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Measurement Techniques for Solar Cells, Quarterly Report: January 1 to March 31, 1978

D. E. Sawyer, H. K. Kessler,
and H A. Schafft

Electron Devices Division
Center for Electronics and Electrical Engineering
National Bureau of Standards
Washington, D.C. 20234

September 1978

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Prepared for the Department of Energy
Division of Solar Technology
Advanced Materials R&D Branch
Under Task Order AO54-SE of Interagency
Agreement EX-77-A-01-6010

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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, ***Secretary***

Dr. Sidney Harman, ***Under Secretary***

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

TABLE OF CONTENTS

LIST OF FIGURES

PREFACE

This work was conducted as a part of the Semiconductor Technology Program of the National Bureau of Standards (NBS). This program serves to focus NBS research to enhance the performance, interchangeability, and reliability of integrated circuits and other semiconductor devices including solar cells through improvements in measurement technology for use in specifying materials and devices in national and international commerce and for use by industry in controlling device fabrication processes. This research leads to carefully evaluated and well-documented test procedures and associated technology. Special emphasis is placed on the dissemination of the results of the research to the appropriate technical community. Application of these results by industry will contribute to higher yields, lower cost, and higher reliability of semiconductor devices. Improved measurement technology also leads to greater economy in government procurement by providing a common basis for the purchase specifications of government agencies and, in addition, provides a basis for controlled improvements in fabrication processes and in essential device characteristics.

The segment of the Semiconductor Technology Program described in this quarterly report is supported by the Division of Solar Technology of the Department of Energy (DOE) under DOE Task Order A054-SE of Interagency Agreement EA-77-A-01-6010. The contract is monitored by Dr. Donald L. Feucht, Chief of DOE's Advanced Materials R&D Branch. The NBS point of contact for information on the various task elements of this project is Dr. David E. Sawyer of the Electron Devices Division at the National Bureau of Standards.

Certain commercial equipment, instruments, or materials are identified in this report in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

Measurement Techniques for Solar Cells

Quarterly Report
January 1 to March 31, 1978

By

D. E. Sawyer, H. K. Kessler,
and H. A. Schafft

EXECUTIVE SUMMARY

This report covers research performed in the period January 1 to March 31, 1978 on the Program on Solar Cell Measurement Technique Development and Other Services by the Electron Devices Division of the National Bureau of Standards. The objectives of the program are to assist the DOE thin-film photovoltaic effort by developing solar cell device and material measurement techniques using the NBS-developed laser flying-spot scanner, and by assisting the Department of Energy (DOE) in organizing and hosting appropriate workshops and symposia and providing general consultation and liaison services.

A major portion of the program is the development of techniques using the scanner to reveal solar cell quantities of interest, such as emitter sheet resistance and portions of the metallization making poor ohmic contact to the underlying emitter. A technique simpler than one using light modulated at high frequencies (described in the previous Quarterly Report [1]) to reveal these quantities was instrumented during the present quarter. It employs forward biasing of the cell during scanning.

The case of scanning between parallel emitter metallization stripes using a line of unmodulated light was analyzed. The analysis takes a form quite similar to that employed last quarter for the case of microwave-modulated light. It is shown for the present case that the minimum-to-maximum signal ratio depends only on the emitter sheet resistance, the stripe separation, and the cell conductance per unit area; the last can be

varied by adjusting the cell current. The analysis predicts that the emitter sheet resistance can be obtained by fitting the analytical value for the minimum-to-maximum ratio to the experimentally observed ratio.

Apparatus development work underway this quarter included the design and initial construction of an intense insolation source for light-biasing cells while scanning and the construction of a preamplifier to couple the low-impedance illuminated cell to the laser scanner display electronics. Work begun last quarter to increase the area scanned is continuing.

The announcement and program for the May 1-3, 1978, Stability of (Thin Film) Solar Cells and Materials Workshop were mailed to prospective attendees and to news sources likely to be read by the photovoltaic community.

1. INTRODUCTION

This report covers work performed in the period January 1 to March 31, 1978 on the Program on Solar Cell Measurement Technique Development and Other Services by the Electron Devices Division of the National Bureau of Standards under Task Order A054-SE of Interagency Agreement EX-77-A-01-6010.

