Changes in output parameters of 1 MeV electron irradiated upright metamorphic GaInP/GaInAs/Ge triple junction solar cell

M. Heini, A. Aierken, Z. H. Li, X. F. Zhao, M. Sailai, X. B. Shen, Y. Xu, H. T. Liu, Y. D. Li, Q. Guo, and C. M. Liu

ARTICLES YOU MAY BE INTERESTED IN

Investigation on high-efficiency Ga_{0.51}In_{0.49}P/In_{0.01}Ga_{0.99}As/Ge triple-junction solar cells for space applications
AIP Advances 7, 125217 (2017); https://doi.org/10.1063/1.5006865

Degradation analysis of 1 MeV electron and 3 MeV proton irradiated InGaAs single junction solar cell
AIP Advances 9, 075205 (2019); https://doi.org/10.1063/1.5094472

Modeling of degradation behavior of InGaP/GaAs/Ge triple-junction space solar cell exposed to charged particles
Journal of Applied Physics 105, 044504 (2009); https://doi.org/10.1063/1.3079522
Changes in output parameters of 1 MeV electron irradiated upright metamorphic GaInP/GaInAs/Ge triple junction solar cell

M. Heini, A. Aierken, Z. H. Li, X. F. Zhao, M. Sailai, X. B. Shen, Y. Xu, H. T. Liu, Y. D. Li, Q. Guo, and C. M. Liu

1 Key Laboratory of Functional Materials and Device for Special Environments, Xinjiang Technical Institute of Phys. & Chem., Chinese Academy of Sciences, No. 40-1 South Beijing Road, Urumqi 830011, P. R. China
2 University of Chinese Academy of Sciences, No. 19-A Yuquan Road, Shijingshan District, Beijing 100049, P. R. China
3 National Key Laboratory of Materials Behavior and Evaluation Technology in Space Environment, Harbin Institute of Technology, No. 92 West Nangang Road, Harbin 150001, P. R. China

(Received 20 July 2018; accepted 9 October 2018; published online 17 October 2018)

The changes in output parameters of 1 MeV electron irradiated MOCVD grown upright metamorphic (UMM) GaInP/GaInAs/Ge triple junction solar cells have been studied. Non-ionizing energy loss (NIEL) approach and MULASSIS simulation were applied for analyzing the effects of irradiation induced displacement damage on cell performance. The influence of base thickness on radiation resistance has been studied by changing the base thickness of top GaInP and middle GaInAs subcell, respectively. The experimental results show that the electrical parameters, \( V_{oc} \), \( I_{sc} \), and \( P_{max} \) of UMM cell degrade with the increase of electron fluence. The change of spectra response indicates middle GaInAs subcell degrades more severe than top GaInP subcells, and the base thickness of two subcells has different effects on spectra response of UMM cell.

I. INTRODUCTION

The fundamental objectives of developing space solar cells are to increase the conversion efficiency, improve the radiation tolerance, reduce the mass and cost of solar cells and solar arrays. Space solar cells have undergone significant development from Si to III-V based materials, from single junction to multijunction configurations, from lattice matched to lattice-mismatched structures for higher conversion efficiencies. III-V multijunction solar cells deliver the highest performance among the current available solar cell technologies, and lattice-matched (LM) GaInP/Ga(In)As/Ge triple junction solar cells are the most matured technology for space photovoltaic applications. However, the conversion efficiency of LM cell is limited by the non-optimal bandgap combinations to the given AM0 solar spectrum. Bandgap matching within the subcells can be obtained by using different materials, and several approaches such as wafer bonding, mechanical stacking, inverted metamorphic (IMM) and upright metamorphic (UMM) have been proposed to solve the lattice mismatch problems between the subcells. These methods, except the UMM, on the other hand, require additional fabrication processes and increase the cost. 40.7 % conversion efficiency of a metamorphic three-junction GaInP/GaInAs/Ge cell under high concentration terrestrial application has been demonstrated. Furthermore, latest GaInP/Ga(In)As/Ge UMM solar cell product of AZUR has been reported with efficiency of 31.0 % under AM0 spectrum, while the highest efficiency of

\[ \text{Corresponding author: erkin@ms.xjb.ac.cn} \]
traditional LM cell is about 30%. Therefore, UMM solar cell is a promising alternative for space application.

