INT. J. ELECTRONICS, 1994, VOL. 76, NO. 5, 865-882

The control of radiation resistance in space solar cells

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Solar cells, powering satellites and other space vehicles, can suffer substantial degradation in performance by electron and proton irradiation experienced in orbit. These effects are first described, and the behaviour of silicon solar cells compared with cells of gallium arsenide and indium phosphide, and the more recent thin film type cells. In particular, the paper will discuss the phenomenon of 'photon degradation' in silicon cells, and recent progress in understanding the defect mechanisms responsible for this effect occurring after illumination of irradiated cells. Strategies for improving the radiation resistance of silicon solar cells, including the use of 'defect gettering' will be discussed, while the effects of annealing radiation damage will be outlined. Finally, the paper will seek to identify areas where an improved understanding of defect behaviour is necessary to produce further improvements in performance. In particular, it highlights the need for fundamental studies of advanced solar cell structures and materials, including CIS cells, where significant improvement in radiation tolerance has been found.

1. Introduction

The development of practical solar cells was initiated at Bell Laboratories in the early 1950s (Chapin *et al.* 1954). Since then, these devices have been used both for space and terrestrial applications. In space, solar cells furnish the long-duration power supply for satellites. It is this application, in particular, which has highlighted the problem of radiation damage, due to the electron and proton flux experienced during the mission. The degradation associated with this irradiation may severely limit the power duration of the satellite and hence is of considerable importance in satellite design. Recently solar cells employing new materials are claimed to be much more resistant to radiation effects than previous, silicon, cells.

2. Principles of solar cells

A diagrammatic representation of a p–n junction solar cell is shown in Fig. 1 (Sze 1985). It consists of a shallow p–n junction formed near the surface, a front ohmic contact stripe and fingers, a back ohmic contact that covers the centre back surface, and an antireflection coating on the front surface.

When the cell is exposed to the solar spectrum, photons with energy equal or greater than band-gap energy generate current carriers. Carriers collected at the junction generate a current I_L, the light-generated current. If I_s is the diode (dark) saturation current, the I–V characteristics of the solar cell are described by the equation

$$I = I_s\{\exp(qV/nkT) - 1\} - I_L \quad (1)$$

which differs from the usual diode equation only by the presence of the light-generated current I_L, normally modelled as being in parallel with the junction, in the simplified equivalent circuit of Fig. 2.

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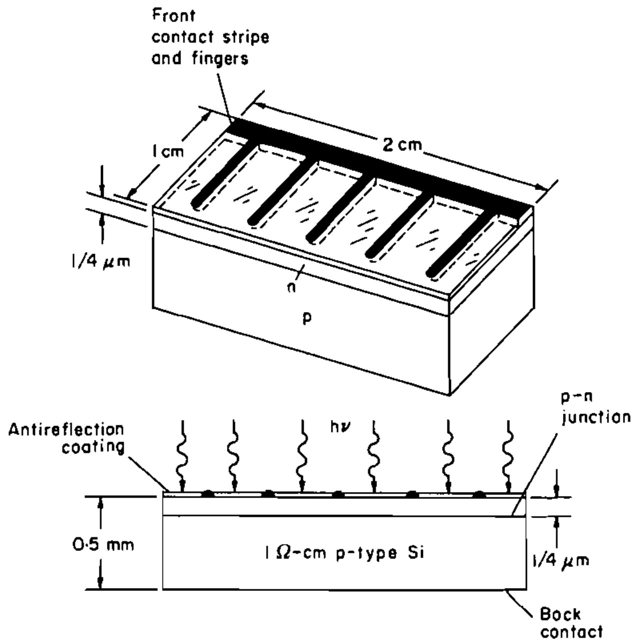


Figure 1. Schematic representation of a silicon p–n junction solar cell (Sze 1985).

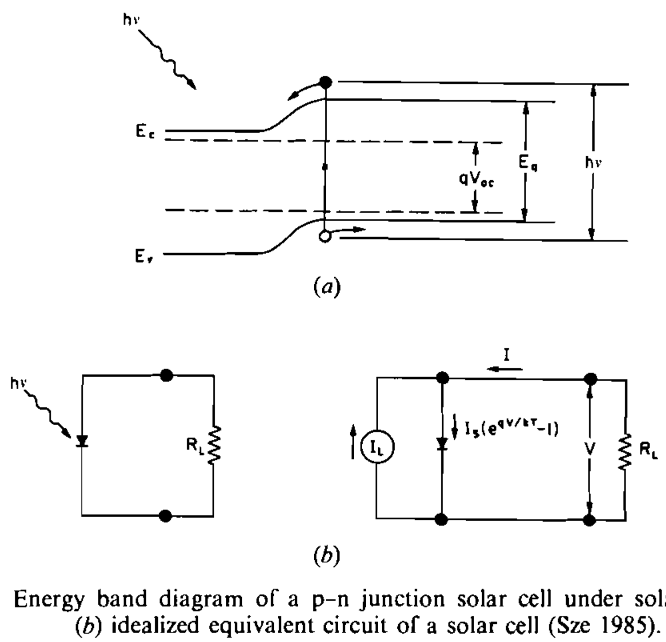


Figure 2. (*a*) Energy band diagram of a p–n junction solar cell under solar irradiation; (*b*) idealized equivalent circuit of a solar cell (Sze 1985).

The I-V curve passes through the fourth quadrant, and therefore power can be extracted from the device. The curve is more usually represented by Fig. 3(*b*) which is an inversion of Fig. 3(*a*) about the voltage axis. By choosing a proper load, close to 80% of the product $I_{sc}V_{oc}$ can be extracted, where I_{sc} is the short circuit current equal to I_L, and V_{oc} is the open-circuit voltage of the cell; the shaded area in the figure is the maximum power rectangle. Also defined in the figure are the quantities I_m and V_m that correspond to the current and voltage, respectively, for the maximum power output $P_m(I_m V_m)$.

