QUALIFICATION TESTING OF 40% METAMORPHIC CPV SOLAR CELLS

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ABSTRACT

Spectrolab is qualifying its fourth generation of terrestrial concentrator multijunction cells (C4MJ). Prototypes of this product have been tested with an average efficiency of 40% at 50 W/cm2 illumination. This new generation is a departure from previous production technology in that, for the first time, it employs metamorphic rather than lattice-matched technology.

The amount of lattice mismatch that must be accommodated by the metamorphic buffer of the C4MJ cell is small. Nevertheless, the metamorphic structure is a new cell design, and as such poses some additional risk over traditional lattice-matched CPV cells. For that reason the C4MJ cell will be subjected to extensive reliability testing at Spectrolab.
Spectrolab also has C4MJ cells in the field for on-sun testing, in cooperation with two customers.

INTRODUCTION

Concentrating photovoltaic systems have the potential to achieve a levelized cost of energy competitive with fossil generated electricity in the near future. Increased solar cell efficiency is critical to reaching that potential. Efficiency of the standard triple junction GaInP/GaInAs/Ge has increased rapidly, with average large volume production efficiencies now approaching 39%. These products have shown to be reliable during 14 years of service in space and over 3 years in concentrating terrestrial systems.

Reaching 40% and beyond will require significant changes to basic device structure, including metamorphic structures, inverted metamorphic, quantum dots, quantum wells and mechanically stacked options being evaluated by many companies around he world. This paper reports progress in qualification testing for the 40% upright metamorphic cell to be introduced for volume production in the 1st quarter 2011.

C4MJ PRODUCT DESCRIPTION

This new generation is a departure from previous production technology in that, for the first time, it employs metamorphic rather than lattice-matched technology. The epitaxial structure of metamorphic devices, illustrated in Figure 1, provides a step-graded buffer layer designed to contain the crystal dislocations in an electrically inactive region.

In metamorphic semiconductor materials and devices, the strain between the epitaxial layers and the substrate is designed to be accommodated by complete or nearly complete relaxation in the metamorphic buffer. The active cell layers, for which low minority-carrier recombination is essential for high efficiency, are then grown with low dislocation density, with the new lattice constant at the top of the metamorphic buffer. Importantly, since all or nearly all of the lattice mismatch has been worked out in the metamorphic buffer, the active cell layers are grown with very low strain, in contrast to pseudomorphic layers in which the lattice mismatch is accommodated entirely by strain in the crystal lattice.

This metamorphic approach allows these layers to be grown as thick as needed for efficient cell operation without worrying about lattice relaxation in these layers, again in contrast to pseudomorphic layers for which one must be concerned about crystal relaxation for layer thicknesses beyond the critical thickness. The low strain in the metamorphic active cell layers removes much of the driving force for any potential post-growth dislocation formation in the active metamorphic cells, for instance, due to thermal cycling.

As mentioned above, the amount of lattice mismatch that must be accommodated by the metamorphic buffer of the C4MJ cell is small. Nevertheless, the metamorphic structure is a new cell design, and as such poses some additional risk over traditional lattice-matched CPV cells. For that reason the C4MJ cell will be subjected to extensive reliability testing at Spectrolab (see Table 1).

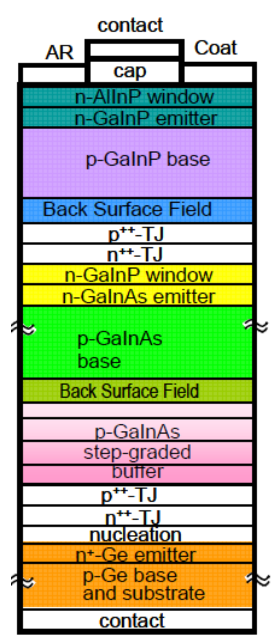

Figure 1. Metamorphic Cell Device Structure

QUALIFICATION PLAN

Table 1 lists the tests that are planned or have been completed for the qualification of the C4MJ product. The rows highlighted show the tests that have been completed or are currently in progress.

Test	Conditions	Requirement
Performance	50 W/cm2	Effmp > 37.6% target avg = 40.0%
	90 W/cm2	
Temperature coefficient	Spectral response with heated	characterization
Temperature and intensity	10, 25, 45, 65, 85 and 110C at 50, 60, 75 and 100 W/cm2	
Thermal cycle without bias	1000 cycles, -40C to +110C	unprotected cell < 2% degradation
Illuminated Thermal Cycle	1000 cycles, -40C to +110C with 50 W/cm2 light intensity	characterization
Humidity Freeze	20 cycles -40 to +85C/85% RH	
Damp heat	1000 hrs, 85C/85% RH	unprotected cell < 3% degradation
Illuminated Humidity	TBD	characterization
High temperature soak	180, 200, 225 and 250 C in N2	
High Temperature Operating Life (HTOL)	TBD	characterization
High Temperature Reverse Bias (HTRB)	-0.8V and -1.6V @ 140C until failure	characterization
High Temperature Reverse Bias (HTRB)	-0.8V and -1.6V @ 125C until failure	characterization
Outdoor test	> 10 kW on sun for 6 months	characterization
ESD	HBM, MM, CDM	characterization

Table 1. Metamorphic Qualification Tests

Spectrolab has a multi-staged process for qualifying new product generations. Some of the tests will be performed up to three times in order to build a high degree of confidence in the product. Table 2. lists the tests that will be done or have been completed for each stage. Tests highlighted in green have been completed or are in progress at this time. Results from completed tests will be discussed briefly in this paper.

