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A study on the variation of c-Si solar cell parameters under 8 MeV electron irradiation

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ABSTRACT

This paper reports on the photon and 8 MeV electron irradiation effects on electrical parameters, quantum efficiency and minority carrier lifetime of a c-Si solar cell. The effect of subsequent photon irradiation on the silicon solar cells, degraded by 8 MeV electron irradiation is also investigated. The current–voltage (I–V) characteristics of solar cells under AM0 illumination condition were studied before and after the irradiation. The solar cell parameters such as short circuit current (I_{sc}), open circuit voltage (V_{oc}), fill factor (FF), and conversion efficiency (η) were found to decrease after electron irradiation. A slight improvement in the electric performance of solar cells is observed after the photon irradiation. The spectral response shows that the quantum efficiency for low energy photons is reduced, suggesting that the damage is mainly inflicted to the bulk of the absorber material. This is strongly supported by the minority carrier lifetime results, which show a clear trend of decreasing carrier lifetime and carrier diffusion length as radiation dose increases.

1. Introduction

Solar cells have come into widespread use for solar energy conversion and in particular, for power supplies in satellites. As the satellites on their orbit suffer space radiations that consist mainly of high energy electrons and protons, it is essential to estimate the performance of solar cell after a substantial exposure to radiation, regardless of the initial performance [1,2].

Electron induced damage to silicon solar cells has been reported in several papers [2,3]. Morita et al. have reported an abrupt decrease in short circuit current (I_{sc}) to nearly zero by irradiations of 1 MeV electrons at the fluence of 5×10^{16} e/cm^2 [4] resulting in the failure of silicon solar cells under higher fluence irradiation above 5×10^{16} e/cm^2 [2]. It has also been shown that the radiation damage occurs primarily in the base of the cell [3] and also at the junction interface by introducing the defects. The defects introduced at the a-Si/c-Si heterojunction interface increase the electron–hole recombination rate due to the introduction of non-radiative recombination centres [5]. These introduced radiation-induced recombination centres reduce the minority carrier lifetime in the base layer of the p–n junction; increasing series resistance and lead to an enormous increase of noise in solar cells [6].

Spectral responsivity systems measure how a device responds to selected narrow bands of irradiance. Responsivity is reported in terms of quantum efficiency (QE), a measure of how efficiently a device converts incoming photons to charge carriers in an external circuit [7]. The main reason to measure the spectral response is to use it as a tool to understand the performance of the solar cell. The red response is governed by the minority carrier lifetime in the p-region. The blue response depends on the charge collection from the n-region, which in turn depends upon the surface recombination velocity and junction depth [8].

Silicon solar cells have demonstrated an effect called Photo-Redegradation. This effect is seen in cells that have been electron irradiated and then exposed to light for an extended period where the cells showed significant recovery from radiation damage. The long-term photo-recovery is a significant portion of the total electron damage [9]. For laboratory electron irradiation, as high as 10% recovery in short circuit current has been observed in a few days to a month, predominantly in 10 Ω-cm cells as reported by Tada et al. [10].

To investigate the damage rates for various electron doses, it is essential to study the degradation of the minority carrier lifetime. The degradation of minority carrier lifetime results in change

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in the device properties. The carrier lifetime is an accurately measurable quantity which is sensitive to damage by penetrating radiation and is independent of other solar cell parameters like surface optical reflectivity, surface recombination velocity, and junction depth, all of which influences measurement of current and power [11]. The importance of effective minority carrier lifetime to a silicon solar cell's efficiency is reflected in its crucial impact on both open circuit voltage and short circuit current [12]. In the present study the reverse recovery transient technique [13,14] is adopted to measure minority carrier lifetime in silicon solar cells. Mulati et al. reported lifetime measurements in multi-crystalline silicon (mc-Si) to be in the range of 20–100 μs using the reverse recovery method [15].

Hence the changes in electrical performance, optical and transport properties of the silicon cells under 8 MeV electron irradiation for various doses at room temperature as well as recovery of the solar cells under photon irradiation are presented in this paper.

