed saturation current.

Recombination Current Density of PN Junction

Under forward biasing of the pn junction structure, the majority carriers of neutral regions are injected via the immobile space charge layer. A few carriers, holes and electrons recombine in ISPL. The peak recombination rate of the carrier occurs at the metallurgical junction. Assume a nondegenerate semiconductor in steady-state equilibrium; the current density of recombination of some carriers, holes and electrons for the pn junction structure is

$$J_{rec} = \frac{eWn_i}{2\tau_0} exp\left(\frac{eV_a}{2kT}\right) = J_{ro}\, exp\left(\frac{eV_a}{2kT}\right) \tag{23}$$

where τ_0 is the average life time.

The sum of carrier diffusion current densities via the ISPL, J_D and the carrier recombination current density in the ISPL, J_{rec} becomes the overall current density for pn junction structure. [6]

$$J_T = J_D + J_{rec} \tag{24}$$

C. Results and Discussions

The electrical capacity to conduct in semiconductors depends on the energy gap between the bands. Table 1 shows the parameters of the GaAs, InP and InSb III-V compound semiconductors.

Table 1. Parameters of band structure the three materials [8,9,10]

Parameters	GaAs	InP	InSb
Eg (eV)	1.424	1.344	0.17
m_n^*/m_0	0.063	0.08	0.14
m_p^*/m_0	0.51	0.6	0.43
$\hbar$(Js)	1.0546e-34	1.0546e-34	1.0546e-34

Figures 1, 2 and 3 show the direct band gaps of three III-V materials that are obtained by using 1 and 2. The energy versus momentum vector (E-k) curves of GaAs and InP have nearly the same gap and InSb has the lowest gap.