Test	ADR	IDR	FDR
Performance	X	X	X
Temperature coefficient		X	
Temperature and intensity			X
Thermal cycle without bias	X	X	X
Illuminated Thermal Cycle			X
Humidity Freeze		X	X
Damp heat	X	X	X
Illuminated Humidity		X	X
High temperature soak	X		
High Temperature Operating Life (HTOL)			X
High Temperature Reverse Bias (HTRB)	X		X
High Temperature Reverse Bias (HTRB)		X	X
Outdoor test	X		
ESD		X	X

Table 2. Three Stage Gates of Qualification Tests

PERFORMANCE

The electrical output of each cell was measured under a pulsed solar simulator set up to match the ASTM G173-03 spectrum at 50 W/cm2. The average efficiency for the cells tested so far is 39.7%, using NREL calibrated standards.

Figure 2 shows the histogram of efficiency at maximum power for Spectrolab's current third generation cell, C3MJ vs. the fourth generation cell C4MJ. A light-IV curve of a typical cell is also shown in Figure 3. C4MJ exhibits a gain in current (compared to C3MJ) of around 10% with an accompanying loss in voltage that is less than half that amount. When combined with other improvements in cell design and fabrication, the relative net gain in performance is between 4% and 6% compared to the C3MJ cell.

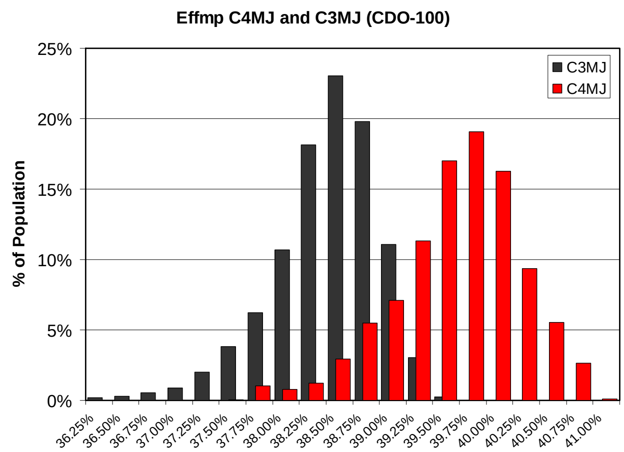

Figure 2. Maximum Power Efficiency of C4MJ & C3MJ

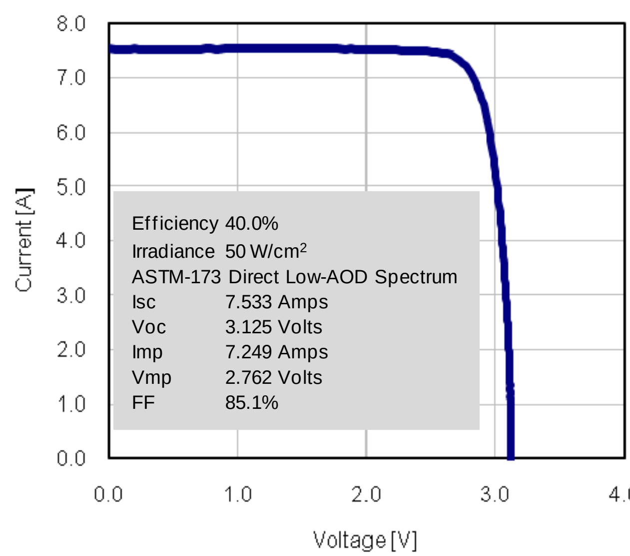

Figure 3. Light-IV curve of a typical C4MJ cell

Spectrolab has also built C4MJ cells on six inch wafers as part of the planning for transition to larger wafers. The results seen so far indicate that the six inch wafers achieve the same average performance as the four inch ones. Another promising observation is that the process distribution is also comparable to the four inch process. Improvements can be expected in both cases as Spectrolab gains experience in manufacturing the new product

