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Analyze the effect of window layer (AlAs) for increasing the efficiency of GaAs based solar cell

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ABSTRACT: *Solar energy is the most important renewable source and convertible into useful form with no transmission cost and environment pollution. The main drawback of currently used photovoltaic cell is its low conversion efficiency and materials with the appropriate band gaps. Recently it has been shown that the GaAs based p-i-n solar cell becomes a promising material for very high efficiency solar cell. An ideal model for p-i-n reference cell has been developed and used to theoretically explore the current-voltage characteristics on the host cell properties. The purpose of this paper is to study the performance of AlAs material use as window layer in p-i-n reference cell instead of AlGaAs and evaluated the performance with various parameters. Short circuit current density, open circuit voltage and efficiency are needed to be calculated with the dependencies of band gap energy, carrier concentration and temperature. Significant effects of width lengths on the performance of window layer are evaluated. These calculations will do at cell temperature of 300k. After all comparing these, GaAs based p-i-n reference cell with AlAs window layer offers the maximum efficiency.*

KEYWORDS – *Solar cell, window layer, efficiency.*

I. INTRODUCTION

Present day civilization and industries are highly dependent on energy. The main sector contributing this huge amount of energy generation is the fossil fuel with limited resources. Some of these resources are only available in few regions of the world. The scarcity also possess risk to national and regional resource security and autonomy as well as international security. The difficulty and cost of safty disposing radioactive material and toxic waste, makes the use of nuclear and chemical energy a questionable solution. Also the fossil fuel is costly for transmitting in remote areas. Therefore, renewable sources of energy need to be considered seriously for two main reasons: (i) To meet the world wide energy demand and (ii) To protect the environment from the destructive burning of fossil and other fuels. Renewable energies such as wind power, water, biomass and active and passive solar energy have the potential to overcome these problem, as they are unlimited. Due to the decentralized and distributed nature of most of these energy sources, they provide the energy when and where it is needed ensure national and regional resource security. The reliability of the power supply from renewable energies is usually higher than the conventional energy sources. The solar energy is the most important renewable source and convertible into useful form with no transmission cost and environment pollution.

To be competitive with the conventional energy, the cost of solar energy must be comparable with the cost of conventional energy. There are many factors, which affect the cost of solar energy. The cost of solar energy may be reduced by improving the performance of solar cells. Among the performance parameters, the efficiency of solar cell is very important. The main drawback of solar energy is their low conversion efficiency. To increase the efficiency of a cell some approaches are being practiced all over the world. Now these days some of these approaches are multi junction solar cell, multi quantum well solar cell, quantum dot solar cell, multiple absorption path solar cells, multiple temperature solar cells etc. Although they provide high efficiency but their fabrication process difficult and costly. Comparatively single junction solar cell plays an important role in this cost minimization issue. These higher efficiency with fabrication processes is comparatively less difficult and it provide minimum cost. GaAs based solar cell offers maximum efficiency among all the single junction solar cell.

II. BASIC PRINCIPLE OF SOLAR CELL

A solar cell basically consists of a photon-absorbing material between a back and a front contact. The absorption is performed by electrons which absorb photon energy, Eph. If Eph is equal to the band gap of the material, Eg , the electron can be excite from the valence band to the conduction band, leaving a hole in the valence band. This is called electron hole pair generation. If Eph is greater than Eg, the electron will be excited above the conduction band are then relax down to the band edge and release the extra energy (Eph-Eg) as heat to the to the lattice, in a process referred to as thermalisation.

The opposite effect to electron hole pair generation is recombination in which electrons and holes recombine i.e. electrons fall back into a hole without contributing to the light generated current. Generation contributes to the number of free carriers. Free carriers are (electrons and in the solar cell whereas recombination decreases the number of free carriers. Free carriers are prerequisites for current output from the solar cell. A polarization occurs if electrons and holes are separated and move towards different contacts . If an electric circuit is connected to the cell, electrons will flow from the one of the contacts through the circuit and recombine with the holes in the other contact and hence, a current will flow in the circuit. A current from a solar cell required the separation of charge carriers i.e. electrons and holes. There are different ways to achieve charge separation in the solar cell.

