Multijunction Solar Cell Technology for Mars Surface Applications

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ABSTRACT

Solar cells used for Mars surface applications have been commercial space qualified AM0 optimized devices. Due to the Martian atmosphere, these cells are not optimized for the Mars surface and as a result operate at a reduced efficiency. A multi-year program, MOST (Mars Optimized Solar Cell Technology), managed by JPL and funded by NASA Code S, was initiated in 2004, to develop tools to modify commercial AM0 cells for the Mars surface solar spectrum and to fabricate Mars optimized devices for verification. This effort required defining the surface incident spectrum, developing an appropriate laboratory solar simulator measurement capability, and to develop and test commercial cells modified for the Mars surface spectrum. This paper discusses the program, including results for the initial modified cells. Simulated Mars surface measurements of MER cells and Phoenix Lander cells (2007 launch) are provided to characterize the performance loss for those missions. In addition, the performance of the MER rover solar arrays is updated to reflect their more than two (2) year operation.

MOST (Mars Optimized Solar Cell Technology)

The development of modified GaInP/GaAs/Ge multijunction solar cells was funded by NASA Code S as part of the Low Cost Mission Technologies Task under the Mars technology program. The overall goal of the program is to develop advanced photovoltaic technologies that will enable low cost and long duration Mars surface missions. The specific objective for MOST is to develop high efficiency solar cells that are optimized for the Mars surface environment. JPL teamed with the two U.S. space cell manufacturers, Spectrolab and Emcore, to appropriately modify conventional high performance 3-junction cells to optimize performance for the Mars. The MOST task is in three phases, each with approximately one year duration, going from Mars surface spectrum definition through establishing manufacturing process adjustments for optimized cells.

The initial step in this activity was to define the surface incident spectrum. Work has been done over past years to establish the surface spectrum based on atmospheric studies and data from previous Mars missions [1, 2]. The model was updated for MOST with recent MER data. The resulting spectra take into account atmospheric opacity (tau) and surface latitude. Tau varies primarily with the amount of dust in the atmosphere and a baseline value of 0.5 was used. This is a level observed during periods essentially free from dust storms. The spectral data was then used to develop a set of optical filters to modify the spectral output of the X-25 solar simulator at JPL. Two filter sets were developed, one for 30^o latitude solar spectrum (Equatorial region) and one for 60^o latitude solar spectrum (near polar region). The filters were placed in aluminum filter plates which can be readily placed in front of the X-25 AM0 beam, allowing for easy change of measurement conditions as shown in Fig. 1.

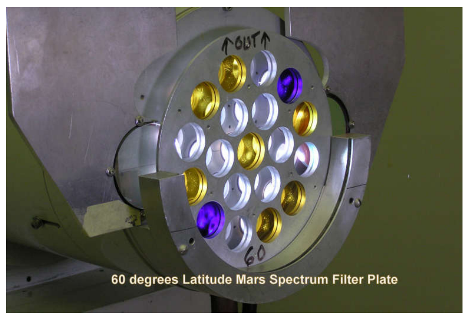

Fig. 1. Filter plate for the Mars 60^o latitude spectrum inserted in the X-25 beam.

The measured 60^o latitude X-25 spectrum is shown in Fig. 2 compared to the calculated spectrum on Mars. The curves are all normalized to AM0 at 580 nm.

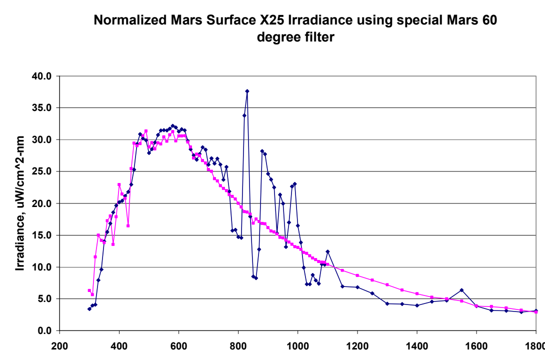

Fig. 2. Measured X-25 solar simulator spectrum for Mars 60^o latitude compared to MER corrected Mars spectrum (magenta).

CONTRACTOR RESULTS

Emcore has fabricated solar cells designed for the 60° Latitude Martian solar spectrum. When tested with the Mars corrected X-25 solar simulator at JPL, the cells have shown a 2.2% absolute efficiency improvement over standard Emcore ATJ cells, which are designed for the Earth AM0 spectrum. The peak efficiency achieved was 27.4%, with a power density of 6.13 mW/cm^2. Modeling suggests the cells can achieve 28% efficiency. JPL measured data is shown below in Fig. 3.

