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N70-27167

NASA CR 110161

Division of Engineering
Brown University
Providence, Rhode Island

FINAL REPORT

Investigation of the Effects of Sub-Threshold High Energy Electrons on the Properties of Silicon Photovoltaic Cells

Contract Period:

February 3, 1969 through November 3, 1969

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Sponsored by: Jet Propulsion Laboratory
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February 1970

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

FORWARD

This is a Final Report on Contract JPL-952386 between the Division of Engineering, Brown University, Providence, R. I. and the Jet Propulsion Laboratory, Pasadena, California. The contract began on February 3, 1969 and ended on November 3, 1969. The principal investigator was Prof. J. J. Loferski Participants in the work included Mr. Everett Crisman, Graduate Assistant; Mr. N. Ranganathan (for 1 month), Graduate Assistant; Mr. Fred Ehrhart (for 3 months), Undergraduate Assistant and Mr. Vernon Goff, Technical Assistant. Mr. Wm. Patterson, III , Graduate Assistant, has contributed valuable discussions and advice throughout the period.

ABSTRACT

The report describes measurements of the photovoltaic characteristics of p/n lithium-doped cells; p/n conventional cells and n/p cells. An experimental comparison of damage rates in a lithium doped p/n cell and a conventional p/n cell at ∿90°K has shown that no effects associated with displacement of lithium ions by electrons whose energy is too low to displace Si atoms has been detected. A difference in damage rates at 200 keV was observed with the lithium doped cell exhibiting very little damage even though Li ions are not mobile at ∿90°K. A deflection circuit to produce a scanned electron beam pattern is described. A summary of work performed during this nine month contract is included.

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1. INTRODUCTION

The Midway Report reviewed the bulk effects and surface changes which can be expected to occur in silicon samples irradiated by electrons whose energy is too low to displace silicon atoms. It was pointed out that bulk effects could occur only if the semiconductor contained impurities whose atomic weight was lower than that of the host lattice atoms. In the case of lithium doped silicon, lithium atoms should be displaced by electrons whose energy is about ~ 30 keV , provided that they are bound to their sites with the same energy as the host silicon atoms.

The concentration of dopant impurities (like lithium) is of course substantially smaller than that of host lattice atoms. Therefore, the production of a specified number of defects by the displacement of the low concentration impurity atoms should require an integrated flux which would exceed that required to produce the same number of defects by the displacement of host lattice atoms in the ratio of concentrations of the two kinds of atoms.

This means that if the lithium ion concentration were 10^{-6} and if the probability of a displacement were the same for the two kinds of atoms, the ratio would be 10^{6}. A prohibitively large flux would, therefore, be required to produce detectable changes. One factor in favor of observation of lithium displacement effects is the fact that even though the lithium ion concentration is only 10^{-6}, the total lithium concentration in silicon is almost an order of magnitude greater.

If the defects associated with displacement of lithium atoms could be detected, their properties could be studied and the role of lithium in radiation defect annealing in silicon would be better understood.

In this report we describe the measurements performed on various silicon cells available to us. We also describe our first experiments involving a comparison of damage thresholds in a p/n Si cell which contained no lithium and in a lithium doped p/n Si cell. A circuit for deflecting the electron beam in order to produce a more uniform distribution over the sample area is also discussed. Finally we will summarize the work performed during the course of this contract.

2. EXPERIMENTAL PROCEDURES

a) Description of Samples

The following samples were supplied by JPL for use in the irradiation experiments.

