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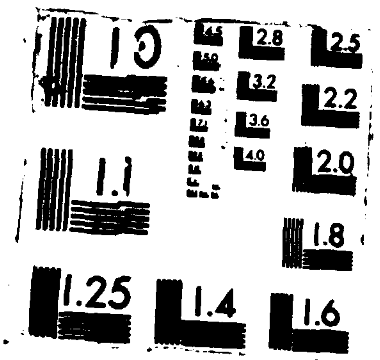
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REPORT DOCUMENTATION PAGE

DTIC ELECTE AUG 1 4 1987 S D

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS None
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT As it appears on the report (12)
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Technical Report No. 6	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Research Foundation of State University of New York; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Office of Naval Research
6c. ADDRESS (City, State, and ZIP Code) SUNY at Buffalo Dept. of Electrical and Computer Engineering Amherst, NY 14260	7b. ADDRESS (City, State, and ZIP Code) 800 N. Quincy St. Arlington, VA 22217-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-86-K-0622
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Electron Irradiation Effects on the Shunt Resistance of Silicon Solar Cells

12. PERSONAL AUTHOR(S)
BANERJEE, Sonali; ANDERSON, Wayne A.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical report	FROM 8/1/86 TO 7/31/87	July 31, 1987	7

16. SUPPLEMENTARY NOTATION
100,000 ohms

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Radiation effects — 5 x 10 to the 6th power

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Shunt resistance R_{sh} values greater than $5\times10^6\Omega$ have been measured for high efficiency silicon solar cells fabricated by a low temperature diffusion technique, whereas lower values ($(0.5-1.0)\times10^5\Omega$) were obtained for ion-implanted solar cells. A degradation in R_{sh} values by an order of magnitude was observed after electron irradiations of 1 MeV to a fluence of $1\times10^{16}e\text{-}cm^{-2}$. Temperature dependence studies indicated a rapid decrease in R_{sh} above a threshold temperature which is sensitive to the device quality. As the fluence of irradiation increased, very little shift in the threshold temperature towards lower values was observed. The degradation in R_{sh} causes an enhancement in the dark saturation current which is partly responsible for degradation in the open-circuit voltage of the devices.

ohms; 10 to the 16th power; per sq cm

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

87 8 11 088

OFFICE OF NAVAL RESEARCH

Contract N00014-86-K-0622

Technical Report No. 6

Electron Irradiation Effects on the Shunt Resistance of Silicon Solar Cells

by

S. Banerjee and W.A. Anderson

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Availability Codes		
Dist	Avail and / or Special	
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Prepared for Publication in

Solar Cells

State University of New York at Buffalo
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July, 1987

ELECTRON IRRADIATION EFFECTS ON THE SHUNT RESISTANCE OF SILICON SOLAR CELLS

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(Received August 28, 1986; accepted in revised form November 19, 1986)

Summary

Shunt resistance R_{sh} values greater than $5 \times 10^6\ \Omega$ have been measured for high efficiency silicon solar cells fabricated by a low temperature diffusion technique, whereas lower values ($(0.5 - 1.0) \times 10^5\ \Omega$) were obtained for ion-implanted solar cells. A degradation in R_{sh} values by an order of magnitude was observed after electron irradiations of 1 MeV to a fluence of 1×10^{16} e$^-$ cm^{-2}. Temperature dependence studies indicated a rapid decrease in R_{sh} above a threshold temperature which is sensitive to the device quality. As the fluence of irradiation increased, very little shift in the threshold temperature towards lower values was observed. The degradation in R_{sh} causes an enhancement in the dark saturation current which is partly responsible for degradation in the open-circuit voltage of the devices.

1. Introduction

The photovoltaic performance of solar cells is significantly influenced by the junction characteristics of the device. It was earlier observed that the carrier transport across the junction deviates from its ideal diffusion-limited mechanism owing to recombination in the space charge layer, series resistance R_s and shunt resistance R_{sh} [1 - 3]. This results in excess current components in the experimental current–voltage (I–V) characteristics which can be expressed as [4]

$$I_D = I_{d0}\left[\exp\left\{\frac{q(V_D)}{kT}\right\} - 1\right] + I_{Excess} + \frac{V_D}{R_{sh}} \tag{1}$$

where I_D is the total measured diode current, I_{d0} is the saturation current for diffusion-limited transport, I_{Excess} is the excess current(s) due to different recombination mechanism(s), the last term represents the shunt current and V_D is the diode voltage which is related to the terminal voltage V by

$$V_D = V - I_D R_s \tag{2}$$

The physical processes responsible for this behavior are fairly well explained in the literature [1, 5, 6] except for that of R_{sh}. Until recently, a limited understanding was available owing to the fact that R_{sh} was usually estimated as a curve fitting parameter to the experimental I–V characteristics [3, 7]. During recent studies regarding I_{Excess} in silicon metal/insulator/n-silicon/p-silicon (MINP) solar cells [4], it was observed that R_{sh} varies with temperature above a threshold temperature which is extremely sensitive to the device quality [8]. As an extension of this work, this paper considers the effect of electron irradiations of 1 MeV on R_{sh} and the shunt current.

