

Effect of solar cell structure on the radiation resistance of an InP solar cell

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Abstract. Effects of electron irradiation-induced deep level defects have been studied on both n/p and p/n Indium Phosphide (InP) solar cells with very thin emitters. The simulation results reveal that the n/p structure offers a somewhat better short-circuit current and that the p/n structure renders an improved open-circuit voltage, not only before electron irradiation but also after 1 MeV electron irradiation with 5×10^{15} electrons per cm^2 fluence. Further, the calculated findings highlight that the n/p solar cell structure is more resistant than that of a p/n structure.

1 Introduction

Research into space solar cells has progressed rapidly over the last couple of decades. The fundamental objectives for developing space solar cells are to uplift their high efficiency and radiation resistance and in this framework, Gallium Arsenide (GaAs) cells have been found to be more promising than silicon (Si) cells for space applications [1, 2]. Developments have also been focused on Indium Phosphide solar cells (InP) for the reason that their radiation tolerance surpasses that of the GaAs and Si ones as reported in variant studies [1, 3, 4]. Moreover, they have several other advantages like a high-efficiency, a thin-film structure, a high-temperature operation and a simple cell structure [5, 6]. InP cells appear then as very attractive materials for space solar cells as of late, elevated conversion efficiencies exceeding 29.2% (AM0 at 25°C) have been achieved [7]. Also, it has been demonstrated that InP solar cells exhibit relatively low levels of performance degradation for both proton and electron irradiation [1, 7].

The development efforts of InP photovoltaic cells have been focused on the n/p structure under AM0 conditions and little has been published on the performance of the p/n structure [8-12]. Table 1 summarizes the designs, the parameters of the emitters and bases, and the reported performances of three InP solar cells in space conditions (AM0, 1.35 kW.m^{-2} , 25°C). As can be seen, Sharps et al. found that n/p solar cells have heightened open-circuit voltage (V_{oc}) and short-circuit current density (J_{sc}) regarding the p/n ones [11]. Nevertheless, Jain et al. shed into light that p/n solar cells achieve greater efficiency in comparison with

n/p solar cells, owing to more elevated V_{oc} even though the value of J_{sc} is somewhat lower than for the n/p structure [12].

Since InP solar cells are promising for space applications, the objective of this paper is twofold: (i) compare the expected performance of n/p and p/n indium phosphide solar cells under space conditions, and (ii) model the effects of 1 MeV electron irradiation on InP solar cells.

2 Numerical modeling

Numerical simulations of InP solar cells have been carried out by using the finite element method in order to solve Poisson equation (1) coupled with the equations of continuity for both the electrons (2) and the holes (3):

$$-\nabla \cdot (\epsilon \cdot \nabla \psi) = q(p-n+N) \quad (1)$$

$$dJ_n/dx = -q(G_{opt} - R_{SRH}) \quad (2)$$

$$dJ_p/dx = q(G_{opt} - R_{SRH}) \quad (3)$$

where the three dependent variables are ψ the electrostatic potential, q the elementary charge, n and p the electron and the hole concentrations respectively. J_n and J_p are the electron and the hole conduction current densities. ϵ is the permittivity and N is the fixed charge associated with ionized donors.

In equations (2) and (3), R_{SRH} describes the non-radiative recombination mechanisms such as Shockley-Read-Hall, Auger and surface recombinations.

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Table 1. Designs and reported performances of InP solar cells [10-12].

| Group | Vilela et al. [10] | Sharps et al. [11] | | Jain et al. [12] | |
|----------------------------------------------|--------------------|--------------------|--------------------|------------------|--------------------|
| Design | p/n | n/p | p/n | n/p | p/n |
| Emitter doping (cm ⁻³) | 2×10 ¹⁸ | | 5×10 ¹⁶ | | 1×10 ¹⁸ |
| Emitter thickness (μm) | 0.08 | | 0.05 | | 0.15 |
| Base doping (cm ⁻³) | 5×10 ¹⁷ | | 5×10 ¹⁶ | | 1×10 ¹⁷ |
| Base thickness (μm) | 1.5 | | 3 | | 5 |
| <i>J_{sc}</i> (mA.cm ⁻²) | 21.5 | 28.87 | 28.68 | 42.37 | 41.49 |
| <i>V_{oc}</i> (V) | 0.803 | 0.848 | 0.814 | 0.941 | 0.997 |
| <i>FF</i> | 0.77 | 0.779 | 0.814 | 0.863 | 0.869 |
| <i>η</i> (%) | 10.5 | 14.1 | 13.9 | 25.1 | 26.2 |

