As a result of a requirement to study small changes in the electrical characteristics of solar cells occurring over an extended period of time, a short interval tester was constructed. In this tester the light source operates steady state, but though the use of a shutter hundreds of data points may be taken in a time interval of less than a second. With both CRT and hard copy graphical display capability, the instrument measures $I_{sc}$, $P_m$, $V_m$, $(dV/dI)_{V_m}$, and $(dV/dI)_{I_m}$. The instrument is able to accurately measure transient effects, such as photon degradation, normally overlooked with other tester types. Circuit block diagrams as well as measurement results are given.

### INTRODUCTION

Electrical evaluation of solar cells is commonly performed by exposing them to simulated sunlight illumination and recording the current-voltage (I-V) characteristic. This can be accomplished by plotting current and voltage with an x-y plotter while varying a load resistance across the cell from zero to infinity. Figure 1 shows a typical trace obtained in this manner. Appropriate parametric values characterizing the cell's performance may then be determined from the curve using overlays (1). While simple and inexpensive, this method has a number of drawbacks. Like other semiconductor devices, solar cells are temperature dependent and must be maintained at a constant temperature during measurement to insure accurate and repeatable results. Heat radiated from the solar simulator necessitates cooling the cells during testing. Conventional water cooling techniques are difficult because many of the cells have irregular back surfaces which provide poor thermal contact to heat sinks.

Another drawback is the painstaking and time consuming operation of determining specific parameters, such as the maximum power point, from the plotted curves, and transferring them to a large digital computer for analysis and manipulation. This is especially true when large numbers of cells must be measured. Thus in order to make rapid and accurate measurements at constant temperature, a digital, short interval tester was designed and constructed. Use of a light shutter enabled the tester to measure up to 200 data points along the I-V curve with an illumination time of less than a second, thus avoiding any appreciable cell temperature rise. Temperature conditioned air was used to maintain the standard temperature of 28°C ± 0.5°C as recommended by ASTM (2). Because the system was digital, parameters such as the maximum power output could be calculated directly from the data, and easily made compatible with any required computer input format.

### SYSTEM DESCRIPTION

A block diagram of the tester is shown in Figure 2 and a photograph in Figure 3. The cell to be tested was held down by vacuum under the solar simulator in a specially constructed jig as shown in Figures 4 and 5. Construction of the jig was such that the cell was exposed to air of constant temperature both top and bottom. The purpose of the vacuum hold down was thus to accurately and repeatably position the cell and to make electrical connection to the back contact, but not to act as a heat sink for the cell. Connection to the top grid was accomplished by clamping the cell's leads to a conducting ring. Separate voltage and current connections were made top and bottom in a Kelvin arrangement so that the resulting characteristic included the effect of lead resistance and of contact resistance from lead to silicon and from the back metalization to silicon, but did not include the often variable contact resistances associated with either the lead clamp or the connection to the back contact. A spring loaded thermocouple, which also served as the back-side voltage probe, served to monitor the temperature. The light source consisted of 4 air cooled quartz-halogen tungsten (ELH) lamps with dichroic reflectors. (These reflectors transmit a significant amount of the light, while reflecting the heat back to the cells.)
of infrared while reflecting visible light, thereby matching more closely the solar spectrum.

An Intel SBC 80/10A single board computer, an Analog Devices Inc. RTI-1200 interface board, a 16K x 8 random-access-memory board, and a digital controller for the programmable power supply provided the logic for the tester. As configured, the tester had 48 programmable I/O lines, a 20 ma TTY interface, 9K x 8 of EPROM, 17K x 8 of RAM, a floppy disk memory, 8 channels of 12 bit analog-to-digital input, and three 12-bit digital-to-analog converters. A program stored in the microcomputer stepped the cell through the I-V curve, storing the voltage and current values of each data point in memory. Operation of the tester was as follows: The desired current value through the solar cell was computed in the microcomputer in digital form and converted to an analog voltage using the digital controller, which in turn controlled the programmable power supply. The programmable power supply electronically loaded the cell to the desired value of current. The voltage across the cell was then measured by the microcomputer using one of the 12 bit analog-to-digital converter channels and the value stored in memory. The process of electronically loading the cell to a current value, measuring the voltage and storing the data was repeated until the entire I-V curve was measured. The I-V curve data points stored in memory could be displayed on the monitor oscilloscope by connecting two digital-to-analog converters to the scope's x and y inputs. A hard copy of the digitized I-V curve could also be plotted using the x-y plotter. The individual data points and/or parametric data was printed out on the teletype and also punched on paper tape to be fed into a large digital computer for further analysis.

