crystals

Communication

Evaluation of the Minority-Carrier Lifetime of IMM3J Solar Cells under Proton Irradiation Based on Electroluminescence

Jing Xu [1,†], Gang Yan [2,†] and Ming Lu [3,*]

[1] Department of Physics, Yantai University, Yantai 264005, China
[2] School of Physics and Electronic Engineering, Sichuan University of Science and Engineering, Yibin 644002, China
[3] College of Nuclear Equipment and Nuclear Engineering, Yantai University, Yantai 264005, China
* Correspondence: lum@ytu.edu.cn
† These authors contributed equally to this work.

Abstract: The shortening of the minority carrier lifetime is the main reason for the degradation of the electrical performance of solar cells; therefore, it is particularly important to evaluate the minority carrier lifetime of inverted metamorphic triple junction (IMM3J) GaInP/GaAs/InGaAs solar cells. We evaluate the minority carrier lifetime of each subcell of IMM3J solar cells before and after 2 MeV proton irradiation by the electroluminescence (EL) method. Before proton irradiation, the minority carrier lifetimes of the GaInP, GaAs, and InGaAs subcells were 6.99×10^{-9} s, 3.09×10^{-8} s, and 2.31×10^{-8} s, respectively. After proton irradiation, the minority carrier lifetime of GaInP, GaAs, and InGaAs subcells degraded significantly. When the proton fluence was 2×10^{12} cm^{-2}, the minority carrier lifetimes of the GaInP, GaAs, and InGaAs subcells degraded to 1.63×10^{-10} s, 1.56×10^{-11} s, and 1.65×10^{-10} s, respectively. These results provide a reference for predicting the degradation of the short-circuit current and open-circuit voltage of each subcell.

Keywords: IMM3J solar cells; EL; minority carrier lifetime; proton irradiation; fluence

check for updates

Citation: Xu, J.; Yan, G.; Lu, M. Evaluation of the Minority-Carrier Lifetime of IMM3J Solar Cells under Proton Irradiation Based on Electroluminescence. *Crystals* **2023**, *13*, 297. https://doi.org/10.3390/cryst13020297

Academic Editor: Stefano Carli

Received: 27 January 2023
Revised: 6 February 2023
Accepted: 9 February 2023
Published: 10 February 2023

1. Introduction

The inverted metamorphic triple junction (IMM3J) GaInP/GaAs/InGaAs solar cells are designed based on the principle of spectral matching and have higher photoelectric conversion efficiency than the lattice-matched triple junction GaInP/GaAs/Ge solar cells [1–6]. The AM0 efficiency of IMM3J solar cells can reach 32% or higher, while that of conventional triple junction devices is limited to below 30% [1]. The high-efficiency IMM3J solar cell manufactured by Spectrolab Company has a conversion efficiency of 32.1% (AM0, 1 sun) [2]. The efficiency of the IMM3J solar cell fabricated by Tianjin San'an Optoelectronics Company reached 32% under one sun and AM0 spectrum, which is 5% higher than that of the lattice-matched GaInP/InGaAs/Ge triple-junction solar cell [3]. Recently, our research group cooperated with the Shanghai Space Power Source Institute to manufacture IMM solar cells with an efficiency exceeding 32% [4]. In addition, IMM3J solar cells can be bonded to lightweight and flexible substrates to fabricate lightweight and flexible thin-film solar cells by epitaxial lift-off [5,6].

The space radiation environment contains a variety of charged particles, which can seriously damage IMM3J solar cells [7–9]. Compared with electron irradiation, proton irradiation will cause greater damage to IMM3J solar cells. The study found that the maximum power of IMM3J solar cells degraded by 13.7% and 26.3% under 1 MeV electron irradiation and 10 MeV proton irradiation, respectively [9]. Because low-energy protons cause greater damage to solar cells than high-energy protons, it is particularly critical to study the low-energy proton irradiation effect on IMM3J solar cells. In previous studies, we predicted the degradation of the short-circuit current, open-circuit voltage, fill factor, and efficiency of IMM3J solar cells under 2 MeV proton irradiation [4]. Furthermore, the

IMM3J solar cell is composed of three subcells in series, the open circuit voltage is equal to the sum of the voltages of the three subcells, and the short-circuit current is determined by the minimum current of the three subcells [9]. Therefore, it is also very important to study the radiation degradation of each subcell to optimize the performance of IMM3J solar cells for space applications.