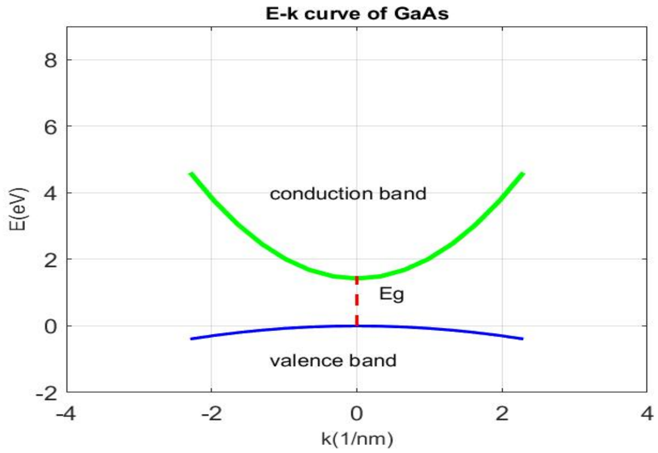

Figure 1. Energy versus momentum vector curve of GaAs

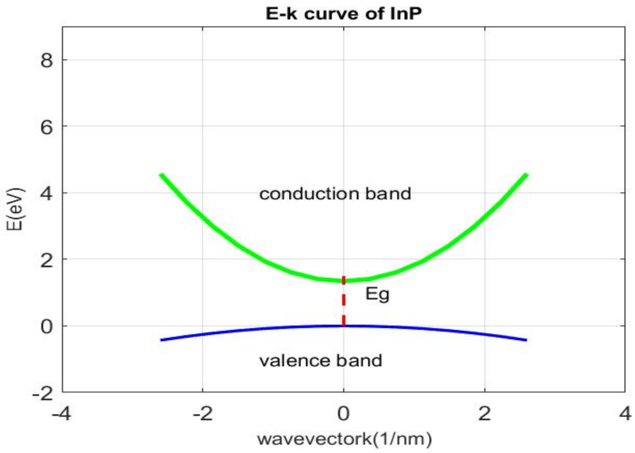

Figure 2. Energy versus momentum vector curve of InP

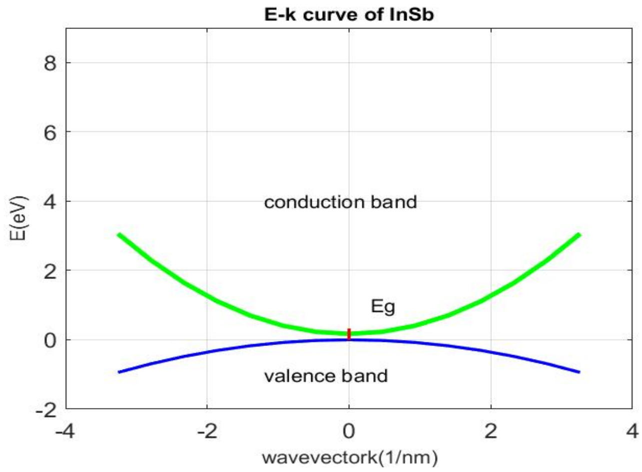

Figure 3. Energy versus momentum vector curve of InSb

Table 2 shows the parameters of the GaAs pn junction diode in the ISPL. Figure 4 shows the charge concentration of the GaAs pn junction under no biasing, forward biasing, and reverse biasing using equations 3,5,6. The ISPW is the smallest region under the forward condition and the largest region under the reverse condition. Under zero-biasing, the carrier depleted layer is between them.

Figures 5 and 6 show the induced field and potential height in the carrier depleted region for GaAs by using equations 8, 9, 10, 11, 12, and 13. Significantly, the electric field strength and barrier potential depend on the applied voltage across the pn junction.

Table 2. Parameters of carrier depleted region for GaAs [8]

Parameters	Va=0.6V	Va=0V	Va= -1V
n_i (cm^{-3})	2.1e6	2.1e6	2.1e6
N_a (cm^{-3})	7e17	7e17	7e17
N_d (cm^{-3})	7e17	7e17	7e17
ε_s	12.9	12.9	12.9
V_{bi} (V)	1.3744	1.3744	1.3744
x_n (cm)	2.8095e-6	3.7429e-6	4.9196e-6
x_p (cm)	2.8095e-6	3.7429e-6	4.9196e-6