However, the harsh space environment, such as vacuum, strong ultraviolet, electron and proton radiation, temperature cycling, brings additional challenges for space solar cell designing. Electron and proton irradiation is the main reason of solar cell degradation in space. The degradation mechanisms of conventional triple junction LM cells upon high energy particles have been studied extensively in past decades.\textsuperscript{12,13,14} Although there are some reports of radiation effects of IMM solar cells,\textsuperscript{15,16} unfortunately, reports of space radiation testing of UMM solar cells are scarce, and a number of design challenges still remain to be addressed.

In this paper, overall performance of 1 MeV electron irradiated metal-organic chemical vapor deposition (MOCVD) grown GaInP/GaInAs/Ge UMM triple junction solar cells have been investigated. The degradation of both electrical and spectral output parameters of UMM cell have been discussed.

\section*{II. EXPERIMENTAL}

Fig. 1 shows the major structure of UMM GaInP/GaInAs/Ge triple junction solar cells used in this work. All samples were grown by an AIXTRON MOCVD reactor on p-type Ge substrate, and solar cells were fabricated with standard lithography processes. The details of epitaxial growth and device fabrication has been reported in our previous work.\textsuperscript{17} Cell structure contains a 3-µm-thick distributed Bragg reflector (DBR) between middle and bottom cell, which is consists of 15 pairs AlGaInAs/GaInAs layers. A compositionally step-graded monolithic GaInAs, with a strain gradient of 0.5 %/µm and total thickness of 2 µm, was used as a buffer layer between DBR and Ge bottom cell. All the devices studied in this work are 4 cm × 8 cm in size and with initial conversion efficiency of 30.5 %, under standard AM0 solar spectrum.

The electron irradiation was conducted by an ELV-8 vertical electron accelerator at room temperature. Samples were placed at a uniform electron flux $5 \times 10^{10}$ e/cm$^2$·s area during the irradiation without bias. Electrical and optical parameters of solar cells were measured prior to irradiation and after irradiated by 1 MeV electron with total fluence of $5 \times 10^{14}$, $1 \times 10^{15}$ and $1.5 \times 10^{15}$ e/cm$^2$, respectively. The applied electron fluence has been selected based on the space solar cell evaluation irradiation test standard.\textsuperscript{18}

Electrical output parameters of solar cell, short circuit current ($I_{sc}$), open circuit voltage ($V_{oc}$), and maximum output power ($P_{max}$) were measured under the standard test conditions.
(AM0, 136.7 mW/cm\(^2\) at 25°C) by Spectrosun X25A solar simulator. The external quantum efficiency (EQE) was measured by a home-build setup. Besides, the structural properties of UMM solar cell have been studied by high-resolution X-ray diffraction (XRD), and, threading dislocation density (TDD) was confirmed from cathodoluminescence (CL) measurement. Result of these measurement, which indicates high quality of as-grown solar cell epilayers, have been reported in our previous work.\(^{17}\)

III. RESULT AND DISCUSSION

A. Electron irradiation simulation

When charged particles go through a solar cell structure, part of its energy is transferred to crystal lattice and result in ionization or atomic displacement of the solar cell. The density of such defects increases rapidly with the increase of the irradiation fluence. These displacement damages introduce point defects in solar cell crystal structure, such as vacancies, interstitials, etc., which is the increase the decreasing the minority carrier diffusion length by increase recombination centres, and, consequently, cause the degradation of solar cell output parameters.\(^{19}\)

The degradation performance of solar cells can be predicted by displacement damage dose \((D_d)\) approach.\(^{20}\) The numerical value of \(D_d\) in a given material can be evaluated by combining irradiation fluence and nonionizing energy loss (NIEL) of target material. Calculated NIEL values for GaInP\(_2\), GaAs and Ge materials upon electron and proton irradiation with different energy have been reported.\(^{21}\) Since the NIEL values of these three materials are very close to each other for 1 MeV electron irradiation, we selected the NIEL value of GaAs and corresponding \(D_d\) of our samples by 1 MeV electron irradiation is calculated by following equation,\(^{22}\)

\[
D_d = \Phi_e(E_e) \times NIEL(E_e) \quad (1)
\]

where \(E_e\) is electron energy, \(\Phi_e\) is the electron fluence. The applied electron fluences for irradiation in this study and its corresponding \(D_d\) values are listed in Table I.