2. Experimental techniques

The space-grade c-Si solar cells procured from Solar Panels Division, ISRO Satellite Centre, Bangalore, are used in the present study. The specifications of c-Si solar cells are shown in Table 1. Spectral response and illuminated *I–V* tests were performed using the facility available at solar cell testing laboratory, ISRO Satellite Centre, Bangalore. Current–voltage characteristics of solar cells under illumination were measured at room temperature using a Keithley 2420 Sourcemeter. The cells were illuminated under AM0 (air mass0) condition using an X-25 solar simulator with illumination intensity set to 0.1353 W cm^{-2}. The spectral response of the solar cell was measured at wavelength ranging from 300 nm to 1100 nm using spectral response measurement system. The *I–V* characteristics and spectral response measurements were performed immediately after the electron irradiation for various doses and then the solar cells are illuminated for 2 h under AM0 condition at lab temperature (28 °C) to observe the amount of recovery in solar cell performance. The *I–V* and spectral response measurements were carried out again after the photon irradiation.

The capacitance–voltage measurements were carried out to determine the variation of carrier density upon electron irradiation. The minority carrier lifetime of the solar cells were carried out under dark condition using a Tektronix TDS2012B 100 MHz, 1 Gs/s digital storage oscilloscope (DSO) and Agilent 33220A 20 MHz arbitrary waveform generator with a 2 ns rise and fall time [15,16].

Solar cells were exposed to 8 MeV electrons at room temperature using a Microtron accelerator, Mangalore University. The features of the Microtron are reported in some papers [17,18]. The cells were exposed to electrons of doses ranging from 5 kGy to 100 kGy. The *I–V* characteristics, spectral response, *C–V* and minority carrier lifetime measurements of the solar cells were repeated after irradiation.

Table 1
The specifications of c-Si solar cell.

Configuration	N/P type, c-Si
Specifics	BSR, dual ARC (TiO_x/Al_2O_3)
Base resistivity	2 ± 1 Ω cm
Base doping levels	$\approx 9 \times 10^{15}$ cm^{-3}
Size	6.5×4 cm^2
Cell thickness (nominal)	200 μm
Cover glass	CMX ($\approx$ 100 μm) (Cerium doped microsheet)
Preparation technique	Diffused junction

The electron irradiation and all the characterisation were performed for two silicon solar cells of the same type. The results obtained for both the cells were similar and, therefore, only the results for cell 1 are presented.

3. Results and discussion

3.1. I–V characteristics under illumination

The parameters of the c-Si solar cell before irradiation are shown in Table 2. The illuminated *I–V* characteristics of silicon solar cells irradiated with 8 MeV electrons at various doses, under AM0 illumination condition are shown in Fig. 1. Solar cell parameters like short circuit current (I_{sc}), open circuit voltage (V_{oc}), fill factor (FF) and efficiency (η) were calculated from these *I–V* characteristics.

The fill factor (FF) is a key performance parameter for solar cells and it can be expressed as

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \tag{1}$$

where V_{mp} and I_{mp} are the voltage and the current at a maximum power point, and V_{oc} and I_{sc} are the open circuit voltage and short circuit current respectively [19,20].

The conversion efficiency (η) of light into electric power, for a solar cell is given by

$$\eta = \frac{I_{sc} V_{oc} FF}{P_{in}} \tag{2}$$

where I_{sc} is the short circuit current, V_{oc} is the open circuit voltage and P_{in} is the incident light power.

Fig. 2 shows the changes in the normalised solar cell performance parameters as a function of electron dose. It was found that the performance degradation of the solar cell parameters is dependent on the electron dose and the irradiation has affected the solar cell parameters to a certain extent. There is no substantial variation in the fill factor. Even after electron irradiation for

Table 2
The parameters of the silicon solar cell before irradiation.

I_{sc} (A)	V_{oc} (V)	P_{max}	Fill factor (FF)	Efficiency (η)
1.06	0.59	0.49	0.78	13.96

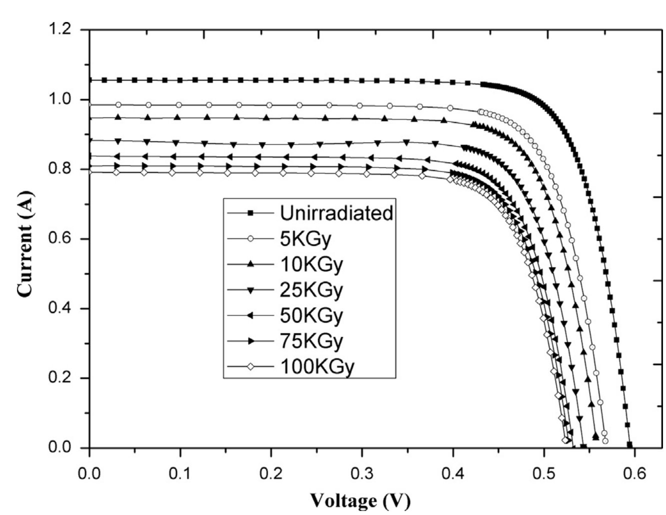

Fig. 1. The *I–V* characteristics of silicon solar cell irradiated with various doses of 8 MeV electron.