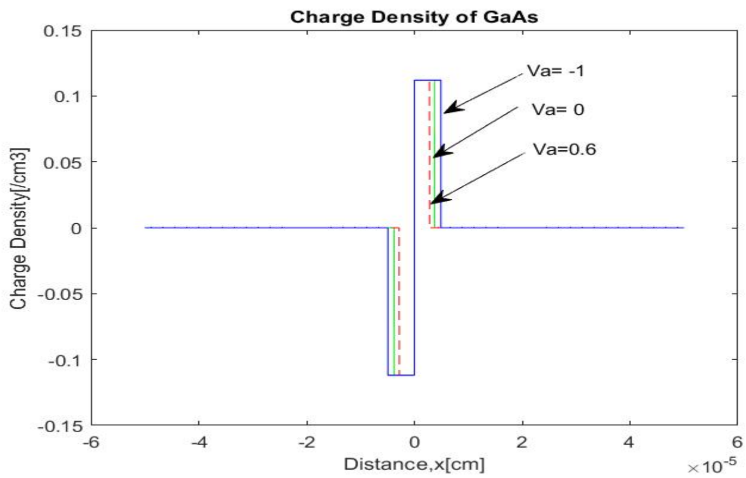

Figure 4. Charge density of GaAs

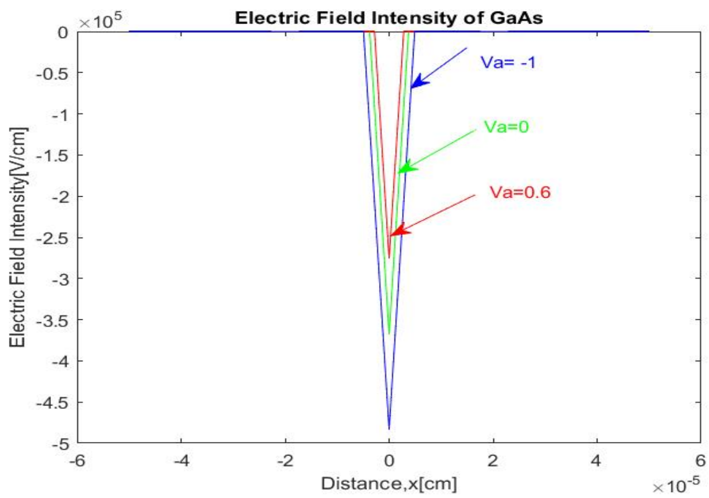

Figure 5. Electric field of GaAs

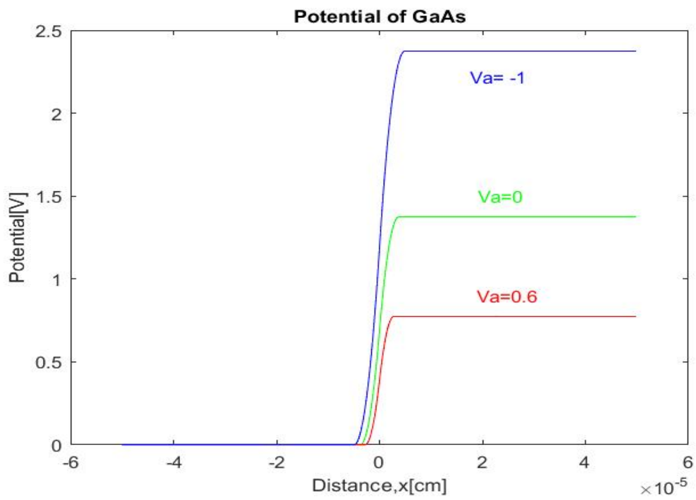

Figure 6. Potential of GaAs

Table 3, shows the parameters of the InP pn junction. The following Figures 7, 8, and 9 indicate the positions due to the immobile charge concentration, the induced electric field strength and the built in potential height for the InP pn junction structure. Similarly to GaAs, the charge concentration, the induced field strength and the barrier potential in the ISPL are changed depending on the applied voltage across the InP pn junction.

Table 3. Parameters of the carrier depleted region on for InP [9]

Parameters	Va=0.6V	Va=0V	Va= -1V
$n_i\ (cm^{-3})$	1.3e7	1.3e7	1.3e7
$N_a\ (cm^{-3})$	7e17	7e17	7e17
$N_d\ (cm^{-3})$	7e17	7e17	7e17
ε_s	12.5	12.5	12.5
V_{bi} (V)	1.2799	1.2799	1.2799
$x_n\ (cm)$	2.5915e-6	3.555e-6	4.7455e-6
$x_p\ (cm)$	2.5915e-6	3.555e-6	4.7455e-6

