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**SILICON MATERIALS TASK OF THE LOW COST SOLAR
ARRAY PROJECT (PHASE II)**

Seventh Quarterly Report, April 1, 1977—June 31, 1977

**By
R. H. Hopkins
J. R. Davis
P. D. Blais
P. Rai-Choudhury
M. H. Hanes
J. R. McCormick**

MASTER

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**Research and Development Center
Westinghouse Electric Corporation
Pittsburgh, Pennsylvania**

**ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy**

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Contract No. 954331

R.H. Hopkins, J.R. Davis, P.D. Blais,
P. Rai-Choudhury, and M.H. Hanes
Westinghouse Research & Development Center
and

J.R. McCormick
Dow Corning Corporation

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Westinghouse R&D Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

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NEW TECHNOLOGY

No new technology is reportable for the period covered by this report.

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1. SUMMARY

The objective of Phase II of this program is to investigate the effects of various processes, metal contaminants, and contaminant-process interactions on the performance of terrestrial solar cells. The majority of the effort this quarter was in three areas: (1) the growth, chemical analysis, and cell characterization of Czochralski ingots for processing studies, extension of the 4 Ω -cm p-type cell impurity data base, and impurity studies of n-base cells, (2) modification of equipment for improved electrical characterization, and (3) extension of mathematical modeling to predict solar cell efficiencies of contaminated devices as a function of impurity type and concentration.

Essentially all n- and p-type baseline ingots and about one third the metal-doped ingots have now been grown and chemically analyzed. Four first generation n-type (phosphorus-doped) ingots, containing Cu, Cr, Mn, and Ti, respectively, have been processed to solar cells. Comparing the cell performance of these n-base devices with p-base cells containing the same four impurities reveals some interesting similarities and differences. For example, the response of the n-base cells to Cu and Cr contamination is virtually identical to previous results on p-type material: Cu has little effect on cell efficiency; Cr reduces efficiency to about 80% of the baseline (uncontaminated) devices. In contrast, 10^{15} at.cm⁻³ Mn which degrades p-type devices to about 71% of baseline efficiency, has virtually no effect on the n-base cells. The harmful effects of Ti also appear mitigated in the n-base cells. At 3×10^{14} at.cm⁻³ Ti doping reduces cell efficiency to 25% of baseline in p-base devices but only to about 80% of baseline efficiency in the n-base cells.

To better evaluate ingots with low lifetime and/or low resistivities, we have set up a 1.06 μ m laser-excited photoconductive

decay apparatus. Equipment for thermally stimulated measurements has also been prepared. Both types of measurements will begin this coming quarter.

Mathematical modeling was extended to describe the efficiency behavior of solar cells contaminated with various types and concentrations of impurities in p-base devices. Overall, the modeling is quite successful in predicting the short circuit currents and efficiencies of the seventeen multiply-doped ingots produced during Phases I and II of the program. The data show no compelling evidence for synergic behavior with the possible exception of two ingots, one containing Cu and Ti, the other Cu and Mn. Further work in this area will be aimed at improving the statistical information for certain impurities and refining the ingot analyses.

2. INTRODUCTION

The first part of this program, Phase I, was primarily concerned with determining how specific metal contaminants affected the performance of terrestrial silicon solar cells. Phase II of the program is an extension of that work designed to investigate the effects of processes, as well as impurities, on solar cell performance so that purity requirements for solar grade materials can be defined. The methodology for carrying out the experimental effort has been described in previous reports, e.g., Refs. 1 and 2; new analytical or experimental techniques will be discussed as they are introduced to the program.

The past quarter's effort has been directed primarily in three areas: (1) preparation and evaluation of ingots for n-base and processing studies and for the extension of multiply-doped ingot data base, (2) improvement of electrical measurement techniques, and (3) extension of mathematical modeling to include prediction of cell efficiency as a function of impurity type and concentration. The results of these studies, as well as some auxiliary experiments and updating of previous analytical results, are described in subsequent sections.

3. TECHNICAL RESULTS

3.1 Silicon Growth and Analysis

Most of the effort to date has involved the growth and evaluation of 4 Ω -cm p-type silicon for processing studies and to increase the data base for the study of multiple contaminants. A second, much lower, resistivity, 0.2 Ω -cm, was recently chosen for further studies after evaluating the performance of cells made on material with resistivity ranging from 0.05 ohm-cm through 4.0 ohm-cm. Growth of first generation n-type ingots containing single metal impurities is also well underway. The metal concentration ranges being investigated for the 4.0 ohm-cm p-type, 0.2 ohm-cm p-type, and 1.5 ohm-cm n-type ingots are summarized in Table 1. A few comments are warranted regarding these impurity ranges. Since the program is dynamic, the impurity concentration range is subject to continuing revision. However, with the exception of aluminum, boron, and phosphorus, which are electrically active, and carbon and oxygen which are always present in Czochralski grown ingots, an attempt has been made to establish the upper limit based on either (1) the solid solubility limit or (2) the maximum concentration achievable without producing constitutional supercooling of the melt. Where sufficient data exists, the lower limit indicated represents a concentration at which little or no solar cell performance degradation occurs.

A total of thirteen ingots were prepared this quarter; analysis is proceeding on these ingots and the thirteen prepared during the last quarter. The results of this effort are discussed in the next two sections.

Table 1. Impurity Matrix Under Investigation

Impurity Element	Approximate Concentration Range Investigated $\times 10^{15}$ atoms per cm^3		
	4 ohm-cm p-type	0.2 ohm-cm p-type	1.5 ohm-cm n-type
Aluminum	3 - 30 **		
Boron *			
Calcium			
Carbon	20 - 125 +		
Chromium	0.1 - 1.0		1.0
Copper	0.4 - 30		1.7
Iron	0.02 - 1.5		
Magnesium	0.003 - 0.03		6.5
Manganese	0.01 - 1.3		
Molybdenum			
Nickel	0.4 - 4.0		
Oxygen	500 - 1700 +		
Phosphorus*	1.0		
Sodium			
Titanium	0.00036 - 0.36		0.36
Tantalum			
Vanadium	0.0004 - 0.4		
Zinc	<0.001		
Zirconium	<0.015		

* Boron, phosphorus, and aluminum are electrically active impurities and therefore cause variations in resistivity when used as a secondary impurity.

** Uncertainty in exact range due to discrepancy between electrical and SSMS measurements.

+ Oxygen and Carbon concentrations measured in 50 ingots doped with additional impurities. No effort yet to correlate effects if any.

3.1.1 Ingot Preparation

The details of the Czochralski crystal growth equipment, growth conditions, and segregation coefficients have been described previously, e.g., Ref. 2. The breakdown of the thirteen ingots prepared this quarter is as follows:

- 1 n-type baseline (1.5 ohm-cm)
- 1 p-type baseline (4.0 ohm-cm)
- 1 p-type baseline - thick slices for process studies (4.0 ohm-cm)
- 5 p-type singly-doped (4 ohm-cm) (processing studies and matrix extension)
- 1 p-type poly crystalline (4 ohm-cm)
- 4 p-type multiply-doped (4 ohm-cm) (matrix extension).

In addition to the preparation and characterization of the above ingots, additional experiments have been conducted related to doping with aluminum, calcium, carbon and sodium. The concentration of aluminum in the melt has been varied over an order of magnitude with good correlation existing between this concentration and the concentration in the ingot based on electrical resistivity measurements. However, considerable variation has occurred in the SSMS analysis of this material with the aluminum concentration determined by SSMS ranging from nearly equal to that based on electrical resistivity to approximately ten times that value. This may be associated with the formation of nonelectrically active aluminum-oxygen complexes; however, insufficient evidence exists to support this conclusion. To insure consistency, it is recommended that concentrations based on electrical measurements be employed where possible.

Attempts to dope with calcium and calcium oxide were made this quarter. Significant loss of calcium occurs from the melt regardless of the source of calcium. The use of an oxide further complicates the experimental situation because the excess oxygen reacts with the graphite heater parts of the Czochralski puller to generate CO. The gas dissolves

in the silicon resulting in high carbon concentrations. The actual concentrations of calcium found in the melt have been only 1 to 5 percent of amount originally added to the charge. To date, we have not been able to produce an ingot which meets the program objectives. Work on the calcium doping problem is continuing.