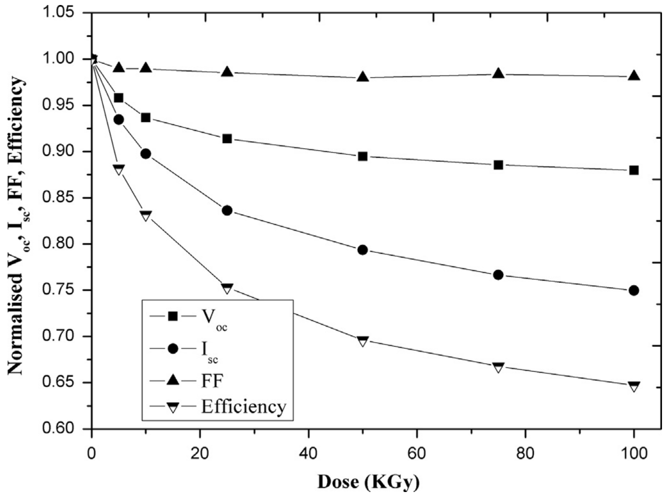

Fig. 2. Normalised solar cell parameters as a function of dose.

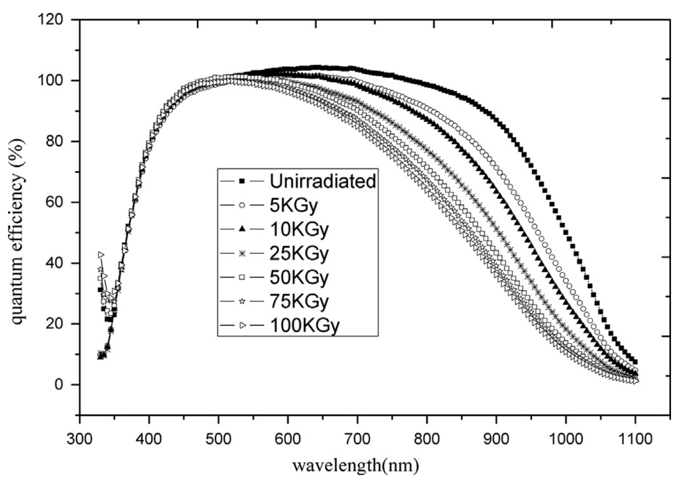

Fig. 3. Quantum efficiency curve of silicon solar cell with various doses of 8 MeV electron irradiation.

100 kGy the normalised values of FF remain at 98%. The electron irradiation causes a reduction in the open circuit voltage and the short circuit current and a large decrease in the efficiency of silicon solar cell.

A sharp decrease in efficiency and short circuit current was observed as increasing the electron dose up to 25 kGy and then linear decrease was observed for higher dose of irradiation. Nearly 25% of the initial efficiency has been decreased for the dose 25 kGy and less degradation ($\approx$ 10%) was observed for further increase in the electron dose up to 100 kGy. The decrease in the short circuit current and efficiency under electron exposure could be related to the lifetime of minority carriers [21,22]. The lifetime of minority carriers is sensitive to the radiation-induced defects and the decrease in the minority carrier lifetime reduced the electric properties of solar cells.

3.2. Spectral response measurement

Fig. 3 shows the change in spectral response of a silicon solar cell under 8 MeV electron irradiation. It can be seen that in the whole wavelength range the highest quantum efficiency values belong to the non-irradiated solar cell and the quantum efficiency values decreased with increasing electron dose.

A constant degradation in quantum efficiency which is due to the decrease in the current output of the solar cell has been found for higher wavelength (red region) and there is no significant degradation for lower wavelength range (blue region). The current output of a solar cell in the longer wavelength region is less because, the electron–hole pairs produced several hundred microns below the junction and minority carriers must diffuse a greater distance through the damaged material to reach the junction as compared to the shorter wavelengths. Therefore exposure to radiation which produces recombination centres, primarily affects the response of a solar cell to red light [11].

