Studies on The Performance of Gaas PIN Photovoltaic Cell With Depleted Intrinsic Layer and No Defect Density

Debashish Pal
M.Tech., Intitute of Engineering and Management, Kolkata

Abstract- *The performance of a p-i-n solar cell is compared to that of a reference p-n junction solar cell. For increased generation of charge carriers, the layer at the top should be very thin. For improved collection probability the excitons are to be generated in the depletion region where they have a greater chance of separation resulting in the short circuit current [1]. Because the depletion region width has inverse square root dependence on the impurity concentration, therefore an intrinsic layer is incorporated between the p-n junction to maximize the depletion region width, resulting in the formation of a p-i-n structure. Investigations have revealed that the presence of the intrinsic layer increased the quantum efficiency of the solar cell from 6.94% to 21.63%.*

Keywords- absorption coefficient, AM1.5 spectrum, compound semiconductor, homojunction, quantum efficiency

I. INTRODUCTION

When sunlight is incident on the surface of the cell, photons with energies higher than the energy bandgap of the semiconductor are absorbed, exciting the electrons which make a transition from the valence band to the conduction band. The electrons in the conduction band and the holes left behind in the valence band act as free charge carriers, which are separated due to the concentration gradient or by the application of an external electric field. These charge carriers are collected by metal electrodes at the top and the bottom, having appropriate work functions.

The performance of a solar photovoltaic cell depends on its fabrication technology, design and material properties. In order to find out the best structure with fitted parameters numerical simulation is the best approach, which helps optimize the performance of a solar cell. This approach also helps reduce the complexity associated with the fabrication process, reduces cost and saves time significantly. Thus numerical modelling is gaining widespread popularity in the scientific community with constantly new improved tools being developed and upgraded with added features. These tools help us provide better insights into the details of the physical operation of devices. The major objectives of numerical modelling and simulation in solar cell research are testing the validity of proposed physical structures, the effect of material and geometry on cell performance and fitting of modelling output to experimental results [2].

Group III–V compound solar cells are usually used as the energy sources on satellites and spacecraft due to their ultra-high conversion efficiency. These materials are well known for their stability, ability to harness radiation and most notably the tenability of the band-gap energy [3]. At present, III–V compound semiconductors provide the materials basis for a number of well-established commercial technologies, as well as new cutting-edge classes of electronic and optoelectronic devices. Ternary and quaternary alloys may be included in addition to the binary compounds, and the materials may be layered in an almost endless variety of configurations [4]. Gallium arsenide is the most technologically important and the most studied compound semiconductor material [5].

In recent years, solar cells based on gallium arsenide have been widely used, particularly for space applications, owing to their high efficiency and a low degradation upon exposure to sunlight. The efficiency achieved for the first gallium arsenide solar cell developed was only about 10% [6-7]. This was due to the significantly high surface recombination rate in the cells, which hampered its overall performance and precluded any further progress in gallium arsenide solar cell research. In the recent past terrestrial efficiencies of over 22% were reported under AM1 spectrum, which is much higher than the corresponding measure of 18% for silicon [8]. Gallium arsenide has an absorptivity so high that it takes only a few microns absorb sunlight whereas crystalline silicon requires a layer which is 100 microns or more thick. Traditional gallium arsenide solar cells with a p-n junction were normally 3μm thick in total, the emitter layer having slightly less thickness compared to the base so that the junction is closer to the surface. Silicon cells, on the other hand, have thicknesses surpassing 250μm because of it being indirect band gap semiconductor [9].

One out of the many kinds of basic solar cell structures is the p-i-n structure, which consists of p- and n-doped regions at the top and the bottom with an intrinsic layer (i-layer) in the middle. It provides a simple way to improve the absorption ability with a thick intrinsic region. However a thicker i-layer may induce more defects degrading the quality of the epitaxially grown layers and resulting in the formation of dangling bonds. The built in electric field is also dependent on the thickness of the i-layer with the field strength decreasing with the increase in thickness of the i-layer [10]. This is undesirable as it is the built in electric field that ensures the isolation of the charge carriers from the generated excitons resulting in the photocurrent.