The distribution of \(D_d\) in each layer of UMM cell has also been simulated by MULASSIS software with \(1.5 \times 10^{15} \text{ e/cm}^2\) electron fluence, shown in Fig. 2(a). The Ge cell thickness were set as 5 \(\mu\)m, and other thin layers in cell structure have been omitted. The result indicates that the simulated \(D_d\) for all layers are in the range of \(4.8 - 5.6 \times 10^{10} \text{ MeV/g}\) and gradually increase with the increase of penetration depth of the electron. Fig. 2(b) shows the simulation result of \(D_d\) corresponding to \(5.0 \times 10^{14}\), \(1.0 \times 10^{15}\), and \(1.5 \times 10^{15} \text{ e/cm}^2\) electron fluence, respectively, up to 35 \(\mu\)m deep Ge substrate. The result shows the MULASSIS software simulation results of \(D_d\) fitted very well with the values obtained from NIEL calculation results listed in Table I.

During the irradiation, the energy transferred from the colliding electron to the target atoms and create defects via nuclear elastic interaction. If the initial energy of electron is much higher than the displacement energy threshold of target atom, then more energy will be transferred to the recoil atom, which will collide with other target atoms and create additional recoil atoms, and, consequently, generate more defects.\(^{23}\) Therefore, the irradiation induced displacement damage by high energy particles increases with the distance away from surface.

B. Degradation of cell performance by irradiation

Fig. 3 shows the degradation of \(I_{sc}\), \(V_{oc}\) and \(P_{max}\) of UMM cells after 1 MeV electron irradiation. All parameters are decreased with the increase of electron fluence, and the trends of degradation are

| electron fluence (e/cm\(^2\)) | \(D_d\) (MeV/g) |
|-----------------------------|---------------|
| \(5.0 \times 10^{14}\)     | \(1.91 \times 10^{10}\) |
| \(1.0 \times 10^{15}\)     | \(3.82 \times 10^{10}\) |
| \(1.5 \times 10^{15}\)     | \(5.73 \times 10^{10}\) |
similar for all three parameters. When the electron fluence reached $1.5 \times 10^{15}$ e/cm$^2$, the value of $P_{max}$ decreased 23.6%, and degradation of $V_{oc}$ and $I_{sc}$ are 11.8% and 9.5%, respectively. The degradation of $V_{oc}$ is bigger than $I_{sc}$, and, $P_{max}$ degraded the most.

The irradiation induced displacement damages in solar cell lattice act as recombination center, generation center, compensation center, and temporary trapping center, etc.

by creating additional energy level in energy bandgap of semiconductor materials. When the fluence of irradiation particles increased, the density of these defects increases rapidly and degrade the output parameters of solar cell severely. The degradation of $I_{sc}$ is mainly caused by the displacement damages in the active layers, base and emitter region, of solar cell. Defects in this region act as non-radiative recombination centers and separate the photo-generated electron-hole pairs when they arrive near to the p-n junction, and, consequently, reduce the minority carrier lifetime and diffusion length which result in the degradation of the $I_{sc}$.

Fig. 4 show the degradation of EQE value of each subcell in UMM triple junction solar cell after 1 MeV electron irradiation. It can be seen from Fig. 4 that the EQE values of top and middle subcells decreased with the increase of electron fluence. However, in bottom Ge cells, the EQE value fluctuated with the increase of electron fluence in irregular order. This abnormal spectral response of Ge bottom cell was also observed by some other groups as artifact EQE response, and the main reasons for this phenomenon are the combined effects of shunt and luminescence coupling.