We know that the main reason for the performance degradation of solar cells is the reduction in minority carrier lifetime by irradiation-induced displacement damage in the active area of solar cells. Protons elastically collide with the lattice atoms of the solar cell, causing them to move out of their normal lattice position, creating displacement defects. These defects act as recombination centers, increasing the probability of carrier recombination and resulting in a shortened minority carrier lifetime, which in turn leads to the degradation of solar cell performance. Therefore, in this work, we intend to evaluate the minority carrier lifetime of each subcell of IMM3J solar cells by using the electroluminescence (EL) spectra before and after proton irradiation to provide a reference for predicting the degradation of the short-circuit current and open-circuit voltage of each subcell. The minority carrier lifetime is determined by time-resolved photoluminescence [10,11]. The minority carrier lifetime can also be obtained indirectly through the minority carrier diffusion length, which is relatively easier to measure [12,13]. In addition, we can also measure the defect introduction rate and the capture cross-section by deep-level transient spectroscopy and then obtain the minority carrier lifetime [14,15]. However, due to the complexity of the structure of multijunction tandem solar cells, it is difficult to evaluate the minority carrier lifetime of all subcells using these methods.

Electroluminescence (EL) and photoluminescence (PL) have been proven to be effective methods to evaluate the minority carrier lifetime of multijunction solar cells. The minority carrier lifetime of conventional lattice-matched 3-junction solar cells has been evaluated by measuring the EL and PL spectra before and after irradiation [16–18]. The PL method needs to select different excitation sources to excite each junction cell separately and then obtain the PL spectrum of each junction cell. However, EL can simultaneously excite all subcells of multijunction solar cells and then generate the measurement of the EL spectra of all subcells. Therefore, EL measurements are easier to obtain and more advantageous than PL measurements for multijunction solar cells. In this work, we first measure the EL spectra of each subcell of the IMM3J solar cell under proton irradiation with different fluences, then fit the EL peak intensity with the relative change in the proton fluences to obtain the product of the introduction rate and minority carrier capture cross-section, and finally give the minority carrier lifetime of each subcell.

2. Materials and Methods

IMM3J solar cells have the advantages of light weight, low cost, flexibility, and high conversion efficiency [4,6,9,19], rendering such solar cells very suitable for space applications. In this work, IMM3J solar cells are fabricated at the Shanghai Space Power Institute and mainly consist of three subcells: GaInP top cell, GaAs middle cell, and InGaAs bottom cell. The detailed structure and growth process of the IMM3J solar cells is shown in Ref. [4].

Proton irradiation was performed using a 2 × 1.7 MV tandem accelerator at Peking University. To ensure uniform irradiation of samples, the proton beam is scanned in the vertical (Y) and horizontal (X) directions by the scanner before hitting the sample. The proton irradiation experiment was carried out at room temperature. The proton energy is 2 MeV in this experiment to ensure that the proton can completely pass through the IMM3J solar cells. The proton fluence is 2×10^{11}, 8×10^{11}, and 2×10^{12} cm^{-2} in this experiment, which mainly refers to our previous proton irradiation experiments on lattice-matched solar cells [20] and other related references [9]. The flux used in the experiment is 2×10^{9} cm^{-2} s^{-1}, which can ensure that the irradiation time is not too long or too short and that it cannot result in an increase in sample temperature due to irradiation. Figure 1 shows the track distribution of 2 MeV protons in IMM3J solar cells obtained by SRIM simulation [21]. Protons with an energy of 2 MeV can pass through the IMM3J solar cell and cause damage to all subcells.