Table 2. Parameters of the InP materials in the model [13,14].

| Parameter | Symbol | Value |
|---------------------------------------------------|------------------------|--------------------------------------------------------|
| Elementary charge | <i>q</i> | 1.602×10 ⁻¹⁹ C |
| Room temperature | <i>T</i> | 300 K |
| Boltzmann constant | <i>k</i> | 1.38×10 ⁻²³ J.K ⁻¹ |
| Gap energy | <i>E_g</i> | 1.35 eV |
| Relative permittivity | <i>ε_r</i> | 12.6 |
| Intrinsic concentration | <i>n_i</i> | 1.2×10 ⁷ cm ⁻³ |
| Effective density of state in the conduction band | <i>N_c</i> | 5.7×10 ¹⁷ cm ⁻³ |
| Effective density of state in the valence band | <i>N_v</i> | 1.1×10 ¹⁹ cm ⁻³ |
| Electron mobility | <i>μ_n</i> | 5900 cm ² .V ⁻¹ .s ⁻¹ |
| Hole mobility | <i>μ_p</i> | 150 cm ² .V ⁻¹ .s ⁻¹ |
| Electron thermal velocity | <i>V_{thn}</i> | 3.9×10 ⁵ m.s ⁻¹ |
| Hole thermal velocity | <i>V_{thp}</i> | 1.7×10 ⁵ m.s ⁻¹ |
| Electron lifetime | <i>τ_n</i> | 0.73 ns |
| Hole lifetime | <i>τ_p</i> | 151.5 ns |
| Radiative recombination coefficient | <i>τ_{rad}</i> | 1.2×10 ⁻¹⁰ cm ³ .s ⁻¹ |
| Surface recombination coefficient | <i>τ_s</i> | 9×10 ⁻³¹ cm ⁶ .s ⁻¹ |

The InP cell is exposed to sunlight outside the atmosphere. The AM0 conditions corresponding to the characteristics of the sun radiation level before the passage of sunlight through the atmosphere of the earth with an integral power of 1.35 kW.m⁻² have hence been considered along with an optical generation *G_{opt}* for the free carriers:

$$G_{opt} = (1-R) \cdot \alpha(\lambda) \cdot \phi \cdot \exp(-\alpha(\lambda)x) \quad (4)$$

where *R* is the reflectivity of the front contact, *α(λ)* is the absorption coefficient dependent on the wavelength *λ*, *φ* is the photon flux and *x* is the depth in the semiconductor along the propagation direction.

The parameters of the materials listed in Table 2 are used in the numerical simulations [13, 14]. The material properties of the n/p structure are detailed in Table 3. Alike properties are utilized in the case of the p/n configuration except for the back surface recombination velocity (10⁷ cm.s⁻¹), the emitter diffusion length (2 μm) and the base diffusion length (5 μm). Values listed in Table 3 are reported from the literature [3, 9, 15]. The geometries of both the n/p and the p/n junctions with their meshes were realized in the same manner. The example of the n/p structure is depicted in Figure 1. Both the meshes contain 860 nodes and 1592 elements. The minimum quality of the elements is of 0.8308.

Table 3. Parameters of the emitter and the base materials for the optimal design of a n/p InP solar cell [3, 9, 15].

| Parameter | Emitter | Base |
|------------------------------------------------------------|--------------------|------------------|
| Thickness (μm) | 0.08 | 5 |
| Doping (cm ⁻³) | 5×10 ¹⁷ | 10 ¹⁸ |
| Front surface recombination velocity (cm.s ⁻¹) | 10 ⁴ | - |
| Surface recombination velocity (cm.s ⁻¹) | - | 10 ⁵ |
| Electron diffusion length (μm) | 0.1 | - |
| Hole diffusion length (μm) | - | 20 |

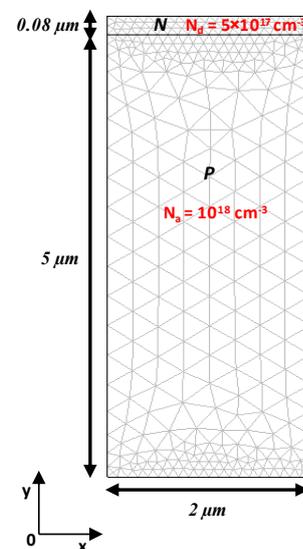


Fig. 1. Geometry of the solar n/p junction with its mesh.

