Div. 721

NBSIR 79-1909

Measurement Techniques for Solar Cells, Quarterly Report: April 1 to June 30, 1978

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and H. A. Schafft

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Center for Electronics and Electrical Engineering
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National Bureau of Standards
Washington, DC 20234

October 1979

Prepared for
Department of Energy
Division of Distributed Solar Technology
Advanced Materials R&D Branch
Under Task Order A054-SE of Interagency
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PREFACE

This work was conducted as 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 Distributed 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 SERI'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 in the NBS Center for Electronics and Electrical Engineering.

Measurement Techniques for Solar Cells

Quarterly Report
April 1 to June 30, 1978

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

EXECUTIVE SUMMARY

This report covers research performed in the period April 1 to June 30, 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 Department of Energy (DOE) thin film photovoltaic effort by developing solar cell device and material measurement techniques by using the NBS-developed laser flying-spot scanner, and by assisting the 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 that use the scanner to reveal solar cell quantities of interest such as emitter sheet resistance and poor ohmic contact of portions of the metallization to the underlying emitter. The technique proposed last quarter, which employs cell forward-biasing during scanning to reveal these quantities, was implemented. With an electrical current source to forward bias the cell, cracks and metallization regions disconnected from the cell output electrode were readily revealed.

The mathematical analysis work relating laser scanning results to cell parameters and defects has been extended to more realistic cell geometries than the one-dimensional case previously treated. This work will be applicable to a wider range of real-life situations.

Apparatus development work conducted this quarter included: completion of the high-intensity insolation source used for light biasing a cell while it is being scanned, improvement in coupling to the display electronics cells that are simultaneously biased and scanned, and increase of the scanning area so that 50-mm cells can be scanned in their entirety without repositioning.

The workshop on Stability of (Thin Film) Solar Cells and Materials was held on May 1 to 3, 1978 at the National Bureau of Standards, Gaithersburg, Maryland.

1. INTRODUCTION

This report covers work performed in the period April 1 to June 30, 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 EA-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. Development of solar cell device and material measurement techniques using the laser flying-spot scanner that was originally developed at NBS for use on integrated circuits and discrete transistors.

2. Assistance to DOE in organizing and hosting appropriate workshops and symposia and providing general consultation and liaison services.

Activities and accomplishments in the various project areas during this reporting period are described in the following sections.

2. WORK PERFORMED DURING REPORTING PERIOD

2.1 Development of Solar Cell Device and Material Measurement Techniques

2.1.1 Cell Scanning Technique Employing Current-Source Biasing

2.1.1.1 Description of Technique. The analysis presented in the previous Quarterly Reports [1,2] shows how one may make use of the distributed nature of a solar cell to determine cell parameters of interest and to detect various cell faults. This distributed nature is an intrinsic property of all cells and so techniques that are based on the distributed nature of the cells should be applicable to a large number of cell types and configurations. The first Quarterly Report [1] described how one might use high frequency (e.g., microwave) modulated light and the distributed junction capacitance to determine cell quantities. The second Quarterly report [2] described a much simpler method which uses the low-frequency conductance of each of the elemental diodes making up the cell. In this simpler method, the cell is scanned with unmodulated light as it is forward biased. It was suggested [2] that biasing could be provided either by shining light on the cell (and calculations were given to allow one to estimate the required light intensity) or by using an external (electrical) current source. During the present reporting period, several types of *p-n* junction solar cells were scanned while so forward biased. Although scanning results obtained with an external source may not be identical to those obtained with light-biasing for the same (internal) current value, it was found that an external current-source provided a very convenient way of assessing cell fabrication and service-connected defects.

2.1.1.2 Cell Scanning Results. The highlights of cell defect-detection experiments performed during the present reporting period were given in a late-news paper delivered at the 13th Photovoltaic Specialists Conference, Washington, D.C. The abstract of this paper is included in Appendix A of this report. A more complete discussion of the results is presented below.

2.1.1.2.1 Metallization Integrity. The upper sketch and photographs in Appendix A are for one of the first cells scanned while energized from a current source. A pair of metallization breaks detected by means of an optical microscope are shown by circles in the sketch. The surrounding shaded rectangle shows the area scanned. Because of the electrical redundancy in connecting the fine (50-μm) herringbone metallization grid lines in the central portion of the cell to the wider (280-μm) metallization splines, two breaks in a fine line are required to disconnect any appreciable length of fine-line metallization from the cell output electrode. On the left is a photomicrograph of the line breaks indicated in the central sketch. On the right are two photographs of the display screen of the laser scanner. The display presentation is a mix of y-axis and z-axis display modes, i.e., an increase in photoresponse simultaneously produces a larger upward deflection of a horizontal scan line and an increase in screen brightness. The upper of the two photographs shows the photoresponse with no applied cell current; the lower shows the photoresponse with an applied current of 126 mA, which corresponds to a value of about 80 percent of the cell's short-circuit output current were it exposed to AM1 insolation. The metallization breaks are not detected at zero bias but are readily observed with forward bias by the lowered photoresponse in their vicinity. The breaks appear to be the only metallization defects in the scanned area. The metallization which is continuous to the splines appears to make uniform electrical contact to the underlying emitter, as evidenced by the photoresponse attaining a maximum adjacent to the metallization. Even though scanning was performed with a spot of light, the general shape of the photoresponse *versus* position away from the broken metallization region is in qualitative agreement with the results predicted by a line-scan analysis [2] and by the mathematical results presented in Appendix B. Other portions of the cell having disconnected metallization regions were laser-scanned with results similar to those reported above.

The results obtained in these experiments suggest several ideas:

1. In order for photoresponse at the edge of a metallization stripe to achieve a common, maximum value, the metallization must be continuous to the output lead and must make a uniform ohmic contact to the underlying semiconductor. These are precisely the "bottom line" requirements for effective metallization, and so the scanning technique described should provide a test for metallization efficacy.

