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Defect Behavior, Carrier Removal and Predicted In–Space Injection Annealing of InP Solar Cells

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DEFECT BEHAVIOR, CARRIER REMOVAL AND PREDICTED IN-SPACE INJECTION ANNEALING OF InP SOLAR CELLS

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Abstract

Defect behavior, observed by DLTS, is used to predict carrier removal and the effects of simultaneous electron irradiation and injection annealing on the performance of InP solar cells. For carrier removal, the number of holes trapped per defect is obtained from measurements of both carrier concentrations and defect concentrations during an isochronal anneal. In addition, from kinetic considerations, the behavior of a dominant defect during injection annealing is used to estimate the degradation expected from exposure to the ambient electron environment in geostationary orbit.

Introduction

Radiation induced carrier removal is believed to be a significant factor in affecting the performance of InP solar cells (1). In addition, annealing by minority carrier injection (2) should play a significant role in determining the performance of these cells in space. In both cases, the observed effect is believed to be directly related to the behavior of radiation induced defects. However, attempts to relate carrier removal to specific defect behavior have been admittedly speculative (1). With respect to injection annealing, there have been no published results utilizing defect behavior to predict the effects of injection annealing under the low radiation fluxes typical of the space environment. Hence, one objective of the present work lies in using specific defect behavior to predict carrier removal rates. A second objective lies in using defect behavior to predict annealing of InP solar cells by minority carrier injection in the space radiation environment.

Carrier Removal

Experimental: DLTS and carrier concentration measurements were carried out, after 1 MeV electron irradiation, on small mesa diodes which had been processed on the same wafer next to InP solar cells by MOCVD (3). The DLTS and carrier concentration data relevant to the present case are shown in figure 1. The numbers following the hole trap designations H3, H4 and H5 are the respective defect activation energies as measured in electron volts from the top of the valence band. Carrier removal rates, after 1 MeV electron irradiations were independently determined for similarly processed InP solar cells (4). All cells and diodes were processed by the Spire corporation. Additional details can be found in the cited refs.(3, 4).

Analysis: For a p-type semiconductor, Rc the carrier removal rate is obtained from the relation

$$R_c = \Delta p / \phi \qquad (1)$$

where Δp is the reduction in hole concentration due to irradiation at the fluence ϕ. In general, the measured Δp could be attributable to charge compensation and/or the trapping of holes by radiation induced defects. Assuming that the trapping mechanism is predominant, the carrier removal rate is expressed by the relation

$$R_c = \sum_j I_j T_j \qquad (2)$$

with $I_j = N_j / \phi$ and $T_j = P_j / N_j$ where I_j is the introduction rate of the jth defect whose concentration is N_j at the radiation fluence ϕ and P_j is the concentration of holes trapped by the jth defect.

Values for the introduction and trapping rates are obtained from the data of figure 1. From the figure it is seen that variations in carrier concentration correspond to changes in defect concentration during the course of the anneal. For example; at T > 200°C. an increase in hole concentration coincides with a decrease in the concentration and eventual disappearance of H5. In this case, the concentration of holes trapped by H5 is obtained from the jump in hole concentration. In a similar manner, the abrupt jump in hole concentration at T ~ 100°C is correlated with the coincident decrease in the concentration of H3 and H4 and the increased concentration of H5. Introduction rates are obtained from the post irradiation defect concentrations and the fluence $(5 \times 10^{15}$ cm^{-2}) cited with the figure. In addition, examination of figure 1 at T > 300°C indicates the presence of residual trapped holes coincident with the almost complete disappearance of all three defects. This is interpreted as indicating the trapping of the residual holes by unannealed defects which are not observed by the present DLTS measurements. These latter carriers are included in the carrier removal calculations by adding the term $P(res)/\phi$ to equation 2 where P(res) is the unannealed carrier concentration at T > 300°C. The results are shown in Table I. In Table II the carrier removal rates, calculated using the data of Table I, are compared with independently measured values for InP solar cells (4). It is seen that there is reasonable agreement between the calculated and independently measured values. Hence, although additional data would be helpful, the present results tend to confirm the use of simultaneous DLTS and carrier concentration measurements during isochronal annealing in predicting values for carrier removal rates. In addition, the trapping rates shown in Table I indicate that the H5 defect, when present at sufficiently high concentration, can be more effective as a hole trap than either H3 or H4. In the present case, the low post irradiation concentration of H5 tends to reduce its effectiveness as a recombination or trapping center. However, it is found that the post irradiation concentration of this defect is observed to increase with increasing dopant concentration while

the concentration of the remaining defects decreases. In fact, at a base dopant concentration of 10^{17}cm^{-3}, the concentration of H5 exceeds that of H4 (5). Hence, at and above this concentration H5 could be more effective than either H3 or H4 in affecting the performance of InP solar cells after 1 MeV electron irradiation.

Injection Annealing

It is known that considerable annealing of radiation induced degradation can be achieved by minority carrier injection, at room temperature, into p-type InP (2). In fact, some cell recovery has been observed when the cell was illuminated during irradiation. Hence, one would expect annealing in space, due to minority carrier injection, to be a major factor in alleviating the effects of radiation induced degradation. To determine the extent of this effect, one needs to perform simultaneous annealing while irradiating the cells at the low radiation fluxes encountered in space. A terrestrial experiment, duplicating the low fluxes observed in space, is impractical because of the extremely long times involved. Instead, we use a kinetic argument to estimate the effects of simultaneous irradiation and annealing in space.