The objectives of the program are to assist the Department of Energy (DOE) Advanced Materials R&D Branch photovoltaic effort in the following ways:

1. by developing solar cell device and material measurement techniques using the laser flying-spot scanner originally developed at NBS for use on integrated circuits and discrete transistors, and
2. by assisting DOE in organizing and hosting appropriate workshops and symposia, and by providing general consultation and liaison services.

Activities and accomplishments in the various project areas during this reporting period are described in section 2. The announcement and program for the first workshop, the one on Stability of (Thin Film) Solar Cells and Materials, is included as Appendix A.

2. WORK PERFORMED DURING REPORTING PERIOD

2.1 Development of Solar Cell Device and Material Measurement Techniques

2.1.1 Analysis

Description of New Technique

One of the major objectives of the program is the development of techniques which can be used to determine solar cell faults, such as regions of poor metallization, and to determine important cell parameters such as "emitter" sheet resistance. During this reporting period a way to achieve this objective was conceived which is simpler than using microwave-modulated light in the manner described in the previous Quarterly Report [1].

The new method makes use of the distributed nature of the cell under forward-bias conditions. The low-frequency small-signal equivalent circuit of the biased and scanned cell is a three-dimensional resistive array, and the scanning light spot is represented by a current generator moving within the array as the spot scans the cell. The array components are normally made up of the cell emitter sheet resistance and the distributed resistance for the *p-n* junction. This distributed resistance is the local slope of the voltage-current curve for each increment in cell area. A simplified, one-dimensional analysis of this array is presented in this section to show that the new technique, with the cell adequately forward-biased, can be expected to reveal all the cell qualities revealed by the technique using microwave-modulated light.

The analysis proceeds in a manner similar to the one for microwave-modulated light in the previous report; in the present case the local voltage-current slope associated with the *p-n* junction plays a role similar to the distributed transition-region junction capacitance for the microwave-modulated light case. Implementation of the newer technique should be easier because high-frequency equipment and techniques are not needed. Cell forward-biasing can be achieved in either of the following ways, or by a combination of both: (1) uniform, unmodulated illumination of the cell with no steady-state current in the cell load, or (2) connecting the cell to a current source. The explanation of the technique is facilitated by the use of figures 1 and 2.

Predicted Behavior

Figure 1 is an end-on view, not to scale, of an idealized solar cell showing the portion between a contiguous pair of (parallel) metallization stripes, and figure 2 is its one-dimensional electrical representation for the case of scanning with a line of light. This type of scanning will probably not be performed in the program, but it is useful to analyze this case because the solution can be obtained as a closed-form expression which may be examined to anticipate the important results for the more realistic two-dimensional case. In figure 2 the cell emitter is represented by the continuous resistance element, and the small-signal voltage-current ratios for the elemental diodes making up the cell between the stripes are represented by the discrete resistors connected with dotted lines. In the absence of significant shunting by the latter, the photocurrent will find its way to the load through one path or another. Thus, the load voltage (the scanner display screen signal), while it may vary from one light spot location to another due to variations in such quantities as local lifetime, will not be influenced by the proximity to a defect such as a region of poor metallization contact. In short, without significant internal shunting, the scanner does not reliably detect cell defects such as cracks, regions of poor contacting, regions of excessive emitter sheet resistance, etc., which may seriously influence cell reliability and conversion efficiency.

The values of the shunt resistances can be varied by varying the diode forward bias. For the simple case in which each elemental diode is equivalent and all are biased to the same voltage, the shunt conductance per unit area is the same for all portions of the cell. With σ_p representing this conductance, and Ω_s the emitter sheet resistance, the signal current and voltage for each increment of distance dx satisfy the pair of differential equations:

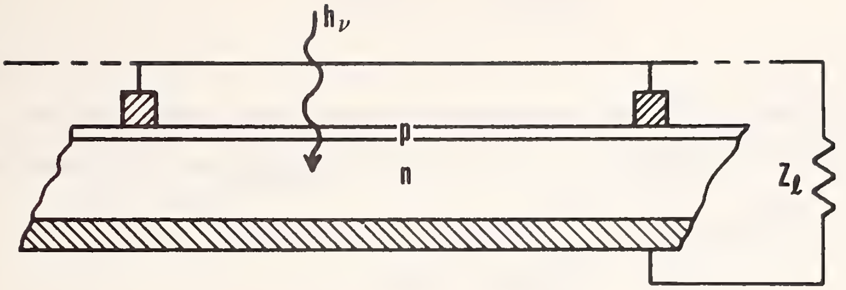

Figure 1. An end-on view, not to scale, of an idealized solar cell showing the portion between a contiguous pair of parallel metallization stripes.

