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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

Guo Hongliang[a], Shi Linfeng[a], Wu Yiyong[a,b,*], Sun Qiang[c], Yu Hui[c], Xiao Jingdong[a], Guo Bin[a,b,*]

[a] School of Materials Science & Engineering, Harbin Institute of Technology, Harbin 150001, China
[b] Research Center of Basic Space Science, Harbin Institute of Technology, Harbin 150001, China
[c] Tianjin Institute of Power Source, Tianjin 300381, China

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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 Σn_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

* Corresponding authors at: School of Materials Science & Engineering, Harbin Institute of Technology, Harbin 150001, China.
E-mail address: wuyiyong@hit.edu.cn (W. Yiyong).

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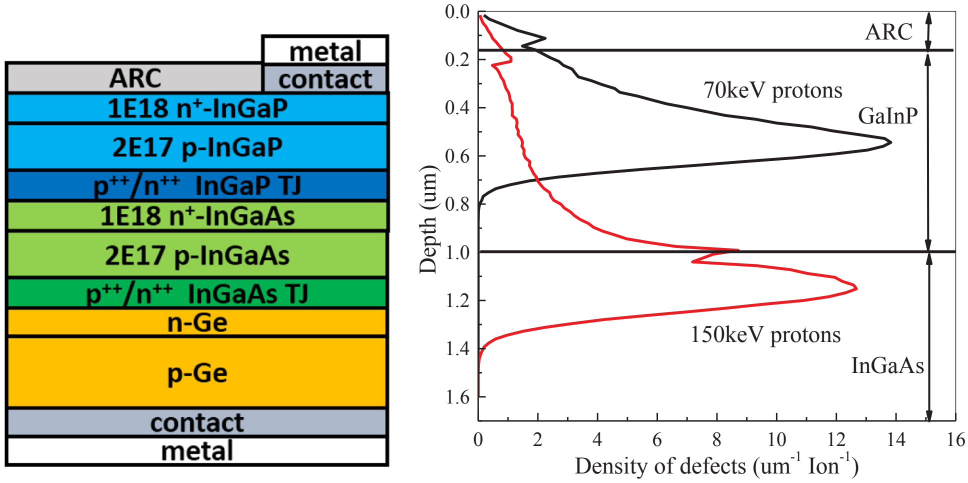

Fig. 1. the configuration of GaInP/InGaAs/Ge solar cells and the defect distributions by 70 keV and 150 keV protons in the solar cell.

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.

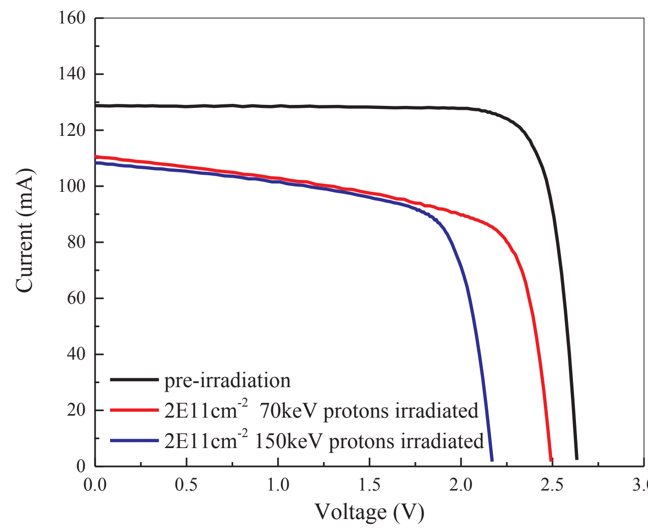

Fig. 2. *I–V* of multijunction solar cells before and after protons irradiation.