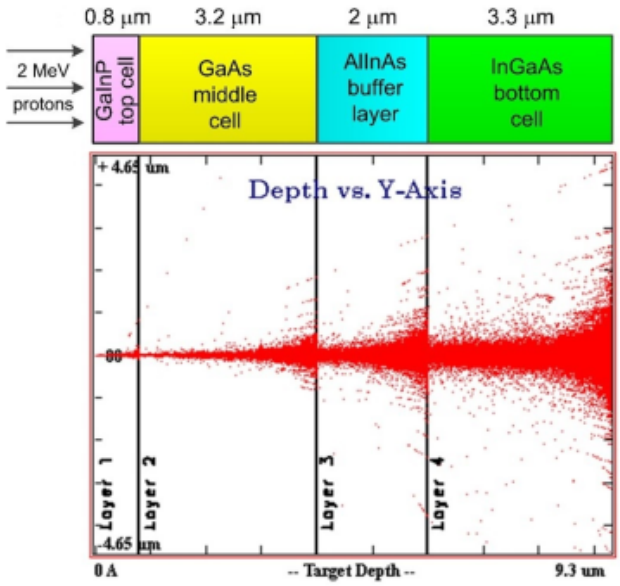

Figure 1. Track distribution of 2 MeV protons in IMM3J solar cells.

EL spectra were measured at room temperature before and after proton irradiation. A current density of 60 mA/cm^2 was injected into the IMM3J solar cell as an excitation source. Due to the difference in the peak position of the emission spectrum, we chose different gratings and detectors to measure the EL spectrum of each subcell. The EL spectra of the GaInP top cell were split by a grating monochromator with a 600 groove/mm, grating blazed at 500 nm, and then detected by a photomultiplier (PMTH-S1-CR131A). The EL spectra of the GaAs middle cell and InGaAs bottom were split by a grating monochromator with a 600 groove/mm, grating blazed at 750 nm, and then detected by a Si photodetector (DSi200). Finally, the detected signal was processed by a lock-in amplifier and then transmitted to the computer to obtain the EL spectrum.

3. Results and Discussion

Figure 2 shows the EL spectra of the GaInP, GaAs, and InGaAs subcells under different proton fluences. The EL spectrum peaks of the GaInP, GaAs, and InGaAs subcells are located at 652 nm, 872 nm, and 1300 nm, respectively. After proton irradiation, the EL spectral intensities of the GaInP, GaAs, and InGaAs subcells all decrease significantly.

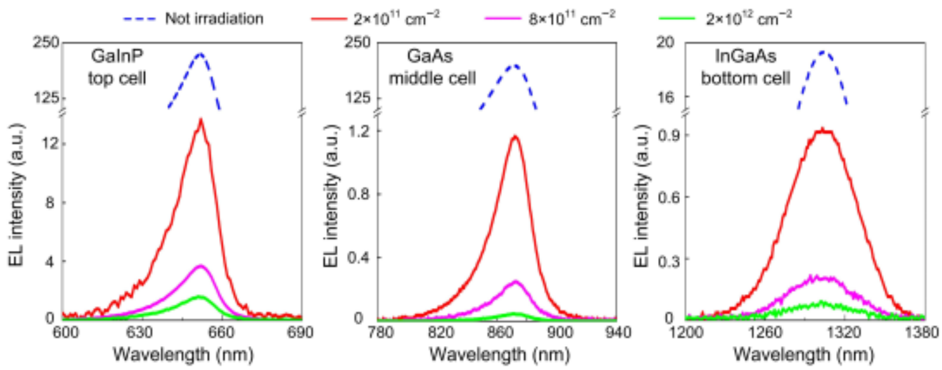

Figure 2. EL spectra of IMM3J solar cells irradiated with 2 MeV protons at fluence ranging from 0 to 2×10^{12} ions/cm^2.

Figure 3 shows the variation in the EL peak intensity of the GaInP, GaAs, and InGaAs subcells with proton irradiation fluence. The EL spectral intensities of all subcells decrease with increasing proton fluence. Under the same fluence, the EL spectral intensity degradation of the GaAs middle cell is the largest, that of the InGaAs bottom cell is the second largest, and that of the InGaP top cell is the smallest. This indicates that the GaAs and InGaAs subcells have weaker radiation resistance than the GaInP top cell. This conclusion is consistent with our previous research results [4].