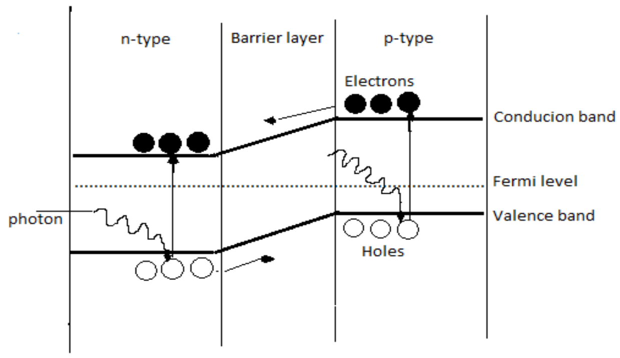

Figure: Solar cell operation

A common way is to use a p-n junction where a p-doped and an n-doped semiconductor are brought together. A p-doped semiconductor has a higher density of holes compared to electrons and an n-doped semiconductor has a higher density of electrons compared to holes. When they are brought together, carriers will flow from regions with high density. Hence, electrons will flow from the n-side to the p-side and holes in the opposite direction due to the concentration gradient. This is known as diffusion.

Electrons which are negatively charged, diffuse to the p-type side they leave positively charged ions in the n-type side. Similarly, holes leave negatively charged ions in the p-type side. Ions on opposite sides of the junction result in an electric field over the p-n junction which will oppose the diffusion. The flow of free carriers in the electric field is called drift current. In equilibrium, drift and diffusion currents are equal. The electric field, introduced into the cell by the p-n junction, provides the force for charge separation since it drives the different charges, generated by electron hole pair generation, in opposite directions. Within some distance on either side of the junction, the materials are depleted of free carriers and this region is called depletion region.

2.1 Basic Principles of a Solar cell

This parameter determines the performance of a solar cell i.e how good that solar cell is.

The main parameters are:

- Short circuit current
- Open circuit voltage
- Fill factor
- Efficiency

2.1.1 Short circuit current J_{sc}

It is defined as the current of a solar cell when the top and bottom (negative and positive leads) are connected with a short circuit. The current drawn when the terminals are connected together is the short circuit currentJ_{sc}. For any intermediate load resistance RLR_L the cell develops a voltage V between 0 and Voc and delivers a current I such that V = IR_L and I(V) is determined by the current voltage characteristic of the cell under that illumination. Thus both I and V are determined by the illumination as well as the load. Since the current is roughly proportional to the illuminated area, the short circuit current density J_{sc} is the useful quantity for comparison.

2.1.2 Open circuit voltage V_{oc}

It is defined as the voltage between the terminals obtained when no current is drawn from the solar cell. The voltage developed when the terminals are isolated (infinite load resistance) is called the open circuit voltageV_{oc}.

2.1.3 Fill factor (FF)

The operating regime of the solar cell is the range of bias, from 0 to Voc, in which the cell delivers power. The cell power density is given by P = JV where P reaches a maximum at the cell's operating point or maximum power point. This occurs at some voltage $V_m$with a corresponding current density J_m. The optimum load thus has sheet resistance given by V_m/J_m. The fill factor is defined as the ratio

$$\text{FF} = \frac{V_m J_m}{V_{oc} J_{sc}}$$

2.1.4 Efficiency η

The efficiency η of the cell is the power density delivered at operating point as a fraction of the incident light power density, P_s,

$$\eta = \frac{V_m J_m}{P_s}$$

Efficiency is related to J_{sc} and V_{oc} using FF,

$$\eta = \frac{V_{oc} J_{sc} \text{FF}}{P_s}$$

2.2 Model of the p-i-n reference cell

Practical solar cells have a complicated structure with several layers in addition to the p-and n-layer we find in the simplest p-n solar cell. The purpose of these layers is to reduce front and back surface recombination and surface reflection. A sketch of a p-i-n reference cell is shown in figure showing all the layers (anti-reflective coating, window, p^+, p, i, n and n^+) included to obtain a high efficiency solar cell.

