Recent Progress of Spectrolab High-Efficiency Space Solar Cells

Daniel C. Law, X.Q. Liu, J.C. Boisvert, E.M. Redher, C.M. Fetzer, S. Mesropian, R.R. King, K.M. Edmondson, B, Jun R.L. Woo, D.D. Krut, P.T. Chiu, D.M. Bhusari, S.K. Sharma, and N.H. Karam

Spectrolab, Inc., a wholly owned subsidiary of Boeing, 12500 Gladstone Ave., Sylmar, CA 91342 U.S.A.

ABSTRACT

High-efficiency Inverted Metamorphic (IMM) multi-junction solar cells are being developed at Spectrolab for use in space and near-space applications. Recently, large-area (26-cm^2) IMM3J cells achieved a 1-sun, AM0 conversion efficiency of 32% with an open-circuit-voltage of 3.04V, a short-circuit current-density of 16.7 mA/cm^2, and a fill factor of 0.84. In addition, IMM4J cells (1-cm^2) reached a 1-sun, AM0 conversion efficiency of 33%. The 4-junction cell achieved an open-circuit-voltage of 3.42V, a short-circuit current-density of 15.8 mA/cm^2, and a fill factor of 0.82. Both the inverted metamorphic 3J and 4J cells reveal excellent component subcell quantum efficiency performance. Improvements in crystal growth, as well as more optimal subcell current density balance, will further raise the 1-sun, AM0 efficiency of the 3J and the 4J IMM cells to 33% and 35% respectively. The latest status of the semiconductor-bonded 5-junction space solar cells and the 72-cm^2 XTJ (based on 150mm Ge substrate) super cells will also be discussed.

INTRODUCTION

Recent progress in III-V multijunction space solar cell technology has led to production GaInP/GaAs/Ge triple-junction space cells with an average 1-sun efficiency close to 30% (AM0, 28ºC, 1-sun) [1]. The latest lattice-matched multijunction solar cell, XTJ, typical-size, 26.62 cm^2, and LEONE, 59.65 cm^2, shown in Figure 1 passed qualification per AIAA S-111-2005 and AIAA S-112-2005 for CIC assembly level qualification and manufacturing change readiness review.

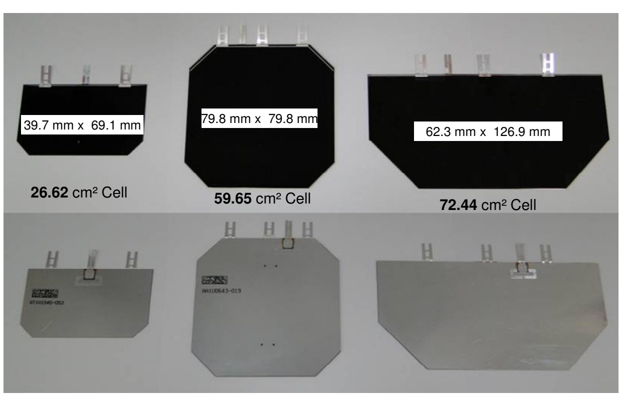

Figure1. Evolution of XTJ space solar cell

After XTJ LEONE cells were successfully introduced. Spectrolab continue on the strategic cost reduction plan by establishing a 150mm based manufacturing line for XTJ SuperCell, 72.44 cm^2, that provide equal electrical and mechanical performance as LEONE cells.

SuperCell is currently undergoing engineering confidence tests per Spectrolab heritage requirements. Over 300 XTJ SuperCells were built thus far (Figure 2). Electrical performance of SuperCells processed for pre-engineering tests from multiple MOVPE reactor systems over a 6-month period showed an excellent result and met the light I-V parameter specifications from both BOL and after radiation. Note that the illuminated current-voltage performance specifications are same for both LEONE and SuperCell as shown in Table 1.

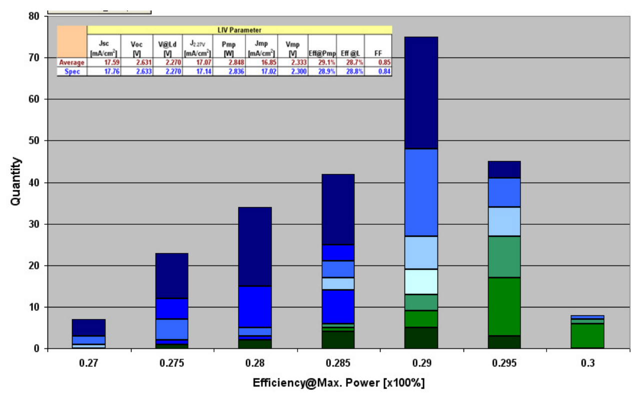

Figure 2. SuperCell max. power efficiency distribution (color represents different cell builds)

