SIMULATION OF THE MARS SURFACE SOLAR SPECTRA FOR OPTIMIZED PERFORMANCE OF TRIPLE-JUNCTION SOLAR CELLS

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Introduction

The unparalleled success of the Mars Exploration Rovers (MER) powered by GaInP/GaAs/Ge triple-junction solar cells has demonstrated a lifetime for the rovers that exceeded the baseline mission duration by more than a factor of five. This provides confidence in future longer-term solar powered missions on the surface of Mars. However, the solar cells used on the rovers are not optimized for the Mars surface solar spectrum, which is attenuated at shorter wavelengths due to scattering by the dusty atmosphere. The difference between the Mars surface spectrum and the AM0 spectrum increases with solar zenith angle and optical depth.

The recent results of a program between JPL and Spectrolab to optimize GaInP/GaAs/Ge solar cells for Mars are presented. Initial characterization focuses on the solar spectrum at 60-degrees zenith angle at an optical depth of 0.5. The 60-degree spectrum is reduced to ~1/6 of the AM0 intensity and is further reduced in the blue portion of the spectrum. JPL has modeled the Mars surface solar spectra, modified an X-25 solar simulator, and completed testing of Mars-optimized solar cells previously developed by Spectrolab with the modified X-25 solar simulator. Spectrolab has focused on the optimization of the higher efficiency Ultra Triple-Junction (UTJ) solar cell for Mars. The attenuated blue portion of the spectrum requires the modification of the top sub-cell in the GaInP/GaAs/Ge solar cell for improved current balancing in the triple-junction cell. Initial characterization confirms the predicted increase in power and current matched operation for the Mars surface 60-degree zenith angle solar spectrum.

Mars Surface Spectrum Modeling

The solar spectrum at the surface of Mars is depleted at shorter wavelengths due to the higher cross section of the suspended dust particles in the atmosphere at shorter wavelengths. In general, the depletion will be greater for higher solar zenith angles and higher optical depth. Landis[1] originally modeled this effect for a solar zenith angle of 0°. (The solar zenith angle is defined by a line perpendicular to the sun and a line directed toward the sun). He found that the transmission coefficient was 85% at long wavelengths but decreased to as low as 69% at ~ 0.35 micron. Crisp[2], et al. modeled transmission of sunlight through the Mars atmosphere for a wide range of zenith angles and optical depths. More recently, David Crisp (JPL) has greatly extended his models and has provided his data to us. In addition, measurements made by the instruments on the MER also provide important data on the Mars spectrum at the surface. The MER measurements were made at near equatorial latitudes. The data was used to apply corrections to the model. The MER corrected and Crisp data is shown in Fig. 1. The average of each data set for the zenith angles of 30- and 60-degree was used for the spectral modeling.

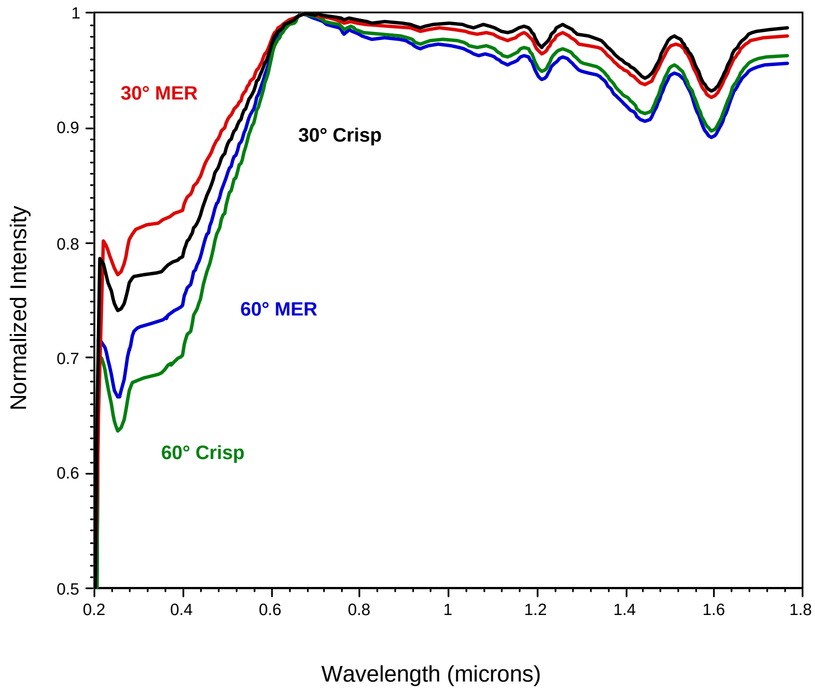

Fig. 1 Data from Crisp and MER for solar zenith angles of 30- and 60-degrees. The y-axis is the Mars surface intensity normalized to the AM0 solar intensity. Each data set is normalized to 1 for relative comparison.

Solar Cell Modeling on the Mars Surface

State-of-the-art GaInP/GaAs/Ge triple junction solar cells are designed to collect the high-energy photons (>~1.8 eV) of the solar spectrum in the top subcell and lower energy photons (~1.8 - 1.42 eV) in the middle subcell. Photons below the bandgap of GaAs (1.42 eV) are collected in the Ge bottom subcell. Commercially available triple-junction solar cells are designed for maximum power under the Air Mass Zero (AM0) space solar spectrum for end of life (EOL) operation. This requires the current generated in all subcells to be as nearly equal as possible, since the subcell with the lowest current will limit the overall current output of the solar cell. This requires that the top and middle subcells to be current-matched for highest efficiency operation. The bottom subcell (Ge) typically generates ~2X the operating current of either the top and middle subcells and therefore is not current limiting. Since commercially available solar cells are designed for maximum power at EOL, they are likely to be somewhat current mismatched at BOL. Most of the power loss for space solar cells during their lifetime is due to radiation losses, but this is not an issue for operation on the surface of Mars. Therefore, Mars cells can be optimized for BOL performance.