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

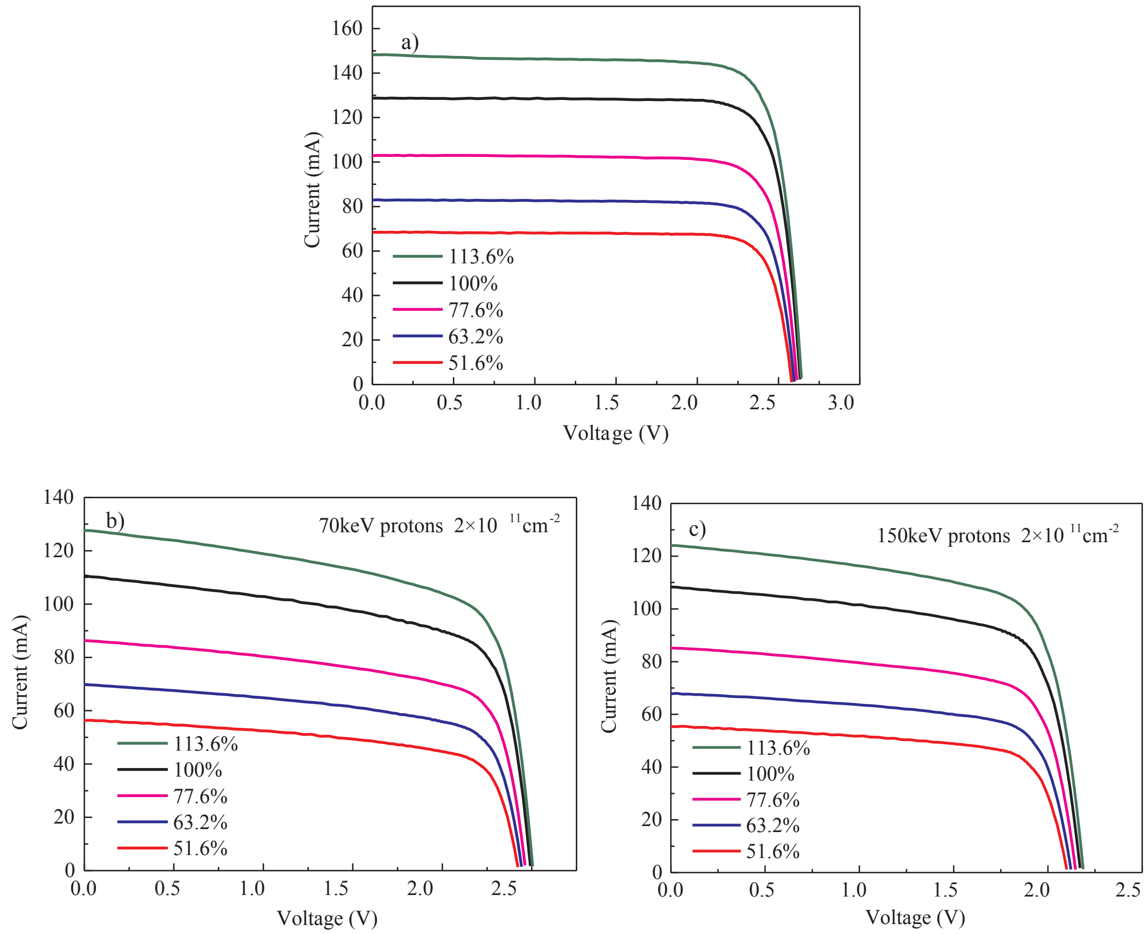

Fig. 3. *I–V* of GaInP/GaAs/Ge solar cells under different intensity of AM0 a) before irradiation b) after 70 keV proton irradiation c) after 150 keV proton irradiation.

many physical models of solar cells, n = 1 refers to recombination happening in quasi-neutral region while n = 2 refers to SRH recombination in space charge region. In a one-diode solar cell model, the range of n is 1–2, depending on the location of recombination [9–11]. The closer n is to two, the more SRH recombination occurs in space charge region.

