239
5/9/79.

12. 2581

DOE/JPL/954817-3

EPITAXIAL SILICON GROWTH FOR SOLAR CELLS

Quarterly Report No. 3, April 1—June 30, 1978

By
R. V. D'Aiello
P. H. Robinson
D. Richman

July 1978

Work Performed Under Contract No. NAS-7-100-954817

RCA Laboratories
Princeton, New Jersey

MASTER

U.S. Department of Energy

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Solar Energy

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy \$4.50
Microfiche \$3.00

EPITAXIAL SILICON GROWTH FOR SOLAR CELLS

R. V. D'Aiello, P. H. Robinson,
and D. Richman
RCA Laboratories
Princeton, New Jersey 08540

QUARTERLY REPORT NO. 3

July 1978

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS7-100 for the U. S. Department of Energy.

JPL Low-cost Silicon Solar Array Project is funded by DOE and forms part of the Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

MASTER

Prepared Under Contract No. 954817
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California 91103

eb
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

PREFACE

This Quarterly Report No. 3, prepared by RCA Laboratories, Princeton, NJ 08540, describes work performed for the period 1 April 1978 through 30 June 1978, under Contract NO. 954817 in the Energy Systems Laboratory, B. Williams, Director. D. Richman is the Group Head and the Project Supervisor. R. V. D'Aiello is the Project Scientist. Others who participated in the research and/or writing of this report are Y. S. Chiang (epitaxial growth), B. W. Faughnan (diagnostic measurements), and D. Redfield (deep level transient capacitance). The RCA Report No. is PRRL-78-Cr-36.

The JPL Project Monitor is A. Kachere.

TABLE OF CONTENTS

Section	Page
I. SUMMARY	1
A. Epitaxial Solar Cells on Low-Cost Substrates	1
B. Solar Cells on Titanium-Doped Substrates	1
C. Solar-Cell Structures Grown in the Rotary Disc Reactor . . .	2
II. EXPERIMENTAL RESULTS	3
A. Solar Cells on Low-Cost Substrates	3
1. Dow Corning Upgraded Metallurgical Grade Silicon	3
(a) X-ray Topographic Evaluation	3
(b) Diffused-Epitaxial Solar Cells on Dow Corning	
Upgraded Metallurgical Grade Silicon	3
(c) All-Epitaxial Solar Cells on Dow Corning	
Upgraded Metallurgical Grade Silicon Substrates . .	10
2. All-Epitaxial Cells on Union Carbide RMS	
Silicon Substrates	11
B. Solar Cells on Titanium-Doped Substrates	14
C. Solar-Cell Structures Grown in the Rotary Disc Reactor . . .	17
D. Deep Level Transient Capacitance Studies of Epitaxial	
Layers	18
III. CONCLUSIONS AND RECOMMENDATIONS	20
IV. PROGRAM PLAN AND ACTIVITIES FOR NEXT QUARTER	21
REFERENCES	22

LIST OF ILLUSTRATIONS

Figure	Page
1. Projection x-ray topograph of a 100- μ m thick epitaxial layer grown on Dow Corning upgraded metallurgical grade silicon	4
2. Section x-ray topographs of the crystal in Fig. 1 showing the epitaxial layer (at the right) and the substrate. The dark strain bands in between result from misfit dislocations	5
3. Junction I-V characteristics and parameters for diffused-epitaxial solar cells on Union Carbide RMS silicon (X-14) and on Dow Corning silicon (25-3)	8
4. Spectral response curves for three diffused-epitaxial solar cells and a bulk cell fabricated on Dow Corning silicon	9
5. Spectral response curves for all-epitaxial solar cells on Dow Corning silicon	11
6. Spectral response curves for all-epitaxial cells on Union Carbide RMS substrates	13
7. Spectral response curves for diffused-epitaxial and all-epitaxial cells on undoped and titanium-doped single crystal substrates	16
8. Typical transient capacitance trace for an n^+ /p-type epitaxial layer	17
9. Milestone for overall program plan	21