Table 4. Electron and hole traps observed by Deep Level Transient Spectroscopy (DLTS) in an InP solar cell irradiated by 1 MeV electrons [16, 17].

| Trap designation | Trap level (eV) | Capture cross section σ (cm ²) | Introduction rate (cm ⁻¹) |
|------------------|-----------------|---------------------------------------------------|---------------------------------------|
| p-type | H2 | 0.22 | 3×10^{-17} |
| | H3 | 0.32 | 6×10^{-16} |
| | H4 | 0.37 | 8×10^{-16} |
| | H5 | 0.52 | 5.5×10^{-15} |
| n-type | E11 | 0.76 | 2.9×10^{-12} |

Additionally, the solar cells are subjected to 1 MeV electron irradiation which produces six hole traps and five electron traps in the p-type layer of an InP cell, while 16 electron and five hole traps appear in the n-type one [16, 17]. The attention is drawn here to dominant traps for which a specific atomic structure has been proposed. Accordingly, H2, H3, H4, H5 and E11 traps which are due to phosphorus atom-electron collisions are accounted for in the present model [16]. Indeed, these centers act both as majority-carrier trap centers and recombination centers, and they also have higher introduction rates than the other centers. The trap levels, the capture cross sections and the introduction rates of these five electron and hole traps are shown in Table 4.

Numerical modeling is used as a means to simulate in 2 dimensions the operation modes of an InP solar cell with both p/n and n/p structures, and this is done with the presence of defects created by electron irradiation. The simulation is performed utilizing the electrostatic and diffusion modules of COMSOL Multiphysics.

3 Results and discussion

The numerical calculations were carried out to solve equations (1) to (4) in the case of both the p/n and n/p junctions, before irradiation and taking into consideration the modifications engendered by a 1 MeV electron irradiation at 5×10^{15} electrons per cm² fluence on an InP solar cell. Figure 2 shows the calculated $J(V)$ characteristics for the n/p structure before and after electron irradiation of 1 MeV whereas Figure 3 depicts them for the p/n junction. Table 5 expresses the various cell performance parameters of the two solar cell structures n/p and p/n before and after electron irradiation.

Table 5 clearly discloses that prior to irradiation, the n/p solar cell structure gives higher efficiencies compared to the p/n structure due to a raised short-circuit current density (J_{sc}). Thus, the usage of a n/p structure appears attractive to reduce the area and the mass of the solar arrays deployed for space power applications.

Table 5. InP cell performance parameters before and after 1 MeV electron irradiation at 5×10^{15} electrons per cm² fluence.

| Output parameter | n/p | | p/n | |
|--------------------------------|--------|-------|--------|-------|
| | Before | After | Before | After |
| J_{sc} (mA/cm ²) | 41.71 | 39.89 | 37.78 | 31.79 |
| V_{oc} (V) | 0.891 | 0.888 | 0.907 | 0.875 |
| FF | 0.844 | 0.845 | 0.853 | 0.811 |
| η (%) | 23.24 | 22.19 | 21.66 | 16.73 |

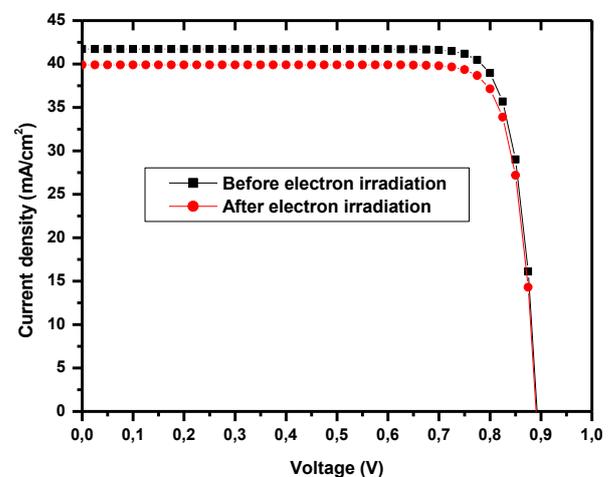


Fig. 2. $J(V)$ characteristics of the n/p solar cell structure before and after 1 MeV electron irradiation.

