VERY HIGH EFFICIENCY InGaP/GaAs DUAL-JUNCTION SOLAR CELL MANUFACTURING AT EMCORE PHOTOVOLTAICS

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ABSTRACT

The electrical performance and space qualification data of very high efficiency dual junction n/p InGaP/GaAs (on Ge) solar cells manufactured at Emcore Photovoltaics are described. The minimum average beginning-of-life (BOL) conversion efficiency of large area (27.5 cm^2) solar cells currently in production is 23.0% (28^{o}C, 1 sum AM0, 135.3 mW/ cm^2). The resulting power output per cell is 0.86 watts. The highest efficiency obtained of 25.3% represents a record for a large area dual junction cell. The results presented here are for solar cells that have an optimized end-of-life (EOL) structure. The power remaining factors after irradiation with 1-MeV electrons at fluences of 5E14, 1E15, and 3E15 e/ cm2 are 0.89, 0.84,and 0.74 respectively. The results of full space qualification testing including electrical, radiation exposure, temperature coefficients, thermal cycling, humidity, optical, and mechanical measurements will be presented.

INTRODUCTION

The need for higher power levels and smaller solar array size in space has enabled the development and volume manufacturing of high-efficiency multi-junction solar cells for the past several years [1-3]. Recently, however, the demand for higher performance and lower cost for these solar cells has intensified. In response to these market conditions, a very high-efficiency n/p InGaP/GaAs (on Ge) dual-junction solar cell was recently developed and manufactured in volume at Emcore Photovoltaics. The Emcore DJ solar cells have both the largest active area (27.5 cm2) and highest minimum lot average efficiency (23.0%) of any production DJ cell today. A schematic diagram of the InGaP/GaAs-on-Ge DJ solar cell is shown in figure 1. The device utilizes the n/p polarity to take advantage of the longer minority carrier lifetime typical of p-type III-V compounds. The two subcells are connected via wide bandgap tunnel junctions so as to minimize optical absorption in these layers.

Acceptance of the space solar cells by the satellite manufactures requires extensive space qualification tests

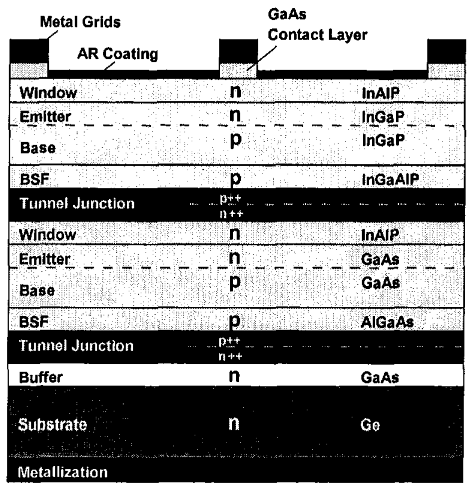

Fig.1 Schematic diagram for an InGaP/GaAs-on-Ge solar cell.

to insure long term stability of the cells on orbit. Space qualification tests include temperature cycling, humidity exposure, radiation exposure, contact metal adhesion, and cosmetic appearance. The results of the space qualification tests as well as the electrical performance of the solar cells will be discussed below.

ELECTRICAL DATA

Current-voltage (I-V) measurements were performed for every fabricated solar cell under AM0 illumination conditions. For selected cells, spectral response (SR) and quantum efficiency (QE) measurements were also performed. As mentioned earlier, the cells were designed for the best end-of-life (EOL) performance, where the thickness of the top InGaP cell is intentionally reduced from optimum. The thinner-than-optimum InGaP cell results in approximately a 7% current mismatch between the top and the bottom cells at beginning-of-life (BOL). This is illustrated in Figure 2, where a typical QE plot for a dual-junction cell is shown. As seen in the figure, the top InGaP cell produced less current than the bottom GaAs cell at BOL. The top tunnel-junction diode is composed of

III-V materials with higher energy bandgaps (Eg) than GaAs which, unlike the conventional GaAs TJ diode, allows for a greater "red" portion of the AM0 spectrum to reach the bottom cell, resulting in a greater output current. Since the InGaP cell electron radiation damage degradation rate is slower than the GaAs cell, the two subcells are expected to be current-matched at EOL (i.e., 1-MeV electron irradiation at a fluence of 1E15 e/cm^2).

