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# Analysis and Troubleshooting of In-House Mono-Crystalline Silicon Solar Modules for Solar Vehicle Applications Using a Keithley Model 2440 SourceMeter® instrument

by

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Oregon State University Solar Vehicle Team Members

## Introduction

The Oregon State University Solar Vehicle Team (OSUSVT: www.osusvt.org) is a group of students, staff, and faculty who are working together to build a solar-powered vehicle for the 2012 American Solar Challenge (www.americansolarchallenge.org). The team is planning on racing their newest vehicle, the Phoenix, in the race of July 2012. The vehicle and solar array are designed and constructed by students. The team was donated bare mono-crystalline solar cells and has developed a soldering, testing, and laminating procedure to produce slightly flexible, lightweight solar modules.

*Figure 1: Shown here is the OSUSVT's second vehicle, the Odyssey. The third vehicle, the Phoenix, will look much like the Odyssey in body shape but is expected to perform much better due to higher solar array power output and a lighter vehicle.*

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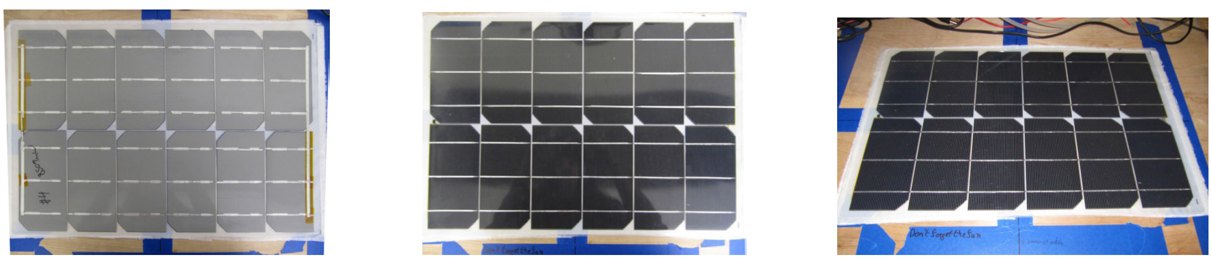
The OSUSVT requires parametric data on each solar module constructed in order to lay out the sub-arrays on the car in the most efficient manner. The overall power output and maximum power point current are measured with an I-V curve tracing test using a Keithley Model 2440 SourceMeter® instrument. This Keithley instrument allows the students in the OSUSVT to obtain fast, easy, and accurate data that reports the performance of each solar module and allows for easy side-by-side comparison. This data is measured before and after lamination of each solar module and is used for both troubleshooting and current matching in the sub-arrays, as well as a way to obtain predictions on the output of the vehicle's entire solar array. The SourceMeter instrument was acquired through a donation arranged between Kathy Han and Chuck Cimino, one of Keithley's marketing directors.

## Experimental Setup

A solar vehicle module consists of 6 full-size SolarWorld 156mm cells, which have each been scribed and diced into two half-cells. The 12 half-cells are wired in series to make one module (see ***Figure 2***). A thin-section bypass diode is connected across the module and contained within the laminated product.



A) B) C)

***Figure 2:** Laminated solar modules for the 2012 OSU Solar Vehicle (the Phoenix). The back side of the module (A) has spots for both the positive and negative connections to the module (on the left side marked by extra Kapton tape under the main bus bar). The front side of the module is seen in (B) and its position under the solar simulator is regulated by consistent placement of the module on the marked tape (C).*

*Figure 3: The solar module team building and testing solar modules. Notice the Keithley Model 2440 SourceMeter instrument tucked safely behind and below the monitor. The most prominent member of this group is the team baby, Penny, who works tirelessly to keep up morale.*

The Solar Vehicle Team uses a halogen lamp with approximately 1/3 sun light output to establish baseline comparisons between both individual cells and modules (see ***Figure 4***). The spectral match between the halogen lamp and typical sunlight is imperfect, but adequate for comparison and troubleshooting purposes and predicting approximate power levels under sun-illuminated conditions (see ***Figure 3***). The measurement probes of the Keithley Model 2440 are used in the Kelvin (4-wire) configuration for accuracy with high test currents present, and are combined and connected at the module test point seen in ***Figure 1A***. A National Instruments GPIB-USB-HS high-speed GPIB controller is used for communication between the Keithley Model 2440 and Oriel PV I-V software.