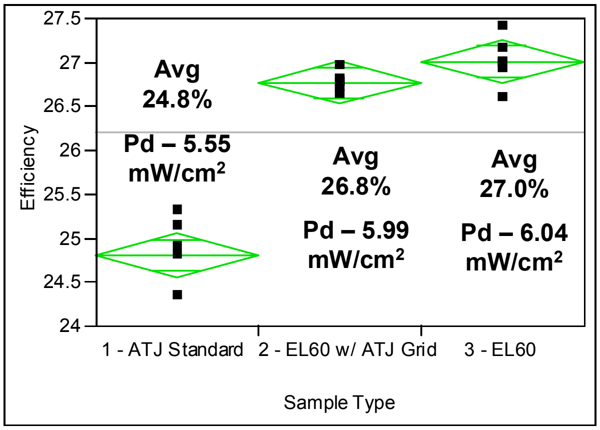

Fig. 3 JPL measured data of ATJ and EL60 (Mars optimized) cells. EL60 Cells were also fabricated with ATJ type grids to evaluate the new grid design.

The Mars optimized cells incorporated modifications to the epitaxial structure of the cells to correct for excessive content in the red portion of the Martian 60° latitude spectrum as well as a grid design optimized for low solar intensity. This design is referred to as "EL60". To achieve current matching, the InGaP top cell must increase current generation by almost 5% compared to an Earth AM0 top cell. V_{oc} and FF were not notably impacted by the modifications. Program restrictions of the first phase of the program dictated that cell modifications were to be made so as to minimize re-qualification cost and complexity. In the second phase of the program this efficiency improvement will be increased by further improvement to the epitaxial structure and anti-reflection coating (ARC) design. The ARC design is believed to be the primary source of the missing 0.6% of efficiency. All cells were fabricated with an ARC that is optimized for use with a coverglass. Future cells will be tested with an ARC optimized for a bare cell.

The EL60 grid design features a significantly increased grid pitch relative to space ATJ designs with a busbar width that was reduced by nearly one third. The current produced by the 60° Martian spectrum is about 15% of that produced from the Earth AM0 spectrum which notably reduces emitter sheet resistance losses. Additional resistive power loss from the reduction of front-side grid metal is less than a quarter of a percent, while shading is reduced by almost 50%. Fig. 3 shows that the Mars optimized grid design improves efficiency by about 0.75% relative.

Future enhancements to the MOST designs will utilize the soon-to-be-released BTJ solar cell platform which is expected provide an absolute 1% improvement to the optimized cell efficiency.

Spectrolab, Inc, continued their efforts at optimizing the Ultra-Triple Junction solar cell (UTJ) for the Mars surface solar spectrum, focusing on the 60-degree latitude spectrum. A previous report showed a 4.4% relative increase in maximum power by current matching in the top two subcells of the triple junction [3]. The current densities in the top and middle cells are appropriately matched for the reduced blue content of the 60-degree latitude solar spectrum on the surface of Mars. The same cells were delivered to JPL for LIV verification testing. Fig. 4 shows the maximum power density obtained by JPL (open circles) on an X25 solar simulator for each cell and the average shown with a solid line. The group averages show a 4.1% relative increase in power. Recalculating based on yielded power (>5.3 mW/cm^2, shown as filled circles), gives 5% relative increase in power over an AM0 optimized device.

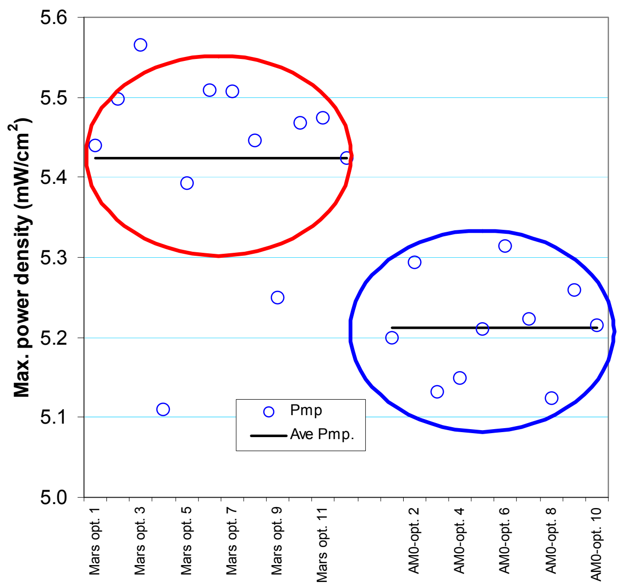

Fig. 4 LIV results of Mars cells optimized for the 60 degree latitude surface spectrum obtained by JPL (left) compared to AM0 optimized cells (right).