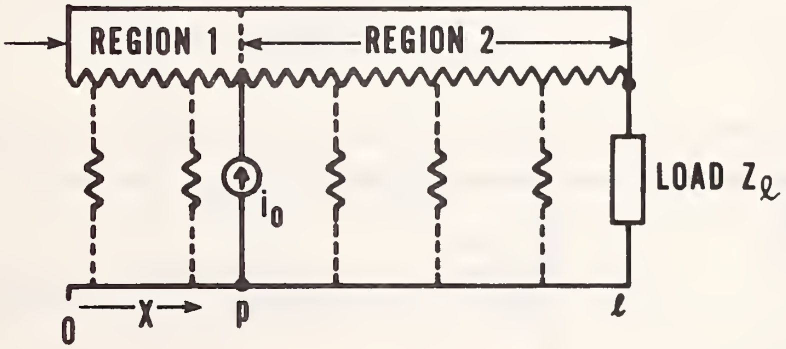

Figure 2. The one-dimensional electrical representation of figure 1 for the case of laser scanning with a line of light. The cell emitter is represented by the continuous resistance element, and the small-signal voltage-current ratios for the elemental diodes making up the cell between stripes are represented by the discrete resistors shown connected with dotted lines.

$$\frac{di(x)}{dx} = - v(x)\sigma_p \tag{1}$$

$$\frac{dv(x)}{dx} = - i(x)\Omega_s \ . \tag{2}$$

The solution of eqs (1) and (2) is carried out in a manner identical to that for the solution of the resistance-capacitance case analysis in the previous report [1], that is, eq (2) is differentiated and substituted into eq (1).

$$\frac{d^2v(x)}{dx^2} - \beta^2 v(x) = 0 \tag{3}$$

where

$$\beta \equiv (\Omega_s \sigma_p)^{1/2} \ . \tag{4}$$

The voltage across the load Z_ℓ, i.e., the output voltage v_{out} for the scanning light line at the arbitrary position $0 \leq p \leq \ell$ is

$$v_{out} = i_o Z_\ell \frac{\{\sinh[\beta(\ell - p)] + \sinh(\beta p)\}}{\{\sinh(\beta\ell) + \frac{2\beta Z_\ell}{\Omega_s}[\cosh(\beta\ell) - 1]\}} \ . \tag{5}$$

As the laser light line is swept from one grid stripe to another, v_{out} undergoes a maximum-minimum-maximum excursion having the ratio

$$\frac{v_{out}(min)}{v_{out}(max)} = \frac{1}{\cosh(\beta\ell/2)} \ . \tag{6}$$

Equation (5) is plotted in figure 3 for a representative value of $(\beta\ell/2)$.

The desired forward biasing of the cell may be achieved by shining light on the cell. It is appropriate now to relate the shunt conductance σ_p to the cell current and associated-air-mass one (AM1) insolation level. Figure 4 shows the I-V characteristics for the dark and illuminated idealized solar cell and its equivalent circuit representation. The well-known effect of shining light on the cell is to displace the I-V characteristic along the I-axis an amount equal to the external current which would exist if the diode were connected to a short circuit. This current will be designated I_L. An alternate description states that charge flows through the cell in the forward-bias direction. For the

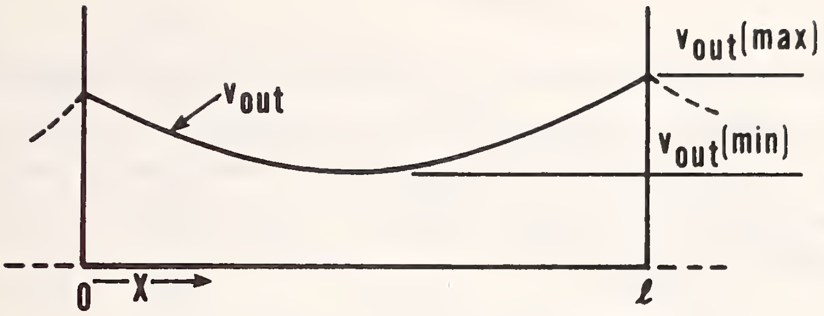

Figure 3. A sketch of eqs (5) and (6) for a representative value for ($\beta\ell/2$) of 1.30.

