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DEPLETION LAYER RECOMBINATION EFFECTS ON THE RADIATION DAMAGE HARDNESS OF GALLIUM ARSENIDE CELLS

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In 1973 Hovel (ref. 1) demonstrated the significant effect of junction depletion layer recombination on the efficiency of 'windowed' GaAs cells. The effect becomes more pronounced as radiation damage occurs and is included in the analyses of later workers. In this paper it is more explicitly considered for 1 MeV electron fluences up to 10^{16} e/cm^2. The cell modeling separates damage in emitter and base or buffer layers using different damage coefficients recently reported by Yamaguchi et al (refs. 2 and 3). The lower coefficient for the emitter predicts less loss of performance at fluences greater than 10^{15} e/cm^2. A method for obtaining information on junction recombination effects as damage proceeds is described; this enables a more complete diagnosis of damage to be made.

INTRODUCTION

In 1973 Hovel (ref. 1) analyzed the effect of junction depletion layer recombination in AlGaAs windowed GaAs cells showing that it could account for a few percent loss of cell efficiency (AM0). Later Loo et al (ref. 2) and Knechtli et al (ref. 3) carried out analyses of electron radiation damage in this type of cell using models which included the junction effects. Their models, which are similar to those of Hovel and Woodall (ref. 4), have been the basis of our analysis. In addition we have looked at the effects of different damage coefficients for the emitter and buffer (or base) regions. We have used the information on these given in the work of Yamaguchi et al (refs. 5 and 6). Compared with the assumption of equal damage coefficients in emitter and buffer (about 10^{-7}/e) the emitter damage coefficient is $3.5 \cdot 10^{-8}$ for a P doping of 10^{18}/cm^2 and the buffer damage coefficient is $1.8 \cdot 10^{-7}$ for N doping of $2 \cdot 10^{17}$/cm^3. Using the separate values shows significant differences in cell damage from that using equal damage coefficients.

It is clear that in order to use the modeling for damage in gallium arsenide to explain experimental data, measurements have to be sufficiently comprehensive at each fluence level to give information on the junction depletion region. One can include a complete dark current characteristic measurement at each fluence but we describe below a simple way to obtain sufficient information by using the variation of V_{oc} and I_{sc} with solar flux.

Our modeling uses a computer code developed here for the HP/3000 'in house' computer. Short circuit current (I_{sc}) is obtained by using the solar AM0 spectrum and the absorption data for the cell window and for the underlying GaAs. Open circuit voltage (V_{oc}), power maximum, efficiency (η), etc. are obtained as in previous models using of course the derived I_{sc} values. The junction effects are found by using the relations of Sah, Noyce and Shockley (ref. 7 as modified by Choo (ref.8)).

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Cell parameters such as thickness of the various layers, doping concentrations, surface and interface recombination velocities, diffusion lengths and coefficients etc. are taken for typical production cells from Hughes Research Laboratories made by the LPE method.

DAMAGE ANALYSIS MODELING

It is assumed that diffusion lengths decrease with fluence of electrons in the following way:

$$1/L^2 = 1/L_o{}^2 + K.\emptyset \qquad (1)$$

where $\emptyset$ is the fluence (e/cm^2), L_o is the BOL (beginning of life) value and L the diffusion length value at $\emptyset$, K being the damage coefficient (usually quoted for L values in cm).

The analytical relations for I_{sc}, V_{oc}, etc. will not be requoted here but it is useful to note that I_{sc} will depend on L values and on absorption spectra for the cell layers as well as on the layer thicknesses, etc.