LIST OF TABLES

Table		Page
1.	Summary of AM-1 Cell Parameters for Diffused-Epitaxial Solar Cells on Dow Corning Upgraded Metallurgical Silicon Substrates .	6
2.	Measured Solar-Cell and Structural Parameters for Diffused-Epitaxial Structures on Union Carbide RMS Silicon	7
3.	AM-1 Solar-Cell Parameters for All-Epitaxial Structures on Dow Corning Upgraded Metallurgical Silicon Substrates	10
4.	Summary of All-Epitaxial Structures n/p/p grade/p ⁺ on Union Carbide RMS Silicon Substrate	12
5.	Summary of Results Using Titanium-Doped Substrates with Epitaxial Cells	15
6.	Cells Made by Diffusion into Bulk Titanium-Doped Substrates . . .	15
7.	Summary of Results of All-Epitaxial Test Structure Grown in the RD Reactor n/p/p grade/p ⁺ on Single Crystal Substrates . . .	18

SECTION I

SUMMARY

The objective of this program is to develop and apply epitaxial growth techniques to the fabrication of efficient solar cells on low-cost forms of silicon.

During this period, progress was made in the following areas:

A. EPITAXIAL SOLAR CELLS ON LOW-COST SUBSTRATES

1. A form of metallurgical grade silicon called "Upgraded Metallurgical Grade" was purchased from Dow Corning.* Evaluations were made of epitaxial layers and solar-cell structures grown on this material. Significantly reduced defect density in the epitaxial layer was observed when compared to the substrate. Solar cells fabricated into 15- μm thick epitaxial layers grown on this material resulted in AM-1 efficiencies ranging from 12-13% compared to only 4-5% when cells were made by direct diffusion. All-epitaxial structures with 1- μm and 0.3- μm junction layers were also fabricated and evaluated.

2. All-epitaxial solar cell structures were fabricated on RMS** substrates and the solar-cell performance is compared to the diffused/epitaxial structures reported last quarter.

B. SOLAR CELLS ON TITANIUM-DOPED SUBSTRATES

Single-crystal substrates (0.2 $\Omega\text{-cm}$, boron doped) purposely doped at $2 \times 10^{14} \text{ A/cm}^{-3}$ with titanium were used to assess the effect of titanium on solar-cell performance. Comparisons were made of all-epitaxial, diffused-epitaxial, and diffused junction solar cells fabricated on these substrates. In all cases, lower than normal short-circuit current densities were obtained due to diminished red response. However, the short-circuit currents and efficiencies for the epitaxial cells were higher than those for the cells made by direct diffusion into the bulk titanium-doped silicon. The highest efficiency obtained for an epitaxial cell on a titanium-doped substrate was 11.7%.

*Dow Corning Corp., Hemlock, Michigan.

**Union Carbide Research Laboratory, Tarrytown, New York.

C. SOLAR-CELL STRUCTURES GROWN IN THE ROTARY DISC REACTOR

Preliminary growth experiments were conducted in a laboratory model of the rotary disc reactor. All-epitaxial solar-cell structures were grown on single-crystal substrates and variations in the junction layer thickness were evaluated. Efficiencies (AM-1) in the 10-12% range were measured and a trend toward higher short-circuit current densities were measured for the shallow (~ 0.1 - $0.2 \mu\text{m}$) grown junction layers.

SECTION II

EXPERIMENTAL RESULTS

A. SOLAR CELLS ON LOW-COST SUBSTRATES

1. Dow Corning Upgraded Metallurgical Grade Silicon

(a) X-ray Topographic Evaluation

Metallurgical grade silicon substrates, 3.5 cm in diam, were purchased from Dow Corning.* This material is p-type with a resistivity of 0.02 Ω -cm with Al, B, and P as the major impurities reported by Dow Corning. Thick epitaxial layers (~ 100 μ m) were grown and examined using x-ray topographic techniques. The projection topograph (Fig. 1) shows a high density array of misfit dislocations and several stacking faults. This is the first time that we have observed misfit dislocations in silicon; however such dislocations have been reported in epitaxial growth on silicon substrates heavily doped with boron [1]. This effect is also commonly observed in III-V compound growth [2]. Since we do not know the degree of compensation present in this material, the true boron concentration could be considerably higher than indicated by the 0.02 Ω -cm resistivity.

