

Multijunction Solar Cells Optimized for the Mars Surface Solar Spectrum

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Introduction

This paper gives an update on the performance of the Mars Exploration Rovers (MER) which have been continually performing for more than 3 years beyond their original 90-day missions. The paper also gives the latest results on the optimization of a multijunction solar cell that is optimized to give more power on the surface of Mars.

The two Mars rovers, Spirit and Opportunity have been operating on Mars for nearly four years. The operational experience has given mission planners more confidence and ability in predicting power performance for continued operation on Mars. The interaction of dust with the solar cell arrays will be discussed.

State of the art multijunction solar cells from Spectrolab have been optimized for the Mars surface solar spectrum at zenith angles of 60°. The surface solar spectrum on Mars is reduced to ~16% of the AM0 intensity, and further reduced in the blue portion of the spectrum. Multiple Mars-optimized cell designs based on space-heritage GaInP/GaInAs/Ge multijunction solar cells have been grown, fabricated, and tested under a number of different light current-voltage (LIV) test conditions. The device modifications have resulted in further improvement in device performance ranging from 3 to 8% increase in maximum power, or equivalently in efficiency, relative to commercially available AM0-optimized cells.

Mars Exploration Rovers (MER) Status

The MER rovers have been demonstrating the capability of photovoltaic arrays to operate for extended periods of time on Mars. Although the original MER rover operation goal was 90 days, as of the end of August, 2007, both rovers had surpassed the previous operations record set by the Viking Lander 2, of 1281 Sols Mars days). Critical to this accomplishment was the removal of dust from the panels apparently by Mars atmospheric winds and creative power management approaches developed by the Mars Surface Operations Team. The operational experience with the MER rovers and the development of higher efficiency cells can expand the possible applications for photovoltaics on the Mars surface.

Fig. 1 depicts the overall power performance of Opportunity since the initial landing. Two parameters are shown, corresponding to diurnal array peak current and energy. Since the rover arrays operate at a fixed voltage, the current and energy obviously track each other for the most part. The data shown reflects the influence of many factors such as dust coverage, atmospheric opacity, sun distance and inclination, as well as rover orientation on the surface. Evident are periods of dust accumulation and dust removal. The recent planetary wide dust storms after Sol 1200 show the rapid decrease in array performance due to the atmospheric opacity increase from high dust content (increased tau).

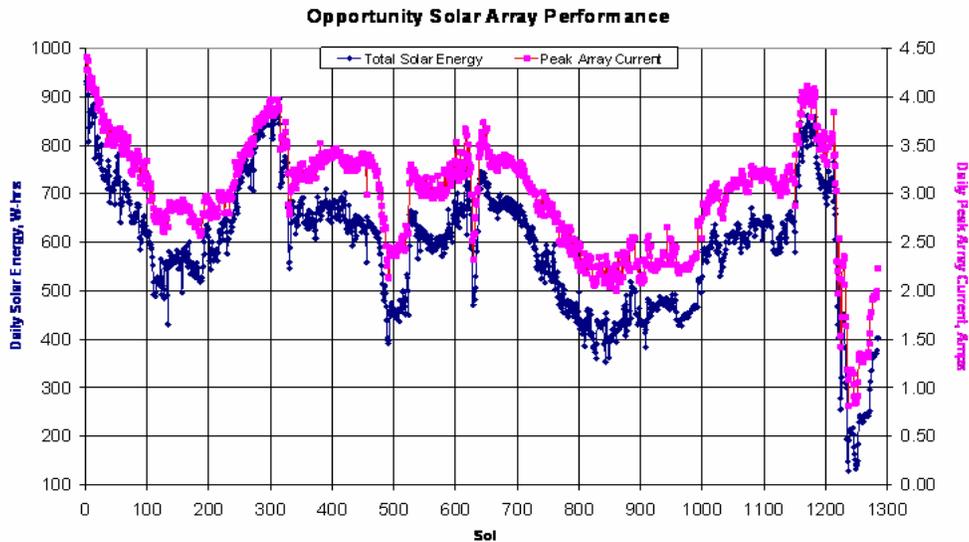


Fig. 1 Opportunity solar array performance

Fig. 2 shows the derived array dust coverage factor after removal of the effects of solar distance, season, tau, and rover orientation.