From (1) we obtain for the open-circuit voltage ($I=0$)

$$V_{oc}=\frac{nkT}{q}\log_e\left[\frac{I_L}{I_s}+1\right] \tag{2}$$

The power conversion efficiency (η) is given by

$$\eta=\frac{I_m V_m}{P_{in}}$$

$$=\frac{\text{FF}\ I_L V_{oc}}{P_{in}} \tag{3}$$

where P_{in} is the incident power and FF is the fill factor defined as

$$\text{FF}=\frac{I_m V_m}{I_L V_{oc}} \tag{4}$$

To maximize the efficiency, all three items in the numerator of (3) should be maximized.

The ideal solar cell efficiency can be calculated from the ideal I-V characteristics defined by (1). Ideal values are shown in Fig. 4 as a function of band-gap energy for various semiconductors.

Many factors degrade the ideal efficiency. One of the major factors is the series resistance R_s from the ohmic loss in the front surface. Another factor is the

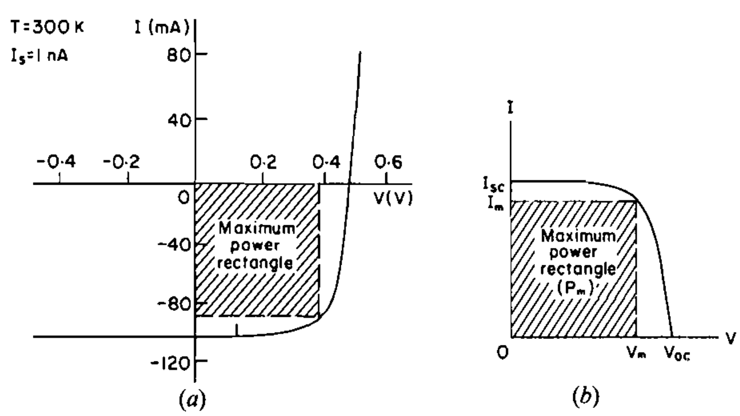


Figure 3. (*a*) Current–voltage characteristics of a solar cell under illumination; (*b*) inversion of (*a*) about the voltage axis (Sze 1985).

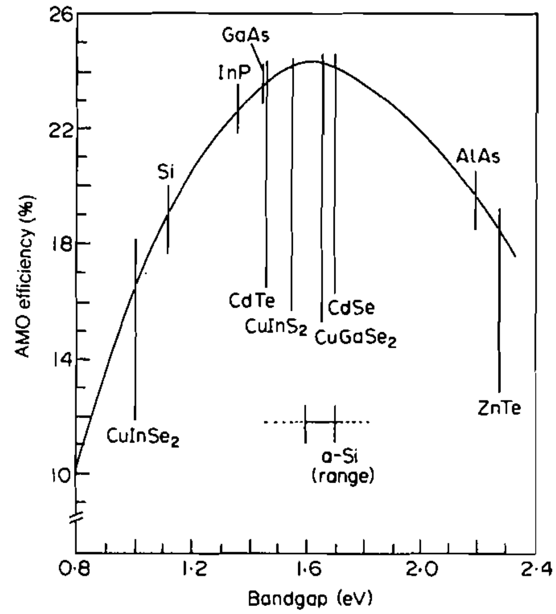


Figure 4. Achievable efficiency for a single junction solar cell as a function of bandgap (Landis *et al.* 1989).

recombination current in the depletion region, and it is this that is the major degradation associated with radiation induced defects, in injecting recombination centres into the device. The main characteristics are summarized in the next section.

In the expression for the efficiency, the light-generated current I_L is determined principally by the minority carrier transport, and depends crucially on the minority carrier lifetime τ. In general terms, only carriers generated within the distance $L=(D\tau)^{1/2}$ of the junction will be collected, the rest will be lost by recombination. It is the diffusion length, L, which is the principal quantity of concern when the cell is subjected to particle bombardment in space.

To illustrate the magnitude of irradiation effects, Fig. 5(*a*) shows the percentage degradation in power output of Si, GaAs and InP cells after 2 MeV proton irradiation (Pearsall *et al.* 1988). Figure 5(*b*) shows the results of a similar study after 1 MeV electron irradiation (Weinberg *et al.* 1986 b, 1987) although we must remember that the starting efficiencies of the three types of cell are different. InP cells show significant advantages over GaAs and Si cells, while more recent reports give even greater advantage to CIS thin film cells, as shown in Fig. 6 (Landis *et al.* 1989).

The effects on cells made from each of the semiconductor materials display particular characteristics, and each will be discussed in turn below together with the state of understanding. In general, however, understanding of the detailed defect mechanisms is at an early stage, and much work remains to be done.

3. Radiation effects

3.1. *Silicon solar cells*

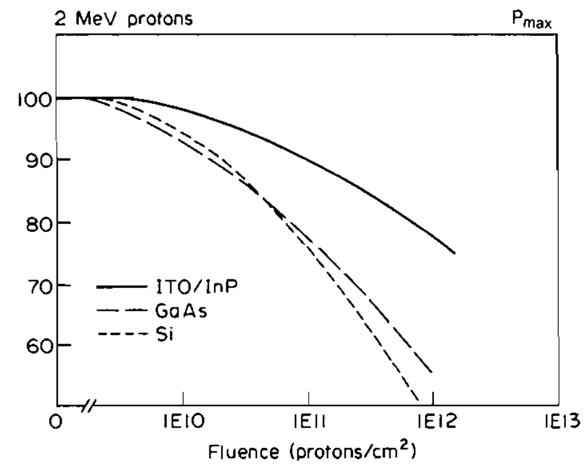
3.1.1. *Dependence on base resistivity.* Photovoltaic arrays based on silicon are, at present, the major source of spacecraft electric power. At present, the n^+p

configuration is preferred exclusively for this application, following the demonstration of superior radiation resistance compared to the p^+n configuration (Mandelkorn *et al.* 1962).