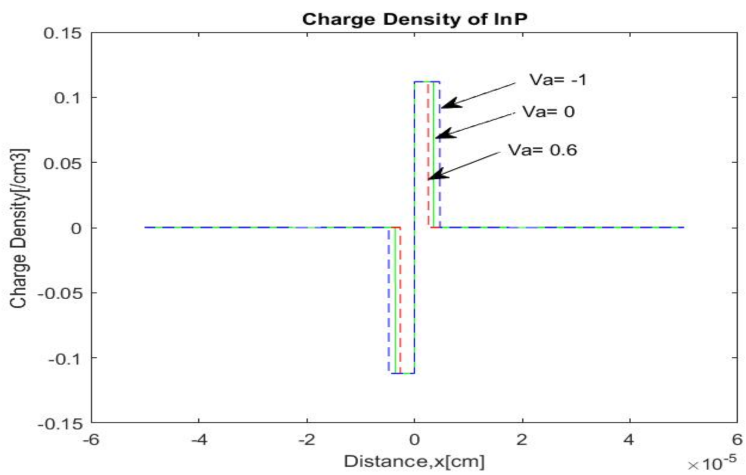

Figure 7. Charge density of InP

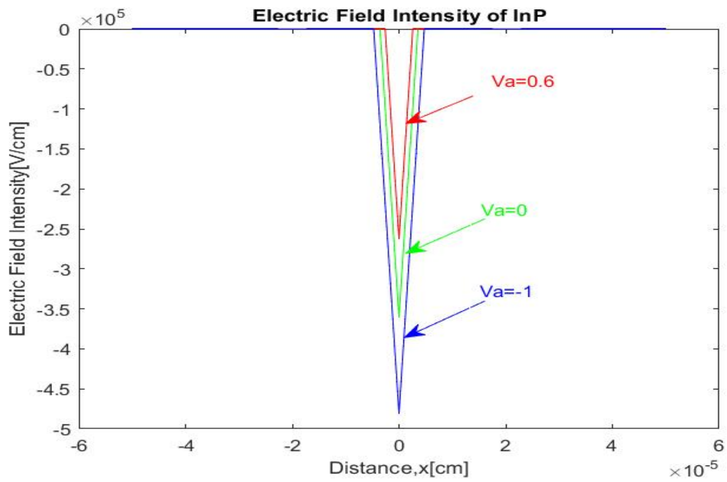

Figure 8. Electric field of InP

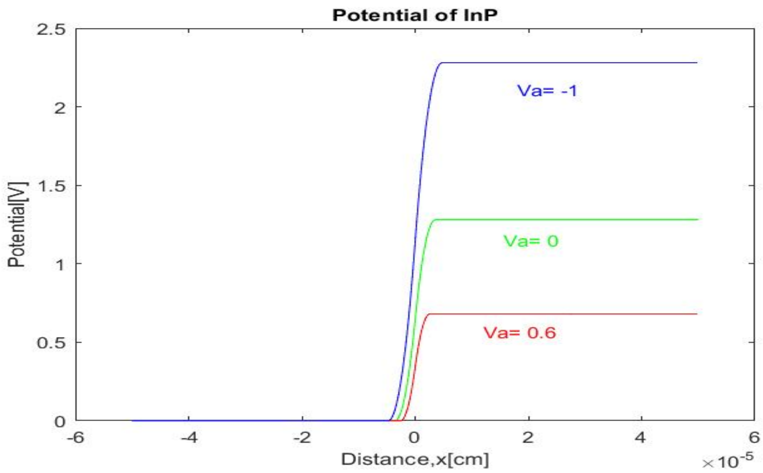

Figure 9. Potential of InP

Table 4 shows the parameters of the InSb pn junction. The below Figures 10, 11, and 12 point out the profile of the charge concentration, the field strength and the potential height in ISPW for InSb pn junction diode by using equations, 3,5,6,8,9,10,11,12 and 13. The situation of ISPW for the InSb pn junction rely the external electrical supply voltage.

Table 4. Parameters of carrier depleted region for InSb [10]

Parameters	Va=0.17V	Va=0V	Va= -1V
n_i (cm^{-3})	2e16	2e16	2e16
N_a (cm^{-3})	7e17	7e17	7e17
N_d (cm^{-3})	7e17	7e17	7e17
ε_s	16.8	16.8	16.8
V_{bi} (V)	0.1842	0.1842	0.1842
x_n (cm)	4.3367e-7	1.5636e-6	3,9648e-6
x_p (cm)	4.3367e-7	1.5636e-6	3,9648e-6