II. MODELING AND SIMULATION

A homojunction is a semiconductor interface that occurs between layers of similar semiconductor material, having equal bandgaps but may have different doping. First a reference p-n homojunction solar cell as shown in Fig.1 was used for simulation. The different parameters used for the reference cell are shown in Table1.

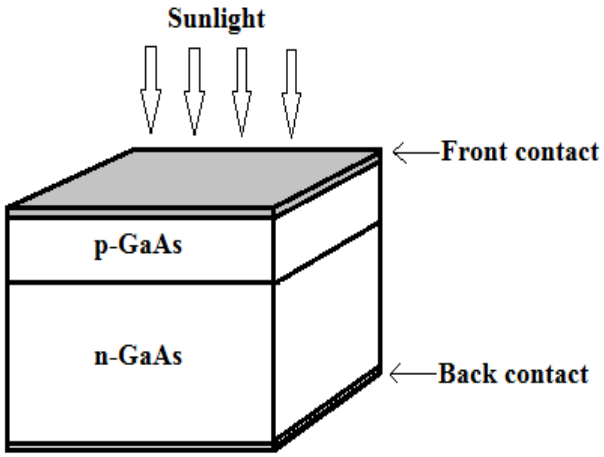

Fig. 1: p-n Junction Reference Cell

Table I: Parameters of the p-n reference cell

Material	GaAs
Bandgap (eV)	1.424
Electron Affinity (eV)	4.070
Dielectric Constant	12.90
Acceptor Concentration, N_A (atoms cm^{-3})	$1x10^{18}$
Donor Concentration, N_D (atoms cm^{-3})	$1x10^{17}$
Electron mobility ($m^2V^{-1}s^{-1}$)	8500
Hole mobility ($m^2V^{-1}s^{-1}$)	400

The following approximation is taken into account while modelling the p-i-n structure. The i-layer placed between the emitter and the base is ideally undoped. In practice it has a background doping much smaller than the doping of the p- and n-layer. The depletion regions in the p-i-n junctions extend furthest into the lightest doped region [11]. In a p-i-n junction the depleted widths of the p- and n-layer are assumed to be very small. For a narrow i-layer with low background doping it is reasonable to consider the whole i-layer as depleted with an electric field present throughout the whole i-layer. Also while modelling the structure it is ensured that there are no defects at the interface. The presence of defect density at the interface adversely affects the performance of a solar cell by decreasing the efficiency. Keeping the thickness of the emitter and the base fixed to 10nm and 40nm respectively, and the other parameters constant, an intrinsic layer of thickness 0.5µm was introduced at the junction of the reference cells as shown in Fig.2.

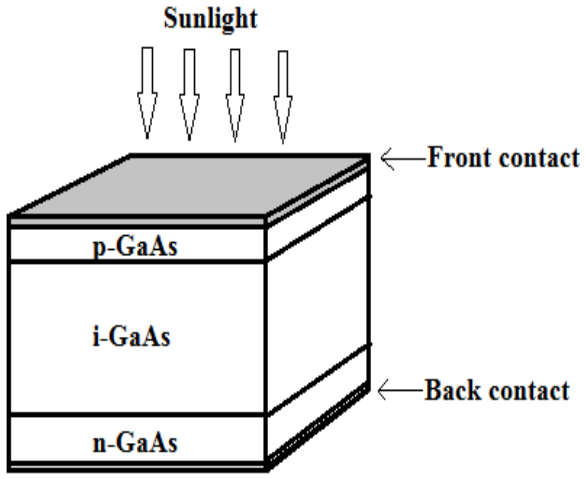

Fig. 2: p-i-n solar cell structure

Solving the one dimensional Poisson's equations (1-3) alongwith the constitutive relations (4-5) together with the appropriate boundary conditions, the solutions can be obtained.