The carbon concentration is monitored via infrared absorption for a large fraction of the ingots produced. Nominal carbon concentration is in the 0.5 ppm to 2.5 ppm range for standard Czochralski grown material. Attempts to add purified graphite to the melt have not increased the carbon concentration of the ingots significantly above 2.5 ppm -- perhaps due to insufficient dissolution prior to crystal growth. High carbon concentrations have been achieved through the controlled introduction of oxygen into the growth chamber. The carbon level, in fact, was sufficiently high to limit single crystal yield. Additional growth experiments using both doping procedures are scheduled for the next quarter.

The high vapor pressure of sodium at the melting point of silicon apparently rules out the use of elemental sodium as a dopant. Previous work with sodium halides also did not prove successful. During this quarter, sodium silicate was tried as a sodium source. Three problems were immediately encountered: (1) above 1100°C, substantial amounts of sodium were evolved from the melt, (2) the sodium reacted with the crucible, and (3) excess oxygen reacted with heater parts producing the same type of problem reported previously for the CaO dopant source. Based on these results, we do not anticipate further attempts to achieve growth from a sodium doped melt.

3.1.2 Ingot Evaluation

The ingot evaluation process has been discussed previously². Analysis has proceeded on twelve of the thirteen ingots prepared this quarter as well as several ingots prepared during the last quarter. Resistivity and etch pit densities measured on slices taken from the seed and tang ends of ingots prepared since the initiation of Phase II

are summarized in Table 2. No problems were encountered in meeting the resistivity targets in either 4 ohm-cm, p-type or 1.5 ohm-cm, n-type materials. Ingot W070-A1-003 has a lower resistivity due to the increased hole concentration produced by the aluminum doping. The variation of resistivity along the length of the ingot (W070) is typical of that encountered when doping with impurities having a small (<0.5) segregation coefficient. There does appear to be a small but real resistivity increase in the ingots heavily doped with Cr, Fe, Mn, and Ti although there is insufficient data to permit a quantitative statement regarding this effort.

The dislocation densities determined by etch pit counting range from zero through approximately 5,000 per cm^2 for the section of ingots used in solar cell fabrication. Due to the relatively high concentration of metal in the melts used for a number of the runs, significant structural degradation is observed in the tang end of many ingots. In general, structure improves rapidly as one moves back through the ingot and the first figure shown for EPD is most indicative of the structural properties of slices employed in cell fabrication.

Target impurity concentration, calculated concentration based on melt analysis, and measured impurity concentration (SSMS data) are compiled in Table 3 for ingots prepared during the last two quarters. Generally good agreement exists between the target concentration and those concentrations determined from melt analysis and SSMS analysis of single crystal seed slices. Copper concentration measured by SSMS for Ingot W056-Cu-005 appears to be high. This was a heavily doped ingot and large variations in copper concentration were observed on a sample to sample basis indicating a non-uniform distribution probably due to copper precipitation.

The manganese concentration determined by SSMS appears high for Ingot W064-N/Mn-001 when compared to the target value and measured values on p-type ingots. Four samples were analyzed to obtain the average concentration value of 6.5×10^{15} . Due to the large spread

Table 2. Ingot Resistivity and Etch Pit Density

<u>Ingot Identification</u>	<u>TGT Resistivity (ohm-cm)</u>	<u>Actual Resistivity (ohm-cm)</u>	<u>Etch Pit Density (/cm²)</u>
W-054-00-000	4.0 (B)	4.3 - 3.8	0 - 4.25 K *
W-055-Cu-004	4.0 (B)	4.1 - 3.7	0.5 K - 25 K
W-056-Cu-005	4.0 (B)	4.4 - 3.75	2.5 K - 10 K
W-057-00-000	0.5 (B)	0.46 - 0.47	0.5 K - 1.25 K
W-058-00-000	0.2 (B)	0.22 - 0.18	0 - 0.2 K
W-059-00-000	0.05 (B)	0.05 - 0.053	0 - 2 K
W-060-00-000	1.5 (P)	2.1 - 1.0	0 - 1 K
W-061-Cr/Ti-001	4.0 (B)	5.0 - 4.0	3 K - Clusters
W-062-N/Cu-001	1.5 (P)	2.0 - 0.95	0.4 - 4 K
W-063-N/Cr-001	1.5 (P)	2.2 - 1.7	1 K - 40 K
W-064-N/Mn-001	1.5 (P)	2.2 - 1.35	1 K - 3 K
W-065-N/Ti-001	1.5 (P)	1.9 - 1.7	0 - 2 K
W-066-Ti-005	4.0 (B)	6.0 - 3.9	1 K - 4 K
W-067-Cr/Mn/Ti-001	4.0 (B)	5.5 - 5.2	1 K - 4 K
W-068-Cr-004	4.0 (B)	5.2 - 5.1	1 K - 5 K
W-069-Fe-004	4.0 (B)	5.8 - 5.0	0.4 K - Gross Lineage
W-070-Al-003	4.0 (B)	2.2 - 1.1	0 - 1 K
W-071-00-000	4.0 (B)	4.1 - 3.3	1 K - 4 K
W-072-Cr-005	4.0 (B)	5.0 - 4.5	0 - 2 K
W-073-Cr/Mn/Ni/Ti/V-001	4.0 (B)	5.0 - 3.8	1 K - 40 K
W-074-Cr/Mn/Ni/Ti/V-002	4.0 (B)	4.4	400 - 30 K
W-075-Ti/V-002	4.0 (B)	4.8 - 3.9	0 - 10 K
W-076-Poly-002	4.0 (B)	4.8 - 3.0	N/A (Poly)

Table 2. (Cont.)

<u>Ingot Identification</u>	<u>TGT Resistivity (ohm-cm)</u>	<u>Actual Resistivity (ohm-cm)</u>	<u>Etch Pit Density (/cm²)</u>
W-077-Mo-001	4.0 (B)	4.3 - 3.8	0 - Gross Lineage
W-078-00-000	4.0 (B)	4.3 - 3.3	0 - 80 K
W-079-00-000	1.5 (P)	2.3 - 1.1	1 K - 10 K

* The first figure is etch pit density of the seed; second figure etch pit density of extreme tang end of ingot. The first value shown is indicative of dislocation density in slices used for cell fabrication.

between calculated and measured concentrations, further analysis of this material will be undertaken including neutron activation analysis.

Calculated and measured impurity concentrations in the five multiply doped ingots shown in Table 3 are in good agreement.

The detection of iron continues to pose a problem. Mass spectrometer sensitivity for iron in silicon is inadequate for detection of iron at the maximum concentration which can be achieved while maintaining single crystal structure. For this reason iron doped samples will be evaluated by neutron activation analysis in the future.

One aluminum ingot was prepared this quarter for solar cell evaluation and processing studies (W070-A1-003). The target, calculated and measured impurity concentrations shown in Table 3, are based on an effective segregation coefficient of 2.8×10^{-3} , a value consistent with resistivity measurements. As noted, relatively large variations have been observed in the past between concentrations determined by SSMS and electrical resistivity measurements. For this particular ingot the results are in excellent agreement as shown in the third column. More measurements are planned in an attempt to discover the source of variability. It should be noted that data reported previously² were based on SSMS measurements and concentrations are approximately one order of magnitude greater for Ingots W028 and W038 than for Ingot W070 although the amount of aluminum in the melt of each ingot was the same.

In the last quarterly progress report¹ we described a background problem with the spark source mass spectrometer at mass to charge ratio lines corresponding to titanium and copper. This has been resolved and detection limit established in the range of 0.2 to 0.25×10^{15} atoms/cm³.

As in the past to facilitate discussion of data relating to solar cell performance, a best estimate has been made for the impurity concentrations in all ingots. These data are presented in Table 4.