Typically, Ge bottom subcell in GaInP/GaInAs/Ge triple junction solar cell produces bigger $I_{sc}$ compared to top and middle subcells before and after irradiation, but the $I_{sc}$ of multijunction solar cell is determined by the smallest $I_{sc}$ among all of subcells. Therefore, the degradation of Ge bottom cell by irradiation will not affect the overall performance and can be ignored in cell performance evaluation. It also can be observed from Fig. 4 that degradation of EQE spectra of
top and middle subcells happened in long-wavelength regions, and, the degradation of GaInAs middle subcell is larger compared to that of GaInP top subcell. This result can be seen more clearly in Fig. 5.

The result of EQE spectral response degradation in each subcell is consistent with irradiation induced displacement damage distribution analysis result shown in Fig. 2(a). The value of $D_D$ in each subcell is bigger in the base layer compared to emitter layer. Therefore, the probability of collection of photo-generated carriers near to the bottom of base layer is low due to the reduction of carrier diffusion length. On contrary, the carriers generated near the depletion region, which is corresponding to short-wavelength region, can be collected more effectively. Top Ga$_{0.43}$In$_{0.57}$P subcell has relatively smaller degradation compared to middle Ga$_{0.92}$In$_{0.08}$As subcell due to the comparatively bigger In-P fraction. The comparison results of InGaP, InGaAsP, and InGaAs solar cells showed that the radiation resistance of these materials can be significantly improved by increasing In and P fractions.$^{28}$ The superior radiation resistance of InP based solar cell is originated from the room-temperature annealing and minority carrier injection-enhanced annealing phenomena of major radiation-induced defects in InP.$^{29}$

C. Effects of top and middle subcell active layer thickness

In order to investigate the effects of subcell active layer thickness on the initial conversion efficiency and radiation resistance of UMM cell, we prepared two groups of samples which are completely identical to previously studied samples except the thickness of the active layer of top GaInP subcell and GaInAs middle cell. Our reference sample, sample ID F00, has subcell active
layer thickness of 500 nm (top)/1.5 µm (middle) and current density of 19.13 mA/cm² (top)/18.65 mA/cm² (middle), respectively. In one group, the thickness of GaInP subcell active layer is decreased from 500 nm to 450 and 400 nm respectively, and in another group, the thickness of GaInAs subcell active layer is increased from 1.5 µm to 1.7 and 1.8 µm, respectively, as shown in Table II. Since the diffusion length of photo-generated carriers are larger than any of these chosen film thickness, the overall extraction of photo carriers will not be affected but only the degradation properties of the cell. All samples went through the same irradiation described as above with electron fluence of $1.5 \times 10^{15}$ e/cm², and electrical and spectral parameters have been measured before and after irradiation. The remaining factors of $I_{sc}$, $V_{oc}$, and $P_{max}$ for each cell have been listed in Table II.

Fig. 6(a) shows the degradation of spectra response of UMM cell with two different GaInP thicknesses before and after irradiation. The initial $I_{sc}$ of top GaInP subcell increases from 18.55 mA/cm² to 18.98 mA/cm² and the initial $I_{sc}$ of middle GaInAs subcell decreases from 19.39 mA/cm² to 18.70 mA/cm² with the thickness increases from 400 nm to 450 nm before electron irradiation, respectively. The degradation of top cell and middle cell $I_{sc}$ after irradiation are shown in the inset of Fig. 6(a) as a remaining factor normalized to their initial values, while the remaining factor of $I_{sc}$, $V_{oc}$, and $P_{max}$ for UMM cell are also plotted in Fig. 6(b) for comparison. The result indicates that thickness of top GaInP cells has less influence on the degradation of spectra response of UMM cells, and the degradation of subcell $I_{sc}$ is equal to 2% and 10% for GaInP top subcell and GaInAs middle subcells, respectively. Therefore, the degradation of $I_{sc}$ of UMM cells should be 10% considering the middle subcell current limiting property after electron irradiation. This is consistent well with degradation of $I_{sc}$ of UMM, the remaining factor of around 0.91, shown in Fig. 6(b). The remaining factor of $V_{oc}$, decreased from 0.900 to 0.894 when the top InGaP subcell thickness increased from 400 nm to 500 nm, while the corresponding degradation of $P_{max}$ is from 0.826 to 0.809. These results indicate that a thinner base layer is very important to reduce $P_{max}$ degradation of top subcell, even GaInP material has good radiation tolerance property.