The open circuit voltage depends on the above factors, including I_{sc} but is also strongly dependent on the resulting saturation currents for the NP GaAs diode system. The so called first diode saturation current I_{01} is the sum of the components due to the emitter and the buffer (Iol_e and Iol_b) while I_{02} is the saturation current for the 'second diode' arising from the depletion layer recombination. The relation determining their effect on V_{oc} is:

$$I_{sc} = I_{01}.\exp(qV_{oc}/kT) + I_{02}.\exp(qV_{oc}/2kT \qquad (2)$$

q being the electronic charge, k Bóltzmann's constant and T the absolute temperature. This relation forms the basis for analyzing experimental data on cell damage. It is not usual to include the junction term when calculating V_{oc} but as gallium arsenide cell modelers show it is too significant to be neglected. However, past experimental data for high fluences cannot be analyzed properly because measurements of a kind giving I_{02} are missing. We show how this can be remedied below.

We now look at results of modeling with respect to saturation currents. Figure 1 gives the saturation currents for a cell as functions of 1 MeV electron fluence for a typical cell specification, which is:

Window and emitter thickness = .5 micron. Buffer thickness 10 micron.
Window is Al(86%)Ga(14%)-As, buffer and base are GaAs.
Window diffusion length .2 micron, emitter diffusion length 5 micron, buffer diffusion length 2 micron.
Window diffusion coefficient .7, emitter value 90, buffer value 5 each in cm^2/s.
Window surface recombination velocity 10^6, emitter interface recombination velocity 10^4 cm/s respectively; buffer assumed 'thick' in cell theory.
Window and emitter doping concentrations $10^{18}/cm^3$ and buffer doping concentration $2.10^{17}/cm^3$. Emitter damage coefficient is $3.5.10^{-8}/e$, buffer damage coefficient is $1.8.10^{-7}$.

(It should be remembered that the formula for I_{02} contains a V_{oc} dependent term in equation (2) and this makes the equation transcendental. However, it is easily solved by a Newton Raphson method.)

Figure 1 shows that the dominating influence in I_{01} for moderate fluences is that of the buffer component. However, at fluences of 10^{15} e/cm^2 or more the emitter contribution becomes significant and at 10^{16} e/cm^2 overtakes that of the buffer. In addition the effect of I_{02} which is almost constant up to 10^{15} e/cm^2 becomes an important factor at higher fluences. The combined effect of these three saturation currents makes the change of cell parameters with damage rather different from that predicted from 'base only' damage (see e.g. JPL Radiation Damage Handbook, ref. 9) usually assumed for silicon cells.

Figure 2 shows the effect of the saturation current behavior on the open circuit voltage, V_{oc}. Curve A is when no effect of I_{02} is included while Curve B shows the effect of its inclusion. The broken curve, C, is for equal damage coefficients in emitter and base of 10^{-7}/e. The % changes for the effect are listed in Table 1 below.

Figure 3 shows the effect of the I_{02} component on the cell maximum power fall off with fluence. Curve A is when no I_{02} term is present, Curve B that when it is there; as in Figure 1, curve C shows the case of equal damage coefficients in emitter and base (10^{-7}/e). Again, % changes are given in Table 1.

It is well established by previous workers that there is a great advantage in making cells with thinner window and emitter layers. We have not given the plots for a 'thin' cell but have included a summary of our modeling in Table 1 for a cell with .2 micron window and .2 micron emitter but keeping all other specifications the same. The improvement in I_{sc}, V_{oc} and maximum power and efficiency is evident. The difference in efficiency at end of life (10^{16} e/cm^2) is .6% when the damage coefficients are assumed different in the emitter and buffer. However, the effect of the I_{02} component of saturation currents is still similar to that for equal damage coefficients.

ANALYSIS OF EXPERIMENTAL DATA

We have already shown that diagnosis of damage in gallium arsenide cells needs a knowledge of the second diode (I_{02}) behavior as electron fluence is increased. We have developed a simple measurement for the same purpose in looking at silicon cells. In addition to the usual measurements of spectral response, V_{oc}, I_{sc} and maximum power (from current voltage load curves) we take an extra pair of readings of I_{sc} and V_{oc} at an illumination less than that at AM0 (about 3 times less). Then using the AM0 values and these new values we can apply Equation 2 to get I_{01} and I_{02} values. As a simple example for an undamaged cell we give measurements of I_{01} and I_{02} for a cell of efficiency 17.5% at AM0 flux from a production run (HRL).

