Fabrication and Irradiation Effect of Inverted Metamorphic Triple Junction GaInP/GaAs/InGaAs Solar Cells

Jing Xu 1, Kunjie Yang 2, Qingguo Xu 3, Xiaofang Zhu 3, Xin Wang 4 and Ming Lu 2,*

1 Department of Physics, Yantai University, Yantai 264005, China; xj2012@mail.bnu.edu.cn
2 College of Nuclear Equipment and Nuclear Engineering, Yantai University, Yantai 264005, China; kjyang@ytu.edu.cn
3 Shanghai Solar Energy Research Center, Shanghai 200241, China; xuqingguo@solarcell.net.cn (Q.X.); zhuxiaofang@solarcell.net.cn (X.Z.)
4 State Key Laboratory of Space Power Sources Technology, Shanghai Institute of Space Power Sources, Shanghai 200245, China; wx19970421@stu.xjtu.edu.cn
* Correspondence: luming.ytu@gmail.com

Abstract: Inverted metamorphic triple junction (IMM3J) GaInP/GaAs/InGaAs solar cells have the advantages of high efficiency, excellent radiation resistance, lightweight and flexible properties, especially suitable for space application. In this paper, we first fabricate the IMM3J GaInP/GaAs/InGaAs solar cell, which has a short circuit current density of 16.5 mA/cm², an open circuit voltage of 3141.8 mV, a fill factor of 84.3%, and an efficiency of 32.2%. Then, the IMM3J solar cell is irradiated by 2 MeV protons with different fluences from $2 \times 10^{11}$ cm$^{-2}$ to $2 \times 10^{12}$ cm$^{-2}$. Finally, the output electrical properties of IMM3J solar cells at the beginning of life and end of life are analyzed by current-voltage characterization. The degradation behaviors of each subcell before and after irradiation can also be described by the external quantum efficiency and short circuit current density.

Keywords: irradiation effects; proton irradiation; IMM3J solar cell; efficiency; short circuit current; open circuit voltage

1. Introduction

Solar cells are the primary source of spacecraft and provide the necessary electric energy for spacecraft operation. To meet the rapid development of the aerospace industry and the continuous increase in space missions, solar cells have been developed from the previous Si and GaAs single junction cells to the current high-efficiency multijunction solar cells. Lattice-matched InGaP/GaAs/Ge triple-junction solar cells were first used on satellites in 2001 and have been in use ever since due to their high conversion efficiency and superior radiation resistance [1–4]. However, Ge with a lower bandgap (0.7 eV) causes a current mismatch between the three subcells, which reduces the efficiency of the InGaP/GaAs/Ge triple-junction solar cells [4]. To overcome this problem, researchers proposed inserting InGaAsN with a band gap of 1 eV between GaAs and Ge to achieve lattice matching and current matching at the same time [5–7]. InGaP/InGaAs/InGaAsN/Ge multijunction solar cells have a theoretical efficiency of more than 50% [6]. However, efficiency (>50%) is difficult to achieve in actual fabrication since high-quality InGaAsN film is difficult to grow and the addition of a small amount of N in InGaAs will produce intrinsic defects in the solar cell [7].

An alternative method is to use InGaAs with a band gap of 1 eV to replace Ge in conventional lattice-matched InGaP/GaAs/Ge solar cells to eliminate current mismatch. However, there is 2% lattice mismatch between In$_{0.3}$GaAs and GaAs [8,9]. The threading dislocations generated by lattice mismatch can be reduced by using graded composition buffer layers [10]. Moreover, the inverted growth of the subcells minimizes the effect of dislocation propagation from the buffer layer [11–13]. At present, the inverted metamorphic
A triple-junction (IMM3J) GaInP/GaAs/InGaAs solar cell has a high conversion efficiency of 37.9% (AM1.5,1-sun) \[14\] and 32.1% (AM0, 1-sun) \[15\]. Furthermore, the weight and cost of IMM3J solar cells can be greatly reduced by removing GaAs substrates \[16\]. A flexible substrate can be bonded to obtain a flexible IMM3J solar cell after removing the temporary substrate, which can be mounted on any nonflat surface \[17,18\]. Therefore, IMM3J solar cells have great potential in space applications due to their high efficiency, light weight, low cost, and flexible properties.