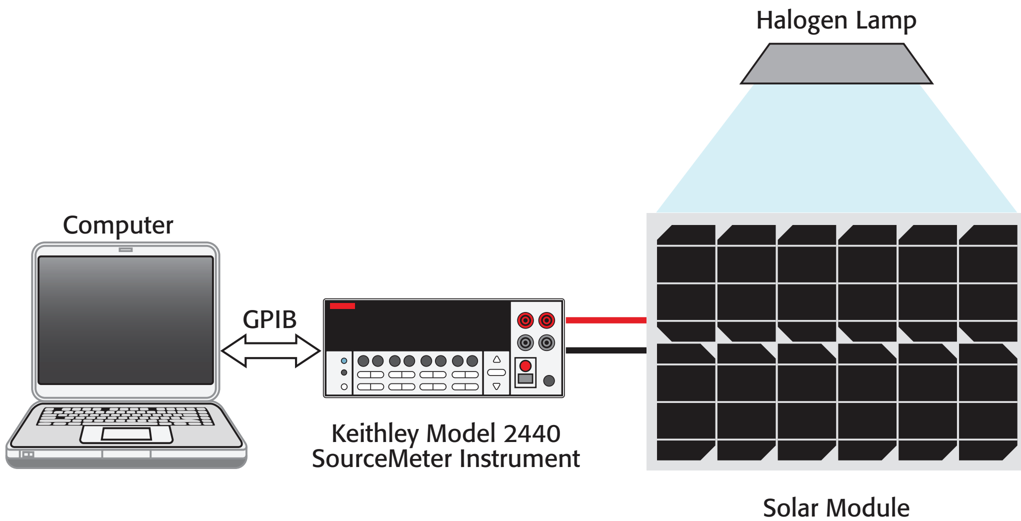



*Figure 4: Experimental set-up concept*

The Model 2440 SourceMeter instrument (***Figure 5***) is part of Keithley's Series 2400 line of source measurement units (SMUs), and is capable of sourcing and measuring up to 40V and 5A. Series 2400 instruments are optimized for test applications that demand tightly coupled sourcing and measurement, like the OSU's Solar Vehicle Team's. All seven models in the Series 2400 SourceMeter line provide precision voltage and current sourcing as well as measurement capabilities. Each is both a highly stable DC power source and a true instrument-grade 6½-digit multimeter. The power source characteristics include low noise, high precision, and flexible voltage, current and resistance readback. The multimeter capabilities include high repeatability and low noise signal conditioning and A-D conversion. The result is a compact, single-channel, DC parametric tester. In operation, these instruments can act as a voltage source, a current source, a voltage meter, a current meter, and an ohmmeter. By linking source and measurement circuitry in a single unit, these instruments minimize the time required for test station development, setup, and maintenance, while lowering the overall cost of system ownership. They also simplify the test process itself by eliminating many of the complex synchronization and connection issues associated with using multiple instruments.


*Figure 5: Keithley's Model 2440 SourceMeter instrument is capable of sourcing and measuring up to 40V and 5A.*

## Experimental Procedure

The module is centered and illuminated by the halogen lamp, and the test program in the Oriel PV I-V Test Station is immediately run to avoid over-heating the module. Consistent timing of measurement with respect to time of illumination is important for testing consistency as the cells undergo heating during illumination, which adds unwanted time-dependent changes in measurements. A desk fan is used to minimize heating of the module due to convection and increases the reproducibility of measurements. For these modules the following test parameters are used:

*Table 1: Oriel PV I-V Test Station measurement parameters*

| | |
|---|---|
| Max reverse bias | –0.1 V |
| Max forward bias | 7.0 V |
| Number of sweep points | 100 |
| Dwell time | 30 ms |
| Current limit | 4200 mA |

Modules with no connection problems and power levels within a margin of error of that of a known-quality reference module are designated to be laminated. After lamination the modules are re-tested with identical parameters to verify final quality and power levels, after which they are attached to the solar vehicle.

