

(Ga_{1-x}Al_x)As/GaAs Solar Cells: A Numerical Analysis

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ABSTRACT. The operation and characteristics of the (Ga_{1-x}Al_x)As/GaAs heterojunction solar cell are studied numerically in detail. The complete system of transport equations governing the behaviour of this p-n device is established and reformulated for computer calculation. With a very thin top layer (below 0.2 μ) the conversion efficiency is computed to be 23.5 percent for $x = 0.8$, provided that the junction depth is less than 0.5 μ. The depletion width at zero bias is determined to be 0.1 micron.

Although this cell type is quite costly, its predicted high AM0 efficiency makes it a promising candidate for both space and terrestrial concentrator applications.

(Ga_{1-x}Al_x)As containing 80% Al ($x = 0.8$) is a semiconductor with an indirect bandgap of approximately 2.1 eV and a direct bandgap of about 2.6 eV (Hovel 1973, Hovel and Woodall 1973). When sunlight is incident on the *p*-type (Ga_{1-x}Al_x)As, photons with energies below 2.1 eV are passed directly through this layer to the underlying GaAs *p/n* homojunction. Photons between 2.1 and 2.6 eV are weakly attenuated by the layer, and photons above 2.6 eV are strongly attenuated by it (depending on the thickness of the layer).

In this paper, the performance and operational characteristics of the *p*-(Ga_{1-x}Al_x)As *p/n*-GaAs cell are studied numerically. The spectral response is derived, including the effects of collection from the alloy layer, recombination at the (Ga_{1-x}Al_x)As surface, and recombination at the (Ga_{1-x}Al_x)As /GaAs interface. Models are developed to calculate the expected spectral response and short-circuit current by integration with the AM0 solar spectrum. Therefore, these investigations, assumptions are made that there are no electric fields present outside the junction depletion region, and that each of the three regions is uniform in lifetime, doping level and mobility.

Spectral Response

The equilibrium energy band structure for $(\text{Ga}_{1-x}\text{Al}_x)\text{As}/\text{GaAs}$ is shown in Fig. 11. The surface recombination velocity, minority carrier lifetime, diffusion coefficient, diffusion length, and absorption coefficient for the $(\text{Ga}_{1-x}\text{Al}_x)\text{As}$ of thickness D are designated S_a , τ_a , D_a , L_a and β (λ), respectively. The same quantities for the p -GaAs are designated S_g , τ_g , D_g , L_g and α (λ). The junction depth is d and the depletion width at zero-bias is W .

When hole-electron pairs are generated in the GaAs, holes diffuse from the n -region into the GaAs p -region and electrons from the p -GaAs enter the n -region. Electrons in the conduction band of the p -GaAs are prevented from entering the $(\text{Ga}_{1-x}\text{Al}_x)\text{As}$ by the energy barrier ΔE_c at the interface, and the only appreciable loss of carriers at this interface is, therefore, due to interface recombination. (The loss due to electron tunneling into the $(\text{Ga}_{1-x}\text{Al}_x)\text{As}$ followed by recombination with holes in this material is small.)

1. Collection from the Top Alloy Layer

The minority carrier continuity equation for the photogenerated (excess) electrons in the alloy layer is:

$$D_a \frac{d^2 \Delta n}{dx^2} + \beta F e^{-\beta x} - \frac{\Delta n}{\tau_a} = 0 \quad (1)$$

where Δn is the excess carrier density and F is the incident photon flux at wavelength λ . The boundary condition at the surface is determined by surface recombination:

$$S_a \Delta n = D_a \frac{d\Delta n}{dx} \quad (x = 0) \quad (2)$$

and at the interface

$$\Delta n = 0 \quad (x = \bar{D}) \quad (3)$$

The photocurrent contribution from the alloy layer is:

$$J_D = q D_a \left. \frac{d\Delta n}{dx} \right|_{x=\bar{D}} \quad (4)$$

Solving for the excess electron density, Δn , and using Eq. (4), the current is:

$$J_D = \frac{q F \beta L_a}{(\beta^2 L_a^2 - 1)} \left\{ \frac{\beta L_a + S_a \frac{\tau_a}{L_a} \left(1 - e^{-\beta D} \text{Cosh} \frac{D}{L_a} \right)}{S_a \frac{\tau_a}{L_a} \text{Sinh} \frac{D}{L_a} + \text{Cosh} \frac{D}{L_a}} \right.$$

$$\left. \begin{aligned} & -e^{-\beta D} \sinh D/L_a \\ & S_a \frac{\tau_a}{L_a} \sinh D/L_a + \cosh \frac{D}{L_a} \end{aligned} \right\} - \beta L_a e^{-\beta D} \quad (5)$$

This flow of electrons is injected into the *p*-GaAs region at the interface.

2. Collection From the Base GaAs

Light which passes through the alloy layer with energy greater than the GaAs bandgap generates hole-electron pairs in the GaAs. The minority carrier continuity equation for electrons in the *p*-GaAs is

$$D_g \frac{d^2 \Delta n}{dx^2} + \alpha F e^{-\beta D} e^{-\alpha(x-D)} - \frac{\Delta n}{\tau_g} = 0 \quad (6)$$

where $F e^{-\beta D}$ is the attenuated photon flux at wavelength λ . The boundary condition at the interface on the GaAs side is:

$$D_g \frac{d\Delta n}{dx} = S_g \Delta n - \frac{J_D}{q} \quad (x = D^+) \quad (7)$$

That is, the current in the *p*-GaAs at the interface is equal to the component due to recombination at the interface minus the component injected from the alloy layer.

The boundary condition at the junction edge is:

$$\Delta n = 0 \quad (x = D + d) \quad (8)$$

After solving for the electron density, the photocurrent at the junction edge becomes:

$$J_{D+d} = \frac{q F e^{-\beta D} \alpha L_g}{(\alpha^2 L_g^2 - 1)} \left\{ \frac{\alpha L_g + S_g \frac{T_g}{L_g} \left(1 - e^{-\alpha d} \cosh \frac{d}{L_g} \right)}{S_g \frac{T_g}{L_a} \sinh \frac{d}{L_g} + \cosh \frac{d}{L_g}} \right. \\ \left. - \frac{e^{-\alpha d} \sinh \frac{d}{L_g}}{S_g \frac{T_g}{L_g} \sinh \frac{d}{L_g} + \cosh \frac{d}{L_g}} - \alpha L_g e^{-\alpha d} \right\} + \frac{J_D}{S_g \frac{T_g}{L_g} \sinh \frac{d}{L_g} + \cosh \frac{d}{L_g}} \quad (9)$$

The last term describes how the current collected from the alloy layer is attenuated by the surface recombination term, S_g , and the bulk recombination term, τ_g .

The photocurrent collected from the base is given by:

$$J_{D+d+w} = \frac{qFe^{-\beta D} \propto L_p}{(\propto L_p + 1)} e^{-\alpha d} d^{-\alpha w} \quad (10)$$

while the current collected from the depletion region is:

$$J_w = qFe^{-\beta D}(1 - e^{-\alpha w})e^{-\alpha d} \quad (11)$$

The spectral response is given by the sum of these photocurrents at the junction edge:

$$S_p R_e(\lambda) = \frac{J_{D+d}(\lambda) + J_{D+d+w}(\lambda) + J_w(\lambda)}{qF(\lambda)} \quad (12)$$

Photogenerated Current

The photocurrent at each wavelength λ is obtained from Eq. 12.

$$J_{ph}(\lambda) = qF(\lambda) \cdot S_p R_e(\lambda) (1 - R(\lambda)) \quad (13)$$

and the total photocurrent for a given spectral input between λ_1 and λ_2 is:

$$J_{ph} = q \int_{\lambda_1}^{\lambda_2} S_p R_e(\lambda) \cdot F(\lambda) \cdot (1 - R(\lambda)) d\lambda \quad (14)$$

where $R(\lambda)$ is the reflection from the surface at (λ) , its negligible for a first approximation.