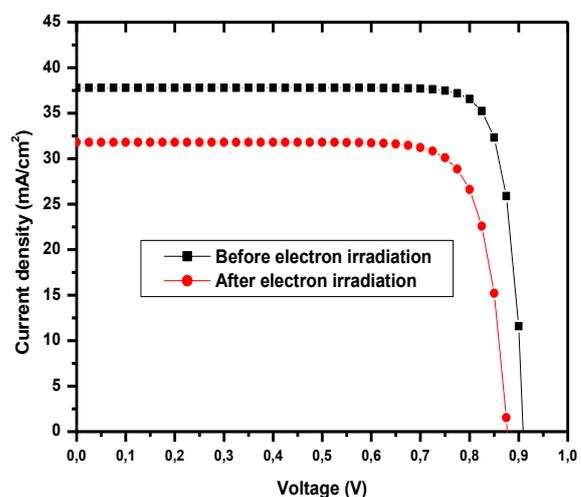


Fig. 3. $J(V)$ characteristics of the p/n solar cell structure before and after 1 MeV electron irradiation.

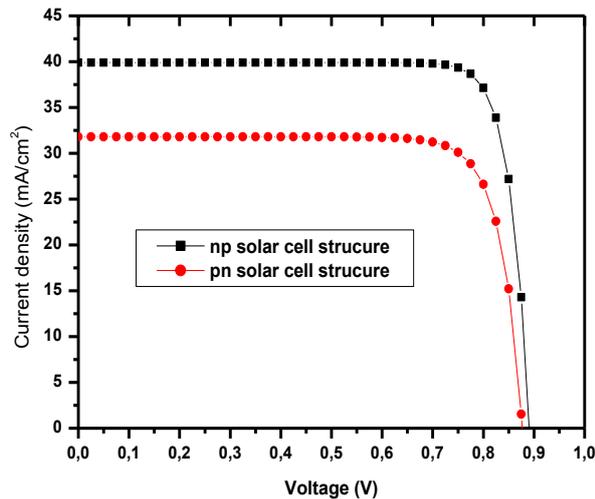


Fig. 4. Comparison of the $J(V)$ characteristics of the n/p and the p/n InP solar cell structures after electron irradiation.

Furthermore, it is found that the solar cell efficiencies are degraded for both the n/p and the p/n structure down to 22.19% and 16.73% respectively. J_{sc} is more affected by electron irradiation for the p/n structure with a decrease from 39.89 to 31.79 mA/cm² against 41.71 to 37.78 mA/cm² for the n/p structure. However, the open-circuit voltage V_{oc} is not altered for the n/p solar cell structure while it is a bit more impacted for the p/n one with a lessening from 0.907 to 0.875 V. Besides, the fill factor FF remains in the same magnitude although it gets slightly lower for the p/n structure after electron irradiation.

In the n/p solar cell structure, the n-InP type layer is the emitter. The electron irradiation creates just one electron trap in this layer which could play the role of a doping level. Concerning the p/n structure, the p-InP type layer is the emitter. The electron irradiation creates four hole traps in this layer. The latter traps are considered as recombination centers. Thereby, they could be responsible for the serious degradation of the J_{sc} and they surely raise the barrier potential at the p/n interface. It is a fact that the open-circuit voltage of a solar cell is related to the barrier built-in voltage. Whereby, the elevation of the barrier potential compensates for the reduction of the V_{oc} by electron irradiation.

For comparison, the $J(V)$ characteristic for both the n/p and p/n solar cell structures after the electron irradiation are plotted in Figure 4. The n/p solar cell structure is more resistant to radiation at 5×10^{15} electrons per cm² fluence than the p/n solar cell structure as J_{sc} is maintained at a 20% higher level. Obtained results are fairly in agreement with the findings in references [11, 19]. A possible explanation of the discrepancies is the type and the depth of the energy gaps of the defects created by irradiation for each solar cell structure. In the p/n structure, the emitter layer has four defects (H₂, H₃, H₄ and H₅), three of them happen to be deep level defects. In the n/p structure, the emitter layer is the n layer having only one defect (E11). The latter deep level defect has no significant influence on the initial $J(V)$

characteristic. This phenomenon can equally be observed in a GaAs based solar cell irradiated by electrons of 1 MeV [20].

4 Conclusion

Numerical simulation was used to compare the radiation resistance and the performances of n/p and p/n solar cell structures for an Indium Phosphide (InP) solar cell. It was noted that the optimum n/p solar cell structure was more efficacious than the optimum p/n solar cell structure on account of a larger short-current density which is in agreement with the outcomes of reference [11]. The same electron irradiation effects are observed on both the n/p and the p/n structures for the short-current density. The present solar cell modeling not only predicts that the n/p InP solar cell structure is more efficient than the p/n one but also that the former is more radiation resistant. As a perspective for space applications, a modeling study of InP solar cells can be developed in order to deal with a p⁺/nn⁺ structure having a very thin emitter layer, by reason that a slim emitter enhances the collection of carriers generated by high energy incident photons from the solar spectrum.

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