### Output data (under approximately 1/3 sun)

- I-V curve between 0V and 7V forward bias
- $P_{MAX}$
- $I_{MAX}$
- $V_{OC}$
- $I_{SC}$
- Fill factor

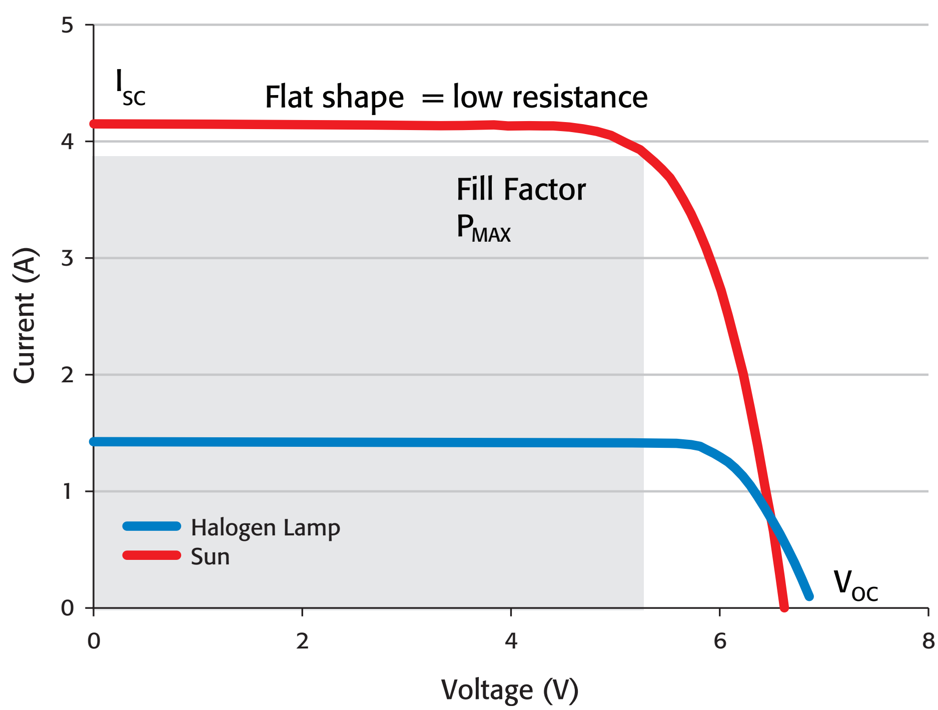



*Figure 6: Representative I-V curve for an entire solar module*

### Data analysis

The output data from the I-V curve tracing tests on the laminated modules are used to determine which modules should be arrayed in series with each other. $P_{MAX}$, the power output in Watts at the maximum power point, is the most useful overall descriptor of a solar module's efficiency when using our fixed illumination source. Thus, $P_{MAX}$ was used to determine whether or not solar modules would be placed on the vehicle, or if they would be excluded due to low power output. The current at maximum power, $I_{MAX}$, was used to current-match modules into five different sub-arrays. The current of a string of cells in series is limited by the lowest-current module, so sub-arrays are designed with current-matched modules to minimize this current-limiting effect.

Once all five sub-arrays have been populated with modules, the $P_{MAX}$ from the I-V curves can be used to predict the overall output of the car's entire solar array. To do this, the current from the module with the lowest $I_{MAX}$ in each string is considered the current-limiter and the voltage of that string is calculated by the $V_{MAX}$ voltages of each module added together. These two numbers are multiplied to get the output power of that sub-array in watts. The power from each of the five sub-arrays is added together to get the overall power of the solar array. Since these tests are done under a halogen lamp that is known to be approximately 1/3 sun, this power output is multiplied by 3 to get a general idea of the power output of the vehicle. We expect this number to be within 10% accuracy, based on previous results.