Io1 (A/cm^2)	Io2 (A/cm^2)	I_{sc} mA/cm^2	V_{oc} mV	Effy %
$8.53.10^{-20}$	$4.11.10^{-11}$	29.0	1026	17.5

It is thus possible to obtain quantitative measurements of first and second diode saturation currents I_{01} (total) and I_{02} for gallium arsenide cells and to compare them with theoretical curves like those in Figure 1 to test the efficacy of the modeling. It is also possible to introduce a constant contribution to I_{02} arising from junction contamination levels into the model.

CONCLUSIONS

(a) The significant effects of junction depletion layer recombination on the radiation hardness of 'windowed' gallium arsenide cells have been explicitly demonstrated. They represent a basic limit to cell hardness especially at high fluence levels. It would appear that improvement in hardness will have to come from an 'offsetting' of damage processes in cell emitter and buffer layers. This might be helped by a greater fundamental understanding of the nature of recombination centers induced by the high energy radiation.

(b) The advantages of thinner window and emitter layers are obvious but they do not alleviate the second diode effects.

(c) It is possible to estimate the second diode effects experimentally at various stages of damage by adding a simple I_{sc}-V_{oc} test at lower light flux levels. Of course more detailed information can be included if dark current voltage measurements are also made at each stage of damage.

(d) In the course of similar modeling for silicon cells we have found that the second diode effects are not insignificant at the high fluence levels. In this case we have considerable experimental evidence from damaged cells. Similar experimental evidence will be obtained for gallium arsenide when damaged samples are available.

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Table 1

Comparison of performance of thick (.5 micron) and thin (.2 micron) windowed gallium arsenide cells with equal and unequal radiation damage coefficients in the emitter and buffer layers.

(K(emit) = K(buff) = 10^{-7}/e or K(emit) = $3.5 \cdot 10^{-8}$/e and K(buff) = $1.8 \cdot 10^{-7}$/e)

(Emitter layer thickness is same as that of window for each cell as given in text.)

	K(emitter) ≠ K(buffer)				K(emitter) = K(buffer)			
	Thick Cell		Thin Cell		Thick Cell		Thin Cell	
Fluence e/cm	With I_{02}	No I_{02}	With I_{02}	No I_{02}	With I_{02}	No I_{02}	With I_{02}	No I_{02}
Open Circuit Voltage (mV)								
0	1016.4	1038.7	1018.7	1041.5	1016.4	1038.7	1018.7	1041.5
10^{14}	997.7	1030.3	1000.3	1033.7	991.0	102.9	994.3	1034.6
10^{15}	929.6	1003.7	931.4	1008.7	916.5	995.2	921.2	1008.2
10^{16}	809.6	958.0	818.6	970.9	783.2	940.0	805.5	960.9
Short Circuit Current (mA/cm^2)								
0	30.23	-	31.36	-	30.23	-	31.36	-
10^{14}	29.72	-	30.69	-	29.73	-	30.93	-
10^{15}	27.63	-	28.41	-	26.69	-	28.95	-
10^{16}	20.47	-	24.52	-	15.14	-	23.76	-
Maximum Power (mW/cm^2)								
0	25.13	25.84	26.11	26.88	25.13	25.84	26.11	26.88
10^{14}	23.93	25.20	24.74	26.11	23.66	25.17	24.65	26.33
10^{15}	20.16	22.82	20.76	23.61	19.15	21.86	20.85	24.02
10^{16}	12.64	16.13	15.32	19.60	9.01	11.71	14.56	18.79
% Efficiency at AM0								
0	18.58	19.10	19.30	19.87	18.58	19.10	19.30	19.87
10^{14}	17.68	18.63	18.28	19.30	17.49	18.61	18.22	19.46
10^{15}	14.90	16.87	15.35	17.45	14.15	16.16	15.41	17.76
10^{16}	9.34	11.93	11.32	14.88	6.66	8.66	10.76	13.80
	(21.7%)	(-)	(21.8%)	(-)	(23.1%)	(-)	(22.5%)	(-)
Cell Fill Factor								
0	.818	.821	.817	.823	.818	.823	.817	.823
10^{14}	.807	.823	.806	.823	.803	.823	.802	.823
10^{15}	.785	.823	.784	.823	.783	.823	.782	.823
10^{16}	.763	.823	.763	.823	.760	.823	.761	.823
	(7.3%)		(7.3%)		(7.65%)		(7.5%)	