$$\frac{\partial}{\partial x}\left(\varepsilon_0\varepsilon\frac{\partial\Psi}{\partial x}\right) = -q\left(p - n + N_D^+ - N_A^- + \frac{\rho_{def}}{q}\right) \quad (1)$$

$$-\frac{\partial J_n}{\partial x} - U_n + G = \frac{\partial n}{\partial t} \quad (2)$$

$$-\frac{\partial J_p}{\partial x} - U_p + G = \frac{\partial p}{\partial t} \quad (3)$$

$$J_n = -\frac{\mu_n n}{q}\frac{\partial E_{Fn}}{\partial x} \quad (4)$$

$$J_p = +\frac{\mu_p p}{q}\frac{\partial E_{Fp}}{\partial x} \quad (5)$$

The quantum efficiency indicates the amount of current a solar cell will produce when irradiated by photons of a particular wavelength and can be calculated using equation (6). If the cell's quantum efficiency is integrated over the whole solar spectrum, the total current generated by the solar cell when exposed to sunlight can be calculated.

$$QE(\lambda) = \int_0^L G(\lambda)\exp\left[\int_0^x \left(-\frac{dx}{L_d}\right)\right] dx \quad (6)$$

III. RESULTS AND DISCUSSION

Modelling and simulations were performed using the standard AM1.5 spectrum with a concentration factor of X=1000.Wavelengths ranging from 300 nm to 900nm are used and iterations of upto 1000 were made to obtain the results. An operating temperature of 300K was chosen. In order for the solutions to converge the structure was first discretized and finer meshing was used at the interfaces and the contacts. The results of the simulation corresponding to the p-n reference cell and the p-i-n solar cell are shown at the top and the bottom.