Table 3. Ingot Impurity Concentration

Ingot Identification	Target Concentration 10^{15} atoms/cm ³	Calc. Concentration 10^{15} atoms/cm ³	Measured Concentration 10^{15} atoms/cm ³
W-054-00-000	N/A	N/A	N/A
W-055-Cu-004	0.05	0.034	<1
W-056-Cu-005	25	39	70*
W-057-00-000	N/A	N/A	N/A
W-058-00-000	N/A	N/A	N/A
W-059-00-000	N/A	N/A	N/A
W-060-00-000	N/A	N/A	N/A
W-061-Cr/Ti-001	Cr: 1.0 Ti: 0.02	Cr: 0.91 Ti: 0.017	Cr: 1.0 Ti: <1.0
W-062-N/Cu-001	1.0	0.86	2.0
W-063-N/Cr-001	0.8	0.85	1.0
W-064-N/Mn-001	1.0	0.64	6.5
W-065-N/Ti-001	0.35	0.28	0.75**
W-066-Ti-005	0.06	0.048	<0.2
W-067-Cr/Mn/Ti-001	Cr: 0.42 Mn: 0.50 Ti: 0.006	Cr: 0.29 Mn: 0.36 Ti: 0.0039	Cr: 0.3 Mn: 0.7 Ti: <0.2
W-068-Cr-004	1.0	1.0	1.0
W-069-Fe-004	1.0	0.92	<1.5
W-070-Al-003	4.75	1.9	2.75 (3.0)+
W-071-00-000	None	N/A	N/A
W-072-Cr-005	0.4	0.21	0.28

* Large Sample to Sample Variation Observed

** High Ti Value Possibly Due to Vacuum Leak in M.S.

+ Value in Parenthesis Based on Resistivity Measurement

Table 3. (Cont.)

<u>Ingot Identification</u>	<u>Target Concentration</u> <u>10^{15} atoms/cm³</u>	<u>Calc. Concentration</u> <u>10^{15} atoms/cm³</u>	<u>Measured Concentration</u> <u>10^{15} atoms/cm³</u>
W-073-Cr/Mn/Ni/Ti/V-001	Cr: 0.4 Mn: 0.5 Ni: 2.0 Ti: 0.004 V: 0.004	Cr: 0.28 Mn: 0.34 Ni: 1.3 Ti: 0.005 V: 0.0068	Cr: 0.28 Mn: 0.8 Ni: <2.0 Ti: <0.35 V: <0.35
W-074-Cr/Mn/Ni/Ti/V-002	Cr: 0.08 Mn: 0.08 Ni: 0.5 Ti: 0.0006 V: 0.0006	Cr: 0.054 Mn: 0.064 Ni: 0.28 Ti: 0.0025 V: 0.0015	Cr: <0.25 Mn: <0.25 Ni: <2.0 Ti: <0.25 V: <0.25
W-075-Ti/V-002	Ti: 0.1 V: 0.1	Ti: 0.075 V: 0.11	Ti: <0.25 V: <0.25
W-076-Poly-002	None	N/A	N/A
W-077-Mo-001	1.0	0.65	Incomp.
W-078-00-000	None	N/A	N/A
W-079-00-000	None	N/A	N/A

Table 4. Best Estimate of Impurity Concentration

<u>Ingot Number</u>	<u>Impurity Concentration</u> (10^{15} atoms/cm ³)
W-054-00-000	N/A
W-055-Cu-004	0.05
W-056-Cu-005	42
W-057-00-000	N/A
W-058-00-000	N/A
W-059-00-000	N/A
W-060-00-000	N/A
W-061-Cr/Ti-001	Cr: 1.0 Ti: 0.02
W-062-N/Cu-001	1.5
W-063-N/Cr-001	0.8
W-064-N/Mn-001	6.0
W-065-N/Ti-001	0.35
W-066-Ti-005	0.06
W-067-Cr/Mn/Ti-001	Cr: 0.04 Mn: 0.05 Ti: 0.006
W-068-Cr-004	1.0
W-069-Fe-004	1.0
W-070-Al-003	2.75
W-071-00-000	N/A
W-072-Cr-005	0.4
W-073-Cr/Mn/Ni/Ti/V-001	Cr: 0.4 Mn: 0.5 Ni: 2.0 Ti: 0.004 V: 0.004
W-074-Cr/Mn/Ni/Ti/V-001	Cr: 0.08 Mn: 0.08 Ni: 0.5 Ti: 0.0006 V: 0.0006
W-075-Ti/V-002	Ti: 0.1 V: 0.1
W-076-Poly-002	N/A
W-077-Mo-001	~1
W-078-00-000	N/A
W-079-00-000	N/A

3.2 Processing Studies

One baseline (W078) and four impurity doped ingots, W066-Ti-005, W068-Cr-004, W069-Fe-004, and W070-Al-003 have been grown for use in processing studies. The impurity concentrations for each were chosen on the basis of previous results² so that cell performance would be reduced to 60 to 80% of the baseline value. In this way any improvements (or reductions) in performance due to processing could be readily deduced. Before initiating the processing studies wafers from the ingots were run through the standard evaluation sequence to obtain baseline data for the material. This also provides further input information to the modeling studies, Section 3.6.

Solar cell data for the first three ingots W066, W068, and W069 are compiled in Tables 5 through 7. The results appear consistent with previous composition-performance data for these impurities.

3.3 n-Base Studies

Studies of the effects of impurities on phosphorus-doped silicon designed to parallel the work on the boron-doped crystals were initiated during the last quarter. These ingots, W062 to W065, representing about half the first generation n-base crystals, have recently been processed to solar cells. The cell process is described in Ref. 1. Compilations of the pertinent I-V data, Tables 8 to 11, show some interesting variations relative to results obtained previously on p-type ingots.

For example, when data for n- and p-type ingots containing the same nominal metal impurity content are compared, Table 12, it appears that both Cu and Cr produce similar effects on each host. Cu at about $10^{15} \text{ at.cm}^{-3}$ introduces essentially no degradation in cell performance while Cr reduces cell efficiency to 70-80% of the baseline. Mn and Ti, however, seem to reduce cell performance much less in the n-type material than they do in the p-type substrate. The Mn-doped ingot, in fact,

Table 5

RUN ID70422

70422 W066TI005 W054 00 000

SOL1 7 / 5 / 77 AM1: P0=91.60MW/CM² NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDB
1R*	22.50	.556	20.22	-6.388	1.96	-.33	.721	9.54	.00	.00	.00
1B	22.70	.558	21.05	-8.267	1.41	-.14	.773	10.35	5.20	.00	6.30
2B	22.70	.553	20.89	-7.610	1.55	-.30	.761	10.11	4.55	.00	6.30
3B	22.90	.554	20.99	-7.311	1.63	-.41	.756	10.15	4.55	.00	6.30
4B	22.50	.553	20.64	-7.336	1.62	-.49	.760	10.00	4.55	.00	6.30
5B	22.80	.558	21.07	-7.958	1.48	-.21	.768	10.33	5.20	.00	6.30
1C	16.50	.500	14.68	-6.210	1.89	-.16	.702	6.12	.26	.00	.00
2C	17.00	.501	15.09	-6.060	1.95	-.33	.700	6.31	.26	.00	.00
3C	16.60	.498	14.72	-6.075	1.94	-.24	.698	6.10	.26	.00	.00
4C	16.60	.498	14.72	-6.075	1.94	-.24	.698	6.10	.26	.00	.00
5C	16.40	.499	14.49	-5.984	1.99	-.12	.690	5.97	.26	.00	.00
6C	17.10	.500	15.10	-5.887	2.03	-.38	.693	6.27	.26	.00	.00
1S	17.30	.503	15.37	-6.123	1.93	-.22	.700	6.44	.26	.00	.00
2S	17.30	.503	15.37	-6.123	1.93	-.22	.700	6.44	.26	.00	.00
3S	16.60	.500	14.80	-6.292	1.85	-.11	.704	6.18	.26	.00	.00
4S	17.10	.502	15.17	-6.084	1.94	-.17	.697	6.33	.26	.00	.00
5S	17.50	.502	15.38	-5.671	2.14	-.63	.690	6.41	.26	.00	.00
1T	16.90	.497	14.92	-5.882	2.02	-.38	.693	6.15	.26	.00	.00
2T	16.60	.499	14.80	-6.314	1.84	.02	.701	6.14	.26	.00	.00
3T	16.50	.497	14.63	-6.044	1.95	-.32	.698	6.06	.26	.00	.00
4T	16.80	.498	14.89	-6.059	1.94	-.14	.695	6.15	.26	.00	.00
AVERAGES: 70422 BASELINE W054 00 000											
	22.72	.555	20.93	-7.696	1.54	-.31	.764	10.19	4.81	.00	6.30
STD	.13	.002	.16	.369	.09	.13	.006	.13	.32	*	*
70422 W066TI005											
	16.85	.500	14.94	-6.059	1.95	-.24	.697	6.21	.26	.00	.00
STD	.33	.002	.28	.157	.07	.15	.004	.14	.00	*	*
PERCENT OF BASELINE											
	74.2	90.0	71.4	121.3	127	122.1	91.3	61.0	5.4	*****	.0
STDx	1.9	.7	1.9	5.9	12	100.3	1.2	2.2	.4	*****	.0