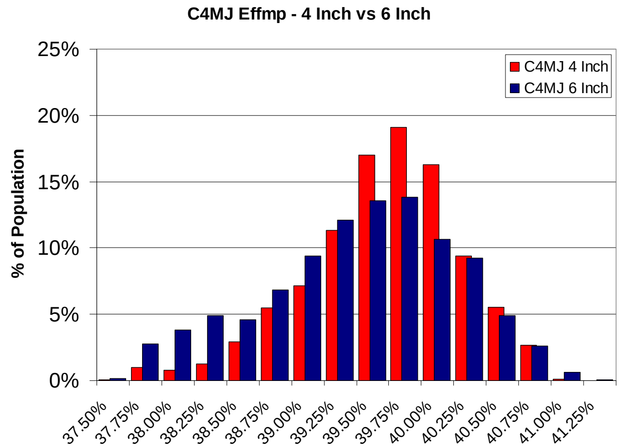

Figure 4. Maximum Power Efficiency of C4MJ, six inch vs. four inch wafers

THERMAL CYCLE TEST

Cells were subjected to 1000 thermal cycles from -40°C to +110°C. All parts were visually inspected and electrically measured initially and post thermal cycle. The requirement of the test was that cells shall have a maximum power loss of less than 10%, and the cells shall pass visual inspection.
All the cells tested showed no observable loss in maximum power, and passed visual inspection.

DAMP HEAT TEST

Cells were exposed to 85°C & 85% relative humidity without electrical bias per IEEE 1513. All parts were LIV tested and visually inspected before humidity exposure and after 500 and 1000 hrs exposure.
The cells tested showed a loss of maximum power of less than 3%.

HIGH TEMPERATURE SOAK

Test parts were placed into high temperature ovens at four different temperatures (180°C, 200°C, 225°C, and 250°C) in a nitrogen atmosphere. This test was conducted without electrical or light bias. The requirement of the test was that cells shall have a maximum power loss of less than 10% after the equivalent of 25 yrs at 110°C.

Previous tests have found the lifetime limiting degradation mechanism is front metal diffusion into active semiconductor layers. The activation energy for that mechanism is Ea = 1.0 eV.

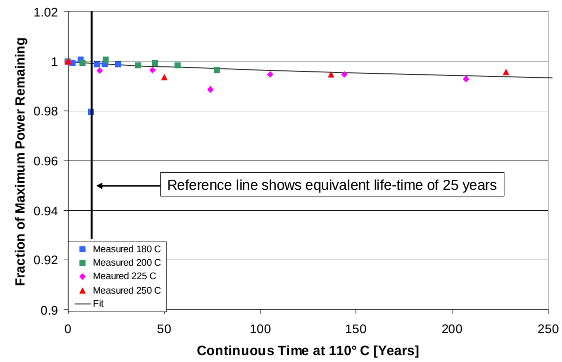

Figure 4. Measured data for maximum power plotted against equivalent time at 110°C

Data from both oven temperatures were converted to a common temperature using the Arrhenius relationship. Equation 1 shows the form used to convert time at a steady oven temperature to time at some predicted steady operating temperature.

$$t_{op}(yr) = t_{meas}(hr)\cdot \exp\left[\left(\frac{E_a}{k}\right)\cdot\left(\frac{1}{273+T_{op}(C)}\right)-\left(\frac{1}{273+Tmeas(C)}\right)\right]\cdot\left[\frac{1(yr)}{8766(hr)}\right] \quad (1)$$

where

t_{op}	time at steady operating temperature
t_{meas}	time (in hrs) at Tmeas
E_a	activation energy
k	Boltzman's constant
T_{op}	operating temperature
T_{meas}	oven temperature

Figure 4 shows the overall average data from all four temperatures plotted against the equivalent time at 110°C determined from Equation 1. The data shows C4MJ cells will survive more than 25 years operating continuously at the maximum operating temperature of 110°C with no observable degradation.

ESD TEST (C3MJ Results)

Cells were tested for ESD resistance under each of the conditions shown in Table 3. All cells passed all voltage levels with no observable effect on maximum power or dark IV characteristics

	Human Body Model	Machine Model	Charged Device Model
Standard	JESD22-A114D	JESD22-A115-A	JESD22-C101D
Voltage Levels [V]	500, 1000, 2000, 4000	100, 200, 400	200, 500, 1000

Table 3. ESD Test Conditions

FIELD TESTING

Field testing is under way with C4MJ cells now on sun at Boeing/SES as well as another Spectrolab customer. The cells have been under sun for three months and are performing as expected.

Figure 5. Boeing/SES test system with C4MJ cells installed

FUTURE PLANS

Spectrolab is planning to use its newly developed Illuminated thermal cycler for the C4MJ qualification. This tester is designed to test the cells under concentrated illumination of up to 1,500 suns. The tester has 8 test stations, each with its own independent temperature control. The cells can be cycled from -60 C to + 140 °C with dark forward current or light bias.

Figure 6. Illuminated Thermal Cycler

REFERENCES

[1] R. King et al., "40% Efficient Metamorphic GaInP/GaInAs/Ge multijunction Solar Cells," *Applied Physics Letter.* **90***,* 2007

[2] R.K. Jones et al., “Status of 40% Production Efficiency Concentrator Cells at Spectrolab”, *IEEE PVSC* **35**, 2010