The major issue for AM0-optimized solar cells for use on the surface of Mars is the reduction of the ‘blue’ portion of the solar spectrum due to scattering and absorption by dust in the atmosphere. This spectral reduction will reduce the current generated in the top subcell and will limit the overall current and produce a loss of efficiency for the solar cell. It is necessary to match the currents of the top two sub-cells for optimal utilization of the solar spectrum for use on the Mars surface.

The short circuit current density (Jsc) generated by the top two subcells can be calculated by the summation of the product of the photon flux from the spectrum irradiance within a wavelength band, and the external quantum efficiency of each junction, defined here by Eq. (1), where $QE(\lambda_i)$ is the external quantum efficiency and $AMx(\lambda_i)$ is the photon flux density per unit wavelength. The summation is performed over the wavelength range of interest.

(1) $$Jsc = \sum_{\lambda_i} QE(\lambda_i) \times AMx(\lambda_i)$$

The mis-match between top and middle cells of an AM0-optimzed cell in the Mars spectrum is illustrated by the comparison of experimental data for an AM0 cell with models, as shown in Table 1. In this table, the measured Jsc for prototype dual-junction (no active Ge), experimental AM0-optimized solar cells from Spectrolab measured on a X-25 at JPL using balloon-traceable reference standards is shown. Also shown are the calculated Jsc for these cells for the AM0, and Mars 30- and 60-degree zenith angle spectra using Eq. (1). The ratio of top cell to middle cell current is shown for each data set. The further this ratio is from unity, the less utilized is the amount of available light in a multi-junction solar cell. The variance between the measured and calculated Jsc values is within the measurement error of ± 2% for each set of data. The table shows that AM0-optimized cells are not well suited for operation on the surface on Mars, as the current-mismatch between the top and middle cell is significant, resulting in a sizable loss of power. This motivates the optimization of multi-junction GaInP/GaAs/Ge solar cells for use on the Mars surface to regain much of the power loss.

Table 1 – Measured and calculated Jsc for AM0-optimized space multi-junction solar cells under the AM0 solar spectrum and the calculated Jsc for the top cell (TC) and middle cell (MC) under the Mars 30- and 60-degree zenith angle surface solar spectra.

	Measured Data		Calculated Properties					
	X-25 (AMO, 28°C)		AM0		Mars 30° zenith angle		Mars 60° zenith angle	
Cell ID	Jsc (mA/cm^2)	error	Jsc (mA/cm^2)	Jsc (TC) /Jsc(MC)	Jsc (mA/cm^2)	Jsc(TC) /Jsc(MC)	Jsc (mA/cm^2)	Jsc(TC) /Jsc(MC)
#A TC	16.97	<2%	16.69	0.96	5.39	0.89	2.68	0.85
#A MC			17.42		6.06		3.15	
#B TC	16.97	<2%	16.71	0.96	5.37	0.89	2.67	0.85
#B MC			17.46		6.05		3.14	
#C TC	16.97	<2%	16.7	0.96	5.38	0.89	2.68	0.85
#C MC			17.44		6.07		3.15	
#D TC	16.97	<2%	16.71	0.96	5.37	0.89	2.68	0.85
#D MC			17.46		6.06		3.15	

X-25 Spectrum Modeling

It is not necessary to modify the X-25 solar simulator to have the same spectrum as the surface of Mars to obtain accurate solar cell performance under Mars simulated conditions. It is only required to have a spectrum sufficiently similar to Mars that each sub-cell in the solar cell will generate the same current in the X-25 as it would generate on the Mars surface. That is, if the energy deposited can be converted to electric current in each sub-cell is the same as it would be on Mars, that is all that is required.

JPL has added Schott FG-13 filters to alter the AM0 X-25 spectrum to simulate the Mars 60-degree zenith angle solar spectrum. Fig. 2 shows the transmission of light through three different thicknesses of filter glass in the wavelength range of interest. The yellow highlighted region corresponds to the spectral range where the top cell may be modified by adjusting layer thickness or band gap.

Fig. 3 illustrates the 19 possible filter positions in the X-25 at JPL. The filters are one-inch in diameter, and the whole assembly is placed in the beam path of the Xenon bulb to reproduce the AM0 spectrum. Each of the 19 filters superimposes a circular beam onto the test plane. The filters shape the spectrum of the Xenon spectrum by reducing certain spectral spikes. The transmission thru the various filters is typically a few percent. JPL has built and installed an additional external filter-mounting ring placed between the X-25 Xenon source and the solar cell test plane. Various combinations of the Schott filters were used to further shape the X-25 spectrum to be more representative of the Mars 60-degree zenith angle solar spectrum with an optical depth of 0.5.