2. Experimental details and analysis

The silicon MINP solar cells have been fabricated on ⟨100⟩ oriented, 0.1 - 0.3 Ω cm resistivity boron-doped float zone silicon. The junctions formed by the solid source diffusion of phosphorus at 950 °C for 5 min using the Carborundum solid source [4, 8] are compared with those ion-implanted at 5.0 keV. A schematic diagram of the device structure, shown in Fig. 1, illustrates the design features which are highlighted by front and back surface passivation. The experimental measurement of R_{sh}, described in an earlier report [8], utilizes I–V data for $V < 0.05$ V in calculating R_{sh}. After the initial testing, the devices were successively irradiated by 1 MeV electrons in a Van de Graaff electron accelerator at three different fluences of 1×10^{14} e$^-$ cm^{-2}, 1×10^{15} e$^-$ cm^{-2} and 1×10^{16} e$^-$ cm^{-2}. All the devices were tested before and after each stage of irradiation. Photovoltaic data comparing the various types of cells are given in Table 1. These data are representative of 10 - 20 cells which were tested. A remarkably good consistency was seen from cell to cell both before and after irradiation.

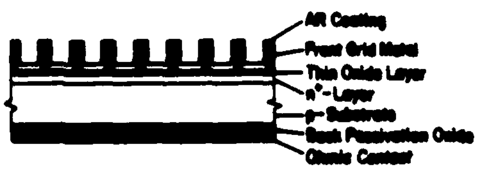

Fig. 1. Schematic diagram of the MINP solar cell.

In an earlier study [8], it was observed that the R_{sh} values remain fairly constant below a threshold temperature T_t and decrease rapidly above this temperature which is very sensitive to the device junction quality. As a result, a rapid rise in the shunt current was observed above this temperature. The threshold temperature $T_t \geq 250$ K is slightly below room temperature. When exposed to 1 MeV electrons, the most obvious change was a reduction in R_{sh} values above the threshold temperature as shown in Fig. 2. As the

TABLE 1

Photovoltaic data before and after irradiation by 1.0 MeV electrons to 10^{16} cm^{-2}

Sample	V_{oc} (V)		J_{sc} (mA cm^{-2})[d]		Shunt resistance[e] (Ω cm^2)	
	Before	After	Before	After	Before	After
1[a]	0.632	0.494	43.1	19.7	8.4×10^6	9.3×10^5
2[b]	0.606	0.506	40.8	23.8	5.0×10^4	1.6×10^4
3[c]	0.626	0.489	42.9	25.7	2.4×10^5	1.2×10^5

[a]Diffused MINP cell with diffusion performed through a window in the oxide: area, 2.0 cm^2.
[b]Ion-implanted MINP cell where junction edges are exposed: area, 2.1 cm^2.
[c]Ion-implanted without passivation: area, 4.0 cm^2.
[d]Illuminated at 135 mW cm^{-2}.
[e]At 300 K.

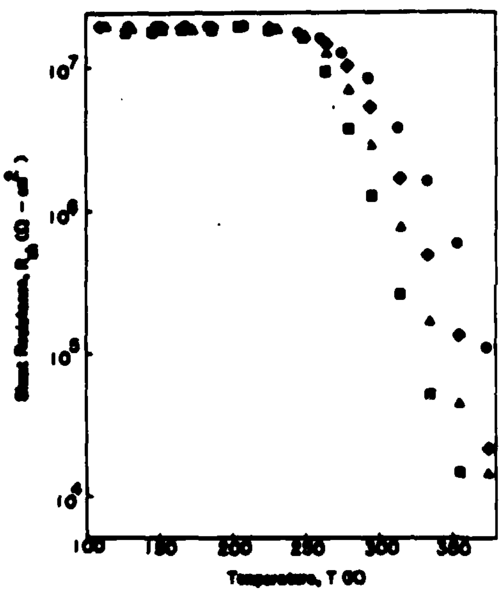

Fig. 2. Temperature dependence of R_{sh} for a diffused MINP solar cell before and after electron irradiation of 1 MeV at different fluence levels: ●, before irradiation; ◆, after 10^{14} e^- cm^{-2}; ▲, after 10^{15} e^- cm^{-2}; ■, after 10^{16} e^- cm^{-2}. R_{sh} is accurate to 1% and the temperature to 0.1%.