Besides collecting electrical performance data, the system also monitored cell temperature by means of the back contacting thermocouple, and cell illumination by means of a photodetector diode embedded in the massive metal jig base. The photodetector diode (Motorola MRD-510) was biased at its minimum temperature coefficient point using a resistor which was also heat sunk to the jig base. The diode, which was shielded by the cell during test, was momentarily illuminated between tests and the signal used to ensure that the simulator output had remained constant. The diode was not used for system calibration purposes, however.

SYSTEM SOFTWARE

Software instructions for the microcomputer were written in a version of PL/M programming language, called PL/M-80. This is a high level language written for implementing PL/M on the Intel 8080 microprocessor.

The Main Program performed a sequence of call instructions of various procedures (subroutines). Initially the user was prompted to enter cell information as to type, lot number, and cell number. Approximately one-half second after the light shutter was opened the Step Through Procedure was called. This delay ensured that the light shutter was fully opened before any data points were measured. The characteristic I-V curve was then traversed by repetitiously setting the cell current using the Compute Current Procedure and reading the corresponding voltage value. In order to avoid transient phenomena the voltage was read repetitively at each current setting and compared with previous values. Only after two identical consecutive readings were obtained was the next value of current selected.

The I-V characteristic may be divided into three regions, each of which requires special concern to ensure that an appropriate number of data points are obtained. Data points measured in the vicinity of I=0 require a small voltage increment in order to accurately calculate the slope (dV/dI) at I=0, which is proportional to the series resistance, R_s, and to determine the open-circuit voltage, V oc. Data points measured in the vicinity of the maximum power point need to be closely spaced in both voltage and current in order to calculate P max accurately. Data points measured in the vicinity of V=0 require a small current increment in order to accurately determine both I sc and the slope (dV/dI) at V=0, which is proportional to the shunt resistance, R sh. Therefore the Compute Current Procedure had separate modes of operation for each of these three regions in order that a sufficient, but not excessive number of data points were taken to obtain maximum accuracy in minimal time. Figure 6 shows the region associated with each mode.

At the start of a cell measurement the Compute Current Procedure was in mode 0, with an output current of zero amperes. In this mode the current was incremented by 32 milliamperes each time the procedure is called, resulting in another data point. The current and voltage value of each point were stored in memory and the cell's power output calculated by computing the product of the two quantities. This value was then compared with the power output value calculated from the previous data point to determine if the maximum power point of the cell had been reached. If the power from the previous data point was greater, the maximum power point had been passed. When this occurred the procedure then went into mode 1 where the current was decremented by 1 milliamp (minimum increment) for each data point. The power of each of these data points was then calculated and compared to the previous value. Mode 1 continued until the calculated power decreased. The previous data point was then identified and stored in memory as the maximum power point, P max, and the Compute Current Procedure changed to mode 2. Mode 2 initially outputed the current value that mode 0 ended with. Current was then incremented by 4 ma and the change in voltage between the two data points used to determine the next increment. This procedure was found necessary, rather than...
using a fixed current increment, because of the large range of possible slopes observed in the region around the short circuit current. When measuring a high efficiency cell with a flat slope (dI/dV near zero at low voltage), an increment as small as one milliamperes was needed to obtain a sufficient number of data points in the vicinity of I_{sc}. Whereas a badly degraded cell could utilize larger increments to obtain the same number of data points. Use of the 1 ma increment on a degraded cell would result in an excessively large number of data points. Thus mode 2 selected each new current increment based on the voltage change observed between the previous two data points. If the change in voltage was between 1.2 mv and 19.5 mv then the current increment remained the same. If the change in voltage was larger than 19.5 mv then the current increment was reduced by 1 ma. On the other hand, the current increment was increased by 1 ma if the change in voltage was less than 1.2 mv. The Compute Current Procedure remained in mode 2 until the measured cell voltage became negative, indicating that the complete curve had been measured, at which time the procedure was reset to mode 0 for measurement of the next cell.

