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An Investigation of The J-V Curve for N-AlGaAs/p-GaAs Heterojunction Solar Cell Due to Influence of Surface Recombination Velocity

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ABSTRACT

Theoretical analysis can substantially reduce the time and costs required for developing a specific device such as solar cell, by allowing the designer to take a suitable geometry and doping profile prior to the fabrication stage. In this paper, theoretical analysis of electric field and electric potential within depletion layer of N-AlGaAS/p-GaAs has been made by solving Poisson's equation numerically using finite difference method (FDM) with Fortran program. Continuity equations of charge carriers in quasi- nature regions in N and p-layers were solved numerically to obtain the current density curve (J-V curve). Boundary conditions related to surface recombination velocity were implemented in this analysis. The effect of front and back surface recombination velocity on the excess minority carriers distribution and photocurrent have been studied. The aim of this work is to find the influence of surface recombination velocity in the output of N-AlGaAs/p-GaAs heterojunction solar cell. The analysis showed that, the low surface recombination velocity produce high efficient solar cell.

فحص منحني كثافة التيار والجهد J-V للوصلة غير المتجانسة N-AlGaAs/p-GaAS للخلية الشمسية تحت تأثير سرعة اعادة التجمع السطحي

*على يصكو دركوي و ايمان فضيل الساكر

قسم الفيزياء، كلية العلوم، جامعة بنغازي، بنغازي، ليبيا

الكلمات المفتاحية:
معادلة الاستمرارية
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المجال الكهربائي
الجهد الكهربائي
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الملخص

التحليل النظري يمكن أن يقلل بشكل كبير الوقت و التكاليف المطلوبة لتطوير جهاز معين مثل خلية شمسية، من خلال السماح للمصمم باتخاذ ما هو مناسب لهندسة ومعالجة الشكل قبل مرحلة التصنيع. في هذه الورقة، التحليل النظري للمجال الكهربائي وللجهد الكهربائي داخل طبقة النضوب للوصلة N-AlGaAs/p-GaAsتم عن طريق حل معادلة بوايسون عدديا باستخدام طريقة الفروق المنتهية بواسطة برنامج فورتران. معادلة الاستمرارية لحاملات الشحن في الطبقات الطبيعية N وp تم حلها عدديا للحصول على كثافة التيار. الشروط الحدودية ذات الصلة بسرعة التجمع السطحي تم تنفيذها في هذا التحليل. تأثير السطح الامامي و الخلفي لسرعة تجمع شحنات الاقلية الزائدة و كثافة التيار الضوئي تمت دراسته. الغرض من هذا الشغل هو ايجاد تأثير سرعة التجمع السطحي على مخرجات الخلية الشمسية N-AlGaAs/p-GaAs غير المتجانسة. و أظهر التحليل بأن السطح ذات سرعة اعادة تجمع منخفض ينتج خلية شمسية عالية الفعالية.

Introduction

Various heterojunctions, including Si-GaAs, Si-GaP, GaAs-Ge and other such materials have been used for making solar cells[1-3]. Gallium arsenide (GaAs) is an excellent semiconductor for the fabrication of high efficient solar cell due to its high absorption of light and has an ideal band gap for solar photovoltaic conversion. There is strong interest in heterojunction solar cells this due to; (a) heterojunction cells can form window absorber which can be used to form structures that shield carriers from top-surface or back-surface recombination sinks. (b)heterojunction cells have a better match to the solar spectrum due to graded band gap. Thus, lot of research work, both experimental and theoretical has been carried out on the p/n heterojunction solar cells. An analysis of the photocurrent of a heterojunction solar cell has been reported [4], [5]. The photocurrent density can be found by evaluating the excess minority carriers Δp and Δn generated by absorption of light in quasi-neutral regions of N and p layers respectively. Concentration of these carriers effected by various parameters such as surface recombination velocities at front and back layer, wavelength of incident light, absorption coefficient

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and energy gap of semiconductors. An analytical analysis of minority carriers concentration and spectral response from the top layer and from the base layer of p/n GaAs-Si heterojunction solar cell has been studied [6]. In this paper, we use numerical analysis for evaluating the minority carriers concentration and photocurrent contribution from front and back layer of the solar cell. The generation rate $G(x,\lambda)$ of electron-hole pairs at each mesh point x_i inside the solar cell is evaluated by using N(λ) photons flux of sun light (AM1) of wavelength range from λ_{min} to $\lambda_{max} = \frac{hc}{E_g}$. The minority carrier equations were solved by implemented surface recombination velocities.