2. Metallization-efficacy testing can be done under production line conditions by unskilled personnel. With the equipment set up for a particular cell type and using the intensity-modulation display mode, one

only requires that the operator note if a dark line (shadow of the metallization stripe) runs through the center of a dark region, and no knowledge of devices or fabrication processes is required.

3. By dividing the scanning response under bias with the zero-bias response on a spatial point-by-point basis, the fabrication and service-related loss mechanisms should be even easier to perceive and measure. The eye can make comparisons of this sort to some extent, but it would be better to use a computer.

4. Electron-beam instruments such as the scanning electron microscope (in the electron-beam-induced-current mode) might also be used in the same manner as was done with light. Most of these instruments appear to be designed to image small areas at high magnification, and hence, devices the size of working solar cells may require appreciable repositioning for their entire area to be scanned.

2.1.1.2.2 Crack Detection. The biased-cell scanning technique was also used to locate cracks in solar cells. This is an important application because cracks have been known to cause cell arrays to fail, sometimes dramatically, with electric arcs and flames produced at the crack [3]. If the cell surface is smooth and the crack is sufficiently wide, the crack may be detected under favorable conditions by its scattered light during optical inspection. If the surface is not smooth, cracks wide enough to stand out against a smooth surface may be lost in the surface texture and go undetected. The NBS-developed method makes use of the fact that the semiconductor electrical conductivity is discontinuous across the crack. By using this method, one might expect to detect cracks which are too fine to be revealed by optical inspection techniques. With the cell forward biased, one sees a change in the cell's photoresponse as one scans across the crack. Experimentally, one sometimes sees this manifested as a slope change and sometimes by an amplitude change in the photoresponse scan. A crack between a pair of metallization grids should not influence the photoresponse outside that region. Occasionally it does, and some areas of the cells delineated by cracks may exhibit a lowered scanning response everywhere. This could be due to differences in resistances between the cell output electrodes and the various semiconductor regions contacted.

The lower half of the figure sheet in Appendix A illustrates both the slope-change (left) and amplitude-change (right) possibilities discussed above of a cell purchased commercially. The crack location of this 4-in. diameter cell was confirmed by optical inspection (cracks in other cells not discernible to the eye were scanned subsequently and located with the forward-biased scanning techniques). In the display photographs, several surface features can be seen that are not cracks but show similar zero-bias scanning signatures. These features appear to be benign and are probably due to scratches, dislocation lines, or the presence of unwanted material. Since cell cracks (when they are wide enough to produce photoresponse perturbations without the cell being biased) and these blemishes can yield the same zero-bias scanning signature, the harmless features could be mistakenly labeled as cracks and the cell rejected needlessly. Alternatively, a true crack might be mistaken as a benign cosmetic blemish. The sets of photographs demonstrate that separation of these classes can be accomplished with forward-bias scanning.

2.1.1.3 Mathematical Modeling of Solar Cells. To support the laser scanning work, K. Lehovec and A. Fedotowsky, under subcontract at the University of Southern California, are performing mathematical modeling of cells containing defects such as regions of open metallization and cracks. Initial modeling work completed this reporting period appears in Appendix B.

2.1.2 Equipment for Light-Biasing Cells

The program needs an illuminator to bias cells optically while they are scanned. Effective insolation levels of 20 suns AM1 are desired. The light output must be free from modulation produced either by the lamp power-supply or by lamp internal processes. An illuminator has been designed and constructed to satisfy these criteria. A photograph of this illuminator with the top cover removed is shown in figure 1. The light source is a 60-W quartz-halogen incandescent lamp. The illuminator uses four groups of heat filters and condensing and focusing lenses arranged symmetrically around the long axis of the lamp. This arrangement, which captures almost all of the light available, is designed so that the light is focused onto the receiving ends of four flexible fiber-optic pipes which direct the light to the cell area being scanned. A muffin-type fan mounted below the bottom plate cools the lenses and filters. A small silicon solar cell, mounted inside the illuminator, powers the external meter shown to monitor the light from the lamp. This circuit permits one to easily adjust the lamp power source for a given light output at the ends of the fiber-optic pipes. Figure 2 shows the laser scanner being used with the illuminator.

2.1.3 Laser Flying-Spot Scanner Modifications

2.1.3.1 Increase in Scanning Area. Increasing the cell size that can be scanned at one setting of the equipment is a continuing activity. Before the beginning of the solar cell program, the scan excursion was limited to about 3 mm by the optical parts available for the particular microscope used for the scanner optics. By removing lenses and replacing the original microscope lenses with lenses purchased from other sources, the scan excursion was increased to 11.5 mm, and the working distance (objective lens to specimen distance) was increased to permit the inclusion of the optical-bias fiber-optic pipes described in section 2.1.2. Additional increases in scan area and working distance were achieved by replacing the entire microscope optical system with a 35-mm camera lens having a focal length of 55 mm. The maximum scan excursion is now 50 mm with a spot resolution of about 25 μm. This resolution is adequate to resolve the finest metallization grids found on nonconcentrator solar cells.

2.1.3.2 Increase in Bandwidth of Cell-Coupling Network. It is necessary to couple forward-biased cells to the scanner display elec-

