Technology Assessment and Modelling of Three Terminal Tandem Solar Cells for In-Space Utilization

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Introduction

NASA seeks a sustained human presence on the lunar surface. High-efficiency and resilient energy systems are critical to supporting habitats, scientific outposts, and lunar surface operations. Photovoltaics have long been the backbone of space power systems, transitioning from silicon solar cells to multi-junction III-V solar cells, which now dominate state-of-the-art (SOA) technology. Multi-junction cells achieve high efficiency by layering semiconductors, each absorbing a specific portion of the solar spectrum. However, efficiency gains are increasingly constrained by device physics and manufacturing complexity. Additionally, higher-order junctions pose challenges for accurate modelling and performance characterization due to difficulties in replicating the AM0 spectrum.

The three-terminal tandem (3TT) solar cell concept offers a promising alternative by introducing an additional shared electrode between the top and bottom junctions. This configuration enables independent operation of sub cells while retaining series or tandem operation capabilities, blending the advantages of two-terminal and four-terminal architectures [1].

NASA maintains an archive of space solar cell technology performance under calibrated AM0 conditions across multiple decades. NASA also demonstrated initial analytical assessment of 3TT space solar cell technology. Using the taxonomy developed by Warren et al., we developed an LTspice simulation framework to model 3TT devices in series and reverse configurations. The models were validated using IV data from a perovskite/silicon tandem, showing a 0.66% efficiency increase for ZTJ solar cells under AM0 conditions. Building on these results, 3TT architectures are gaining importance because they reduce spectral mismatch while enabling integration of emerging materials such as perovskites and advanced III-V compounds for more efficient and durable space power systems.

Objectives

Validate our 3TT models with ZTJ isotype testing.
Update models for different 3TT architecture combinations.
Demonstrate 3TT performance of different 3TT architecture.
Analyze P-V-V curves to determine voltage ranges sub cells can operate in while maintaining high-efficiency.

Method

Multijunction solar cell calibration involves isolating the performance of each junction to allow independent bias, otherwise known as isotypes. Following the taxonomy of Warren et al [3], We created our initial model based on the isotypes of SolAero ZTJ solar cells.

Typically, for a triple junction (InGaP/GaAs/Ge) cell, the middle junction is considered the current limiting and shapes the output power of the solar cell, and the bottom junction is considered "current-rich" and have a 1.5x mismatch in current due to the losses of the second junction. Figure 1. shows the ZTJ model with the first two junctions of the ZTJ operating in series as a single sub cell while the third is independent. This mode shows the solar cell performance without the effect of the current limiting of the bottom junction.

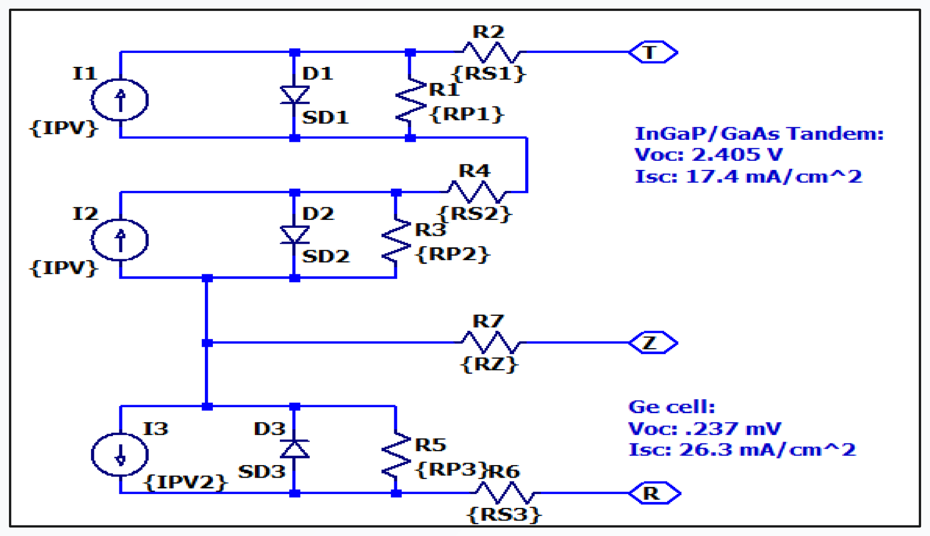

Figure 1: Spice Model Developed to simulate r-type 3TT devices.