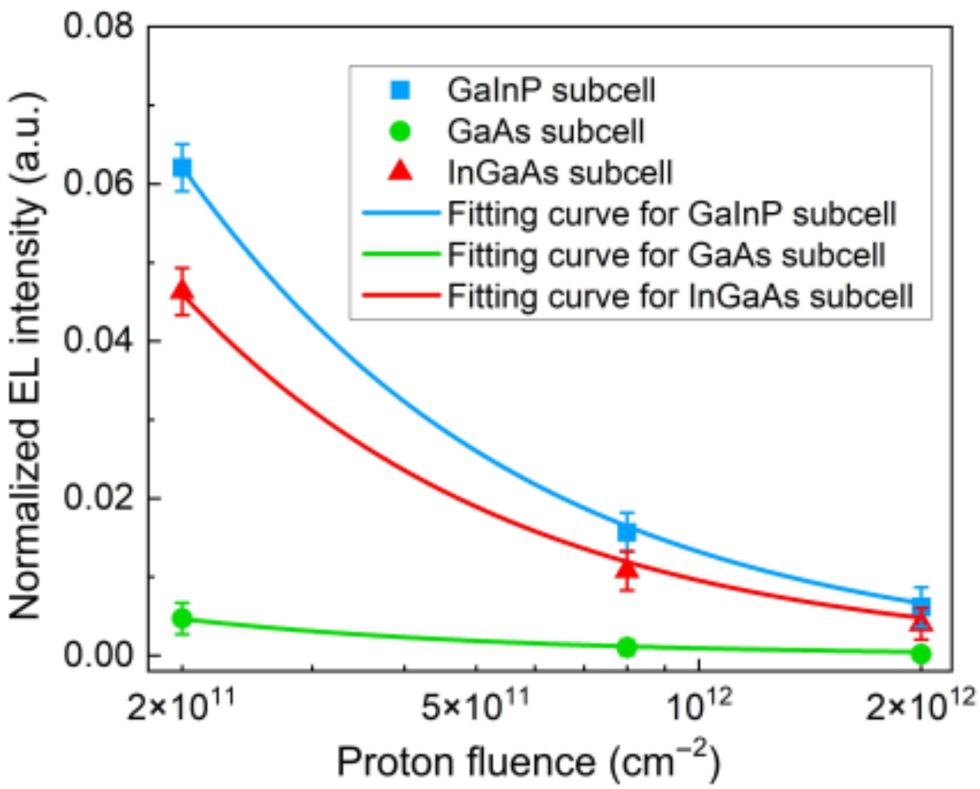

Figure 3. The variation in EL peak intensity of GaInP, GaAs, and InGaAs subcells with proton irradiation fluence.

For a given injection current density, the normalized EL peak intensity is given by the radiative efficiency (η) [16,22]:

$$\eta = \left(1 + \frac{\tau_r}{\tau_{nr}}\right)^{-1} \quad (1)$$

where τ_r is the radiative recombination lifetime, which is independent of the fluence. τ_{nr} is the nonradiative recombination lifetime.

$$\tau_r = \frac{1}{BN} \quad (2)$$

$$\tau_{nr} = \frac{1}{k\sigma\nu\varphi} \quad (3)$$

where $\boldsymbol{B}$ is the probability of radiative recombination, $\boldsymbol{N}$ is the doping concentration, $\boldsymbol{k}$ is the introduction rate of the nonradiative recombination centers, σ is the minority carrier capture-cross section, ν is the thermal velocity of carriers, and φ is the fluence. Combining Equations (1)–(3), the change in EL peak intensity to the fluence can be fitted by $\eta = (1 + \alpha\varphi)^{-1}$, with $\alpha = k\sigma\nu/BN$. The fitting results are shown in Figure 3 and are in good agreement with the experimental data. The α and $k\sigma\nu$ on the GaInP, GaAs, and InGaAs subcells are listed in Table 1. Table 1 shows that GaInP and InGaAs have the same damage coefficient ($k\sigma v$) of minority carrier lifetime, while GaAs has the largest damage coefficient. This indicates that under 2 MeV proton irradiation, the GaAs subcell of the IMM3J solar cell degrades the most and has the weakest radiation resistance.

Table 1. The parameters ***B***, ***N***, $k\sigma v$ and α on GaInP, GaAs and InGaAs subcells.

	GaInP	GaAs	InGaAs
B * (cm^3/s)	2×10^{-10}	1.5×10^{-10}	1.43×10^{-10}
N (cm^{-3})	2×10^{17}	2×10^{17}	2×10^{17}
α	$(7.54 \pm 0.05) \times 10^{-11}$	$(1.07 \pm 0.04) \times 10^{-9}$	$(1.04 \pm 0.02) \times 10^{-10}$
$k\sigma v$	3.0×10^{-3}	3.2×10^{-2}	3.0×10^{-3}

* Refs. [16,23].