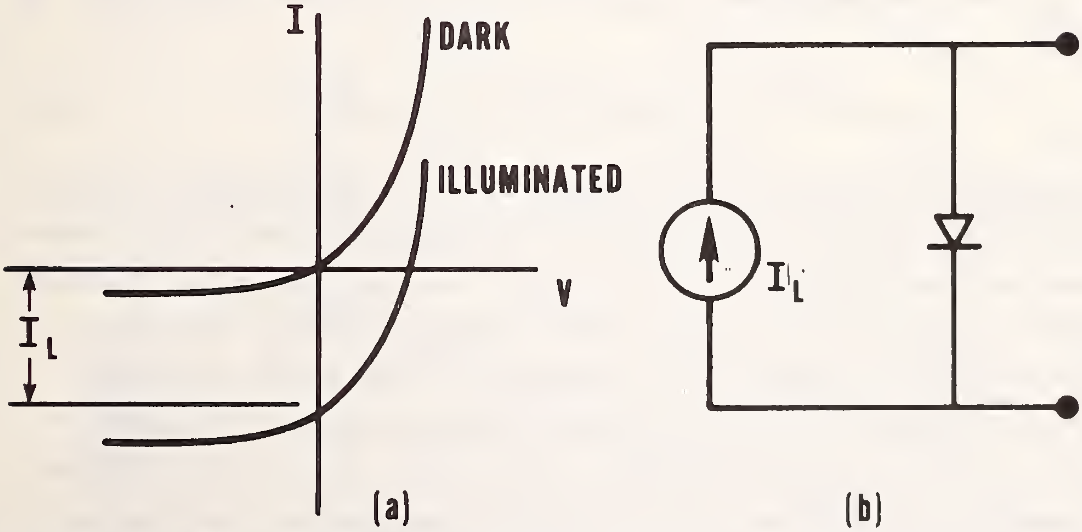

Figure 4. The I-V characteristics for the dark and illuminated idealized solar cell is shown in (a), and (b) shows the equivalent circuit. In the latter, the strength of the current generator is proportioned to the light intensity.

idealized case discussed, and with uniform illumination, I_L is equal to the product of the cell junction area and the cell current density J_L due to illumination. In turn, J_L is related to the cell voltage V and J_o, the junction saturation-current density, by

$$J_L = J_o(e^{qV/kT} - 1) \ . \tag{7}$$

In the scanning method described, the cell is dc open-circuited and illuminated by a constant light source while it is scanned with a much weaker (laser) source. The constant source, by forward-biasing the cell, produces a small-signal junction conductance per unit area readily calculated by differentiating eq (7)

$$\sigma_p = dJ_L/dV = (q/kT)(J_L + J_o) \ . \tag{8}$$

The current J_L will usually be several orders of magnitude larger than J_o, and so the quantity multiplying (q/kT) for all practical purposes is simply J_L. At room temperature, and with J_L expressed in amperes per unit area,

$$\sigma_p = 38.4 \ J_L \text{ siemens per unit area} \ . \tag{9}$$

The insolation level for a representative cell and measurement condition can be readily calculated. The assumed conditions are stripe separation, ℓ = 2 mm, and emitter sheet resistance, Ω_s = 50 $\Omega/\square$; 0.9 is the value of $v_{out}(min)/v_{out}(max)$ judged to just yield adequate scanning sensitivity. From eqs (4) and (6), the σ_p value required is 0.442 S/cm^2, and from eq (9), the required value of light-generated current is 11.5 mA/cm^2. The short-circuit photocurrent from a good quality silicon cell exposed to an insolation of one sun with an air-mass-one spectral distribution is about 38 mA/cm^2 [2]. Using this value, the required cell insolation level in the present example is found to be approximately 0.30 suns, a value which can be reached quite easily in the laboratory. In figure 5, required insolation levels are plotted versus desired scanning-sensitivity ratios for various combinations of stripe spacing and emitter sheet resistance. The insolation values required to give unambiguous v(min)/ v(max) values of 0.5 for line-scanning typical nonconcentrator cell de-

