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Cleveland, Ohio

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16. Abstract

The necessity for a rapid method of measuring diffusion lengths of silicon solar cells in radiation damage and subsequent annealing studies led to the development of a new procedure utilizing a standard X-ray machine. After the machine was calibrated with cells of known diffusion lengths, measurements on test cells could be made at the rate of one every 2 min with a standard deviation of less than 2 percent.

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SUMMARY

The necessity for a rapid method of measuring diffusion lengths of silicon solar cells in radiation damage and subsequent annealing studies led to the development of a new procedure utilizing a standard X-ray machine. After the machine was calibrated with cells of known diffusion lengths, measurements on test cells could be made at the rate of one every 2 minutes with a standard deviation of less than 2 percent.

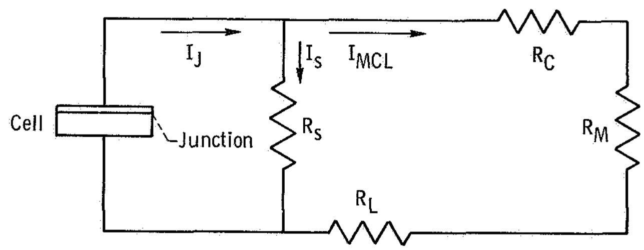
INTRODUCTION

Investigation of radiation damage and subsequent annealing of silicon solar cells calls for numerous measurements of minority carrier diffusion length. These measurements are usually determined by the method of Rosenzweig (ref. 1), which relies on the measurement of short-circuit current generated by electron-beam irradiation. This method necessitates the use of an expensive bombardment facility and many man-hours of experimental work. Consequently, only a limited amount of information can be obtained in a reasonable time.

Another method of measurement is needed to increase the speed and ease of determining diffusion lengths. As an extension to the work described in references 1 to 5, a new procedure was developed at the NASA Lewis Research Center for the rapid measurement of diffusion lengths of silicon solar cells by utilizing a standard X-ray machine. This report presents a description of the procedure for measuring diffusion lengths and the accuracy and precision of the results.

THEORY

The procedure described herein is not an absolute method for determining diffusion lengths but depends on a comparison between test cells and calibration cells whose diffusion lengths have been measured accurately by another method such as the electron beam. The calibration cells are produced by bombardment with an electron beam to various dosage levels yielding cells with diffusion lengths covering a range up to 210 micrometers. Since diffusion-length stability is imperative, these cells are fabricated from high-quality 10-ohm-centimeter float-zone silicon (ref. 6). The test and calibration cells should be approximately the same thickness and size and have electrical contacts of the same materials and configurations. Any differences between the cells will ultimately affect the accuracy of the results. In addition, the electrical properties of the calibration cells as well as those of the measuring circuit influence the current actually recorded. A simplified equivalent circuit of the apparatus can be used to correct for these variations:



where

I_J	total junction current of cell in forward direction
I_{MCL}	current produced by cell flowing in external circuit
I_s	shunt or leakage current of cell
R_C	contact resistance of cell
R_L	resistance of lead wires
R_M	internal resistance of current measuring device
R_s	shunt resistance within cell

Values of R_L and R_M will be the same for both the calibration and test cells. The value of R_C will vary somewhat but in all cases has been in the range of 0.2 to 1 ohm. These three resistances will be combined and called R_{MCL}.

The current in the cell generated by the X-rays can be expressed by

$$I_J = I_s + I_{MCL} = \frac{V_s}{R_s} + I_{MCL} \tag{1}$$

but

$$V_s = V_{MCL} = R_{MCL} I_{MCL}$$

and

$$I_J = \frac{R_{MCL} I_{MCL}}{R_s} + I_{MCL} = I_{MCL}\left(\frac{R_{MCL} + R_s}{R_s}\right) \qquad (2)$$

where I_{MCL} is the current actually measured. The term R_s is obtained from the expression $R_s = 0.6/I_r$, where I_r is the reverse leakage current as measured on a curve-tracer oscilloscope at 0.6 volt. The term R_C is also measured on the curve tracer by utilizing the forward current-voltage I-V curve. The values of R_s, R_C, R_L, and R_M are used to correct I_{MCL} to I_J. The I_J values are then divided by the cell areas to obtain current densities. These corrected values are plotted against the diffusion-length L values previously obtained by the electron beam to produce a calibration curve. The corrections just described must be applied also to test cell current when the calibration curve is used to estimate test cell diffusion length.