The data in Fig. 5(*b*) on silicon cells illustrates a widely observed phenomenon: the radiation resistance in such n^+p cells is improved with increasing cell base resistivity. This follows, empirically, from the effect of base resistivity on the damage constant K_L in the expression

$$\frac{1}{L}=\frac{1}{L_0}+K_L\phi \tag{5}$$

where L_0 is the minority carrier diffusion length in the unirradiated cell, ϕ is the particle fluence, and L is the diffusion length in the irradiated cell. The diffusion



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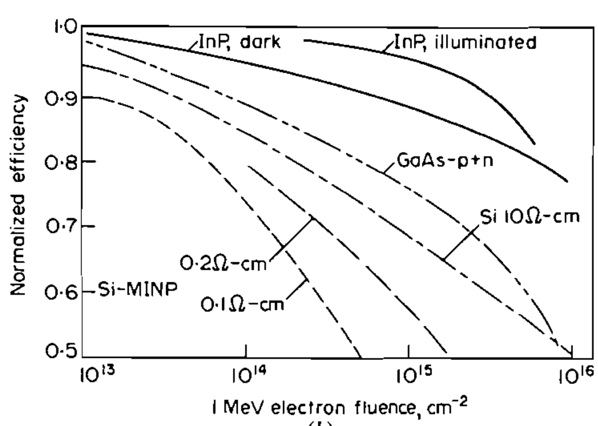


(*b*)

Figure 5. (*a*) Comparison of percentage degradation in maximum power output of InP, GaAs and Si solar cells after 2 MeV proton irradiation (Pearsall *et al.* 1988); (*b*) normalized efficiencies of InP, GaAs and Si solar cells of various base resistivity after 1 MeV electron irradiation (Weinberg *et al.* 1987).

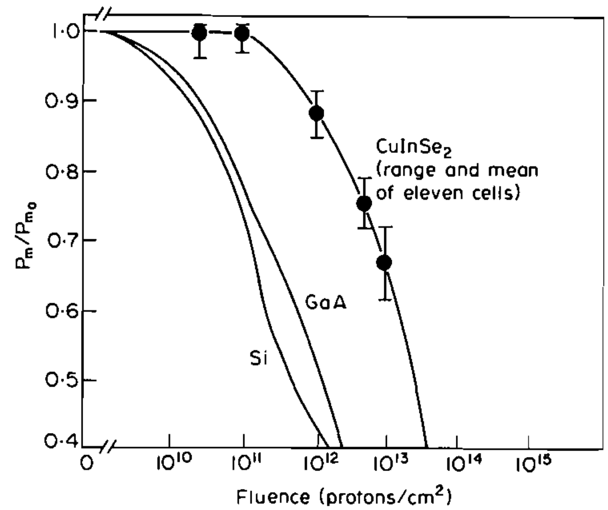


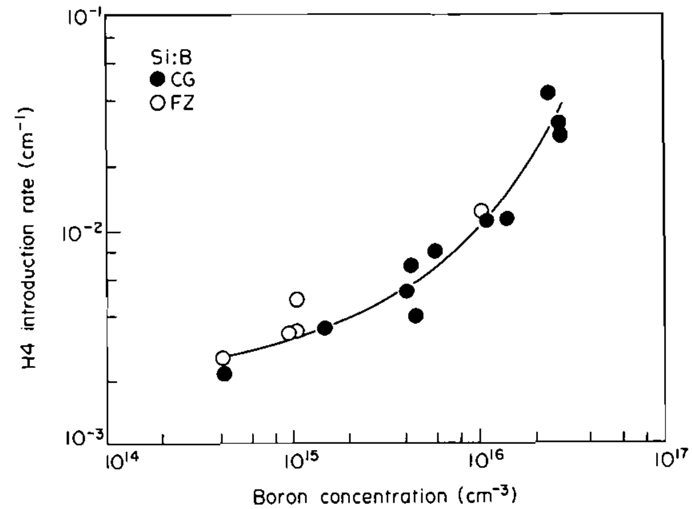
Figure 6. Effect of 1 MeV proton irradiation on maximum power of Si, GaAs and CIS solar cells (Landis *et al.* 1989).

length damage constant K_L has been found to increase with decreasing base resistivity (Markvart *et al.* 1982, Srour *et al.* 1987). Thus, low resistivities imply high values of K_L and hence a larger reduction in minority carrier diffusion length, and a poorer radiation resistance. The effect is a substantial disappointment, since, all things being equal, we would prefer a low base resistivity in such cells to maximize the dark saturation current I_s and hence maximize V_{oc} from (2).

The understanding of the resistivity dependent performance of irradiated silicon has recently been improved considerably by DLTS studies. Drevinsky *et al.* (1990) have shown that the most prominent boron-related defect in FZ silicon influencing the carrier lifetime has an energy level at $E_v + 0{\cdot}29\,eV$, and have argued that it is a B_iC_s defect, from studies of silicon with controlled carbon levels. The introduction rate of this defect, by room temperature irradiation with 1·0 MeV electrons, depends on boron concentration as shown in Fig. 7(*a*). Drevinsky *et al.* (1990) showed that in CZ silicon both B_iC_s and C_iO_i correlate with lifetime degradation and recovery (Table 1).

It is now accepted that the B_iC_s defect appears during annealing as a result of the disappearance of B_iO_i, whose level is at $E_c - 0{\cdot}26\,eV$, the latter's identification being initially by Mooney *et al.* (1977). Kimerling *et al.* (1989) have described the hierarchy of self-interstitial defect reactions in silicon shown in Fig. 7(*b*), indicating how this transition takes place. Earlier, Weinberg *et al.* (1984, 1986 a) had associated solar cell degradation with the $E_c - 0{\cdot}26\,eV$ level, since they found that lithium-counterdoped solar cells showed improved radiation resistance, and no $E_c - 0{\cdot}26\,eV$ defects were observed by DLTS in lithium doped cells. Recent evidence, however, suggests that B_iC_s arising by reaction is the dominant boron-related defect affecting lifetime.