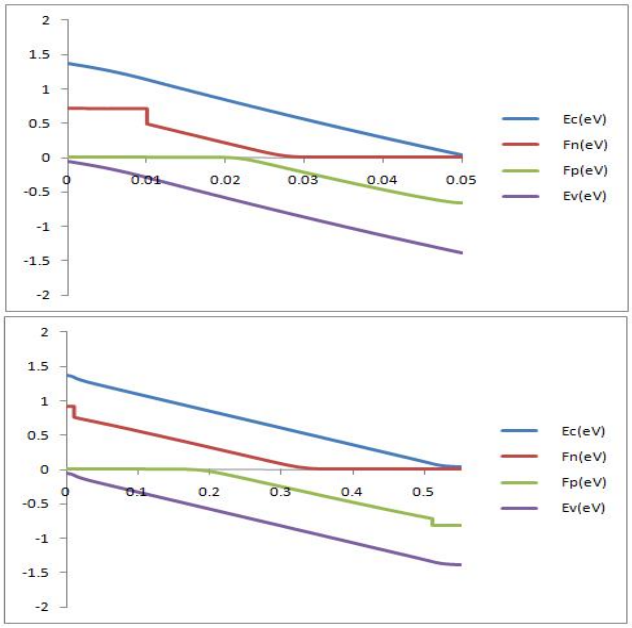

Fig. 3: Energy Band Diagrams

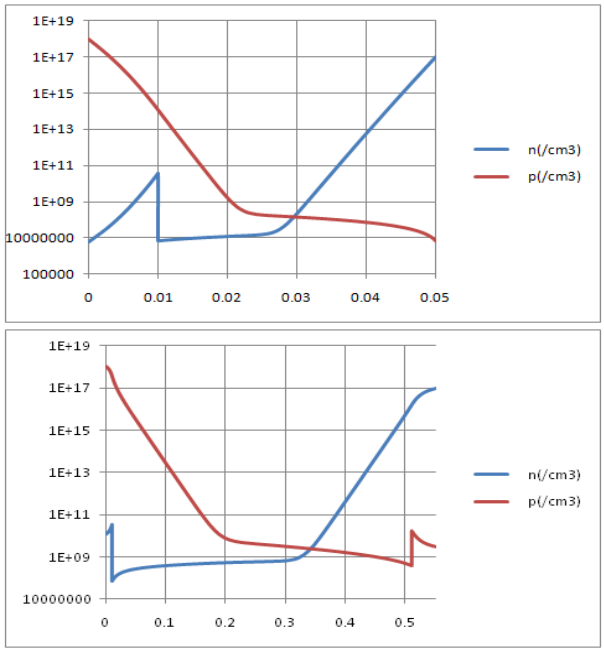

Fig. 4: Charge Concentrations

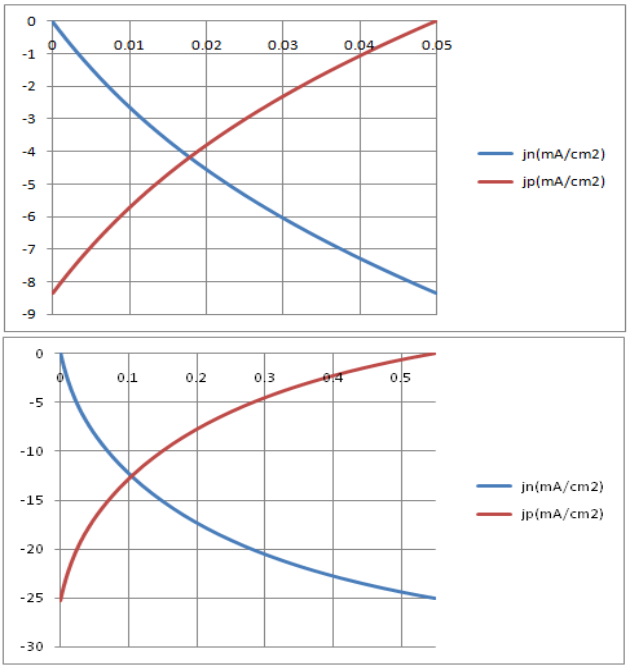

Fig. 5: Current Densities

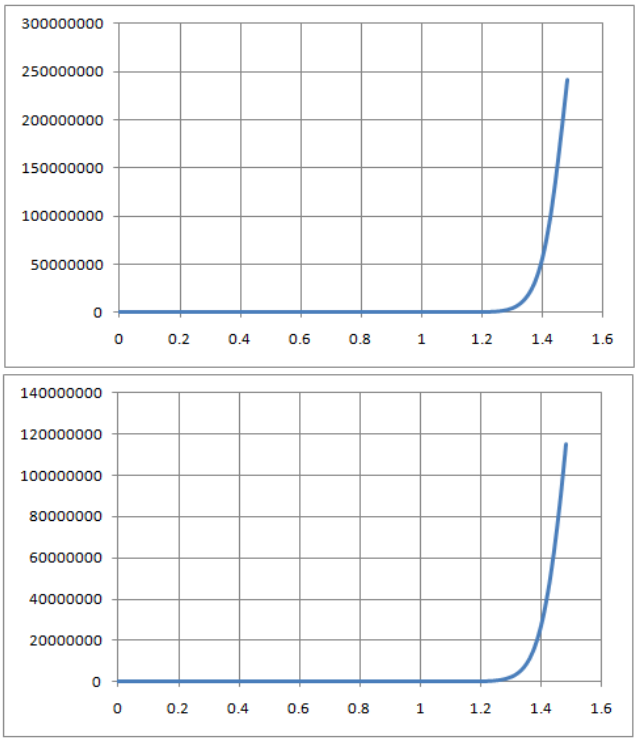

Fig. 6: I-V Characteristics

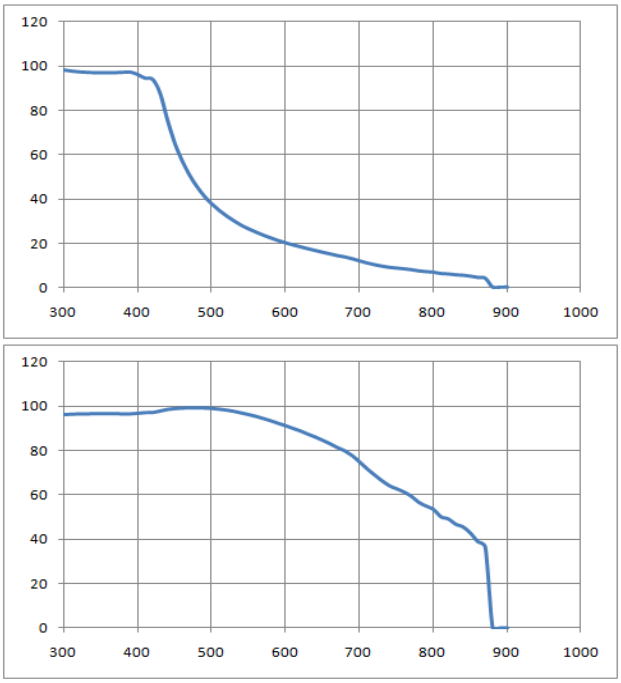

Fig. 7: Quantum Efficiencies

Table II: Summary of results from the J-V curve

Structure	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η (%)
p-n	0.9493	8.361158	87.43	6.94
p-i-n	0.9832	25.040806	87.84	21.63

The wavelength range utilized here is 300nm to 900nm since higher wavelengths are not present in sunlight in large quantities, and lower wavelengths are absorbed by all structures. So the quantum efficiency over these range of wavelengths provide the best idea about the performance of the cell. It is evident from the fig. 7 that the total area under the quantum efficiency curve for the p-i-n structure is greater than the reference cell. This is indicative of the fact that the intrinsic layer also absorbs lower energy photons. Investigations carried out in the past firmly establish that the graphs obtained after simulation is in good agreement with the expected results. The curve shows that the absorption coefficient of the p-i-n solar cell is greater than that of the reference cell. Finally the results of the simulation demonstrate that the overall efficiency of the PN junction reference cell is only η=6.94% against η=21.63% for the p-i-n solar cell, which can be attributed to the increased photocurrent generated in the p-i-n structure.

IV. CONCLUSION

This article analyses the performance of a gallium arsenide homojunction p-n reference cell and the effect of

incorporating an intrinsic layer with the same material at the middle of the oppositely doped layers. The inclusion of the intrinsic layer increases the depletion region width which in turn increases the electric field, facilitating the transport of charge carriers by the drift mechanism. In addition the relatively high conversion efficiency can be attributed to the absence of any defect density at the interfaces. Further studies can be done to investigate the performance of the p-i-n cell by varying the thickness of the intrinsic layer, the doping concentration and introduction of defect densities.