When $I_{sc} \gg I_0$, where I_0 is the dark current at zero bias, an expression of the open circuit voltage for a single junction solar cell (SJSC) is Eq. (1), where k_B is the Boltzmann constant, T is temperature, q is the charge of an electron and I_{sc} is the short-circuit current.

$$V_{oc} = \frac{nk_BT}{q}\text{In}\left(\frac{I_{sc}}{I_0}+1\right) \tag{1}$$

If I_{sc} is proportional to X, the open-circuit voltage V_{oc} is proportional to ln$X$. Thus, the open circuit voltage could be expressed as Eq. (2), where $I_{sc,AM0}$ is the short-circuit current under AM0, $V_{oc,i}$ is the open circuit voltage of each sub-cell.

$$V_{oc} = \frac{nk_BT}{q}\text{In}\left(\frac{I_{sc}}{I_0}+1\right) \approx \frac{nk_BT}{q}(\text{In}X + \text{In}I_{sc,AM0} - \text{In}I_0) \tag{2}$$

For MJSCs, the open circuit voltage of a multijunction solar cell $V_{oc,t}$ is the sum of $V_{oc,i}$, thus the output voltage could be described as Eq. (3). From the equation, the slope of V_{oc}-ln$X$ is $k_BT\sum n_i/q$, where n_i is the ideality factor of each sub-cell.

$$V_{oc,t} = \frac{kT}{q}\Sigma n_i \ln\left(\frac{I_{sc,i}}{I_{0,i}}+1\right) \approx \frac{kT}{q}(\Sigma n_i \ln X + \Sigma n_i \ln I_{sc,i,AM0} - \Sigma n_i \ln I_{0,i}) \tag{3}$$

The V_{oc}-X curves of MJSCs after irradiation were shown in Fig. 4. From Eq. (3), we could calculate the sum of ideality factor Σn_i. For

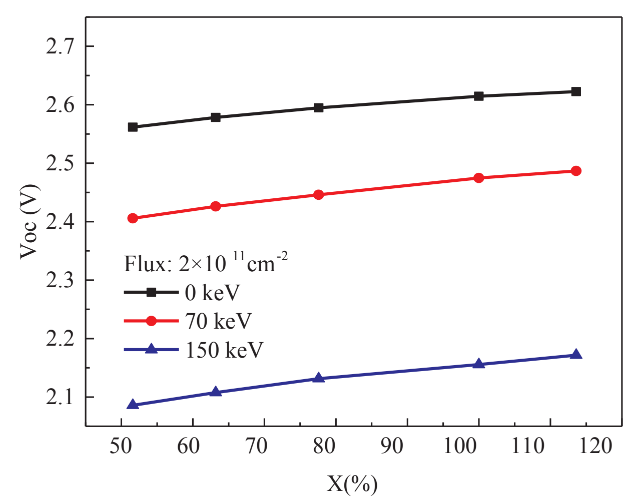

Fig. 4. The V_{oc}-X curve in GaInP/GaAs/Ge solar cells in different states.

undamaged solar cells, $\Sigma n_i = 3.0$, indicating the high-quality of GaInP, GaAs and Ge sub-cells. However after 2×10^{11} cm^{-2} 70 keV proton irradiation, the solar cells could obtain Σn_i of 3.99, implying that the ideality factor n is 1.99 for GaInP top sub-cell, as the ideality factor n of middle and bottom sub-cells are both undamaged during 70 keV protons irradiation by SRIM calculation and external quantum efficiency (EQE). A significant increase of ideality factor in GaInP indicates that SRH recombination dominates for the solar cells after radiation. After 2×10^{11} cm^{-2} 150 keV proton irradiation, $\Sigma n_i = 4.26$. If n is one for

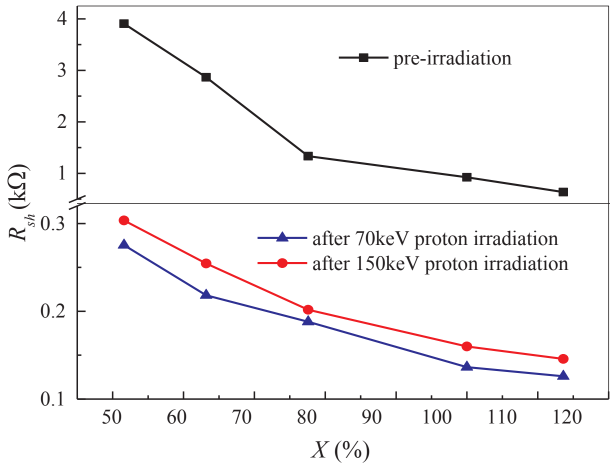

Fig. 5. The R_{sh}-X curve in GaInP/GaAs/Ge solar cells in different states.

undamaged Ge bottom cells, the sum of ideality factors for GaInP and GaAs sub-cells is 3.26, which means the proportion of SRH recombination greatly increased in the top two cells. The decrease of intercept after radiation indicates the enlargement of dark current I_0 and/or decrease of I_{sc} from Eq. (3).