Similar conclusions from a direct correlation of DLTS with solar cell performance were made by Peters *et al.* (1992). They found an increase in the production



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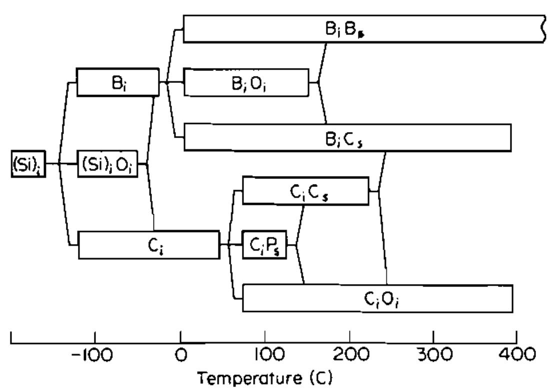


(*b*)

Figure 7. (*a*) Introduction rate of B_iC_s as a function of boron concentration (Drevinsky *et al.* 1990); (*b*) self-interstitial defect reactions in silicon (Kimerling *et al.* 1989).

rate of the B_iC_s level with boron doping in irradiated float zone solar cells, the degradation in performance also increasing with the production rate of this level.

3.1.2. *Photon effects.* Exposure to a prolonged or an intense photon flux, following particle irradiation, has been shown in some instances to *degrade* solar cell performance, and in other instances to *enhance* it. Crabb (1972) found that electron irradiated float zone silicon solar cells degrade severely when irradiated with photons in the wavelength range 0·2–1·0 μm and ten suns intensity for periods up to 200 h. This degradation can amount to as much as 12% of the post electron irradiation performance, but was believed to saturate. The effect was attributed to a

Anneal temp. (°C)	Concentrations ($\times 10^{12}\,cm^{-3}$)		Lifetime (μS)
	C_iO_i	B_iC_s	
Pre-rad.	ND	ND	41·80
Post-rad.	7·96	ND	0·42
100	9·74	ND	0·52
150	6·57	4·36	0·49
200	6·15	6·42	0·41
250	5·60	5·94	0·40
300	7·23	5·53	0·38
325	8·06	4·72	0·43
350	10·70	2·40	0·77
375	3·80	ND	3·68
400	1·35		10·80
425	ND		17·70

ND = not detected.

Table 1. Lifetime correlation with defects (Drevinsky *et al.* 1990).

degradation of base region minority carrier lifetime which led to a loss of 'red' spectral response, but the culprit recombination centres were not identified.

Originally Crabb noted that Czochralski silicon did not show this effect, and later (Crabb 1973) concluded that the effect was intimately associated with dislocation density, dopant atom type (boron rather than aluminium) and dopant concentration. Figure 8 shows his original measurements of the I–V performance before and after photon irradiation.

This photon degradation effect was investigated further by Markvart *et al.* (1982). They studied the dependence of this effect on the base resistivity of boron doped float-zone cells, in the base resistivity range 0·3–115 Ω cm. Figure 9 shows their measurements of short-circuit current I_{sc} as a function of fluence ϕ, and the effect of post-electron illumination on 0·94 and 10 Ω cm cells, photon degradation being shown by arrows. The authors concluded that photon degradation had a complex dependence on base resistivity and defined the ratio

$$r=\frac{K_{ph}}{K_{el}}=\frac{\Sigma_{ph}}{\Sigma_{el}} \qquad (6)$$

where K_{ph}, K_{el} are the damage coefficients and Σ_{ph}, Σ_{el} are the total minority carrier capture cross sections of defects introduced by illumination or electron irradiation. The measured dependence of r on base resistivity is plotted as points in Fig. 10 together with a theoretical curve.

The theoretical curve is derived on the basis that illumination induces a pairing reaction of defects which, as a pair, has a higher minority carrier capture cross section than the sum of their individual cross sections. This model was put forward as a working hypothesis, but the curve showed that such an explanation could, in principle, explain the observations. The authors also suggested that Coulombic charge effects might be responsible for limiting the resistivity range over which photon degradation was significant.

The above observations all concerned *degradation* of cell performance by photons. Corbett *et al.* (1980), however, pointed out that researchers had found

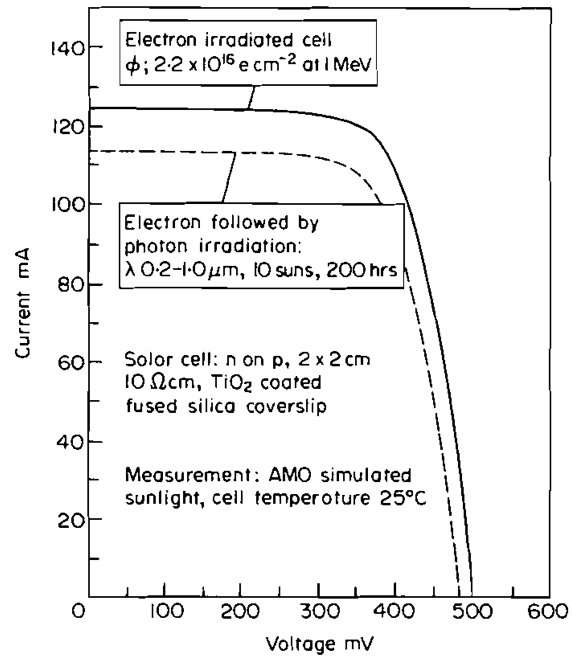


Figure 8. Silicon solar cell *I–V* characteristics following sequential electron-photon irradiation (Crabb 1972, 1973).