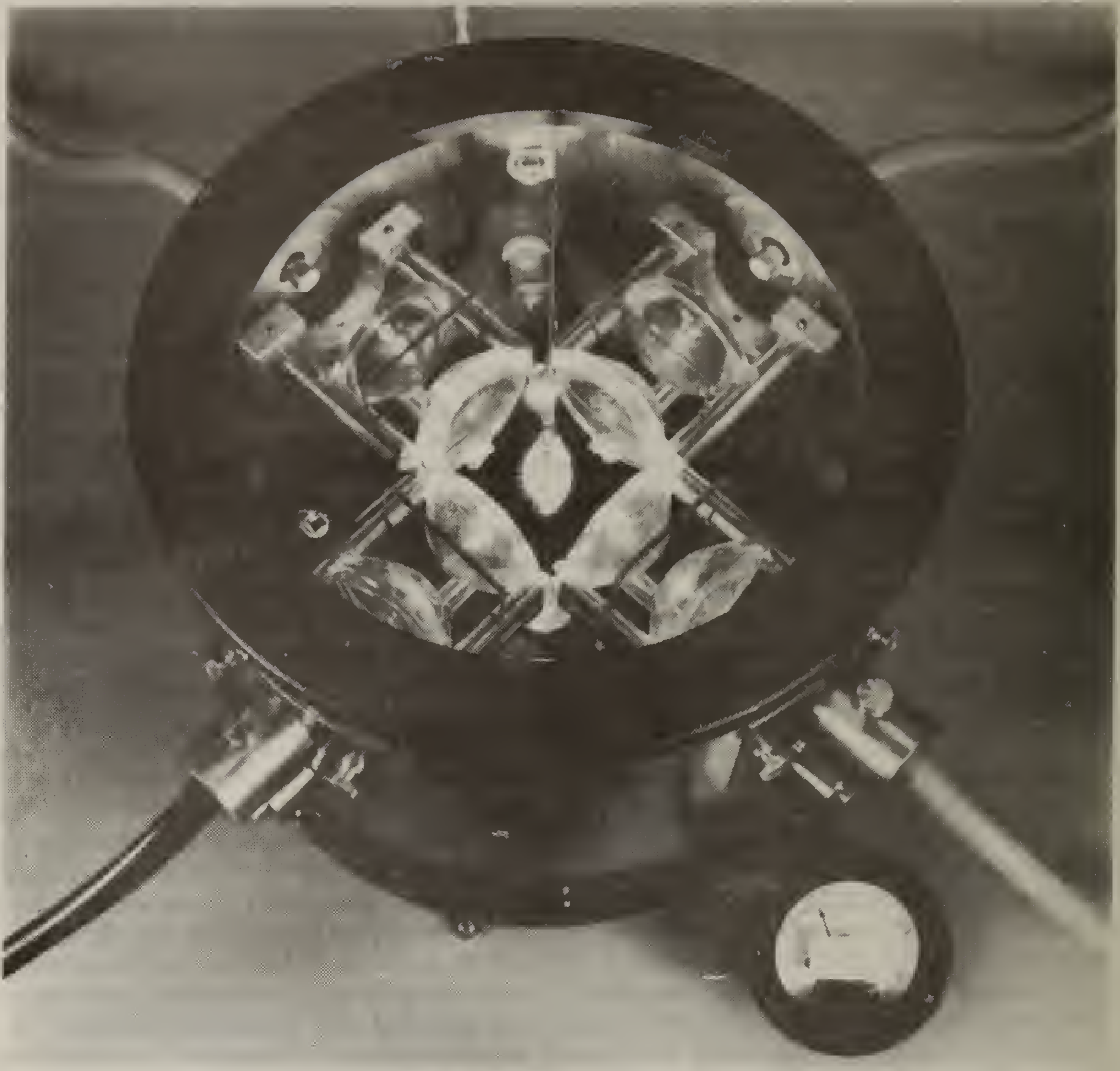

Figure 1. The high-intensity light source with the top cover removed.