Depletion Layer Approximation

Figure 1, shows the AlGaAs/GaAs N-p heterojunction. The energy band diagram of a N-p heterojunction under thermal equilibrium is shown in Fig.2 before and after the intimate contact [7]. It is noted that the Fermi level is aligned [8,9].

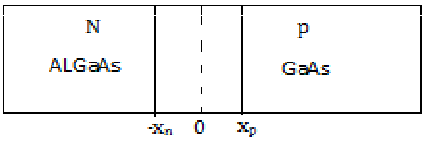

Fig.1 The AlGaAs/GaAs N-p heterojunction

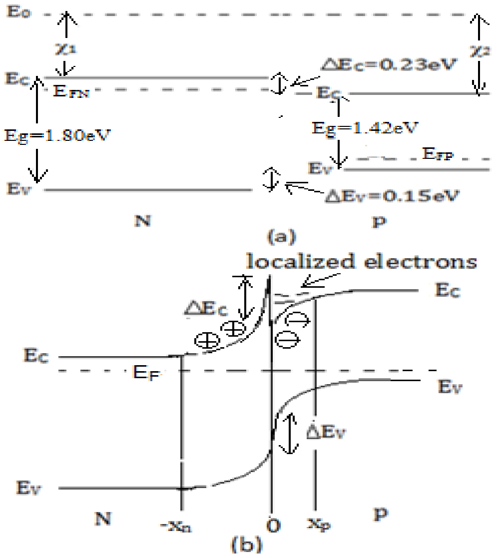

Fig. 2: The band energy diagram of AlGaAs/GaAs N-p heterojunction (a) before contact and (b) after the intimate contact [7].

The Poisson's equation in depletion layer in N-p heterojunction is

$$\frac{d}{dx}\left(\varepsilon_s(x)\frac{d\phi(x)}{dx}\right) = -\frac{q}{\varepsilon_0}\left(N_D^+ - N_A^- + p(x) - n(x)\right) \qquad (1)$$

Where ε_s is dielectric of semiconductor, ϕ is the electrostatic potential, q is electric charge, N_D^+ ionized donor and N_A^- ionized acceptor densities. The n(x) and p(x) are the free electron and hole density respectively.

Neglecting a free charge n(x) and p(x), the Poisson's equation can be solved analytical given the depletion layer in each side of the junction as [10].

$$x_n = \sqrt{\frac{2\,\varepsilon_n}{qN_D}\,\frac{\varepsilon_p\,N_A\,\phi_{bi}}{\varepsilon_n N_D + \varepsilon_P N_A}} \qquad (2)$$

$$x_p = \sqrt{\frac{2\,\varepsilon_p}{qN_A}\,\frac{\varepsilon_p\,N_D\,\phi_{bi}}{\varepsilon_n N_D + \varepsilon_P N_A}} \qquad (3)$$

Where $\emptyset_{bi}$ is built in potential given by [9].

$$\emptyset_{bi} = \Delta E_v + \frac{KT}{q} ln\left(\frac{p_{po}\,N_{vn}}{p_{no}\,N_{vp}}\right) \qquad (4)$$

Where ΔE_V is the offset energy at valance band, K is Boltzmann constant, T is room temperature, p_{po} and p_{n0} are the hole concentration in p-and N-materials respectively, N_{vn} and N_{vp} are the effective density of state functions in the N-and p-materials respectively.