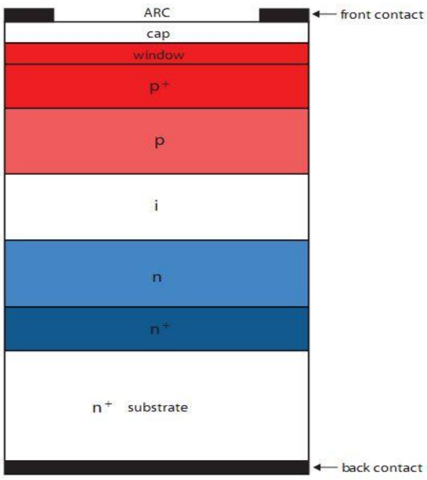

Figure: Structure of the p-i-n reference cell. It consists of an anti-reflective coating, a cap-, window-,p^+-, p-, i-, n- and n^+ layer placed on top of the substrate. The effect of using all these layers is described in the text.

2.3 Materials used in solar cell

Various materials are used in solar cell at table below

Table Materials used in a solar cell

Layers	**Materials**
Window	AlAs
p^+	GaAs
p	GaAs
i	GaAs
n	GaAs
n^+	GaAs

2.4 Purpose of using AlAs as window layer

Recombination of excess carriers occurs not only within the bulk of a semiconductor crystal, but at the surface of the crystal as well. The periodicity of the atoms is interrupted at the surface of the crystal, and the surface acts as an interface between the semiconductor and another material. As a result the recombination rate at the surface is different (and usually higher) than in the bulk of the semiconductor. Surface recombination is reduced by a passivating or window layer which prevents minority carriers from reaching the surface. Surface recombination velocity is strongly dependent on the surface roughness, contamination, ambient gases used during oxidation and the annealing conditions. In gallium arsenide, the surface recombination velocity is very high (of the order of 10^6 cm/s). The deposition of a thin layer of AlAs, however, reduces the recombination velocity at the interface to 10-10^3 cm.

III. CALCULATION OF PHOTO CURRENT AND QUANTUM EFFICIENCY

The photocurrent generated by a solar cell under illumination at short circuit is dependent on the incident light. To relate the photocurrent density, J_{sc}, to the incident spectrum we need the cell's quantum efficiency, (QE). QE (E) is the probability that an incident photon of energy E will deliver one electron to the external circuit. Then the photocurrent can be written in terms of the quantum efficiency QE(E)

$$J_{light} = q\int F(E)QE(E)dE$$

Where QE (E) is the probability that a photon of energy E will contribute with one electron to the current. The quantum efficiency is the sum of the quantum efficiency in the p-layer and n- layer given as

$$QE_p = \left[\frac{(1-R)\alpha L_n}{\alpha^2 L_n^2 - 1}\right] \times \left\{\frac{(K_n + \alpha L_n) - e^{-\alpha l_p}\left(K_n \cosh(\frac{l_p}{L_n}) + \sinh\left(\frac{l_p}{L_n}\right)\right)}{K_n \sinh\left(\frac{l_p}{L_n}\right) + \cosh\left(\frac{l_p}{L_n}\right)} - \alpha L_n e^{-\alpha l_p}\right\}$$

And

$$QE_n = \left[\frac{q(1-R)\alpha L_p}{(\alpha^2 L_p^2 - 1)}\right] e^{-\alpha(z_p + w_n)} \times \left\{\alpha L_p - \frac{K_p\left(\cosh\left(\frac{l_n}{L_p}\right) - e^{-\alpha L_n}\right) + \sinh\left(\frac{l_n}{L_p}\right) + \alpha L_p e^{-\alpha l_n}}{K_p \sinh\left(\frac{l_n}{L_p}\right) + \cosh\left(\frac{l_n}{L_p}\right)}\right\}$$