irradiation fluence increased, very little shift in T_t towards lower temperatures was observed. The change in R_{sh} values below the threshold temperature is however negligible. This behavior can be explained in terms of the proposed mechanism of R_{sh} [8]. The radiation-induced defects can introduce additional energy states in the band gap of the space charge layer [9]. The energy levels and densities of these states depend strongly on the energy and fluence of the irradiating particles. At low temperatures, tunnelling through these states is the most probable mode of carrier transport and is almost temperature independent. This causes R_{sh} to remain practically constant in a certain temperature span. As the temperature rises, thermal re-emission of carriers from the traps becomes appreciable and R_{sh} tends to drop at a faster pace. The energy level of these traps and their density are the two important factors governing the rate of emission which is expressed as [8]

$$\frac{dn_t}{dt} = -n_t \nu \exp\left(\frac{-E_A}{kT}\right) \tag{3}$$

where n_t is the number of carriers trapped in the state, E_A is the energy level of the state, k is the Boltzmann constant, T is the temperature in degrees Kelvin and ν is the attempt-to-escape frequency given by

$$\nu = N_{eff} S v \tag{4}$$

where N_{eff} is the density of states in the conduction (valence) band, S is the capture cross-section of electrons (holes) and v is the thermal velocity of the carriers. If the density and population of these states are extremely high and the traps are relatively shallow, thermal emission will be significant at a relatively lower temperature. The presence of shallow traps is also reflected in the activation energy values obtained from the slope of the temperature dependence of the saturation current density [10]. As the fluence of irradiation is increased, the defect levels become deeper [10], and the densities increase further, resulting in a shift in the threshold temperatures shown in Fig. 2.

Following these arguments, a low threshold temperature was expected for ion-implanted devices before irradiation, because ion implantation induces defects, similar in nature to those created by particle irradiation. Results on ion-implanted devices shown in Fig. 3 demonstrate this fact quite clearly. Although the implantation energy was only 5 keV, and was followed by annealing, the higher mass of phosphorus caused sufficient damage to the lattice. A larger change in T_t after electron irradiation of 1 MeV was observed for the ion-implanted devices which can be associated with the additional damage caused by irradiation. It is likely that the exposed junctions at the edges of the ion-implanted devices [4] can compound the role of defects in lowering the R_{sh} values. In order to verify this, surface-passivated n^+–p junction solar cells fabricated by ion-implantation (obtained from the Spire Corporation) were studied. The implantation was performed through windows in a thick masking oxide [11]. The cells were isolated by scribing the surrounding area on the oxide. The results for the temperature dependence of R_{sh} after electron irradiation, also given in Fig. 3, show a trend similar to that observed for the ion-implanted MINP solar cells. However, the R_{sh} values in the n^+–p cells remain marginally higher than in the MINP cells even after irradiation. This small difference is due to a better edge design in the n^+–p cells.

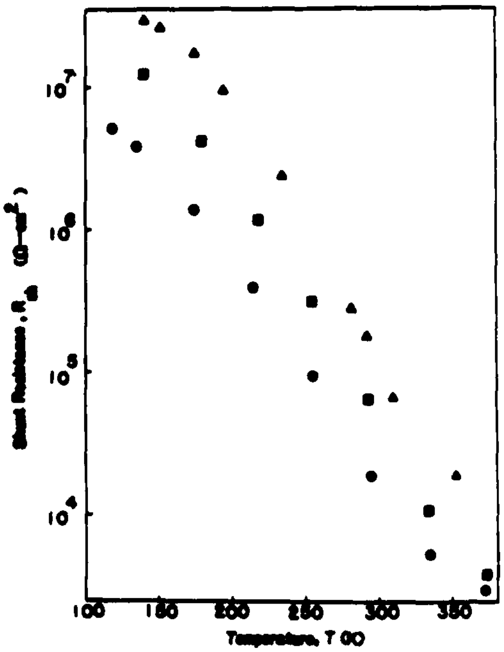

Fig. 3. Temperature dependence of R_{sh} on ion-implanted MINP and n^+–p solar cells before and after electron irradiation of 1 MeV at a fluence of 1×10^{16} e$^-$ cm^{-2}: MINP cell ■ before and ● after irradiation; n^+–p cell ▲ after irradiation.