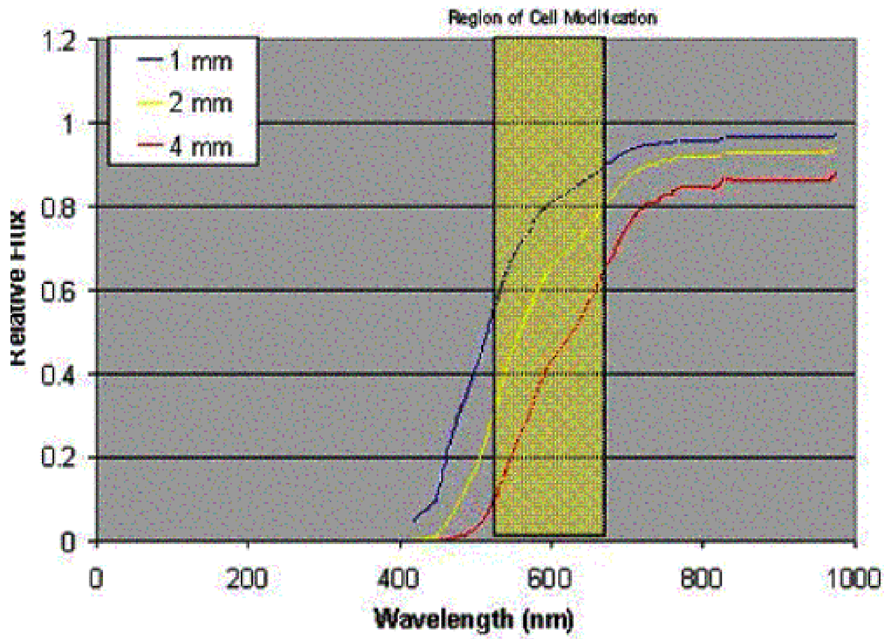

Fig. 2 Schott FG-13 transmittance spectrum for 1, 2 and 4 mm thick filters. The yellow region highlights the spectral range where the top cell is active and where the Mars surface solar spectra are attenuated.

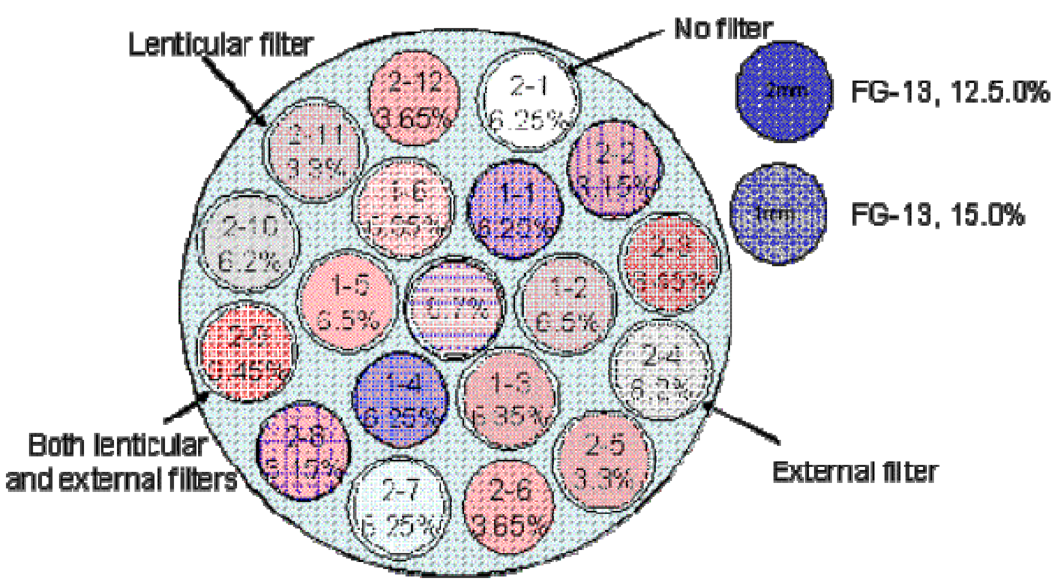

Fig. 3 Nineteen-position filter-mounting ring with lenticular and external filters installed. Transmission percent and position of filter are labeled.

In order to determine which filters provide the best approximation to operation on Mars at 60-degree zenith angle, an initial selection of filters was evaluated by multiplication of the measured X-25 AM0 spectrum and the known transmittance of various Schott filters to derive an approximate Mars surface spectrum. The approximate Mars spectrum was combined with the quantum efficiency of the solar cell and Eq. (1) was used to calculate Jsc for the cell. This calculated Jsc was compared to the calculated Jsc values in Table 1. This process was repeated with a modified set of filters until the appropriate spectrum shaping was achieved, as evidenced by agreement of the value of Jsc calculated from the spectrum with the measured X-25 spectral output. The appropriate filters were purchased and installed in the X-25 at JPL. Light I-V (LIV) measurements were performed to verify the spectral shaping of the X-25 at JPL for the Mars 30- and 60-degree zenith angle solar spectra and are discussed next.

X-25 Calibration and Test Results

The X-25 solar simulator is generally calibrated with solar cells that have been previously calibrated to reference solar cells flown on a high-altitude balloon. Solar cells calibrated on the Mars surface do not exist. As an alternative, JPL calculated the Jsc for a variety of solar cells under the Mars 60-degree zenith angle spectrum defined earlier. These included single-junction high altitude flight cells, AM0-optimized cells and cells previously optimized to an earlier estimate of the Mars surface solar spectrum[3]. The Jsc of the cell at the Mars 30- or 60-degree solar zenith angle solar spectra was calculated using Eq. (1). The Schott filters were adjusted in the X-25 beam until all Jsc measurements were within ±2 % of the calculated values. The Jsc of the Mars-optimized surface cells were current limited by the middle cell when tested under the AM0 spectrum. The cells were biased with an external infrared lamp to determine the Jsc of the top cell under the simulated Mars spectrum.