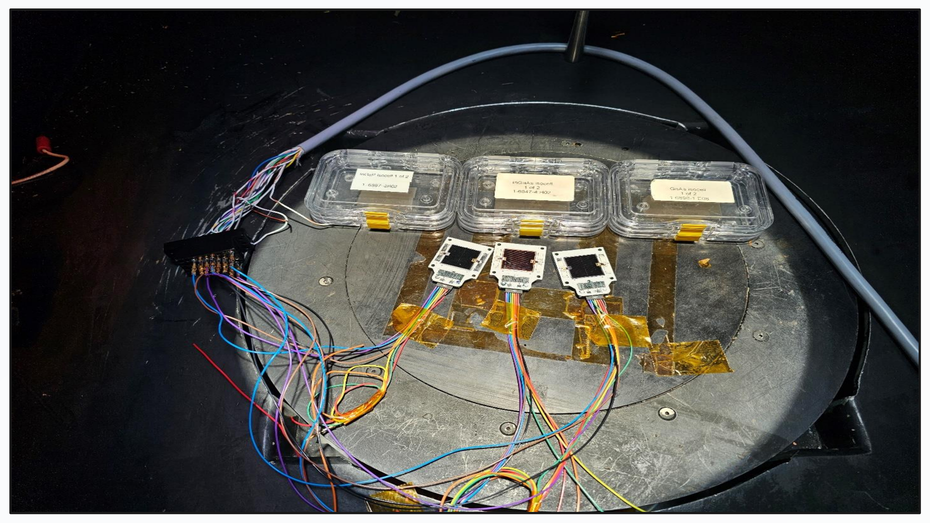

Figure 2: X-25 solar simulator with 3 ZTJ Isotypes with interconnects fed to the multiplexer.

To validate the results of our theorical model, ZTJ, Z4j and Imm-α solar cell isotypes, were tested using GRC's triple source solar simulator, which has a long-standing history of AM0 calibration through high-altitude flights. The 3TT devices were configured using isotypes for solar simulator calibration. The cells are fed into a multiplexer to allow flexible configuration of the "third electrode". Two source-measure units were utilized to simultaneously perform IV scans on each of the 3TT junctions.

A triple junction solar cell will have 3 isotypes, therefore each one was connected in series to replicate the functionality and behavior of a fully integrated multijunction solar cell. The multiplexer was used to interrupt this series configuration and isolate the bottom junction isotype. This gives us the 3TT configuration. The test was repeated with 4 junction and 5 junction solar cell isotypes.

Results

- **ZTJ**

The full-stack ZTJ junction measures a power density of 0.1821 W/cm² and by making a 3TT connection we achieve 0.1858 W/cm². Giving an overall efficiency of 33.399% and 33.979%. That is an increase in efficiency of 1.72%.