APPARATUS

The X-ray machine (fig. 1) is housed in a concrete vault and is an industrial inspection unit capable of highly stabilized continuous production of X-radiation at 300 kilovolts peak up to 8 milliamperes. The angle of effective uniform radiation is a cone with a solid angle of approximately 55^{o}. The tube head is mounted on a jib crane type of support structure and is therefore readily adjustable. A beryllium window 0.32 centimeter thick is used for the X-ray port so that long wavelength absorption is minimized.

The solar cells to be measured are placed on a small brass block with pressure contacts positioned onto the centers of the main contact strips (fig. 1). A 0.1-percent precision resistor R_M is placed across the cell contacts. A value of 10 ohms was chosen for R_M. The X-ray port is positioned over the solar cells with the 5.08-centimeter-diameter beryllium window approximately 8 centimeters above the cell surfaces. Connecting cables lead from the cells to digital voltmeters placed at the X-ray control cabinet.

CALIBRATION AND TESTING

Calibration

The contact resistances R_C and leakage currents I_r (see THEORY) of the set of 10 calibration cells are measured on the oscilloscope and should be less than 1 ohm for R_C and less than 100 microamperes for I_r. A float-zone cell with a diffusion length of over 150 micrometers was selected as a monitor cell. This cell was mounted on the test block in the position shown in figure 1.

The X-ray machine was then activated and the controls were set for nearly maximum beam strength. Current output from the monitor cell was noted and a slightly smaller and more convenient value was chosen as the monitor cell current to be used for calibration and testing. The X-ray controls were readjusted to achieve this selected current from the monitor cell. One of the calibration cells was placed in the test cell position and its current recorded. Values of current I_{MCL} for all the calibration cells were then determined by using the same value of monitor cell current.

The cell area was measured for each 1- by 2-centimeter cell used. The entire area was utilized for purposes of current density calculation for nonsoldered cells, but for cells with soldered contacts, the area covered by the contact was subtracted from the total area. The value of lead resistance R_L was measured and was of the order of 0.1 ohm. Values of I_J were calculated and divided by the areas to obtain the current densities i_J. The values of i_J were plotted against the known diffusion lengths. A typical calibration curve is shown in figure 2.

Testing

In measuring a test cell, it is only necessary to note its current output when the X-ray beam is adjusted to give a current reading from the monitor cell equal to that used in the calibration procedure. This test cell current is corrected to I_J and divided by the cell area. The resulting current density value can be transposed into a diffusion length by using the appropriate calibration curve.

ACCURACY AND PRECISION OF RESULTS

Rosenzweig (ref. 1) stated that diffusion lengths could be determined by the electron beam with an absolute accuracy of ±5 percent and that measurements are reproducible to within ±3 percent. Since the electron-beam method was used to calibrate the cells, values determined by the X-ray method will be of equal or lesser accuracy and dependent on the uniformity of cell size, shape, and contact material.

In many investigations, comparisons and changes of diffusion lengths among cells and within a cell are more important than the absolute value. The X-ray technique is ideally suited for measurements of this type. Reproducibility of cell current measurements is good. Table I shows a determination of the standard deviation in diffusion length measurements made on 12 typical solar cells over a range of diffusion lengths from 4 to 210 micrometers. The data were obtained over a period of 3 days with the order of repeat measurements on cells being governed by the use of a random numbers table. Ten current output readings were taken on each cell and the standard deviations of i_J calculated. The standard deviations in diffusion length were then obtained from the current calculations by using the proportionality factor K, which is a measure of the change in diffusion length per unit change in current. Values of K are determined from the slope of the calibration curve at the various levels of diffusion length.

The data show that, at diffusion lengths greater than 140 micrometers, the standard deviations were less than 0.5 micrometer or about 0.2 percent. At lower values of diffusion length, the standard deviations were usually less than 1 micrometer or less than 2 percent.

TABLE I. - REPRODUCIBILITY OF DIFFUSION-LENGTH MEASUREMENTS

Cell	Diffusion length, L, μm	Current density,[a] i_J, mA/cm^2		Proportionality factor, $K = \Delta L/\Delta i_J$, $(\mu m)(cm^2)/\mu A$	Standard deviation		
		Minimum	Maximum		Current density, σi_J, mA/cm^2	Diffusion length	
						σ_L, μm	σ_L/L, percent
1	210	0.1522	0.1530	1.8×10^3	0.00024	0.43	0.20
2	190	.1423	.1427	1.8	.00015	.27	.14
3	177	.1351	.1356	1.8	.00016	.29	.16
4	140	.1163	.1167	1.8	.00015	.29	.21
5	86	.0866	.0890	1.6	.00070	1.12	1.30
6	56	.0698	.0719	1.4	.00062	.87	1.55
7	49	.0605	.0620	1.2	.00049	.59	1.20
8	26	.0447	.0451	.8	.00013	.10	.38
9	19	.0327	.0338	.6	.00032	.19	1.00
10	12	.0223	.0228	.6	.00018	.11	.92
11	11	.0214	.0222	.5	.00025	.13	1.18
12	4	.0081	.0086	.5	.00015	.08	2.00

[a]Range of 10 random readings.