The minimum lot average conversion efficiency for the dual-junction cells was 23.0% under AM0, 135.3 mW/cm^2 illumination condition, and 28°C temperature. The average values for the open-circuit voltage (V_{oc}), voltage at maximum power point (V_{mp}), short-circuit current (J_{sc}), current at maximum power point (J_{mp}), maximum power point (P_{mp}), fill factor (FF), and efficiency (η) for the cells are given in Table I.

Voc (V)	Vmp (V)	Jsc mA/cm^2)	Jmp (mA/cm^2)
2.35	2.1	16.3	14.9

Fill Factor (%)	Pmp (W)	Efficiency(%)
81.5	0.86	23.0

Table I. Minimum average electrical performance of InGaP/GaAs-on-Ge dual junction solar cells under 28° C, 1 sun AM0, 135.3 mW/cm^2 solar constant (cell area= 27.5 cm^2)

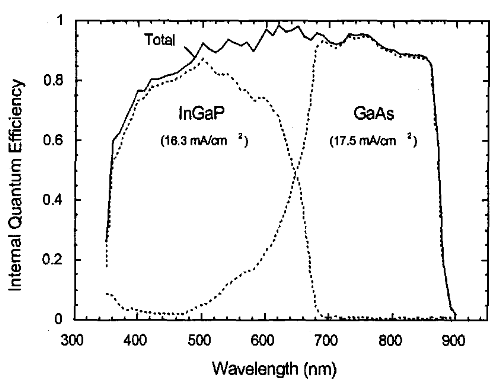

Fig. 2 Typical QE plot for a dual-junction InGaP/GaAs production solar cell optimized for EOL conditions.

The highest measured efficiency for the large-area (27.5 cm^2) solar cell was 25.3% (AM0, 135.3 mW/cm^2, 28°C). To the best of our knowledge, this is the highest measured efficiency for a large-area InGaP/GaAs dual-junction solar cell grown on a Ge substrate. The I-V plot for this cell is shown in Figure 3.

A typical yielded efficiency distribution curve for 7498 large-area dual-junction cells is shown in Figure 4. As seen in the figure, a relatively narrow distribution of performance is observed with these cells. This narrow distribution is very desirable for the purpose of selecting cells for panel and array fabrication, where balance of output power is critical in the panel circuit strings. The high BOL efficiency values and tight performance distribution observed with these cells are mainly due to the high degree of epitaxial growth material quality and uniformity across the wafer, as well as, across the wafer platter that accommodates twelve 100-mm diameter Ge wafers.

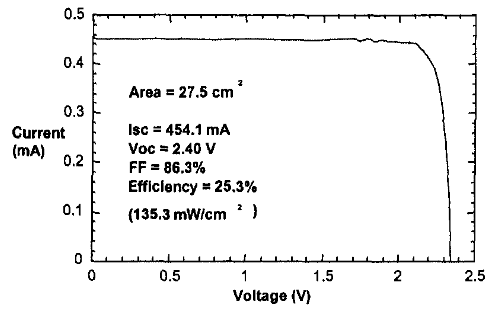

Fig. 3 Illuminated I-V plot of a large area InGaP/GaAs-on-Ge production solar cell with a record AM0 efficiency of 25.3%.

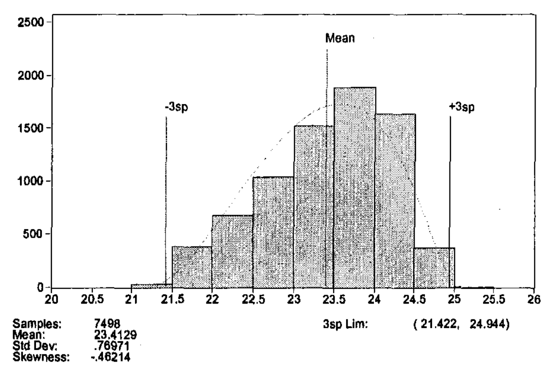

Fig 4.Ttypical yielded efficiency distribution curve for a batch of 7498 large-area dual-junction solar cells.