Table 2 summarizes the LIV data measured on two-junction cells at JPL on the modified X-25 calibrated to the Mars 60-degree zenith angle surface solar spectrum. This data indicates that the previously Mars-optimized solar cells from Spectrolab are a good match to the Mars surface solar spectra, especially at the 60-degree zenith angle, as evidenced by the ratio of the top cell and middle cell currents being near unity. Column one lists the current for the Mars-optimized cells tested under the AM0 spectrum. The three other columns show the calculated Jsc for each subcell for the AM0, Mars 30- and 60-degree zenith angle spectra. The fourth column shows that the cells are well current matched for this spectrum. It should be noted that the cells were originally optimized to a slightly different Mars surface solar spectrum.

Table 2 – Measured Jsc for prototype Mars-optimized solar cells. The expected Jsc for the AM0, Mars 30- and 60-degree zenith angle spectra is shown as well as the ratio of top subcell to middle subcell current density.

	Measured Data		Calculated Properties					
	X-25 (AMO, 28°C)		AM0		Mars 30° zenith angle		Mars 60° zenith angle	
Cell ID	Jsc (mA/cm^2)	Vari-ance	Jsc (mA/cm^2)	Jsc(TC) /Jsc(MC)	Jsc mA/cm^2)	Jsc(TC) /Jsc(MC)	Jsc (mA/cm^2)	Jsc(TC) /Jsc(MC)
#M1 TC	16.1	0.99	18.04	1.13	5.8	1.05	2.89	1
#M1 MC			15.91		5.55		2.88	
#M2 TC	16.1	1.00	17.91	1.11	5.75	1.02	2.87	0.98
#M2 MC			16.13		5.63		2.92	
#M3 TC	16.1	1.00	17.98	1.12	5.78	1.03	2.89	0.99
#M3 MC			16.07		5.61		2.91	
#M4 TC	15.99	1.00	18.03	1.13	5.7	1.04	2.9	1
#M4 MC			16.02		5.59		2.9	
#M5 TC	16.1	1.00	18.24	1.13	5.86	1.04	2.93	1
#M5 MC			16.11		5.63		2.92	
#M6 TC	16.21	1.00	18.03	1.11	5.79	1.02	2.89	0.99
#M6 MC			16.18		5.65		2.93	
#M7 TC	16.21	1.00	18.16	1.12	5.83	1.03	2.91	0.99
#M7 MC			16.16		5.64		2.93	
#M8 TC	16.1	1.00	18.14	1.12	5.83	1.04	2.91	1
#M8 MC			16.13		5.63		2.92	

Fig. 4 shows the power density of 2J prototype AM0-optimized and Mars-optimized cells tested under AM0 conditions. It can be seen that the Mars-optimized cells do not perform as well as AM0-optimized cell in the AM0 spectrum. Fig. 5 shows a similar plot for the Mars spectrum (60-degree zenith angle and optical depth = 0.5). The first four data points are the AM0-optimized cell and the last seven are Mars-optimized cells. The blue columns are the maximum power density for AM0 cells and the red columns are for the Mars 60-degree zenith angle cells. Overall, there is a ~6% gain in maximum power for the Mars-optimized cells.

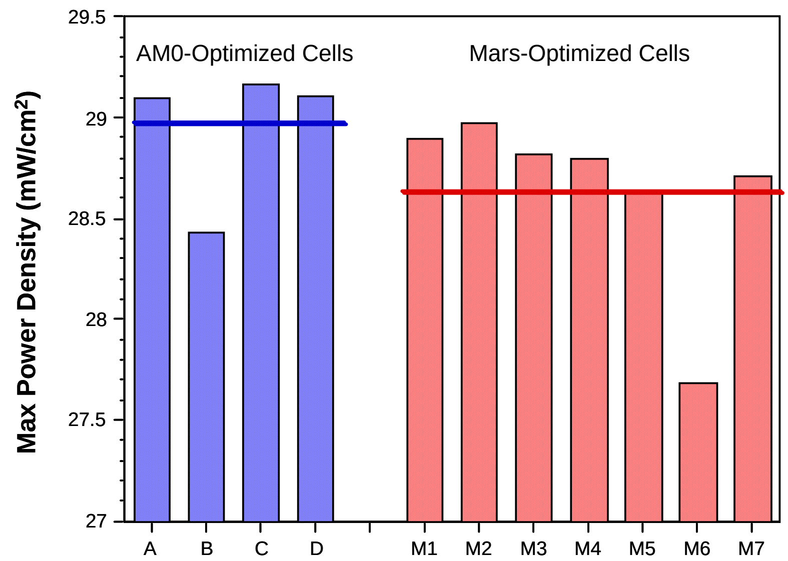

Fig. 4 Performance of AM0-optimized and Mars-optimized cells tested in the AM0 spectrum. Horizontal lines represent average of cells.

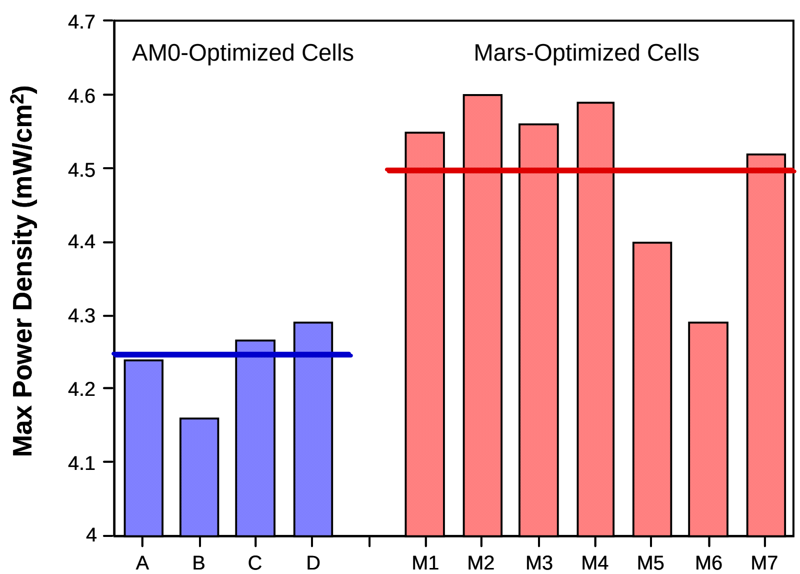

Fig. 5 Performance of AM0-optimized and Mars-optimized cells tested in the Mars surface spectrum. Horizontal lines represent average of cells.