Diode Current

The p -(Ga_{1-x}Al_x)As - p -GaAs - n -GaAs is basically a p - n GaAs solar cell in which top alloy layer plays the part of an ohmic contact to the p -GaAs. The (I-V) characteristics of the cell should consist, at least, of minority carrier injection over the junction barrier with subsequent diffusion of the carriers, the recombination of the injected holes and electrons inside the depletion region, and the photocurrent due to the photogenerated hole - electron pairs.

The injection-diffusion current (in the absence of electric fields) is given by:

$$J_{id} = J_o(e^{qV/kT} - 1) \quad (15)$$

where

$$J_o = \frac{qn_i^2 D_g}{N_a L_g} \left\{ \frac{\sinh \frac{d}{L_g} + S_g \frac{L_g}{D_g} \cosh \frac{d}{L_g}}{S_g \frac{L_g}{D_g} \sinh \frac{d}{L_g} + \cosh \frac{d}{L_g}} \right\} +$$

$$+ \frac{qn_i^2 D_p}{N_d L_p} \coth \left[\frac{(H-D) - (d+W)}{L_p} \right] \quad (16)$$

where the first term is the current from the *p*-GaAs region while the second is the contribution from the base, and $(H-D)$ is the width of the GaAs portion of the cell. It has been assumed that the contribution to the dark current from the top alloy layer is negligible due to the wide bandgap and high doping level in these layers.

The current due to hole-electron recombination in the depletion region has a maximum value, according to the Sah-Noyce-Schokky theory (Sah *et al.* 1957, Hutchby and Fudurick 1976), is given by:

$$J_r = \frac{qn_i W}{\sqrt{\tau_{po}\tau_{no}}} \frac{2 \sinh(qV/2kT)}{q(\psi_d - V)/kT} \frac{\Pi}{2} \quad (17)$$

where ψ_d is the 'built-in' junction voltage, V is the forward bias voltage, and τ_{po} , τ_{no} are the minority carrier lifetime on the *n* and *p* sides of the junction, respectively.

Overall Efficiency

The expected efficiencies of (Ga_{1-x}Al_x)As/GaAs solar cell are calculated as a function of the top alloy layer thickness for the device parameters of Table 1.

The net current output (J) for the cell is given by:

$$J = J_{ph} - (J_{id} + J_r) \quad (18)$$

The output power (P) per unit area delivered to the load is:

$$P = JV \quad (19)$$

The efficiency of the cell is (Hovel 1975):

$$\eta = \frac{V_{mp} I_{mp}}{P_{in}} \times 100\% \quad (20)$$

where V_{mp} and I_{mp} are the current and voltage at the point of maximum power, P_{in} is the solar input power.

Results and Conclusions

In order to calculate the overall efficiency from the above complete system of transport equations one must first compute W , the depletion width at zero bias. For an abrupt junction which was defined from Eqn (10, 11, 16 and 17), and it is:

$$W = \left(\frac{2\epsilon_s}{q} \left(\frac{N_a + N_d}{N_a N_d} \right) \psi_d \right)^{1/2} \quad (21)$$

Table 1. Material parameter used in computer program

$(\text{Ga}_{1-x}\text{Al}_x)\text{As}$		$p\text{-GaAs}$		$n\text{-GaAs}$		Units
N_A	2×10^{19}	N_A	2×10^{17}	N_d	2×10^{17}	cm^{-3}
S_a	10^6	S_g	10^4		-	cm Sec^{-1}
D_a	0.74	D_g	32.4	D_p	5.7	$\text{cm}^2\text{Sec}^{-1}$
L_a	0.27	L_g	1.8	L_p	3.0	$\times 10^{-4} \text{ cm}$
τ_a	10^{-9}	τ_p	10^{-9}	τ_p	1.58×10^{-8}	Sec.

