Solar Simulator and I-V Measurement System For Large Area Solar Cell Testing

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Abstract

This paper describes the design, operation and use of a PC controlled test setup designed specifically to measure the I-V characteristics of large area solar cells operated under simulated solar irradiation for the purpose of testing their quality and determining their optimal operational points for maximum electrical output. The project included design of a wafer-prober and solar-simulator combination so that large area wafers (up to 8 inch in diameter) could be tested at/up to AM1.5 standard solar insolation. Rather than simply looking at the short circuit current and the open circuit voltage of a solar cell, our system measures its full I-V characteristics while the cell is irradiated with an artificial light source which simulates the solar radiation. The artificial sunlight is created by combining metal-halide and quartz halogen light sources. The measurement is done in an automated way by employing standard bench top GPIB instruments interfaced to a PC and by using the function generator as a stepped voltage source. High test currents needed by the large area solar cell are provided by a unity gain DC power amplifier driven by the function generator. A Mathematica code written creates plots of measured I-V data and determines the maximum electrical power output of the cell as well as the series resistance, the parasitic effect most effective in lowering maximum power and efficiency.

1. Introduction

This project was inspired by a university-industry cooperation project between National Semiconductor Corporation and the University of Southern Maine to recycle industrial byproducts into useful devices, namely, Silicon wafers which have been used as test wafers in production lines into solar cells. The size of the Silicon wafers used in the fabrication of modern day integrated circuits is greater than 6 inches (=150 mm), typically 8 inches (=200 mm). Considering a solar intensity of 100 mW/cm2 (approximately AM1.5 conditions) an average Silicon solar cell is expected to generate more than 20 mA/cm2. [Ref. 1, 2, 3]. If a whole 8-inch wafer is turned into one single solar cell, it should generate more than 6 Amps of photo current. At such high current levels the voltage burden of a DC ammeter runs close to 300 mV, i.e. about 65% of the cell's voltage (which runs at about 450 mV), making a direct short circuit current measurement highly inaccurate if not impossible. Besides, the short circuit current of a solar cell alone is not enough to determine the cell's power delivering capability. The maximum power delivered is also dependent on the internal voltage drops caused by the internal series resistances of the cell. There is an optimum point of operation on the I-V characteristics of the cell which needs to be determined in order to extract solar generated electrical power most efficiently. For this reason, a complete I-V characterization of the cell is needed covering the full range of operation at high current levels. This involves applying a stepped voltage and measuring the cell's current at each step. True short circuit current can then be extracted from the plots of the I-V data at the zero volt point. Such a complete I-V measurement would also reveal the solar cell's open circuit voltage and allow a plot of its electrical power output to be made as a function of its operating voltage, and therefore, help determine its optimum operating point for maximum possible power extraction. Having full I-V data would also help to extract parameters such as the internal series resistance, and therefore, provide feedback to the device designer to do a fine tuning of both the doping profiles and the metallization pattern design of the cell for optimization.

With such large size solar cells, testing the cell at high currents becomes an equipment issue. The issue is to find equipment that can do automated I-V measurements at such high current values. Semiconductor industry uses highly sophisticated (and expensive) computer controlled DC characterization equipment. Unfortunately, even the highest current rated systems (Agilent's E5273A and 4145 series, Keithley Instrument's Models 2400 and 238) cannot handle currents above 1 Amp (some 2 Amps) level [Ref. 7, 8]. This has been the main reason to start the project presented here.

2. The Measurement System

The automated measurement system reported here employs a standard set of bench-top instruments consisting of a Hewlett Packard Digitizing Oscilloscope (Model 54501A), a Tektronix Arbitrary Function Generator (AFG 5101), a Tektronix Programmable Digital Multimeter (DM 5120). All of these instruments are equipped with GPIB interface. A Pentium IV computer equipped with National Instrument's IEEE488.2 card controls the setup. A system schematic of the measurement setup is given in Figure 1. This is an extension of a "Computer-Integrated-Electronics" teaching laboratory setup which was featured to do automated measurement of I-V and C-V characteristics of semiconductor devices and sensors and, to extract SPICE parameters from them for undergraduate electrical engineering education at the University of Southern Maine. Creative utilization of this standard test equipment for 2- and 3-terminal device measurements and their automation were reported earlier (see Guvench [4] and [5]).