R_{sh} values at 300 K for all these devices before and after irradiation at a fluence of 1×10^{16} e$^-$ cm^{-2}, summarized in Table 1, indicate that the changes in R_{sh} for the diffused MINP solar cells are more than those observed for ion-implanted MINP and n^+–p solar cells. This can be attributed to the fact that a relatively damage-free material is more sensitive to the creation and modification of defects due to irradiation than previously damaged material. However, the R_{sh} values of diffused MINP devices still remain higher than the others after irradiation. Figure 4 shows the behavior of R_{sh} at 300 K as a function of irradiation fluence. It is quite difficult to determine the exact functional form of the variation of R_{sh}. It is likely that the variation in R_{sh} with fluence is extremely sensitive to the initial conditions of the devices.

The effect of shunt resistance on the device is reflected in an additional current component usually referred to as the shunt current. The magnitude of this current can substantially increase the total diode current for a low shunt resistance device. This study shows that the room temperature shunt current can increase by an order of magnitude or more owing to a reduction in shunt resistance after irradiation, as shown in Fig. 5 for a diffused MINP cell. At times, the shunt current is as high as I_{Excess} in eqn. (1), especially after irradiation, so that it becomes quite difficult to differentiate between

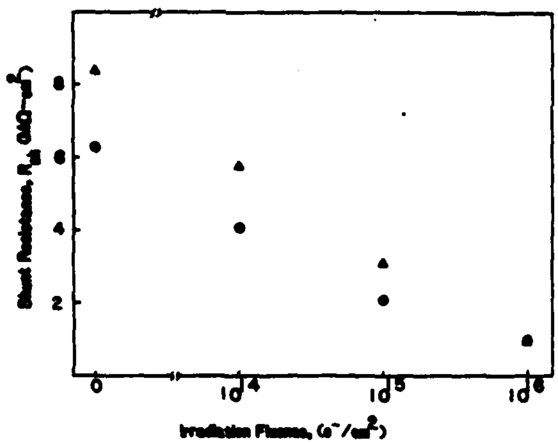

Fig. 4. Variation of R_{sh} at room temperature with irradiation fluence for two diffused MINP solar cells.

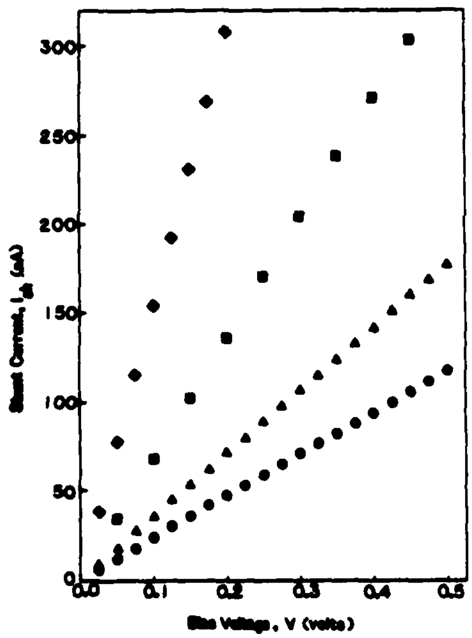

Fig. 5. Voltage dependence of shunt current as a function of irradiation fluence at room temperature for a diffused MINP solar cell: ●, before irradiation; ▲, after irradiation of 10^{14} e^- cm^{-2}; ■, after irradiation of 10^{15} e^- cm^{-2}; ◆, after irradiation of 10^{16} e^- cm^{-2}.

them except in the case of temperature dependence. The overall effect is an upward shift in the I–V characteristics. Saturation currents obtained from such I–V characteristics are much higher than those predicted by diffusion and recombination components. This greatly affects the open-circuit voltage V_{oc} and therefore the overall photovoltaic performance.

3. Conclusions

A systematic study of shunt resistance on electron-irradiated silicon MINP solar cells reveals considerable radiation-induced structural damage which affects R_{sh}. The magnitude of the change in shunt resistance after the irradiation depends on the processing techniques and the junction quality of the devices. It has been observed that a large decrease in shunt resistance can cause the shunt current to increase by an order of magnitude or more, resulting in a decrease in V_{oc}. A careful analysis of shunt resistance is therefore quite important to determine the reliability of the devices in the space environment.

Acknowledgments

We wish to acknowledge partial financial support from the Office of Naval Research under Contract N0001485K0727. We would like to thank Mr. P. M. Orlosky of Buffalo Materials Research Center at S.U.N.Y. at Buffalo, NY, for electron irradiations, and Dr. M. B. Spitzer of Spire Corporation, Boston, MA, for the n^+–p junction solar cells.

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