## Troubleshooting

Troubleshooting problems in stringing or laminating the modules began with looking at $P_{MAX}$. Most major problems that these cells develop could be detected by a low $P_{MAX}$. These problems include low current ($I_{MAX}$, $I_{SC}$), low voltage ($V_{MAX}$ and $V_{OC}$), or low fill factor (FF) and high internal resistance.

***Figure 7*** shows an I-V curve for a single solar cell that was laser cut from the front side. The p/n junction is located on the very front of the solar cell and the back side is made of bulk mono-crystalline silicon. Thus, laser cutting a cell from the front side results in some melting of the p/n junction, which causes internal shorts and increased internal resistance in the cell. This is seen by the slope in the I-V curve of ***Figure 7***, which significantly decreases the maximum power point. The sloped portion of the I-V curve indicates ohmic resistance, which is highly undesirable in a solar cell. One of the team's previous solar arrays was constructed entirely of cells that had been cut thus. This problem was not detected until the team was able to borrow a Keithley SourceMeter instrument from one of the labs at OSU, the data from which helped the team re-design a solar array with 60% more power.

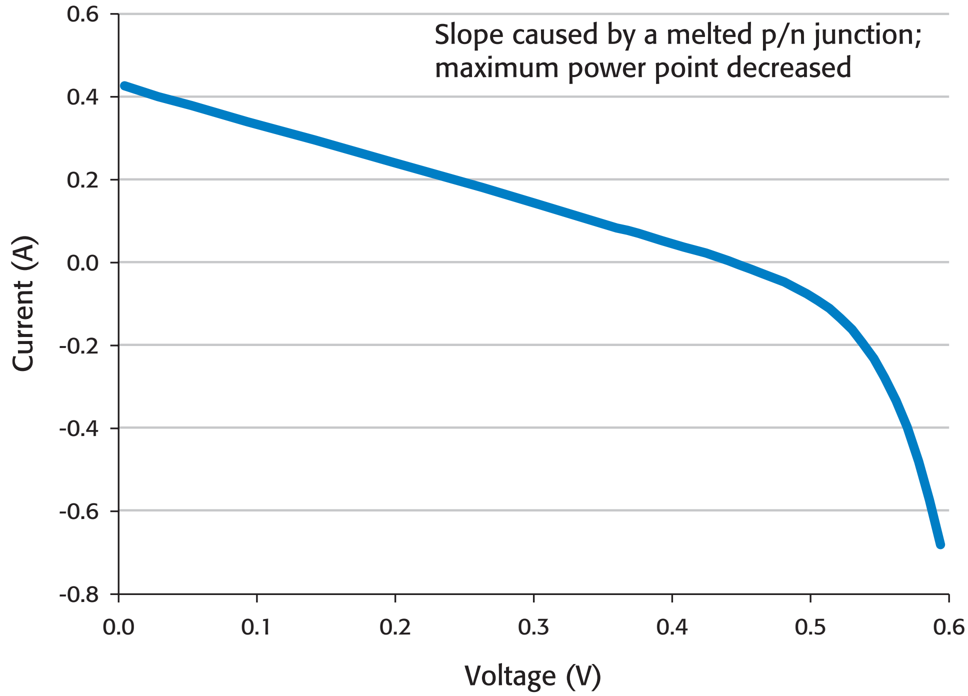



*Figure 7: I-V curve for a single solar cell that has been laser cut from the front side under low illumination.*

An abnormally low $V_{OC}$ may indicate a problem with the solder joints. In one instance, the leads on one cell were too long and shorted the cell by touching the next cell in series. This problem was diagnosed by observing the low $V_{OC}$ value (see ***Figure 8***) and the offending lead was found and fixed, resulting in a complete fix of the problem. $V_{OC}$ can also drop due to increased cell temperature, which is an indication that the cooling fan was not on during the test and should be re-run.