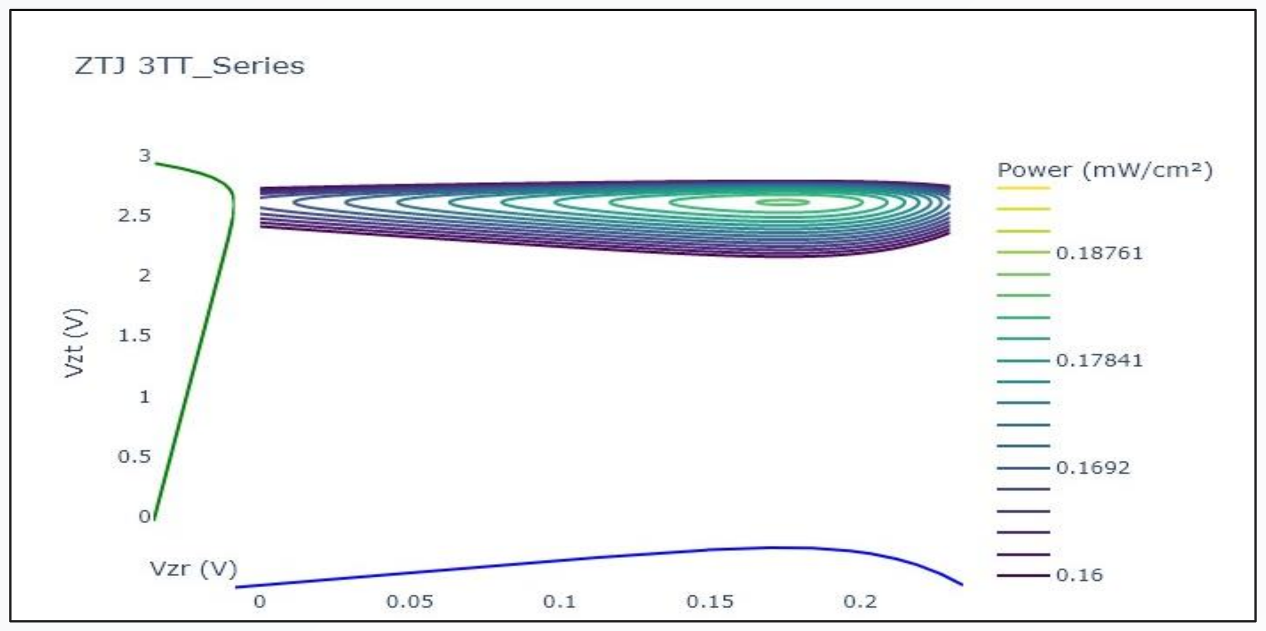

Figure 3: P-V-V contour plot for the ZTJ. Voltage will vary in the region shown. The small oval represented the MPP (maximum power point) of the device.

- **IMM-α**

The Imm-α solar cells which have 5 total junctions. Since this cell is in the GRC archives, its characteristics in AM0 are known. The goal is to change the interconnection between junctions and observe how it behaves. In a full stack, the IMM-α produces 0.1735 W/cm² and 31.721% efficiency. Table 1 shows the result when changing the position of the 3TT connection and figures 4-7 show the contour plot region of their power densities.

Top junctions connections	Bottom junction connections	Power (W/cm²)	Efficiency (%)	Overall efficiency increase (%)
J1	J2 J3 J4 J5	0.1757	32.13	1.28
J1 J2	J3 J4 J5	0.1791	32.75	3.20
J1 J2 J3	J4 J5	0.1827	33.41	5.19
J1 J2 J3 J4	J5	0.1823	33.33	4.97

Table 1: Power densities when changing the placement of the third terminal for the IMM-α