Table 1. XTJ Light I-V parameter specification

Parameter	2 Per XTJ (100mm) (26.62cm^2~32.3 cm^2)	1 Per XTJ (100mm) (53.3cm^2~59.65cm^2)	SuperCell (150 mm) (70 cm^2 ~72.44cm^2)
Jsc[mA/cm^2]	17.76	17.76	17.76
Voc [V]	2.633	2.633	2.633
Vload	2.310	2.270	2.270
Jload@2.31V [mA/cm2]	17.14	N/A	N/A
Jload @ 2.27V [mA/cm^2]	N/A	17.14	17.14
Jmp [mA/cm^2]	17.02	17.02	17.02
Vmp [V]	2.348	2.300	2.300
Eff @Pmp [%]	29.54%	28.91%	28.91%
Eff@2.31V [%]	29.26%	N/A	N/A
Eff@2.27V [%]	N/A	28.76%	28.76%
Fill Factor	0.85	0.84	0.84
Absorptance [Bare]	0.88	0.88	0.88
EOL]	0.87	0.87	0.87
Absorptance [CIC, 5 mil AR]	0.90	0.90	0.90
Pm @1 MeV electron, 5E14	0.89	0.89	0.89
Pm @1 MeV electron, 1E15	0.85	0.85	0.85

Future space solar cells will likely utilize new technology pathways such as 3- to 6-junction cell structure, highly metamorphic materials, and inverted crystal growth to achieve the desired bandgaps for 1-sun, AM0 efficiency of 33% and beyond. Inverted metamorphic 3-junction and 4-junction solar cells are envisioned to be the next space solar cell architecture beyond the current Ge-based cells. Figure 1 shows a cross-section schematic of the IMM3J and the IMM4J cells.

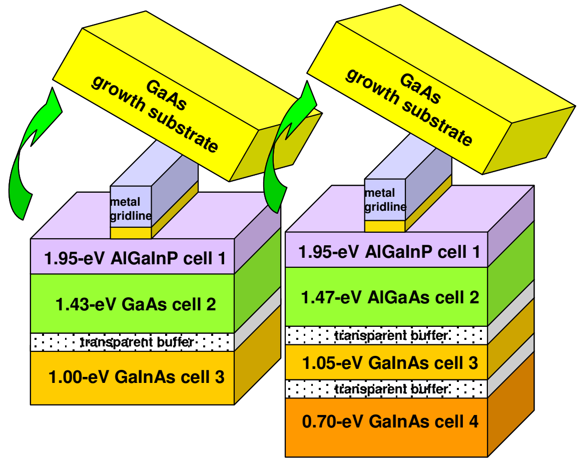

Figure 1. Cross-sections schematic of the IMM3J and the IMM4J space solar cells.

Spectrolab's IMM space solar cells are grown in an inverted configuration using production MOVPE reactors on 100mm GaAs substrates. The highest bandgap alloy (Subcell 1) is grown first followed by the second highest bandgap materials (Subcell 2), and depending on whether it is a 3J or a 4J structure, one or two pairs of metamorphic buffers and corresponding low bandgap subcells at the buffer lattice constants are grown. The IMM cells discussed in this work have bandgap combinations of 2.0, 1.4, and 1.0-eV for IMM3J cells and 2.0, 1.5, 1.1, and 0.7-eV for IMM4J cells. Subsequent wafer processing converts the inverted cell structure to an upright configuration and transfers the device semiconductor layers to a cell handle. Processes typical of standard, high-volume space solar cell are then used to complete the device fabrication. Cell-Interconnect-Coverglass (CICs) are then assembled based on conditions nearly-identical to typical production space solar cell assembly processes.

RESULTS

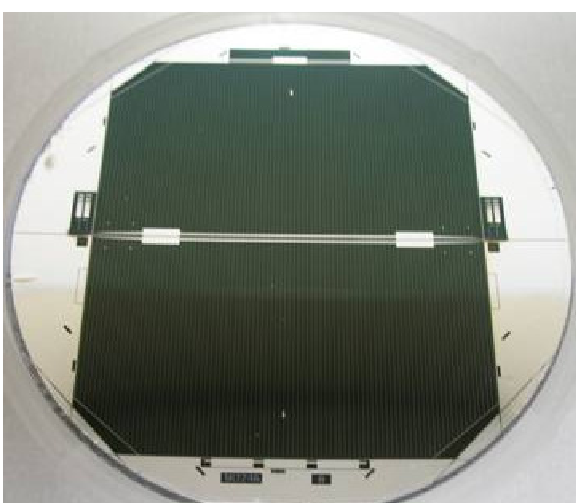

Figure 2. Picture of a large-area (>24-cm^2) IMM3J solar cells taken right before final cell isolation.