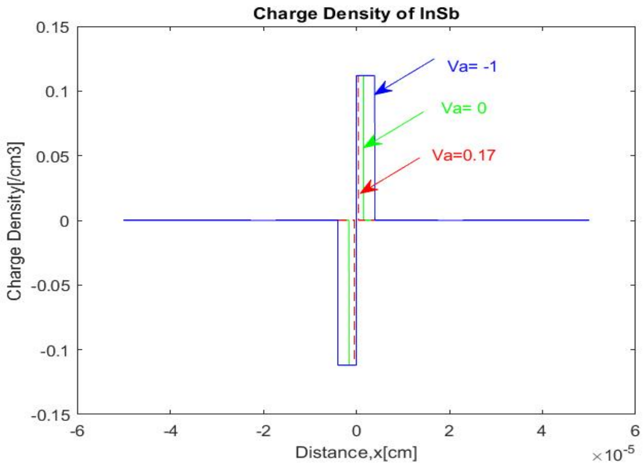

Figure 10. Charge density of InSb

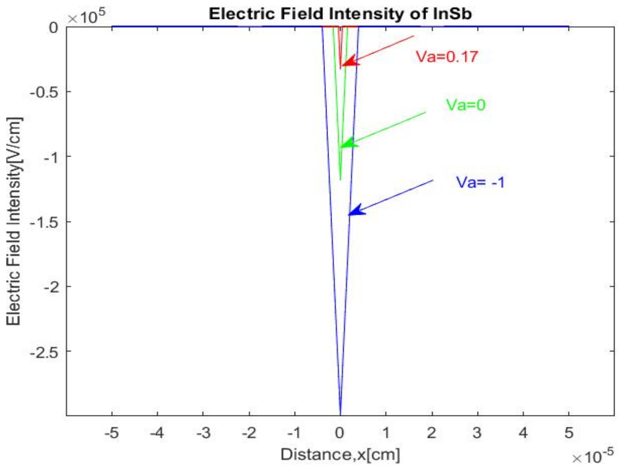

Figure 11. Electric field Intensity of InSb

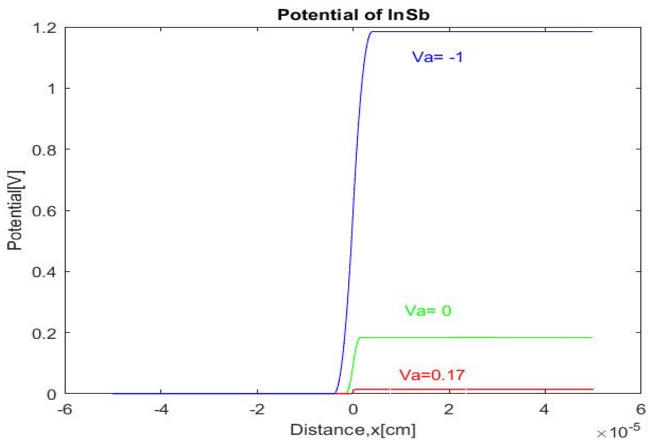

Figure 12. Potential of InSb

Table 5 represents the input parameters of the carrier distribution and current density for the three materials pn junctions. Under forward biasing of the pn junction, the carrier, hole from p region and electron from n region are injected into n and p neutral region. Figures 13,14 and 15 are the injected carrier distribution curves of GaAs, InP and InSb by using equations 18 and 19. Obviously, the hole diffusion length in n neutral region for InSb has the greatest distance with +x direction and also the electron diffusion length in the p neutral region for InSb has the smallest distance in - x direction.

Table 5. Parameters of current density for three III-V compounds [8,9,10]

Parameters	GaAs	InP	InSb
$L_n\ (\mu m)$	10	8	10
$L_p\ (\mu m)$	40	40	100
$D_n(cm^2 s^{-1})$	200	130	2e3
$D_p(cm^2 s^{-1})$	10	5	22
$\tau_0\ (s^{-1})$	8e-4	8e-4	5e-6