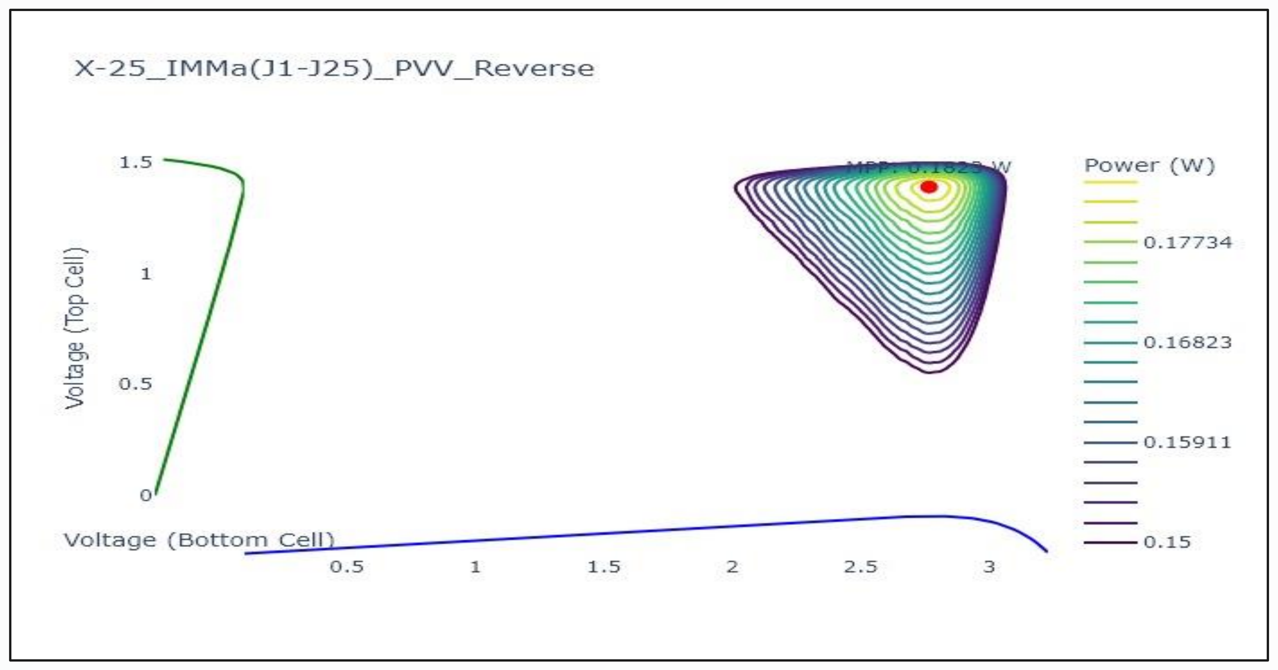

Figure 4: IMM-α P-V-V plot with 3TT connection between junction one and two

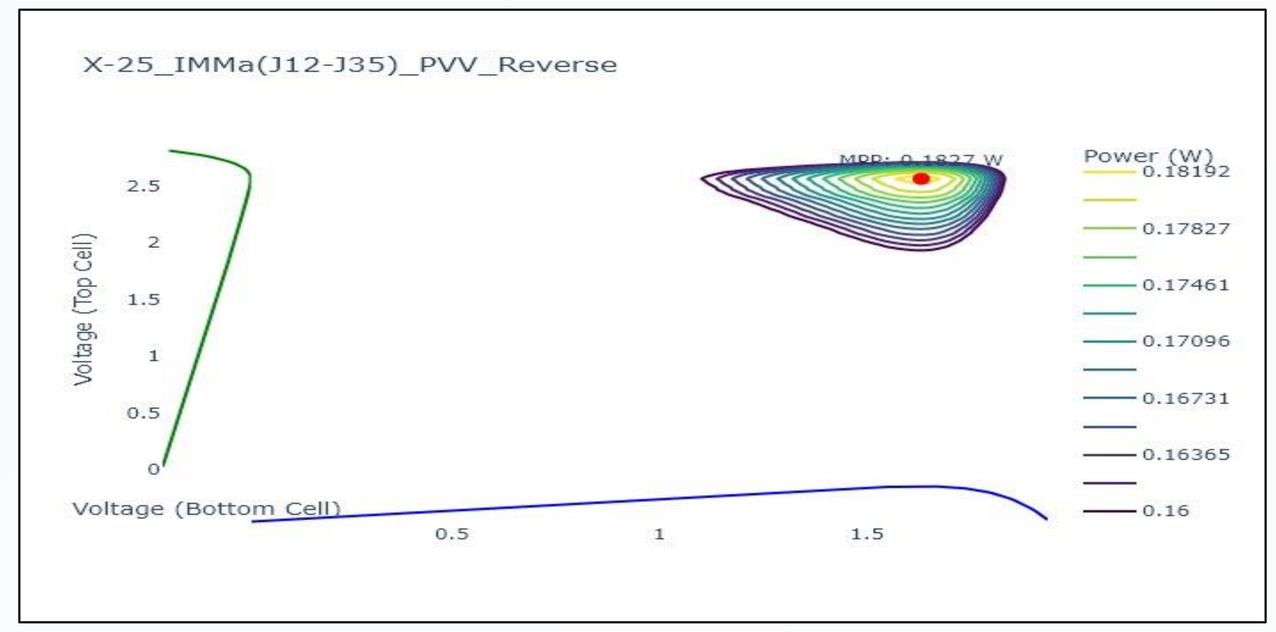

Figure 5: IMM-α P-V-V plot with 3TT connection between junction two and three

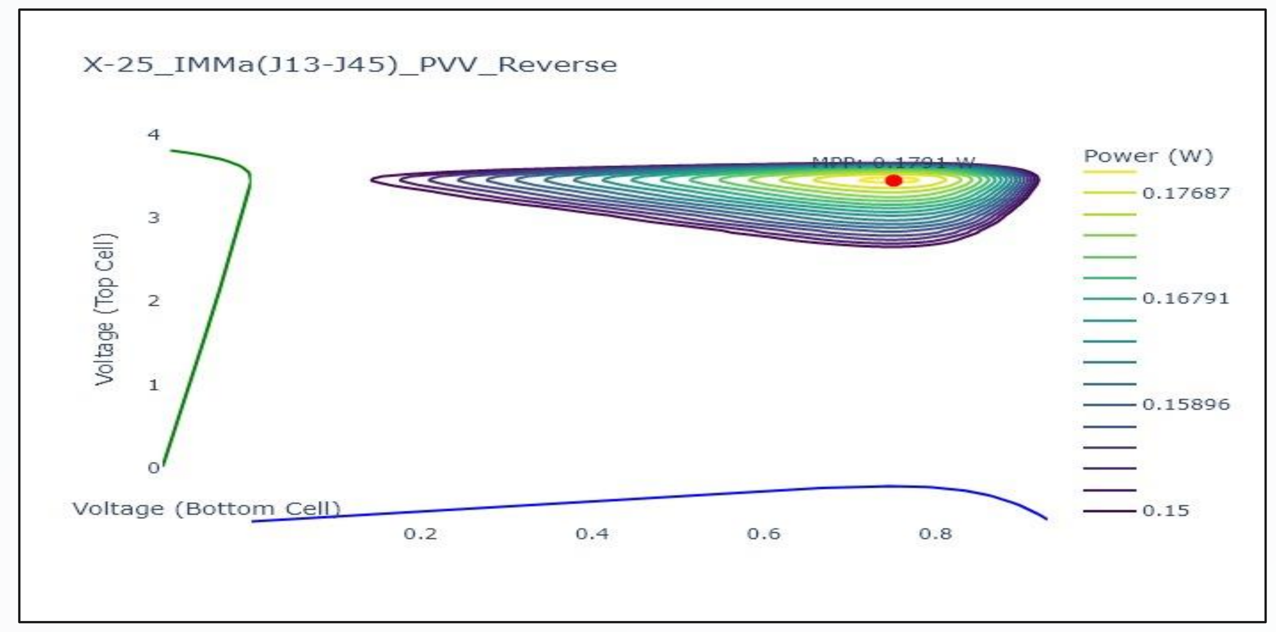

Figure 6: IMM-α P-V-V plot with 3TT connection between junction three and four

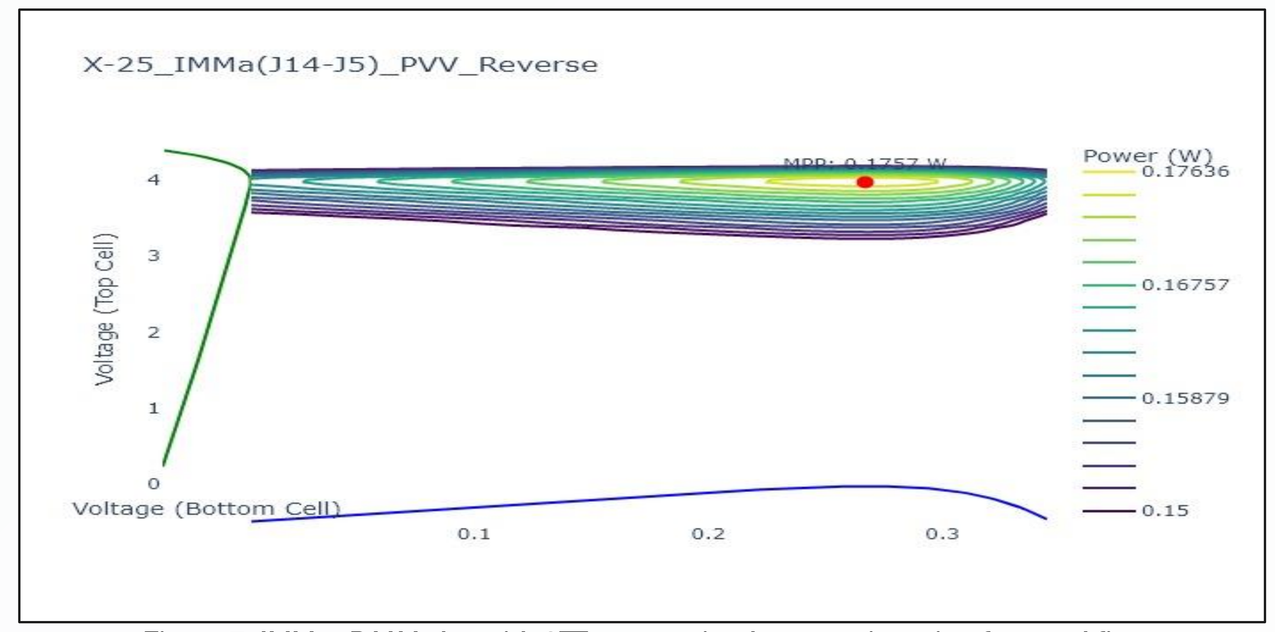

Figure 7: IMM-α P-V-V plot with 3TT connection between junction four and five

Conclusion

This work evaluates the potential of three-terminal tandem (3TT) solar cells to enhance photovoltaic efficiency for space applications. Building on NASA GRC's extensive archive of space