The space radiation environment contains various charged particles, especially protons and electrons. These particles will degrade the performance of solar cells, which will affect the long-term safe and stable operation of the spacecraft. Therefore, to meet the requirements of space applications, we need to imitate the real space environment as much as possible to carry out electron and proton irradiation experiments with different energies and fluences on solar cells. The effects of 1 MeV electron irradiation on IMM3J solar cells have been studied by spectral response, photoluminescence and electrical properties \[15,19,20\]. The radiation resistance of IMM3J solar cells can also be investigated by analyzing the degradation of each subcell (InGaP, GaAs, and InGaAs) under electron and proton irradiation \[17\]. Recently, 10 MeV proton irradiation effects on IMM3J solar cells have been studied, and the results demonstrated that this solar cell has very good radiation resistance and current matching \[13\]. Therefore, the radiation effect of IMM3J solar cells has been investigated to a certain extent, but these studies mainly focus on the irradiation of 1 MeV electrons and high-energy protons. We know that the degradation of solar cells caused by proton irradiation is stronger than that of electrons, and middle energy proton irradiation is stronger than that of high energy protons \[21\]. Hence, it is necessary to study the irradiation effect of middle energy protons.

In this paper, we first fabricate the IMM3J GaInP/GaAs/InGaAs solar cell, which has the best conversion efficiency of 32.2%. Then, the IMM3J solar cell is irradiated by 2 MeV protons with different fluences from $2 \times 10^{11}$ cm$^{-2}$ to $2 \times 10^{12}$ cm$^{-2}$. The characterization of IMM3J solar cells and each subcell at the beginning of life (BOL) and end of life (EOL) are analyzed by current-voltage (I–V) properties and external quantum efficiency (EQE).

### 2. Materials and Methods

#### 2.1. The Fabrication of the IMM3J Solar Cell

All inverted metamorphic (IMM3J) GaInP/GaAs/InGaAs solar cells in this study are fabricated at the Shanghai Institute of Space Powers Sources, and their dimensions are $3 \times 4$ cm$^2$. The GaInP, GaAs, and InGaAs subcells have bandgaps of 1.9 eV, 1.42 eV, and 1.0 eV and thicknesses of 0.8 µm, 3.2 µm, and 3.3 µm, respectively. The epitaxial growth of the IMM3J solar cell structure is carried out by metalorganic chemical vapor deposition (MOCVD) using an AIX2600-G3 reactor with a 4-inch substrate, and the growth order is the opposite of that of conventional GaInP/GaAs/Ge solar cells. The n-GaAs substrates were used with a 15° offset from the (001) to (111) B plane, and the carrier concentrations were $(1\sim4) \times 10^{18}$ cm$^{-3}$. During the fabrication of solar cells, the hybrid sources arsine and phosphine, Trimethylgallium (TMGa) and trimethylindium (TMIn), SiH$_4$ and CCl$_4$ were used as group-V growth, group III precursors and doping, respectively \[13,22\]. The MOCVD growth condition for each subcell was optimized to yield a high-quality material with minimum defects and optimal electrical performance. Figure 1 shows the epitaxial growth process of the IMM3J GaInP/GaAs/InGaAs solar cell. All sub-cells are of PN structure, where the doping of P-type base and N-type emitter for the GaInP, GaAs, and In$_{0.3}$GaAs sub-cells is $2 \times 10^{17}$ cm$^{-3}$ and $2 \times 10^{18}$ cm$^{-3}$, respectively. First, the GaInP top cell is grown on GaAs temporary substrates, then the GaAs middle cell is grown, and finally, the In$_{0.3}$GaAs bottom cell is grown. Each subcell is connected by GaInP/AlGaAs wide bandgap tunnel junction with a thickness of 30 nm. To reduce lattice mismatch between In$_{0.3}$GaAs and GaAs subcells, a 2-µm-thick step-grade buffer layer AlInAs was deposited between them. Second, the temporary GaAs substrate was removed by an epitaxial lift-off process using hydrogen fluoride solutions, and then the solar cell structure was inverted.
and transferred onto a Si-handle. Finally, Al₂O₃/TiOₓ anti-reflection coating (ARC), Ag/Au front contact and grid structure are fabricated on the upper surface of the solar cell.