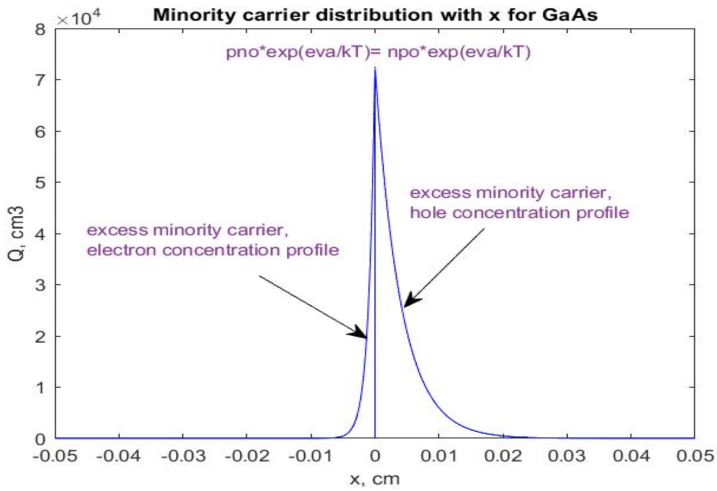

Figure 13. Carrier Distribution of GaAs

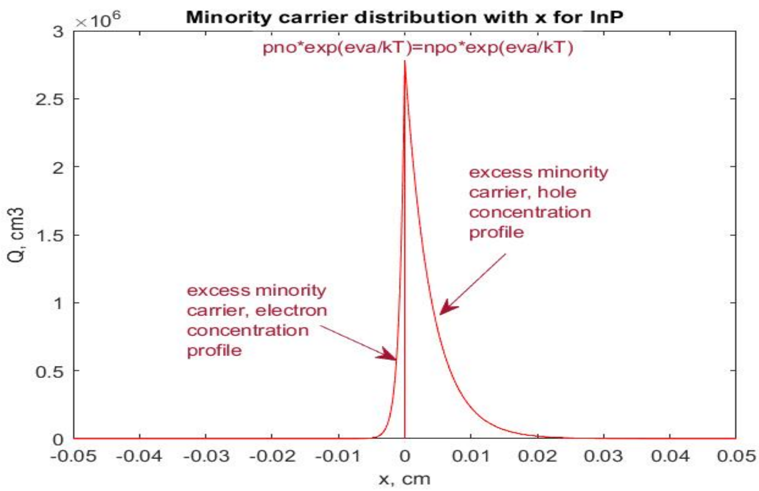

Figure 14. Carrier Distribution of InP

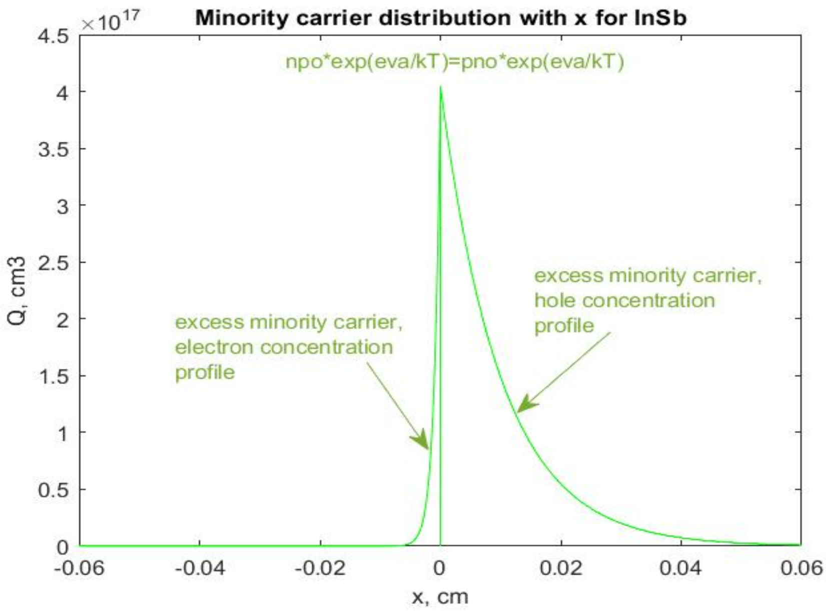

Figure 15. Carrier Distribution of InSb

Using equations 22, 23, and 24, the J-V characteristic curves of GaAs, InP, and InSb are shown in Figures 16, 17, and 18. For GaAs and InP, carrier recombination current density, is dominant by a small factor of $\left(\frac{eV_a}{kT}\right)$. On the large scale of $\left(\frac{eV_a}{kT}\right)$ the carrier diffusion current density is dominant. However, in every factor of $\left(\frac{eV_a}{kT}\right)$ the diffusion current density is more effective than the recombination current density for the InSb pn junction structure.

