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A study of Proton Radiation Effects on a Silicon Based Solar Cell

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SRIM

Abstract

In this study, the changes in the performance parameters of silicon photovoltaic cells were investigated before and after irradiation. For this aim, the current-voltage and power-voltage characteristics of structures were obtained before and after irradiation. The electrical parameters were determined using obtained characteristics. High energetic (24.5 MeV) proton beam was used as the radiation source. In addition, radiation-induced displacement damages were determined using SRIM/TRIM simulations, and the effect of these damages on the photovoltaic cell was investigated. This study, which depends on the radiation hardness as a result of irradiation with protons, was important. Because the displacement damage caused changes on the electrical properties of device. This behavior was attributed to the defects generated by proton irradiation. On the other hand, it was seen that proton irradiation can be a tool for controlling the material and cell properties.

Cite

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1. INTRODUCTION

Photovoltaic power systems have been known for many years as a source that produces the electricity with solar effect. Photovoltaic cells are widely used in energy systems due to reasons such as efficiency. It is important to examine the conditions that can affect the performance of photovoltaic devices under different conditions in converting light energy to electrical energy. Especially, the performance of a photovoltaic cell plays an important role in space applications such as satellite technology (Tada et al., 1982; Alurralde et al., 2004; Miyazawa et al., 2018). Monocrystalline silicon solar cells are not only the most complex, but they are generally used in near-earth satellites because of their low expense and lightweight material. However, as a continuous power supply, solar cells and other optoelectronic components of satellites are irradiated by charged particles such as protons and electrons within Earth's radiation belts. Defective fields are formed due to displacement damage caused by space particles penetrating solar cells. They cause some changes in the performance of the devices due to the damage caused (Song et al., 2022). These variations are seen in some common performance parameters such as fill factor, open circuit voltage and short circuit current. The change in the parameters of photovoltaic cells affects the efficiency, optimum current and voltage parameters. A brief inspection of radiation-induced damage of photovoltaic cells has been studied for space applications (Raya-Armenta et al., 2021). In addition, different studies have been carried out for photovoltaic devices (Wang et al., 2017; Hadjdida et al., 2018; Yu et al., 2021; Liu et al., 2022).

The problem of radiation damage arises with the introduction of solar cell power systems into satellites. A solar cell on a satellite is bombarded by these particles due to the high-energy activity of an electron and proton trapped in the earth's electromagnetic field. The reason of the distorting effect of radiation on materials and devices are the particles such as electrons, neutrons, protons and ions. The source of these particles can be particle accelerators, natural space radiation, nuclear reactions, radioactive sources or

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electrons that produced by gamma rays. These particles can interact with materials in a variety of ways because of their mass, energy and charge. When the application areas of particle accelerators are examined, especially discovery of the atomic nucleus, its importance is understood with the continuation of its development in the fields of science and technology. In our country, many activities have been carried out within the scope of accelerator technology, and studies that contribute to its development are still continuing (Sultansoy, 1993; Adıgüzel et al., 2023). Researches have also been conducted to test various radiation applications such as materials, detectors and other electronic devices interacting with protons (Bilge Demirkoz et al., 2020).

In this study, the characteristics of performance parameters of photovoltaic devices have been investigated before and after proton irradiation. The variation in the electrical properties of silicon cells irradiated with protons has been investigated, and information about their performances has been provided. Moreover, the effects of radiation-induced degradation on cell performance have been analyzed using the SRIM/TRIM simulation program.

2. MATERIAL AND METHOD

The Si based polycrystalline solar cells with effective area of 12.5 cm x 12.5 cm used in this study were purchased from Shenzhen Topsky Energy Co., Ltd. A polycrystalline p-type silicon was used in the solar cell. The back and front contacts are made of aluminum (Al) and silver (Ag), respectively. The detailed characteristics of the solar cell are listed in Table 1. The electrical properties of polycrystalline silicon cell have investigated before being exposed to radiation. First, current, voltage and power parameters of the polycrystalline silicon cell have measured under AM0 (136,6 mW/cm^2 at 25°C) solar spectrum condition using Sciencetech Solar Simulator and computer controlled Keithley 2400 SourceMeter device. The schematic illustration of measurement setup is displayed in Figure 1. Current-voltage (I-V) and power-voltage (P-V) curves have drawn with the data obtained as a result of these measurements. Then, the same polycrystalline silicon cell has exposed to proton irradiation at the Proton Accelerator Facility, and the electrical properties have examined again. During the irradiation, the used proton energy and total number of ions are 24.5 MeV and 1x10^6 cm^{-2}, respectively. The angle of the proton beam on the cell is 90 degrees, and the total irradiation time is 12 seconds. The irradiation process was performed at room temperature and in an atmospheric environment. As a result of these processes, the changes before and after radiation of the polycrystalline silicon cell have compared. SRIM/TRIM simulation has performed to investigate of proton-induced displacement damage on device performance.

