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LIGHTWEIGHT, FLEXIBLE, HIGH-EFFICIENCY III-V MULTIJUNCTION CELLS

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ABSTRACT

Large-area (26.6 cm^2), thin GaInP/GaInAs/Ge triple-junction (TJ) solar cells with thickness as low as 50 μm were demonstrated. The average conversion efficiency of fifty thin TJ cells is 28 %, 1-sun AM0. The thin TJ cells showed nominal performance after welding of interconnects and flexibility test (50 mm curvature radius). Prototype coupons made with these thin TJ cells met flexible solar module bending requirement of 100 mm radius. The thin-cell coupons showed a specific power of 500 W/kg and a power density of 325 W/m^2. Ultra-thin (<10 μm thick) GaInP/Ga(In)As dual-junction (DJ) cells with size ranges from 0.5 to 26.6 cm^2 were fabricated using 4" Ge or GaAs wafers. Preliminary test data of the ultra-thin DJ cells showed a specific power of 2067 W/kg and a power density of 283 W/m^2. The ultra-thin solar cells continued to demonstrate nominal performance after handling and flexing to a radius of 12 mm. Our results suggested that both the thin cell and the ultra-thin cell technologies can be incorporated with current and future solar cell designs

INTRODUCTION

The economic and design factors of space solar arrays are compelling. Maximizing electrical power available to spacecraft while reducing overall stowage volume and mass of solar array is an on-going challenge. Solar arrays with low specific power or power density solar cells can result in high launch and operation cost. Recent progress in crystalline III-V solar cell technologies has led to a best-cell efficiency of 30.5% and an average production cell efficiency of 28% (1-sun AM0, 28ºC) [1,2]. Typical solar panels (honeycomb substrate) with multijunction cells can achieve a specific power of 150 W/kg and a power density of 350 W/m^2 depending on the exact solar panel design.

Considerable improvements in specific power and cost savings are possible if current rigid solar panel materials and III-V solar cells can be replaced by blanket-like panel substrate and lightweight, flexible multijunction solar cells. Table 1 compares the technology readiness level, the cell efficiency, the specific power, and the power density of three solar array technologies: the crystalline multijunction (MJ) solar array, the thin-film solar array, and the flexible multijunction solar array. Note that flexible solar arrays with lightweight MJ cells and flexible components can potentially provide the same electrical power for much less mass or for the same size or mass a much higher power solar panel. Table 2 lists the target specific power and power density of thin, blanket-like flexible array with 26.5%, 28.3%, 30%, and 33% efficient multijunction cells at a cell packing factor of ~0.94. In addition, flexible solar array enable module designs with low stowage mass and volume. This can have a profound impact on mission capabilities, satellite weight, and overall cost.

Table 1 Comparison of solar array technologies.

	Crystalline Multijunction (UTJ Arrays)	Thin Film on Flexible Substrate*	Flexible III-V MJ Solar Blanket
TRL Level Demonstrated	8 (on orbit)	5	**3**
Best cell efficiency (AM0 1353 W/m^2, 28°C)	30%	15% (rigid substrate)	**29% (target: 33%)**
Avg. cell efficiency (AM0 1353 W/m^2, 28°C)	28%	10% (flexible film)	**28% (50 cells)**
Specific power (cell)	180 W/kg	> 1280 W/kg	**DJ: 2000 W/kg TJ: 1000 W/kg**
Specific power (panel / array)	150 W/kg (panel) / 70 W/kg (array)	600 W/kg (panel) / 250 W/kg (array)	**target: 500 W/kg (panel) / TBD (array)**
Stowage volume power density	10 – 15 kW/m^3	target: 80 kW/m^3	**target: >200 kW/m^3**
Min. area for 100 kW electrical power	290 m^2	660 m^2 (assuming 15%)	**target: <290 m^2**

Table 2 Ultra-high specific power density solar blanket target.