The effective minority carrier lifetime τ_{eff} is represented as:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_r} + \frac{1}{\tau_0} + \frac{1}{\tau_{nr}} \tag{4}$$

where τ_0 is the nonradiative recombination lifetime before irradiation. τ_0 is calculated by $\tau_0 = L_0^2/D$ (D is the diffusion coefficient, and L_0 is the diffusion length before irradiation). D is equal to 60, 200, and 188 $cm^2\ s^{-1}$ for the GaInP, GaAs, and InGaAs subcells of the IMM3J solar cell, respectively [16,24]. L_0 is equal to 5.21×10^{-3} cm, 7.94×10^{-3} cm, and 3.63×10^{-4} cm for the GaInP, GaAs, and InGaAs suncells of the IMM3J solar cell, respectively. Therefore, the τ_0 of the GaInp, GaAs, and InGaAs subcells can be calculated to be equal to 4.52×10^{-7} s, 3.15×10^{-7} s, and 7.01×10^{-10} s, respectively. Thus far, the effective minority carrier lifetime τ_{eff} can be calculated by Equation (4) and listed in Table 2. The minority carrier lifetimes of the GaInP, GaAs, and InGaAs subcells are 6.99×10^{-9} s, 3.09×10^{-8} s, and 2.31×10^{-8} s, respectively, before proton irradiation, such values being of the same order of magnitude as those in the Refs. [16,24,25].

Table 2. The effective minority carrier lifetime τ_{eff} of GaInP, GaAs, and InGaAs subcells of IMM3J solar cells under different proton fluences.

Parameter	Fluence (cm^{-2})	GaInP	GaAs	InGaAs
τ_{eff} (s)	0	6.99×10^{-9}	3.09×10^{-8}	2.31×10^{-8}
	2×10^{11}	1.35×10^{-9}	1.55×10^{-10}	1.55×10^{-9}
	8×10^{11}	3.93×10^{-10}	3.90×10^{-11}	4.09×10^{-10}
	2×10^{12}	1.63×10^{-10}	1.56×10^{-11}	1.65×10^{-10}

Figure 4 shows the normalized effective minority carrier lifetime of each subcell of IMM3J solar cells as a function of irradiation fluence. The effective minority carrier lifetimes of all subcells decrease with increasing proton fluence. The carrier lifetime of the GaInP subcell degrades by 1–2 orders of magnitude, that of the GaAs subcell degrades by 3–4 orders of magnitude, and that of the InGaAs subcell degrades by 2–3 orders of magnitude. Therefore, the radiation resistance of the GaInP top cell is the best, that of the GaAs middle cell is the worst and that of the InGaAs bottom cell is in between the two. Therefore, we need to strengthen the protection of GaAs middle cells and InGaAs bottom cells of IMM3J solar cells in space applications.

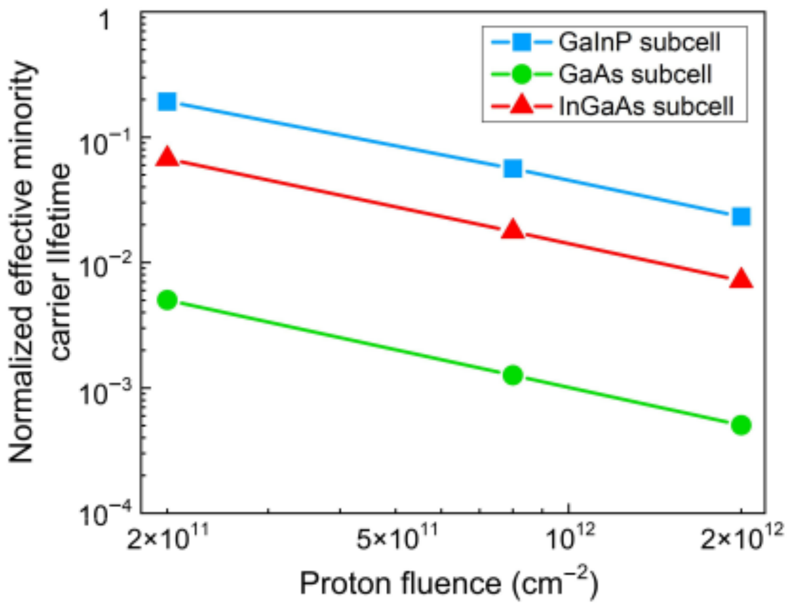

Figure 4. Normalized minority carrier lifetime of each subcell of IMM3J solar cells as a function of irradiation fluence.