REFERENCES

[1] Solanki, C. S. (2013). Solar Photovoltaics: Fundamentals, Technologies and Applications (pp. 112). Delhi.
[2] SJ Fonash. Solar Cell Device Physics. Academic Press, New York, USA, 2nd edition, 2010.
[3] M. Yamaguchi, "Potential and present status of III–V/Si tandem solar cells," 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC), Denver, CO, 2014, pp. 0821-0826.
[4] I. Vurgaftman, J. R. Meyer, L. R. Ram-Mohan Band parameters for III–V compound semiconductors and their alloys, APPLIED PHYSICS REVIEW, 2001
[5] S. Adachi, GaAs and Related Materials: Bulk Semiconducting and Superlattice Properties ~World Scientific, Singapore, 1994.
[6] S. C. Tsaur, "Theoretical and experimental results for GaAs solar cells", Proceedings of the fourth international symposium on GaAs and related compounds, conference series no. 17, The Institute of Physics, London, U.K., (1972), pp. 156.
[7] C. Hardingham, S. P. Wood., "High efficiency GaAs solar Arrays in Space," GEC Review. vol. 13, no. 3 (1998), pp. 163-171.
[8] Green, M. A. (1981).Solar Cells: Operating Principles, Technology and System Applications. N. Holonyak, Ed.,Australia: Prentice-Hall. pp 46-47.
[9] Talukdar.T.H., Siddique, R., Hasan, M.(2015).Study of single junction solar cell characteristics varying different parameters.2015 International Conference on Electrical Engineering and Information Communication Technology (ICEEICT), Dhaka, Bangladesh.
[10] Tsung-Shine Ko, Der-Yuh Lin, You-Chi He, Chen-Chia Kao, Bo-Yuan Hu, Ray-Hua Horng, Fan-LeiWu, Chih-HungWu, and Yu-Li Tsai (2015) Optoelectric Properties of GaInP p-i-n Solar Cells with Different i-Layer Thicknesses, International Journal of Photoenergy
[11] J. Nelson. The Physics of Solar Cells.