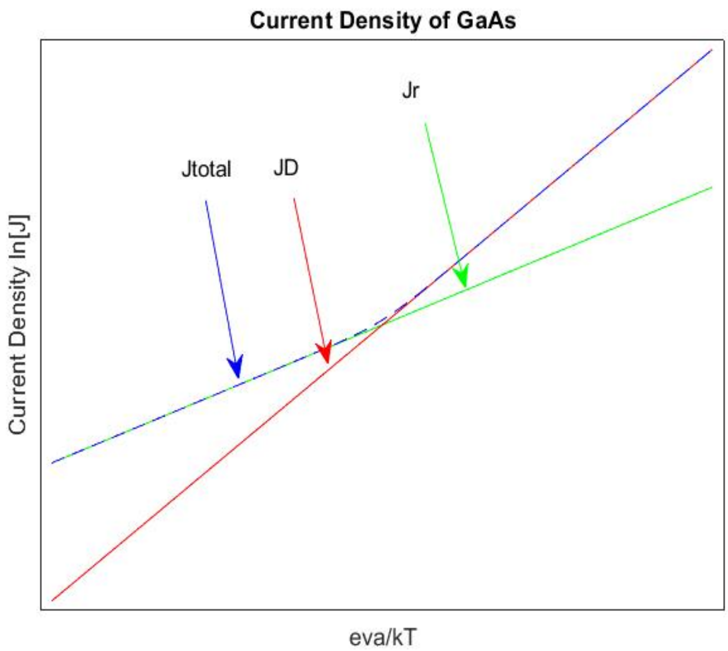

Figure 16. J-V curve of GaAs

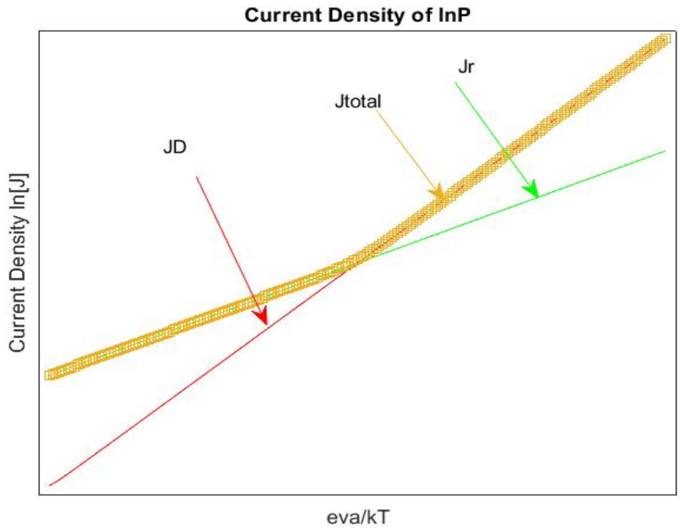

Figure 17. J-V curve of InP

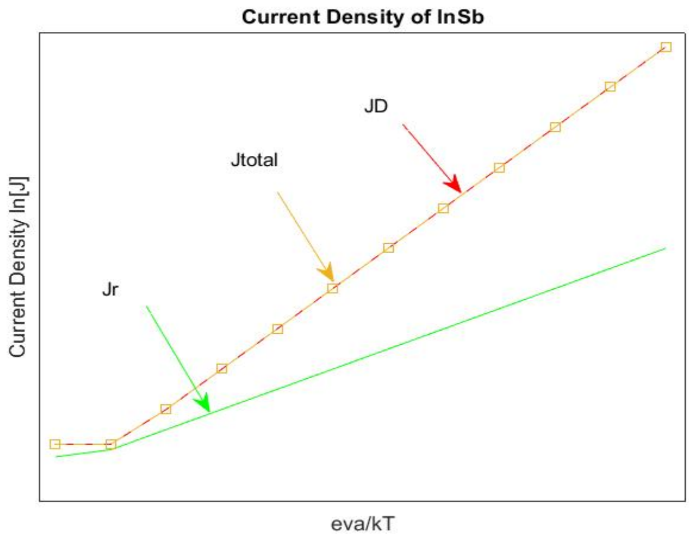

Figure 18. J-V curve of InSb

D. Conclusions

The electrical features of the semiconductor pn junction structure based III-V compound have been predicted by the gap between the materials' energy levels, and the ISPL characteristics that is provided by charge concentration, the space charge induced field and the built in potential height under zero voltage and forward and reversed applied voltage. Then the electrical properties of pn junction structure depend on the excess electron and hole distributions in the bulk regions and the J-V characteristic curves. Clearly, according to the band structure, the smallest amount of energy (0.17 eV) is needed to conduct in InSb material. Morever, among the three III-V materials, InSb has the most conductivity and InP has a more conductivity than GaAs. Due to the behavior of the ISPL, the external minimum voltage, (1.3744 V) is required to conduct in GaAs pn junctions, and (1.2799 V) is needed to conduct in InP pn junctions. Electrical conduction occurs in

InSb pn junctions under 0.17 V, the minimum required applied voltage. Due to the carrier distribution in the bulk region, InSb has the largest electron diffusion length in n region and the smallest hole diffusion length in p region. From J-V curves, the diffusion and recombination curve behaviors for GaAs and InP are nearly the same and those of InSb are a little different. Among the three materials of the pn junction