4. Discussion and Conclusions

In this work, we found that the GaAs subcell has the worst radiation resistance among the three subcells of the IMM3J solar cell. However, some previous studies suggest that the InGaAs subcell of IMM3J has the weakest radiation resistance [9,26]. The reason for this may be due to the difference in type and energy of the irradiated particles or the content of **In** in the InGaAs subcell. The study noted that the radiation resistance of InGaAs with different **In** contents is different [19]. In addition, different energies and types of particle irradiation produce different defects in solar cells, and the damage caused to them is also different [15].

Usually, for a solar cell, the short circuit current density (J_{sc}) can be expressed as [6,9]:

$$J_{sc} = \frac{\alpha A e^{\alpha x_j} - A/\sqrt{D\tau_{eff}}}{1/D\tau_{eff} - \alpha^2} \tag{5}$$

where $A = q\alpha F(1-R)\exp(-\alpha x_j)$, $\boldsymbol{q}$ is the electron charge, α is the absorption coefficient, $\boldsymbol{F}$ is the flux of incident light, $\boldsymbol{R}$ is the reflectivity, and x_j is the p–n junction depth. It can be seen from Equation (5) that the shortening of the minority carrier lifetime will lead to the degradation of the short-circuit current, which in turn will lead to the degradation of the open-circuit voltage, fill factor, and conversion efficiency. Therefore, we can predict the short-circuit current degradation of each subcell of the IMM3J solar cell by evaluating the minority carrier lifetime before and after irradiation.

Under proton irradiation, the relationship between the degradation of the open circuit voltage of each junction cell and the intensity of the EL spectrum can be derived by the optoelectronic reciprocity relation [27,28].

$$\Delta\varnothing_{EL} = \exp\left(\frac{q\Delta V_{oc}}{kT}\right) \tag{6}$$

where $\Delta\varnothing_{EL}$ is the ratio of the EL intensity after irradiation and before irradiation and ΔV_{oc} is the ratio of the open-circuit voltage after irradiation and before irradiation. According to Equation (6), the change in the open circuit voltage can be predicted by the change in the EL intensity. Therefore, we can also predict the degradation of the open circuit voltage of each subcell through the change in EL intensity before and after irradiation.

5. Conclusions

We evaluate the effective minority carrier lifetime of each subcell of IMM3J GaInP/GaAs/InGaAs solar cells using the EL method and reveal how it varies with proton irradiation fluence. Compared with GaInP subcells, GaAs and InGaAs subcells have poorer radiation resistance and need to be further optimized for space applications.