Finite Difference Methods

For nonhomogeneous material eq.(1) become

$$\varepsilon_s\frac{d^2\phi}{dx^2} + d\phi\,\frac{d\varepsilon_s}{dx} = -\frac{q}{\varepsilon_0}\Big(N_D(x) - N_A(x) + n_{ir}e^{\frac{-(\phi - V_p - \phi_p)}{kT}} - n_{ir}e^{\frac{(\phi + V_n - \phi_n)}{kT}}\Big) \qquad (5)$$

Where n_{ir} is the intrinsic charge carrier related to semiconductor, the $\phi_p(\phi_n)$ are the quasi-Fermi potentials and $V_p(V_n)$ are so-called band parameters [11].

Using finite difference method, eq.(5) can be written as

$$\frac{\emptyset_{i-1} - 2\emptyset_i + \emptyset_{i+1}}{h^2} + \frac{1}{\varepsilon_i}\,\frac{\emptyset_{i+1} - \emptyset_{i-1}}{2h}\,\frac{\varepsilon_{i+1} - \varepsilon_{i-1}}{2h} = -\frac{q}{\varepsilon_i}\Big(N_{DA}(x_i) + n_{ir}e^{\frac{-(\phi_i - V_p - \phi_p)}{kT}} - n_{ir}e^{\frac{(\phi_i + V_n - \phi_n)}{kT}}\Big) \qquad (6)$$

or

$$\emptyset_{i-1} - 2\emptyset_i + \emptyset_{i+1} = -\frac{h^2 q}{\varepsilon_i}\left(N_{DA}(x_i) + n_{ir}e^{-\frac{(\phi_i - V_p - \phi_p)}{kT}} - n_{ir}e^{\frac{(\phi_i + V_n - \phi_n)}{kT}}\right) - \frac{h^2}{\varepsilon_i}\,\frac{\emptyset_{i+1} - \emptyset_{i-1}}{2h}\,\frac{\varepsilon_{i+1} - \varepsilon_{i-1}}{2h} \qquad (7)$$

Where $\varepsilon_i = \varepsilon_0\varepsilon_s$ and the h is spacing between the grid points.

Continuity Equation for Charge Curriers

When light incident in solar cell, the generation rate G of electron-hole pairs is given by

$$G(x,\lambda) = \sum_{0}^{\lambda=\frac{hc}{E_g}} \alpha(\lambda)N(\lambda)[1 - R(\lambda)]\exp(-\alpha(\lambda)x)\ d\lambda \qquad (8)$$

Where $\alpha(\lambda)$ is absorption constant, the $N(\lambda)$ is photon density, the $R(\lambda)$ is reflection at front side of the solar cell, the h is the Plank constant , the c is the velocity of light, and $E_g$is the energy gap of semiconductor. Fig,3 Shows light incident in N-p heterojunction solar cell.

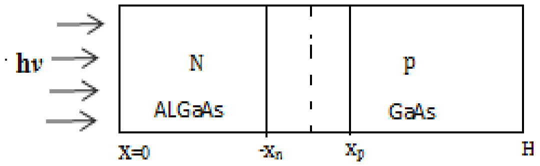

Fig.3: The AlGaAs/GaAs N-p heterojunction solar cell.

The minority carrier continuity equations are

$$D_p\frac{d^2\Delta p_n}{dx^2} - \frac{\Delta p_n}{\tau_p} + G_p = 0 \qquad (9)$$

$$D_n\frac{d^2\Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n} + G_n = 0 \qquad (10)$$

Where $D_p(D_n)$ is hole (electron) diffusion constant, τ_p (τ_n) is lifetime of holes (electrons) and $\Delta p_n(\Delta n_p)$ is the excess hole (electron) density in N-layer (p-layer).

The boundary conditions to be employed are;

At x=0 $\quad D_p\frac{d\Delta p_n}{dx} = s_p\Delta p_n \quad (11)$

And at $x = -x_n$ $\quad \Delta p_n = 0 \quad (12)$

Because of the presence of electric field at depletion layer Δp_n goes to zero [12].