Table 6

RUN ID?70426

70426 W068CR004 W054 00 000
 SOL1 7 / 5 / 77 AM1: P0=91.60MW/CM² NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDB
1R*	22.50	.556	20.22	-6.388	1.96	-.33	.721	9.54	.00	.00	.00
1B	22.30	.556	20.57	-7.730	1.53	-.42	.768	10.08	4.55	.00	.00
2B	22.90	.558	21.21	-8.150	1.43	-.17	.771	10.42	5.60	.00	.00
3B	22.40	.555	20.39	-6.781	1.81	-.87	.754	9.91	5.20	.00	.00
4B	23.10	.556	21.24	-7.520	1.58	-.40	.763	10.36	5.60	.00	.00
5B	22.50	.553	20.72	-7.551	1.56	-.58	.769	10.12	4.81	.00	.00
1C	19.30	.519	17.43	-6.563	1.79	-.65	.734	7.77	.65	.00	.00
2C	20.00	.519	17.89	-6.060	1.99	-.97	.724	7.95	.65	.00	.00
3C	20.10	.518	17.87	-5.790	2.11	-1.19	.718	7.91	.65	.00	.00
5C	19.70	.514	17.24	-5.354	2.35	-1.20	.694	7.43	.52	.00	.00
6C	19.10	.515	16.88	-5.638	2.19	-1.21	.708	7.37	.52	.00	.00
7C	19.90	.520	17.88	-6.241	1.91	-.92	.730	7.99	.65	.00	.00
8C	20.20	.519	17.95	-5.770	2.13	-1.18	.717	7.95	.65	.00	.00
9C	20.60	.524	18.55	-6.312	1.89	-.94	.735	8.39	.78	.00	.00
1S	20.40	.524	18.36	-6.319	1.89	-.85	.732	8.28	.91	.00	.00
2S	20.20	.524	18.15	-6.241	1.93	-.91	.731	8.18	.78	.00	.00
3S	20.20	.524	18.12	-6.223	1.93	-.78	.726	8.12	.78	.00	.00
4S	20.30	.524	18.11	-5.990	2.04	-.88	.719	8.08	.78	.00	.00
5S	20.90	.527	18.90	-6.621	1.78	-.55	.736	8.57	.91	.00	.00
1T	19.60	.520	17.64	-6.414	1.85	-.66	.729	7.86	.78	.00	.00
2T	19.60	.517	17.47	-5.943	2.04	-1.01	.719	7.70	.52	.00	.00
3T	19.80	.517	17.75	-6.244	1.90	-.63	.721	7.81	.52	.00	.00
4T	20.00	.519	17.32	-5.247	2.44	-.57	.669	7.35	.52	.00	.00
5T	19.60	.517	17.51	-6.069	1.98	-.88	.721	7.73	.65	.00	.00

AVERAGES: 70426 BASELINE W054 00 000

	22.64	.556	20.83	-7.546	1.58	-.49	.765	10.18	5.15	.00	.00
STD	.31	.002	.34	.444	.12	.23	.006	.19	.42	*	*

70426 W068CR004

	19.97	.520	17.83	-6.058	2.01	-.89	.720	7.91	.68	.00	.00
STD	.44	.004	.48	.370	.18	.21	.016	.33	.13	*	*

PERCENT OF BASELINE

	88.2	93.6	85.6	119.7	127	18.6	94.1	77.8	13.2	*****	*****
STD%	3.2	.9	3.8	9.9	22	148.8	2.9	4.7	3.7	*****	*****

Table 7

RUN ID?70512

70512 W069FE004 (<1.5E15) W054 00 000

SOL1 7 / 5 / 77 AM1: P0=91.60MW/CM² NO AR COATING

ID	ISC	VOC	IP	LOG(I/O)	N	R	FF	EFF	OCD	PCDA	PCDB
1R*	22.50	.553	20.21	-6.362	1.96	-.33	.720	9.47	.00	.00	.00
1B.*	22.30	.550	19.87	-5.735	2.25	-1.49	.729	9.45	3.25	.00	.00
2B	22.50	.552	20.60	-7.213	1.66	-.56	.758	9.96	3.25	.00	.00
3B	22.50	.552	20.43	-6.621	1.85	-.93	.750	9.85	3.90	.00	.00
4B*	22.10	.550	19.78	-5.953	2.14	-1.27	.732	9.41	3.12	.00	.00
5B	22.80	.550	20.45	-6.020	2.10	-1.17	.734	9.73	3.64	.00	.00
1C	20.30	.564	17.71	-5.160	2.72	-1.80	.697	8.44	.91	.00	.00
2C	20.90	.571	19.08	-7.067	1.77	-.65	.753	9.51	1.17	.00	.00
3C	20.30	.570	18.59	-7.284	1.70	-.55	.756	9.25	1.30	.00	.00
4C	19.00	.563	17.30	-6.882	1.82	-.92	.751	8.50	.65	.00	.00
5C	20.30	.567	17.72	-5.076	2.80	-2.36	.706	8.60	.91	.00	.00
6C	18.90	.562	17.26	-7.111	1.74	-.77	.755	8.48	.91	.00	.00
7C	20.50	.572	18.60	-6.651	1.93	-1.04	.749	9.29	1.04	.00	.00
8C	20.30	.575	18.52	-6.956	1.82	-.89	.755	9.32	1.30	.00	.00
9C	20.30	.568	17.91	-5.491	2.50	-1.64	.712	8.68	1.30	.00	.00
10C	20.20	.570	18.07	-5.874	2.28	-1.85	.738	8.99	1.30	.00	.00
11C	20.80	.573	18.60	-5.946	2.24	-1.37	.730	9.20	1.30	.00	.00
1S	21.20	.575	18.79	-5.547	2.48	-1.83	.723	9.32	1.17	.00	.00
2S*	20.90	.500	15.67	-4.958	2.55	6.69	.455	5.03	.13	.00	.00
3S	21.40	.573	19.11	-5.855	2.29	-1.44	.729	9.45	1.30	.00	.00
4S	21.40	.571	18.68	-5.066	2.81	-2.18	.705	9.11	1.30	.00	.00
5S*	21.20	.455	15.44	-5.314	2.09	7.74	.424	4.32	.13	.00	.00
1T*	17.10	.551	15.68	-7.404	1.63	-.74	.760	7.58	.65	.00	.00
2T*	17.90	.400	13.25	-5.566	1.75	7.88	.433	3.28	.13	.00	.00
3T*	17.70	.317	13.06	-4.985	1.64	5.36	.442	2.62	.13	.00	.00
4T	18.30	.555	16.69	-7.116	1.72	-.54	.748	8.03	.52	.00	.00
5T*	16.70	.403	12.53	-5.654	1.74	8.17	.443	3.15	.13	.00	.00
6T	17.90	.552	16.42	-7.594	1.58	-.21	.753	7.87	.65	.00	.00

AVERAGES: 70512 BASELINE W054 00 000

	22.60	.551	20.49	-6.618	1.87	-.88	.747	9.85	3.60	.00	.00
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STD	.14	.001	.08	.487	.18	.25	.010	.09	.27	*	*
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70512 W069FE004 (<1.5E15)

	20.13	.568	18.07	-6.292	2.14	-1.25	.735	8.88	1.06	.00	.00
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STD	1.02	.007	.80	.848	.41	.62	.020	.50	.26	*	*
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PERCENT OF BASELINE

	89.0	****	88.2	104.9	114	58.4	98.4	90.2	29.6	*****	*****
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STD%	5.1	1.4	4.3	20.7	35	131.2	4.1	5.9	10.1	*****	*****
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Table 8. Solar Cell I-V Data for
n-Type Ingot Containing Copper.