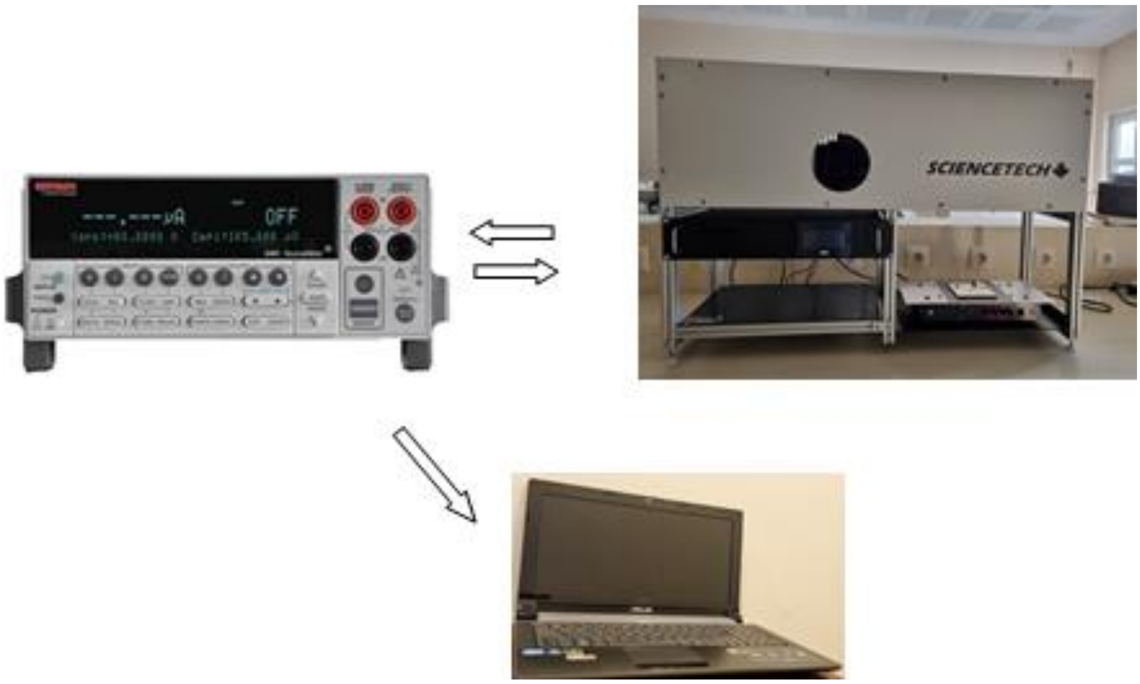


Figure 1. *Schematic illustration of measurement setup*

Table 1. *Characteristics of silicon photovoltaic cell*

Dopant element	Boron
Process of surface pyramid	Texture
Anti-reflection coating material	Hydrogenated silicon nitride (SiN_x:H)
Production process of anti-reflection coating	Plasma Enhanced Chemical Vapor Deposition (PECVD)

3. RESULTS AND DISCUSSION

Figures 2a and 3a depict the I-V and P-V plots before irradiation of the silicon cell. The short-circuit current (I_{sc}) of a solar cell is measured when the output is zero or short-circuited. At a given light intensity, the value of the output current (I) is given as follows, and it represents the distribution capacity of a solar cell.

$$I = I_{sc} = I_{photon} \tag{1}$$

Where I_{photon} is the current that produced by the photons. When the current-voltage graph is examined, it is seen that I_{sc} of the silicon cell is 615.96 mA. The open circuit voltage (V_{oc}) of a solar cell is measured when the output terminals of the device are open or I is zero. At a given light intensity, V_{oc} represents the maximum output voltage of the solar cell and given as follows.