The location of the misfits were determined from section topographs as shown in Fig. 2. As seen in Fig. 2, the misfits are confined to a narrow band at the epitaxial layer and substrate interface. Aside from stacking faults, it can also be seen that the defect density in the epitaxial layer is considerably less than in the substrate.

(b) Diffused-Epitaxial Solar Cells on Dow Corning Upgraded Metallurgical Grade Silicon

Epitaxial solar-cell structures I, II, and III [3], comprising p/p grade layers were grown on the Dow Corning substrates. In a subsequent step, ~ 0.3 μ m

*Dow Corning Corp., Hemlock, Michigan.

1. Y. Sugita, M. Tamura, and K. Sugarawa, J. Appl. Phys. 40, 3089 (1969).
2. G. H. Olsen, J. Cryst. Growth 31, 223 (1975).
3. R. V. D'Aiello, P. H. Robinson, and D. Richman, *Epitaxial Silicon Growth for Solar Cells*, Quarterly Report No. 1, prepared under Contract No. 954817 for the Jet Propulsion Laboratory, January 1978.

Figure 1. Projection x-ray topograph of a 100- μm thick epitaxial layer grown on Dow Corning upgraded metallurgical grade silicon.

Vertical Scale , 0.2 mm

Figure 2. Section x-ray topographs of the crystal in Fig. 1 showing the epitaxial layer (at the right) and the substrate. The dark strain bands in between result from misfit dislocations.

deep junction was formed into the epitaxial layers by a POCl_3 diffusion. Solar cells of 4.5 cm^2 area were fabricated and tested along with control samples prepared in the same manner but on single crystal substrates of about the same resistivity as the Dow Corning material.

The AM-1 parameters for these cells are shown in Table 1. These results represent the best efficiencies and cell parameters that we have achieved with

TABLE 1. SUMMARY OF AM-1 CELL PARAMETERS FOR DIFFUSED-EPITAXIAL SOLAR CELLS ON DOW CORNING UPGRADED METALLURGICAL SILICON SUBSTRATES

Substrates/Structure RCA Run #	Base Thickness μm	X_j μm	J_{sc} mA/cm^2	V_{oc} mV	F.F. -----	η %
Single crystal control I-25	15	.3	26.1	605	0.81	12.7
Dow Corning metallurgical I-25	15	.3	25.8	602	0.80	12.4
Dow Corning metallurgical I-25	15	.3	25.3	610	0.80	12.4
Single crystal control II-26	20	.3	26.2	598	0.80	12.6
Dow Corning metallurgical II-26	20	.3	26.2	605	0.81	12.8
Dow Corning metallurgical II-26	20	.3	25.3	610	0.81	12.6
Single crystal control III-27	50	.3	28.0	595	0.79	13.2
Dow Corning metallurgical III-27	50	.3	27.1	592	0.80	12.9
Dow Corning metallurgical III-27	50	.3	27.0	598	0.81	12.9

a potentially low-cost silicon substrate. For comparison, the results which we reported last quarter on cells made with Union Carbide RMS silicon substrates are listed in Table 2. It can be seen from these data that the higher efficiencies for the epitaxial cells on the Dow Corning material are due primarily to higher open-circuit voltages and fill factors. Since the Dow Corning material is single crystal and the RMS silicon is polycrystalline, it is interesting to explore these differences a little further. For this purpose, the illuminated junction I-V characteristics of epitaxial cells made in Union Carbide and Dow Corning silicon were measured. Typical I-V curves and junction parameters are

TABLE 2. MEASURED SOLAR-CELL AND STRUCTURAL PARAMETERS
FOR DIFFUSED-EPITAXIAL STRUCTURES ON UNION
CARBIDE RMS SILICON

Sample/Substrate	AM-1 Parameters *					Diffused Junction	
	W_{epi} μm	J_{sc} mA/cm^2	V_{oc} mV	F.F. --	η %	X_1 μm	$R_{\square}$ $\Omega/\square$
X-13/Single crystal	14	28.2	578	0.790	13.2	~ 0.25	72
X-13/RMS (1 1/2")	16	25.4	535	0.660	9.3	~ 0.25	133
X-13/RMS (2 1/4")	14	25.0	555	0.745	10.6	~ 0.25	71
X-14/Single crystal	21	26.7	550	0.770	11.6	~ 0.25	132
X-14/RMS (1 1/2")	20	25.9	538	0.726	10.4	~ 0.25	119
X-14/RMS (2 1/4")	20	23.9	535	0.700	9.2	~ 0.25	121
X-15/Single crystal	47	28.6	562	0.782	13.0	~ 0.25	111
X-15/RMS (1 1/2")	50	25.9	538	0.720	10.3	~ 0.25	79
X-15/RMS (2 1/4")	43	24.3	542	0.717	9.7	~ 0.25	117