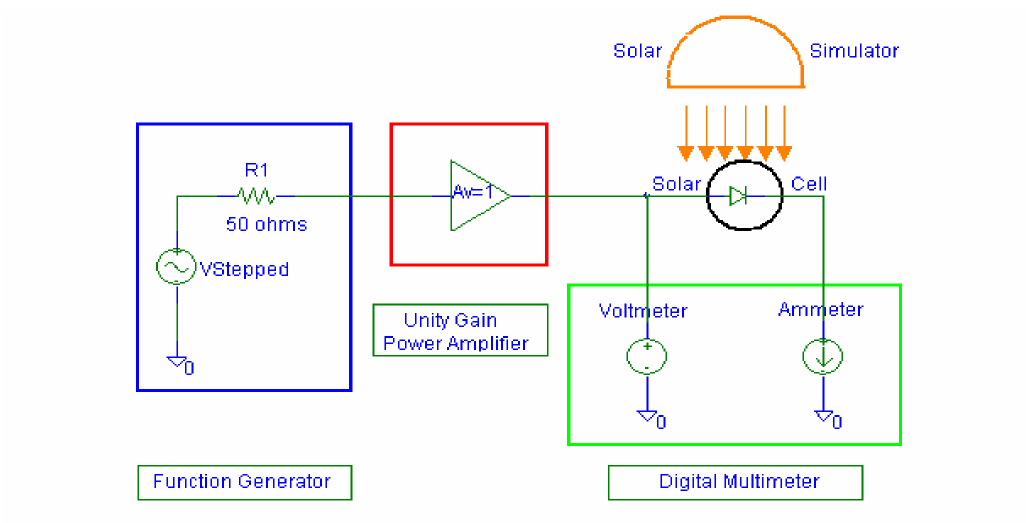

Figure 1. Schematic Drawing of the High-Current Solar-Cell Test Set up

In the I-V measurements the GPIB controlled function generator is used in its DC setting as a stepped DC voltage source. The digital multimeter measures both the voltage across the solar cell and also the current flowing through it. This is accomplished by taking advantage of the separate voltmeter and ammeter inputs of the multimeter and by employing the multimeter as a multiplexing meter switched between voltmeter and ammeter modes by the controlling computer. The circuit diagram is shown in Figure 1. Note that the voltmeter and the ammeter inputs of the multimeter share a common (ground) terminal. Therefore, the voltage measurement has to be corrected by calculating and subtracting the voltage burden of the ammeter depending on the range (which is determined by the internal resistance of the ammeter mode) of the ammeter setting. Details of this technique can be found in Ref. 4. In our measurements, we adapted Guvench's technique and the QBasic code to achieve automated measurement of the I-V characteristics of the solar cell. A special high-current DC amplifier was designed and built to boost the current of the function generator to cover the large current swings needed by these large area solar cells.

The amplifier is a DC coupled unity gain buffer, designed and implemented by employing a general purpose operational amplifier. In order to boost the current delivering capacity of the amplifier, the operational amplifier's output current is amplified by a push-pull Darlington BJT stage. Note that unlike the standard Darlington pairs which employ the same type transistors, we employed complementary devices which eliminate the doubling of the base-emitter junction voltage drops. Figure 2 displays the schematic diagram of the buffer amplifier. Note that one can limit the maximum short circuit current to the load through R5 in the circuit.

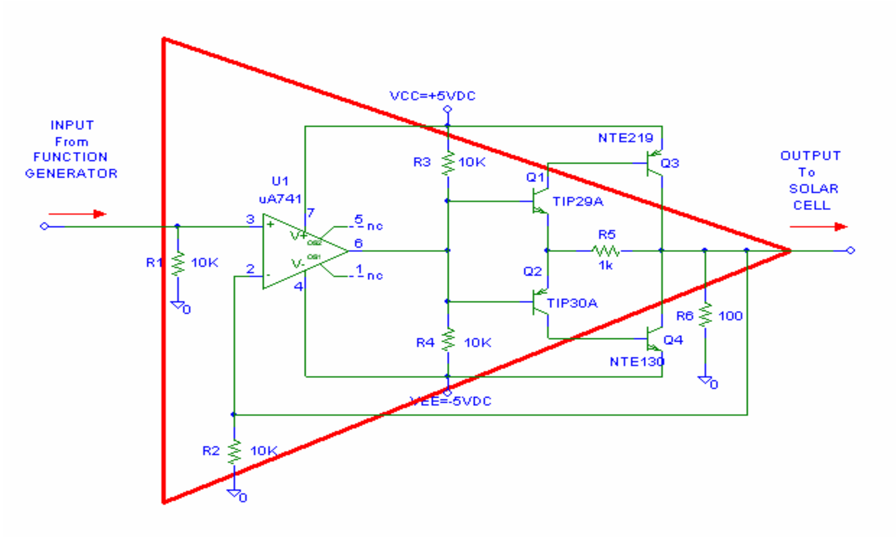

Figure 2. Schematic Diagram of the Unity Gain Buffer Amplifier

The Darlington power transistors are heat sinked to the thick aluminum chassis (box) of the buffer amplifier. As a matter of fact, the circuit was fitted into the box of the off-the shelf analog power supply which similarly used the case as heat sink for its regulator power transistors. A photograph of the amplifier is shown in Figure 3.