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_{photon}}{I_o} + 1\right) \tag{2}$$

Where k is the Boltzmann constant, T is absolute temperature, I_o is the saturation current and q is the electronic charge. While I_o depends on device design and material selection, I_{photon} depends on device design and material selection as well as lighting intensity. The value of V_{oc} is determined as 613.03 mV from current-voltage graph.

The maximum output power (P_m) of a solar cell has calculated using the following expression.

$$P_m = V_m I_m \tag{3}$$

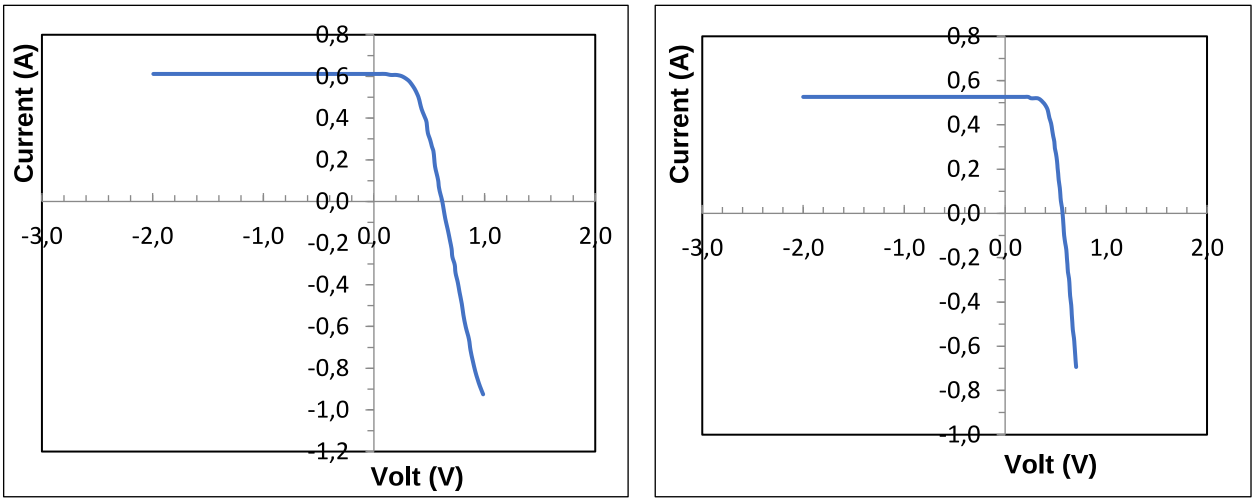
Where V_m and I_m are the maximum voltage and current, respectively at a maximum power point (P_m). The I_m and V_m values from the power-voltage graph have found as 534.10 mA and 371.85 mV, respectively. The P_m is calculated as 198.61 mW using the Equation (3).

The efficiency (η) of a solar cell is given as follows.

$$\eta = \frac{V_m I_m}{P_{in} A} \tag{4}$$

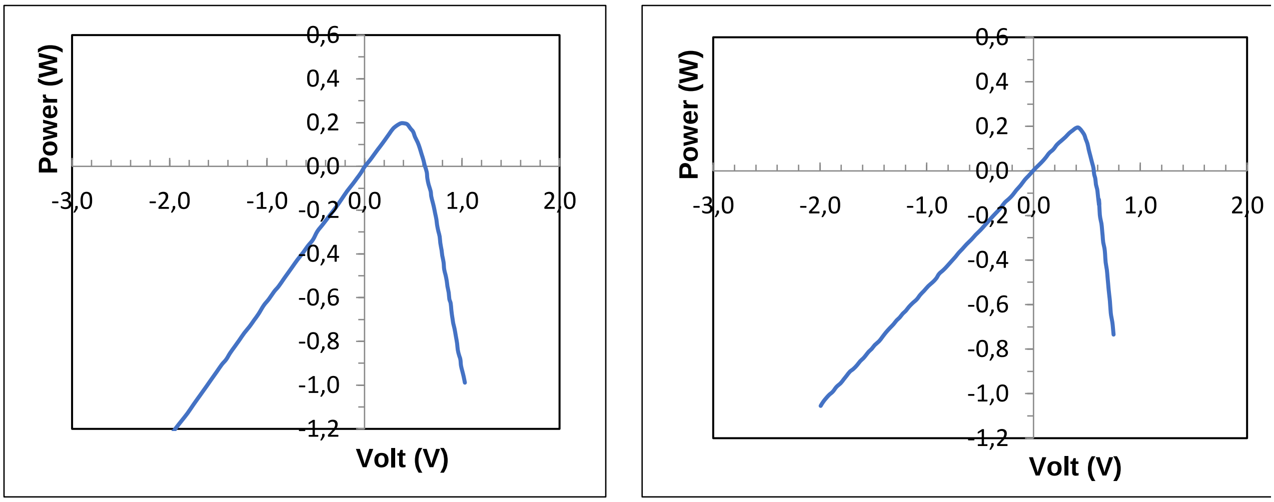
Where P_{in} is the total power of the light intensity on the cell and A is the effective area. The η value of the non-irradiated silicon cell has calculated as 15.59%. The performance parameters of the solar cell are given in Table 2.