Author Contributions: Conceptualization, J.X. and M.L.; methodology, G.Y. and M.L.; software, J.X.; validation, J.X., G.Y. and M.L.; formal analysis, J.X.; investigation, J.X. and G.Y.; resources, G.Y. and M.L.; data curation, J.X. and G.Y.; writing—original draft preparation, M.L.; writing—review and editing, J.X., G.Y. and M.L.; visualization, J.X.; supervision, M.L.; project administration, M.L.; funding acquisition, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China under Grant 11905181.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Rehder, E.; Jun, B.; Chiu, P.; Wierman, S.; Edmondson, K.; Liu, X.-Q.; Mesropian, S.; Pien, P.; Boisvert, J.; Karam, N. Environmental Testing of Inverted Metamorphic Solar Cells for Space. In Proceedings of the 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC), Denver, CO, USA, 8–13 June 2014; IEEE: Piscataway, NJ, USA, 2014; pp. 3608–3611.
2. Boisvert, J.; Law, D.; King, R.; Rehder, E.; Chiu, P.; Bhusari, D.; Fetzer, C.; Liu, X.; Hong, W.; Mesropian, S. High Efficiency Inverted Metamorphic (IMM) Solar Cells. In Proceedings of the 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC), Tampa, FL, USA, 16–21 June 2013; IEEE: Piscataway, NJ, USA, 2013; pp. 2790–2792.
3. Song, M.-H.; Wang, D.-X.; Bi, J.-F.; Chen, W.-J.; Li, M.-Y.; Li, S.-L.; Liu, G.-Z.; Wu, C.-Y. Inverted metamorphic triple-junction solar cell and its radiation hardness for space applications. *Acta Phys. Sin.* **2017**, *66*, 188801. [CrossRef]
4. Xu, J.; Yang, K.; Xu, Q.; Zhu, X.; Wang, X.; Lu, M. Fabrication and Irradiation Effect of Inverted Metamorphic Triple Junction GaInP/GaAs/InGaAs Solar Cells. *Crystals* **2022**, *12*, 670. [CrossRef]
5. Tatavarti, R.; Wibowo, A.; Martin, G.; Tuminello, F.; Youtsey, C.; Hillier, G.; Pan, N.; Wanlass, M.; Romero, M. InGaP/GaAs/InGaAs Inverted Metamorphic (IMM) Solar Cells on 4 ″Epitaxial Lifted Off (ELO) Wafers. In Proceedings of the 2010 35th IEEE Photovoltaic Specialists Conference, Honolulu, HI, USA, 20–25 June 2010; IEEE: Piscataway, NJ, USA, 2010; pp. 002125–002128.
6. Wang, X.; Li, B.; Zhou, L.; Shi, X.; Sun, L.; Wang, X. Improving the irradiation resistance of inverted flexible 3J solar cells by adjusting the structure. *Sol. Energy* **2023**, *249*, 744–750. [CrossRef]
7. Walters, R.; Warner, J.; Summers, G.; Messenger, S.; Lorentzen, J. Radiation response mechanisms in multijunction III-V space solar cells. In Proceedings of the Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference, Lake Buena Vista, FL, USA, 3–7 January 2005; IEEE: Piscataway, NJ, USA, 2005; pp. 542–547.
8. Uma, B.; Krishnan, S.; Radhakrishna, V.; Campesato, R. Effect of space radiation on CTJ new version multijunction solar cells. *Radiat. Eff. Defects Solids* **2021**, *176*, 382–395. [CrossRef]
9. Li, J.; Aierken, A.; Zhuang, Y.; Xu, P.Q.; Wu, H.Q.; Zhang, Q.Y.; Wang, X.B.; Mo, J.H.; Yang, X.; Chen, Q.Y.; et al. 1 MeV electron and 10 MeV proton irradiation effects on inverted metamorphic GaInP/GaAs/InGaAs triple junction solar cell. *Sol. Energy Mater. Sol. Cells* **2021**, *224*, 111022. [CrossRef]
10. Gauffier, A.; David, J.-P.; Gilard, O. Analytical model for multi-junction solar cells prediction in space environment. *Microelectron. Reliab.* **2008**, *48*, 1494–1499. [CrossRef]
11. Gauffier, A.; David, J.-P.; Gilard, O.; Nuns, T.; Inguimbert, C.; Balocchi, A. Experimental methods for defect introduction rates determination in multijunction solar cells. *IEEE Trans. Nucl. Sci.* **2009**, *56*, 2237–2241. [CrossRef]
12. Anspaugh, B. *GaAs Solar Cell Radiation Handbook*; NASA: Washington, DC, USA, 1996.
13. Sato, S.-I.; Miyamoto, H.; Imaizumi, M.; Shimazaki, K.; Morioka, C.; Kawano, K.; Ohshima, T. Degradation modeling of InGaP/GaAs/Ge triple-junction solar cells irradiated with various-energy protons. *Sol. Energy Mater. Sol. Cells* **2009**, *93*, 768–773. [CrossRef]
14. Dharmarasu, N.; Yamaguchi, M.; Bourgoin, J.C.; Takamoto, T.; Ohshima, T.; Itoh, H.; Imaizumi, M.; Matsuda, S. Majority-and minority-carrier deep level traps in proton-irradiated n+/p-InGaP space solar cells. *Appl. Phys. Lett.* **2002**, *81*, 64–66. [CrossRef]
15. Bourgoin, J.; Zazoui, M. Irradiation-induced degradation in solar cell: Characterization of recombination centres. *Semicond. Sci. Technol.* **2002**, *17*, 453. [CrossRef]