RADIATION TESTS

In order to accommodate the high energy particle beam uniformity limitations, solar cells that were sent for radiation testing had a 4 cm^2 cross-sectional area instead of the production value of 27.5 cm^2. A batch of 40 solar were irradiated with 1-MeV electrons at fluences of 5E13, 1E14, 5E14, 1E15 and 3E15 e/cm^2. The light I-V characteristics was measured for every cell before and after 1E15 and 3E15 e/cm^2. The average remaining power factors (P/Po) after electron irradiation at each fluence is given in table II.

The power remaining factors shown in table II indicate a high radiation resistance to electron damage. In fact these power remaining factors are the highest reported to date for production dual device on Ge. The radiation hardness was improved by implementing a doping profile for both top and bottom cells that was optimized via modeling studies. The modeling looked at the effect of the doping profile upon the minority carrier lifetime under various 1-MeV electron doses. [4]

Radiation Dose (e/cm^2)	P/Po
5×10^{13}	0.98
1×10^{14}	0.96
5×10^{14}	0.89
1×10^{15}	0.84
3×10^{15}	0.74

Table II. Average remaining power factors (P/Po) for dual-junction cells after 1-MeV electron irradiation.

TEMPERATURE COEFFICIENT MEASUREMENTS

The solar cell BOL and EOL electrical measurement results are normally reported at an ambient temperature of 28°C. The actual operating temperature of the cells in an array in space is usually greater than the room temperature on earth. Solar arrays in space normally operate in the approximate temperature range of 50-70°C in the geosynchronous orbit (GEO) and 70-90°C in the low-earth orbit (LEO). Hence, the electrical characterization of the cells as a function of temperature were also carried out. From the measured solar cell power output as a function of temperature, a linear degradation rate is extracted. This degradation rate is a figure of merit for a cell, and it is referred to as the temperature coefficient. The temperature coefficients were measured on 48 2x2 cm2 cells before and after being irradiated with 1 MeV electrons.

The temperature coefficient measurements were performed in the temperature range of 28-80°C in 10°C increments. Under the BOL conditions, a coefficient of -0.033 absolute percentage per degree Celsius (abs.%/°C) was measured. The BOL temperature coefficient measurement results for P_{mp}, and η are presented in Table III. These results are comparable to what has been reported previously for the dual-junction InGaP/GaAs-on-Ge solar cells [6].

To determine the EOL temperature coefficients, the performance of the cells was measured as a function of temperature after they were irradiated with 1-MeV electrons in the fluence range of 5E13 to 3E15 e/cm^2. The EOL temperature coefficient measurement results for P_{mp}, and η for the fluence range of 5E13 to 3E15 e/cm^2 are presented in Table III.

Dose (e/cm^2)	ΔPmax (μW/ °C-cm^2)	ΔEff (abs. %/°C)
0	-49.4	-0.036
5×10^{13}	-51.4	-0.037
1×10^{14}	-50.6	-0.037
5×10^{14}	-54.1	-0.039
1×10^{15}	-51.6	-0.038
3×10^{15}	-48.8	-0.036

Table III. Temperature coefficients as a function of radiation dose (1-MeV e's) for InGaP/GaAs-on-Ge dual-junction solar cells.

TEMPERATURE CYCLING AND HUMIDITY EXPOSURE

As part of a satellite, solar cells in space experience many temperature cycles while orbiting the earth. The cells must retain a great deal of their electrical performance and mechanical robustness in the course of this temperature cycling. Accelerated testing is normally performed on earth to characterize the electrical and mechanical performance of the cells. Fifteen thermal cycles were performed in the temperature range of -180 to +140°C, followed by 2000 cycles in the temperature range of -180 to +90°C to simulate the GEO thermal conditions. The following tests were performed before and after temperature cycling: electrical I-V measurements, welded interconnect adhesion pull strength measurements, and anti-reflection coating (ARC)/cell surface adhesion strength test.