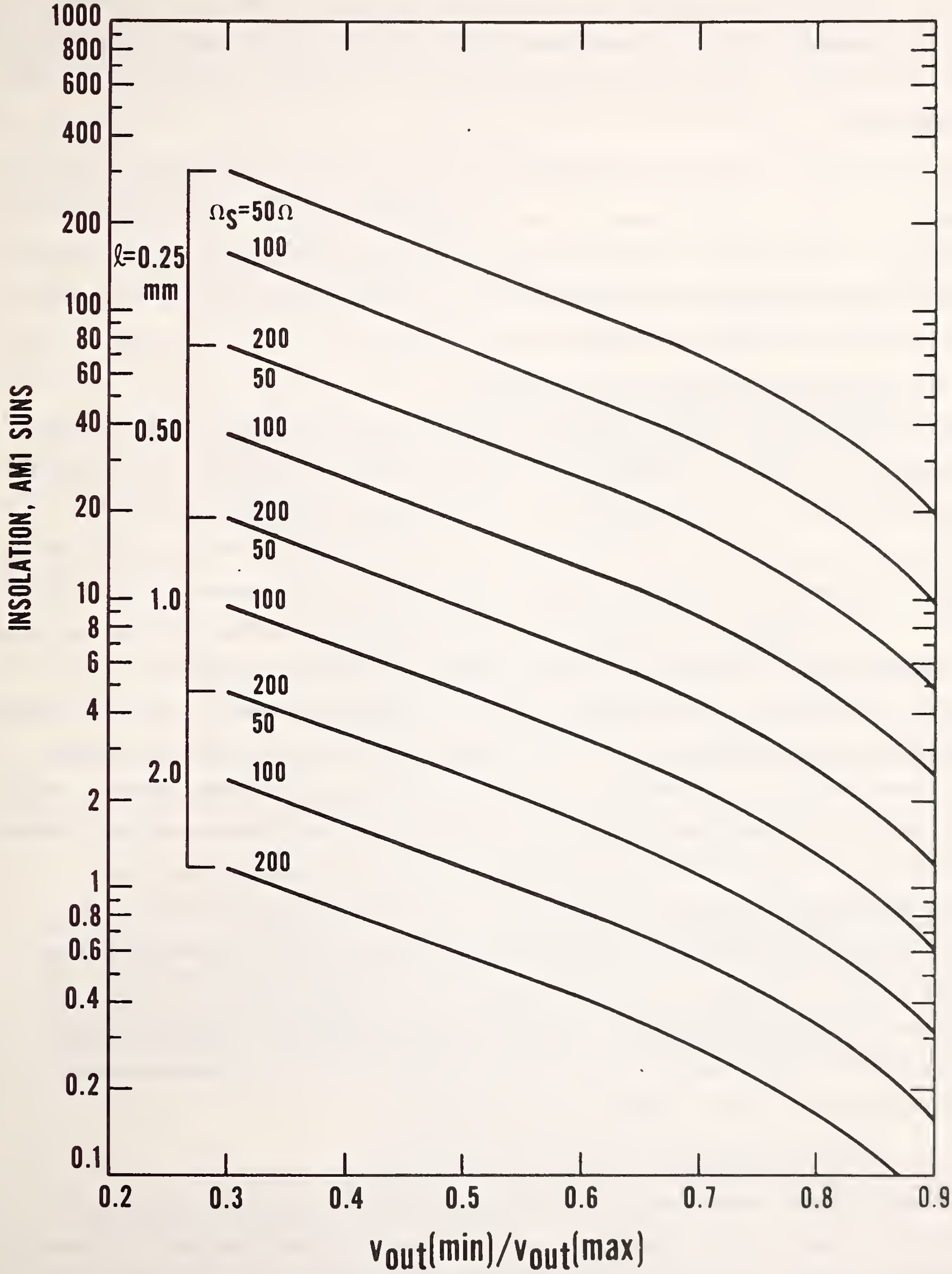

Figure 5. Air-mass-one insolation levels plotted versus desired scanning-sensitivity ratios for various combinations of cell stripe spacing and emitter sheet resistance.

signs having ℓ-values from 1 to 3 mm and Ω_s values from 50 to 200 $\Omega/\square$ can be achieved with an insolation source of 10 suns or less, according to this figure. Such an insolation source is reaching completion in the laboratory.