70502 W062N-CU001 N BASE W060 00 000

SOL1 6 / 8 / 77 AM1: P0=91.60MW/CM² NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD	PCDA	PCDR
1K*	22.50	.556	20.28	-6.553	1.89	-.21	.723	9.57	.00	.00	.00
1B	22.30	.562	20.61	-8.154	1.44	.21	.758	10.05	.26	.00	.00
2B	22.00	.559	19.84	-6.398	1.97	-.78	.735	9.56	4.03	.00	.00
3B.*	22.70	.565	20.23	-5.857	2.24	-1.00	.719	9.76	3.25	.00	.00
4B	22.30	.560	20.11	-6.393	1.97	-.75	.734	9.70	5.20	.00	.00
5B	22.20	.562	20.44	-7.739	1.54	-.14	.759	10.01	5.85	.00	.00
1C	22.60	.565	20.88	-8.020	1.48	.00	.762	10.29	7.80	.00	.00
2C.*	15.60	.560	13.20	-4.403	3.60	-4.99	.681	6.29	7.15	.00	.00
3C	22.50	.561	20.91	-8.533	1.36	.01	.774	10.33	10.40	.00	.00
4C	22.60	.554	19.64	-5.272	2.57	-.52	.673	8.98	6.50	.00	.00
5C	22.60	.569	21.11	-9.141	1.27	.27	.777	10.57	1.30	.00	.00
6C	21.60	.560	19.75	-7.196	1.69	-.41	.751	9.61	6.50	.00	.00
7C	22.40	.554	19.37	-4.895	2.85	-1.74	.686	9.00	3.64	.00	.00
8C	21.70	.547	18.90	-5.135	2.63	-1.43	.691	8.67	5.85	.00	.00
1S	21.90	.550	19.71	-6.292	1.98	-.84	.733	9.33	.39	.00	.00
2S	22.00	.555	20.03	-6.901	1.77	-.58	.747	9.65	5.20	.00	.00
3S	22.60	.560	21.09	-9.022	1.27	.27	.775	10.37	10.40	.00	.00
4S	22.30	.555	20.49	-7.602	1.56	-.15	.755	9.89	6.50	.00	.00
5S	22.30	.555	20.20	-6.591	1.88	-.70	.741	9.70	6.11	.00	.00
1T	22.10	.572	20.46	-8.267	1.45	.16	.762	10.19	9.10	.00	.00
2T	22.70	.568	21.05	-8.360	1.41	.09	.767	10.46	9.10	.00	.00
3T	22.70	.568	20.95	-7.946	1.51	-.02	.761	10.37	5.20	.00	.00
4T	22.00	.567	20.21	-7.529	1.61	-.27	.757	9.99	8.19	.00	.00
5T	22.50	.568	20.70	-7.636	1.58	-.22	.759	10.25	6.50	.00	.00

AVERAGES: 70502 BASELINE W060 00 000

	22.20	.561	20.25	-7.171	1.73	-.37	.747	9.83	3.84	.00	.00
STD	.12	.001	.30	.789	.24	.42	.012	.21	2.16	*	*

70502 W062N-CU001 N BASE

	22.30	.561	20.32	-7.314	1.76	-.36	.745	9.86	6.39	.00	.00
STD	.34	.007	.65	1.270	.47	.55	.031	.56	2.71	*	*

PERCENT OF BASELINE

	100.5	****	100.3	98.0	101	102.6	99.8	100.3	166.7	*****	*****
STD%	2.1	1.5	4.7	30.9	45	432.0	5.8	8.0	204.6	*****	*****

Table 9. Solar Cell I-V Data for
n-type Ingot Containing Chromium.

70518 W063N-CR001 (8.5E14) W060 00 000

SOL1 6 / 8 / 77 AM1: P0=91.60MW/CM^2 NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCB	PCDA	PCDB
1R*	22.50	.552	20.27	-6.517	1.89	-.21	.722	9.48	.00	.00	.00
1B	22.10	.555	20.13	-7.211	1.67	.18	.733	9.50	1.04	.00	.00
2R	22.00	.562	20.44	-8.750	1.32	.51	.761	9.96	8.71	.00	.00
3R	21.30	.559	19.64	-7.275	1.48	.13	.756	9.52	7.80	.00	.00
4R	21.50	.560	19.63	-7.187	1.69	-.25	.746	9.49	6.50	.00	.00
5R*	21.40	.551	19.18	-6.219	2.02	-.62	.722	9.00	5.20	.00	.00
1C	18.40	.523	16.12	-5.929	2.08	.83	.664	6.76	1.30	.00	.00
2C	18.50	.522	17.09	-8.465	1.30	.81	.746	7.62	1.69	.00	.00
3C	18.40	.522	16.98	-8.268	1.33	.52	.750	7.62	1.56	.00	.00
4C	18.30	.524	16.96	-8.643	1.27	.65	.755	7.66	1.69	.00	.00
5C.*	18.50	.527	15.06	-3.966	3.94	-3.09	.620	6.39	1.17	.00	.00
6C	19.00	.526	17.59	-8.678	1.26	.91	.747	7.90	1.69	.00	.00
7C	18.60	.524	16.66	-6.229	1.95	-.76	.722	7.44	1.56	.00	.00
8C	18.40	.521	16.21	-5.859	2.11	-.03	.684	6.94	1.30	.00	.00
9C	18.70	.525	17.28	-8.405	1.31	.58	.751	7.80	1.30	.00	.00
1S.*	18.80	.516	14.50	-3.268	5.54	-6.29	.590	6.05	1.04	.00	.00
2S	18.90	.521	17.30	-7.578	1.49	.25	.740	7.71	1.30	.00	.00
3S	19.10	.522	17.66	-8.534	1.28	.77	.748	7.89	1.69	.00	.00
4S.*	19.10	.523	14.89	-3.506	4.87	-3.88	.580	6.13	1.30	.00	.00
5S	19.10	.522	17.49	-7.637	1.47	.34	.739	7.79	1.69	.00	.00
1T	18.70	.524	17.22	-8.024	1.39	.33	.750	7.77	1.69	.00	.00
2T	18.60	.526	17.10	-7.786	1.45	.08	.751	7.77	1.56	.00	.00
3T	18.80	.524	17.23	-7.673	1.50	.10	.744	7.75	1.30	.00	.00
4T	18.80	.524	17.14	-7.345	1.56	.22	.734	7.65	1.30	.00	.00
5T	19.10	.523	17.61	-8.120	1.36	.34	.752	7.94	1.30	.00	.00
6T	18.80	.522	17.18	-7.423	1.53	.04	.742	7.70	1.56	.00	.00

AVERAGES: 70518 BASELINE W060 00 000

21.73 .559 19.96 -7.781 1.54 .14 .749 9.62 6.01 .00 .00

STD .33 .003 .34 .643 .15 .27 .011 .20 2.98 * *

70518 W063N-CR001 (8.5E14)

18.72 .523 17.11 -7.676 1.51 .35 .736 7.63 1.50 .00 .00

STD .26 .002 .42 .880 .27 .40 .024 .31 .17 * *

PERCENT OF BASELINE

86.2 93.6 85.7 101.3 98 250.4 98.3 79.3 94.9 *****

STDZ 2.5 .7 3.6 20.4 29 ***** 4.7 4.9 16.7 *****

Table 10. Solar Cell I-V Data for
n-type Ingot Containing Manganese.