solar cell performance under AM0 conditions, simulations and experiment were conducted to assess the performance ZTJ solar cell in a 3TT configuration, along with the Z4J and IMM-α. An increase in performance was observed experimentally on all the cells. The ZTJ improved its power density by 1.7%, the Z4J improved by 6.5% and IMM-α improved 5.19%.

Using this space solar cells isotypes, we validated that an increase in efficiency can be achieved when changing to a 3TT configuration. This improvement underscores the significance of 3TT architectures in addressing challenges such as spectral mismatch and current-limiting effects in traditional multijunction cells.

Reference

[1] F. Gota, M. Langenhorst, R. Schmager, J. Lehr, and U. W. Paetzold, "Energy Yield Advantages of ThreeTerminal Perovskite-Silicon Tandem Photovoltaics," Joule, vol. 4, no. 11, pp. 2387–2403, Nov. 2020, doi: 10.1016/j.joule.2020.08.021.

[2] P. K. Chiang et al., "Experimental results of GaInP/sub 2//GaAs/Ge triple junction cell development for space power systems," in Conference Record of the Twenty Fifth IEEE Photovoltaic Specialists Conference - 1996, May 1996, pp. 183–186. doi: 10.1109/PVSC.1996.563977.

[3] E. L. Warren et al., "A Taxonomy for Three-Terminal Tandem Solar Cells," ACS Energy Lett., vol. 5, no. 4, pp. 1233–1242, Apr. 2020, doi: 10.1021/acsenergylett.0c00068.