**Figure 1.** Schematic of the epitaxial growth process of the IMM3J GaInP/GaAs/InGaAs solar cell.

### 2.2. Proton Irradiation Experiment

The 2 MeV proton irradiation experiment was performed on a 2 × 1.7 MV tandem accelerator of Peking University. Figure 2 shows the details of the proton irradiation experiment. A set of six solar cells was exposed to a series of fluences from 2 × 10¹¹ cm⁻² to 2 × 10¹² cm⁻². In all cases, the irradiation flux was 2 × 10⁹ cm⁻² s⁻¹. By rotating the target plate, solar cells Nos. 1–6 are irradiated in sequence from small to large fluence. We put two solar cells for each fluence to reduce accidental errors. All solar cells were irradiated in a vacuum chamber at room temperature. There is no shielding on the surface of these solar cells. Fluxes and fluences were monitored by a Faraday cup mounted in the center of the target plane.

**Figure 2.** Photograph of the proton irradiation experiment. Six solar cells (No. 1–6) are used for the irradiation experiment. The proton fluences of solar cells No. 1–2, No. 3–4 and No. 5–6 are 2 × 10¹¹ cm⁻², 8 × 10¹¹ cm⁻² and 2 × 10¹² cm⁻², respectively.
2.3. Characterization of the IMM3J Solar Cell

The IMM3J GaInP/GaAs/InGaAs solar cells were characterized before and after proton irradiation by I–V measurements and EQE measurements. The output parameters of IMM3J solar cells, including the short circuit current density ($J_{sc}$), the open circuit voltage ($V_{oc}$), the fill factor (FF) and the efficiency ($\eta$), were measured by a light I–V measurement system with an X25A solar simulator under the AM0 spectrum at $T = 25$ °C. Before the test, three individual single junction reference cells were used to adjust the solar simulator to an appropriate solar spectrum, i.e., 136.7 mW/cm$^2$. EQE was measured with an Enli QE-R solar cell spectral response measurement system using a Xe lamp as a white light source, which passes through a Czerny-Turner monochromator and an external filter wheel. The light is chopped, and a monitor cell is used to compensate for any intensity fluctuations coming from the Xe lamp. $J_{sc}$ of each sub-cell can be calculated by [23]:

$$J_{sc} = q \int_{0}^{\infty} F(\lambda) EQE(\lambda) d\lambda$$  

where, $F(\lambda)$ is the number of photons per cm$^2$ per sec per unit bandwidth incident on solar cell at wavelength $\lambda$, $q$ is the electron charge.

3. Results

3.1. IMM3J Solar Cell Performance at the Beginning of Life

Figure 3 shows $J_{sc}$, $V_{oc}$, FF and $\eta$ of eight samples (S1–S8) at the beginning of life (BOL). S1–S6 are used to perform proton irradiation experiments, S7 and S8 are used as backup solar cells. The maximum (average) $J_{sc}$, $V_{oc}$, FF and $\eta$ are 16.8 mA/cm$^2$ (16.5 mA/cm$^2$), 3141.8 mV (3097.5 mV), 84.3% (82.2%), and 32.2% (31.1%), respectively. The root mean square of $J_{sc}$, $V_{oc}$, FF and $\eta$ is 0.34 mA/cm$^2$, 35.95 mV, 1.9% and 0.8%, respectively, which indicates that all samples have similar output electric parameters. These output parameters of IMM3J solar cells at the BOL are comparable to the results recently reported by other research groups, and the efficiency is slightly higher (32.2% vs. 31.3%) [13].

![Figure 3](image_url). The (A) $J_{sc}$, (B) $V_{oc}$, (C) FF and (D) $\eta$ of the eight samples (S1–S8) at the beginning of life. The average and maximum $J_{sc}$, $V_{oc}$, FF and $\eta$ are marked in each figure.

3.2. IMM3J Solar Cell Performance at the End of Life

For space applications, accurate prediction of the end-of-life (EOL) performance of solar cells is especially important. Figure 4 shows the degradation of normalized $J_{sc}$, $V_{oc}$, FF and $\eta$ for the IMM3J GaInP/GaAs/InGaAs solar cell at the EOL with different fluences. The $J_{sc}$, $V_{oc}$, FF and $\eta$ of IMM3J solar cells are degraded more by the increase in proton irradiation fluence. With fluences up to $2 \times 10^{12}$ cm$^{-2}$, the $J_{sc}$, $V_{oc}$, FF and $\eta$ of IMM3J
solar cells decrease to 93.8%, 83.1%, 93.3% and 73.4% of their original values for 2 MeV proton irradiation, respectively. Compared with other parameters, the degradation rate of $\eta$ is the largest, mainly because $\eta$ is proportional to the product of $J_{SC}$, $V_{OC}$, and FF. The degradation of $J_{SC}$ is minimal, mainly due to changes in the current-limiting junction of the IMM3J solar cell before and after irradiation. We will discuss the conversion process of the current-limiting junction in detail in a later section.