Figure 3. Photograph of the High Current Buffer Amplifier

The code developed basically sets the function generator at its DC voltage mode and instructs it to start from a minimum bias voltage and step up in increments until the maximum bias or a maximum safe current value is reached. All these values are initially inputted by the user. During each and every stepped bias point, the code instructs the digital multimeter to measure the voltage and then switch over to ammeter mode and measure the current. The voltage drop in the ammeter is determined and subtracted from the measured voltage to determine the actual cell voltage, and the results are sent into a data (*.txt) file for further processing and interpretation.

Data analysis done using a Mathematica code developed. The code inputs the data, plots the I-V graphs, extracts the series resistance and calculates the power output from the cell, and determines the optimum point of operation, i.e. the bias point where the power output is maximized. Figure 4 is displaying a typical output generated by the code. Note that this sample measured was relatively poor performing since its fill factor which is defined as F.F. = (maximum power output possible) / ($V_{Open}\,I_{SC}$) is small due to its high internal resistance loss.

Part number = TestCell4
Power max = 0.0855 Watts
V_{PMAX} = 0.225 Volts
I_{PMAX} = -0.380 Amps
V_{Open} = 0.436 Volts
I_{SC} = -0.709 Amps
F.F. = 28%

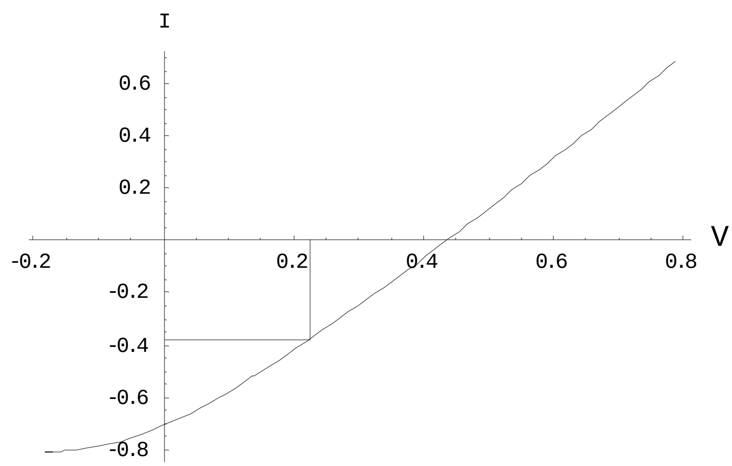

Figure 4. A Solar Cell's I-V Characteristics Measured, Plotted and Parameters Extracted

3. The Solar Simulator

Sun's light is received on Earth at about 100 mW/cm2 intensity with a wide spectral distribution resembling the radiation emitted from a black body heated to 6000ºK. Commonly used incandescent light sources, including the quartz halogen bulbs, operate at temperatures around 3000ºK. Since they operate at half the temperature of the sun they radiate weaker in the shorter wavelengths but stronger in the infrared. The sun's light also passes through a thick layer of atmosphere, undergoing attenuation (depending on the angle of incidence, latitude, etc.) and also absorption due to water vapor, ozone and other chemicals in the atmosphere. Our target was to create a light source which can simulate the solar standard AM1.5 (see Green [4]) as closely as possible for testing silicon solar cells using inexpensive components. Silicon does not respond to light below 1.12 eV (or, above 1.1 µm wavelength.) Priority in the design of the simulator was the intensity and spectral output as sensed and converted to electricity by a typical Silicon solar cell rather than to create a simulator for the entirety of the solar spectrum. Another challenge was to achieve uniformity of the light intensity across a large wafer, as large as 8 inches in diameter. Originally a 500W quartz halogen light source was found satisfactory in delivering the intensity and uniformity of light over an 8-inch Silicon solar cell wafer. However a comparison of the spectral distribution of light generated by the quartz halogen sources and that of the actual solar radiation measured outdoors has shown that the two differ significantly for such quartz halogen light sources to be acceptable as artificial solar radiation sources for solar cell testing. In particular the quartz halogen spectrum, because of its lower color temperature is heavy on the red and infrared part of the spectrum but weaker on the green and blue (shorter wavelengths) side, and cannot be a substitute for solar radiation which has a color temperature of about 6000˚K. Our approach has been to supplement the quartz-halogen spectrum with a high color temperature light source which has a sufficient light output. For this purpose, recently developed metal-halide family of lamps were targeted as potential candidates instead of the standard mercury vapor lamps. The latter, although being commonly used for street lighting for their "white" color perceived by the human eye, show highly peaked discrete mercury emission lines rather than a smooth distribution, and cannot be a true substitute for solar radiation. In the final design, results of spectral measurements done earlier were used to calculate the power ratio for a balanced combination of metal-halide and quartz halogen lamps that would yield an acceptable artificial solar spectrum. The resulting combination created a well balanced artificial solar radiation within the wavelength range of 300 nm to 1100nm which is the range of sensitivity of Silicon photodetectors and solar cells.