photo-*enhancement* in p^+ on n cells, as well as degradation in n^+ on p cells. They further pointed out that there have been several instances of defect alteration by photons, including photon-induced dissociation of defect pairs (Watkins *et al.* 1979), in the first mechanism of which a simple charge state change might negate the Coulombic attraction of the two defects, and elastic repulsion causes dissociation of the pairs. In the second mechanism, they put forward an *energy-release* mechanism for the enhancement of defect migration, which could just as readily aid defect dissociation. In this way, Corbett and his co-workers suggested that ionization can enhance both the formation and dissociation of defect-pairs, and hence could account for both photo-degradation and enhancement phenomena in solar cells. These ideas, appearing before the measurements, link very closely with modern ideas of recombination-enhanced defect reactions. Roux *et al.* (1984) later studied the photon effect by DLTS (Fig. 11), while Peters *et al.* (1992) recently correlated their DLTS studies to parallel solar cell measurements. The latter authors proposed that illumination promoted the transition of B_iO_i defects to the lifetime-killing B_iC_s defects in float-zone material. In CZ material, where the effect is not normally observed, C_iO_i defects are produced preferentially by irradiation at room temperature, and these appear to dominate.

3.1.3. *Control of radiation resistance.* Since the degradation of silicon solar cells by irradiation is one of the most severe limitations of silicon for satellite applications, there have been a number of attempts to reduce this effect, an example of which was the lithium counterdoping method discussed above. More recently, Markvart *et al.* (1987) succeeded in reducing the degradation considerably by fabricating solar cells

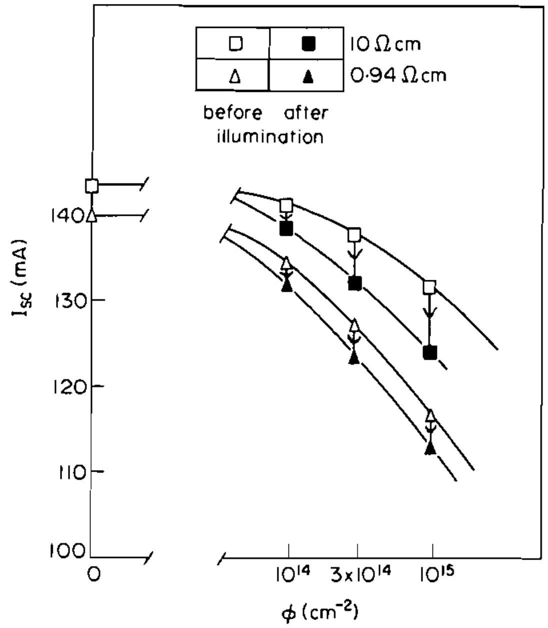


Figure 9. The effect of post-electron illumination on the short-circuit current I_{SC} at various electron fluence levels for 0·94 and 10 Ωcm base resistivity silicon cells. Photon degradation is shown by arrows. All cells received 1 MeV electron irradiation (Markvart *et al.* 1982).

of material incorporating an intrinsic gettering zone within the wafer. These wafers, commonly used for impurity gettering, contain a surface ('denuded') zone with a relatively low oxygen concentration, and a region rich in oxygen precipitates deeper in the wafer. Solar cells fabricated in the denuded zone of such wafers, while showing a lower starting efficiency than cells made in standard wafers, exhibited a considerable improvement in the radiation resistance. An example is shown in Fig. 12, where the percentage degradation after both electron and proton irradiation is compared. The cells fabricated in denuded zone material show radical improvements

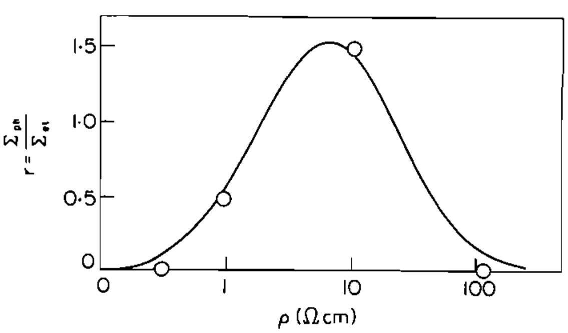


Figure 10. The base resistivity dependence of the ratio r (Equation (6)) determined from experimental points and a theoretical curve (Markvart *et al.* 1982).

which, despite the lower starting power listed in Table 2, result in closely similar performance after irradiating with the maximum fluence. These studies were undertaken without optimizing cell performance and further improvements are likely to achieve considerable absolute power advantages for cells from denuded zone material.

The defect interactions responsible for these effects are currently being investigated, and it is too early to make a definitive conclusion. However, DLTS studies (Peters *et al.* 1992) of denuded zone cells show that at least some of the defect levels are also present in low oxygen Czochralski material that exhibits considerable degradation. One level, at $E_v + 0{\cdot}47\,\mathrm{eV}$, however, is not present in the denuded zone cells, and is present in the standard cells, and further work is under way to examine the possible role of the defect responsible. In particular, the defect interaction with oxygen precipitates and the possible reduction in complex formation will be examined in these wafers.

In summary, empirical methods to reduce radiation induced degradation appear to be attractive, but fundamental defect understanding is necessary to put these on a sound basis.

3.2. *GaAs and InP cells*

It was noted earlier that the radiation resistance of GaAs and InP cells is significantly better than that of silicon solar cells. Figure 13 due to Yamaguchi and Ando (1988) compares the radiation resistance of various InP structures as a function of electron fluence, and shows that the best normalized performance can be obtained from InP cells, remembering of course that the absolute efficiency may not necessarily favour InP over GaAs. While the effects differ somewhat between proton and electron irradiation, and with the particular device structure, we will attempt to discuss the characteristics of particular relevance to defect behaviour.