70519 W064N-MN001 (8E15) W060 00 000

SOL2 6 /10/77 AM1: P0=91.60MW/CM² NO AIR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD	PCDA	PCDB
1R*	22.50	.555	20.22	-6.379	1.96	-.33	.721	9.52	.00	.00	.00
1B	22.60	.568	20.82	-7.770	1.55	-.13	.759	10.31	1.43	.00	.00
2B	22.10	.553	19.81	-6.125	2.07	-.87	.727	9.39	5.85	.00	.00
3B	22.30	.553	20.44	-7.627	1.55	.27	.742	9.67	7.54	.00	.00
4B	22.20	.556	20.06	-6.637	1.86	-.30	.729	9.52	5.20	.00	.00
5B*	21.90	.553	19.35	-5.480	2.42	-1.51	.714	9.15	4.81	.00	.00
1C	21.40	.547	19.40	-6.840	1.77	-.23	.733	9.08	5.20	.00	.00
2C	21.90	.559	20.43	-9.041	1.27	.33	.773	10.01	6.76	.00	.00
3C	21.30	.546	19.73	-8.591	1.32	.66	.753	9.26	5.20	.00	.00
4C	21.00	.541	19.28	-7.926	1.45	.68	.736	8.85	3.25	.00	.00
5C*	17.80	.524	15.33	-5.053	2.65	-1.28	.670	6.61	1.95	.00	.00
6C	21.70	.547	20.16	-8.871	1.27	.70	.757	9.50	6.50	.00	.00
7C	21.50	.550	19.92	-8.387	1.37	.22	.763	9.54	5.20	.00	.00
8C	21.20	.547	19.71	-8.855	1.27	.55	.762	9.34	4.55	.00	.00
9C	21.20	.543	19.39	-7.394	1.59	-.02	.744	9.66	3.90	.00	.00
10C	22.00	.545	19.98	-6.521	1.87	-1.34	.759	9.62	5.20	.00	.00
1S	21.20	.544	19.01	-6.259	1.98	-.55	.721	8.79	3.90	.00	.00
2S	21.80	.546	19.58	-6.363	1.94	-.33	.720	9.06	4.16	.00	.00
3S	21.60	.545	19.90	-8.110	1.41	.57	.744	9.27	5.85	.00	.00
4S	21.90	.555	20.33	-8.566	1.34	.28	.765	9.83	6.50	.00	.00
5S	21.40	.549	19.83	-8.413	1.36	.28	.761	9.46	5.46	.00	.00
6S	21.70	.544	19.95	-7.870	1.46	.35	.745	9.31	4.94	.00	.00
1T	20.80	.549	19.11	-7.660	1.53	-.10	.754	9.11	4.29	.00	.00
2T	21.00	.545	19.20	-7.322	1.61	-.13	.746	9.03	3.90	.00	.00
3T	21.60	.556	19.97	-8.176	1.43	.12	.761	9.67	5.20	.00	.00
4T	21.00	.536	18.45	-5.458	2.37	-1.07	.698	8.31	2.34	.00	.00
5T	21.00	.541	18.98	-6.642	1.82	-.35	.730	8.77	2.99	.00	.00
6T	21.60	.553	19.79	-7.375	1.62	-.32	.754	9.53	3.90	.00	.00

AVERAGES: 70519 BASELINE W060 00 000

	22.30	.558	20.28	-7.040	1.76	-.26	.739	9.72	5.01	.00	.00
STD	.19	.006	.38	.685	.22	.41	.013	.35	2.23	*	*

70519 W064N-MN001 (8E15)

	21.42	.547	19.62	-7.650	1.57	.01	.747	9.26	4.72	.00	.00
STD	.34	.005	.48	.974	.28	.54	.018	.39	1.15	*	*

PERCENT OF BASELINE

	96.0	98.1	96.7	91.3	90	205.6	101.0	95.2	94.4	*****	*****
STDZ	2.4	2.0	4.2	25.8	29	558.3	4.2	7.6	75.2	*****	*****

Table 11. Solar Cell I-V Data for
n-type Ingot Containing Titanium.

70520 W065N-TI001 (2.8E14) W060 00 000

SOL2 6 /10/77 AMF: PO=91.60MW/CM² NO AN COATING

ID	ISC	VOC	IP	LOG(10)	N	n	FF	EFF	OCB	PCDA	PCDB
1A*	22.50	.555	20.34	-6.794	1.80	.10	.722	9.53	.00	.00	.00
1B	22.10	.565	20.41	-7.972	1.49	-.07	.763	10.07	9.75	.00	.00
2B	22.40	.569	20.86	-8.805	1.33	.25	.771	10.40	10.40	.00	.00
3B	22.40	.562	20.51	-7.385	1.64	-.14	.749	9.97	8.45	.00	.00
4B	21.90	.563	19.97	-7.068	1.74	-.35	.745	9.72	7.80	.00	.00
5B	22.60	.568	20.95	-8.672	1.35	.72	.753	10.22	9.10	.00	.00
1C	19.10	.531	17.53	-7.643	1.50	-.06	.752	8.06	1.69	.00	.00
2C	19.10	.525	17.37	-6.948	1.68	-.47	.742	7.87	1.56	.00	.00
3C	19.20	.529	17.52	-7.202	1.61	-.28	.745	8.00	1.04	.00	.00
4C	19.20	.529	17.57	-7.380	1.56	-.25	.750	8.05	1.56	.00	.00
5C	19.10	.526	17.18	-6.390	1.88	-.70	.728	7.73	1.30	.00	.00
6C	19.20	.524	17.33	-6.594	1.79	-.46	.729	7.76	1.30	.00	.00
7C	18.90	.534	17.22	-7.105	1.66	-.34	.743	7.93	1.30	.00	.00
8C	19.00	.529	17.30	-7.122	1.64	-.18	.739	7.86	1.30	.00	.00
9C	19.20	.532	17.61	-7.530	1.53	-.18	.752	8.12	1.30	.00	.00
1S	19.30	.531	17.68	-7.518	1.53	-.07	.748	8.11	1.56	.00	.00
2S	19.30	.528	17.59	-7.088	1.64	-.40	.745	8.03	1.30	.00	.00
3S	19.80	.534	18.23	-7.954	1.43	.22	.752	8.40	1.69	.00	.00
4S	19.10	.529	17.48	-7.394	1.56	-.20	.748	8.00	1.30	.00	.00
5S	19.30	.530	17.71	-7.584	1.51	-.10	.751	8.13	1.56	.00	.00
1T	19.10	.531	17.44	-7.327	1.58	-.02	.741	7.95	1.56	.00	.00
2T	19.00	.527	17.29	-7.102	1.64	-.18	.739	7.82	1.56	.00	.00
3T	18.90	.530	17.29	-7.471	1.54	.00	.744	7.89	1.30	.00	.00
4T	19.00	.527	17.11	-6.476	1.85	-.60	.728	7.71	1.30	.00	.00
5T	19.10	.528	17.33	-6.867	1.71	-.40	.737	7.86	1.30	.00	.00
6T	19.10	.528	17.40	-7.074	1.65	-.40	.744	7.94	1.30	.00	.00

AVERAGES: 70520 BASELINE W060 00 000

22.28 .565 20.54 -7.980 1.51 .08 .756 10.07 9.10 .00 .00

STD .25 .003 .35 .685 .16 .37 .010 .23 .92 * *

70520 W065N-TI001 (2.8E14)

19.15 .529 17.46 -7.188 1.62 -.25 .743 7.96 1.40 .00 .00

STD .19 .003 .24 .391 .11 .22 .007 .16 .17 * *

PERCENT OF BASELINE

86.0 93.6 85.0 109.9 108 ***** 98.2 79.0 15.4 ***** *****

STD% 1.8 .9 2.6 13.0 20 ***** 2.2 3.4 3.6 ***** *****

Table 12. I-V Data for n- and p-Base Solar Cells
With Similar Metal Impurity Concentrations

Cell Type	Impurity	Impurity Concentration (10^{15} at.cm $^{-3}$)	I_{sc}/I_{sc0}^*	V_{oc}/V_{oc0}^*	η/η_0^*
p	Cr	1.0	83.5	93.9	77.9
n	Cr	0.85	86.2	93.6	79.3
p	Cu	1.7	100.	99.7	99.8
n	Cu	1.5	100.	100.	100
p	Mn	1.3	76.7	94.2	71.2
n	Mn	6.0	96.0	98.1	95.2
p	Ti	0.36	34.0	79.5	25.9
n	Ti	0.35	86.0	93.6	79.0

* Data normalized to baseline cells containing no added impurity.

exhibits performance almost identical to that of the baseline ingot, while the Ti-doped ingot is about 80% as efficient as the baseline devices. Comparable efficiencies for Mn and Ti in boron-doped silicon would be about 70 and 25%, respectively, as the table indicates. Some of the variability is certainly due to the fact that the metal concentrations are not equivalent for the p- and n-type ingots. However, even taking this into account it appears that the two base dopings do exhibit very real differences in their response to various impurity types.