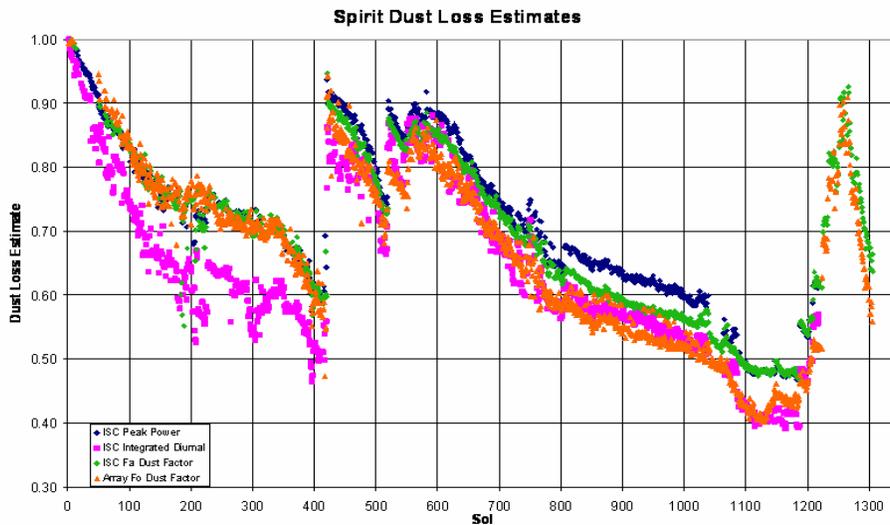


Fig. 2 Opportunity dust loss estimates

The pattern of panel dust deposition and dust removal is clear. Also noteworthy is that the dust accumulation for Opportunity never reduced the array performance by more than 40%. In the case of Spirit, array performance fell by 50% and 60% before recovering through dust removal. It is interesting that for both rovers, dust removal is observed at the beginning of the major Martian dust storm at ~ Sol 1200. The re-accumulation of dust then begins before the storm ends. A possible interpretation is that the increased winds of the storms initially remove dust from the panel and then as the winds begin dissipating, a large quantity of the atmospheric dust then falls onto the panel surfaces. Consequently the array output represents a balance between dust removal/deposition on the panels and atmospheric dust content (related to level of atmospheric turbulence).

In terms of a "visual" impact, Fig. 3 combines photos taken over a sequence of days with increasing atmospheric dust content (tau), at approximately the same time of day (near noon). The change in lighting is quite evident. In the last photo, it is difficult to visually separate the sky from the ground. For comparison, much of the rovers' operations have been with a tau of approximately 0.5.

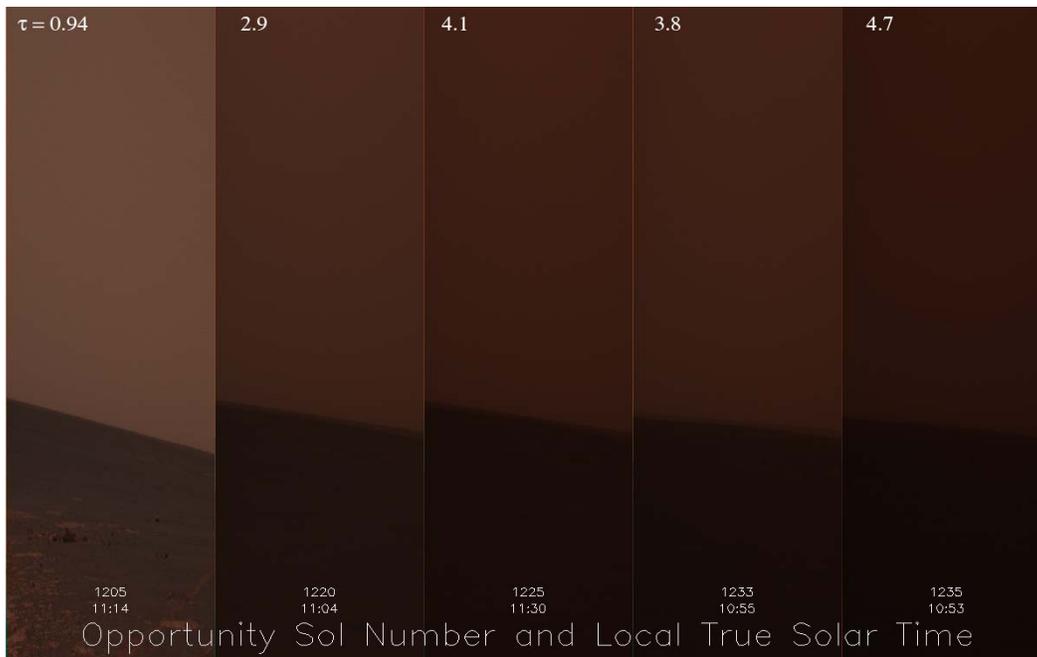


Fig. 3 Brightness photos for change in atmospheric tau

Mars Surface Optimized Multijunction Cell

Because of the success of the Mars Exploration Rovers (MER), Spirit and Opportunity, further work has been pursued on the optimization of multijunction solar cells similar to the ones used on MER. The goal is to develop higher performance solar cells that will be used to power the next generation of rovers and other missions planned to operate on the surface of Mars.