Following Heinbockel et al, the production rate of the jth defect is given by (6)

$$dN_j/dt = f_j\sigma_d N_a(d\phi/dt) - W_jN_j \qquad (3)$$

where σ_d is the cross section for atomic displacement, N_a is the concentration of atoms, $d\phi/dt$ is the radiation flux, W_j is the probability per unit time for annealing of the jth defect and f_j is the fractional concentration of defect N_j. At equilibrium dN_j/dt is zero. Hence from equation 3,

$$N_j = \sigma_d N_a\phi_{ej} \qquad (4)$$

with $\phi_{ej} = f_j(d\phi/dt)/W_j \qquad (5)$

ϕ_{ej} is defined as the effective fluence for production of the jth defect. In general, the effective fluence is the radiation fluence which would produce the equilibrium defect concentration in the absence of

annealing (6). In the present case we concern ourselves with the post irradiation defect and preirradation carrier concentrations typical of those in the tables. In that case, H4 is considered to be the dominant defect in reducing cell output (1). Hence, evaluation of the effective fluence for H4 should result in an estimate of cell degradation in a specific orbit. In the present case, we evaluate an effective fluence for a satellite in geostationary orbit.

To evaluate Wj we use the relation obtained for injection annealing of H4 (2),

$$W_{inj} = 19.35 \text{ J} \exp-(E_A/kT) \qquad (6)$$

where J is the cell current density in A/cm2, E_A=0.133 eV is the activation energy for injection annealing (2). The temperature T=333 K is chosen as characteristic of arrays in Geo. Using these values with J=3×10^{-2} A/cm^2 it is found that W_{inj}=5.64×10^{-3} sec^{-1}. It is noted that we consider only injection annealing in the present case. This is justified by noting that, at this temperature, $W_{inj} \gg W_{th}$ where the latter is the probability per unit time for thermal annealing (7).

The greatest uncertainty lies in obtaining values for the flux. This is estimated from a compilation of radiation measurements in space where integral electron fluxes in Geo are listed over the energy range from 0.04 to 7 MeV (8). An upper limit to the flux is obtained by using the "worst case" integral fluence (4.64×10^7 cm^{-2} sec-1) for electron energies greater than 0.04 MeV (8). Hence, using f=0.7, we obtain ϕ_A=5.8×10^9 cm^{-2} as the upper limit for the effective fluence due to electron irradiations in geostationary orbit. At this fluence, no cell degradation is expected (1). However one needs to be cautious in interpreting this result. Although steady state (or ambient) electron irradiations dominate over the ambient proton irradiations in Geo, the intermittent proton irradiations associated with solar flares are significant components of the space radiation environment (8). Although statistical models can be used to obtain rough estimates of the effects of solar flares, insufficient DLTS data exists to enable inclusion of the effects of solar flares on the effective fluence. However, the present results are significant in the sense that electron irradiations predominate over protons in the ambient environment of this particular orbit.

Conclusion

Due to the controversy associated with identifying the atomic constitution of the defects observed by DLTS (5, 9) we have avoided designation of submicroscopic structures with the presently observed defects. However, it has been shown that hole trapping and carrier removal can be related to the behavior of specifically labelled defects. Defect behavior has also been used to estimate the performance of InP solar cells under simultaneous injection annealing and electron irradiation in geosynchronous orbit.

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Table I: Introduction and Trapping Rates
Used in Calculating R_c

^{c}Hole Conc. cm^{-3}	Introduction Rates cm^{-1}			Trapping Rates			P(Res)/ϕ cm^{-1}
	I_3	I_4	I_5	T_3	T_4	T_5	
^{a}2.55 X 10^{16}	0.88	1.7	0.01	0.63	0.62	3.1	1.1
^{b}4.1 X 10^{16}	0.82	1.2	0.04	0.63	0.62	3.1	1.1

^{a} From Fig. 1; ^{b} Intro. Rates from Ref. 3; ^{c} Error = ±5%

Table II: Calculated and Measured
Carrier Removal Rates

^{c}Hole Concentrations cm^{-3}	Carrier Removal Rates cm^{-1}	
	^{a} Calculated	^{b} Measured
2.4 X 10^{16}	2.7	2.8
3.9 X 10^{16}	2.5	2.4

^{a} From Table I; ^{b} Independently Meas. (Ref. 4); ^{c} Error = ± 5%

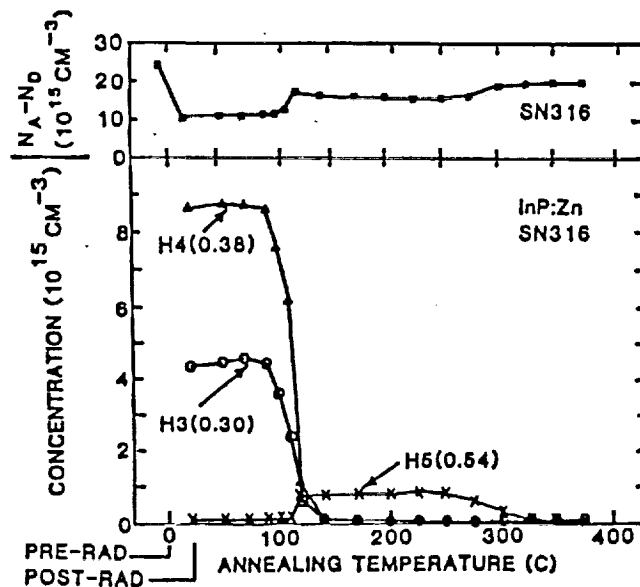Figure 1. Isochronal Anneal After 1 MeV
Electron Irradiation (ϕ=5X10^{15}/cm^2)

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