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# Degradation analyses of GaInP/GaAs/Ge solar cells irradiated by 70 keV and 150 keV protons by current-voltage curves under various intensities of light

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ABSTRACT

Low energy protons damage GaInP/GaAs/Ge solar cells seriously. Traditional degradation researches require many supplementary tests, such as quantum efficiency (QE) or photoluminescence (PL). In this paper, we would establish a method that could analysis degradation of solar cells without any other equipment except a solar simulator. A voltage-current analysis technique under various intensities ($X$) of light was developed to study the degradation mechanisms of proton-irradiated GaInP/GaAs/Ge solar cells. Sum of ideality factor of every sub-cell $\Sigma n_i$ could be calculated from the change of open circuit voltage ($V_{oc}$) with light intensities in multi-junction solar cells. The change of ideality factor shows significant increase of Shockley-Read-Hall (SRH) recombination after 70 keV and 150 keV protons irradiation. Shunt resistance $R_{sh}$ increases with intensities, which is different from silicon solar cells. The change of $R_{sh}$ with light intensities was used to describe the current mismatch among the sub-cells in the multijunction solar cell. After irradiation, the current mismatch becomes larger. The relative degradation rate is different under different intensities of light. The max-power degradation tends to be smaller at high intensities.

## 1. Introductions

Multijunction GaInP/GaAs/Ge solar cell has a wide range of applications in aerospace. However, radiation environment in space causes degradation of solar cells, leading to slow decrease of efficiency. Proton radiation is one of the most significant one. In Medium Earth Orbit (MEO), there are an enormous number of relatively low energy protons [1] damaging the solar cells on satellites. Although the cover glass could stop protons with less than a few MeV energies, there still leave a lot of lower-energy protons penetrating the shield cover layer to damage solar cells. In this case, it is necessary to study on how the low energy protons affect the solar cells. Previous studies have demonstrated that the low energy particles could generate large degradation in the top GaInP sub-cell, even the mid-GaAs one, depending on the energy. Low energy proton irradiation leads to decrease of the short circuit current and the fill factor [2–5]. The decrease of short circuit current $I_{sc}$ may attribute to change of mobility, carrier density or minority lifetime, so does the open circuit voltage $V_{oc}$. Single $I$–$V$ curve could show the degradation behavior but can't reflect the internal mechanism of degradation. Direct measurements of electrical characters such as mobility, carrier density and lifetime need extra test instruments and data process. We estimate the change of these electrical characters without no any instruments but an $I$–$V$ test system. Thus, current-voltage characteristic curves under various light intensities were applied to analyze the degradation mechanism of protons irradiated GaInP/GaAs/Ge solar cells in this paper.

The method of measuring $I$–$V$ under diverse light intensities has been used to diagnose the quality of silicon solar cells [6–8]. Varying the light-concentration factor $X$, we could get the change of $V_{oc}$, which is used to extract the ideality factor that could reflect the main form of recombination under open circuit condition [6]. The ideality factor gained in this way is not affected by series resistance and low-voltage regions, thus it is more creditable. In our research, the ideality factor shows the location and form of recombination, reflecting the change of lifetime of carriers in semiconductors further. Besides, the effect of light intensities on shunt resistance was also studied. The relation between $R_{sh}$ and concentration factor $X$ could reflect the shunting effects and current mismatch caused by low energy protons. In this paper, we would use $I$–$V$ curves under various light intensities to study the degradation behavior of multijunction GaInP/GaAs/Ge solar cells after protons irradiation, and revealing the degradation mechanism.

Voltage-current curves under various intensities of lights are also

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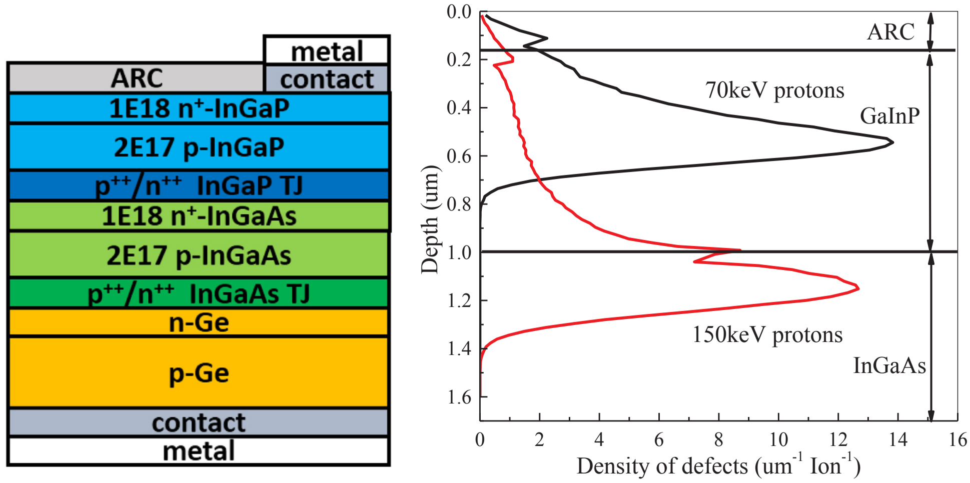


**Fig. 1.** the configuration of GaInP/InGaAs/Ge solar cells and the defect distributions by 70 keV and 150 keV protons in the solar cell.

used to estimate the properties of solar cells under weak light condition. Under weak light condition, the effect of series resistance get more obvious. In this research, we have discovered that weak light condition not only impacts the electrical properties, i.e. current or fill factor *FF*, but also affects the relative degradation rate of solar cells. The degradation is more serious under weak light condition, which reminds us the light intensity would modulate the degradation behavior of multi-junction solar cells.