6. Shunt resistance analysis in MJSCs and its relation with light intensity

For Single Junction Solar Cells (SJSCs), when the bias voltage is near zero, the recombination current goes mainly through shunt resistance, i.e. in shunting state. Shunt resistance of SJSCs could be calculated by approximation Eq. (4) [12,13]. The minus was used to ensure the resistance is not negative.

$$R_{sh} = -\left(\frac{dI}{dV}\bigg|_{Isc}\right)^{-1} = -\frac{dV}{dI}\bigg|_{Isc} \tag{4}$$

For Si SJSCs, the previous researches [6,8] had demonstrated the shunt resistance R_{sh} gets a little change with increasing light intensity. While our research results show that shunt resistance decreases noticeably from Figs. 3 and 5. The abnormal results may result from the current mismatch in MJSCs.

For MJSCs, we can also define Eq. (4) as the equivalent shunt resistance, that is, the shunt resistance can be extracted from the slope of I–V curve near the short circuit condition. As the total voltage equals $V_t = V_1 + V_2 + V_3$, definition Eq. (4) could be rewritten as Eq. (5), where V_i is the voltage applied on the i-th sub-cell ($n = 1$ for GaInP and $n = 3$ for Ge in this paper).

$$R_{sh} = -\frac{dV_1 + dV_2 + dV_3}{dI}\bigg|\, I_{sc} \tag{5}$$

When sub-cell is reverse biased, or in shunting state, one could get $-\frac{dV_i}{dI} = R_{sh}$; while when sub-cell is forward biased, one could also get $-\frac{dV_i}{dI} = (\frac{n_i k_B T}{q})\frac{1}{I_{sc,i} - I}$, derived from Eq. (6), the expression of the current in the equivalent circuit of the solar cells.

For non-radiated solar cells, Ge and GaAs sub-cells are forward biased and GaInP sub-cells are reversed biased, so Eq. (5) could be rewritten as Eq. (7), where $V_T = n_i k_B T/q$. When the intensities of light increase, the second and third items in Eq. (7) decrease, resulting in decrease of shunt resistance. As $I_{sc,2} - I_{sc} = X(I_{sc,2,am0} - I_{sc,am0})$, the relation between R_{sh} and X could reflect the current mismatch in MJSCs.

$$I = I_{sc,i} - I_0\left[\exp\left(\frac{qV_i}{n_i k_B T}\right) - 1\right] \tag{6}$$

Table 1
The moralized properties of the proton-irradiated GaInP/GaAs/Ge solar cells under different light intensities. The proton fluence is fixed at $2 \times 10^{11}\mathrm{cm}^{-2}$.

Proton energy	Concentration factor (X)	51.6%	63.2%	77.6%	100%	113.6%
70 keV	I_{sc}/I_{sc0}	82.4%	83.9%	83.7%	85.6%	86.1%
	V_{oc}/V_{oc0}	93.9%	94.1%	94.3%	94.6%	94.8%
	P_{max}/P_{max0}	61.9%	64.0%	65.3%	66.1%	67.4%
150 keV	I_{sc}/I_{sc0}	80.8%	81.9%	82.6%	84.1%	83.7%
	V_{oc}/V_{oc0}	81.4%	81.7%	82.1%	82.4%	82.8%
	P_{max}/P_{max0}	55.8%	56.7%	58.1%	58.5%	59.2%

$$R_{sh} = R_{sh,1} + \frac{V_T}{I_{sc,2} - I_{sc}} + \frac{V_T}{I_{sc,3} - I_{sc}} \tag{7}$$

After 2×10^{11} cm^{-2} 70 keV proton irradiation, GaInP is still the current limiting sub-cell. After irradiation, $I_{sc,2,am0} - I_{sc,am0}$ and $I_{sc,3,am0} - I_{sc,am0}$ increase significantly, which makes the shunt resistance less sensitive to intensities of light from Eq. (7), as shown in Fig. 5.