ITJ Cells	UTJ Cells	XTJ Cells	NJ Cells
26.5%	28.3%	30%	33%
339 W/m^2	357 W/m^2	378 W/m^2	420 W/m^2
948 W/kg	**1013 W/kg**	**1074 W/kg**	**1181 W/kg**

Thin and ultra-thin single-junction (SJ) GaAs cells were demonstrated in previous works. The substrates of the SJ cells were thinned or completely removed during cell fabrication [3-6]. However, the GaAs cells were relatively small in size for solar array applications. Most of the GaAs SJ cells were also attached to rigid handle material, limiting their use in flexible solar array. Recently, triple-junction cells made from 100 μm thick Ge substrates were demonstrated [7]. In addition, multijunction solar cells with substrate completely removed were reported [8-9].

EXPERIMENT

The device structures of the flexible thin TJ cells and the ultra-thin DJ cells are similar to that in Spectrolab production solar cells. Dual-junction and triple-junction structures were deposited by metalorganic vapor phase epitaxy (MOVPE) on 4" substrates. Figure 1 shows a cross-sectional schematic of the thin triple-junction cell structure. For the ultra-thin dual-junction cells, a sacrificial etch-stop layer and a contact layer were added to the structure. When processed by a quick evaluation process, both thin and ultra-thin structures showed nominal electrical performance compare to production cell structures.

Anti-reflection coating and gridline design of the large-area (26.6 cm^2) flexible cells mimics Spectrolab production solar cells. Small-size cells (0.5 to 4 cm^2) were also fabricated using a simplified experimental process. Prototype thin cell coupons were fabricated using thin TJ

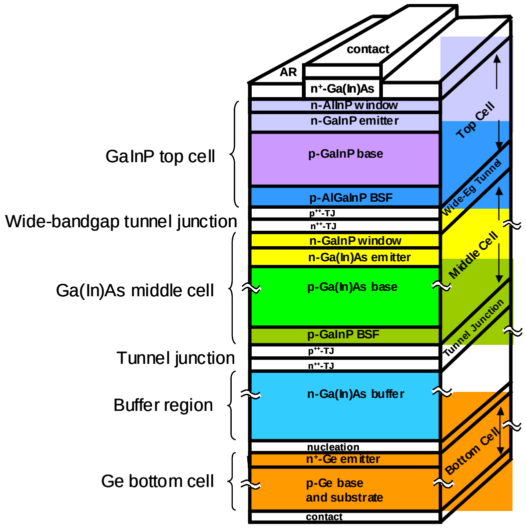

Fig. 1 Cross-sectional schematic of a thin TJ cell structure.

cells with welded interconnects, 50-µm thick Kapton sheet, and other space-qualified materials. By-pass diodes were also included in one of the flexible cell coupons.

Illuminated current-voltage characteristic of the flexible solar cells were measured using X-25 solar simulator calibrated to the AM0 spectrum. Large-area pulse solar simulator (LAPSS) calibrated to the AM0 spectrum was used to determine the performance of the prototype coupons. A fixture with a 50 mm curvature radius was used to determine the flexibility of the thin multijunction cells. The thin MJ cells were flexed when the two sections of the fixture pressed against each other by a 250 g weight. Both front and backside of the thin cells were tested. A metal cylinder with a radius of 95 mm was used to test the flexibility of the prototype thin-cell coupons. The cylinder radius met the flexible module requirement of 100 mm. The coupons were wrapped around the cylinder for over 6 hours.