*ELH lamp simulation at $97 \text{ mW}/\text{cm}^2$

shown in Fig. 3. For the solar cell on the Dow Corning silicon, the diode n-factor of unity and the low value of saturation current indicate that a good junction was formed and that excess recombination is low. In the case of the RMS silicon, the n-factor is 1.23 and a second slope is seen for voltages lower than 0.465 V, indicating shunt currents or recombination are present. These two effects lower the open-circuit voltage and fill factor and could be related to the polycrystalline nature of the RMS silicon.

Figure 3. Junction I-V characteristics and parameters for diffused-epitaxial solar cells on Union Carbide RMS silicon (X-14) and on Dow Corning silicon (25-3).

Typical spectral response curves for the cells on the Dow Corning substrates are shown in Fig. 4. As with the case for the Union Carbide material, the apparent base diffusion lengths (listed in the inset) derived from the red response of the curves are approximately equal to the actual base layer

Figure 4. Spectral response curves for three diffused-epitaxial solar cells and a bulk cell fabricated on Dow Corning silicon.

thickness. Figure 4 also shows the spectral response for a cell formed by direct diffusion into the Dow Corning material. The blue response for this

cell is similar to the epitaxial cells; however the peak and red responses are significantly reduced. The base diffusion length is only $\sim 3 \mu\text{m}$ and the efficiency of this cell is 4%. This clearly demonstrates the advantages gained by the epitaxial growth approach for the fabrication of solar cells on such materials.

(c) All-Epitaxial Solar Cells on Dow Corning Upgraded Metallurgical Grade Silicon Substrates

Epitaxial solar-cell structures I, II, and III were grown with $1\text{-}\mu\text{m}$ thick junction layers. Solar cells were fabricated and tested and the AM-1 results are shown in Table 3.

TABLE 3. AM-1 SOLAR-CELL PARAMETERS FOR ALL-EPITAXIAL STRUCTURES ON DOW CORNING UPGRADED METALLURGICAL SILICON SUBSTRATES

Substrate/Structure RCA Run No.	J_{sc} mA/cm ²	V_{oc} mV	F.F. ----	η %
Single crystal control/I-28-2	21.0	590	0.77	9.6
Dow Corning metallurgical/I-28-1	20.1	571	0.78	9.0
Dow Corning metallurgical/I-28-3	20.5	576	0.75	8.9
Single crystal control/II-29-5	22.2	579	0.73	9.4
Dow Corning metallurgical/II-29-4	22.2	583	0.78	10.0
Dow Corning metallurgical/II-29-6	22.2	577	0.74	9.5
Single crystal control/III-30-8	22.7	578	0.71	9.3
Dow Corning metallurgical/III-30-7	20.9	558	0.77	9.0
Dow Corning metallurgical/III-39-9	21.8	562	0.73	8.9

The spectral response of the all-epitaxial solar cells on Dow Corning material are shown in Fig. 5. The blue response of these cells are lower than the epitaxial-diffused cells shown in Fig. 4 because of the thicker junctions.

Another interesting point is that the quantum efficiency curves shown in Fig. 5 are very similar to the all-epitaxial cells grown on the Union Carbide material described in Paragraph 2, All-Epitaxial Cells on Union Carbide RMS Silicon Substrate, p 11, of this report. In spite of this similarity, the efficiencies of the all-epi cells are significantly higher for the Dow Corning material. One major difference is that the Union Carbide material is polycrystalline whereas the Dow Corning material is essentially single crystal.

Figure 5. Spectral response curves for all-epitaxial solar cells on Dow Corning silicon.