## 2. Experiments and measurements

GaInP/GaAs/Ge solar cells were grown on Ge substrates by MOVPE (Metalorganic vapor phase epitaxy). The configuration of GaInP/GaAs/Ge solar cell is shown in Fig. 1. The thicknesses of GaInP and InGaAs are 800 nm and 1.5um respectively. 70 keV and 150 keV proton radiation tests were performed on a space simulator at Harbin Institute of Technology, China. The defect distribution by protons was calculated by SRIM (Stopping and Range of Ions in Matter) [9–10]. The threshold energy for In, Ga and P is 25 eV. The densities for GaAs and InGaP are 5.32 g/cm$^3$ and 4.46 g/cm$^3$ respectively in SRIM calculation.

*I–V* curves were measured by a Spectrosun X25A solar simulator under AM0 solar spectrum (135.3 mW/cm$^2$) at 25 °C ± 2 °C. The intensity of light could be adjusted and it is measured by a standard solar cell.

## 3. Degradation of GaInP/GaAs/Ge solar cells after proton irradiation

Current-voltage characteristic curves before and after proton irradiation are shown in Fig. 2. The figure contains three aspects of information: the decrease of $V_{oc}$, the falling of $I_{sc}$ and the decline of equivalent shunt resistance.

The decrease of $V_{oc}$ results mainly from the increase of recombination in solar cells. Meanwhile, the increase of recombination enlarges the dark current. The decrease of the total $V_{oc}$ is the result of the increase of recombination in both top and middle sub-cells, as 150 keV protons are mainly distributed in middle sub-cell. The detailed information of recombination would be presented in Section 5.

The decrease of $I_{sc}$ is related to the damage in the current-limiting sub-cell, i.e. GaInP and GaAs for 70 keV and 150 keV proton irradiation respectively.

In multijunction solar cells (MJSCs), the decrease of shunt resistance may be caused by a cluster of defects in solar cells. Besides, current mismatch is a key factor that affects shunt resistance, which will be discussed in Section 6.

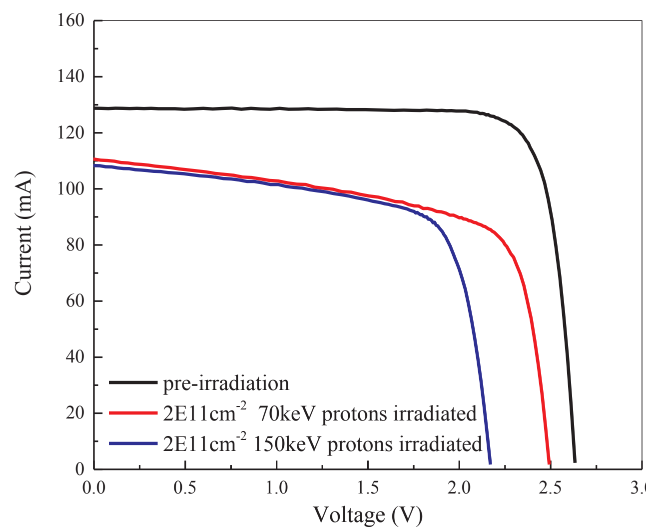


**Fig. 2.** *I–V* of multijunction solar cells before and after protons irradiation.

In the following sections, current-voltage characteristic curves under various intensities of light would be applied to study the degradation mechanisms of MJSCs under 70 keV and 150 keV proton irradiation.

## 4. Current-voltage characteristic curves under various intensities of light of MJSCs under 70keV and 150keV proton irradiation

Current-voltage characteristic curves of MJSCs under various intensities of light are shown in Fig. 3. With increasing intensities, $I_{sc}$ increases in proportion, while the change in $V_{oc}$ is much smaller. *FF* decreases seriously with intensities. In this research, the changes of $V_{oc}$ and $R_{sh}$ with $X$ have been studied, where $X$ is the light concentration factor. In the following sections, $V_{oc}$-$X$ curves could be utilized to get ideality factor $n$ which is usually used to analyze the location and type of recombination. $R_{sh}$-$X$ curves were studied in the resistance change and current mismatch after irradiation.

## 5. Ideality factor analyses under different intensity of AM0 in MJSCs

The $V_{oc}$-$X$ curve could provide more microscopic information about the solar cells, such as carrier recombination, to give an accurate ideality factor $n$ to analyze the main form of recombination further. In