At $x = x_p$ $\quad \Delta n_p = 0 \quad (13)$

And at $x = H$ $\quad -D_n\frac{d\Delta n_p}{dx} = s_n\Delta n_p \quad (14)$

Using these boundary conditions, equation (9) and (10) can be solved numerically using finite difference method (FDM). The photocurrent density J_{ph} can be evaluated through the equation

$$J_{ph} = -qD_p \frac{d\Delta p_n}{dx}|_{-x_n} + qD_n \frac{d\Delta n_p}{dx}|_{x_p} \quad (15)$$

The J-V curve for the solar cell will be

$$J(V) = J_{ph} - J_0\left(1 - \frac{V}{V_{bi}}\right)\left[e^{\frac{qV}{kT}} - 1\right] \quad (16)$$

Where J_0 is the current density given by [10]

$$J_0 = \frac{qA^*T\phi_{bi}}{k} e^{-\frac{q\phi_{bi}}{kT}} \quad (17)$$

Where A^* is Richardson constant.

Result and Discussions

We solved Poisson's equation by finite difference method as a boundary value problem. The boundaries are the quasi-Fermi potentials ϕ_n, ϕ_p at $-x_n$ and x_p. First, the equation was translated into a system of equations and then solved by iteration method using Fortran program. Fig.4 shows the flowchart.

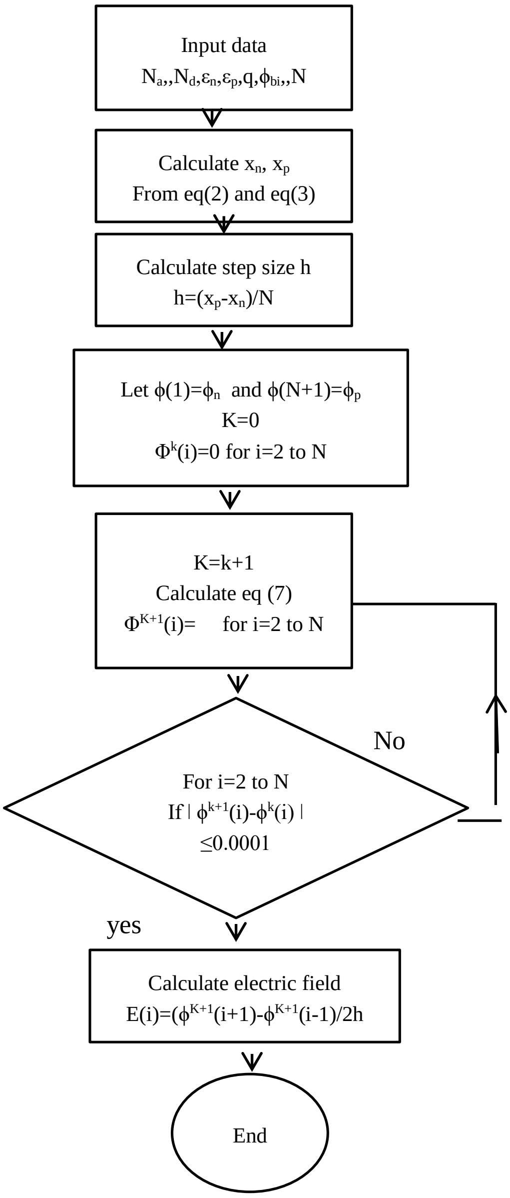

Fig.4: Flowchart for solving Poisson's equation

The material parameters used in the calculation are shown in Table I and Table II.