2. All-Epitaxial Cells on Union Carbide RMS Silicon Substrates

For a complete comparison of structures and materials, all-epitaxial solar cells were fabricated on Union Carbide RMS silicon substrates. Six RMS samples along with single crystal controls containing a 1- μ m thick epitaxially grown junction layer with base layers of 15 μ m, 20 μ m, and 50 μ m (structures I, II, and III) were fabricated with solar cells and tested. The AM-1 parameters for this series are shown in Table 4. These results for the RMS samples show efficiencies of ~8% with short-circuit current densities not very much lower than the single crystal controls. However, the fill factors are somewhat more degraded with respect to the controls than for the epi-diffused case (see Table 2). The data for sample 18-2-III suggests that this may be related to

TABLE 4. SUMMARY OF ALL-EPITAXIAL STRUCTURES n/p/p GRADE/p⁺ ON UNION CARBIDE RMS SILICON SUBSTRATE

Structure	J _{sc} mA/cm ²	V _{oc} mV	FF	η %
16-1-I Control	23.0	585	0.760	10.6
16-2-I RMS (1½)	21.8	556	0.65	8.1
16-3-I RMS (2¼)	23.1	542	0.68	8.0
17-1-II Control	23.1	562	0.74	9.9
17-2-II RMS (1½)	22.2	540	0.67	8.4
17-3-II RMS (2¼)	20.4	528	0.60	7.3
18-1-III Control	23.3	565	0.73	9.9
18-2-III RMS (1½)*	20.3	500	0.62	6.4
18-3-III RMS (2¼)	20.9	540	0.68	7.8

*This sample has smaller grains than all others.
ELH lamp simulation at 97 mW/cm².

grain boundary effects as this sample has smaller grains than all others and has the lowest fill factor and open-circuit voltage. In addition, it has been reported in the literature [4,5] that junction formation by low temperature diffusion can "passivate" grain boundaries and reduce their effect on cell properties.

In comparing the solar-cell performance for the all-epitaxial cells on Union Carbide RMS substrates with the same structures grown on Dow Corning upgraded metallurgical grade silicon (see Tables 3 and 4), it is seen as in the case of the diffused-epitaxial structures that the higher efficiencies result from higher open-circuit voltages and fill factors for the Dow Corning material.

Figure 6 shows the spectral response curves (quantum efficiencies) for all-epitaxial cells on Union Carbide RMS substrates. A curve is shown for three different base widths (structures I, II, and III). The three cells have very similar blue responses as expected, since only the base width is varied.

4. T. H. DiStefano and J. J. Cuomo, *Proc. National Workshop on Low-Cost Polycrystalline Silicon Solar Cells*, Southern Methodist University, Dallas, Texas, p. 230 (May 1976).
5. J. Lindmayer, *Proc. XIII IEEE Photovoltaic Specialists Conference*, Washington, D.C., June 1978.

Figure 6. Spectral response curves for all-epitaxial cells on Dow Corning silicon.

The red response is increased as the base width increases, as it should. In fact, the minority carrier base diffusion lengths calculated from the red portion on the spectral response agree quite well with the widths of the epitaxially grown layers, as seen from the data in the inset of figure 6. This suggests that the apparent "diffusion length" is actually determined by the base width rather than the intrinsic electron diffusion length of the epitaxial material. The overall cell efficiencies or short-circuit currents do not reflect this increase red response, however. For cell 18-3 the benefit of

increased red response is cancelled by the poorer spectral response in the middle or peak response portion of the spectrum. The reason for this behavior is not understood.

B. SOLAR CELLS ON TITANIUM-DOPED SUBSTRATES

Single-crystal substrates purposely doped at 2×10^{14} A/cm³ with titanium and 10^{17} A/cm³ with boron were chem-mechanically polished. Epitaxial-diffused and all-epitaxial solar cells have been fabricated and tested for the three structures previously described. In addition, three cells were made by direct diffusion into this material. For each of the structures, a single crystal control having the same resistivity but with no titanium was used for comparative purposes. A summary of these results is tabulated in Tables 5 and 6. The spectral response of cells 19-1 and 19-3 (epitaxial-diffused on single crystal undoped and titanium doped) are shown in Fig. 7. Comparing curves, the short wavelength response for the diffused-epitaxial cells is significantly superior to the thick-junction layers in the all-epitaxial cells as was noted previously. The undoped single-crystal cells have better red response than the titanium-doped cells indicating a lower diffusion length in the epitaxial layers grown on the titanium-doped substrates. Analysis of the red response of the data of Fig. 7 shows that the base diffusion length is 27 μ m for the control cells and 9 μ m for the titanium-doped cells of both types.