Table I

Quantity	Type	Description
10	P/N H-1 cells	Heliotek, Crucible Grown, Starting resistivity: > 200 Ω cm Diffused 90 min @ 425°C Redistributed 60 min @ 425°C Paint-on lithium source.
10	P/N H-9 cells	Heliotek, Float Zone Starting resistivity ≈ 20 Ω cm Diffused 90 min. @ 425°C Paint-on lithium source
10	N/P D-cells	Centralab, 10 Ω cm cells (non-lithium doped)

In addition we purchased the following samples:

Table II

Quantity	Type	Description
9	P/N - C - cells	Heliotek; Standard p/n, Boron Diffused Cells; 1 Ω cm Base; No Lithium

Finally in anticipation of surface conductance and field effect experiments we also purchased 10 Float Zone silicon 1 x 2 cm wafers, Li doped to 20 ohm-cm . The source was Heliotek.

b) Measurement of Cell Characteristics

The i-V characteristics of most of these cells have been measured to check cell quality and to provide a reference against which to measure changes. For these measurements the samples were pressed against a brass plate and illuminated by a 150 Watt tungsten lamp; the light was unfiltered. The samples were kept at uniform temperature with the help of a blower. One of the p/n cells was chosen as a standard cell and the light intensity was adjusted to maintain constant I_{sc} for this cell. The i-V properties of the other cells were measured relative to this standard cell. A separate standard is chosen for each series since there could be differences in their spectral response curves.

The i-V curves were recorded by a Moseley 2030A x-y plotter and the values of open circuit voltage V_{oc} and short circuit current were recorded by a Hewlitt-Parkard Model 740B digital voltmeter.

Table III gives the values of V_{oc} and I_{sc} for the lithium doped silicon cells, series H-1, and for the ordinary 1 ohm cm base, p/n silicon cells, series C. Sample C-1201 F was chosen as the reference cell for the C series and sample H-1-39 performs the same function for the H-1 series.

Table III

Cell No.	I_{sc} (ma)	V_{oc} (volts)	Remarks
*C 1201 F	40.0	0.555	Reference Cell
C 1203 F	42.0	0.578	
C 1206 B	38.8	0.568	
C 1256	40.1	0.568	
C 1207 F	39.8	0.568	
C 1210 B	38.8	0.565	
C 1208 F	40.2	0.565	Irradiated at 78^{o}K
C 1257	43.0	0.572	
C 1704 B	41.6	0.575	
*Reference cells			
H1 - 40	27.0	0.543	
*H1 - 39-3439	27.6	0.538	Reference Cell
H1 - 38-3431	31.8	0.528	
H1 - 37	29.8	0.538	Irradiated at 78^{o}K
H1 - 36	31.0	0.530	
H1 - 35-3384	29.3	0.533	
H1 - 34-3358	31.0	0.534	
H1 - 33-3355	27.0	0.532	
H1 - 32-3344	29.8	0.546	
H1 - 31-3341	26.8	0.546	

Figure 1 shows plots of i-V characteristics of one of the cells, C -1208 F, at 300°K and at 78°K. As anticipated V_{oc} increases substantially; I_{sc} decreases by a factor of about two, which while it is in accord with observations reported by others (1) is somewhat surprising. This behavior implies that the diffusion length L of minority carriers has changed by a factor of about two. Now $L^2 = D\tau$ where D is the minority carrier diffusion constant and τ is the minority carrier life-time. Furthermore, $D = \frac{\mu kT}{e}$. Since T has changed by a factor of 3.8 the $\mu\tau$ product must have decreased very little in the course of the change in T from 300 to 78°K. It should be possible to control the temperature dependence of the $\mu\tau$ product by controlling the type of recombination centers and the type of scattering centers in the silicon and thus to design cells more desirable for low temperature operation.

Only one sample of the D-series (ordinary n/p cells) has had its i-V characteristics measured. ($V_{oc} = 0.532$ V, $I_{sc} = 27$ mA with reference cell C-1201 F values as given in the Table). This cell has been mounted on the cold finger of the stainless steel, organic vapor free, irradiation chamber. It will be the first cell run in that system.

One of the lithium doped 1 x 2 cm silicon samples has been loaned to Professor Roessler of the Division of Engineering at Brown. He will attempt to locate lithium precipitates by means of the Lang technique.