SUMMARY OF RESULTS

A new rapid method for measuring the diffusion lengths of silicon solar cells by X-ray was demonstrated. Good accuracy was obtained within the limitations of the method, namely, a set of calibrated cells of the same size, shape, and contact material as the test cells. Reproducibility measurements showed a standard deviation of less than 2 percent of the diffusion-length value.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 8, 1969,
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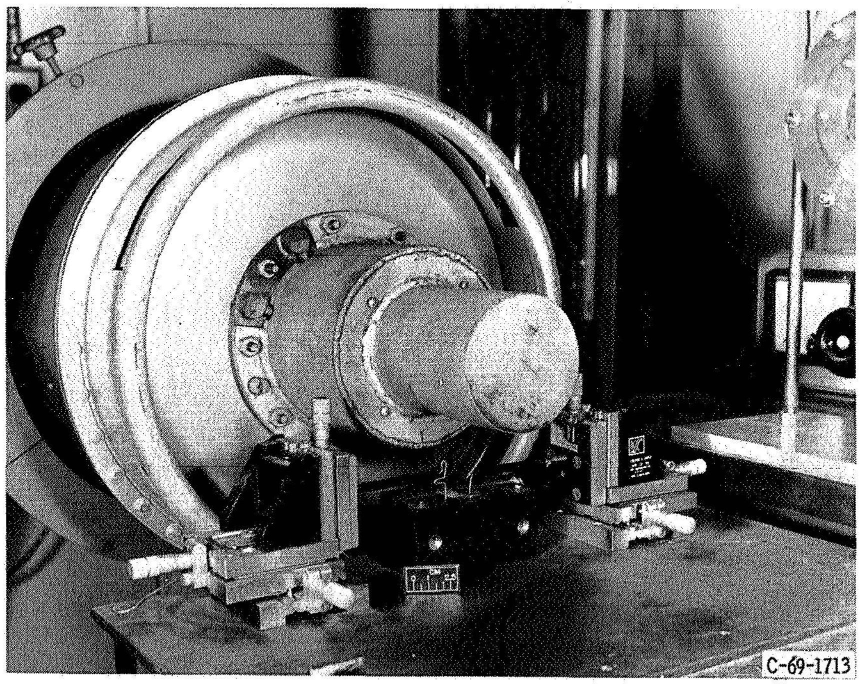

Figure 1. - X-ray tube head and test block with cells.

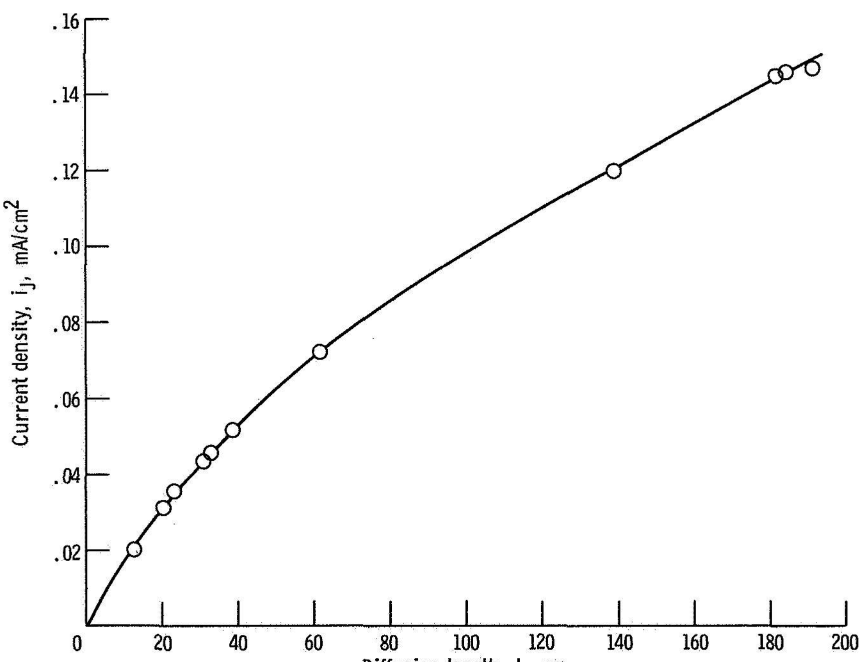

Figure 2. - Relation between diffusion length and X-ray-generated solar cell current.

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