Figures 2b and 3b represent the I-V and P-V plots after irradiation of the silicon cell. After proton irradiation, the I_{sc} and V_{oc} of the silicon cell have found to be 522.33 mA and 572.94 mV, respectively. It is seen that the maximum current, maximum voltage and maximum power values are 475.62 mA, 412.06 mV and 195.98 mW, respectively. The efficiency of the irradiated silicon cell has calculated as 15.08%. When the graphs are examined, it is seen that there is a decrease of 93.626 mA in I_{sc} of the irradiated silicon cell. The reduction is due to the fact that new energy levels emerging in the proton radiation band gap reduced the number of minority carriers. It is seen that there is a decrease of 40.08 mV in V_{oc}. By proton irradiation applied to the silicon cell, the radiation has increased the number of recombination centers and caused a decrease in V_{oc}. The maximum power has decreased by 2.62 mW. Since minority carriers at deep levels are short-lived, they are trapped by the reunification centers before they can reach the exit terminals of the structure. Thus, it also reduced other performance parameters such as the power parameter of solar cell (Srivastava et al., 2006).



(a) **(b)**

Figure 2*. I-V plot of silicon cell, **a)** before proton irradiation and **b)** after proton irradiation*



(a) **(b)**

Figure 3. *P-V plot of silicon cell, **a)** before proton irradiation and **b)** after proton irradiation*

Table 2 *The performans parameters of the solar cell before and after proton irradiation*

	I_{sc} (mA)	V_{oc} (mV)	P_m (mW)	η(%)
Before irradiation	615.96	613.03	198.61	15.59
After irradiation	522.33	572.94	195.98	15.08

The SRIM simulation results of particle trajectories are shown in Figure 4. The purpose of the SRIM simulation program is to examine the interactions of matter and ions with each other (Ziegler, 2004). The results of the interactions are expressed with graphical and numerical data that take place during the transition of ions in the target substance. SRIM/TRIM can be studied not only the spacing of ions in matter, but also many other aspects of damage to the target during the deceleration process. The used cell thickness has 250 µm. Thus, particle trajectories and displacement damage distribution have determined more clearly.