The result of another group cells, with different GaInAs middle subcell thickness, are plotted in the same way in Fig. 6(c) and 6(d). The $I_{sc}$ of top GaInP subcells is unchanged and the $I_{sc}$ of middle GaInAs subcells increases a little from 19.84 mA/cm² to 20.02 mA/cm² with the increase of GaInAs middle subcell thickness from 1.5 µm to 1.7 µm. It indicates that middle GaInAs thickness has less influence on the spectra response of UMM cells, and this can be attributed to the DBR shown in Fig. 1. The variation of GaInAs subcell thickness has no influence on the degradation of spectra response of top GaInP subcell, and the degradation of $I_{sc}$ is equal to 2%. However, it has significant influence on the degradation of spectra response and $I_{sc}$ of middle GaInAs subcell, and degradation scale of $I_{sc}$ is consistent with the value shown in Fig. 6(d). The remaining factors of all $I_{sc}$, $V_{oc}$, $P_{max}$ decrease as the GaInAs thickness increases from 1.5 µm to 1.8 µm. The degradation of $I_{sc}$ and $V_{oc}$ indicate that GaInAs has relatively weak radiation resistance compared to GaInP, and it is consistent well with the report of Imazuri et al. The optimized cell with an initial conversion efficiency of 30.5% with subcell active layer thickness of 470 nm (top)/1.5 µm (middle) is fabricated based on above study.

| Sample ID | $I_{sc}$ | $V_{oc}$ | $P_{max}$ |
|-----------|----------|----------|-----------|
| Non-irra  | 1        | 1        | 1         |
| F00 (top 500) | 0.931      | 0.894    | 0.809     |
| F02 (top 450) | 0.911      | 0.900    | 0.813     |
| F03 (top 400) | 0.919      | 0.899    | 0.826     |
| F00 (mid 1.5) | 0.931      | 0.894    | 0.809     |
| F04 (mid 1.7) | 0.896      | 0.895    | 0.801     |
| F06 (mid 1.8) | 0.891      | 0.885    | 0.784     |

TABLE II. Remaining factor of $I_{sc}$, $V_{oc}$, and $P_{max}$ of UMM cells with different top and middle subcell thickness irradiated by 1 MeV electron with fluence of $1.5 \times 10^{15}$ e/cm².
**FIG. 6.** EQE spectra of top and middle subcells of UMM solar cell (a) with different top cell thickness, (c) with different middle cell thickness, irradiated by 1 MeV electron with fluence of $1.5 \times 10^{15}$ e/cm$^2$; remaining factor of $I_{sc}$, $V_{oc}$, and $P_{max}$ of UMM cells (b) with different top cell thickness, (d) with different middle cell thickness.

### IV. CONCLUSION

In this paper, the electrical and spectral response of 1 MeV electron beam irradiated MOCVD grown GaInP/GaInAs/Ge UMM triple junction solar cells have been studied. Non-ionizing energy loss (NIEL) approach and MULASSIS simulation were applied for analyzing the effects of irradiation induced displacement damage on output parameters of solar cell. The result shows that both electrical and spectral parameters of UMM cell were degraded along with the increase of electron fluence, $V_{oc}$, $I_{sc}$, and $P_{max}$ decreased by 11.8%, 9.5% and 23.6%, respectively, when the electron fluence reached $1.5 \times 10^{15}$ e/cm$^2$. The main reason for these degradations is the displacement damage in solar cell active layers induced by the irradiation. EQE spectral response of top GaInP and middle GaInAs subcells mainly happened in long wavelength due to the bigger displacement damage density in base layer of subcell compared to that of in emitter layer. Radiation resistance of subcells have been studied by different base layer thickness of top and middle subcells, respectively. It indicated that a thinner base layer results in better resistance of GaInP top subcell, and, increase of GaInAs middle subcell base layer thickness decrease the radiation resistance of middle subcell significantly.