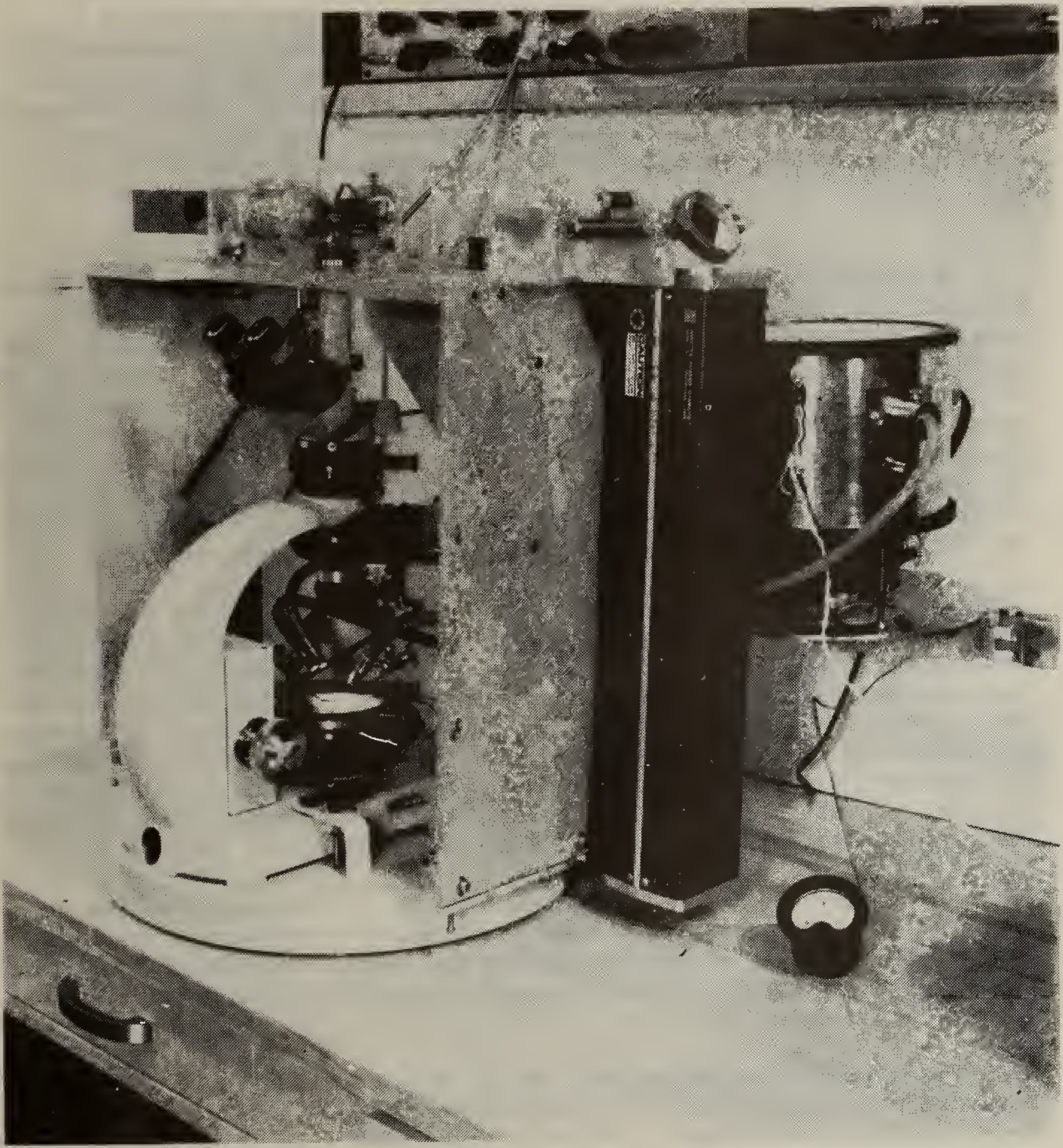

Figure 2. The high-intensity light source being used with the laser scanner.

tronics by a means that ensures that the cell sees a low impedance, necessary [2] to maintain the scanned cell signal-to-noise ratio and to minimize the effects of the cell's capacitance at the maximum permissible scanning rate. The coupling found to be most satisfactory to date is a transformer in conjunction with a large-value dc blocking capacitor. Further improvements have been achieved in bandwidth, and hence in display-screen detail, by increasing the capacitance of the blocking capacitor from 9,000 μF to 27,000 μF, and by replacing the coupling transformer with a more suitable one. The bandwidth for the combination is now 5 Hz to 13 kHz (3-dB points); this bandwidth yields adequate display-screen definition.

2.2 Workshops and Symposia

A workshop on the Stability of (Thin Film) Solar Cells and Materials was conducted at the National Bureau of Standards on May 1 to 3, 1978 as part of the Department of Energy's National Photovoltaic Program. The workshop program is included as Appendix C. The workshop addressed many of the obstacles to achieving stability and long life of terrestrial solar cell devices using forefront technology. The following three groups of exploratory solar cell materials and concepts were considered: (1) Cu_2S/[CdZn]S, Cu-ternaries/CdS, InP/CdS, and amorphous Si, (2) polycrystalline, MIS, and conducting oxide Si, and (3) polycrystalline and AMOS (antireflection-coated metal-oxide-semiconductor) GaAs.

Researchers in the field reviewed modes and mechanisms for failure and degradation of these systems and the status of present reliability testing. Speakers from related device technologies discussed measurement and test approaches that have been used to achieve high device reliability. Two talks were of particular interest. One described a technique for detecting changes in the physics of failure with increasing severity of a stress parameter to establish the maximum possible acceleration factor for a given failure. The other described a technique for uncoupling different failure mechanisms by an analysis of failure rate data.

Discussions in the working groups of the workshop led to the identification of a number of needs that require attention before meaningful headway can be made in the achievement and quantification of stability and long life for solar cells developed using forefront materials and device technologies.

The main conclusion reached by the 102 scientists and engineers who attended the workshop was that more research needs to be conducted in this forefront technology. In particular, they identified the need to study the chemical, mechanical, and physical compatibility of the various materials used in these solar cell devices and the influence of compatibility on device characteristics. Also expressed was the need for the development of performance and measurement standards for use in characterizing these devices. Finally, the need for adequate device manufacturing process controls and adequately described test procedures and data was underscored as a prerequisite for meaningful headway in the quantification of solar cell stability and long life.

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. Sawyer, D. E., Kessler, H. K., and Schafft, H. A., Measurement Techniques for Solar Cells, Quarterly Report, January 1 to March 31, 1978, NBSIR 78-1513 (September 1978).

3. Ross, R. G., private communication.

APPENDIX A

A Technique for Using an Optical Scanner to Reveal Solar Cell Defects*†

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Except for grossly deficient solar cells, most of the previous attempts to use an optical-spot scanner to reveal cell defects such as cracks and poor metallization have not been very successful. In the work reported here, the cell is forward biased while scanning with the optical spot. Under these conditions, one makes use of the cell's distributed nature, an intrinsic property shared by all solar cells, to readily reveal such defects. The low-frequency small-signal equivalent circuit of the biased and scanned cell is a three-dimensional resistive array, and the 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 for each increment in cell area. A simplified, two-dimensional analysis of this array predicts that cracks and regions of poor metallization can be pinpointed while scanning the cell if it is adequately forward biased. This predicted behavior has been confirmed by measurements made on cells with known defects. Measurements have been made on silicon flat plate and gallium arsenide concentrator cells using forward-bias current somewhat less than those which would flow with the cells exposed to their normal insolation levels. The technique is non-damaging; it requires no electrical contacts to the cell other than those already present, and it can be used on encapsulated or unencapsulated cells in almost any laboratory or test environment.

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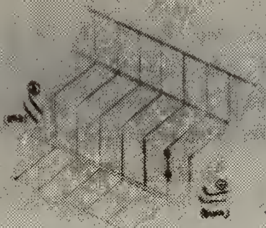
*This work was supported by DOE's Advanced Materials R&D Branch under Task Order A054-SE of the Interagency Agreement EA-77-A-01-6010.