Building on the initial success of these prototype Mars-optimized cells from Spectrolab, Spectrolab has begun work on a new program, funded by JPL, to further optimize triple-junction GaInP/GaAs/Ge solar cells based on the new MER solar spectral data. The recent progress in solar cell optimization for the Mars surface at Spectrolab is discussed next.

Approach to Mars-Optimized UTJ Cell

Fig. 6 shows the intensity of the AM0, AM0 @ 1.52 A.U., Mars 30 and 60 degree zenith angle solar spectra. The AM0 is the highest intensity spectrum on the chart and is the usual focus of cell optimization and improvement. The spectrum below the AM0 is simply the AM0 @ 1.52 A.U. The AM0 @ 1.52 A.U is the spectrum for a Mars-orbiting solar cell and is reduced to ~43% of the 1 A.U. intensity. The two lower spectra are the 30- and 60-degree zenith angle Mars surface spectra calculated from data by JPL. Closer inspection of the two spectra, normalized to AM0, is shown on the right-hand axis. On average, the 30-degree zenith angle intensity is ~33% of AM0 with increased attenuation in the range of 200-600 nm. The normalized 60-degree spectrum is also shown. It is reduced to an average intensity of ~17% and also attenuated in the blue portion of the spectrum.

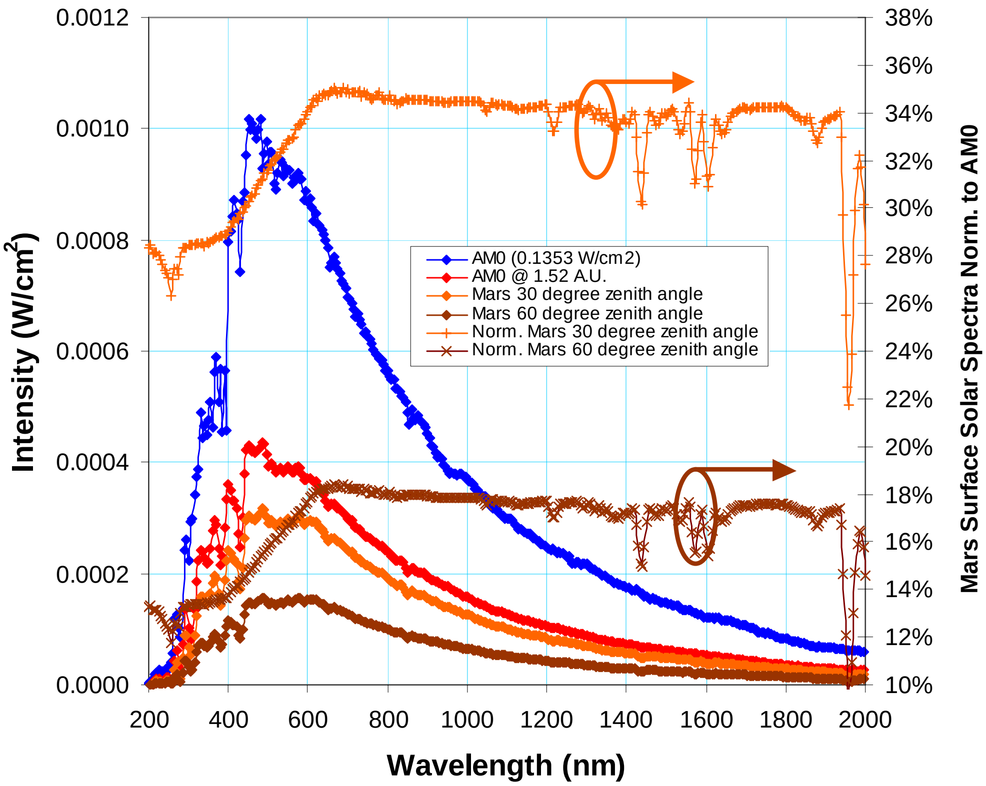

Fig. 6 Solar spectra showing the AM0, Mars 30- and 60-degree zenith angle surface solar spectra.

Fig. 7 further highlights the difference between the 30 and 60-degree zenith angle surface spectra on Mars by plotting the relative normalized spectra vs. the photon energy. While both spectra are attenuated in the blue, the 60-degree spectrum is further attenuated by the increased absorption and scattering of the atmosphere. Superimposed is the AM0 current density spectrum on the right-hand axis. The x-axis corresponds to the wavelength range of the spectra in which the top and middle subcells are active. The region indicated by the light blue rectangle shows the range of bandgaps in GaInP. This is the semiconductor material for the top subcell in a triple-junction GaInP/GaAs/Ge solar cell. In the design of a GaInP/GaAs/Ge triple-junction solar cell, the top cell bandgap and thickness can be used as adjustable parameters.

Since the voltage of a solar cell is proportional to the bandgap, the strategy is to choose as high a band gap for the top cell as possible while retaining a current-matched output between the top and middle cells[4]. This approach will give the highest usable power for a triple-junction design for a given input spectra. There is some flexibility in the design of the middle cell as well, but since the top cell produces more than 50% of the total power in a triple-junction solar cell, it is the main focus of optimization in this effort. As in the case with the AM0 spectra, the Ge bottom subcell has ~2x the operating current density of either of the two overlaying subcells and is not the current limiting subcell in the triple-junction stack.