Figure 8 shows typical spectral response curves for cells made by direct diffusion into the titanium-doped silicon and into a bulk control sample. By comparing Tables 5 and 6 and Figs. 7 and 8 it can be seen that the epitaxial cells are less effected by the presence of titanium than are the bulk diffused cells. For example, the average short-circuit current density of the titanium-doped bulk cells is 64.5% of the control sample while the average short-circuit current for the epitaxial cells on the titanium-doped substrates is 87.7% of the controls. It should be noted that the degradation for the bulk cells is in good agreement (68%) with similar experiments conducted by Westinghouse and Dow Corning [6]. Also the better tolerance of the epitaxial cells to the

6. R. H. Hopkins, J. R. Davis, P. D. Blais, P. Rai-Choudry, M. H. Haines, and J. R. McCormick, Silicon Materials Task of the Low-Cost Solar Array Project - Phase II, 7th Q. Rep., 954331-77/3, 49 (April 1977).

TABLE 5. SUMMARY OF RESULTS USING TITANIUM-DOPED SUBSTRATES - EPITAXIAL CELLS

Structure	AM-1* Parameters			
	J_{sc} mA/cm ²	V_{oc} mV	FF	η %
<u>Diffused-Epitaxial</u>				
19-1-I Single Crystal	27.6	.586	.78	13.1
19-2-I Ti Doped	24.5	.580	.78	11.5
19-3-I Ti Doped	24.3	.580	.79	11.4
20-1-II Single Crystal	28.2	.594	.80	13.7
20-2-II Ti Doped	24.9	.576	.78	11.5
20-3-II Ti Doped	25.0	.582	.78	11.7
21-1-III Single Crystal	27.3	.560	.81	12.8
21-2-III Ti Doped	22.7	.543	.78	10.0
21-3-III Ti Doped	24.3	.550	.79	10.8
<u>All-Epitaxial</u>				
22-1-I Single Crystal	22.7	.586	.70	9.6
22-2-I Ti Doped	20.1	.554	.65	7.4
22-3-I Ti Doped	19.1	.553	.70	7.7
23-1-II Single Crystal	24.5	.570	.71	10.3
23-2-II Ti Doped	20.2	.548	.70	7.9
23-3-II Ti Doped	20.0	.545	.69	7.7
24-1-III Single Crystal	23.4	.525	.39	5.0 ←Problem with
24-2-III Ti Doped	17.9	.521	.79	7.2 metalization
24-3-III Ti Doped	19.5	.532	.67	7.2

*ELH lamp simulation at 97 mW/cm²

TABLE 6. CELLS MADE BY DIFFUSION INTO BULK TITANIUM-DOPED SUBSTRATES

Sample No.	Substrate	J_{sc} mA/cm ²	V_{oc} mV	F.F.	η %
31-1	Titanium-doped	17.8	558	0.79	8.1
31-2	Titanium-doped	18.0	545	0.77	7.8
31-3	Titanium-doped	17.1	542	0.79	7.5
31-4	Control	27.3	628	0.80	14.2

Figure 7. Spectral response curves for diffused-epitaxial and all-epitaxial cells on undoped and titanium-doped single crystal substrates.

presence of titanium may be related to the base layer thickness. Since the epitaxial cells are thin (15-50 μm) they do not depend as much on long diffusion length as do the bulk cells and, in addition, back surface field effects can enhance the short-circuit current.

In seeking an explanation for the better performance of the epitaxial cells, it should be noted that the diffusion length for the epitaxial cells containing titanium is 9 μm as compared to about 5 μm for the bulk cells. This could be due to a lower concentration of titanium in the epitaxial layer compared to the substrate.

Figure 8. Typical transient capacitance trace for an n^+/p -type epitaxial layer.