These differences are due to a combination of factors, since differences in band structure, optical absorption coefficients, minority carrier diffusion lengths, and size of cell active layers all have a contribution as well as defect characteristics. Yamaguchi and Ando (1988) pointed out that, in fact, the damage constant for GaAs is not necessarily lower than Si, even though InP damage constants are lower at high carrier concentrations, as shown in Fig. 14. Thus, III-V compound solar

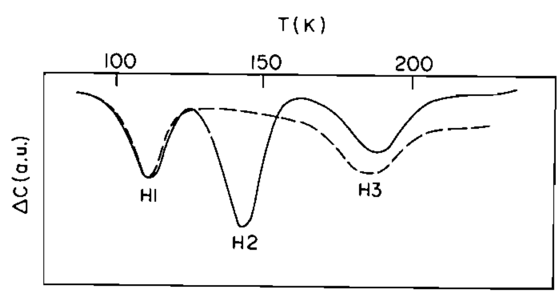
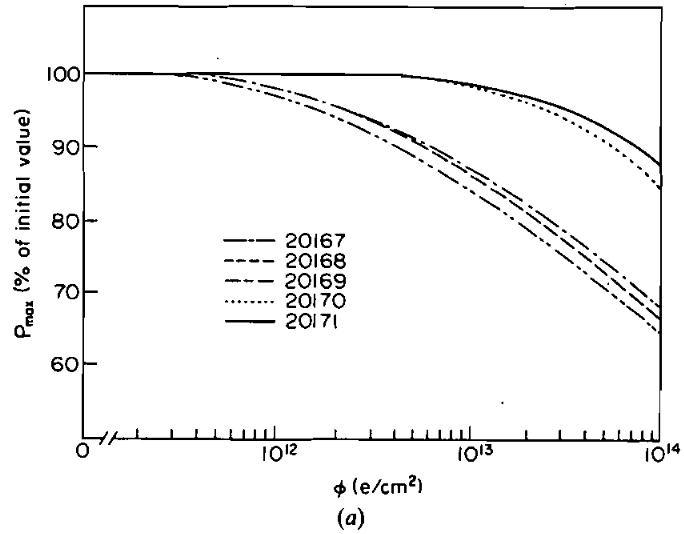


Figure 11. DLTS spectra of a silicon FZ $10\,\Omega\mathrm{cm}$ solar cell after irradiation by 1 MeV electrons ($\phi = 10^{15}\,\mathrm{cm}^{-2}$) for a cell irradiated and kept in the dark after irradiation (broken curve) and a cell illuminated after irradiation (continuous curve) (Roux *et al.* 1984).



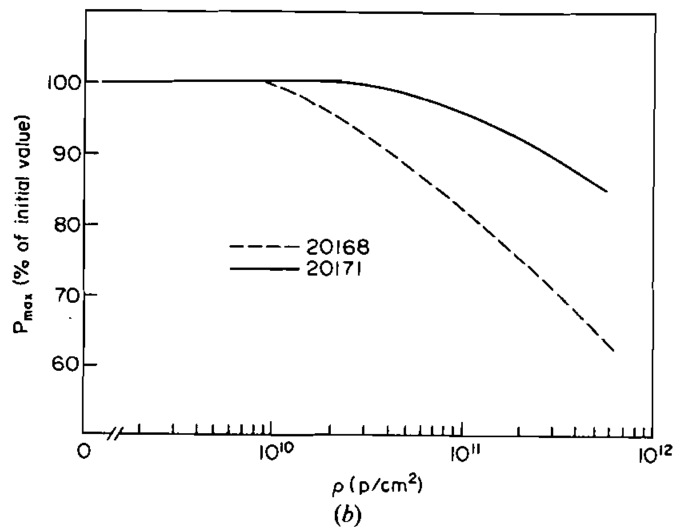


Figure 12. (*a*) Percentage degradation in maximum power (P_{max}) after electron irradiation with 1 MeV electrons followed by illumination for 48 h. Cells 20170 and 20171 were fabricated in denuded zone silicon wafers, while 20167 to 20169 were from homogeneous Czochralski wafers (Markvart *et al.* 1987); (*b*) as (*a*), except using proton irradiation with 10 MeV protons (Markvart *et al.* 1987).

cells are more resistant to radiation even though higher defect introduction rates occur than in the Si solar cells.

Under proton irradiation, InP shows a significant advantage, as pointed out by Pearsall *et al.* (1988) using proton energies from 2 MeV to 50 MeV. They showed that GaAs was more radiation resistant than Si but was, at least in normalized terms, not as resistant as InP.

In addition to these advantages in as-irradiated performance, other features have been found in InP solar cells which offer particular benefits. The benefits claimed

Batch	Oxygen content	Denuded zone	P_{max} (mW cm^{-2})
20167	$2{\cdot}8$–$3{\cdot}8 \times 10^{17}$	No	11·53
20168	$5{\cdot}1$–$8{\cdot}7 \times 10^{17}$	No	11·51
20169	$11{\cdot}5$–13×10^{17}	No	11·21
20170	$3{\cdot}6$–$4{\cdot}0 \times 10^{17}$	Yes	8·31
20171	$2{\cdot}7$–$3{\cdot}0 \times 10^{17}$	Yes	8·46

Table 2. Details of the silicon cells in Fig. 12. Cells are without antireflection coating (Markvart *et al.* 1987).

include room-temperature annealing, minority-carrier injection annealing, and possibly light-illumination-enhanced annealing (Yamaguchi and Ando 1988).