Table I: Value of parameters

Temperature	T=300K
Boltzmann constant	K=8.62x10^{-5}eV/K
Richardson constant	A*=114A/K^2.cm^2
Dopant concentrations	$N_D=10^{17}cm^{-3}$, $N_A=10^{17}cm^{-3}$
Quasi-Fermi energy	ϕ_n=0.75eV , ϕ_p= -0.73eV
Width of layers (N and p)	$W_n = 0.5\mu m,\ W_p = 1.7\mu m$
Incident photon flux N(λ)	AM1(100mW/cm^2)

Table II: Values of constant

Parameters	N-AlGaAS	p-GaAs
Energy gap	Eg=1.82eV	Eg=1.42Ev
Electron affinity	χ_n=3.74V	χ_p=4.07V
Effective density of state at CB	$N_{Cn}=6.5x10^{17}cm^{-3}$	$N_{cp}=4.7x10^{17}cm^{-3}$
Effective density of state at VB	$N_{Vn}=1.12x10^{19}cm^{-3}$	$N_{Vp}=7.0x10^{18}cm^{-3}$
Relative Dielectric constant	$\varepsilon_{rn} = 12.04$	$\varepsilon_{rp} = 13.1$
Intrinsic carrier concentration	$n_{in}=2.1x10^3cm^{-3}$	$n_{ip}=2x10^6cm^{-3}$
Diffusion coefficient of minority carrier	$D_p=100cm^2s^{-1}$	$D_n=200cm^2s^{-1}$
Diffusion length of minority carrier	$L_p=1.41x10^{-4}cm$	$L_n=2x10^{-4}cm$
Lifetime	$\tau_p=1.9x10^{-7}$ s	$T_n=2x10^{-7}$ s

The distribution of impurity charge density in abrupt N-AlGaAs/p-GaAs heterojunction is shown in Fig.5. The distribution of free charges are very low in-order of 10^4 as seen in Fig.6. The electrostatic potential is shown in Fig.7.

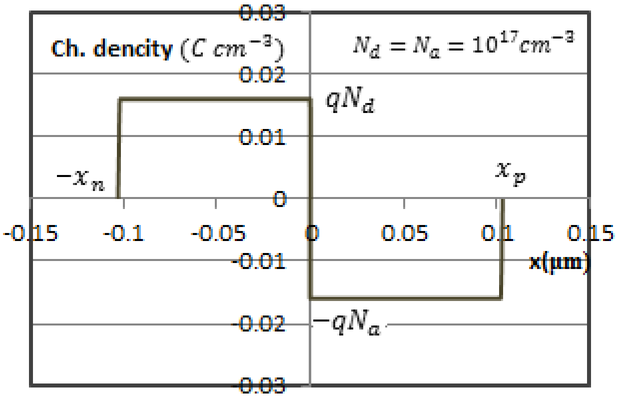

Fig.5: Distribution of impurity charge density in depletion layer.

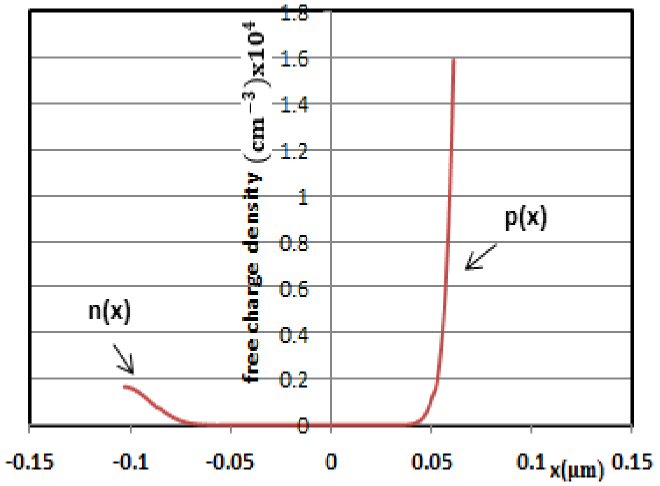

Fig.6: The free charge density in depletion layer.

