Recovery in the electrical parameters of the aging silicon solar cells by annealing

D. M. TOBNAGHI*, R. MADATOV[a]
Department of Electrical Engineering, Parsabad Moghan Branch, Islamic Azad University, Parsabad Moghan, Iran
[a]*Institute of Radiation Problems, Azerbaijan National Academy of Science, Baku, Azerbaijan*

In this paper, to simulate and accelerate the effects of aging, solar cells were exposed to the different doses of co^{60} gamma radiation. The current–voltage (I–V) characteristics of mono-crystalline solar cells under AM1.5 illumination condition were studied before and after the gamma irradiation. Experimental results showed that the solar cell parameters such as open circuit voltage (V_{oc}), short circuit current (I_{sc}) and efficiency (η) decrease with the increase of the gamma radiation doses. The effect of subsequent thermal annealing on solar cells degraded by gamma irradiation is investigated. A significant improvement in the electric parameters of by low doses gamma irradiated silicon solar cells is observed after the thermal annealing.

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1. Introduction

Using the clean and free energy from the sun, crystalline silicon solar cells are still the mostly used element for solar cell production. Regardless of the very high standards in the production of solar cells, proved that under ordinary working conditions, solar cells are prone to the effects of aging. This process of aging is more pronounced when the cells are in some kind of radiation fields (natural space and atmospheric, as well as military and civil nuclear environments, etc.). Since operating conditions often prevent regular maintenance, stability of output electrical characteristics and lifetime of solar cells are of great significance [1-3]. Because of radiation and aging produces similar effects in solar cells, studying radiation resistance of solar cells is interesting not only for the purpose of predicting lifespan and end-of-life output characteristics of solar cells, but also to improve design of solar cells used in high radiation environments. In this paper, to simulate and accelerate of the effects of aging on solar cells parameters, solar cells were exposed to the different doses of gamma radiation [4].

Crystalline silicon solar cells, however, exhibit a response to electromagnetic radiation having substantially shorter wavelengths such as gamma ray. The irradiation of solar cells by high-energy levels of radiation in the form of gamma rays, neutrons, charged particles, etc. leads to radiation defects and electrical damage in the solar cells bulk and results a significant degradation of the silicon solar cells parameters. The lifetime of the semiconducting device is restricted by the degree of radiation damage that the solar cell receives [5].

When silicon solar cells irradiated with gamma rays, two types of radiation damage occur within it: displacement damage and ionization effects. Displacement damage is the movement of atoms from their initial location in the crystal lattice to another placement that results a defect in the crystal lattice of solar cells. Ionization effect is the generation of electron-hole pairs in the bulk of solar cell that results radiation effects. These defects mostly act as recombination points that decreased the diffusion length and life time of minority carrier as well as increased internal parameters of cells. output parameters of solar cell such as maximum output power, fill factor, efficiency, short circuit current, and open circuit voltage-P_m, ff, η, I_{sc}, V_{oc} respectively strongly depend on internal parameters of solar cells such as series resistance, R_S, saturation current, I_0 and ideal factor, n. it has been proved that increasing each of above internal parameters of solar cell causes that the output characteristics of solar cells decreased [6-8].

Silicon solar cells have demonstrated an improvement by thermal annealing. Atoms of crystalline solar cells exposed to gamma rays (or aging) that have been displaced from their initial place, Can be removed from their place by thermal annealing and return to the previous location where the cells showed a recovery from radiation damage [9].

Hence the changes in the electrical parameters of silicon solar cells under various doses of gamma radiation as well as recovery of solar cells by thermal annealing are presented in this paper.

2. Experimental methods

In this paper, the four samples of the commercially silicon solar cells having same characteristics are used for experimental measurements. The specifications of samples are shown in Table1. The solar cells were fabricated mono-crystalline structure using phosphorus diffusion into a p-type silicon wafer. The solar cell forms an n-p junction very close to the front surface by diffusing 2-3-µm-thick n-type doping into an approximately 300-µm -thick p-type silicon.