While the relative improvement in the Mars-optimized cells calculated from both data sets is similar, the absolute values measured at Spectrolab are higher. The values obtained by Spectrolab are higher in Voc by ~22 mV and in Jsc by 0.24 mA/cm^2. The difference seems larger than just from the calibration standards used by each facility. It is important to find the source of this difference and additional characterization is underway. Component top and middle cells will be built by Spectrolab for more accurate LIV testing once a more finalized device design is chosen and a round robin LIV characterization between JPL and Spectrolab will be performed.

Nevertheless, both data sets show nearly the same relative gain in power density for the Mars optimized cell.

A subset of prototype Mars-optimized cells has been CIC'd (cell interconnect coverglass) to determine the subcell current balance at the CIC'd level. The cells were CIC'd using standard production techniques and CMG coverglass. Any changes in current balancing need to be incorporated for maximum power at the CIC level. Preliminary characterization of Mars-optimized bare cells, i.e. no coverglass, at temperatures between 6 and 28C was performed with both LIV and EQE. The measurements were performed in air. Fig. 5 shows the integrated short circuit current density (Jsc) as a function of temperature from EQE on the left-hand axis. Voc as a function of temperature is shown on the right-hand axis. The initial results indicate that there is no difference in temperature coefficients for the Mars optimized cell for ΔVoc/ΔT and ΔJsc/ΔT.

It will be important to characterize the performance as a function of temperature over a wider range of temperatures on the final cell design. Further electrical characterization is in progress over a wide range of operating conditions a cell on Mars may expect to encounter. Additional characterization is planned to determine □Pmp/□T for the Mars optimized cell under various operating conditions.

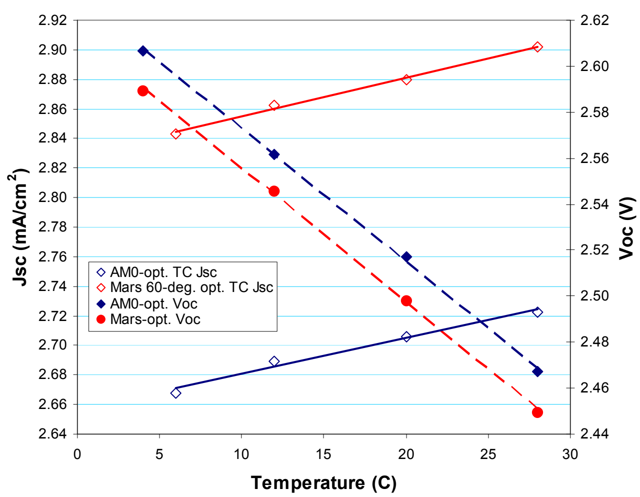

Fig. 5 Top cell integrated Jsc for AM0 and Mars 60-deg. optimized cell vs. temperature.

PHOENIX

The Phoenix Lander, scheduled for launch in 2007, has significantly different requirements than MER. The lander will not have a capability to move. Therefore, its 90 day lifetime requirement is based on the time expected to complete the primary science which utilizes expendable analysis "packets." Whereas the MER rovers are located near the equator where the solar incidence is highest, Phoenix will land close to the North Pole (between 60° and 70° latitude) where the solar intensity is greatly reduced, the sun position being low in the sky. In addition, the time of landing will be when Mars is at its furthest distance from the sun. The power analysis assumes that the lander lands on "flat" terrain. Power generation for the lander consists of two deployable ATK Ultraflex solar arrays of 2 meter diameter, using Ultra Triple Junction (UTJ) solar cells from Spectrolab. (MER uses previous generation Improved Triple Junction, ITJ, solar cells from Spectrolab). Unfortunately, the Phoenix array assembly schedule precluded to opportunity to use Mars optimized UTJ cells.

The impact of the Mars atmosphere on the UTJ solar cell performance was measured by testing with the JPL Mars solar simulator. A filter set for 60° latitude was assembled and verified. The solar intensity was calculated for 60° solar illumination incidence AM0, corresponding to the solar intensity at the top of the atmosphere, or on the Martian surface without an atmosphere. A group of 20 UTJ CICs (Phoenix spares) was measured with the X-25 using AM0 filters using the calculated intensity. A second intensity was calculated for the same illumination angle, but at the Mars surface with an atmosphere. The UTJ cells were then tested using the 60° Mars setup. The results of these tests are as follows:

AM0 efficiency (at Mars)	24.9%.
Mars surface efficiency	23.7%
Mars effective efficiency	22.0%

Mars effective efficiency is defined as the actual power on the Mars surface compared to the AM0 fluence at Mars. For Phoenix cells, this leads to 21.97%**,** or 13% less than the corresponding AM0 efficiency. It is a measure of the cell power reduction due to the Martian atmosphere.

