SEMICONDUCTOR-BONDED III-V MULTIJUNCTION SPACE SOLAR CELLS

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ABSTRACT

Boeing-Spectrolab recently demonstrated monolithic 5-junction space solar cells using direct semiconductor-bonding technique. The direct-bonded 5-junction cells consist of (Al)GaInP, AlGa(In)As, Ga(In)As, GaInPAs, and GaIn(P)As subcells deposited on GaAs or Ge and InP substrates. Large-area, high-mechanical strength, and low-electrical resistance direct-bonded interface was achieved to support the high-efficiency solar cell structure. Preliminary 1-sun AM0 testing of the 5-junction cells showed encouraging results. One of the direct-bonded solar cell achieved an open-circuit-voltage of 4.7V, a short-circuit current-density of 11.7 mA/cm^2, a fill factor of 0.79, and an efficiency of 31.7%. Spectral response measurement of the five-junction cell revealed excellent external quantum efficiency performance for each subcell and across the direct-bonded interface. Improvements in crystal growth and current density allocation among subcells can further raise the 1-sun, AM0 conversion efficiency of the direct-bonded 5-junction cell to 35 - 40%.

INTRODUCTION

Recent progress in III-V multijunction space solar cell technology has led to production triple-junction space cells with an average 1-sun efficiency close to 30% (AM0, 28ºC, 1-sun) [1]. The triple-junction cells are based on GaInP/GaAs/Ge device structure that is lattice-matched to Ge substrates. Future space solar cells will likely utilize new technology pathways such as 4- to 6-junction cell structure, highly metamorphic materials, inverted crystal growth, direct semiconductor-bonding, or their combinations to achieve 35% or higher 1-sun, AM0 efficiency [2-13]. Recently, Spectrolab has achieved a 5-junction cell structure with desirable bandgap combinations using direct semiconductor-bonding. Semiconductor-bonding technique provides unique advantages since the component subcells can be lattice-matched to multiple growth substrates instead of one. A large selection of III-V material is available for component subcells. This enables different bandgap combinations and device designs that are difficult to achieve with one growth substrate. In addition, the 5-junction design divides the solar spectrum more efficiently and trades excess current densities for higher open-circuit voltage and higher conversion efficiency.

The semiconductor-bonded 5-junction cells discussed in this work have a bandgap combination of 2.0, 1.7, 1.4, 1.1, and 0.8-eV. Figure 1 shows the partitions of the AM0 spectrum by the 5-junction cell. Schematics of the bonded 5-junction cell and the location of the direct bonded interface are shown in the insert.

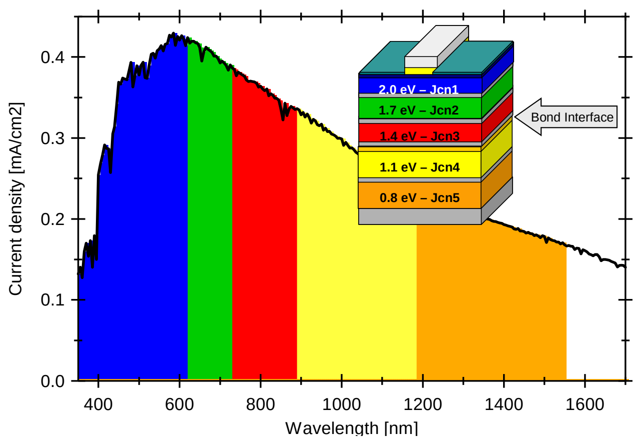

Fig. 1 Partitions of the AM0 spectrum by the 5-junction solar cell and a schematic of the semiconductor-bonded 5-junction solar cell.

EXPERIMENT

The upper three component subcells, AlGaInP, AlGa(In)As, and Ga(In)As, were deposited on GaAs or Ge substrates while the lower two subcells, GaInPAs and GaIn(P)As, were deposited on InP substrates by metalorganic vapor phase epitaxy. The epitaxial wafers were directly bonded together to form the 5-junction structures. The growth substrate(s) of the bonded structures were then removed to reveal the cell material in the "sun-side-up" direction. The bonded III-V materials utilized a device fabrication process that is more complex than the conventional up-right 3-junction cells to fabricate the 5-junction solar cells. Standard space anti-reflection coating and space solar cell metal contacts were used for the 5-junction cells.

Some of the bonded 5-junction solar cells prepared in this work were fabricated using an experimental gridline design that has excess metal coverage. For comparison, the data from those high metal coverage cells was normalized to the grid shadowing of standard space solar cells used in the other bonded 5-junction cells. Illuminated current-voltage characteristics of the 5-junction cells were measured using an XT-10 solar simulator calibrated with conventional 3-junction standards. At this point, Spectrolab does not have dedicated simulator calibration standards for bonded 5-junction cells. This is an active area of development for bonded 5-junction cell. Majority of the bonded 5-junction cells fabricated are 1-cm^2 in size.