$I_{SC}$ is proportional to the cell efficiency, cell area, and light input. Low current is usually caused by cracks in the cells that electrically isolate large areas from the tab ribbon (See ***Figure 9***). This is usually not a repairable problem and results in the module being excluded from the vehicle.

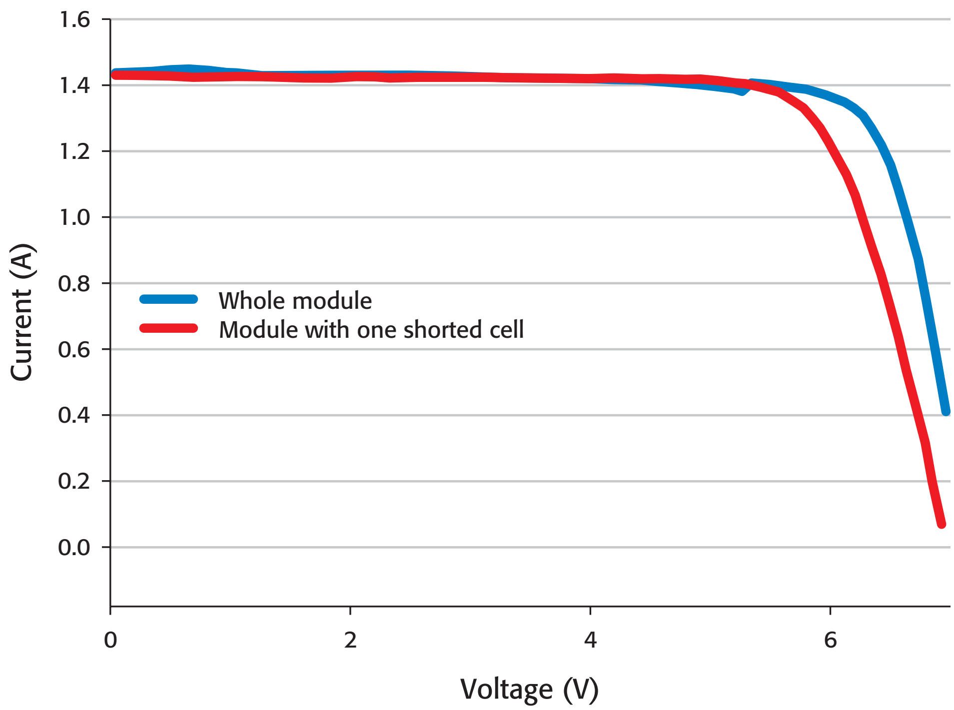



*Figure 8: Shorting one cell in a string of twelve cells decreases the $V_{OC}$ and $V_{MAX}$.*