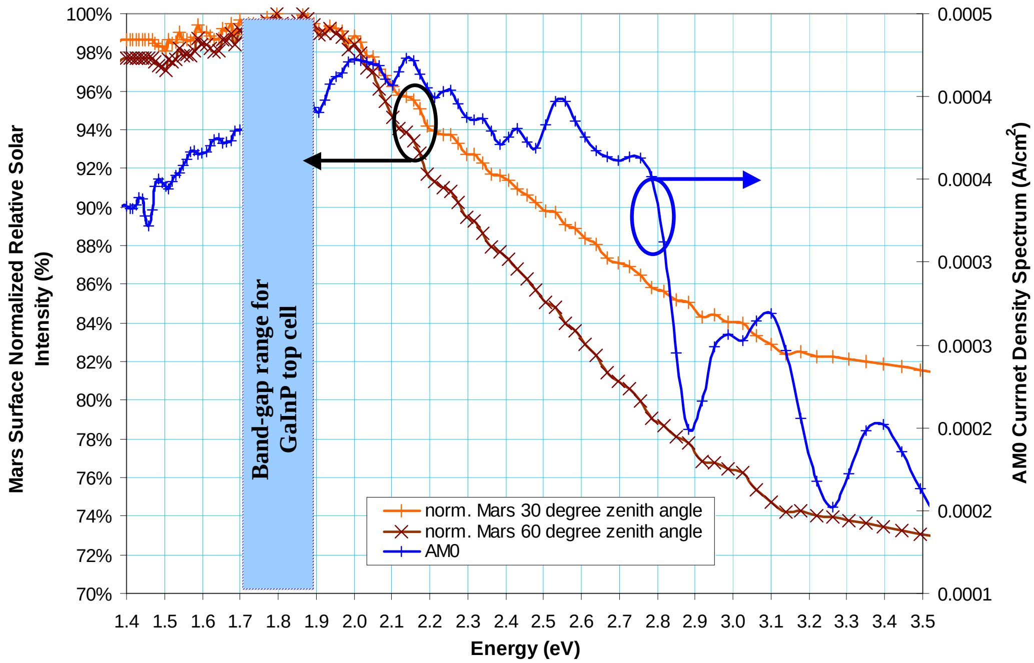

Fig. 7 Relative Mars 30- and 60-degree surface solar spectra normalized to the AM0 spectrum.

Device Modeling

The initial solar cell device modeling utilized closed-form equations for spectral response from the literature[5]. The model was used to fit to measured data from a Spectrolab UTJ solar cell as the baseline for a Mars-optimized device. This is performed by adjusting the band gap and cell thickness to produce a reasonable fit to the measured QE of the both the UTJ top and middle cells. The absorption and electronic properties of the materials are interpolated from sources in the open literature. Once the model fits the data, it is a matter of cell optimization utilizing a given input solar spectrum and modeled QE using Eq. (1) to calculate the Jsc for each subcell. The model gives an optimized result that serves as a starting point for experimental cell growth.

The device simulation results were used to generate simulated LIV curves to calculate the maximum power and operating efficiency for the spectrum of interest. Table 3 summarizes the modeling results and predicted gain in power for a Mars 60-degree solar cell.

Table 3 - Predicted results for a Mars-optimized solar cell.

	AM0	Mars 30-deg. zenith angle	Mars 60-deg. zenith angle
	Top cell/Middle cell Jsc ratio	Top cell/Middle cell Jsc ratio	Top cell/Middle cell Jsc ratio
UTJ QE (modeled)	0.979	.89	0.86
Mars-opt. (modeled)	1.136	1.04	1.01
Predicted increase in power		2.9%	**4.6%**

The predicted increase for a Mars 60-degree zenith angle cell is ~ 4.6% (relative) at 28°C in power over an AM0-optimized version of the cell. The predicted operating Jsc for the 30-degree spectrum is ~ 6 mA/cm^2 and ~3 mA/cm^2 for the 60-degree spectrum.

It's interesting to also check the 30-degree performance of a Mars 60-degree optimized cell as shown in the second column. The 60-degree zenith angle cell gives ~3% (rel.) improvement in power even if it is not fully optimized for the 30-degree zenith angle spectrum.

The predicted results gave the target current match conditions for the growths described next.

Experimental Results

Growth runs were performed to demonstrate the predicted gain in current and power as predicted. Based on initial growth evaluation, selected epitaxial wafers were fabricated into AR-coated, 2 cm x 2 cm sized triple-junction cells with standard processing techniques. Preliminary LIV measurements were performed on a subset of the total population (10 control cells, 12 experimental cells) and spectral response measurements on several of these cells.

LIV was performed on a Spectrolab XT-10 solar simulator. Reference Isc values for the AM0, 30- and 60-degree spectra at 28°C were calculated for top and middle cell component cells with external QE and the Mars current density spectra using Eq. (1). The intensity of the XT-10 was decreased using wire mesh screens and a blue notch filter (~450-650 nm) to reduce the blue component of the spectrum. The output of the XT-10 simulator and filter positions were adjusted until the Isc values were within ~ 1% of the calculated Isc's for each spectrum. Fig. 8 and Fig. 9 show the increase in power for AM0-optimized and Mars 60-deg optimized cells tested in the AM0 spectrum (Fig. 8) and the Mars 60-degree zenith spectrum (Fig. 9).