All four samples were irradiated with ^{60}Co gamma source with the energy of 1.23 MeV. The samples 1, 2…, 4 were irradiated with dose 100, 500, 1000, 2000 krad respectively. Irradiation of cells was carried out in professional laboratory at the institute of Radiation Problems of Azerbaijan National Academy of science.

Thermal annealing steps (at 150 ^{0}C, 200 ^{0}C and 250 ^{0}C: each step during 30 minutes) for all of the four samples was performed so that after each step the all electrical parameters of cells messured.

Voltage-current (I-V) characteristics of all samples before and after irradiation as well as after thermal annealing were measured. To obtain of solar cells I-V characteristics samples were illuminated by reflective lamp with Light intensity equal to 1000 $\frac{w}{m^2}$ (corresponding to AM1.5).

The measurements were performed at room temperature with highly accurate measuring equipment.

Table 1. Properties of four samples of the experimental solar cells (before irradiation).

Cells type	V_{OC} [mv]	I_{SC} [mA/cm^2]	P_{mmp} [mw/ cm^2]	FF	η [%]
Si-monocrystalline	570	34	14	0.72	13.95

Notes: Condition for measurement: 1000 W/m^2, AM 1.5, 25^{0}C.

3. Results and discussion

3.1 I-V characteristics under gamma radiation

Voltage-current characteristics of four solar cell samples before and after various doses of gamma radiation at under AM 1.5 illumination condition have been showed in Fig. 1. As can be seen, I-V characteristics of cells deteriorated with increasing gamma irradiation. From Fig. 1, fundamental parameters of solar cells like open circuit voltage (V_{oc}), short circuit current (I_{sc}), fill factor (ff) and efficiency (η) could be extracted.

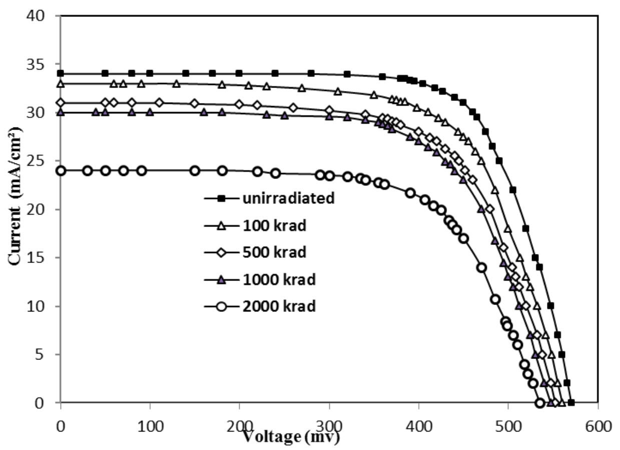

Fig. 1. The I–V characteristics of silicon solar cell irradiated with various doses of gamma radiation.

The fill factor (FF) parameter for solar cells can be expressed as

$$FF = \frac{V_{mp} \cdot I_{mp}}{V_{oc} \cdot I_{sc}} \quad (1)$$

Where V_{oc} and I_{sc} are the open circuit voltage and short circuit current, V_{mp} and I_{mp} are the voltage and the current at a maximum power point respectively.

The efficiency (η) for a solar cell is given by

$$\eta = \frac{V_{oc} I_{sc} FF}{P_{in}} \quad (2)$$

Where, P_{in} is the incident light power [14].

Fig. 2 shows the changes in solar cells parameters as a function of gamma dose. The parameters are normalized to the values obtained before samples irradiated. It was found that the degradation of the solar cell parameters is dependent on the gamma radiation dose and the irradiation has affected the solar cell parameters to a certain extent. There is no substantial variation in the fill factor, which in some cases showed increased or relatively steady values. According to the results, the gamma radiation causes a significant Reduction in the short circuit current and efficiency while the open circuit voltage is slightly reduced. The decrease in the efficiency and short circuit current of solar cells under gamma radiation could be related to the minority carrier life time. The minority carrier life time is sensitive to the radiation induced defects and the decrease in the minority carrier life time reduced the electric properties of solar cells. According to results a large amount of radiation induced defects in the high dose have been formed [11-12].