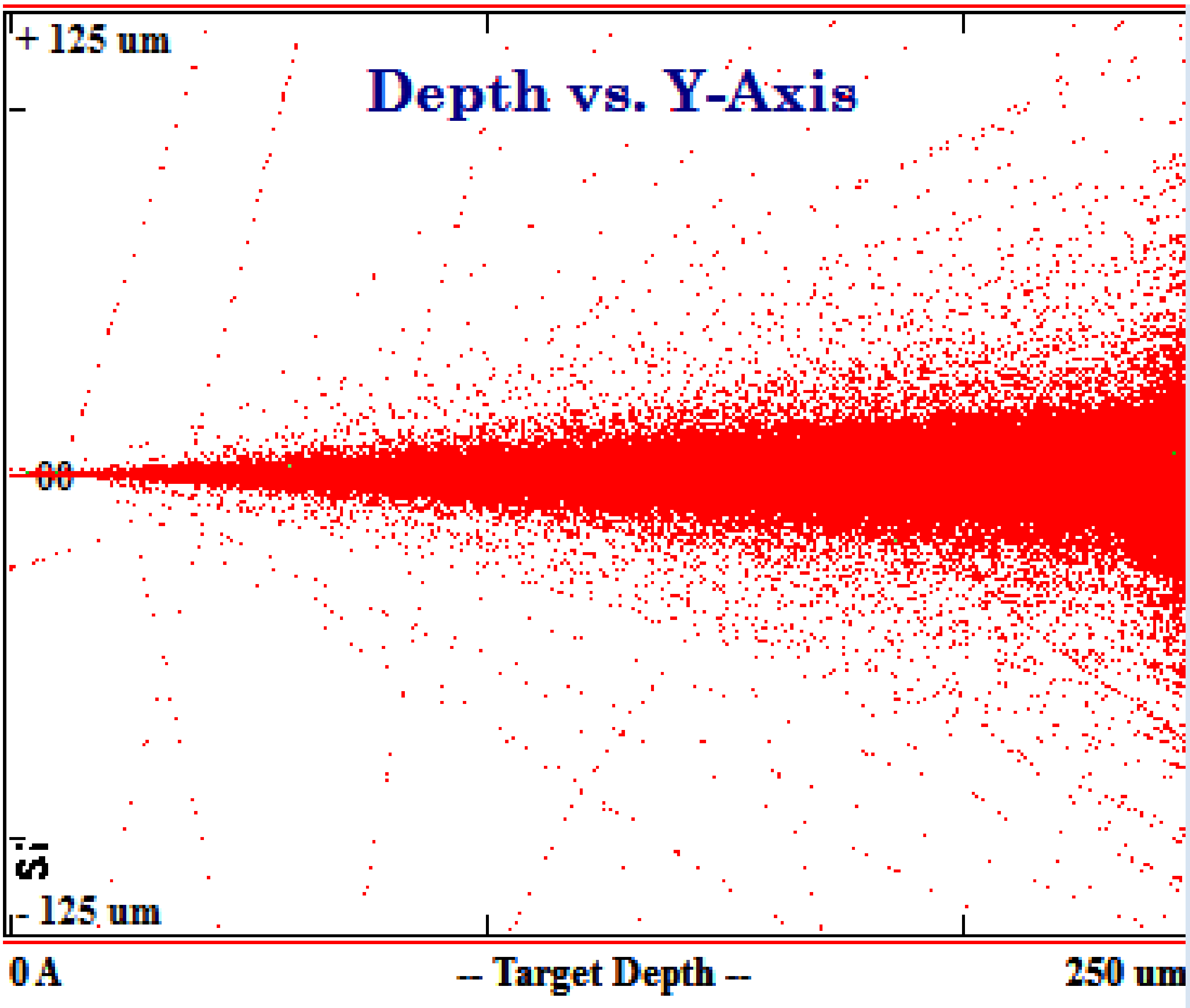


Figure 4. *Particle trajectories in SRIM/TRIM*

The final distribution of the ion has been determined by directing into the complex target in the SRIM/TRIM, and the change in the structure of the silicon cell interacting with the proton beam has examined. The energy and dose of the ions required by implanting atoms have calculated at a given depth and concentration into a target. Thus, the displacement damage is modeled using SRIM (Messenger et al., 2003). Figure 5 has shown the number of displaced target atoms created by the colliding ions. As seen in Figure 5, the ions have released 99.96% of their energy directly to the target and 0.04% to the recoil stages.