16. Zazoui, M.; Mbarki, M.; Aldin, A.Z.; Bourgoin, J.; Gilard, O.; Strobl, G. Analysis of multijunction solar cell degradation in space and irradiation induced recombination centers. *J. Appl. Phys.* **2003**, *93*, 5080–5084. [CrossRef]
17. Yan, Y.; Fang, M.; Tang, X.; Chen, F.; Huang, H.; Sun, X.; Ji, L. Effect of 150 keV proton irradiation on the performance of GaAs solar cells. *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. At.* **2019**, *451*, 49–54. [CrossRef]
18. Makham, S.; Zazoui, M.; Bourgoin, J. Analysis of multijunction solar cells: Electroluminescence study. *Moroc. J. Condens. Matter* **2004**, *5*, 181–185.
19. Imaizumi, M.; Nakamura, T.; Takamoto, T.; Ohshima, T.; Tajima, M. Radiation degradation characteristics of component subcells in inverted metamorphic triple-junction solar cells irradiated with electrons and protons. *Prog. Photovolt. Res. Appl.* **2017**, *25*, 161–174. [CrossRef]
20. Lu, M.; Wang, R.; Liu, Y.H.; Hu, W.T.; Feng, Z.; Han, Z.L. Adjusted NIEL calculations for estimating proton-induced degradation of GaInP/GaAs/Ge space solar cells. *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. At.* **2011**, *269*, 1884–1886. [CrossRef]
21. Ziegler, J.F.; Ziegler, M.D.; Biersack, J.P. SRIM—The stopping and range of ions in matter (2010). *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. At.* **2010**, *268*, 1818–1823. [CrossRef]
22. Zazoui, M.; Bourgoin, J. Space degradation of multijunction solar cells: An electroluminescence study. *Appl. Phys. Lett.* **2002**, *80*, 4455–4457. [CrossRef]
23. Ahrenkiel, R.; Ellingson, R.; Johnston, S.; Wanlass, M. Recombination lifetime of In 0.53 Ga 0.47 As as a function of doping density. *Appl. Phys. Lett.* **1998**, *72*, 3470–3472. [CrossRef]
24. Sukeerthi, M.; Kotamraju, S. Study of degradation in 3J inverted metamorphic (IMM) solar cell due to irradiation-induced deep level traps and threading dislocations using finite element analysis. *Phys. E Low Dimens. Syst. Nanostruct.* **2021**, *127*, 114566. [CrossRef]
25. Elfiky, D.; Yamaguchi, M.; Sasaki, T.; Takamoto, T.; Morioka, C.; Imaizumi, M.; Ohshima, T.; Sato, S.-I.; Elnawawy, M.; Eldesoky, T. Theoretical optimization of base doping concentration for radiation resistance of InGaP subcells of InGaP/GaAs/Ge based on minority-carrier lifetime. *Jpn. J. Appl. Phys.* **2010**, *49*, 121201. [CrossRef]
26. Zhang, Y.; Wu, Y.; Zhao, H.; Sun, C.; Xiao, J.; Geng, H.; Xue, J.; Lu, J.; Wang, Y. Degradation behavior of electrical properties of inverted metamorphic tri-junction solar cells under 1 MeV electron irradiation. *Sol. Energy Mater. Sol. Cells* **2016**, *157*, 861–866. [CrossRef]
27. Hoheisel, R.; Messenger, S.; Scheiman, D.; Jenkins, P.; Walters, R. Analysis of Radiation Hardness and Subcell IV Characteristics of GaInP/GaAs/Ge Solar Cells Using Electroluminescence Measurements. In Proceedings of the Physics, Simulation, and Photonic Engineering of Photovoltaic Devices, San Francisco, CA, USA, 23–26 January 2012; SPIE: Bellingham, WA, USA, 2012; pp. 361–367.
28. Yan, G.; Wang, J.-L.; Liu, J.; Liu, Y.-Y.; Wu, R.; Wang, R. Electroluminescence analysis of VOC degradation of individual subcell in GaInP/GaAs/Ge space solar cells irradiated by 1.0 MeV electrons. *J. Lumin.* **2020**, *219*, 116905. [CrossRef]