The solar cell used for this measurement has n-shallow layer on p-silicon; light photons near the blue end of the spectrum are absorbed and produce electron–hole pairs near the surface. The cells derive a smaller fraction of their power from red end of the solar spectrum and are less sensitive to degradation of diffusion length in base. It is observed that after irradiation there is variation only in the longer wavelength side of the spectrum indicating that the degradation is mainly due to defect creation in the crystalline silicon substrate. This is evident from the fact that there is large decrease in quantum yield for wavelengths above 550 nm [23] which are strongly supported by the decrease in minority carrier diffusion length after electron irradiation.

3.3. Capacitance–voltage measurements

The carrier density of the solar cells can be estimated using the following formula:

$$C = A\left[\frac{q\varepsilon_0\varepsilon_r N_D}{2(V_{bi}+V)}\right]^{1/2} \tag{3}$$

where A is the solar cell area, q is the charge of electron, N_D is the carrier density, ε_r is the dielectric constant of silicon, ε_0 is the vacuum permittivity, and V_{bi} is the built-in potential [20]. Before electron irradiation the carrier density was $9.2\times10^{15}\ \mathrm{cm}^{-3}$ and it decreases down to $8.8\times10^{15}\ \mathrm{cm}^{-3}$ for the electron dose of 100 kGy. The reduction in the carrier density may be due to the trapping of charge carriers by radiation induced defects only.

3.4. Photon irradiation

Figs. 4–6 show change in the short circuit current, maximum power and efficiency of the solar cell after 2 h of photon irradiation under AM0 illumination condition with illumination intensity of $0.1353\ \mathrm{W\,cm}^{-2}$. A slight improvement in solar cells electric performance was observed after the photon irradiation. The percentage of gain in efficiency varied from 0.2% to 1.3% for different doses of electron irradiation. Similarly 0.4–1% of

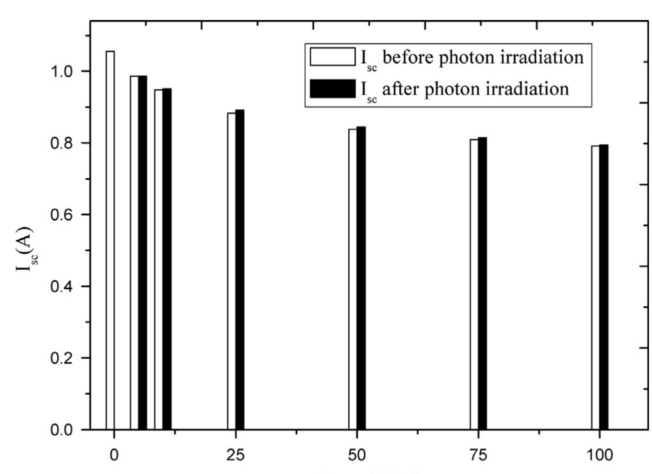

Fig. 4. The difference in short circuit current before and after photon irradiation.

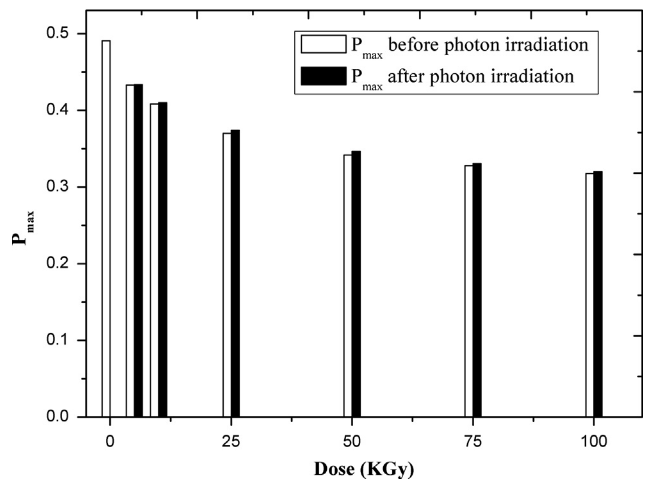

Fig. 5. The improvement in solar cell power output before and after photon irradiation.