MER

The MER rovers were required to survive for 90 days. This was based on an estimate of the time needed to carry out the primary science activities and also the estimate of time before dust deposition would reduce the array performance below minimum power levels. Similar to Phoenix the performance of the Spectrolab ITJ cells is reduced by the Martian atmosphere. Measurements made at JPL on ITJ CICs (residuals from MER) using a 30 degree Mars latitude filter pack, lead to the following characteristics:

AM0 efficiency (at Mars)	25.8%
Mars surface efficiency	23.6%
Mars effective efficiency	22.0%

As is now obvious, the initial 90 day life has been extended by almost an order of magnitude. In part, this is due to creative management of the Rover electronics during periods of low array energy generation. However, the largest factor, by far, has been the finding that dust does not continue to build up on the arrays. Rather, Mars weather turns out to have frequent windy – even dust devil – periods when much or even most of the dust is removed. Although predicting future performance has its risks, it now appears that the mission life may be determined by factors other than low array power.

Fig. 6 shows the Rover overall power performance since mission commencement through mid April, 2006. This includes seasonal cycles, sun to Mars distance variation, Rover location, atmospheric conditions, and array dust accumulation status. In addition, Fig. 7 shows the array loss due to dust accumulation, based on current from the Isc cell. The dust re-accumulation rate after dust removal appears similar to the initial accumulation rate. Data is shown for Opportunity; Spirit is similar.

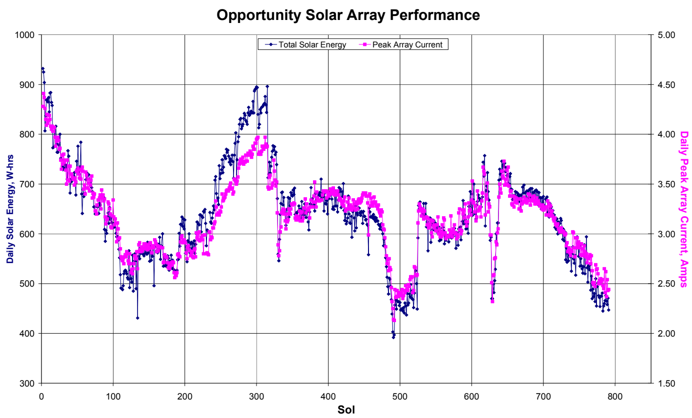

Fig. 6 Opportunity Power Performance (Magenta – peak array current, dark blue – total solar energy)

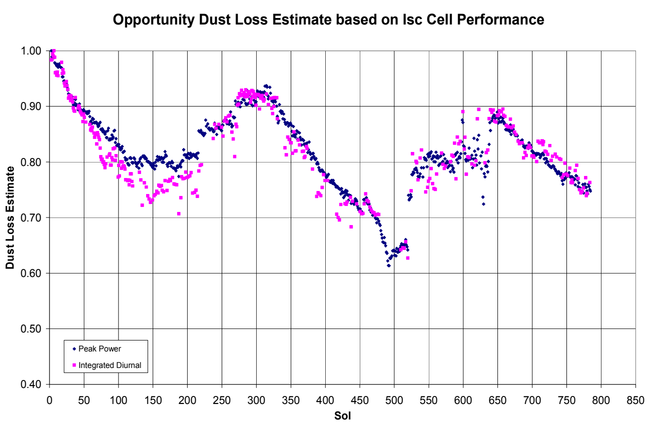

Fig. 7 Opportunity Dust Loss Estimated from Isc Performance (magenta – peak power, dark blue – integrated diurnal)

CONCLUSION

Prior to the advent of the MOST program, the estimated Mars surface solar array performance was based on its AM0 output at the distance of Mars, modified by a factor to account for the atmosphere. With the continuing success of the MER rovers, it is clear that the use of multijunction photovoltaics on the surface is a realistic option for high power, long lived operation. The MOST program has resulted in development of a solar simulator that can provide the appropriate spectrum of sunlight on the Martian surface. Measurements of MER and Phoenix Lander cells show a loss of ~10-15% in effective efficiency. Preliminary cells from the MOST program have demonstrated that it is possible to regain much of the cell efficiency lost by the change in the spectrum from AM0 to that incident on the Mars surface. The MOST program is in the process of demonstrating that AM0-optimized high efficiency solar cells can be tailored to operate more optimally under Mars surface conditions and generate higher power and predictability over a range of conditions. Teaming with the two U.S. space cell manufacturers is expected to result in a low cost process for providing these cells.

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