3.2.1. *Annealing of radiation damage.* Yamaguchi and co-workers have reported partial recovery of power after room temperature annealing of both n^+p and p^+n InP solar cells as shown in Fig. 15. A further annealing phenomenon noted by Yamaguchi and Ando (1988) was that InP n^+p solar cells under light illumination, i.e. under solar cell operation, have significantly more radiation resistance than those under dark conditions, as shown in Fig. 16. Flood (1987) has similarly noted thermal annealing recovery effects, and that cells irradiated in the light have more radiation resistance than those irradiated in the dark. Lastly, Yamaguchi has observed power recovery caused by forward-bias injection. These effects are most interesting particularly in the light of the photon effects in silicon discussed above.

3.2.2. *Defect studies in InP.* Yamaguchi and Ando (1988) have carried out DLTS studies of irradiated InP solar cells and the effects of annealing. Although these are at an early stage, they associate the major degradation phenomena with a hole trap H4 whose energy level is 0·37 eV. On annealing, this hole trap H4 is completely annealed out around 100°C, and the annealing kinetics were characterized. At the same time, the density of another hole trap H5 *increases* as annealing proceeds as

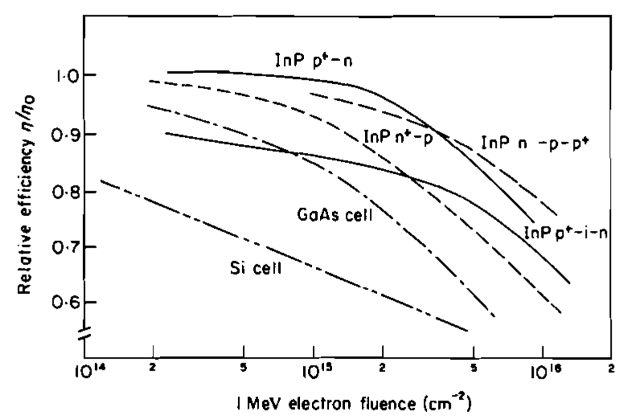


Figure 13. Relative AM1.5 efficiency for InP solar cells with various structures as a function of 1 MeV electron fluence, in comparison with irradiation effects on Si and GaAs solar cells (Yamaguchi and Ando 1988).

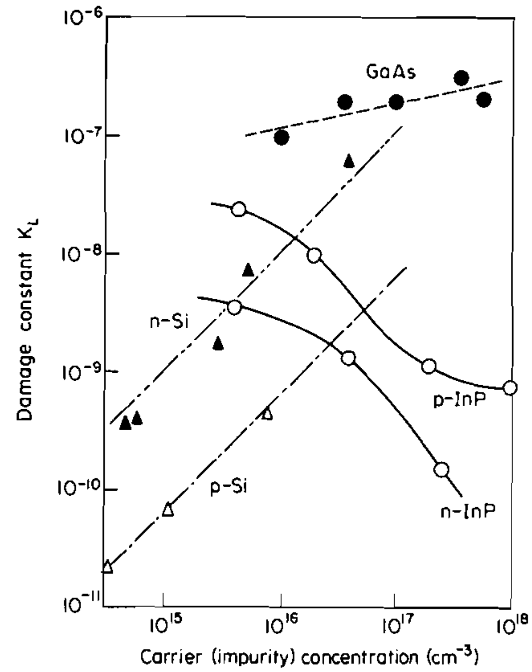


Figure 14. The effect of carrier concentration on the diffusion length damage constants in InP, GaAs and Si determined with 1 MeV electron irradiation (Yamaguchi and Ando 1988).

shown in Fig. 17 and Yamaguchi and Ando suggest that this is a point-defect impurity complex resulting from this annealing process. Tentative proposals by Yamaguchi were that H4 is a Frenkel pair of V_p–P_i, with H5 a P_{In}-impurity complex. Recent work by Drevinsky *et al.* (1991), however, has thrown some doubt on the V_pP_i assignment for the H4 level, and has identified a shoulder on the DLTS H4 peak as due to another defect state H3 (E_v+0·30 eV). Sibille and co-workers (1986)

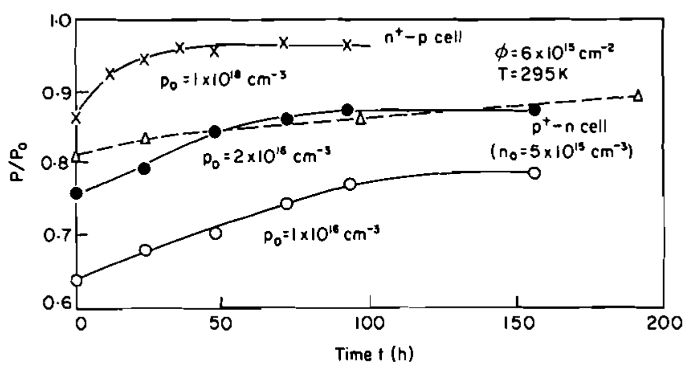


Figure 15. Recovery in maximum power P/P_0 after room temperature annealing (295 K) of 1 MeV electron-irradiated InP solar cells with various structures and substrate carrier concentrations (Yamaguchi and Ando 1988).

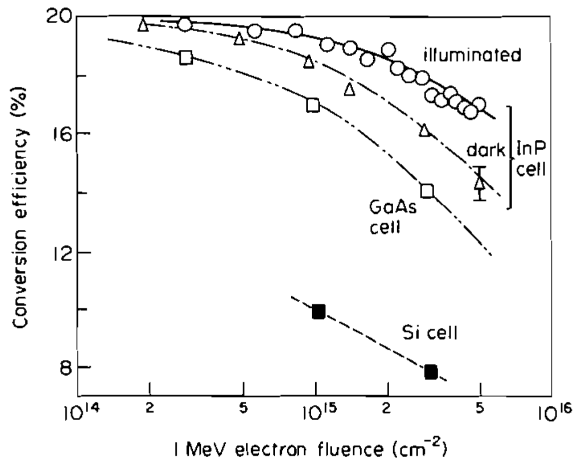


Figure 16. Changes in AM1.5 efficiencies of InP cells irradiated under light illumination or dark conditions as a function of 1 MeV electron fluence. GaAs and Si cells are shown for comparison (Yamaguchi and Ando 1988).