The second way suggested to achieve the desired internal resistive shunting, by using a current source, is conceptually simpler than flooding the cell with light. Preliminary experiments performed near the end of the present reporting period indicate that this method may offer a convenient way to detect a variety of cell defects.

2.1.2 Equipment for Light-Biasing Cells

One of the project needs mentioned in the previous section is an illuminator to bias cells optically while they are being scanned. An interim specification on the illuminator is that it should produce, for flat plate (nonconcentrator) cells, a short-circuit current response equivalent to exposing the scanned area of the cell to an insolation of 20 suns. It is obvious that noise and modulation of the light by, e.g., an inadequately filtered lamp power supply should be a minimum. One type of light source which should satisfy the requirements is the quartz-halogen incandescent lamp. An illuminator using such a lamp has been designed this quarter and its construction is reaching completion. Its optical system uses four groups of heat filters and condensing and focusing lenses arranged symmetrically around the long axis of the lamp. This arrangement captures almost all of the light available from the lamp and it is designed so that it focuses the light onto the receiving ends of four flexible fiber-optic light pipes which direct the light to the cell area being scanned. Preliminary measurements indicate that more than 30 suns insolation can be achieved at the cell surface and that extraneous noise sources are negligible.

2.1.3 Laser Flying-Spot Scanner Modifications

The capacitance associated with the injection of minority carriers in forward-biased solar cells may severely limit the spot deflection rates allowable, when one employs the method to pin-point cell defects described in section 2.1.1. One way of solving this problem is to reduce the RC time-constant of the cell and its load. This reduction can be accomplished by coupling the cell to the scanner display electronics with a transformer input. Initial and promising results have been achieved using a transformer having an input impedance of 1.75 Ω. The transformer secondary was connected to the 3.3-kΩ display screen input, and a 9,000-μF electrolytic capacitor was put in series with the primary to block the cell dc voltage.

A number of ways are being pursued to increase the scanning area. When the scanner was used for discrete transistor-like devices and ICs, a large scanning area was not needed, and the ability to achieve a scanning area 3 mm on a side was quite adequate. For solar cells, one would like to increase this value by at least an order of magnitude. Various ways are being investigated to achieve this by modifying the scanner optics through replacing or supplementing the original optical elements.

2.2 Workshops and Symposia

The plans for the workshop "Stability of (Thin Film) Solar Cells and Materials" scheduled to be held at NBS, Gaithersburg, Maryland, on May 1-3, 1978 were completed this quarter. The announcement and program were mailed to a number of publications read by the photovoltaic community; copies are included as Appendix A. This material with a general information sheet, hotel reservation card, etc., were mailed to about 800 people believed to be engaged in various aspects of solar cell work.

3. REFERENCES

1. Sawyer, D. E., Kessler, H. K., and Schafft, H. A., Measurement Techniques for Solar Cells, Quarterly Report, September 15 to December 31, 1977, NBSIR 78-1488 (July 1978).

2. Hovel, H. J., Solar Cells, *Semiconductors and Semimetals*, R. K. Willardson and A. C. Beers, Eds, Vol. 11, p. 47 (Academic Press, New York, 1975).

APPENDIX A

WORKSHOP

Stability of (Thin Film) Solar Cells and Materials

May 1-3, 1978
National Bureau of Standards
Gaithersburg, Maryland

The National Bureau of Standards is conducting a workshop on the Stability of (Thin Film) Solar Cells and Materials for the Department of Energy's Advanced Materials R&D Branch. The workshop is part of the Department of Energy's National Photovoltaic Program and is directed to those engaged in research on various types of cells. One of its main purposes is to identify and discuss problems and obstacles to achieving 20-year life for terrestrial solar cells and to plan how these may be overcome by the use of test and measurement procedures designed to enhance the prediction of material and device stability.