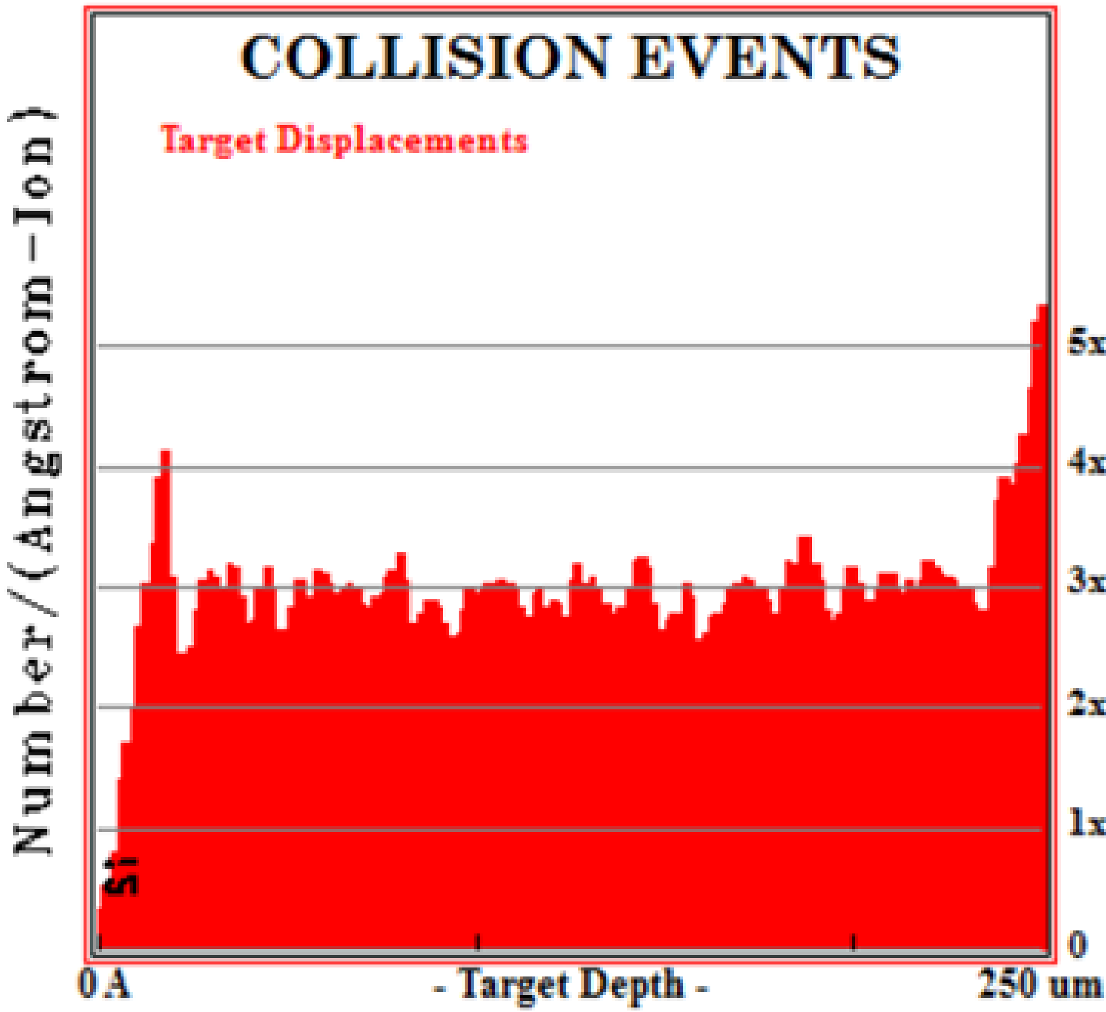


Figure 5. *Total target displacement*

4. CONCLUSION

In this study, the electrical characterizations of silicon cell have realized before and after proton irradiation. The changes in the electrical parameters of photovoltaic cell after irradiation have investigated with the help of obtained data. In addition, calculations have made about the damage by the proton on the silicon cell with the SRIM/TRIM program, and graphics have created.

When the parameters of silicon cells have compared before and after irradiation, a decrease in open circuit voltage has observed. Radiation has created new energy levels and reduced the number of minority carriers. Therefore, the short circuit current has also reduced. Moreover, radiation has increased the number of reunification centers. Therefore, a decrease in open circuit voltage value has occurred. On the other hand, it has been observed that the proton beam affects the maximum power value of the silicon cell. As a result, the efficiency of the cell decreased 0.51%.

The average displacement value of the proton per target atom has calculated as $0.5x10^3$. The number of displaced target atoms formed by the colliding ions have appears to be constant for a silicon cell. As a result of the interaction between the proton and the solar cell, energy loss occurs due to displacement. It is seen that the penetration depth of the protons is higher than mentioned energy. Hence it has been observed that the proton has damaged the silicon cell and caused a decrease in device performance. On the other hand, it was seen that proton irradiation can be a tool for controlling the material and cell properties.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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