have proposed an alternative model for H4 consisting of complexes between shallow acceptors and either the phosphorus interstitial or phosphorus vacancy. There is, however, agreement between Drevinsky *et al.* (1991) and Yamaguchi and Ando (1988) on the importance of the H4 hole trap in solar cell degradation and annealing, and Drevinsky *et al.* (1991) show that carrier loss and degradation of V_{oc}, I_{sc} and cell efficiency correlate with the production of both H4 and H3. Observed recovery correlates with the anneal of H4 and H3 (Fig. 18). Weinberg *et al.* (1992) have subsequently modelled defect behaviour to estimate the performance of InP solar cells under simultaneous injection annealing and electron irradiation in

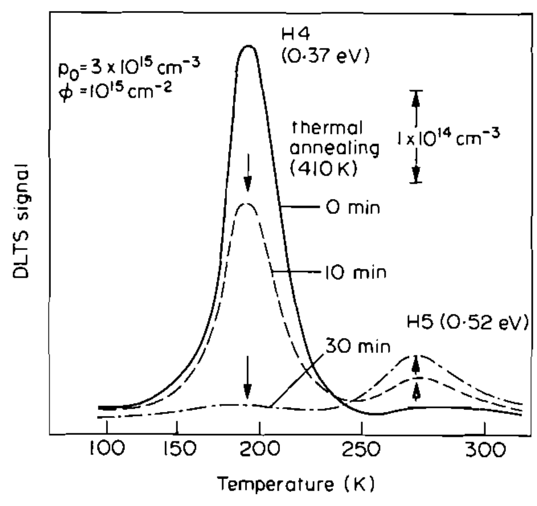


Figure 17. DLTS spectra in p-InP with a carrier concentration of $3 \times 10^{15} cm^{-3}$ following 1 MeV electron irradiation of $1 \times 10^{15} cm^{-2}$ fluence and successive thermal annealing at 410 K (Yamaguchi and Ando 1988).

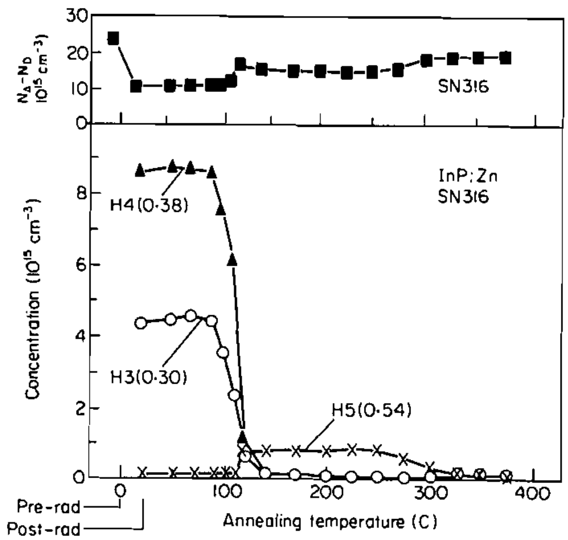


Figure 18. Isochronal annealing of InP epi-diode showing correlation of defect annealing stages with two majority carrier recovery stages (annealing for 20 min periods in dry N_2) (Drevinsky *et al.* 1991).

geosynchronous orbit. Thus substantial progress in understanding of InP cells has been made but more work is needed to identify the defects involved.

3.3. *Advanced solar cell structures and materials*

As mentioned above, thin film CIS solar cells have been reported to have the highest radiation tolerance of any solar cell measured to date. Burgess *et al.* (1989) found no degradation with 1·0 and 2·0 MeV electrons to a total fluence of 5×10^{15} cm^{-2}. The proton fluences affected the cell parameters as shown in Fig. 19,

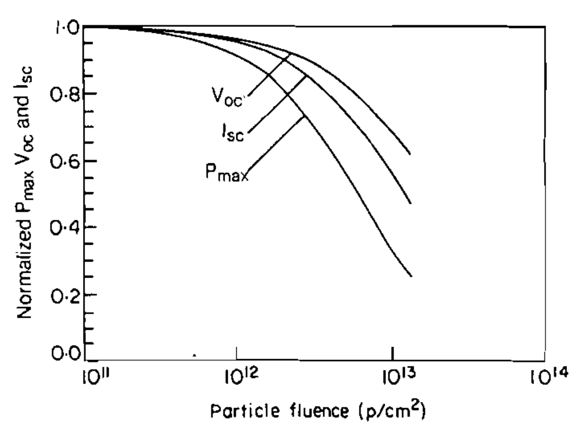


Figure 19. Normalized P_{max}, V_{oc} and I_{sc} of CIS cells before and after 0·2 MeV proton irradiation (Burgess *et al.* 1989).

the greatest damage to P_{max} being through the I_{sc} contribution. As pointed out earlier, these effects are much less severe than in Si, GaAs and InP cells.

At this stage there is little fundamental understanding of radiation effects on CIS cells, or on other advanced structures presently being developed, for example GaAs/Ge, CdTe, thin-film cascades and a range of other thin-film cells. Studies of these new structures and materials will provide an essential element of future work in this area.

4. Conclusions

We have seen that advances in defect understanding have proved extremely valuable in the control of the radiation resistance of solar cells. DLTS studies, in particular, have provided new evidence to assist in the characterization of defect levels introduced in silicon and InP. A common feature emerging is the observation of photon effects, causing further changes in performance in some silicon solar cells, and recovery in indium phosphide cells. Recent progress in CIS cells is promising, but requires fundamental study.

ACKNOWLEDGMENTS

The author acknowledges helpful discussions with T. Markvart, J. Peters, C. Goodbody, P. A. Taylor and P. J. Drevinsky.

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