As mentioned previously, the insolation on the surface of the planet Mars depends on many factors, such as season, time of day (sol), latitude, optical clarity (tau), and atmospheric dust that accumulates on the surface of the solar cells, not unlike that encountered on the surface of earth in terrestrial solar cell applications. A Mars surface spectrum at the 60-degree zenith angle and tau = 0.5 was defined by JPL for the purposes of optimization, to provide a direct comparison to the AM-optimized Phoenix solar cells. The optimized cell is also applicable to use at lower latitudes. One observation regarding the Mars surface spectrum is that its blue content is reduced in intensity; therefore if an AMO-optimized cell is used on the surface, there is a loss in performance due to the non-optimal condition that the top cell current limits the total multijunction current.

A Mars-optimized baseline design was developed earlier in this program, resulting in higher performance from improved current matching in the triple-junction solar cell [1]. Preliminary LIV verification testing at JPL was performed and confirmed the results. The optimization described here started with the baseline design of this previous work.

The new Mars-optimized designs are based on space heritage commercially available GaInP/GaInAs/Ge triple-junction solar cells. All of the Mars-optimized solar cell designs have a current-matched top cell. Additional changes that are easy to implement were made to the baseline design and are labeled as types A-C. The type A design is similar to the baseline with one change to the structure. Types B and C both contain type A changes and additional modifications. Type A only had one MOVPE run in addition to the baseline, whereas the other designs had two runs each. Selected wafers from each MOVPE run and design type were fabricated into fully processed 2 cm x 2 cm cells using standard production processing.

For illuminated current-voltage (LIV) characterization, the cells were measured on a Spectrolab X-25 solar simulator at 28°C. The X-25 was calibrated to a simulated Mars 60-degree spectrum using spectrally calibrated top and middle component subcells and information from JPL.

Blue reduction filters were placed within the beam path to simulate the reduction in the blue portion of the Mars 60-degree spectrum. Wire mesh screens were placed in the beam path to reduce the overall intensity of the simulator. Cells were measured on a water cooled fixture using a four-probe configuration.

Preliminary Results

Fig. 4 shows the average relative percent increase in Jsc, Jmp, and Pmp, for the baseline design as well as for the three experimental designs. The first green diagonally striped bar is the average increase in short-circuit current density (Jsc) relative to the AM0-optimized control. Jsc is increased over the AM0 control by 7% or more, which is due to current matching the top and middle cells. The blue solid bar is the average increase in maximum power current density (Jmp) relative to the AM0-control. This increase ranges from 5 to 7%. The third red vertically striped bar is the average increase in maximum power (Pmp) relative to the control. This average relative gain in maximum power ranges from 3 to 8%, which is a major improvement in cell performance. Cells were yielded at FF>78%. The cell populations are 42, 84, 36, 48, and 78 cells, for the AM0, baseline, type A, type B, and type C groups, respectively.

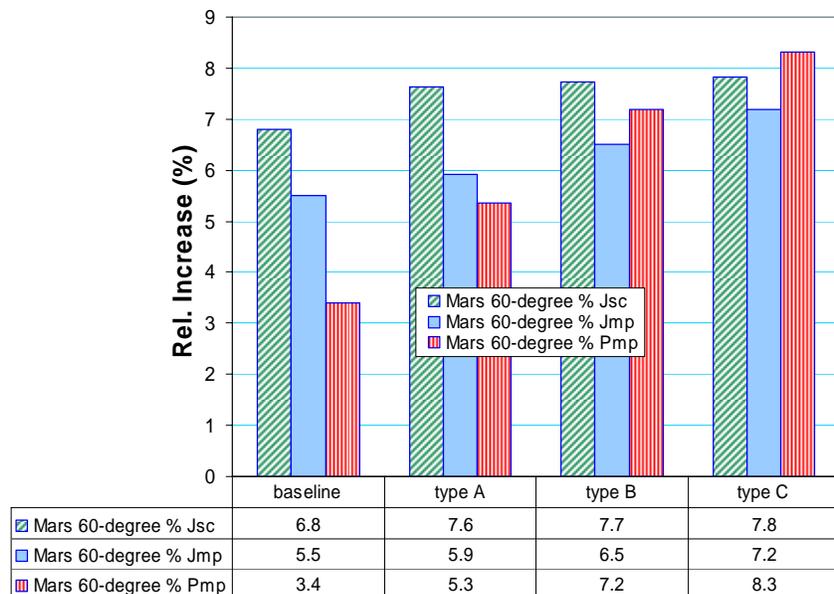


Fig. 4 Percent increase in Jsc, Jmp, and Pmp of Mars 60-degree optimized cells relative to baseline AM0-optimized cell.