METALLIZATION INTEGRITY



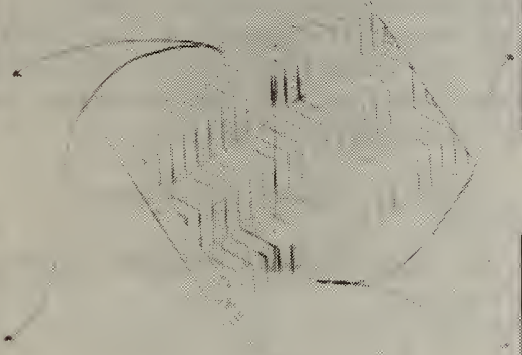
NO APPLIED BIAS

126 mA DC BIAS ≈ 80%
AM1 CELL CURRENT

CRACK DETECTION

NO APPLIED BIAS

0.9 A DC BIAS 29%
AM1 CELL CURRENT



NO APPLIED BIAS

0.9 A DC BIAS 29%
AM1 CELL CURRENT

APPENDIX B

Light Beam Probing of Solar Cells

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B.1. Introduction

D. Sawyer and coworkers at NBS are scanning solar cells by a modulated light spot as a means to locate and identify cell faults by inspection of the cell output pattern. Our aim is the modeling of various faults and the computation of the resulting output patterns. Comparison of the computed patterns with observations will assist in identifying the faults in experimental cells.

The solar cell will be modeled by a two-dimensional distributed network of diodes connected by semiconductor sheets having sheet resistances ρ_T on top of the junction and ρ_S on the bottom. The corresponding bulk resistivities are Ω_T and Ω_S, respectively. An edge view of the model is shown in figure B1. The effect of light is to place a current source of total magnitude I_L across the diodes illuminated. A top view of the electrode configuration is shown in figure B2. The electrodes are of length W. Figure B3 shows an element of the distributed network of figure B1 and indicates the notation used in the analysis; $\delta(x - x_1)$ is a delta function centered at $x = x_1$. The notation used here is consistent with that used in reference [B-1].

B.2. Basic Equations

The dark current per unit area J_D depends exponentially on the voltage across the junction:

$$J_D = J_o(e^{BV} - 1) \ . \qquad \text{(B-1)}$$

The pre-exponential coefficient J_o is the reverse saturation current per unit area and $B = q/\alpha kT$ with α the diode quality factor.

By neglecting lateral diffusion currents, the lateral sheet current densities are

$$\vec{J}_T = - \nabla V_T/\Omega_T \qquad \text{(B-2a)}$$

and

$$\vec{J}_S = - \nabla V_S/\Omega_S \qquad \text{(B-2b)}$$

where the subscripts refer to top and substrate (i.e., base) of the junction, respectively. Conservation of charge requires that

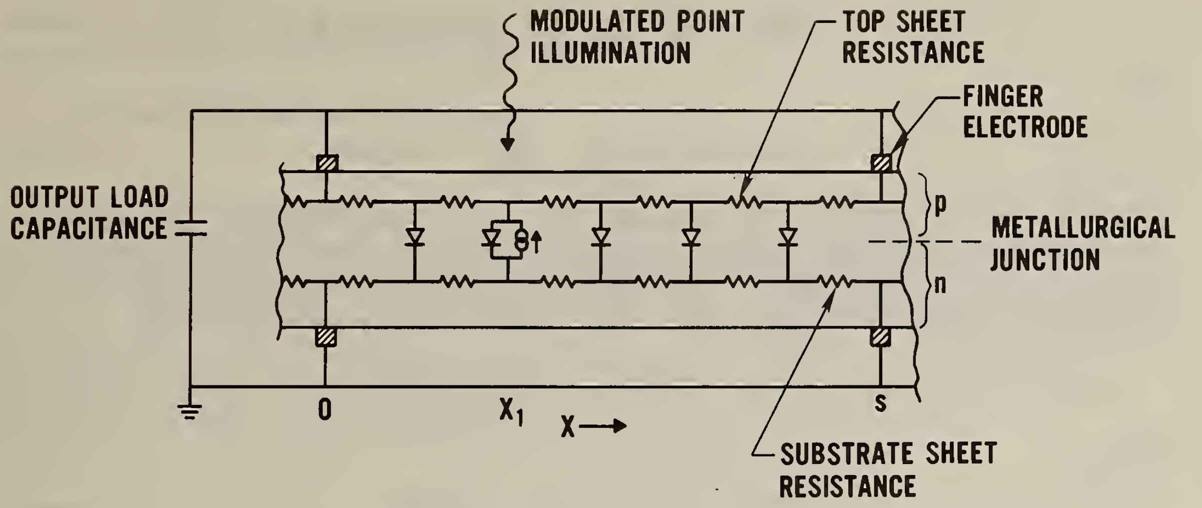

Figure B1. One-dimensional cross-section through the equivalent circuit of a solar cell portion illuminated by a modulated light beam at $x = x_1$. Output is ac-shorted by a large capacitive load.

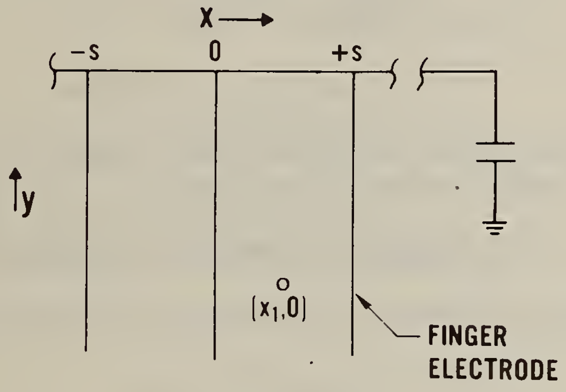

Figure B2. Top view of the solar cell showing finger electrodes spaced by distance s and an illuminated spot at $(x_1, 0)$.