(% in brackets give loss in cell efficiency and fill factor due to second diode I_{02}.)

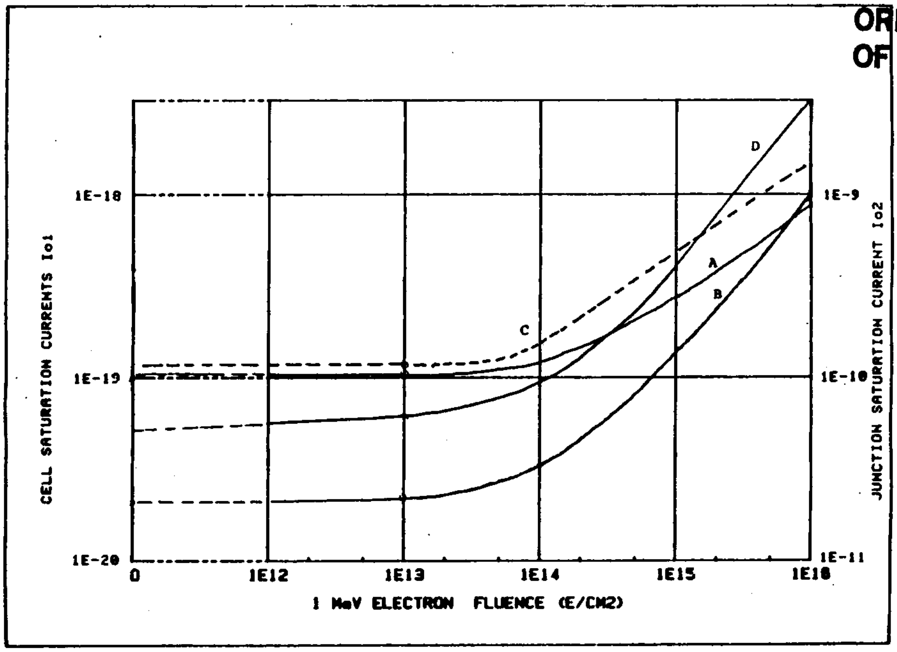

Figure 1. Dependence of diode saturation currents on 1 MeV electron fluence for a 'windowed' gallium arsenide cell with specification and damage coefficients as in text.