Another figure of merit is the solar cell efficiency. Fig. 5 shows the average solar cell efficiency for the group of cells tested above. The Mars optimized cells show efficiency between 26% and 28%, as measured under a simulated Mars 60-degree spectrum. Note that the integrated intensity for this spectrum is 22.36 mW/cm².

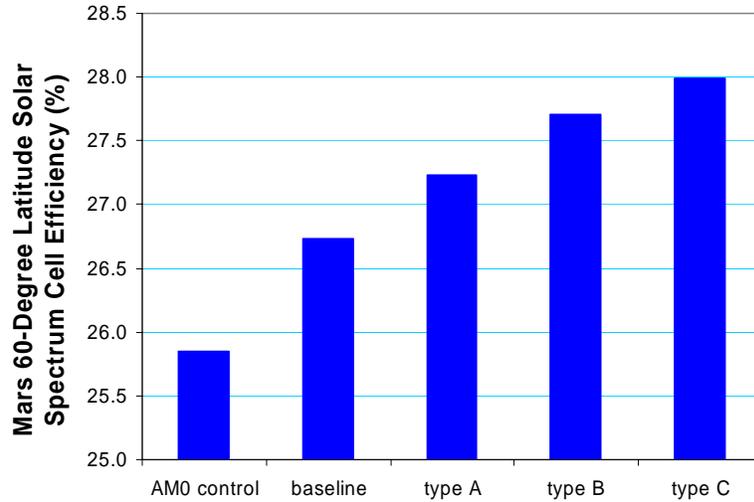


Fig. 5 Average solar cell efficiency on the Mars surface at 60-degree latitude.

Intensity and Temperature Measurements

A subset of each cell type was chosen for further LIV characterization under different illumination and temperature conditions. Preliminary LIV measurements of the subset of each group of cells were performed under the conditions shown in Table 1. This initial matrix of test conditions is intended to examine how the Mars-optimized designs behave under different operating conditions. The test matrix is not intended to cover the full range of operating conditions expected on Mars, but rather only to obtain preliminary data on cell performance under different operating conditions.

Table 1 Additional LIV characterization of Mars-optimized cells

		Mars 60-deg	Mars 60-deg
Relative Int.	Actual Int	T = 28°C	T = 12°C
1X	1	X	X
0.7X	0.68	X	
0.5X	0.42	X	

For each intensity setup, the simulator was first adjusted to the 1-sun Mars 60-degree calibration settings, and then additional wire mesh screens were placed in its beam path to reduce the light intensity. Fig. 6 shows the main result of these measurements demonstrating the average relative maximum power increase over the AM0 control for all of the cases listed in the table above. As can be seen from the chart, the type C design consistently shows the highest gain in performance over all the other designs under different test conditions.

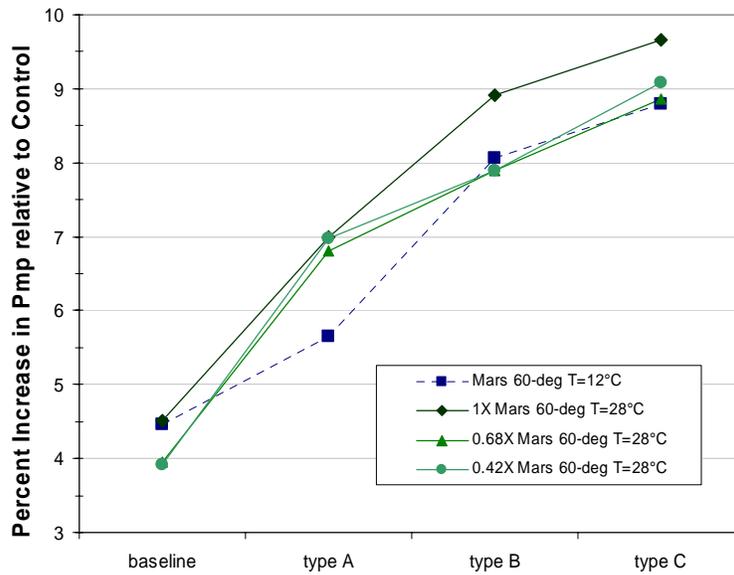


Fig. 6 Percent increase in average power for Mars-optimized cells relative to control for different operating conditions.