For an ideal diode the dark current density J_{dark}(V) varies like

$$J_{dark}(V) = J_0\left(e^{qV/k_BT} - 1\right)$$

where J_0 is a constant, k_BIs Boltzmann's constant and T is temperature in degrees Kelvin.
With this sign convention the net current density in the cell is

$$J(V) = J_{SC} - J_{dark}(V)$$

This becomes, for an ideal diode,

$$J = J_{SC} - J_0\left(e^{qV/k_BT} - 1\right)$$

When the contacts are isolated, the potential difference has its maximum value, the open circuit voltage V_{OC}. For the ideal diode

$$V_{OC} = \frac{k_B T}{q} ln\left(\frac{J_{SC}}{J_0} + 1\right)$$

IV. FIGURES AND TABLES

Effect of width of the window layer

The maximum efficiency and short circuit current density has been calculated for the devices with various width of the window layer while other parameter including width of the other layer kept constant. For comparison between AlGaAs window layer device and AlAs window layer device both data are included in Table.

Table. Simulation results of varying width of window layer:

Device no	Width of the window layer nm	AlGaAs as a window layer			AlAs as a window layer		
		V_{oc} Volt	J_{sc} mA/cm^2	Max efficiency	V_{oc} Volt	J_{sc} mA/cm^2	Max efficiency
1	5	0.9965	43.4839	35.5257	0.9966	43.5735	35.6028
2	10	0.9964	43.3942	35.4486	0.9966	43.5733	35.6026
3	50	0.9957	42.6856	34.8393	0.9966	43.5713	35.6010
4	100	0.9948	41.8211	34.0958	0.9966	43.5689	35.5989
5	150	0.9939	40.9794	33.3719	0.9966	43.5664	35.5968

Maximum efficiency vs. width of window layer

The efficiency variation due to thickness of the window layer is shown in Figure for AlGaAs and AlAs respectively.

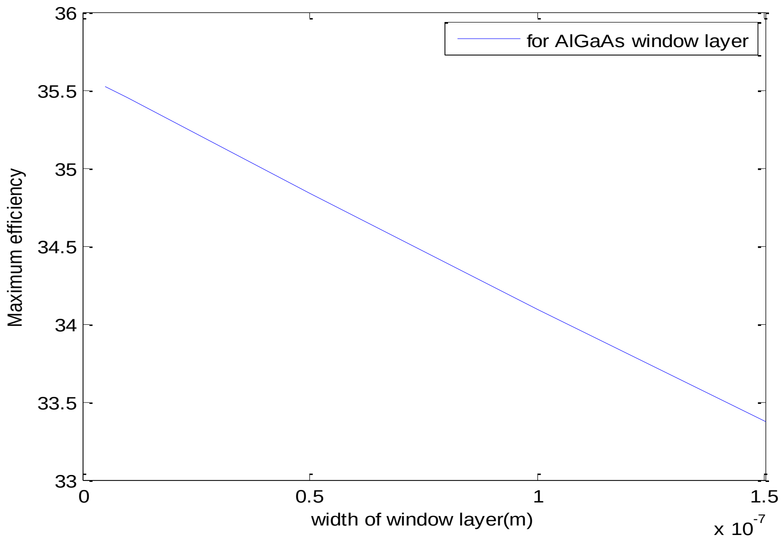

Figure: Variation of efficiency due to thickness of the $Al_xGa_{1-x}As$ (x=.804) window layer