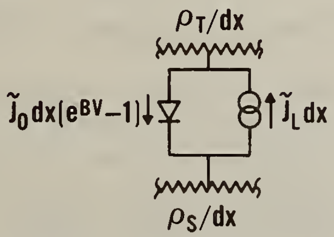

Figure B3. Element of the distributed network shown in figure B1 indicating the notation used in this report.

$$- \Omega_T/\rho_T \, \nabla\cdot\vec{J}_T + J_L - J_D = \partial Q_T/\partial t \quad \text{(B-3a)}$$

and

$$\Omega_S/\rho_S \, \nabla\cdot\vec{J}_S + J_L - J_D = - \partial Q_S/\partial t \quad \text{(B-3b)}$$

where Q_T and Q_S are the net charges per unit area above and below the metallurgical junction. Charge neutrality in any vertical section of the panel requires that $\partial Q_T/\partial t = - \partial Q_S/\partial t \equiv \partial Q/\partial t$. When eqs (B-2a) and (B-2b) are substituted into eqs (B-3a) and (B-3b), respectively,

$$\nabla^2 V_T = - \rho_T [J_L - J_D - \partial Q/\partial t] \quad \text{(B-4a)}$$

and

$$\nabla^2 V_S = \rho_S [J_L - J_D - \partial Q/\partial t] \, , \quad \text{(B-4b)}$$

so that

$$\nabla^2 V \equiv \nabla^2 (V_T - V_S) = - (\rho_T + \rho_S) \cdot [J_L - J_D - \partial Q/\partial t] \, . \quad \text{(B-5)}$$

Now $\partial Q/\partial t \equiv \partial Q/\partial V \cdot \partial V/\partial t \equiv C\partial V/\partial t$, so that

$$\nabla^2 V = - \rho [J_L - J_D - C\partial V/\partial t] \quad \text{(B-6)}$$

with $\rho \equiv \rho_T + \rho_S$ the sum of the sheet resistances and $C = \partial Q/\partial V$ the incremental diode capacitance per unit area.

B.3. Low Intensity, Modulated Illumination

Next, consider the case of a generation current comprising dc and ac components:

$$J_L = \bar{J}_L + \tilde{J}_L \, . \quad \text{(B-7)}$$

There will then be both dc and ac voltage components:

$$V = \bar{V} + \tilde{V} \, , \quad \text{(B-8)}$$

and eq (B-6) separates for small ac signals ($B\tilde{V} << 1$) into the relations

$$\nabla^2 \bar{V} = - \rho [\bar{J}_L - \bar{J}_D] \quad \text{(B-9)}$$

and

$$\nabla^2 \tilde{V} = - \rho [\tilde{J}_L - Y\tilde{V}] \quad \text{(B-10)}$$

where

$$Y = G_D + j\omega C \qquad \text{(B-11)}$$

is the diode admittance per unit area and $G_D = B(J_D + J_o)$ is the incremental diode conductance per unit area.

In the unilluminated region,

$$\nabla^2\tilde{V} = \tilde{V}Y\rho \ . \qquad \text{(B-12)}$$

Since $Z = Z(\overline{V})$, there will be in general a positional dependence of ρ/Z. Equation (B-12) defines a position-dependent complex characteristic length. For scanning in the X-direction with a line of light oriented parallel with the electrodes, $\tilde{V}$ will vary only along the X-direction, and the characteristic length may be designated x_o. It is convenient to work with the inverse of x_o. The inverse has both a real and imaginary component; these may be designated x_o' and x_o'', respectively,

$$x_o^{-1} = (x_o')^{-1} + j(x_o'')^{-1} = (Y\rho)^{1/2} \ . \qquad \text{(B-13)}$$

The real part of this length provides an attenuation of $\tilde{V}(x)$, while the imaginary part provides an oscillatory component. The characteristic decay length is

$$x_o' = \sqrt{1/\rho\,|Y|}\ /\cos(\phi/2) \qquad \text{(B-14)}$$

and

$$x_o'' = \sqrt{1/\rho\,|Y|}\ /\sin(\phi/2) \ . \qquad \text{(B-15)}$$

The wavelength of the oscillating component is

$$\lambda = 2\pi x_o'' = 2\pi\sqrt{1/\rho\,|Y|}\ /\sin(\phi/2) \ , \qquad \text{(B-16)}$$

where

$$\phi = tg^{-1}\ (\omega C R_D) \qquad \text{(B-17)}$$

and

$$|Y| = (R_D^{-2} + \omega^2 C^2)^{1/2} \ . \qquad \text{(B-18)}$$

B.4. Fault-Free Cells; Uniform x_o

Now apply these considerations to the special case of a fault-free cell operated under conditions that x_o defined in eq (B-13) is independent of position. This can be realized by using a cell without external bias and without background illumination and by modulating the scanning light beam at a sufficiently high frequency that x_o has the desired value of about the finger electrode spacing s.

While the solution for line illumination of the perfect cell has previously been derived by D. Sawyer [B-2], its derivation here is still of interest as a starting point of calculations for faulty cells, completed subsequent to the present reporting period.

B.4.1. Illumination of a fault-free cell by a line-shaped light beam at $x = x_1$

This line shape is of interest since it leads to simple analytical solutions. In case of only one pair of electrodes (at $x = 0$) of length W, one electrode contacting the top semiconductor sheet and the other contacting the bottom semiconductor sheet, the small-signal photovoltage for a short-circuit load is

$$\tilde{V}(x) = \tilde{I}_L x_o \rho/W \begin{cases} e^{-x_1/x_o} \sinh(x/x_o) & \text{for } x \leq x_1 \\ e^{-x/x_o} \sinh(x_1/x_o) & \text{for } x \geq x_1 \end{cases} \tag{B-19}$$

The photocurrent crossing unit length of a line parallel to the finger electrode and located at $0 \leq x \leq x_1$ is

$$\tilde{J} = \tilde{J}_L \exp(-x_1/x_o) \cosh x/x_o \ . \tag{B-20}$$

The short-circuit output current is

$$\tilde{I}_{SC} = \tilde{I}_L \exp(-x_1/x_o) \ . \tag{B-21}$$

The quantities x_o' and x_o'' can be obtained from the magnitude

$$|\tilde{I}_{SC}| = |\tilde{I}_L| \exp(-x_1/x_o') \tag{B-22}$$

and phase

$$\mathrm{Arg}(\tilde{I}_{SC}/\tilde{I}_L) = -x_1/x_o'' \tag{B-23}$$

of the short-circuit output current. The limit for $\tilde{I}_{SC}$ for $x_1 \rightarrow 0$ is $\tilde{I}_L$. From these data, R_D/ρ and CR_D can be derived. Since the dc diode conductance per unit area is I/R_D, C and ρ can be determined.