This x-ray technique requires that the crystal, which has been cut so that the plane of the wafer is a (111) plane, will be exposed to a collimated x-ray beam (molybdenum target will be used) at the Bragg angle for reflection from the (220) plane. The diffracted beam will be recorded on fine grain, high resolution photographic plates with the help of a scanning topographic (Lang) camera. The image produced on the film in this way reflects strain fields associated with defects like precipitates and dislocations. Exposure times are of the order of a day or more. The developed plate is then examined through an optical microscope at a magnification of 20 to 200 times. The pattern from a lithium containing crystal will be compared to the pattern of a crystal which does not contain lithium. The Lang technique is extremely sensitive to very small strains in the crystal. It is not possible to predict a priori that lithium precipitates will be detected by this technique, but the question is worth exploring.

c) Effects of Electron Irradiation on Lithium-Doped and Ordinary p/n Cells at 90°K.

Samples C-1209 F and H-1-37 were irradiated at 90°K according to the scheme described in the Midway Report for this contract.

The cells were soldered to metallized Al_2O_3 wafers which in turn were cemented with GE cement to the copper cold finger. Two leads were soldered to each of the cells and connected to electrical feed-through connectors built into the glass dewar. A grounded copper mask was placed in front of the sample to assure that the current measured between the sample and ground was in fact I_B. The sample was grounded through an Elcor Current Indicator and Integrator which provided an accurate measure of the total flux delivered to the sample.

The output of the Elcor d.c. amplifier was fed to one channel of a strip chart recorder. A signal proportional to I_{sc} , i.e., the potential drop across a 10 Ω resistor, was recorded via a second channel in this strip chart recorder.

The electron beam of the Van de Graaff was scattered so that it would cover an area at least as large as the cell. The scattering of the beam was accomplished by directing the beam through mutually perpendicular electrostatic deflection plates. In our system, one set of plates is fed a sinusoidal signal at a frequency of 400 Hz of sufficient magnitude to deflect the electron beam about one inch. The other set of plates is fed a sinusoidal signal at a frequency of 30 Hz of sufficient magnitude to deflect the beam about one inch in the other direction. The deflected beam is incident on a metal plate covered with zinc sulfide phosphor dispersed in an organic binder. The image on the phosphor screen can be viewed by a telescope into which the image is reflected by suitable placed mirrors. The distance is such that the telescope can resolve lines 1/32" apart. With this deflection scheme and this viewing system, the phosphor screen appears to be uniformly illuminated. The frequencies of the voltages driving the two sets of mutually perpendicular plates are incommensurable and there are certainly no Lissajous figures visible on the screen.

The beam energy was kept constant to within about ±2% with the help of a feedback system designed for the Brown University Van de Graaff by Wm. Patterson, III. The system allows the operator to set the voltage of the machine and to expect that the current will not change by any large amount.

The experiment proceeded according to the following scheme. The initial beam energy was chosen to be 75 keV. The sample was irradiated until the integrated flux received by the sample corresponded to about 10^{15} el/cm . (Such a flux of 1 MeV electrons produces a substantial change in an ordinary n/p silicon cell.) The energy was then increased by 25 keV and the process repeated.

The samples were kept at liquid nitrogen temperature throughout the experiment. (No problems because of thermal shocks were encountered initially with either of the two samples.)

Table IV shows the results of the irradiations of the two cells. No changes in I_{sc} were detected in the lithium doped sample below 200 keV. The lowest energy at which changes were observed in the ordinary p/n samples was also 200 keV. In other words, our experiment did not reveal any difference in defect production thresholds for lithium doped and ordinary silicon, at least not for integrated fluxes of 10^{16} el/cm^2. However, Table IV does indicate that at 200 keV there was a substantial difference in the amount of damage produced in the two cells by 10^{16} el/cm^2.

Table IV

Radiation damage data for two p/n cells, one of which was lithium doped. Temperature of irradiation and measurement ∿90°K.