![Figure 4](image)

**Figure 4.** Degradation of (A) $J_{SC}$, (B) $V_{OC}$, (C) FF, and (D) $\eta$ of the IMM3J solar cell as a function of fluence for 2 MeV proton irradiation.

Figure 5 shows the degradation of the external quantum efficiency (EQE) spectra in each subcell of the IMM3J solar cell before and after 2 MeV proton irradiation with different fluences. The results show that EQE degradation mainly occurs in the GaAs middle and InGaAs bottom subcells, while the EQE of the GaInP cell shows almost no degradation. Consistent with the electrical performance degradation law of IMM3J solar cells in Figure 3, the degradation of EQE increases with increasing proton fluence.

![Figure 5](image)

**Figure 5.** EQE measurements were performed on an IMM3J solar cell before and after proton irradiation.

Figure 6 shows the $J_{SC}$ calculated by Equation (1) for each subcell in IMM3J solar cells in the AM0 spectrum. For multijunction solar cells composed of tandem subcells, the current is determined by the subcell that produces the lowest current in the cell [24]. The subcell with the smallest current is called the current-limiting junction of the multijunction solar cell. As shown in Figure 6, the GaInP subcell is the current-limiting junction before
proton irradiation due to its minimum short circuit current. At fluences of $2 \times 10^{11} \text{ cm}^{-2}$ and $8 \times 10^{11} \text{ cm}^{-2}$, the current-limiting junction is changed to the GaAs subcell. When the proton fluence is increased to $2 \times 10^{12} \text{ cm}^{-2}$, the current-limiting junction changes again to the InGaAs subcell. As a result, the degradation of IMM3J solar cells is primarily controlled by the response of GaAs middle cells at small fluences and InGaAs bottom cells at large fluences.

Figure 6. Comparison of $J_{sc}$ of GaInP, GaAs and InGaAs subcells before and after proton irradiation for IMM triple junction solar cells.

4. Discussion and Conclusions

We fabricated an IMM3J GaInP/GaAs/InGaAs solar cell, and the efficiency of this solar cell is higher than that of a conventional InGaP/GaAs/Ge 3J solar cell (32% vs. 30% [25,26] at AM0 and 1 sun). Moreover, this efficiency is comparable to the latest results reported by other research groups [13,19]. Then, the IMM3J solar cells are irradiated homogeneously by 2 MeV protons with different fluences. The electrical properties of the IMM3J solar cell degrade as the proton fluence increases. In particular, the efficiency degradation is the largest. When the fluence is $2 \times 10^{12} \text{ cm}^{-2}$, the efficiency degrades to 73.4% of the initial value. The EQE measurement results indicate that GaInP top cells have better radiation resistance, while GaAs middle cells and InGaAs bottom cells have poor radiation resistance.

The space radiation environment mainly consists of protons and electrons over a broad energy range. However, the current research on the irradiation effect of IMM3J solar cells has only been carried out with a limited number of energies, such as 1 MeV electrons [14,19], 10 MeV protons [13], and the 2 MeV protons proposed in this paper. Obviously, these studies are not sufficient for space applications, and more research on the electron and proton irradiation effects of IMM3J solar cells at other energies must be performed in the future. Deep-level transient spectroscopy (DLTS) is an effective method to detect and characterize radiation-induced defects. Defects induced by electron and proton irradiation in GaInP and GaAs have been extensively studied by DLTS [27–29]. Recently, Zhang et al. detected a shallow electron trap (Ec-0.03 eV) in the In$_{0.3}$Ga$_{0.7}$As after 1MeV irradiation by DLTS method [20]. However, there are no related reports on the defects generated by proton irradiation in In$_{0.3}$Ga$_{0.7}$As. Therefore, it is particularly important to carry out studies on the defects generated by proton irradiation in In$_{0.3}$Ga$_{0.7}$As in future work to clarify the radiation damage mechanism of IMM3J solar cells.