Figure 2 shows a picture of two large-area (>24-cm^2) IMM3J solar cells taken right before final cell isolation. Similar to current Ge-based space solar cells two large-area IMM cells can be yielded from each 100-mm substrate. Figure 3 reveals the illuminated current-voltage characteristic of a "two-per" large-area IMM3J cells tested under 1-sun, AM0 simulator illumination. The solar simulator (AX25) was calibrated using IMM3J LEAR Jet flown calibration standards. One of the IMM3J cells measured an open-circuit voltage (V_{OC}) of 3.04V, a short-circuit current density (J_{SC}) of 16.7 mA/cm^2, and a fill factor of 0.84 for a 1-sun, AM0 efficiency of 31.5%. Spectral response measurements for the IMM3J cells are shown in Figure 4. Note that all three components of the IMM3J cell achieved or exceeded 90% external quantum efficiency. The current density values of the limiting subcell is also consistent with the measured J_{SC} data shown in Figure 3.

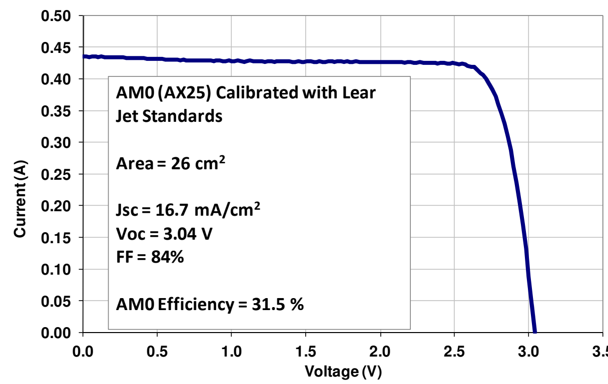

Figure 3. Illuminated current-voltage characteristic of a large-area IMM3J cell tested under 1-sun, AM0 simulator illumination.

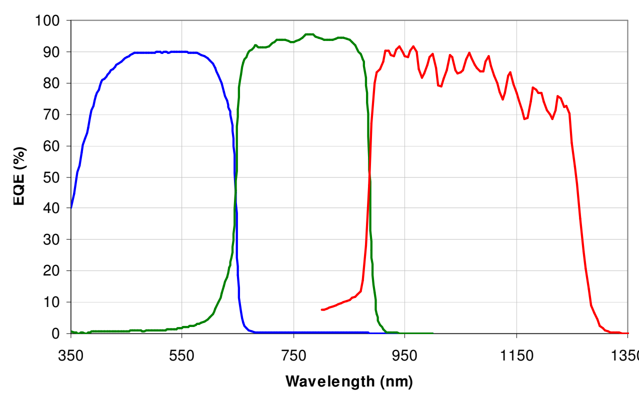

Figure 4. Spectral response measurements of a IMM3J cell.

Figure 5 plots the illuminated current-voltage characteristic of recent Spectrolab IMM 4-junction cells. One of the IMM4J cells measured an V_{OC} of 3.42V, a J_{SC} of 15.8 mA/cm^2, a fill factor of 0.82, or an 1-sun, AM0 efficiency of 32.7%. Again, the solar simulator was calibrated using IMM3J LEAR Jet flown calibration standards. As a measure of solar cell quality, it is desirable to achieve a small bandgap-voltage offset, [(Eg/q) – V_{OC}], such that the open-circuit voltage is as close to the device material bandgap as possible [Ref]. The overall (Eg/q) - V_{OC} of the IMM 4-junction cell was calculated to be 1.75V or an average offset of 437mV per subcell. It is estimated that high performance IMM 4-

junction cells with target efficiency of 35% 1-sun, AM0 efficiency will likely have an average offset of 413mV per junction. The fill factor of the IMM4J cells can also be increased with further improvement in current collection and current balance among the four subcells.

The internal quantum efficiency (IQE) data of the IMM4J component subcells are presented in Figure 6. The IQE data showed that the two lattice-matched subcells, AlGaInP and AlGaAs, as well as the ~1-eV MM GaInAs subcells achieved or exceed quantum efficiencies of 90%. In comparison, the highly lattice-mismatched 0.7-eV GaInAs subcells achieved or exceed quantum efficiencies of 85%.