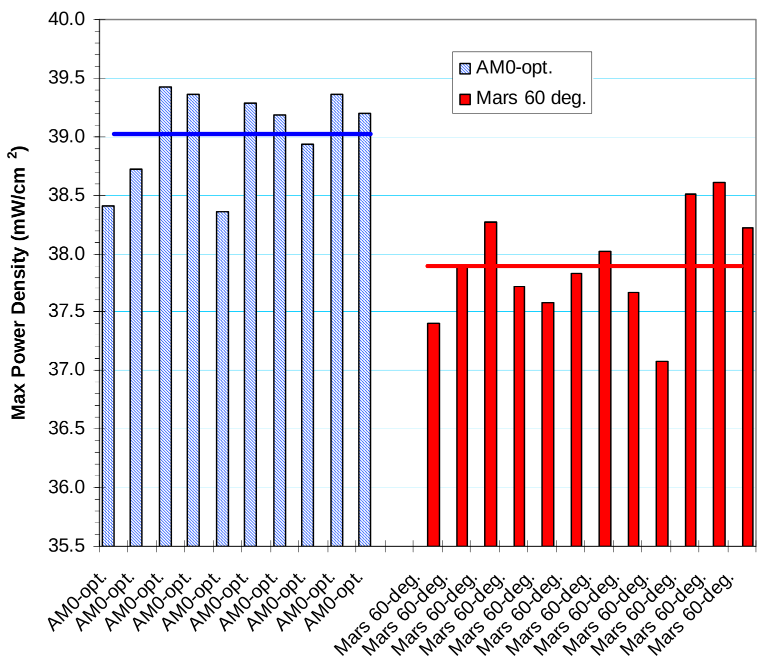

Fig. 8 Performance of UTJ-based AM0-optimized and Mars-optimized cells tested in the AM0 spectrum. Horizontal lines represent average of cells.

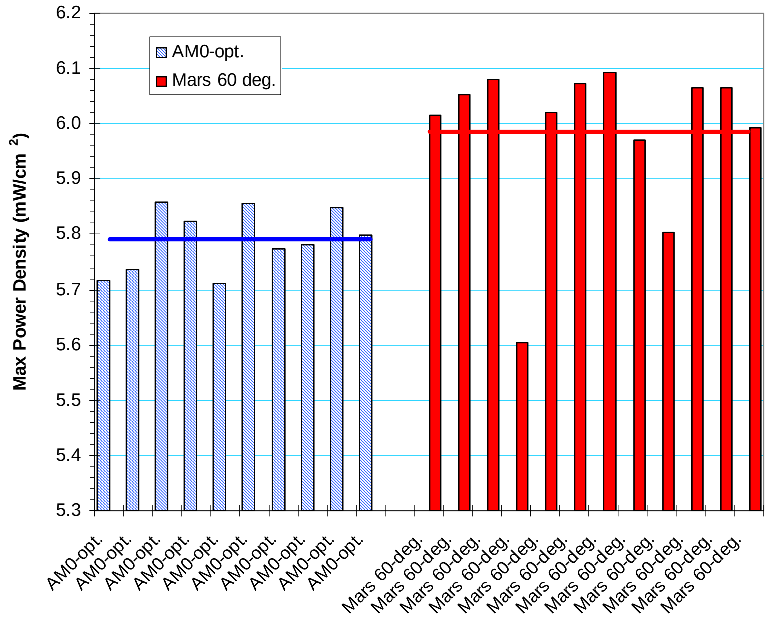

Fig. 9 Performance of UTJ based AM0-optimized and Mars-optimized cells tested in the Mars surface spectrum. Horizontal lines represent average of cells.

Based on this data set there is an efficiency increase of 3.4% for the Mars 60-degree zenith angle spectrum. Recalculating for yielded efficiency (>27%) gives an average increase of 4.4% and verifies the prediction in Table 3. The uncertainty in the XT-10 measurements is ±2%. This is almost a full 1% absolute gain in efficiency. The measured improvement in Jsc is almost 7%. This equates to an absolute increase in Jsc of 0.2 mA/cm^2. This is an important increase for the 60-degree zenith angle optimized cell in efficient utilization of the available sunlight at this zenith angle.

It is worthwhile to point out, that a lower bandgap top-subcell is not beneficial here. There is a beneficial gain by using the higher band-gap cell vs. the lower band-gap for the absolute increase in power. For example, based on data from this experiment, there is ~2.5% (rel.) power increase using the AM0-optimized versions of the lower- and higher band-gap cell measured at the 60-degree zenith angle solar spectrum. In other words, if one were to choose from these two types of AM0 optimized cell for use at the Mars 60 degree zenith angle, then the UTJ cell will be ~2.5% (rel) higher in efficiency than the ITJ. We have leveraged this increase by optimizing for the 60-degree solar spectrum as well.

Table 4 shows the current matching condition for the baseline and two Mars-optimized designs based on external quantum efficiency (QE) measurements and integration with the appropriate spectrum. An initial Mars run is current-matched for the 30-degree spectrum and the final design #2 is current-matched for the 60-degree spectrum. An alternate cell could also be optimized between the two zenith angles for a cell design that could be used between 30- and 60-degree zenith angles on Mars. Spectrolab is able to obtain the appropriate current-matching conditions for a number of various solar spectra.

Table 4 Top cell to middle cell current ratio for two Mars-optimized runs for the Mars 30- and 60-degree zenith angle solar spectra.

	AM0	Mars 30-deg.	Mars 60-deg.
Mars 30-deg. growth run	1.08	**0.99**	0.96
Mars 60-deg. growth run	1.10	1.02	**0.99**

Fig. 10 shows the illuminated I-V characteristics for an AM0-optimized and a Mars 60-degree optimized cell measured under both AM0 and Mars 60-degree spectral conditions. Note there is no evidence of cell shunting under the low intensity Mars spectrum. Characterization for a range of operating conditions of the performance of the Mars 60-degree zenith angle optimized cell will be explored in the next phase of this program.