By analyzing the current density $J_{sc}$ of each subcell, it can be concluded that the current-limiting junction changes from the GaInP top cell to the GaAs middle cell and then to the InGaAs bottom cells as the proton fluence increases. The radiation resistance of
multijunction solar cells is dominated by the subcells with the worst radiation resistance. Therefore, it is especially necessary to study the irradiation effect of protons with two energies when the range ends are in the middle subcell and the bottom subcell because protons of these two energies will cause the greatest degradation of solar cell performance at this time. These results will provide support for the structural optimization and radiation resistance improvement of solar cells.

**Author Contributions:** Conceptualization, J.X. and M.L.; methodology, J.X. and K.Y.; validation, Q.X., X.Z. and X.W.; formal analysis, J.X.; resources, K.Y., Q.X., X.Z. and X.W.; data curation, J.X. and K.Y.; writing—original draft preparation, J.X.; writing—review and editing, M.L.; 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, Grant number 11905181.

**Data Availability Statement:** Not applicable.

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

**References**

1. Strobl, G.; Dietrich, R.; Hilgarth, J.; Kostler, W.; Kern, R.; Nell, M.; Rothenbacher, S.; Bett, A.; Dimroth, F.; Meusel, M. Advanced GaInP/Ga (In) As/Ge triple junction space solar cells. In Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion, Osaka, Japan, 11–18 May 2003; pp. 658–661.

2. Ochoa, M.; Yaccuzzi, E.; Espinet-González, P.; Barrera, M.; Barrigón, E.; Ibarra, M.L.; Contreras, Y.; García, J.; López, E.; Alurralde, M. 10 MeV proton irradiation effects on GaInP/GaAs/Ge concentrator solar cells and their component subcells. Sol. Energy Mater. Sol. Cells 2017, 159, 576–582. [CrossRef]

3. Xu, J.; Guo, M.; Lu, M.; He, H.; Yang, G.; Xu, J. Effect of Alpha-Particle Irradiation on InGaP/GaAs/Ge Triple-Junction Solar Cells. Materials 2018, 11, 944. [CrossRef] [PubMed]

4. Yamaguchi, M. III–V compound multi-junction solar cells: Present and future. Sol. Energy Mater. Sol. Cells 2003, 75, 261–269. [CrossRef]

5. Guter, W.; Schöne, J.; Steiner, S.P.; Steiner, M.; Siefer, G.; Wekkeli, A.; Welser, E.; Bett, A.W.; Dimroth, F. Current-matched triple-junction solar cell reaching 41.1% conversion efficiency under concentrated sunlight. Appl. Phys. Lett. 2009, 94, 223504. [CrossRef]

6. Uesugi, K.; Kuboya, S.; Sanorpim, S.; Onabe, K. Characterization of InGaAsN solar-cell structures on Ge substrates. Phys. Status Solidi 2014, 11, 561–564. [CrossRef]

7. Sukeerthi, M.; Kotamraju, S.; Meetei, R.; Rao, P.N. Degradation analysis of 3J InGaP/InGaAs/InGaAsN solar cell due to irradiation induced defects with a comparative study on bottom homo and hetero InGaAsN subcell. Sol. Energy 2018, 174, 728–734. [CrossRef]

8. 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. Physica E 2021, 127, 114566. [CrossRef]

9. Geisz, J.; Kurtz, S.; Wanlass, M.; Ward, J.; Duda, A.; Friedman, D.; Olson, J.; McMahon, W.; Moriarty, T.; Kiehl, J. High-efficiency Ga In P/ Ga As/ In Ga As triple-junction solar cells grown inverted with a metamorphic bottom junction. Appl. Phys. Lett. 2007, 91, 023502. [CrossRef]

10. France, R.M.; García, I.; McMahon, W.E.; Norman, A.G.; Simon, J.; Geisz, J.F.; Friedman, D.J.; Romero, M.J. Lattice-mismatched 0.7-eV GaNAs solar cells grown on GaAs using GaN compositionally graded buffers. IEEE J. Photovolt. 2013, 4, 190–195. [CrossRef]

11. Adams, J.G.; Elarde, V.C.; Hillier, G.; Stender, C.; Tuminello, F.; Wibowo, A.; Youtsey, C.; Bittner, Z.; Hubbard, S.M.; Clark, E.B. Improved radiation resistance of epitaxial lift-off inverted metamorphic solar cells. In Proceedings of the 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC), Tampa, FL, USA, 16–21 June 2013; pp. 3229–3232.