$$W = 0.09 \mu\text{m}$$

$$V_d = 1.4 \text{ Volt}$$

$$n_i = 1.1 \times 10^7 \text{ cm}^{-3}$$

$$\epsilon_s/\epsilon_o = 13.2$$

where ϵ_s is the dielectric constant for top layer material, N_a and N_d are the doping levels, and ψ_d is the 'built-in' voltage. Using the material parameters in Table 1, W was found to be ≈ 0.1 micron. The solar irradiance was found by using the solar spectrum $F(\lambda)$ for air mass zero (AMO) which presented in Fig. 1. Absorption coefficients $\alpha(\lambda)$ and $\beta(\lambda)$ for GaAs and $(\text{Ga}_{1-x}\text{Al}_x)\text{As}$ alloy with $x = 0.8$ are shown in Fig. 2 and 3. The spectral response of devices with $d = 0.5 \mu\text{m}$ junction depths are calculated as a function of top layer thickness, including the contribution to the photocurrent due to the generation of carriers within the $(\text{Ga}_{1-x}\text{Al}_x)\text{As}$. This is shown in Fig. 4a-c. The response cuts-off between 2.5 and 2.75 eV for thick alloy layers, with the cut-off moving to higher energies as the thickness is reduced. The computed maximum efficiency is applicable since no reflection, contact area, series resistance, or shunt resistance losses are considered. With a very thin top layer, the efficiency is computed to be $\sim 23.5\%$ (AMO). As expected, the efficiency decreases as the top layer alloy thickness increases (Fig. 5).

The short circuit currents are shown in Fig. 6. The maximum is found to be $\approx 36.0 \text{ mA/cm}^2$, while the corresponding open-circuit voltage, shown in Fig. 7, is found to be > 1.0 volt. Dark (J-V) characteristics are presented in Fig. 8. These include both the injection-diffusion component J_{id} and the depletion region recombination current J_r . Finally, the total J-V characteristics and output power are shown in Fig. 9 and 10, respectively.

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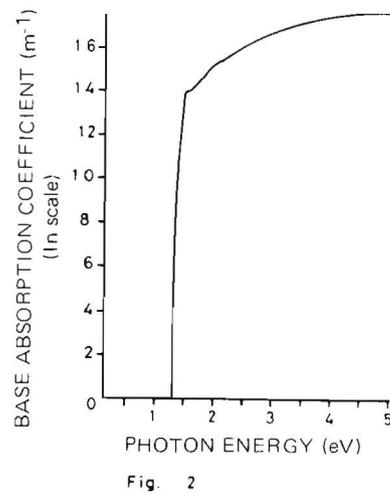
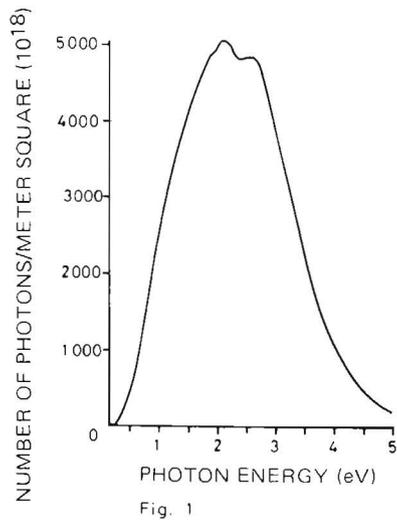


Fig. 1. Air mass zero solar spectrum

Fig. 2. Absorption coefficient $\alpha(\lambda)$ of the base absorber (GaAs) as a function of photon energy.

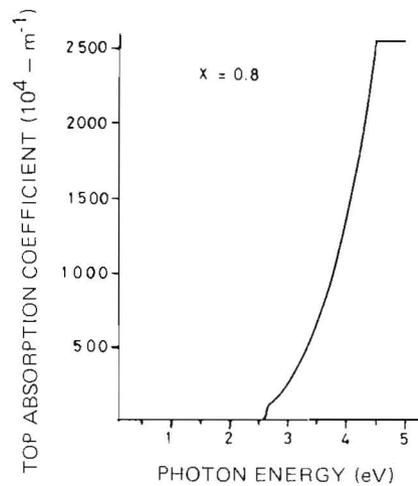


Fig. 3. Absorption coefficient $\beta(\lambda)$ of the window $(\text{Ga}_{1-x}\text{Al}_x)\text{As}$ as a function of photon energy.