Beam Energy E_B, keV	Beam Current I_{sc}, μA	Total Flux delivered to sample ϕ, el/cm^{2}x10^{-16}	$(I_{sc}/I_B)_{initial}$	$(I_{sc}/I_B)_{Final}$	Fractional change in (I_{sc}/I_B)
		A: Sample C-1208 F; no lithium; p/n			
75	1.25	1.32	$1.5\text{x}10^4$	$1.5\text{x}10^4$	0
100	1.25	0.80	$1.5\text{x}10^4$	$1.5\text{x}10^4$	0
150	1.25	1.00			
175	1.20	2.01			
225	1.00	0.71	$1.5\text{x}10^4$	$9.8\text{x}10^3$	0.35
200	1.00	1.00	$9.8\text{x}10^3$	$8.0\text{x}10^3$	0.19
		B: Sample H-1-40; lithium doped; p/n			
150	1.10	1.0	$2.02\text{x}10^4$	$2.02\text{x}10^4$	0
175	1.10	1.0	$2.02\text{x}10^4$	$2.03\text{x}10^4$	∿0
200	1.10	0.55	$2.01\text{x}10^4$	$2.00\text{x}10^4$	∿0
200	0.85	1.0	$2.03\text{x}10^4$	$\geq 1.92\text{x}10^4$	≤ 0.055

According to the data in Table IV, the only irradiation in which any change was observed in the lithium doped p/n cell H-1-40 was the second irradiation at 200 keV. However, there is some uncertainty in the measurement because the readings had become somewhat erratic. It was not possible to irradiate the lithium doped cell for E_B > 200 keV because part of the contact to the sample had become detached. Irradiation of the cell containing no lithium continued up to E_B = 375 keV ; the data are not included in Table IV because the I_{sc}/I_B ratio had become too low.

The main purpose of this irradiation was to determine whether effects caused by lithium displacements could be detected when silicon was irradiated by electrons whose energy was below that necessary to displace silicon atoms. Our results indicate that no differences are detectable between samples containing lithium and those containing other impurities only, at least not for fluences up to 1×10^{16} el/cm^2. We intend to repeat the measurement on fresh samples and to extend the fluence scale by an order of magnitude.

The relative absence of damage in the lithium doped cell when it was irradiated by 200 keV electrons is unexpected. The irradiation and measurement temperature (∿90°K) was well below the temperature at which lithium ions are mobile. Yet very little damage ($\leq$5%) was observed during the irradiation of the lithium doped cell, while the conventionally doped cell experienced a substantial (20%) decay when it was subjected to the same fluence. Additional data are of course necessary before firm conclusions can be drawn and, therefore, more samples must be irradiated.

d) Deflection Circuit for High Energy Van de Graaff Electron Beam

The experiments described above and those involving the studies of effects of electrons on surface properties require a uniform exposure of the sample area. In our system this is accomplished by means of an electrostatic deflection system driven by oscillators capable of producing an 800 V peak to peak signal. The frequencies supplied to the horizontal and vertical plates must be incommensurable in order to avoid the formation of Lissajous patterns on the sample.

Earlier versions of circuits for producing the scanning voltages in our system operated at frequencies below a few hundred cps. In order to produce a finer scan pattern, we have designed a new circuit whose schematic is included as an Appendix. This circuit can deliver a 5 KHz 800 V RMS sinusoidal voltage to the deflection plates. This variable signal is superposed on a d.c. biasing voltage which allows deflection of the whole electron beam pattern.

3. SUMMARY OF WORK PERFORMED DURING THIS PROGRAM

1. Radiation induced changes in two p/n cells, one of which had a lithium doped base, were compared at electron energies below and slightly above the threshold for displacement of silicon atoms. No changes which could be attributed to displacement of lithium ions were observed in these irradiations which were performed at ∿90°K. The rate of damage at 200 keV was, however, substantially lower in the lithium containing sample than in the cell doped with a conventional Group V donor. Additional experiments are, however, required.

2. A specially designed stainless steel irradiation chamber which will allow irradiation of samples in an organic vapor free vacuum produced by sorption pumps and Vac Ion Pumps has been designed and constructed. Samples can be cooled by liquid nitrogen or other coolants during the irradiation. The system has been tested and a vacuum of 10^{-8} torr was achieved without bakeout on first trial. This system is therefore ready for use.