RESULTS AND DISCUSSIONS

Figure 2 plots the illuminated current-voltage (LIV) characteristic of two bonded 5-junction solar cells. One of the 5-junction cells measured an open circuit voltage (V_{OC}) of 4.7V, a short-circuit current density (J_{SC}) of 11.7 mA/cm^2, a fill factor of 0.79, and an AM0 efficiency of 31.7%. Included in Fig. 2 is the current-voltage data of another 5-junction cell corrected for excess metal coverage. Modeled LIV outputs of a 32% and a 34% 5-junction cell with the same bandgap combination as the bonded cell are included for comparison.

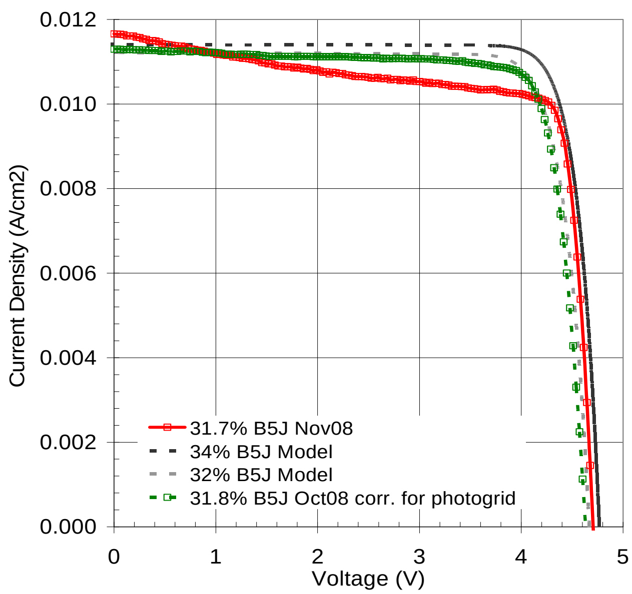

Fig. 2 Illuminated current-voltage characteristic of two bonded 5-junction solar cells, as well as a 32% and a 34% modeled LIV curves.

External quantum efficiency (EQE) data of the bonded 5-junction cells are plotted in Fig. 3. Subcell 1, 2, 3, and 4 show peak EQE performance ranging from 80% to 90%. Note that the overall cell thickness of Subcell 1 is reduced to balance the current densities of Subcell 1, Subcell 2, and Subcell 3. The bandgap difference between Subcell 1 (2.0-eV) and Subcell 2 (1.7-eV) is not sufficient for Subcell 2 to current match the other subcells if typical Subcell 1 cell thickness is used. Thus, Subcell 2 has significant response at high photon energies (>650 nm). Advanced features were also incorporated in Subcell 3 to help balance the current density across the bonded interface. The cumulative external quantum efficiency data of the five subcells is also plotted in Fig. 3. Note that the cumulative EQE exceeds 90% across Subcell 3 (on GaAs substrate) and Subcell 4 (on InP substrate) where the bonded interface is located. In addition, the EQE data of Subcell 4 and Subcell 5 in the bonded 5-junction cell is nearly identical to that of the stand-alone (non-bonded) component dual-junction cells for wavelength range beyond Subcell 3 band-cutoff. These results suggested that the bonded interface is highly transparent for wavelength range greater than 850nm.

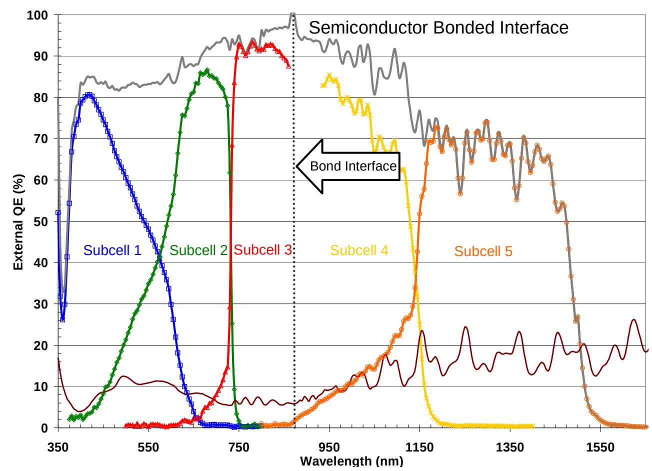

Fig. 3 External quantum efficiency data of the semiconductor-bonded 5-junction cell.

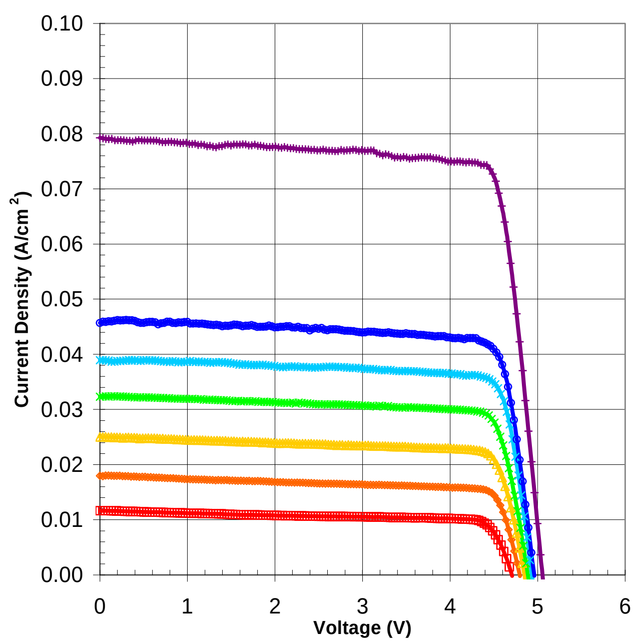

Fig. 4 Performance of the semiconductor-bonded 5-junction cell as a function of AM0 concentration.