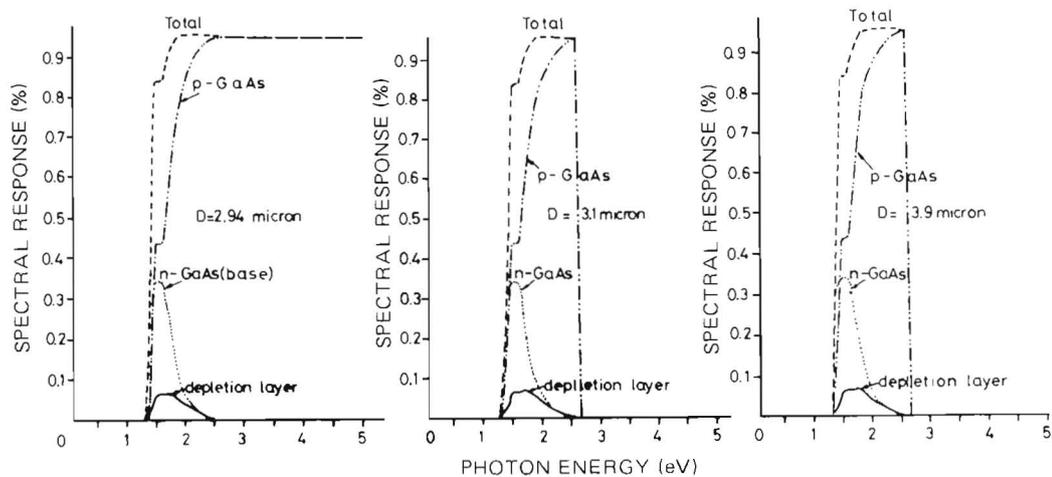


Fig. 4.a

Fig. 4.b

Fig. 4.c

Fig. 4. Spectrum response of three different devices at $D = 2.94 \mu\text{m}$ (a), $D = 3.1 \mu\text{m}$ (b) and $D = 3.9 \mu\text{m}$ (c).

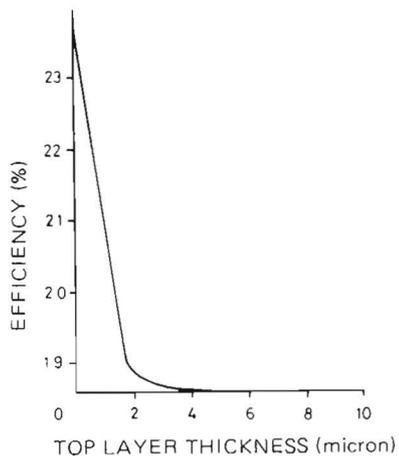


Fig 5

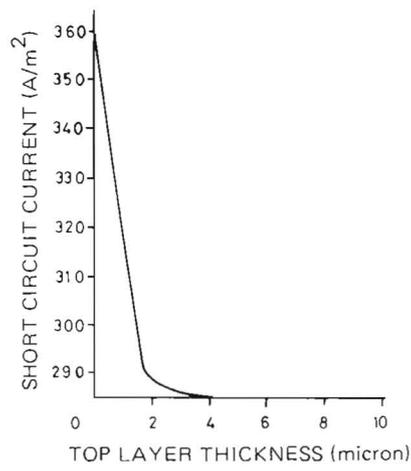


Fig 6

Fig. 5. Efficiency as a function of the top layer thickness.

Fig. 6. Short circuit currents as a function of the top layer thickness.

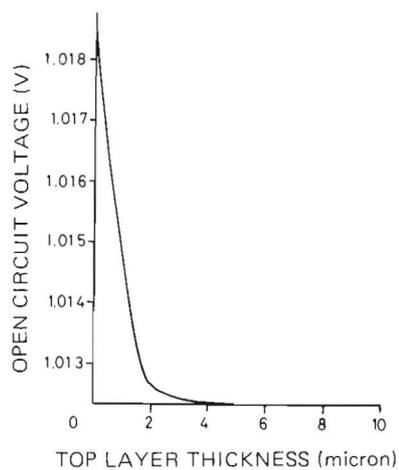


Fig. 7

Fig. 7. Open circuit voltage as a function of top layer thickness.