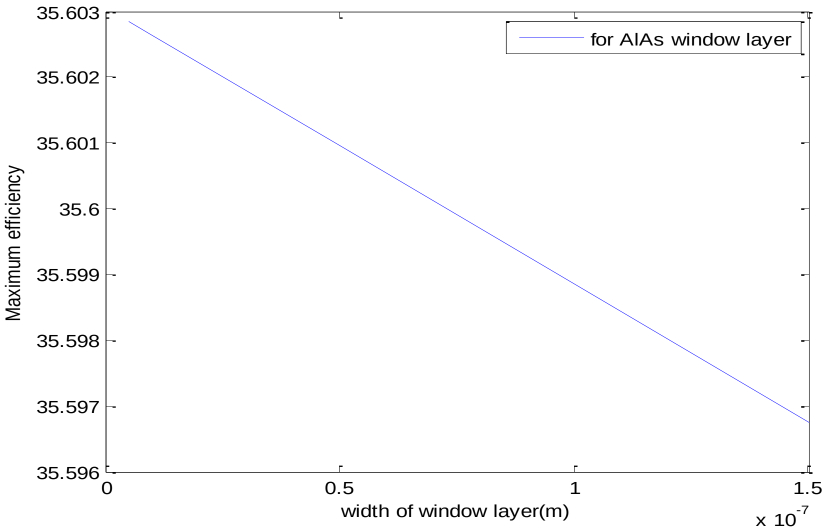

Figure: Variation of efficiency due to thickness of the AlAs window layer

- It can be observed from Figure that efficiency of AlGaAs is 35.527 and AlAs is 35.6028.
- The efficiency increases 0.08 by using AlAs as window layer.
- So we can observe that efficiency of the device decrease slowly due to increase width of AlAswindow layer than AlGaAs window layer.

Voltage versus Current density curve

Figure shows the voltage vs. current density for different width of the AlGaAs and AlAs window layer respectively.

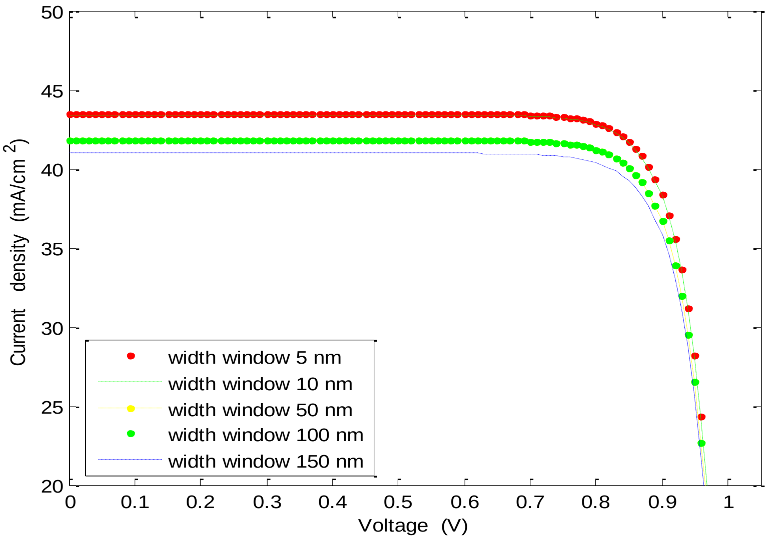

Figure: Voltage versus current density curve for different width of the AlGaAs window layer

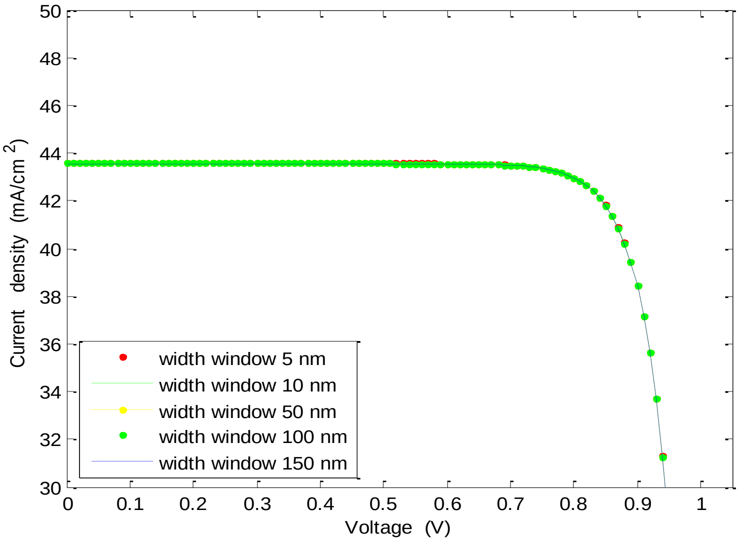

Figure: Voltage versus current density curve for different width of the AlAs window layer

- From Figure we can observe that both case current density decrease due to increase in width of the window layer.
- We can also observe that current density reached in saturation point when voltage is 0.83v for AlGaAs and 0.79 v for AlAs.