12. Wang, B.; Fang, L.; Aierken, A.; Yang, W.; Chen, K. Effects of Zn diffusion in tunnel junction and its solution for high efficiency large area flexible GaInP/GaAs/InGaAs tandem solar cell. Sol. Energy Mater. Sol. Cells 2021, 230, 112577. [CrossRef]

13. Li, J.; Aierken, A.; Zhan, Q.; Wang, X.; Mo, J.; Yang, X.; Chen, Q. 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, 234, 11022. [CrossRef]

14. Takamoto, T.; Washio, H.; Juso, H. Application of InGaP/GaAs/InGaAs triple junction solar cells to space use and concentrator photovoltaic. In Proceedings of the 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC), Denver, CO, USA, 8–13 June 2014; pp. 0001–0005.
15. 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; pp. 2790–2792.

16. Li, J.; Aierken, A.; Liu, Y.; Zhuang, Y.; Yang, X.; Mo, J.; Fan, R.; Chen, Q.; Zhang, S.; Huang, Y. A brief review of high efficiency iii–v solar cells for space application. Front. Phys. 2021, 8, 631925. [CrossRef]

17. 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. 2017, 25, 161–174. [CrossRef]

18. Schön, J.; Bissels, G.M.; Mulder, P.; van Leest, R.H.; Gruginskie, N.; Vlieg, E.; Chojniak, D.; Lackner, D. Improvements in ultra-light and flexible epitaxial lift-off GaInP/GaAs/GaInAs solar cells for space applications. Prog. Photovolt. 2022. [CrossRef]

19. 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]

20. Zhang, Y.; Qi, C.; Wang, T.; Ma, G.; Tsai, H.-S.; Liu, C.; Zhou, J.; Wei, Y.; Li, H.; Xiao, L. Electron Irradiation Effects and Defects Analysis of the Inverted Metamorphic Four-Junction Solar Cells. IEEE J. Photovolt. 2020, 10, 1712–1720. [CrossRef]

21. Rong, W.; Yunhong, L.; Xufang, S. Effects of 0.28–2.80MeV proton irradiation on GaInP/GaAs/Ge triple-junction solar cells for space use. Nucl. Instrum. Methods Phys. Res. Sect. B 2008, 266, 745–749. [CrossRef]

22. 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, 18.

23. Hovel, H.J. Semiconductors and semimetals. Sol. Cells 1975, 11, 7284142.

24. Jianmin, H.; Yiyong, W.; Jingdong, X.; Dezhuang, Y.; Zhongwei, Z. Degradation behaviors of electrical properties of GaInP/GaAs/Ge solar cells under < 200 keV proton irradiation. Sol. Energy Mater. Sol. Cells 2008, 92, 1652–1656. [CrossRef]

25. Wang, J.; Yan, G.; Wu, R.; Wang, R. Electron-induced degradation of JV characteristics of GaInP top cell and GaAs middle cell by electroluminescence measurements. J. Appl. Phys. 2018, 123, 205704. [CrossRef]

26. Cariou, R.; Medjoubi, K.; Vauche, L.; Weinberg-Vidal, E.; Park, S.; Lefèvre, J.; Baudrit, M.; Voarino, P.; Mur, P.; Boizot, B. Evaluation of III–V/Si multi-junction solar cells potential for space. In Proceedings of the 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), Waikoloa, HI, USA, 10–15 June 2018; pp. 3335–3338.

27. Zaidi, M.; Zazouii, M.; Bourgoin, J. Defects in electron irradiated GaInP. J. Appl. Phys. 1993, 73, 7229–7231. [CrossRef]

28. Pons, D.; Bourgoin, J. Irradiation-induced defects in GaAs. J. Phys. C 1985, 18, 3839. [CrossRef]

29. Bourgoin, J.; Zazouii, M. Irradiation-induced degradation in solar cell: Characterization of recombination centres. Semicond. Sci. Technol. 2002, 17, 453. [CrossRef]