C. SOLAR-CELL STRUCTURES GROWN IN THE ROTARY DISC REACTOR

The objective of our work here is to demonstrate the feasibility of using a rotary disc type epitaxial reactor for the all-epitaxial fabrication of solar-cell structures. These experiments were conducted in a laboratory model reactor capable of holding ten 3-in.-diam wafers per run. Scale-up versions of this reactor are under construction at RCA. Such reactors could provide the throughput required to significantly reduce the cost of solar cells fabricated by the epitaxial method.

In our first experiment, p^+ boron-doped single-crystal substrate wafers were used and structures were grown having $\sim 40 \mu\text{m}$ thick base layers with junction layer thicknesses varying from about $0.1 \mu\text{m}$ to $1.0 \mu\text{m}$. A summary of the results obtained from solar cells made on these structures is given in Table 7. The results show the expected trend toward increased short-circuit current density for the shallow junction structures. A comparison of these data with that for structures with both diffused-epitaxial and all-epitaxial junction of similar base thickness grown in our horizontal reactor shows that comparable cell performance was obtained.

TABLE 7. SUMMARY OF RESULTS OF ALL-EPITAXIAL TEST STRUCTURE GROWN IN THE RD REACTOR n/p/p GRADE/p⁺ ON CRYSTAL SUBSTRATES

Sample No.	Layer Thickness μm	Junction Thickness μm	J_{sc} mA/cm^2	V_{oc} mV	FF	η %	Sheet Resistance $R_{\square}$
RD 011078P1 Y-5	44	0.125	27.7	572	0.689	11.2	360
RD 011178A1 Y-3	41	0.10	27.8	570	0.683	11.1	440
RD 012678A1 Y-9	33	0.40	27.5	588	0.734	12.1	260
RD 011678P1 Y-8	27	0.50	23.4	585	0.587	8.3	80
RD 012778P1 Y-4	33	1.0	25.5	600	0.744	11.7	110
RD 012378P1 Y-1	40	1.0	24.8	595	0.667	10.1	80
RD 012478P1	40	1.0	25.3	600	0.728	11.4	110

ELH lamp simulation at $100 \text{ mW}/\text{cm}^2$

D. DEEP LEVEL TRANSIENT CAPACITANCE STUDIES OF EPITAXIAL LAYERS

To complement other diagnostic measurements on these materials we have recently added the new technique of deep level transient spectroscopy (DLTS) [7]. The addition of DLTS is permitting the location of deep energy levels that may act as recombination centers which limit carrier lifetime in the base of solar cells. The apparatus centers on a transient capacitance measuring system that was designed here as an alternative to that described by Miller, Lang, and Kimmerling [7]. The complete system has proved to be both sensitive and easily calibrated; measurements of trap concentrations less than $5 \times 10^{10} \text{ cm}^{-3}$ have been made.

Data on currently prepared epitaxial silicon have already provided useful results [8]. All of the p-type material tested have shown evidence for a hole trap 0.32 eV above the valence band in epi-Si but not in Czochralski-silicon. This center appears at concentrations of $\sim 4 \times 10^{11} \text{ cm}^{-3}$ in the most common epitaxial silicon which is doped to $\sim 2 \times 10^{14} \text{ cm}^{-3}$ with boron. In some cases a second peak is found as shown in Fig. 8; in still another sample from the

7. G. L. Miller, D. V. Lang, and L. C. Kimmerling, *Annu. Rev. Mater. Sci.* **1977**, 377 (1977).
8. D. Redfield, *Bull. Amer. Phys. Soc.* **23**, 257 (1978).

same wafer a third peak was found on the low-energy side of the low-temperature peak. Thus there is a noticeable range of densities of some of the secondary peaks. Figure 8 also shows the effect of pulse width which can be used to evaluate capture cross sections.

Similar measurements on n-type epitaxial material show lower concentrations, $6 \times 10^{10} \text{ cm}^{-3}$, of a different level. Fewer samples of this type have been used so less information is available about the reproducibility. It is plausible, however, to associate the deep levels seen in the n- and p-type epitaxial silicon with recombination centers that generally restrict lifetimes to values lower than for Czochralski material. This suggestion is consistent with the observation that n-type epitaxial-silicon solar cells perform better [9].