Wavelength versus Quantum efficiency

Figure shows the wavelength vs. quantum efficiency curve for different width of the AlGaAs and AlAs window layer respectively.

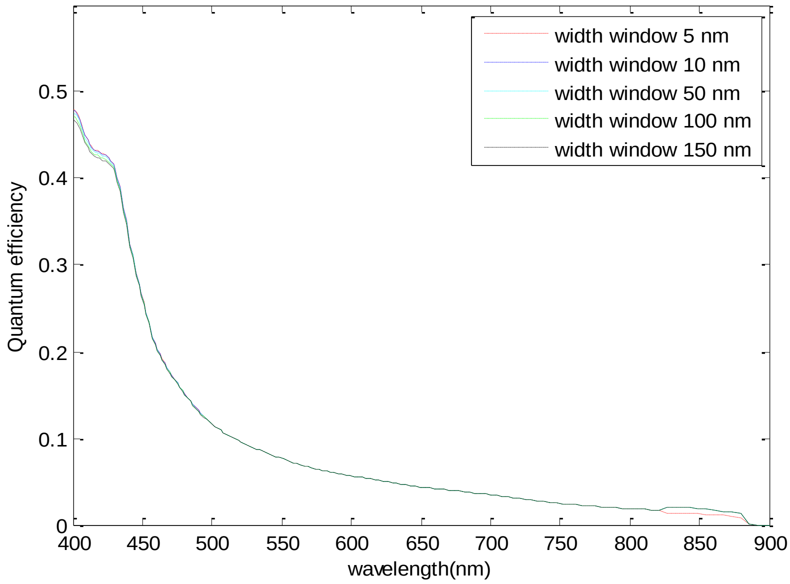

Figure: Wavelength versus Quantum efficiency for different width of the AlGaAs window layer

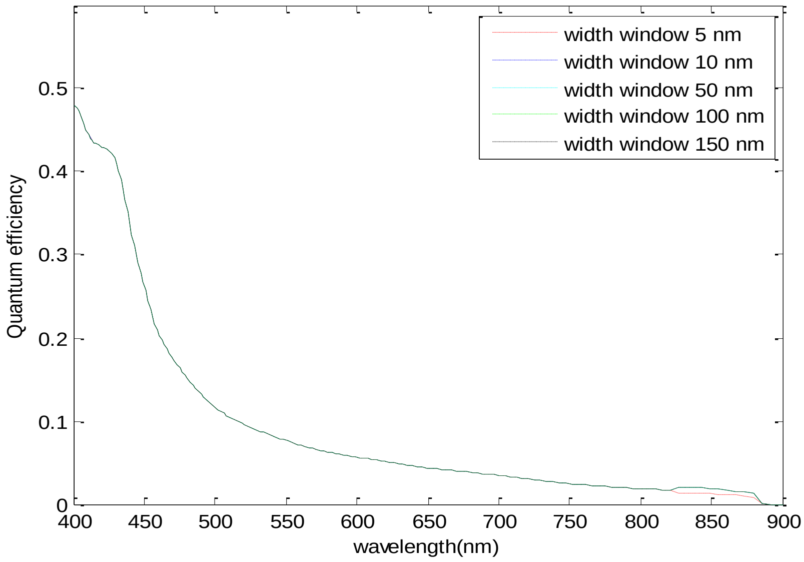

Figure: Wavelength versus Quantum efficiency for different width of the AlAs window layer

- It can be observed from Figure that quantum efficiency decrease with the increase of the width of the window layer.

Effect of width of the p^+ layer

The maximum efficiency and short circuit current density has been calculated for the devices with various width of the p^+ layer while other parameter including width of the other layer kept constant. For comparison between AlGaAs window layer device and AlAs window layer device both data are included in Table.