### ACKNOWLEDGMENTS

The authors would like to thank Tianjin Institute of Power Source for the help of sample preparation and measurements. This work was supported by the National Natural Science Foundation of China [Grant number: 61534008, 11675259], Director Foundation of Xinjiang Technical Institute of Phys. & Chem. CAS, [Grant number: Y55B171101], 1000-Talent Project of Xinjiang Technical Institute of Phys. & Chem., Chinese Academy of Sciences [Grant number: Y52H121101] and Western Light Foundation, Chinese Academy of Sciences [Grant number: 2017-XBQNXZ-B-004]. Personal thanks are due to Liu Chaoming for assistance with the experiments and to Yang Jianqun for valuable discussion.

1. S. Mokkapati and C. Jagadish, “III-V compound SC for optoelectronic devices,” Materials Today 12, 22–32 (2009).
2. M. Yamaguchi, T. Takamoto, K. Araki et al., “Multi-junction III–V solar cells: Current status and future potential,” Solar Energy 79, 78–85 (2005).
3. L. Sun, M. Zhang, X. Fang et al., “Recent progress of high-efficiency III-V multijunction solar cells,” 39th PVSC, June 16-21, 2013, Tampa, Florida, USA, pp. 2832–2834.
4. F. Dimroth, M. Grave, P. Beutel et al., “Wafer bonded four-junction GaInP/GaAs//GaInAsP/GaInAs concentrator solar cells with 44.7% efficiency,” *Prog. Photovolt: Res. Appl.* 22, 274–282 (2014).

5. S. Essig, M. A. Steiner, C. Allebé et al., “Realization of GaInP/Si dual-junction solar cells with 29.8% 1-sun efficiency,” *IEEE Journal of Photovoltaics* 6, 1012–1019 (2016).

6. H. Yoon, M. Haddad, S. Mesropian et al., “Progress of inverted metamorphic III–V solar cell development at spectrolab,” *IEEE 33rd Photovoltaic Specialists Conference, May 11-16, 2008, San Diego, CA, USA*, pp. 1–6.

7. J. Boisvert, D. Law, R. King et al., “High efficiency inverted metamorphic (IMM) solar cells,” *IEEE 39th Photovoltaic Specialists Conference (PVSC), June 16-21, 2013, Tampa, Florida, USA*, pp. 2790–2792.

8. W. Guter, J. Schöne, S. P. Philips et al., “Current-matched triple-junction solar cell reaching 41.1% conversion efficiency under concentrated sunlight,” *Appl. Phys. Lett.* 94, 223504 (2009).

9. X. Q. Liu, C. M. Fetzer, E. Rehder et al., “Organometallic vapor phase epitaxy growth of upright metamorphic multijunction solar cells,” *Journal of Crystal Growth* 352, 186–189 (2012).

10. R. R. King, D. C. Law, K. M. Edmondson et al., “40% efficient metamorphic GaInP/GaInAs/Ge multijunction solar cells,” *Appl. Phys. Lett.* 90, 183516 (2007).

11. W. Guter, F. Dunzer, L. Ebel et al., “Space solar cells-3G30 and next generation radiation hard products,” *E3S Web of Conferences* 16, 03005 (2017).

12. R. J. Walters, G. P. Summers, and S. R. Messenger, “Analysis and modeling of the radiation response of multijunction space solar cells,” *IEEE 28th Photovoltaic Specialists Conference (PVSC), Sep 15-22, 2000, Anchorage, USA*, pp. 1092–1097.

13. M. Yamaguchi, N. Kojima, A. Khan et al., “Radiation-resistant and high-efficiency InGaP/InGaAs/Ge 3-junction solar cells,” *International Symposium on Compound Semiconductors, Aug 25-27, 2003, San Diego, USA*, pp. 189–190.

14. S. Sato, T. Ohshima, and M. Imaizumi, “Modeling of degradation behavior of InGaP/GaAs/Ge triple-junction space solar cell exposed to charged particles,” *J. Appl. Phys.* 105, 044504 (2009).