The potential $\tilde{V}(x)$ in eq (B-19) has been composed of two exponential terms to satisfy the boundary conditions $\tilde{V}(x) = 0$ at the electrode $x = 0$. If there is a second finger electrode at $x = s > x_1$, the boundary conditions $\tilde{V}(x) = 0$ at $x = 0$ and $x = s$ may be satisfied by adding an infinite series of potentials from line source images with respect to these electrodes. This is a well-known procedure in electrostatic and optical problems. The result is

$$\tilde{V}(x) = \frac{\tilde{J}_L \rho x_o}{\sinh(s/x_o)} \begin{cases} \sinh(x/x_o)\sinh[(s-x_1)/x_o] & \text{for } 0 \le x \le x_1 \\ \sinh[(s-x)/x_o]\ \sinh(x_1/x_o) & \text{for } x_1 \le x \le s \end{cases} \qquad \text{(B-24)}$$

and

$$\tilde{I}_{SC} = \tilde{I}_L \{[\sinh[(s-x_1)/x_o] + \sinh(x_1/x_o)]\}/\sinh(s/x_o) \qquad \text{(B-25)}$$

where the first term in brackets results from the current collected by the finger electrode at x = s, and the second term results from the current collected by the finger electrode at x = 0.

B.4.2. Point illumination of a fault-free cell

The illumination of the point x_1, 0 induces the current source $\tilde{I}_L$ at x_1, 0 in the equivalent circuit of figure B1. The resulting potential in the case of the presence of only one set of finger electrodes located at x = 0, i.e., assuming that $s - x_1 \gg x_o$, is

$$\tilde{V}(x,y) = (\tilde{I}_L \rho/2\pi)[K_o(r^*(x_1)) - K_o(r^*(- x_1))] \qquad \text{(B-26)}$$

where

$$r^*(x_1) = [(x - x_1)^2 + y^2]^{1/2}/x_o \qquad \text{(B-27)}$$

and K_o is a modified Bessel function of the second kind. The second term in the bracket of eq (B-26) results from the mirror image of the current source with respect to the finger electrode. The short-circuit current collected by the finger electrode is

$$\tilde{I}_{SC} = \rho^{-1}\int_{-\infty}^{+\infty} (\partial\tilde{V}/\partial x)\Big|_{x=0} dy = (\tilde{I}_L x_1/\pi x_o)\int_{-\infty}^{+\infty} \frac{K_1(\sqrt{x_1^2 + y^2}/x_o)}{\sqrt{x_1^2 + y^2}} dy \qquad \text{(B-28)}$$

assuming infinite finger electrode length. The integral is a simple case of the general Sonine-Gegenbauer Type [B-3]:

$$\tilde{I}_{SC} = \tilde{I}_L \exp(- x_1/x_o) . \qquad \text{(B-29)}$$

Note that the current for the point illumination is identical to the current, eq (B-21), for the line illumination. This result illustrates the equivalence theorem (to be proven generally in the next report) of currents generated by point and line illumination. This equivalence theorem also applies to the case of two finger electrodes so that eq (B-24) derived for line illumination applies also to point illumination.

B.5. Output of Faulty Cells Having a Noncontacting Electrode Section

The general solution to the potential problem of a point current source located at $\vec{r}_1 \equiv (x_1, y_1)$ surrounded by an arbitrarily shaped ac-grounded electrode contour Γ is

$$\tilde{V}(\vec{r}) = G(\vec{r}_1, \vec{r}) - \int_\Gamma \tilde{J}(\vec{r}\,')G(|\vec{r} - \vec{r}\,'|)d\vec{r}\,' \qquad \text{(B-30)}$$

where $G(\vec{r}_1, \vec{r}) = G(|\vec{r} - \vec{r}_1|)$ is the potential at $\vec{r}$ due to the point source located at $\vec{r}_1$, and $\tilde{J}(\vec{r}\,')$ is the current density entering the electrodes. This current density satisfies the integral equation

$$G(\vec{r}_1, \vec{r}\,') = \int_\Gamma \tilde{J}(\vec{r}\,')G(|\vec{r} - \vec{r}\,'|)d\vec{r}\,' , \qquad \text{(B-31)}$$

thus assuring that $\tilde{V}(\vec{r}\,') = 0$. The effect of a poor electrode contact is taken into account by excluding the noncontacting electrode section from the contour. The poor contact problem is mathematically related to a diffraction optical aperture problem.

References

B-1. Lehovec, K., and Fedotowsky, A., Degradation of Solar Cell Efficiency by Sheet Resistance, *Solar Energy* 21, 81-86 (1978).

B-2. Sawyer, D. E., Kessler, H. K., and Schafft, H. A., Measurement Techniques for Solar Cells, Quarterly Report, January 1 to March 31, 1978, NBSIR 78-1513 (September 1978).

B-3. Petian, G., *La Theorie des Functions de Bessel*, p. 210 (Centre National de la Recherche Scientifique, Paris, 1955).