RESULTS AND DISCUSSION

Thin GaInP/GaInAs/Ge Triple-Junction (TJ) Cells

Over fifty large-area (26.6 cm^2), thin GaInP/GaInAs/Ge triple-junction cells were fabricated. The thin TJ cells were

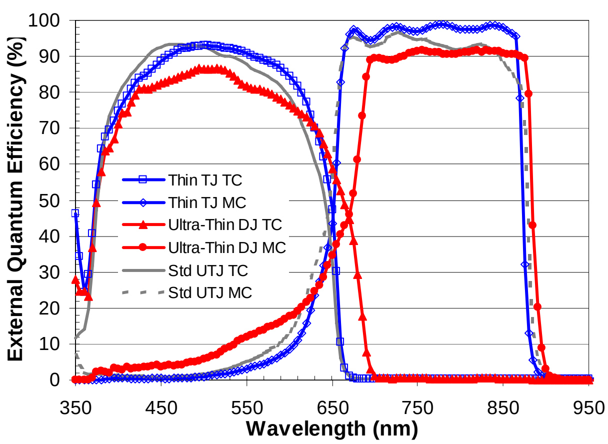

Fig. 2 Comparison of thin TJ cells, ultra-thin DJ cells, and UTJ cells external quantum efficiency performance.

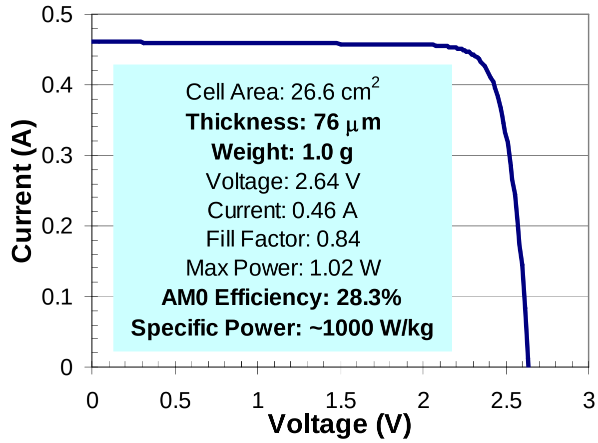

Fig. 3 Illuminated I-V data of prototype thin-cell coupons with (#1) and without (#2) bypass diodes.

50, 75, and 100 µm thick and 0.67, 1.0, and 1.3 gram in weight respectively. Figure 2 reveals the external quantum efficiency (EQE) performance of the thin TJ cells. Note that both the top and the middle component subcells showed an EQE of over 90%, comparable to that of standard UTJ cells. Figure 3 shows the illuminated I-V performance of a thin TJ cell. The thin TJ cell demonstrated an AM0 efficiency of over 28 % and an open-circuit voltage of 2.64 V. At about 1.0 gram in weight and 26.6 cm^2 in size, the 75-µm TJ cell achieved a specific power of 1000 W/kg. Figure 4 shows the efficiency distribution of the fifty thin, large-area TJ cells fabricated in this work. The thin cells demonstrated an average efficiency of 28.6 %, with the best cell achieving over 29 %. Depending on the cell weight, the specific power of the thin TJ cells ranges from 750 W/kg for the 100-µm thick cells to 1500 W/kg for the 50-µm thick cells. All thin TJ cells passed the flexibility test with the 50-µm thick cells conform to bending more than the 75 and 100-µm thick cells. The thin cells returned to their original form when removed from the bend test fixture. Interconnects were successfully welded to the three thickness types of thin TJ

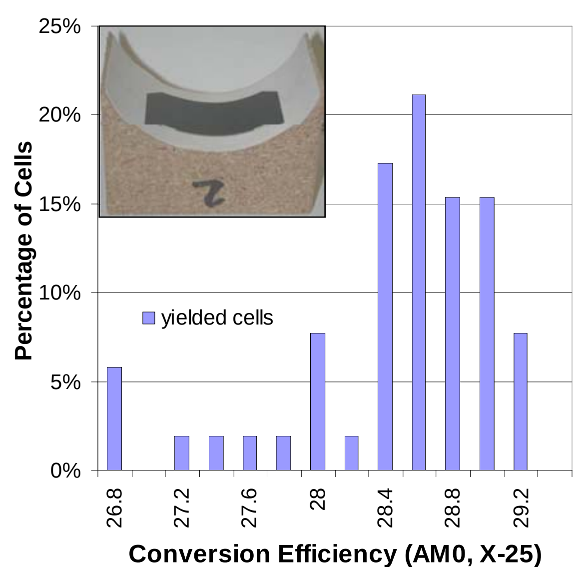

Fig. 4 Efficiency distribution of 50 large-area thin, TJ cells.