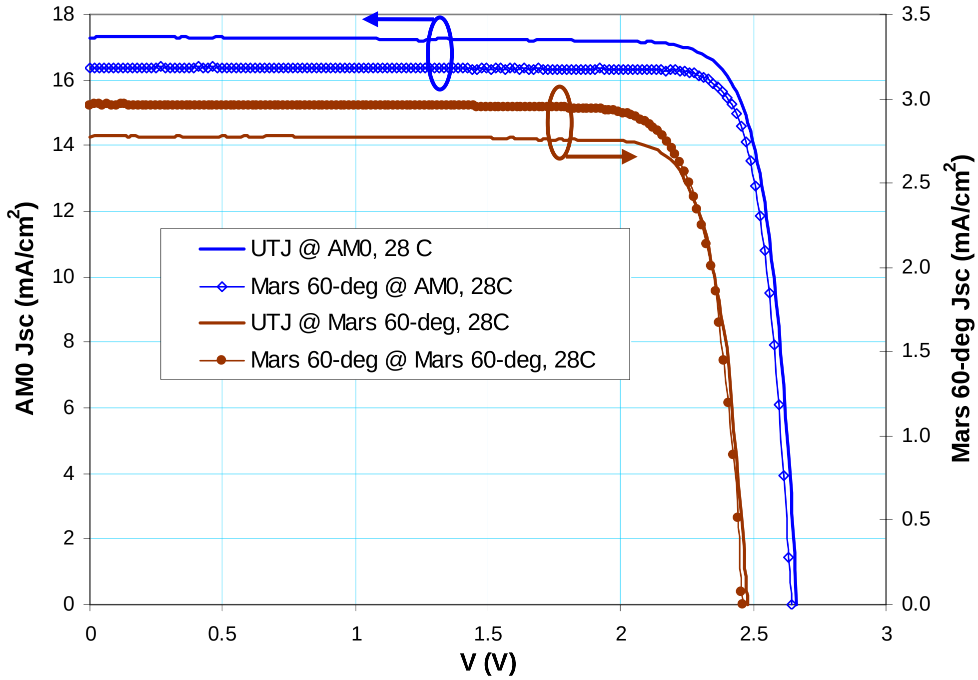

Fig. 10 Illuminated I-V curves for baseline and Mars 60-degree zenith angle Mars-optimized cell.

Discussion and Next Steps

A couple of points should be made about the data in Table 4. The quantum efficiency measurements were made on AR-coated cells with no coverglass. A cell to be used on the Mars surface will have coverglass. The glassing gain for these cells may change the TC Jsc/MC Jsc ratio slightly, but this will have to be determined experimentally. The cell will need to be characterized for a range of potential operating temperatures on the surface of Mars. It should also be pointed out, there is a small voltage drop of ~30 mV in the Mars-optimized cell compared to the baseline. It is being investigated and should be fully recoverable in the next round of cell growths.

However, the main goal of improving the current match between the top and middle subcells for the Mars surface solar spectra has been achieved. These changes are quite important to achieve overall better utilization of the blue attenuated and lower intensity Mars 60-degree zenith angle surface spectrum. Spectrolab has demonstrated AR coated triple-junction GaInP/GaAs/Ge solar cells optimized for the Mars 60-degree zenith angle solar spectra with ~4.4% improvement in power, achieving nearly all of the predicted gain in this initial effort.

Summary

New solar spectral data on the Mars surface at zenith angles of 30- and 60-degrees has been obtained by JPL from measurements from the Mars Exploration Rovers. JPL has modeled the spectral data based on MER data. JPL has modeled the necessary changes required to modify the spectral content of an X-25 solar simulator at JPL to reproduce the surface solar spectrum at Mars 30- and 60-degree zenith angles.

JPL has modified the spectral output of an X-25 solar simulator using appropriate spectrum shaping filters to reproduce the Mars 30- and 60-degree solar spectra and has verified the X-25 modifications using previously Mars-optimized prototype 2J solar cells from Spectrolab. They were able to demonstrate that the solar cells are appropriately current matched for the 60-degree zenith angle Mars spectrum.

Spectrolab has modeled the necessary changes needed for a baseline UTJ solar cell to be better current-matched for the blue-attenuated Mars 60-degree surface solar spectrum. Spectrolab predicted an increase in power of 4.6% relative over an AM0-optimized solar cell. The optimized cell will give higher absolute power than previous Mars-optimization work.

Spectrolab had implemented the necessary changes to the solar cell design and has performed growth runs and performed characterization to verify the targeted changes and have fabricated prototype ~2 cm x 2 cm AR-coated solar cells optimized for the Mars 60-degree surface solar spectrum. Spectrolab is able to achieve appropriate current matching conditions through calculation, measurement, and growth changes for a variety of solar spectra and cell designs has produced cells that are current matched to the 30- and 60-degree zenith angle Mars surface spectra.

Preliminary electrical characterization at Spectrolab has verified the expected gain with a measured increase in power of ~4.4% over the AM0-optimized baseline at 28C. Spectrolab has demonstrated AR coated triple-junction GaInP/GaAs/Ge solar cells optimized for the Mars 60-degree zenith angle solar spectra with ~4.4% improvement in power, achieving nearly all the predicted gain in this initial effort.

JPL and Spectrolab are poised to continue cell optimization and electrical characterization for the expected Mars operating conditions.

Acknowledgements

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