structure, InSb has the highest conductivity behavior based on its electrical nature and is very sensitive to conducting current in materials under a small range of forward bias. So, while GaAs and InP pn junction structures have lower conductivity than InSb, they have the most effective current conductivity of the semiconductor materials due to their electrical properties. Furthermore, the two materials, GaAs and InP, are used as good semiconductor materials due to their electrostatic natures under a very suitable range of forward bias voltage.

E. References

[1] [PDF] III-V compound SC for optoelectronic devices | Semantic Scholar.
[2] https://www.intechopen.com/chapters/73955
[3] https://byjus.com/physics/band-theory-of-solids/
[4] Abdel-Rahman Mohammed," P-N Junction" Technical Report · April 2020, DOI: 10.13140/RG.2.2.13294.23363.
[5] Donald A. Neamen, "Semiconductor Physics and Devices" Fourth Edition, The McGraw-Hill Companies, 2012, ISBN 978-0-07-352958-5.
[6] S. O. Kasap, "Principles Of Electronic Materials And Devices", Fourth Edition, The McGraw-Hill Companies, 2018, ISBN 978-0-07-802818-2.
[7] S. M. SZE and M. K. LEE, "Semiconductor Devices", Third Edition, John Wiley & Sons,Inc, 2012, ISBN 978-0470-53794-7.
[8] https://www.ioffe.ru/SVA/NSM/Semicond/GaAs/
[9] https://www.ioffe.ru/SVA/NSM/Semicond/InP/
[10] https://www.ioffe.ru/SVA/NSM/Semicond/InSb/
[11] http://www.jiwaji.edu/pdf/ecourse/physics/SemiconductorBand%20Structure.pdf
[12] https://sciencepublishinggroup.com/journal/paperinfo?jornalid=522&doi=10.11648/j.ijem.20220602.11
[13] http://www.ugr.es/~tejada/Componentes/ftp/CEpractica02.pdf