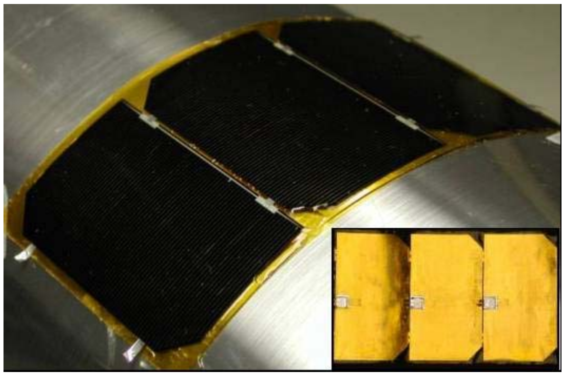

Fig. 5 A prototype thin-cell coupon rested on a 95-mm radius cylinder.

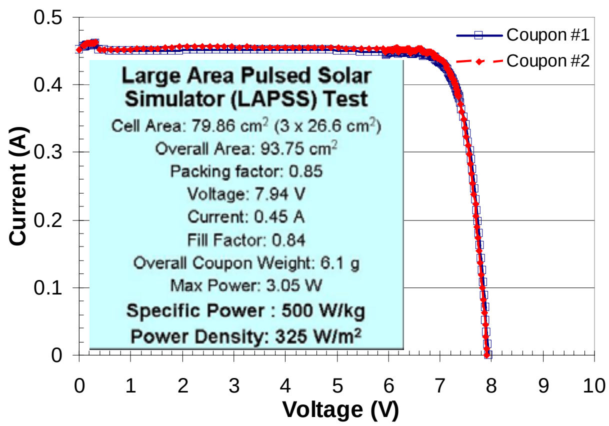

Fig. 6 Illuminated I-V data of prototype thin-cell coupons with (#1) and without (#2) bypass diodes.

cells and retested for flexibility. The cells continued to demonstrate nominal electrical performance when tested under 1-sun, AM0 conditions.

Figure 5 shows a picture of a prototype 3-cell coupon fabricated with thin TJ cells. As shown in the insert, by-pass diodes were also incorporated in the coupon. Figure 6 displays the illuminated I-V performance of 2 thin-cell coupons: with (#1) and without (#2) by-pass diodes. The 3-cell coupons generated a maximum power of 3.1 W, an AM0 conversion efficiency of 28%. At about 6 grams and 94 cm^2 in size, this translates to a specific power of over 500 W/kg and a power density of about 325 W/m^2. The thin-cell coupons were then re-tested for flexibility, followed by LAPSS testing. We have identified areas and steps in cell processing that will allow further advancements in thin TJ cell fabrication. Successful implementation of those improvements will allow large-area, thin TJ cells to reach a thickness of 25 µm or less.