Table. Simulation results of varying width of the p^+ layer

Device no	Width of the p^+ layer nm	AlGaAs as a window layer			AlAs as a window layer		
		V_{oc} Volt	J_{sc} mA/cm^2	Max efficiency	V_{oc} Volt	J_{sc} mA/cm^2	Max efficiency
1	50	0.9922	39.3290	31.9529	0.9923	39.4101	32.0227
2	100	0.9930	40.0648	32.5857	0.9931	40.1474	32.6567
3	150	0.9937	40.7587	33.1824	0.9938	40.8428	33.2547
4	200	0.9944	41.4069	33.7398	0.9945	41.4923	33.8132
5	250	0.9950	42.0062	34.2551	0.9951	42.0928	34.3296

- It is observed form the data table, efficiency is also related to the width of the p^+ layer. Increasing the width of the p^+ layer also increase the efficiency. This is due to the more photon can be absorbed by this layer.

Voltage versus Current density curve

Figure shows the voltage vs. current density for different width of the p^+ layer.

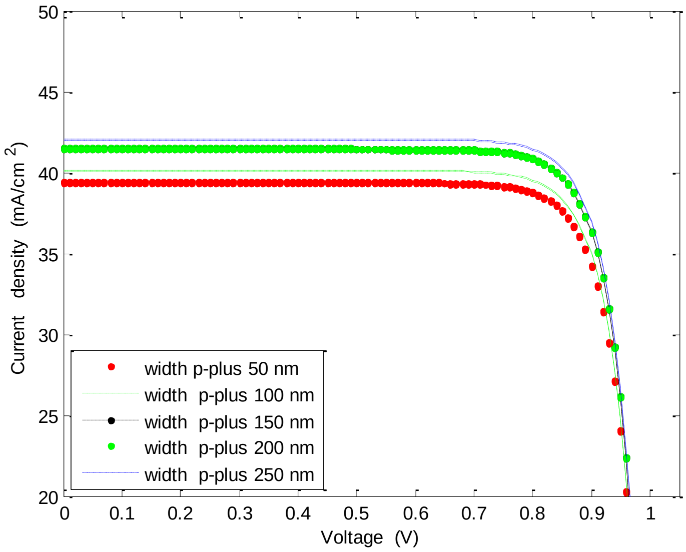

Figure: Voltage versus current density curve for different width of the p^+ layer (using AlGaAs as a window layer)

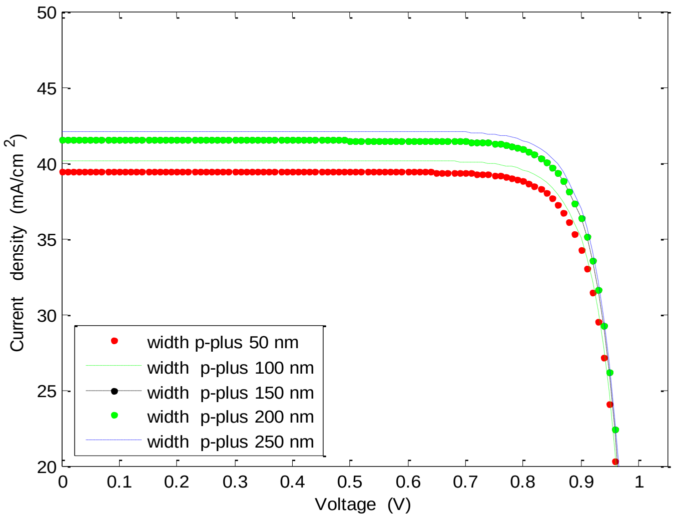

Figure: Voltage versus current density curve for different width of the p^+ layer (using AlAs as a window layer)

- From Figure we can observe that current density reached in saturation point when the voltage is 0.84 v for AlGaAs and 0.85 v for AlAs.
- It is also observed that the device performance for both solar cell about same because of GaAs based solar cell used. So there is no appreciable change can observe between voltage vs. current density curves as shown in Figure.

Wavelength versus Quantum efficiency

Figure shows the wavelength vs. quantum efficiency curve for different width of the p^+ layer.