3.4 Matrix Extension

Part of this program is devoted to increasing the preparation and analysis of multiply-doped 4 Ω -cm p-base ingots since these provide the experimental data for testing models of cell performance, and also because in practice combinations of contaminants would be expected to be the norm. As part of this task we are also undertaking to grow and evaluate extra singly-doped ingots to fill in gaps in the available data for a particular metal species. These results also become input information to the modeling studies, viz., Section 3.6.

During this quarter one singly-doped and three multiply-doped ingots were evaluated as part of this effort. The I-V performance data for each ingot appear in Tables 13 through 16. Note that ingots W073 and W074 contain the same five impurities but at different concentrations in each ingot. The impurity levels were chosen according to previous calculations² in order to obtain slight and more severe degradations in cell performance.

3.5 Electrical Measurements

3.5.1 Recombination Lifetime Measurements (PCD)

So far, photoconductive decay lifetime measurements on this program have been performed using an LPE gallium arsenide IR-emitting diode as the pulsed light source. This source has several undesirable

Table 13

RUN ID?W072CR005

70608 W072CR005 (4E14) W054 00 000

SOL1 7 /5 /77 AM1: P0=91.60MW/CM² NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDB
1R*	22.50	.552	20.27	-6.517	1.89	-.21	.722	9.48	.00	.00	.00
1B	21.40	.555	19.70	-7.591	1.57	-.48	.765	9.61	4.81	.00	.00
2B	21.90	.552	19.89	-6.680	1.84	-.88	.749	9.58	3.90	.00	.00
3B	21.70	.552	19.91	-7.366	1.62	-.49	.759	9.62	3.90	.00	.00
4B	21.70	.549	19.52	-6.097	2.07	-1.41	.742	9.35	3.25	.00	.00
5B.*	22.40	.549	19.95	-5.730	2.25	-1.38	.726	9.44	2.34	.00	.00
1S	18.80	.524	16.94	-6.499	1.83	-.64	.730	7.61	1.30	.00	.00
2S	19.50	.162	12.36	-3.815	1.28	2.86	.365	1.22	.13	.00	.00
3S.*	20.80	.387	13.69	-4.056	2.72	6.40	.380	3.24	.13	.00	.00
4S.*	20.40	.527	17.02	-4.099	3.65	-3.57	.660	7.51	.78	.00	.00
5S.*	20.10	.244	13.00	-3.601	2.13	3.26	.381	1.98	.13	.00	.00
1C	21.20	.541	19.36	-7.119	1.66	-.46	.750	9.10	2.34	.00	.00
2C.*	21.30	.528	16.37	-3.137	5.96	-6.52	.594	7.06	.78	.00	.00
3C.*	21.40	.533	17.31	-3.557	4.70	-5.40	.644	7.76	1.04	.00	.00
4C	21.30	.541	19.31	-6.656	1.81	-.73	.743	9.05	2.21	.00	.00
5C	21.40	.544	19.65	-7.466	1.57	-.38	.759	9.34	2.60	.00	.00
6C	21.50	.541	19.55	-6.825	1.75	-.63	.746	9.18	2.21	.00	.00
7C	21.30	.541	19.19	-6.336	1.94	-.90	.736	8.97	1.95	.00	.00
8C	21.50	.542	19.69	-7.329	1.60	-.34	.753	9.28	2.34	.00	.00
9C	21.40	.544	19.57	-7.187	1.65	-.46	.753	9.26	2.60	.00	.00
10C.*	19.00	.132	12.24	-4.964	.68	3.34	.356	.94	.13	.00	.00
11C	20.30	.163	13.02	-3.644	1.39	2.34	.375	1.31	.13	.00	.00
1T	21.30	.537	18.99	-5.859	2.14	-1.19	.724	8.75	1.69	.00	.00
2T	20.80	.537	18.79	-6.470	1.87	-.89	.740	8.74	1.67	.00	.00
3T	21.00	.538	18.95	-6.356	1.92	-1.05	.741	8.85	1.95	.00	.00
4T	20.90	.535	18.83	-6.363	1.91	-.85	.735	8.69	1.56	.00	.00
5T	20.70	.535	18.97	-7.422	1.56	-.22	.751	8.80	1.87	.00	.00
6T	20.90	.536	18.74	-6.097	2.03	-1.10	.731	8.66	1.87	.00	.00

AVERAGES: 70608 BASELINE W054 00 000

	21.68	.552	19.75	-6.933	1.77	-.81	.754	9.54	3.97	.00	.00
STD	.18	.002	.16	.588	.20	.38	.009	.11	.56	*	*

70608 W072CR005 (4E14)

	20.86	.491	18.25	-6.340	1.74	-.29	.696	7.93	1.79	.00	.00
STD	.73	.124	2.19	1.091	.22	1.13	.124	2.55	.71	*	*

PERCENT OF BASELINE

	96.3	89.0	92.4	108.6	98	164.4	92.3	83.1	45.1	*****	*****
STD%	4.2	23.0	11.9	24.8	25	220.2	17.7	28.0	26.8	*****	*****

Table 14

RUN ID 70425

70425 W067CR-MN-TI001 W054 00 000

SOL1 7 / 5 / 77 AM1: P0=91.60MW/CM² NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD	PCDA	PCDB
1R*	22.50	.554	20.24	-6.452	1.93	-.27	.721	9.51	.00	.00	.00
1B	22.70	.553	20.96	-7.898	1.48	-.17	.765	10.15	4.94	.00	.00
2B*	22.70	.548	20.06	-5.591	2.32	-1.01	.707	9.30	3.64	.00	.00
3B	22.70	.549	20.69	-7.113	1.68	-.14	.741	9.76	5.20	.00	.00
4B	22.90	.556	21.18	-8.092	1.44	-.06	.766	10.31	5.85	.00	.00
1C	18.70	.519	16.77	-6.267	1.91	-.79	.725	7.44	.39	.00	.00
2C	19.10	.519	17.13	-6.431	1.84	-.14	.713	7.48	.52	.00	.00
3C	19.70	.529	17.69	-6.464	1.86	-.18	.716	7.90	.78	.00	.00
4C	19.80	.529	17.74	-6.331	1.91	-.34	.716	7.93	.78	.00	.00
5C	19.60	.518	16.61	-4.633	2.96	-1.59	.654	7.02	.52	.00	.00
6C	19.20	.518	17.28	-6.554	1.79	-.22	.721	7.58	.39	.00	.00
7C	19.00	.514	16.59	-5.436	2.31	-.72	.683	7.05	.39	.00	.00
1S	19.30	.529	17.33	-6.252	1.95	-.92	.729	7.87	.78	.00	.00
2S	19.60	.526	17.45	-6.165	1.97	-.08	.701	7.64	.78	.00	.00
3S	19.60	.526	17.50	-6.067	2.02	-.80	.718	7.83	.78	.00	.00
4S	19.30	.525	17.37	-6.546	1.82	-.24	.721	7.72	.78	.00	.00
5S	19.70	.529	17.53	-5.907	2.10	-.94	.715	7.88	1.04	.00	.00
1T	18.60	.516	16.27	-5.382	2.36	-1.21	.692	7.02	.52	.00	.00
2T	19.00	.515	16.73	-5.636	2.20	-.85	.697	7.21	.39	.00	.00
3T	18.90	.511	16.57	-5.598	2.20	-.52	.686	7.00	.26	.00	.00
4T	18.60	.513	16.58	-6.076	1.97	-.67	.713	7.19	.39	.00	.00
5T	18.90	.514	16.91	-6.247	1.90	-.51	.716	7.36	.39	.00	.00