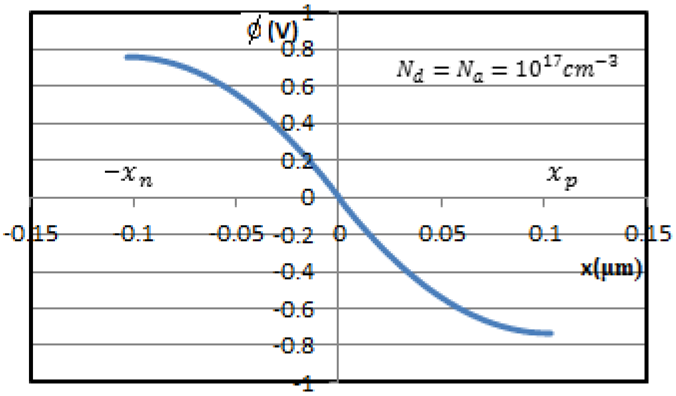

Fig.7: Electrostatic potential in depletion layer.

The profile of electric field E(x) which is the gradient of electrostatic potential $E(x) = -\frac{d\phi}{dx}$ is shown in Fig.8. The discontinuity at the interface is due to different in dielectric of the two media.

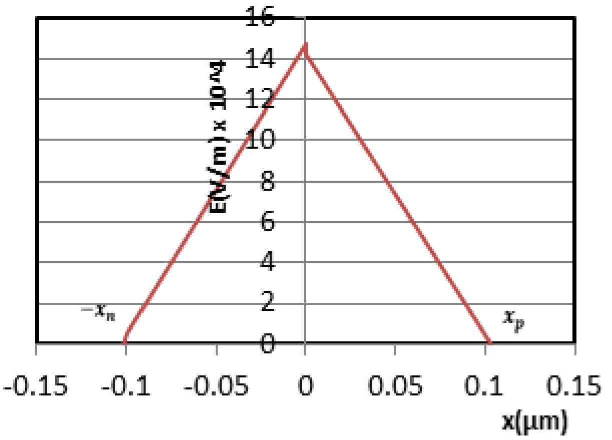

Fig. 8: Electric field distribution within depletion layer.

The continuity equations for minority charge carriers were solved numerically with boundary condition related to surface recombination velocity. The flowchart program is just as has been done for solving Poisson's equation but different physical quantity. Fig.9 shows the distribution of excess charge carriers obtained which were identical to that obtained by Sayantan *et. al* [4] for an analytical analysis of a GaAs-Si n/p heterojunction solar cell. The corresponding current densities for these excess charge were shown in Fig.10.

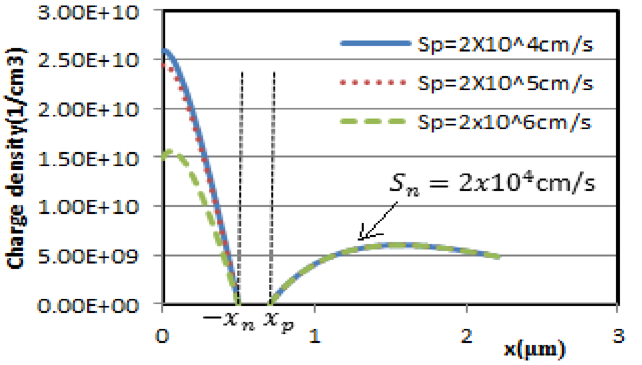

Fig.9: Distribution of excess holes Δp_n in n-layer and electrons Δn_p in p-layer calculated with different surface recombination velocity.

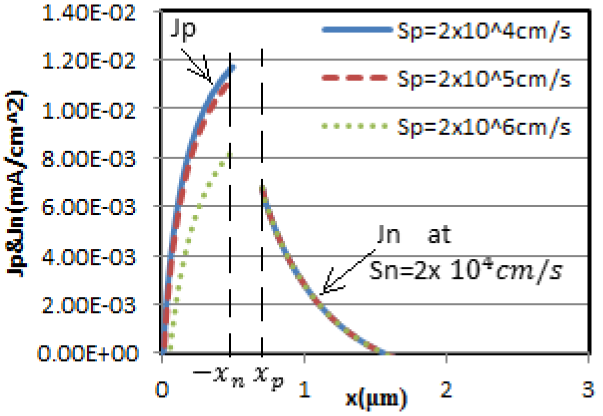

Fig.10: Distribution of excess minority current density J_P and J_n in n-layer and p-layer calculated with different surface recombination velocity.