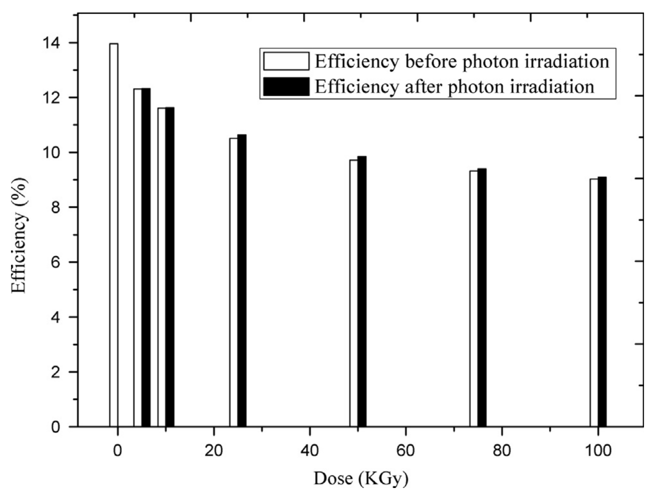

Fig. 6. The difference in efficiency of solar cell before and after photon irradiation.

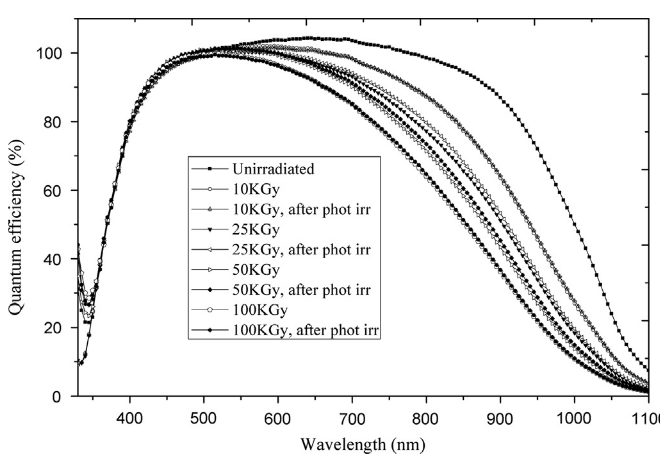

Fig. 7. The variation in quantum efficiency of the solar cell before and after photon irradiation.

improvement in short circuit current was observed after photon irradiation. The light illumination causes the minority carrier density to increase, which then enhances damage recovery [10,24].

Fig. 7 shows the small improvement in quantum efficiency at larger wavelength ($\lambda > 600$ nm) region. This result confirms the increased performance of the cell which is mainly due to the infrared absorption at photon energies around 1.2 eV sensitive to the optical processes that detaches an electron from a defect and promotes it to the conduction band [25]. From this study we can conclude that the photon irradiation annihilates the electron damage in solar cells. As per the observation of the study, we feel that recovery of the electrical characteristics ($\approx 1.24\%$) upon photon irradiation on the solar cells irradiated with electrons up to 75 kGy, would contribute a lot for space application as far as the use of solar panels in space is concerned. If electron damage to solar cells recovers totally with extended exposure to sunlight, the financial implications to the satellite community are immense. Despite the high exposure of damaging electrons and protons, the utility of the satellite would be extended years beyond their previous design lifetimes. However this effect must be confirmed by an extended illumination study.

3.5. Minority carrier lifetime measurement

The minority carrier lifetime and diffusion length in silicon solar cells were measured using the reverse recovery transient (RRT) method to investigate the influence of electron irradiation on solar cell performance. In this method a solar cell in forward bias is switched abruptly to reverse bias, but the stored minority carriers cannot abruptly fall to zero concentration and hence a constant reverse current flows for a certain period of time (reverse recovery time, t_{rr}).

An equation for the reverse recovery time and how it is related to minority carrier lifetime by the use of RRT method can be seen below [13,26,27].

$$\operatorname{erf}\sqrt{\frac{t_{rr}}{\tau}} = \frac{1}{1+(I_r/I_f)} \tag{4}$$

where I_f and I_r are the forward and the reverse currents, t_s is the charge storage time and τ is the carrier lifetime. The minority carrier lifetime is extracted from the graph of t_{rr} versus $\ln(1+(I_f/I_r))$.

The variation of minority carrier lifetime of silicon solar cell before and after irradiation as a function of dose is shown in Fig. 8. The minority carrier lifetime is found to decrease from 21.19 μs to 15.67 μs with increasing dose, which is interpreted as due to the creation of non-radiative recombination centre which affects the diffusion current [5].