Ultra-Thin GaInP/GaInAs Dual-Junction (DJ) Cells

Ultra-thin (<10-µm thick) GaInP/GaAs DJ cells with size ranges from 0.5 to 26.6 cm^2 were fabricated. Figure 7 shows a picture of sixteen 2.25-cm^2 ultra-thin cells in the original 4" wafer format. The Ge substrate (or the GaAs substrate) and the sacrificial etch-stop layer were completely removed. The remaining active DJ solar cell layers were supported by a 50-µm thick Kapton sheet. Note that >95 % of the active dual-junction layers deposited on the substrate were recovered from the process, enabling the fabrication of large-area ultra-thin multijunction cells. Preliminary results suggested that the ultra-thin solar cells fabricated by Spectrolab were fairly robust. With minor modification of the test fixture, the ultra-thin DJ cells can be handled and characterized using conventional testing protocol. Figure 2 shows the external quantum efficiencies performance of the ultra-thin DJ cells. Both the top and the middle component cells EQE were over 85%. Figure 8 shows the AM0 performance of an ultra-thin DJ cell. The ultra-thin cell demonstrated a cell efficiency of 21 % and an open-circuit voltage of 2.36 V, both comparable to that of a rigid DJ cell. However, the ultra-thin cell exhibited a relatively low shunt resistance leading to a relatively low fill factor of 0.72. At about 0.24 gram in weight and 17.5 cm^2 in size, the ultra-thin cell achieved a specific power of 2067 W/kg. Process improvements are underway to improve the shunt resistance of the ultra-thin cells in order to achieve higher specific power and high power density. The ultra-thin cells exceeded the flexibility requirement needed for the flexible module. Figure 9 shows the bending (~12 mm radius) of a large-area ultra-thin DJ cell. The cell continues to demonstrate nominal performance as shown in Fig 8.

Fig. 7 Sixteen 2.25-cm^2 ultra-thin DJ cells in 4" wafer format.

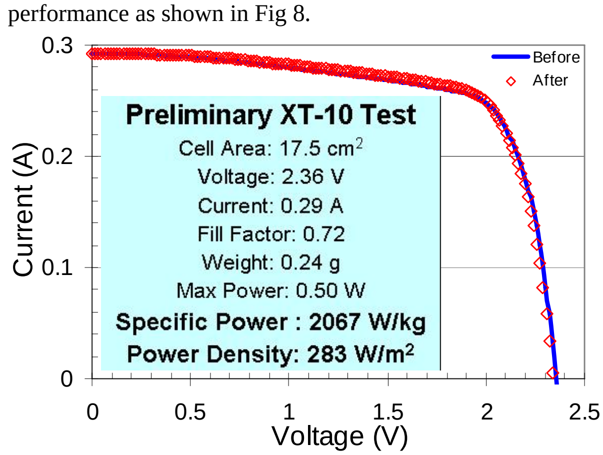

Fig. 8 Illuminated I-V characteristic of a ultra-thin DJ cell before and after flex.

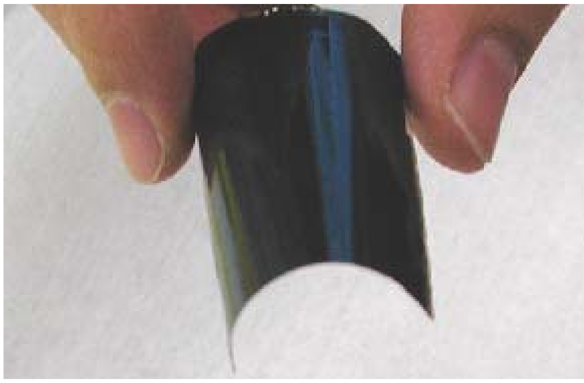

Fig. 9 Flexing of a large-area ultra-thin DJ cell.

SUMMARY

Lightweight, flexible III-V multijunction solar cells fabricated by Spectrolab demonstrated comparable performance as standard rigid MJ cells. Thin TJ solar cells showed an average AM0 efficiency of 28 % with the best cell achieving over 29 % and 1500 W/kg. The thin TJ cells also met the flexibility requirement for flexible solar array application. Prototype thin cell coupons showed a specific power of 500 W/kg and a power density of 325 W/m^2. Ultra-thin DJ cells ranges from 0.5 to 26.6 cm^2 in size were also fabricated. Preliminary performance data showed that the ultra-thin cells achieved an AM0 efficiency of 21% and a specific power of 2067 W/kg. The ultra-thin DJ cells exceed the flexibility requirement for a flexible solar array. Our results suggested that both the thin cell and the ultra-thin cell technologies can be incorporated with current and future III-V multijunction solar cell designs.

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