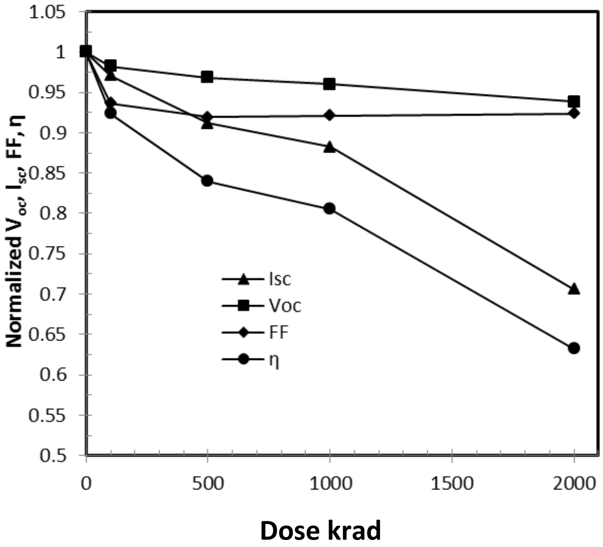

Fig. 2. Normalized solar cell parameters as a function of gamma radiation dose.

The short circuit current is because of the generation and collection of light-generated carriers. it was determined as:

$$I_{sc} = q.G.P \qquad (3)$$

Where q is electron charge, G is number of carriers generated in the solar cell, and P is the collection probability of carriers. Since the amount of G remains approximately constant [13], decrease in the I_{sc} essentially relevant to the collection probability. The collection probability of carriers depends on the surface passivation and the minority carrier diffusion length in the base. Gamma radiation causes the activation of solar cell surface and also increases defects near the upper surface. Ultimately recombination is increased in the solar cell so P is decreased. In the base layer, irradiation of ɣ ray reduces the lifetime of minority carrier and the diffusion length of minority carriers much smaller than the base thickness,$L_n \ll d_p$, the P value can be determined as:

$$P = \frac{\alpha L_n}{\alpha L_n + 1} \qquad (4)$$

Where α is light absorption coefficient, $L_n = \sqrt{D_n t_n}$, and D_n is the electron diffusion coefficient and t_n is the minority carrier lifetime. The open circuit voltage can be obtained using the following equation:

$$V_{oc} = \frac{nkT}{q} ln\frac{I_{sc}}{I_0} \qquad (5)$$

According to Eq. (5) V_{oc} does not change significantly with increasing n and I_0 and decreasing I_{sc}.

3.2 Annealing improvement

Figs. 3 and 4 show change in the short circuit current and efficiency of the solar cells samples after 30 minutes thermal annealing steps: 150 ^{0}C, 200 ^{0}C and 250 ^{0}C under AM1.5 illumination condition with illumination intensity of 1000 Wm^{-2}. At low doses, 100 and 500 Krad, A significant improvement in electric parameters of solar cells was observed after the thermal annealing while there is no recovery has occurred at high doses.

At low doses, the percentage of gain in short circuit current varied from 0.2% to 8%. Similarly 5-17% of improvement in efficiency was observed after thermal annealing. The thermal annealing causes the crystalline atoms of the aged solar cells (or exposed to gamma rays) that have been displaced from their initial place, Can be removed from their place and return to the previous location where the cells showed a recovery from radiation damage. At high doses the defects are stable and by thermal annealing don't recovery by thermal annealing [15, 16]. The experimentally measured values are listed in Table 2.