Based on the subcell bandgaps and the open circuit voltage, the bandgap voltage offsets [(E_g/q) - V_{OC}] was calculated as a way to determine the overall 5-junction cell quality. It is desirable to achieve a small bandgap-voltage offset such that the open-circuit voltage is as close to the bandgap as possible [2]. The 5-junction cell achieved an

$[(E_g/q) - V_{OC}]$ offset of 2.7V or an average offset of 454 mV per junction. Based on stand-alone (non-bonded) upper-three and bottom-two component subcell data, the high-bandgap upper-three subcells have an average bandgap-voltage offset of 505 mV per junction and the low-bandgap bottom-two subcells have an average bandgap-voltage offset of 382 mV. As a comparison, a high performance 5-junction with ~35% AM0 efficiency will have an average $[(E_g/q) - V_{OC}]$ offset of 420 mV or lower per junction.

The bonded 5-junction space solar cells were also tested under concentrated AM0 spectrum. Figure 4 shows the preliminary performance data of a 5-junction cell as a function of AM0 concentration. The 5-junction cell performance continue to improve as concentration increase and showed an open-circuit-voltage of 5.1V, a short-circuit current-density of 79.3 mA/cm^2, a fill factor of 0.83, or an efficiency of 35.7% at 7-suns.

CONCLUSION

Boeing-Spectrolab continues to develop high efficiency solar cells for space power systems. We have recently demonstrated 5-junction cells using direct wafer-bonding technique. Preliminary testing of the direct bonded 5-junction cells reported a 1-sun AM0 efficiency of 31.7% and a 7-suns AM0 efficiency of 35.7%. More importantly these results validate the feasibility to integrate ultra-high efficiency solar cell architectures through direct semiconductor bonding. Further advancement in crystal growth and current density allocation will allow the bonded 5-junction cells to reach an AM0 efficiency of 35-40%.

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REFERENCES

[1] B. Jun, C. Fetzer, K. Rouhani, R. Barfield, K. Bui, D. Hom, M. Gillanders, S. K. Sharma, 34th IEEE Photovoltaic Specialist Conference (PVSC) (2009).

[2] R. R. King, D. C. Law, K. M. Edmondson, C. M. Fetzer, G. S. Kinsey, D. D. Krut, J. H. Ermer, R. A. Sherif, and N. H. Karam, Proc. 4th International Conf. on Solar Concentrators (ICSC-4), (2007).

[3] R. R. King, D. C. Law, K. M. Edmondson, C. M. Fetzer, G. S. Kinsey, H. Yoon, R. A. Sherif, and N. H. Karam, Appl. Phys. Lett., 90, 183516, (2007).

[4] D. C. Law, C. M. Fetzer,; R. R. King, P. C. Colter, H. Yoon, T. D. Isshiki, K. E. Edmondson, M. Haddad, N. H. Karam, Proc. 31st IEEE Photovoltaic Specialist Conference (PVSC), Lake Buena Vista, Florida, 575, (2005).

[5] C. M. Fetzer, R .R. King, P. C. Colter, K. M. Edmondson, D. C. Law, A.P. Stavrides, H. Yoon, J. H. Ermer, M. J. Romem, N.H. Karam, J. Cryst Growth, vol. 261, 341, (2004).

[6] F. Dimroth, U. Schubert, and A. W. Bett, IEEE Elect. Device Lett., vol. 21, 209, (2000).

[7] M. W. Wanlass et al., Proc. 31st IEEE PVSC, Lake Buena Vista, Florida, 530, (2005).

[8] J. F. Geisz et al., Appl. Phys. Lett., vol. 91, 023502, (2007).

[9] H. Yoon, M. Haddad, S. Mesropian, J. Yen, K. M. Edmondson, D. C. Law, R. R. King, D. Bhusari, A. Boca, and N. H. Karam, *in preparation*.

[10] M. J. Griggs, D. C. Law, R. R. King, A. C. Ackerman, J. M. Zahler, and H. A. Atwater, Proc. of 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion (2006)

[11] M. J. Archer, D. C. Law, S. Mesropian, M. Haddad, C. M. Fetzer, R. R. King, A. C. Ackerman, C. Ladous, and H. A. Atwater, Applied Physics Letters, *in press*.

[12] K. Tanabe, A. Fontcuberta i Morral, D. J. Aiken, M. W. Wanlass, and H. A. Atwater, Proc. 47th TMS Elect. Mat. Conf., Santa Barbara, S7, (2005)

[13] J. M. Zahler, K. Tanabe, C. Ladous, T. Pinnington, F. D. Newman, and H. A. Atwater, Appl. Phys. Lett., vol. 91 (1), 012108, (2007)