15. A. Mehrrota and A. Alemu, “Optimized device design for radiation resistant and high dislocation solar cells for space,” *IEEE 35th Photovoltaic Specialists Conference (PVSC), June 20-25, 2010, Honolulu, USA*, pp. 002574–002577.

16. M. Imaizumi, T. Nakamura, T. Takamoto et al., “Radiation degradation characteristics of component subcells in inverted metamorphic triple-junction solar cells irradiated with electrons and protons,” *Prog. Photovolt. Res. Appl.* 25, 161–174 (2017).

17. A. Aierken, L. Fang, M. Hein et al., “Effects of proton irradiation on upright metamorphic GaInP/GaInAs/Ge triple junction solar cells,” *Solar Energy Materials and Solar Cells* 185, 36–44 (2018).

18. International Organization for Standardization (ISO), “ISO 23038: Space systems -space solar cells- electron and proton irradiation test methods,” 2014 (available at https://www.iso.org/standard/36600.html).

19. J. R. Srou, C. J. Marshall, and P. W. Marshall, “Review of displacement damage effects in silicon devices,” *IEEE Transactions on Nuclear Science* 50, 653–670 (2003).

20. G. P. Summers, R. J. Walters, M. A. Xapsos et al., “A new approach to damage prediction for solar cells exposed to different radiations,” *Proceedings of IEEE 1st World Conference on Photovoltaic Energy Conversion Vol. II, December 5-9, 1994, Waikoloa, HI, USA*, pp. 2068–2075.

21. S. R. Messenger, E. A. Burke, R. J. Walters et al., “Quantifying low energy proton damage in multijunction solar cells,” *Proceedings of the 19th Space Photovoltaic Research and Technology Conference, September 20-22, 2005, Brook Park, Ohio, USA*, pp. 8–17.

22. G. P. Summers, E. A. Burke, P. Shapiro, S. R. Messenger, and R. J. Walters, “Damage correlations in semiconductors exposed to gamma, electron and proton radiations,” *IEEE Transactions on Nuclear Science* 40, 1372–1379 (1993).

23. A. Johnston, “Optoelectronic devices with complex failure modes,” July 24–28, 2000, Reno, NV, USA, Part 2 of the Short Course.

24. N. Dharmarasu and M. Yamaguchi, “Analysis of radiation response of InGaP, InGaAsP, and InGaAs solar cells by displacement damage dose approach,” *Proceedings of 3rd World Conference on Photovoltaic Energy Conversion Vol. I, May 11-18, 2003, Osaka, Japan, pp. 730–733.

25. N. Dharmarasu, A. Khan, M. Yamaguchi et al., “Effects of proton irradiation on n+p InGaP solar cells,” *Journal of Applied Physics* 91, 3306–3311 (2002).

26. J. J. Li, S. H. Lim, C. R. Allen, D. Ding, and Y. H. Zhang, “Combined effects of shunt and luminescence coupling on external quantum efficiency measurements of multijunction solar cells,” *IEEE Journal of Photovoltaics* 1(2), 225–230 (2011).

27. S. H. Lim, J. J. Li, E. H. Stenbergen et al., “Luminescence coupling effects on multijunction solar cell external quantum efficiency measurement,” *Progress in Photovoltaics* 21, 344–350 (2013).

28. N. Dharmarasu, M. Yamaguchi, and A. Khan, “High-radiation-resistant InGaP, InGaAsP, and InGaAs solar cells for multijunction solar cells,” *Appl. Phys. Lett.* 79, 2399 (2001).

29. M. Yamaguchi and K. Ando, “Mechanism for radiation resistance of InP solar cells,” *Journal of Applied Physics* 63, 5555 (1988).

30. M. Imaizumi, T. Nakamura, T. Takamoto et al., “Radiation degradation characteristics of component subcells in inverted metamorphic triple-junction solar cells irradiated with electrons and protons,” *Prog. Photovolt. Res. Appl.* 25, 161–174 (2017).