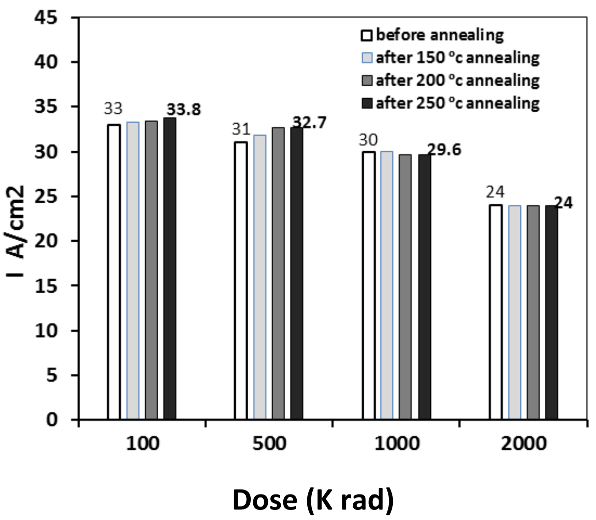

Fig. 3. The recovery in solar cells short circuit current by thermal annealing.

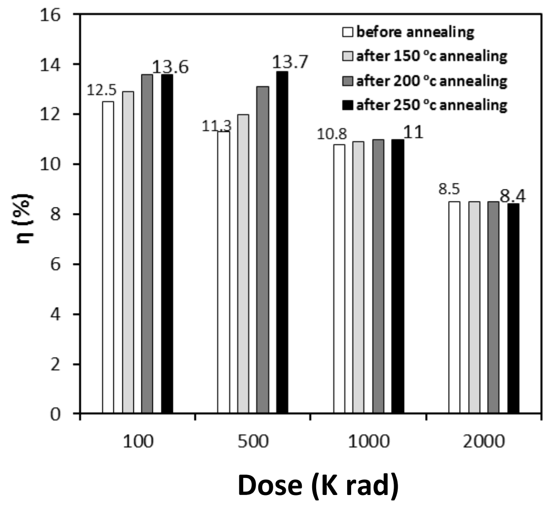

Fig. 3. The recovery in solar cells efficiency by thermal annealing.

Table 2. Recovery of solar cells by thermal annealing.

Cell samples	Gamma irradiation (k rad)	Degradation ratio (%)		Recovery ratio of I_{sc} (%)			Recovery ratio of η (%)		
		I_{sc}	η	150 ^{0}c	200 ^{0}c	250 ^{0}c	150 ^{0}c	200 ^{0}c	250 ^{0}c
1	100	2.9	10.4	98	98.2	99.4	92.4	97.4	97.4
2	500	8.8	19	93.5	96	96	86	94	98.2
3	1000	11.7	22.5	88.2	87.3	87	78	78.8	78.8
4	2000	29.4	39	70	70	70	61	61	60.2

Notes: Degradation ratio = $\frac{a-b}{a} \times 100\%$
Recovery ratio = $\frac{c}{a} \times 100\%$
a: Short Circuit Current or Efficiency before gamma irradiation.
b: Short Circuit Current or Efficiency after gamma irradiation.
c: Short Circuit Current or Efficiency after thermal annealing.

4. Conclusions

To simulate and accelerate of the effects of aging on solar cells parameters, four solar cell samples were exposed to the different doses of gamma radiation. The effects of different doses of gamma radiation on the properties of silicon solar cells and subsequent thermal annealing on solar cells degraded by gamma irradiation have been studied and the following conclusions were drawn:

- A deterioration of the electric properties of solar cells was observed when the gamma dose was increased (100-2000 krad). Except the fill factor, which in some cases showed increased or relatively steady values, gamma radiation causes a significant Reduction in the I_{sc} and η while the V_{oc} is slightly reduced. The decrease in short circuit current and other fundamental parameters is mainly related to the minority carrier life time. The life time of minority carriers is sensitive to the radiation induced defects that mostly act as recombination points, and the decrease in the minority carrier life time reduced the solar cells parameters.
- Thermal annealing results show the aging solar cells that their efficiency is missed 20% compared to the initial value, can be recovery by thermal annealing.
- The solar cells that with time operation, their efficiency drop greater than 22%, can't recovered by thermal annealing.

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*Corresponding author: d.mostafa@iaupmogan.ac.ir