3. Improvements have been made in the Van de Graaff electronic system which will insure more uniform irradiation of the sample areas.

4. The literature describing methods of measuring electronic properties of semiconductor surfaces has been studied. It was decided that an electrode screen placed close to the surface would be used to change the surface

potential Φ_s in order to determine the extent to which radiation induced changes in surface recombination velocity should be attributed to changes in surface potential and how much of the change is caused by radiation induced alterations in the concentration and nature of surface recombination centers.

RECOMMENDATIONS FOR FUTURE WORK

1. The search for bulk effects associated with the displacement of lithium atoms should include observations at fluences up to 10^{17} el/cm^2. Differences in damage rates at 90°K between samples containing lithium and those doped with conventional donors should be explored slightly above the threshold.

2. The effects of sub-threshold electrons on the surface recombination properties of conventional n/p, p/n and lithium doped p/n cells in the organic vapor free vacuum should be measured. The irradiation chamber is in readiness; samples are mounted and ready for irradiation.

3. Experiments aimed at separating effects of surface potential changes from changes in the surface recombination center population should be executed. These experiments require that a large field be applied perpendicular to the surface and that the variations in surface recombination velocity be measured as a function of the magnitude of this applied field. The special stainless steel irradiation chamber described in the Midway Report is fitted with a high voltage electrical feed-through which will allow the application of the required fields to the surface region.

APPENDIX - DETAILS OF DEFLECTION CIRCUIT

Figure 2 is a block diagram of the deflection circuit. It consists of a 22 V power supply feeding transistorized circuits which generate the variable voltage needed to deflect the beam. Figure 3 shows the details of the power supply circuit. It consists of a power transformer whose output feeds a full wave rectifier and capacitor input filter. The ripple will be ±4% and the output d.c. voltage is 22 V. Figure 4 gives the details of the deflection circuit which consists of a twin-T oscillator; a buffer circuit and an amplifier.

OSCILLATOR

The R-C oscillator consists of a twin T feedback circuit and employs a 2N3391, (ϕ_1) as active element. C_1 and R_2 constitute a T circuit and R_1 and C_2 constitute another T network in the twin-T feedback circuit. The feedback is provided from collector to base. Thus the oscillator is a collector-base feedback type. R_3 is the input resistor in the base of the transistor whose value is chosen to satisfy the quiescent conditions of this transistor. R_4 is the collector load in this oscillator. The oscillator is designed to operate at 5 KHz.

BUFFER CIRCUIT

The buffer is required to match the high output impedence of the oscillator to the low input impedence of the power amplifier. Q_2 and Q_3 form the compound connected emitter follower with an emitter load R_8, a potentiometer which can be varied to adjust the signal fed to the subsequent amplifier stage. R_5 and R_6 form a biasing network for the emitter follower. The 2N3053 and 2N3054 transistors are chosen to serve as Q_2 and Q_3 respectively. C_3 and C_4 are interstage coupling capacitors.

THE AMPLIFIER

Q_4 is a 2N5036 transistor which serves as amplifier; it has an 83 W power dissipating capacity. An input biasing network is formed by R_9 and R_{10}. R_{11} is emitter resistor for Q_4. The quiescent collector current of Q_4 is 600 mA. The transformer connected in the collector steps up the signal, which is sinusoidal to about 800 V RMS. The connecting coaxial cable serves as a capacitative connection between the deflecting plates, and the oscillator output.

PERFORMANCE CHARACTERISTICS

Output frequency: 5 k Hz
Transformer response: satisfactory up to the 5 k Hz
Signal magnitude: 800 V RMS
Output wave shape: sinusoidal

CONSTRUCTION FEATURES

The oscillator section and power supply will be mounted in a single chasis. The amplifier transistor (Q_4) 2N5036 is mounted on a heat sink to dissipate 12 w.

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