DLTS measurements have also been used to detect the possible effects of titanium present at concentrations of 10^{14} cm^{-3} in the epitaxial substrates on the properties of the normally-grown p-type grown layer. The only deep levels attributable to the titanium are a low shoulder ($\sim 1 \times 10^{11} \text{ cm}^{-3}$) on the low-energy side of the usual 0.32 eV peak and a much stronger peak ($> 2 \times 10^{12} \text{ cm}^{-3}$) at considerably lower energy. This latter peak is so shallow ($< 0.2 \text{ eV}$) as to be out of range of our quantitative measurements. It is surprising that no really deep levels were seen in view of the known ease of recombination via titanium in silicon.

Other DLTS measurements were made to test the possible gettering effects of back-surface damage. No differences were found on the used substrates whose backs were either saw-damaged, lapped, or etched before epitaxial growth.

Identification and control of the deep levels are the major goals of future work. A series of experiments is planned to answer the specific question of whether the universal 0.32 eV hole trap is due to carbon. Another series is being designed to determine if it comes from contaminants in the boron doping source.

9. R. V. D'Aiello, et al., Appl. Phys. Lett. 28, 231 (1976).

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

This quarter the epitaxial growth of thin solar-cell structures was extended to include another potentially low-cost form of silicon: upgraded metallurgical grade silicon obtained from Dow Corning. An AM-1 efficiency of 12.4% was achieved with a cell structure having only 14 μm of silicon grown on the Dow Corning. The best efficiency obtained was 13% on a 50- μm thick structure. This material and lower-cost derivative forms are being further explored with Dow Corning.

We have found that titanium ($2 \times 10^{14} \text{ A/cm}^{-3}$ level) intentionally incorporated into the substrates primarily causes a reduction in the short-circuit current for both epitaxial and bulk cells. However, the epitaxial cells were much less effected by the presence of titanium and efficiencies as high as 11.7% were obtained while the efficiency for bulk cells was ~8%.

Preliminary experiments in a laboratory model of RCA's advanced rotary disc reactor have produced solar cells with 10-12% efficiency. These cells were grown on single-crystal control substrates and the growth which included studies of submicron surface layers showed a trend toward increased short-circuit current density for shallower junctions.

SECTION IV

PROGRAM PLAN AND ACTIVITIES FOR NEXT QUARTER

The work is on schedule. A milestone chart for our program plan is given in Fig. 9.

Figure 9. Milestone for overall program plan.

Plans for the next quarter include:

1. Fabricate, using the laboratory model rotary disc reactor, a matrix of solar cell structures on Dow Corning upgraded metallurgical grade substrates having submicron surface layers.
2. Perform an economic analysis of the epitaxial process for the large scale production of solar cells.
3. Evaluate further Dow Corning material availability.
4. Evaluate silicon received from Crystal Systems Inc.

REFERENCES

1. Y. Sugita, M. Tamura, and K. Sugarawa, J. Appl. Phys. 40, 3089 (1969).
2. G. H. Olsen, J. Cryst. Growth 31, 223 (1975).
3. R. V. D'Aiello, P. H. Robinson, and D. Richman, *Epitaxial Silicon Growth for Solar Cells*, Quarterly Report No. 1, prepared under Contract No. 954817 for the Jet Propulsion Laboratory, January 1978.
4. T. H. DiStefano and J. J. Cuomo, *Proc. National Workshop on Low-Cost Polycrystalline Silicon Solar Cells*, Southern Methodist University, Dallas, Texas, p. 230 (May 1976).
5. J. Lindmayer, *Proc. XIII IEEE Photovoltaic Specialists Conference*, Washington, D.C., June 1978.
6. R. H. Hopkins, J. R. Davis, P. D. Blais, P. Rai-Choudry, M. H. Haines, and J. R. McCormick, Silicon Materials Task of the Low-Cost Solar Array Project - Phase II, 76h Q. Rep., 954331-77/3, 49 (April 1977).
7. G. L. Miller, D. V. Lang, and L. C. Kimmerling, *Annu. Rev. Mater. Sci.* 1977, 377 (1977).
8. D. Redfield, *Bull. Amer. Phys. Soc.* 23, 257 (1978).
9. R. V. D'Aiello, et al., *Appl. Phys. Lett.* 28, 231 (1976).