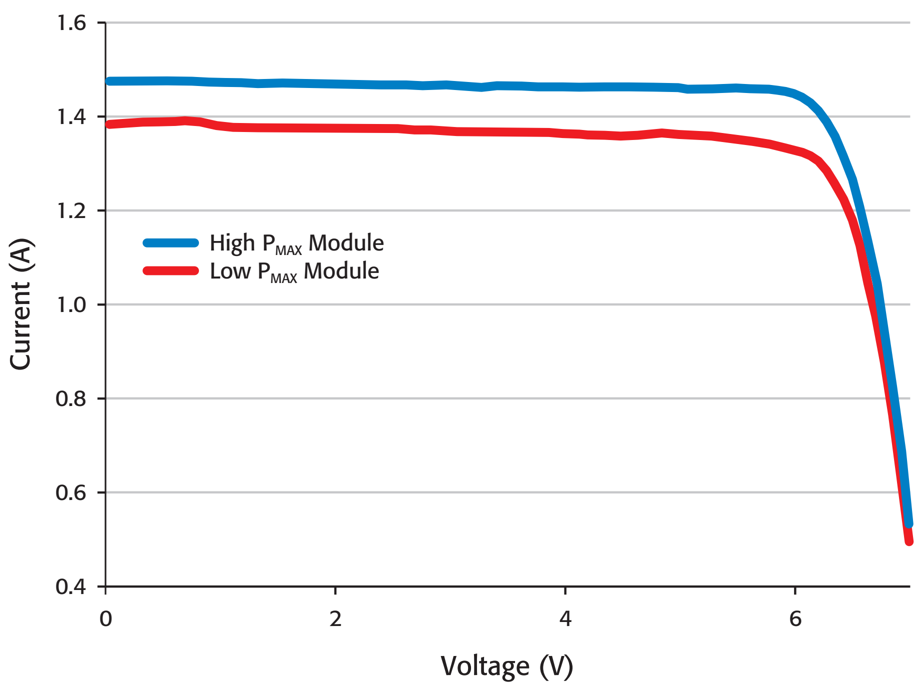



*Figure 9: Significant differences in power output are primarily due to higher $I_{SC}$ values, often due to significant cracking in the cells that electrically isolates a portion of the cell area.*

## Conclusion

The OSU Solar Vehicle Team successfully used the Keithley Model 2440 SourceMeter instrument to obtain I-V curve data accurately, consistently, and easily for all solar modules before and after lamination. The $P_{MAX}$, $V_{OC}$, $I_{SC}$, $V_{MAX}$, and $I_{MAX}$ were used in both troubleshooting as well as deciding which modules would go on the car and into which sub-arrays. These data were used to detect problems such as shorted cells and cracked cells. The overall power output for the solar vehicle was maximized using the data provided by the Keithley Model 2440. This device made it easy to set up, train students, explain solar module performance and behavior, collect data on all modules, and make decisions regarding the construction of the vehicle's solar array.

## About the Authors

**Kathy Han** is a Ph.D. student at Oregon State University working in the Chang lab in the School of Chemical, Biological, and Environmental Engineering. Her thesis is on nanostructures for photovoltaics with a focus on anti-reflective coatings for flexible substrates, such as the materials used to laminate the array for this vehicle. She has been working with the OSU Solar Vehicle Team since its founding in 2005. Kathy is currently the team manager and lead for the body and co-lead for the solar module team. Her background is in botany, chemistry, and genetics, but after working with the OSU Solar Vehicle Team she decided to become an engineer focusing on renewable resources and education.

**Josh Triska** recently received his master's degree in electrical engineering from Oregon State University. His thesis topic was transparent nano-laminate dielectric-semiconductor interfaces. Although formally educated in electrical engineering, his contributions to the mechanical design of the last two OSU solar vehicles have been invaluable. Josh was also instrumental in the correct and accurate dicing of the silicon solar cells into half cells, designing the solar module construction methods, and modifying the soldering methods and stringing fixture as needed for the rapid and accurate completion of all of the solar modules.

**Danielle Sitts** is one of the co-leads of the solar array portion of the OSU Solar Vehicle Team. She has been an active member for the past two years, and helped build the 2nd car (the Odyssey) as well as the current car (the Phoenix). She is also part of the electronics and body work teams. Danielle is currently pursuing a BS in Electrical and Computer Engineering at Oregon State University. She received a degree in geology from Portland State University in 2008, but later decided that she had a greater interest in engineering (specifically robotics and alternative energy sources).

**Zeno Le Hericy** is a sophomore in Industrial Engineering and has been working on the Solar Vehicle Team for two years. He helped in designing the fixturing for the module testing area and programming the module lamination system, as well as laminating and testing many modules. He is currently pursuing a double major in Industrial and Manufacturing engineering, with possible minors of Physics and French, with an eventual goal of getting a Ph.D. in robotics engineering and design. As an avid outdoorsman, Zeno has a personal connection to environmental engineering, and projects like the solar car let him push to make our world a better place.

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