APPENDIX C

STABILITY OF (THIN-FILM) SOLAR CELLS AND MATERIALS

WORKSHOP PROGRAM

Monday, May 1, 1978

8:30 a.m. REGISTRATION

9:15 a.m. WELCOME, PERSPECTIVE, AND WORKSHOP OVERVIEW

9:45 a.m. SESSION I: Status of Present Reliability Testing, Failure Modes, Failure Mechanisms, and Data for Advanced-Cell Materials

Chairman: A. Barnett (Institute for Energy Conversion, U. of Delaware, Newark, DE)

[CdZn]S/Cu_2S
J. D. Meakin and J. E. Phillips (Institute for Energy Conversion, U. of Delaware, Newark, DE)

CdS/Cu-Ternaries
L. Kazmerski (Solar Energy Research Institute, Golden, CO)

Polycrystalline Si
T. L. Chu (Southern Methodist U., Dallas, TX)

COFFEE

MIS and Conducting Oxide/Si
W. Anderson (Rutgers U., Piscataway, NJ)

Conducting Oxide/Si Heterojunctions
R. L. Anderson (Syracuse U., Syracuse, NY)

MIS
S. J. Fonash (Pennsylvania State U., University Park, PA)

1:00 p.m. LUNCH

2:00 p.m. SESSION I (Continued)

AMOS GaAs
R. Stirn (Jet Propulsion Laboratory, Pasadena, CA)

Polycrystalline GaAs
S. Chu (Southern Methodist U., Dallas, TX)

Amorphous Si
D. Carlson (RCA Corp., Princeton, NJ)

COFFEE

SESSION II: Measurements and Tests used to Define Stability in Related Technologies

Chairman: R. I. Scace (National Bureau of Standards, Washington, DC)

Silicon Cell Space Program Experience
P. Iles (Optical Coating Laboratory, Inc., City of Industry, CA)

Concentrator Solar Cells
W. McLevige (Sandia Laboratories, Albuquerque, NM)

5:00 p.m. ADJOURN

6:30 p.m. CASH BAR (Ramada Inn)

7:30 p.m. WORKSHOP DINNER (Ramada Inn)

Tuesday, May 2, 1978

9:15 a.m. SESSION II (Continued)

DoD Experience
J. Adolphson (NASA Goddard Space Flight Center, Greenbelt, MD)

Methods and Tests for Devices at the Bell Telephone Laboratory
C. W. Green (Bell Telephone Laboratories, Allentown, PA)

Power and CMOS Devices
S. Kukumaris (RCA Corp., Somerville, NJ)

COFFEE

Interdiffusion Phenomena
L. Kazmerski (Solar Energy Research Institute, Golden, CO)

Corrosion
R. Frankenthal (Bell Telephone Laboratories, Murray Hill, NJ)

Terrestrial Silicon Array Field and Test Experience
R. Ross (Jet Propulsion Laboratory, Pasadena, CA)

1:00 p.m. LUNCH

2:00 p.m. SESSION II (Continued)

Designing Accelerated Aging Tests for Predicting Array Life
D. Carmichael (Battelle Columbus Laboratories, Columbus, OH)

2:30 p.m. SESSION III: Working Group Sessions — 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.

GROUP 1: [CdZn]S/Cu_2S, CdS/Cu-Ternaries, CdS/InP, and Amorphous Si
Chairman: L. Kazmerski (Solar Energy Research Institute, Golden, CO)
Location: Green Auditorium

GROUP 2: Polycrystalline Si, MIS, and Conducting Oxide Si
Chairman: J. Shewchum (McMaster U., Hamilton, Ontario)
Location: Lecture Room A

GROUP 3: Polycrystalline and AMOS GaAs
Chairman: R. Stirn (Jet Propulsion Laboratory, Pasadena, CA)
Location: Lecture Room D (n.b.: Wednesday, Group meets in Employee's Lounge)

5:00 p.m. ADJOURN

Wednesday, May 3, 1978

9:15 a.m. SESSION III (Continued)

GROUP 1: [CdZn]S/Cu_2S, CdS/Cu-Ternaries, CdS/InP, and Amorphous Si
Chairman: L. Kazmerski (Solar Energy Research Institute, Golden, CO)
Location: Green Auditorium

GROUP 2: Polycrystalline Si, MIS, and Conducting Oxide Si
Chairman: J. Shewchum (McMaster U., Hamilton, Ontario)
Location: Lecture Room A

GROUP 3: Polycrystalline and AMOS GaAs
Chairman: R. Stirn (Jet Propulsion Laboratory, Pasadena, CA)
Location: Employee's Lounge

10:50 a.m. COFFEE

11:20 a.m. TOUR (Selected Energy-Related Projects of NBS)
Tour is for all participants not involved in the preparation of working group summaries for presentation in Session IV.

1:00 p.m. LUNCH

2:00 p.m. SESSION IV: Working Group Presentations of Summaries and Recommendations
Chairman: H. A. Schafft (National Bureau of Standards, Washington, DC)

3:30 p.m. SESSION V: Closing Remarks
Chairman: D. E. Sawyer (National Bureau of Standards, Washington, DC)

4:00 p.m. ADJOURN

CREDITS:

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Division of Solar Technology
Department of Energy

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NBS-114A (REV. 9-78)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 79-1909	2. Gov't. Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Measurement Techniques for Solar Cells: Quarterly Report for the Period April 1 to June 30, 1978

5. Publication Date

October 1979

6. Performing Organization Code

7. AUTHOR(S)

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

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, DC 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

Task Order A054-SE

12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

Advanced Materials R & D Branch
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20 Massachusetts Avenue, N.W., Washington, DC 20545

13. Type of Report & Period Covered

Interim
Apr 1 to June 30, 1978

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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 in a program on solar cell measurement technique development and other services which was performed in the period April 1 to June 30, 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, by assisting DOE in organizing and hosting appropriate workshops and symposia, and by providing general consultation and liaison services.

The technique proposed last quarter employing cell forward-biasing during scanning to reveal cell defects was implemented. Using an electrical current source, cell cracks and metallization regions disconnected from the cell output electrode have been readily revealed. The mathematical analysis work supporting the experimental scanning of cells has been extended to more realistic cell geometries than the one-dimensional one previously treated. Developments in scanner equipment and ancillary techniques include the completion of the high-intensity insolation source for forward-biasing cells with light during scanning, an improvement in coupling biased and scanned cells to the display-screen electronics, and an increase in the cell scanning area.

The workshop on Stability of (Thin Film) Solar Cells and Materials was held May 1-3, 1978 at the National Bureau of Standards, Gaithersburg, Maryland.

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 cell stability; solar cells.

18. AVAILABILITY ☒ Unlimited

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☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PRINTED PAGES 27
20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price $4.00