The J-V characteristic curve for the simulation is shown in Fig.11 under illumination of solar radiation AM1. The power profile for three solar cells at fixed S_n is shown in Fig.12. The solar cell output parameters were given in Table.III. The data shows that by decreasing surface recombination velocity higher efficient solar cell can be obtained.

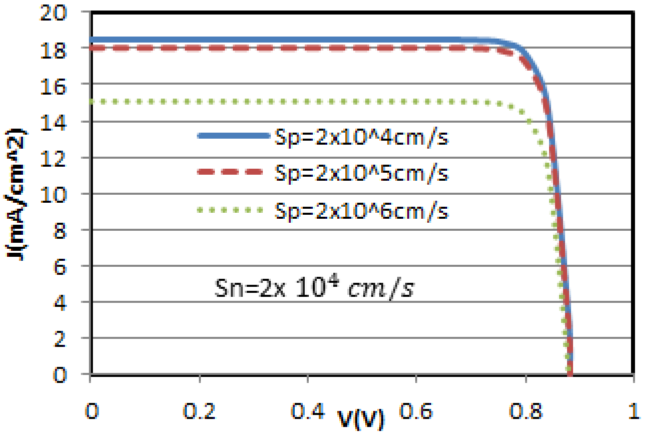

Fig.11: Calculated J-V curve for N-AlGaAs/p-GaAs heterojunction with different Surface recombination velocity.

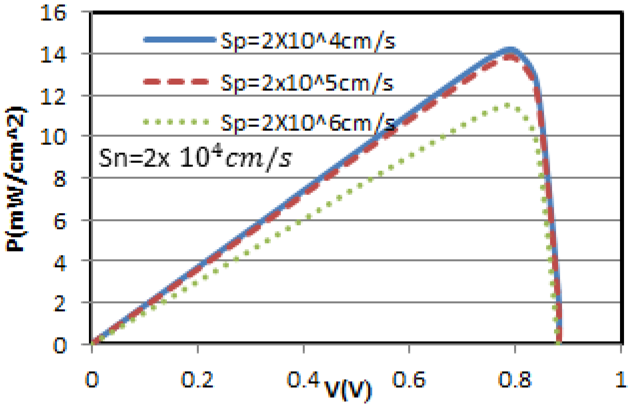

Fig.12: Power profile for three different solar cells

Table III: The solar cell parameters

Surface recombination Velocity (cm/s)		V_{oc} (v)	J_{sc} (mA/cm^2)	V_{max} (v)	J_{max} (mA/cm^2)	P_{max} (mW/cm^2)	ff	η%
$S_n(2x10^4)$	$S_p(2x10^4)$	0.88	18.49	0.80	17.68	14.14	0.87	14.14
	$S_p(2x10^5)$	0.88	18.03	0.80	17.21	13.77	0.87	13.77
	$S_p(2x10^6)$	0.88	15.08	0.78	14.72	11.45	0.86	11.45
$S_p(2x10^4)$	$S_n(2x10^4)$	0.88	18.49	0.80	17.68	14.14	0.87	14.14
	$S_n(2x10^5)$	0.88	18.45	0.79	17.97	14.12	0.87	14.12
	$S_n(2x10^6)$	0.88	18.15	0.79	17.67	13.88	0.87	13.88

Conclusion

In this paper, we have presented the electric field profile in depletion layer of N-AlGaAs/p-GaAs heterojunction. We find that the electric field is discontinues and high at interface in the side of N-layer. This is due to different in dielectric of the two media. The analysis of the current density showed that, the low surface recombination velocity produce high efficient solar cell. Ideally, for optimum performance, the surface recombination velocity goes to zero($S\rightarrow0$) for minority carriers and $S\rightarrow\infty$ for majority carriers at ohmic contact. This will allow photo generated minority carriers to be directed to the depleted barrier region which generally is the core of photovoltaic response. The numerical simulation is useful to study the relation between parameters involving the transport mechanism of charge carriers.

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