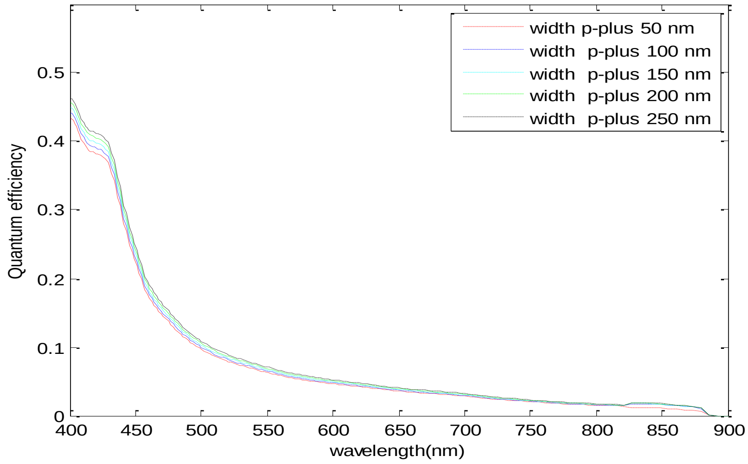

Figure: Wavelength versus Quantum efficiency for different width p^+ layer (using AlGaAs as window layer)

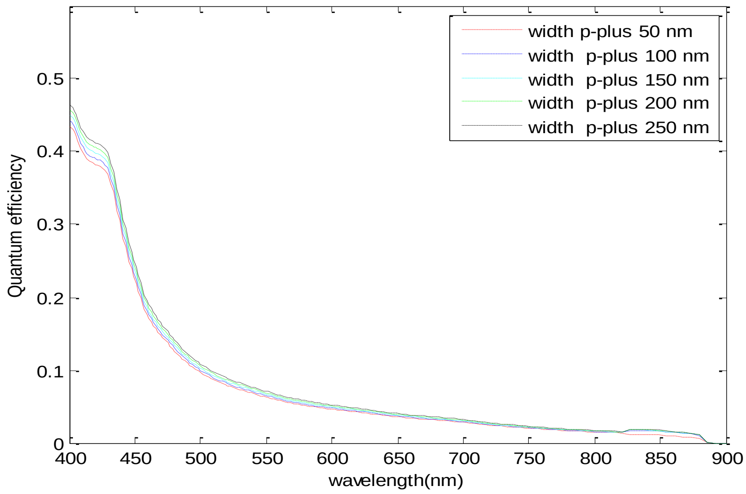

Figure: Wavelength versus Quantum efficiency for different width p^+ layer (using AlAs as window layer)

- It can be observed from Figure that quantum efficiency increase with the increase of the width of the p^+ layer.
- As photo current is directly related to the quantum efficiency, increasing quantum efficiency photo current also increase. That can be observed from Figure.

V. CONCLUSION

In this thesis we study the GaAs based p-i-n reference cell for high performance. In order to realize the high performance of the p-i-n reference cells theoretical study and performance evaluation are very much essential. The design and performance evaluations are made by developing a simulation model which optimizes the design of p-i-n reference cell for high efficiency.

The modeling of the reference cells shows the importance of using a window layer and heavily doped p^+ and n^+ layers to obtain a low effective surface recombination velocity together with an anti-reflective coating minimizing the reflection losses. By using these layers, high quantum efficiency is obtained. Due to a model of a p-i-n solar cell with the intrinsic material placed in a flat band region, a model of high efficiency solar cell is developed and high short circuit current and open circuit voltage is obtained, because additional short circuit current density comes from intrinsic region. Here we have derived mathematical equation for current density, voltage and quantum efficiency.

Simulation is done for two different types of window material (AlGaAs and AlAs) with changing the values of different parameters specially width of the different layers. From those simulation results maximum efficiency is obtained 35.5257% for AlGaAs as a window layer and 35.6028% is obtained for AlAs . So efficiency increase .08% if AlAs is used as window layer instead of AlGaAs.

By comparing the results from the modeling with experimental data it is found that device performance for AlAs as window layer is better than AlGaAs.

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