The solar cell prober-solar simulator was constructed by adapting a commercial wafer prober and outfitting it with the solar simulator designed. The radiation intensity was tested to be within +/-10% up to 8-inch diameter wafers, and much better (+/3%) for the smaller 6-inch diameter wafers. Figures 5, 6 and 7 give a photograph of the solar cell prober/solar simulator, the intensity distribution uniformity achieved, and a comparison of the spectral output the simulator with actual solar radiation spectrum, respectively.

Figure 5. The Solar Cell Prober/SolarSimulator

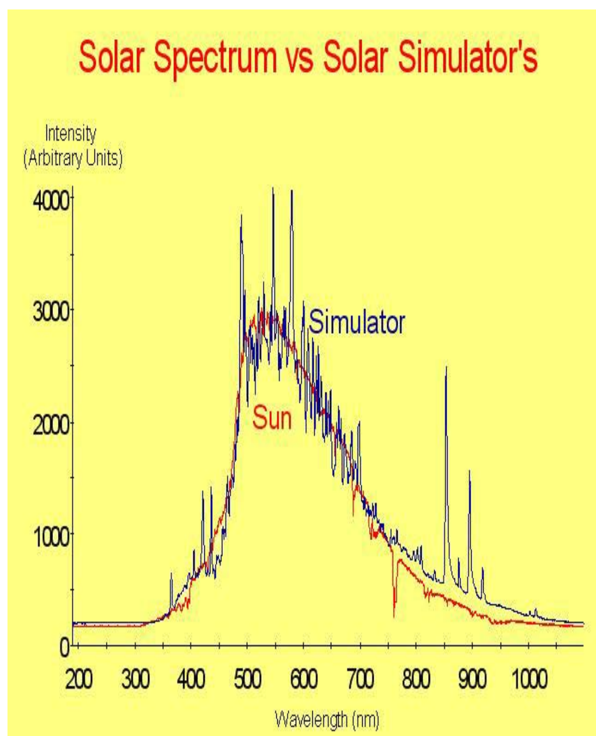

Figure 7. Spectral Distribution of Radiation from the Sun vs. from the Simulator Designed

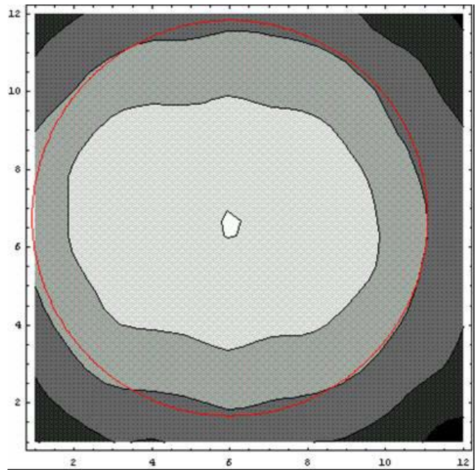

Figure 6. Distribution of Radiation Intensity from the Solar Simulator on the Test Plane of Solar Cell

4. Conclusions and Remarks

The system was built and the programming was done as a part of senior electrical engineering capstone projects at the University of Southern Maine. It is currently being used in the characterization solar cells that are being made at National Semiconductor, South Portland as a part of a joint project to salvage and recycle the 8 inch wafers that are rejects of a state of the art submicron CMOS technology but perfectly suitable for making solar cells

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[8] www.agilent.com
[9] www.keithley.com

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Mustafa G. Guvench received his B.S. and M.S. degrees in Electrical Engineering from M.E.T.U., Ankara in 1968 and 1970, respectively. He did further graduate work at Case Western Reserve University, Cleveland, Ohio between 1970 and 1975 and received M.S. and Ph.D. degrees in Electrical Engineering and Applied Physics. He is currently a full professor of Electrical Engineering at the University of Southern Maine. Prior to joining U.S.M. he served on the faculties of the University of Pittsburgh and M.E.T.U., Ankara and Gaziantep campuses, Turkey. His research interests and publications span the field of microelectronics including I.C. design and semiconductor technology and its application in sensor development, finite element and analytical modeling of semiconductor devices and sensors, and electronic instrumentation and measurement.

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Caglar Gurcan was a senior level Electrical Engineering student at the University of Southern Maine and was working as as coop student in product engineering and testing at National Semiconductor Corporation, S. Portland while working on this project. He graduated in May 2003. Upon graduation he was hired by National as a product engineer. Caglar's interests are semiconductor device fabrication, CMOS integrated circuit design and testing.