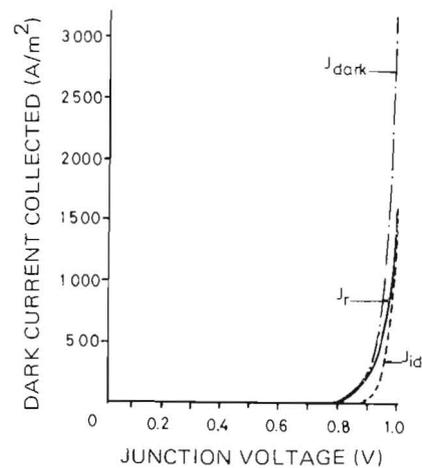


Fig. 8

Fig. 8. Dark current as a function of the junction voltage.

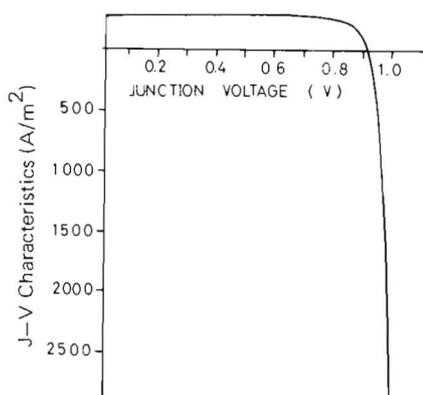


Fig. 9

Fig. 9. J - V characteristic as a function of junction voltage.

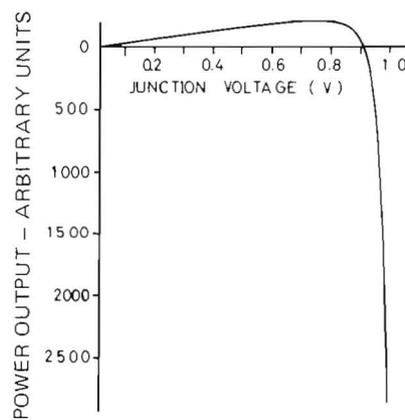


Fig. 10

Fig. 10. Output power as a function of the junction voltage.

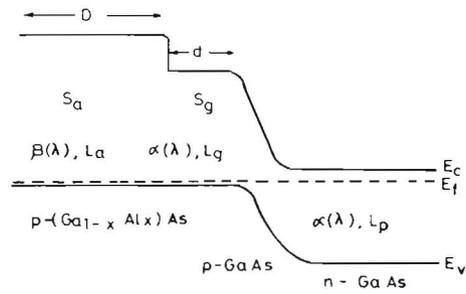


Fig. 11

Fig. 11. Energy band diagram of $(\text{Ga}_{1-x}\text{Al}_x)\text{As}/\text{GaAs}$ solar cell.

الخلايا الشمسية $(\text{Ga}_{1-x}\text{Al}_x)\text{As}/\text{GaAs}$: تحليل عددي

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تمت دراسة عمل وسعات الخلية الشمسية غير المتجانسة الوصل $(\text{Ga}_{1-x}\text{Al}_x)\text{As}/\text{GaAs}$ عددياً وبالتفصيل. وان النظام الكامل لمعادلات الانتقال التي تحكم سلوكية هذا الجهاز ذو النوع $(P-n)$ قد وضعت وأعيدت صياغتها لأغراض حساب الحاسبة، كما أن كفاءة التحويل قد حسبت ووجد أنها تساوي 23.5 في المائة لطبقة عليا رقيقة جداً (أقل من 0.2μ) ولقيمة (x) المساوية الى (0.8) شرط أن يكون عمق الوصل أقل من (0.5μ). وقد تم تعيين عمق النضوب للانحياز الصفرى فوجد مساوى الى 0.1 مايكرون.

وبالرغم من أن هذا النوع من الخلية مكلف نوعاً ما إلا أن كفاءتها العالية (AMO) المتنبأ بها تجعلها قابلة للتطبيقات العملية الجيدة، كمركز في الفضاء وفي الأرض.