Minority carrier diffusion length is a more applicable parameter for solar cell analysis than minority carrier lifetime. With increasing the electron dose, the concentration of minority carrier traps increases and thus the mean free path of diffusion for the

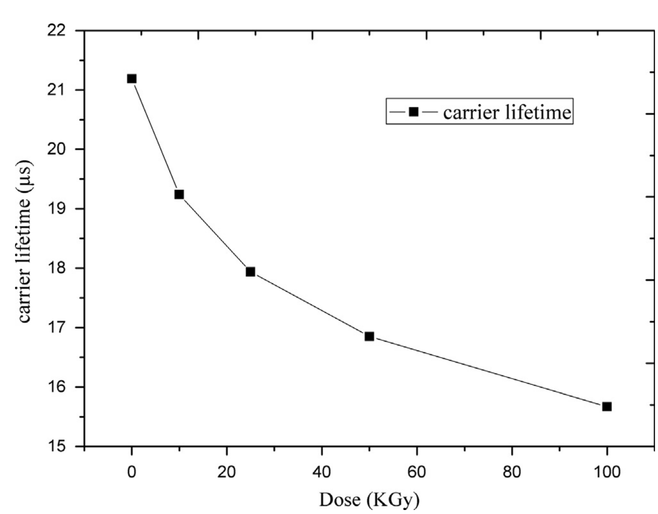

Fig. 8. The variation of minority carrier lifetime with electron dose.

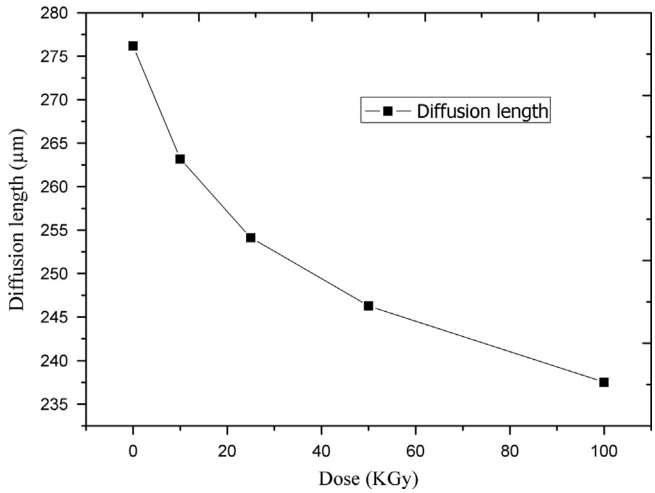

Fig. 9. The variation in diffusion length with electron dose.

minority carriers should be decreased. The relation of the diffusion length (L) after irradiation with electron fluence ϕ can be expressed as follows [10]:

$$\frac{1}{L^2} = \frac{1}{L_0^2} + K_L\phi \tag{5}$$

where L_0 is the initial minority carrier diffusion length and K_L is the diffusion length damage coefficient. The diffusion length damage coefficient (K_L) is an important parameter required for evaluating the damage effectiveness of electrons of various energies.

The minority carrier diffusion length L is related to the carrier lifetime τ as given by $L = \sqrt{D\tau}$ where D is the diffusion constant. In Fig. 9 the irradiation dose dependence of the minority carrier diffusion length (L) has been shown. Before irradiation the calculated value of diffusion length is 276 μm and it decreases exponentially down to 237 μm for the highest dose of 100 kGy.

4. Conclusions

The effects of 8 MeV electron irradiation on the properties of silicon solar cells and also the photon induced damage recovery method have been studied systematically and the following conclusions were drawn:

- After irradiation with dose 100 kGy of 8-MeV electrons the performance of c-Si solar cell decreased to 65% of its original conversion efficiency. The decrease in efficiency and other cell parameters is mainly related to the lifetime of minority carriers. The lifetime of minority carriers is sensitive to the radiation-induced defects and the decrease in the minority carrier lifetime reduced the electric properties of solar cells.
- From the quantum efficiency it can be concluded that most of the performance is lost in the low energy part of the spectrum, because of decrease in minority carrier diffusion length.
- The decrease in the carrier density may be due to the trapping of charge carriers by radiation induced defects only.
- As per the observation of the study, we feel that recovery of the electrical characteristics ($\approx$1.24%) upon photon irradiation on the solar cells irradiated with electrons up to 75 kGy, would contribute a lot for space application as far as the use of solar panels in space is concerned. If electron damage to solar cells recovers totally with extended exposure to sunlight, the financial implications to the satellite community are immense.
- The minority carrier lifetime is found to decrease with increasing dose, which can be interpreted as due to the creation of non-radiative recombination centre which affects the diffusion current.

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