Three different groups of exploratory solar cell materials and concepts will be addressed. These are: (1) [CdZn]S/Cu_2S, CdS/Cu-ternaries, CdS/InP, and amorphous Si; (2) polycrystalline, MIS, and conducting oxide Si; and (3) polycrystalline and AMOS GaAs. Modes and mechanisms for failure and degradation of these systems and the status of present reliability testing will be reviewed by current workers. A number of speakers have been invited to discuss measurements and test approaches that have been used for achieving high reliability in related device technologies. For example, representatives from DoD, NASA, and the power transistor community will speak to provide enhanced perspective for the solar cell community and to promote cross-fertilization. Time will be available for the presentation of a limited number of unsolicited papers that provide data pertinent to the topics of the workshop. Discussion groups will be formed to identify tests and measurement procedures that can be used to enhance the prediction of material and device stability for each of the three solar cell groups.

Advanced registration is requested. For more information, including registration and hotel reservation forms, contact Mrs. Elaine Cohen, Division 425.00, National Bureau of Standards, Building 225, Room A-327, Washington, D.C. 20234. Telephone: (301) 921-3625.

Workshop on Stability of (Thin Film) Solar Cells and Materials

National Bureau of Standards
Washington, D.C.
May 1-3, 1978

MONDAY, May 1

8:30-9:15 a.m.	REGISTRATION
9:15-10:00 a.m.	SESSION I. Welcoming, Perspective, and Workshop Overview
10:00-1:00 p.m.	SESSION II. Status of Present Reliability Testing, Failure Modes, Failure Mechanisms, and Data for Advanced-Cell Materials (a) [CdZn]S/Cu_2S, CdS/InP, CdS/Cu-Ternaries, amorphous Si (b) polycrystalline, MIS and conducting oxide Si (c) polycrystalline and AMOS GaAs
1:00-2:00 p.m.	LUNCH
2:00-2:30 p.m.	SESSION II. (continued)
2:30-5:00 p.m.	SESSION III. Types of Measurements and Tests Used to Define Stability in Related Technologies (a) DoD Experience (b) Semiconductor Power Devices (c) Methods and Tests at BTL (Solar Cell and Other) (d) "JPL/NASA" Experience (e) Concentrator Cells (f) Corrosion and Measurement Tools for Corrosion (g) (Inter)Diffusion Phenomena (h) Encapsulants
6:30 p.m.	CASH BAR (Ramada Inn)
7:30 p.m.	WORKSHOP DINNER (Ramada Inn)

TUESDAY, May 2

9:15-11:00 a.m.	SESSION III. (continued)
11:00-1:00 p.m.	SESSION IV. Working Groups Sessions
1:00-2:00 p.m.	LUNCH
2:00-5:00 p.m.	SESSION IV. Working Groups Sessions (continued)

WEDNESDAY, May 3

9:15-11:20 a.m.	SESSION IV. Working Groups Sessions (concluded)
11:20-1:00 p.m.	SESSION V. Preparation of Working Groups Summaries
1:00-2:00 p.m.	LUNCH
2:00-4:00 p.m.	SESSION VI. Working Groups Present Summaries and Recommendations
4:00 p.m.	END OF WORKSHOP

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This is the quarterly report of the work performed in the three month period January 1 - March 31, 1978. The objectives of the program are to assist the DOE thin-film photovoltaic effort by developing solar cell device and material measurement techniques using the NBS-developed laser flying-spot scanner, and by assisting DOE in organizing and hosting appropriate workshops and symposia and providing general consultation and liaison services.

A technique simpler than the one using light modulated at high frequencies, described in the previous quarterly report, is set forth which employs forward-biasing solar cells during scanning to pin-point certain cell defects and to obtain values of cell quantities such as emitter sheet resistance. An analysis appropriate for laser scanning forward-biased cells with a line source is presented. Results from initial experiments suggest that the new technique should work quite well on real-world solar cells. Apparatus development work included the design and initial construction of a high-sun insolation source for forward-biasing cells by light while scanning, and the construction of a matching network to couple the low-impedance illuminated cell to the scanner display electronics.

The announcement and program for the May 1-3, 1978 Workshop on the Stability of (Thin Film) Solar Cells and Materials at NBS is presented.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*
Device measurements; laser scanning; light-biasing; metallization; ohmic contacts; reliability; semiconductor measurements; sheet resistance; solar cells; solar cell stability.

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