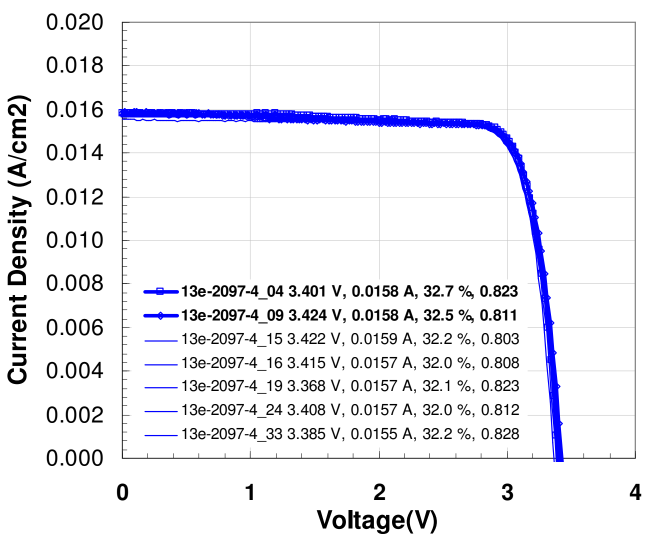

Figure 5. Illuminated current-voltage characteristic of IMM4J cells (1-cm^2) tested under 1-sun, AM0 simulator illumination.

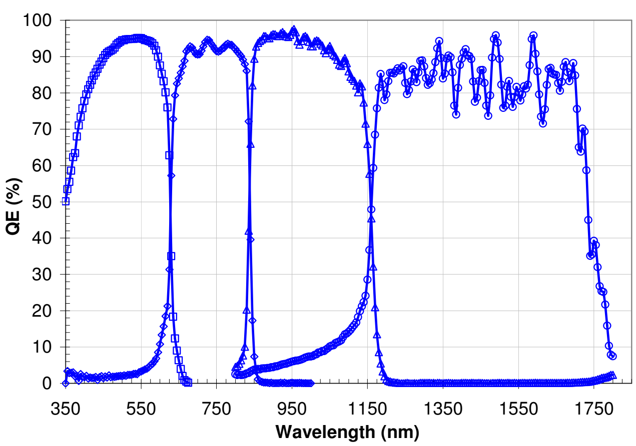

Figure 6. Internal quantum efficiency data of an IMM4J space solar cells.

CONCLUSIONS

Spectrolab continues to develop high-efficiency inverted metamorphic solar cell technology for space and near-space applications. Large-area IMM3J space solar cells with 1-sun, AM0 efficiency of 32% have been demonstrated. In addition, the IMM4J cells (1-cm^2) have also reached an 1-sun, AM0 conversion efficiency of 33%. Improvements in crystal growth, as well as more optimal subcell current density balance, will further raise the 1-sun, AM0 efficiency of the IMM3J and the IMM4J cells to 33% and 35%, respectively.

ACKNOWLEDGEMENTS

The authors would like to thank the entire R&D team at Spectrolab and the financial support from the U.S. Government, the U.S. Air Force Research Laboratory Space Vehicles Directorate under Contracts FA9453-09-C-0373, and Boeing Internal Research and Development funds is gratefully acknowledged.

REFERENCES

[1] M. W. Wanlass, S. P. Ahrenkiel, R. K. Ahrenkiel, D. S. Albin, J. J. Carapella, A. Duda, J. F. Geisz, S. Kurtz, T. Moriarty, R. J. Wehrer, and B.Wernsman, Proceedings of the 31st IEEE Photovoltaic Specialists Conference, p. 530 (2005).

[2] R. R. King, D. C. Law, C. M. Fetzer, R. A. Sherif, K. M. Edmondson, S. Kurtz, G. S. Kinsey, H. L. Cotal, D. D. Krut, J. H. Ermer, and N. H. Karam, Proc. 20th European Photovoltaic Solar Energy Conference, p. 118 (2005).

[3] Yoon, Hojun; Haddad, Moran; Mesropian, Shoghig; Yen, Jason; Edmondson, Kenneth; Law, Daniel; King, Richard R.; Bhusari, Dhananjay; Boca, Andreea; Karam, Nasser H., Proceedings of the 33st IEEE Photovoltaic Specialists Conference, p. 1 (2006).

[4] J. Boisvert, D. Law, R. King, D. Bhusari, X. Liu, A. Zakaria, W. Hong, S. Mesropian, D. Larrabee, R. Woo, A. Boca, K. Edmondson, D. Krut, D. Peterson, K. Rouhani, B. Benedikt, and N.H. Karam, Proceedings of the 35th IEEE Photovoltaic Specialists Conference, p. 123 (2010).