The widely accepted criterion for the performance of the solar cells after temperature cycling is that the cells must not degrade in efficiency by more than 2% (relative). Twelve dual-junction solar cells were subjected to the temperature cycling schedule described above. The average degradation in efficiency was measured to be less than 1.4% (relative). For the inter-connect pull strength test, the interconnects (usually silver tabs) that are welded to the cell metal contact pads were pulled, at an angle of 45°, until the weld integrity was compromised. The three possible failure mechanisms for welded contact pull test were: metal contact de-lamination, interconnect tab breakage, or cell breakage. The pull-strength force values for front and back metal contacts were 698 and 669 gram-force, respectively. These values exceeded the traditional requirement for the pull strength force of ≥500 gram-force. The pull-strength force values were measured when either the silver tab tore or the cell broke, i.e., no front or back metal contact de-lamination was observed.

Fifteen solar cells were also subjected to a relativehumidity (RH) atmosphere of 95% for 30 days at an ambient temperature of 45°C. The average degradation in efficiency was measured to be less than 1.35% (relative).

Welded contact integrity test was also carried out after the humidity test. The pull-strength force values for front and back metal contacts were 605 and 740 gram-force, respectively. These values again exceeded the traditional requirement for the pull strength force of ≥500 gram-force. As before, the front and back metal contacts never delaminated during the pull-strength tests

The adhesion of the AR-coating to the solar cell surface was tested by two traditional methods: the eraser rub and 3M adhesive tape pull tests. The structural integrity and adhesion of the AR-coating was maintained after these tests. The surface appearance of the coating also remained unaffected. In addition, the average solar cell absorptance and emittance were measured to be 0.90 and 0.87, respectively.

A summary of the mechanical test results for electrical degradation, pull-strength tests after temperature cycling, and humidity exposure are given in Table IV.

Test Items	Test Results
Metal Contact Thickness	Ave. 4.8 um
Contact pull strength	650 gm
Electrical performance degradation after temperature cycle	1.84%
Contact pull strength after temperature cycling	665 gm
Electrical performance degradation after humidity soak	1.33%
Contact pull strength after humidity soak	672 gm
Absorptance from bare cells	0.9
Emittance from bare cells	0.874
Contact and coating adhesion	No peel
Appearance	No chips or cracks

Table IV. Mechanical Qualification Test Results

SUMMARY

High-volume manufacturing of large-area (27.5 cm^2) dual-junction n/p InGaP/GaAs solar cells, grown on 100-mm diameter Ge substrates, has been established at Emcore Photovoltaics (EPV). The minimum lot average conversion efficiency was measured to be 23.0% (AM0, 135.3 mW/cm^2, 28°C). Record BOL efficiencies as high as 25.3% were measured for the large-area solar cells. The cell structure was optimized for the best EOL performance.

As part of the space qualification program, irradiation tests with 1-MeV electrons were conducted under several fluence levels. The average measured remaining power fraction (P/P_o) after irradiation were 0.97, 0.94, 0.88, 0.83, and 0.67 for 5E13, 1E14, 5E14, 1E15, and 3E15 e/cm^2 fluences, respectively.

Temperature coefficient measurements were performed in the temperature range of 28-80°C in 10°C increments. The solar cell efficiency temperature coefficients for the 1-MeV 5E13, 1E14, 5E14, 1E15, and 3E15 $electrons/cm^2$ fluences were measured to be -0.031, -0.030, -0.031, -0.028, and -0.021 absolute percent per °C, respectively.

The dual-junction solar cells were subjected to fifteen thermal cycles in the temperature range of -180 to +140°C, followed by 2000 cycles in the temperature range of -180 to +90°C to simulate the GEO thermal conditions. The average degradation in cell efficiency was measured to be less than 1.4% (relative). The cells were also tested for mechanical metal contact weld integrity. The pull-strength force values for front and back metal contacts were measured to be 698 and 669 gram-force, respectively. These values exceeded the traditional requirement for the pull strength force of ≥500 gram-force.

The solar cells were subjected to a relative humidity (RH) atmosphere of 95% for 30 days at an ambient temperature of 45°C. The average degradation in cell efficiency was measured to be less than 1.35% (relative). Welded contact integrity test was also carried out after the humidity test. The pull-strength force values for front and back metal contacts were measured to be 605 and 740 gram-force, respectively.

The adhesion of the AR-coating to the solar cell surface was tested by the eraser rub and 3M adhesive tape pull tests. The structural integrity and adhesion of the AR-coating, as well as, the surface appearance of the coating were maintained after these tests. The average solar cell absorptance and emittance were measured to be 0.90 and 0.87, respectively.

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