The Scope Procedure was called from the Main Program after all I-V data points had been measured and stored in memory. This procedure executed in a loop that output the voltage and current values of each data point to D/A converter 1 and D/A converter 2 respectively. The outputs of the D/A converters were connected to the X and Y-inputs of an oscilloscope to display the I-V curve. Return to the Main Program occurred after any key was pressed on the TTY keyboard. The purpose of the visual display was to indicate to the operator that, 1) the measurement had been made and the data properly stored in memory, and 2) the cell had functioned properly during testing with all electrical connections correctly made. Instant visual operator feedback was found to be important in preventing erroneous data from entering the system. Since the purpose of the visual display was only qualitative it was possible to use an inexpensive oscilloscope (which was also able to double as a built-in trouble shooting tool) rather than a more expensive video display.

At the end of the measurement the Parametric Data Output Procedure was called which printed out the parameters, V, I, V, I, P, and cell temperature on the teletype while simultaneously recording the values on the floppy disk.

TIME VARYING EFFECTS

It was noticed on two types of n/p silicon cells that the output performance varied when measurements were made a few seconds apart. After further investigation this instability was found to be a time varying effect caused previously as photon degradation (4). The V, I, and P parameters were found to decay exponentially after being exposed to light under open circuit conditions. This time varying effect was observed on every cell of one n/p type cell and on a few cells of another n/p type. All cells recovered to their original performance after being in the dark for a few minutes. This effect would have gone unnoticed using the equilibrium method of measuring cells with an X-Y plotter, ammeter, and voltmeter. Figure 7 shows plots from the tester of one susceptible cell's output initially, after illumination of 20 seconds, and after 10 minutes. Digitized I-V curves can be measured as often as every second and stored in memory to be plotted and/or printed out later. Reduced parametric data can also be printed out. Aside from general scientific interest, time varying effects are important because they need to be taken into account when initially calibrating the system.

The simulator lamp intensity is normally adjusted, after at least a one hour warm up period, using a calibrated reference cell (5). If the reference cell is subject to time varying change it should be used in the steady state mode with the shutter open to correspond to its original sunlight calibration procedure. This will necessitate either controlling the cell's temperature accurately or measuring the temperature and mathematically relating the measurements to standard conditions.

SYSTEM MEMORY REQUIREMENTS

System software programs required approximately 10 kilobytes of memory while storage of each V-I characteristic required 1K of memory and the miscellaneous scratchpad calculations another 1K. In addition, the tester operating system required approximately 5K bytes. The final memory configuration decided on consisted of 1) 9K of EPROM for storage of the relatively unchanging operating system, 2) 16K of RAM which could accept the tester software programs from disk, provide memory for the scratch pad calculations, and store up to 5 separate V-I characteristics, and 3) a floppy disk system for both the long term storage of programs and the collection of test data. Some early work was done using EPROM memory for program storage and paper tape for collection of the test data, but it quickly became evident that the system lacked both capacity and flexibility. In addition, with paper tape transfer of the data to an IBM 370 computer for statistical analysis was awkward and time consuming. Consequently the floppy disk storage system was added. With the addition of a floppy disk system it was possible to store the entire V-I characteristic rather than just the reduced data, although in practice this was seldom necessary.

CONCLUSION

The microcomputer based short interval tester represents a significant improvement over the analog method of plotting an I-V curve, reading and recording data points. It has decreased cell measurement time by a factor of 5 or more, along with a reduction in human error. Despite less direct personal involvement in the measurement process, the user retains a feeling for the integrity of the data because of the visual display.
on the monitor oscilloscope. The individual current and voltage data points, as well as the reduced parametric values, are IBM compatible for detailed statistical analysis.

The instrument's accuracy and repeatability comes about as a result of being able to measure each cell at the same constant temperature under the same conditions of illumination. Use of the tester allowed time varying and transient phenomenon to be studied under controlled condition. Capital equipment costs for the tester were under $10,000 ($1980).

REFERENCES


Figure 1. Solar Cell Voltage vs. Current Characteristic

Figure 2. Block Diagram of Solar Cell Tester
Figure 3. Photograph of Solar Cell Tester

Figure 4. Cross Section Diagram of Cell Holder

Figure 5. Photograph of Cell Holder

Figure 6. Regions of the VI Characteristic Utilizing Different Modes of the Compute Current Procedure

Figure 7. Changes in VI Characteristic with Time for a Sample Cell