A. Saturation current I_{01} for buffer layer

B. Satuation current I_{01} for emitter layer

C. Total I_{01} (curve A + curve B)

D. Second diode saturation current I_{02} for junction

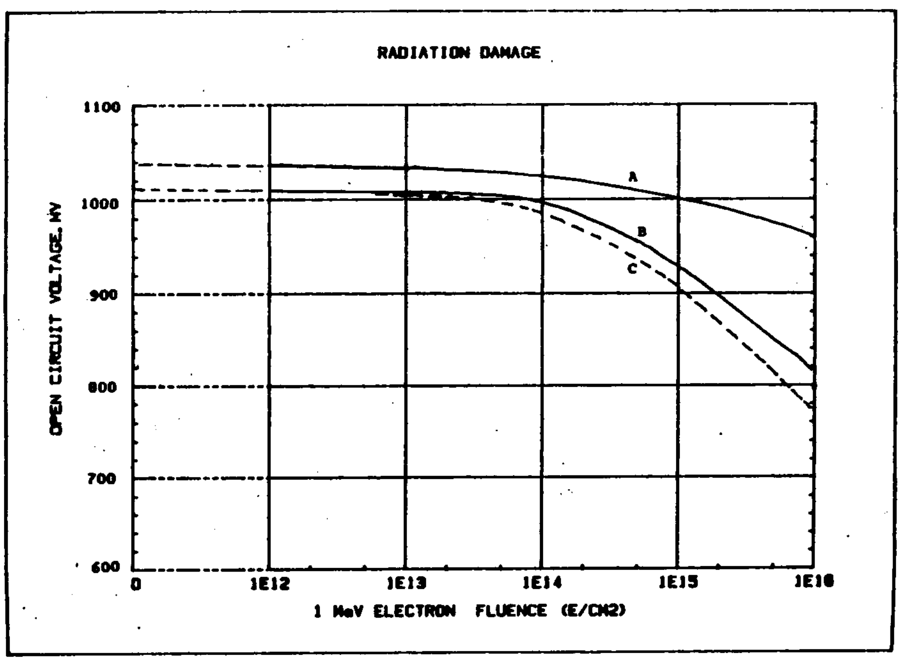

Figure 2. Dependence of open circuit voltage V_{oc} on 1 MeV electron fluence for a 'windowed' gallium arsenide cell with specification and damage coefficients as in text.

A. Variation of V_{oc} when no second diode current is present

B. Variation of V_{oc} when second diode current is present

C. Variation of V_{oc} when second diode current is present and same damage coefficients for emitter and buffer (10^{-7}/e)

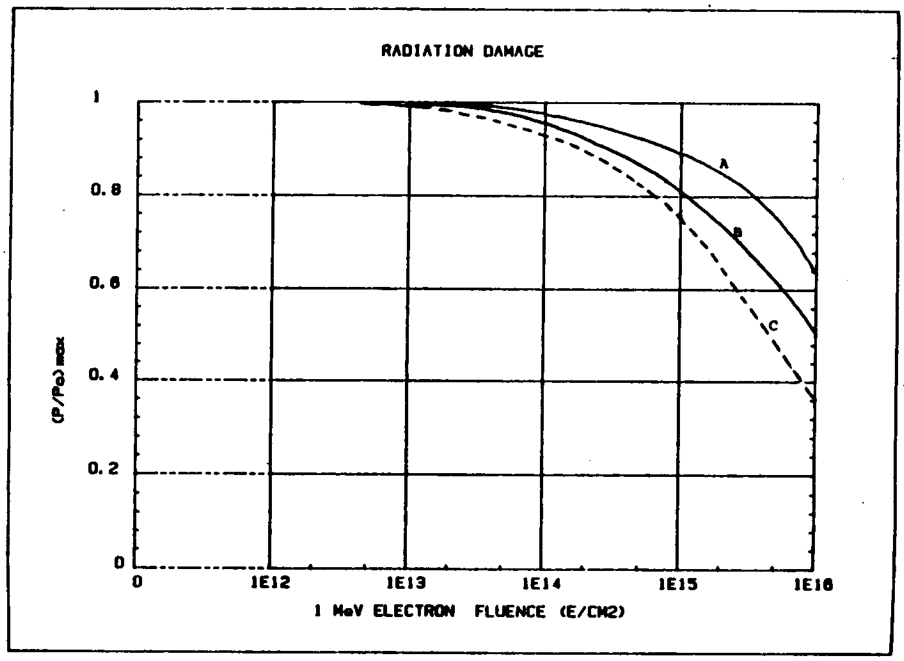

Figure 3. Dependence of ratio (power max. at given fluence/initial power max.) as a function of 1 MeV electron fluence for a 'windowed' gallium arsenide cell with specification and damage coefficients as in text.

A. Variation of ration when no second diode is present

B. Variation of ratio when second diode is present

C. Variation of ratio when second diode is present and for equal damage coefficients in emitter and buffer (10^{-7}/e)