After 2×10^{11} cm^{-2} 150 keV proton irradiation, the short circuit current in GaAs sub-cells decays significantly and becomes the current limiting sub-cell. Eq. (7) changes to $R_{sh} = R_{sh,1} + R_{sh,2} + \frac{V_T}{I_{sc,3} - I_{sc}}$. Thus the increase of light intensities results in the decrease of R_{sh}.

7. Discussion

Low energy protons could cause serious damage in solar cells. In this research, the shape of I–V curve changes with light intensities. However, the research is more meaningful in studying the degradation under weak light condition, for example, in the orbit of Mars. There comes a question whether the relative degradation rate of solar cells changes with the light intensities. Table 1 is the comparison of remaining factors of the irradiated solar cells under different light intensities. The data in the table tell us that degradation is more obvious under weak light condition. This may be due to the trapping effects. Traps are introduced by particles. Under low injection, i.e. weak light condition, the photon-generated excess carriers are trapped by defects, leading to smaller increasing rate of short circuit current with intensities. The principle of trap effect can be sketched and seen in Fig. 6. Irradiation simultaneously changes the intercept and slope of the I_{SC}-X curve, resulting in the remaining factor, i.e. the blue dashed curve in Fig. 6, increasing with concentrations X. As the remaining factor of I_{sc} increases with concentrations, the remaining factor of V_{oc} also increases with concentrations, as suggested by Eq. (2) and (3). Table 1 also

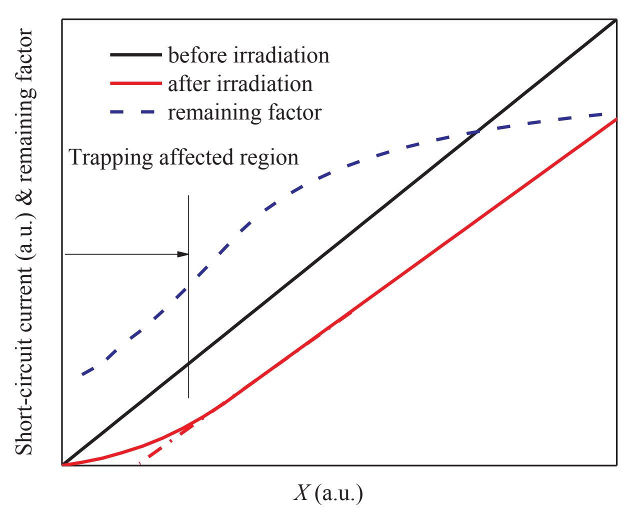

Fig. 6. Schematic diagram of current and remaining factors as a function of concentration X.

indicates that concentrator solar cells may be more radiation-resistant against low energy protons.

8. Conclusions

In this research, voltage-current curves under various intensities were used to study the degradation behavior GaInP/GaAs/Ge solar cells under 70 keV and 150 keV proton irradiation. We could get the following conclusions from our research:

(1) After protons irradiation, electrical parameters of solar cells decay seriously. The decrease is attributed to the increase of recombination rate and shunt effect.
(2) The relation between concentration and open circuit voltage indicates that SRH recombination dominates in GaInP after 70 keV proton irradiation, as the ideality factor Σn_i varies from 3.0 to 3.99. After 150 keV protons irradiation, Σn_i varies from 3.0 to 4.26, showing SRH recombination rate gets stronger both in GaInP and Ge than those undamaged.
(3) The relation between concentration and shunt resistance could reflect the current mismatch in multijunction solar cells. The results indicate the mismatch is larger after 70 keV and 150 keV proton irradiation.
(4) The relative degradation rate is influenced by light intensities, and it is more obvious under weak light condition.

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