Discussion

While the Mars-optimized designs all show an increase in power, it is the type B and C designs that show the highest gain in average relative power. These designs also retain the highest power when measured under different test conditions. From closer examination of the data, it is apparent that the improvement in the fill factor (FF) of these designs, as shown in Fig. 7, along with the current matching that gives the biggest improvement in performance.

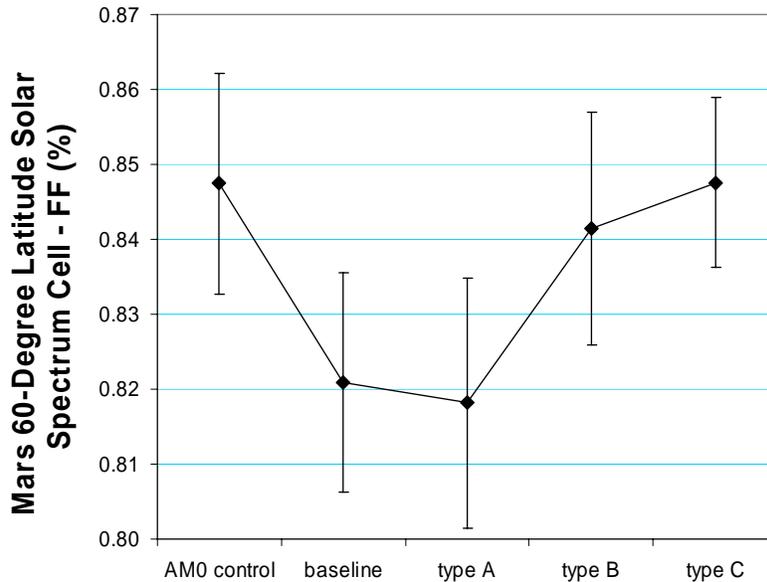


Fig. 7 Fill factor (FF) for each cell type.

The high fill factor of the AM0-control cell is due to the effect of the current mismatch when measured under the Mars 60-degree zenith angle solar spectrum. The average fill factor of the baseline and type A cells are around 82% and are both current matched. The very high average fill factors of the type B and C cells are what gives these designs the highest increase in performance for the Mars-optimized cell. As mentioned previously, all the Mars-optimized cells are current matched for this spectrum, so the high fill factor is not due to current mismatching of the top and middle subcells for types B and C. Both of these designs contain modest device modifications to the baseline design and are easy to implement in MOVPE.

Next Steps

Next steps for this program are to reproduce some of the designs in larger quantities and also to fabricate large area cells ($>20 \text{ cm}^2$). These cells will be characterized under a simulated Mars surface solar spectrum with the goal of producing a higher performance Mars-optimized solar cell ready for the next mission to the surface of Mars.

Summary

The Mars Exploration Rovers have resulted in an increase in the knowledge about the surface of the planet Mars. Additionally, nearly four years of rover performance data and the effect of dust have given mission planners at JPL more confidence and ability in predicting power requirements for the current and next generation rovers and Mars surface missions.

Dust accumulation on the panels has resulted in temporary losses in power, of up to 60%. In contrast, dust removal events (winds) have removed dust leading to recoveries of approximately 90% of initial power in some instances. This has led to a complex balance between dust deposition/removal on the panel surfaces and atmospheric dust content for array power generation. The lowest power situations have been met with innovation power management techniques by the MER rover operations personnel at JPL.

Mars-optimized triple junction solar cells have been grown, fabricated, and tested under a simulated Mars surface solar spectrum. The Mars-optimized cells are based on heritage GaInP/GaInAs/Ge multijunction designs and only require minor changes from a baseline AM0-optimized design. A baseline design and three additional designs have been characterized and all show an improvement in device performance including an increase in average J_{sc} and an average relative gain in Pmp from 3 to 8% for the Mars-optimized designs relative to an AM0-optimized solar cell.

A subset of experimental cells has been tested under a preliminary matrix of test conditions of lower intensity and temperature. All of the Mars-optimized designs show a gain in maximum power output when measured under different test conditions with the type B and C designs consistently showing the highest gains. The type B and C designs benefit from an improved FF which gives the most increase in power up to 9.5% under certain test conditions. Further work is in progress to fabricate large area Mars-optimized cells for characterization with the goal of using one of these designs on the next Mars surface mission.

Acknowledgements

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References

[1] K. Edmondson, et al. "Simulation of the Mars surface solar spectrum for optimized performance of triple-junction solar cells", Proceedings of the 19th Space Photovoltaics Research and Technology Conference, Cleveland, OH. Sept. 20-22, 2005.