AVERAGES: 70425 BASELINE W054 00 000

	22.77	.553	20.94	-7.701	1.53	-.12	.757	10.07	5.33	.00	.00
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STD	.10	.003	.20	.423	.10	.05	.011	.23	.38	*	*
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70425 W067CR-MN-TI001

	19.21	.521	17.06	-5.999	2.06	-.63	.707	7.48	.58	.00	.00
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STD	.39	.006	.45	.498	.28	.40	.019	.33	.21	*	*
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PERCENT OF BASELINE

	84.4	94.2	81.5	122.1	135	*****	93.4	74.2	10.9	*****	*****
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STD%	2.1	1.6	2.9	11.1	29	662.9	3.9	5.1	5.1	*****	*****
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Table 15

70610 W074MN-CR-NI-TI-V002(8E13-8E13-5E14-6E11-6E12) W054 00 000
 SOL1 7 / 5 / 77 AM1: P0=91.60MW/CM² NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD	PCDA	PCDB
1R*	22.50	.555	20.16	-6.256	2.01	-.36	.717	9.47	.00	.00	.00
1B	22.00	.554	20.19	-7.413	1.61	-.39	.758	9.77	4.68	.00	.00
2B	22.20	.554	20.38	-7.417	1.61	-.47	.761	9.89	4.55	.00	.00
3B	22.30	.551	20.31	-6.983	1.73	-.41	.745	9.68	4.94	.00	.00
4B	22.50	.551	20.63	-7.362	1.61	-.40	.757	9.93	4.55	.00	.00
5B.*	22.30	.551	19.88	-5.765	2.24	-1.40	.727	9.45	4.29	.00	.00
1C	20.70	.541	18.81	-6.758	1.78	-.78	.747	8.85	1.82	.00	.00
2C	20.60	.538	18.56	-6.399	1.91	-.77	.733	8.59	1.30	.00	.00
3C	20.80	.539	18.83	-6.580	1.84	-.79	.741	8.79	1.56	.00	.00
4C	20.80	.540	18.97	-7.056	1.68	-.46	.748	8.88	1.82	.00	.00
5C	20.60	.538	18.53	-6.310	1.94	-.85	.732	8.58	1.69	.00	.00
6C	21.00	.537	18.98	-6.514	1.85	-.76	.738	8.80	1.56	.00	.00
7C	21.10	.537	18.97	-6.275	1.95	-.84	.731	8.76	1.56	.00	.00
8C	20.90	.539	18.95	-6.674	1.80	-.76	.744	8.86	1.82	.00	.00
9C	21.20	.539	19.06	-6.365	1.92	-.53	.725	8.76	1.95	.00	.00
10C	21.10	.539	19.17	-6.836	1.74	-.51	.742	8.93	1.95	.00	.00
11C	20.50	.533	18.30	-5.999	2.07	-.92	.720	8.32	1.30	.00	.00
1S	20.60	.545	18.83	-7.229	1.64	-.37	.750	8.91	2.34	.00	.00
2S	21.10	.543	18.79	-5.832	2.18	-1.15	.720	8.73	1.95	.00	.00
3S	21.30	.545	19.34	-6.800	1.77	-.51	.741	9.10	2.60	.00	.00
4S	21.30	.545	19.53	-7.387	1.59	-.38	.756	9.28	2.60	.00	.00
5S	21.40	.546	18.94	-5.567	2.34	-1.43	.716	8.84	2.60	.00	.00
1T	20.10	.539	18.16	-6.606	1.83	-.50	.732	8.39	1.30	.00	.00
2T	20.30	.538	18.40	-6.776	1.77	-.44	.737	8.51	1.30	.00	.00
3T	20.50	.538	18.57	-6.591	1.83	-.87	.744	8.67	1.56	.00	.00
4T	20.40	.536	18.44	-6.722	1.78	-.21	.728	8.41	1.69	.00	.00
5T	20.70	.539	18.90	-7.138	1.65	-.44	.749	8.84	1.69	.00	.00
6T	20.40	.537	18.46	-6.639	1.81	-.65	.738	8.55	1.69	.00	.00
AVERAGES: 70610 BASELINE W054 00 000											
	22.25	.553	20.38	-7.294	1.64	-.42	.755	9.82	4.68	.00	.00
STD	.18	.002	.16	.181	.05	.03	.006	.10	.16	*	*
70610 W074MN-CR-NI-TI-V002(8E13-8E13-5E14-6E11-6E12)											
	20.79	.540	18.79	-6.593	1.85	-.68	.737	8.74	1.80	.00	.00
STD	.35	.003	.33	.426	.17	.27	.010	.22	.40	*	*
PERCENT OF BASELINE											
	93.4	97.7	92.2	109.6	113	37.5	97.6	89.0	38.5	*****	*****
STD%	2.3	.9	2.4	8.2	14	82.1	2.2	3.2	10.2	*****	*****

Table 16

RUN ID 70609B

70609B W073CR-MN-NI-TI-V001 (5E14-5E14-2E15-4E12-4E12) W054 00 000
 SOL1 7 / 5 / 77 AM1: P0=91.60MW/CM² NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDB
1R*	22.50	.555	20.31	-6.666	1.85	-.05	.722	9.54	.00	.00	.00
1B	22.80	.553	21.04	-7.933	1.47	.00	.760	10.13	4.55	.00	.00
2B	22.70	.556	20.97	-7.994	1.46	-.07	.764	10.19	5.07	.00	.00
3B	22.70	.556	20.97	-7.994	1.46	-.07	.764	10.19	5.20	.00	.00
4B	22.70	.555	20.94	-7.951	1.47	.05	.758	10.11	4.94	.00	.00
5B	22.70	.553	20.93	-7.809	1.50	-.14	.761	10.11	4.94	.00	.00
1C	17.50	.501	15.56	-6.047	1.95	-.55	.706	6.55	1.04	.00	.00
2C	17.70	.499	15.58	-5.693	2.12	-.68	.693	6.47	.91	.00	.00
3C	17.60	.500	15.42	-5.449	2.26	-1.27	.695	6.47	.65	.00	.00
4C	17.80	.500	15.83	-6.127	1.91	-.29	.703	6.62	.65	.00	.00
5C	17.60	.496	15.24	-5.211	2.40	-1.03	.675	6.23	.52	.00	.00
6C	17.20	.500	15.14	-5.935	2.00	.21	.680	6.19	.65	.00	.00
7C	17.70	.501	15.86	-6.441	1.78	-.17	.713	6.69	.65	.00	.00
8C	17.50	.500	15.81	-6.830	1.65	-.01	.723	6.69	.65	.00	.00
9C	17.70	.498	15.88	-6.548	1.73	.04	.711	6.63	.65	.00	.00
10C	17.60	.496	15.52	-5.908	1.99	-.05	.686	6.34	.52	.00	.00
11C	17.70	.496	15.42	-5.449	2.24	-.59	.678	6.29	.52	.00	.00
1S	18.00	.507	16.24	-6.625	1.74	-.43	.728	7.03	.65	.00	.00
2S	17.90	.503	16.09	-6.526	1.76	-.27	.720	6.85	.65	.00	.00
3S	17.50	.507	15.73	-6.578	1.76	-.10	.716	6.72	.78	.00	.00
4S	18.00	.505	16.20	-6.500	1.77	-.52	.726	6.98	.78	.00	.00
5S	18.50	.504	16.05	-5.179	2.44	-1.23	.681	6.71	.52	.00	.00
1T	17.50	.499	15.68	-6.423	1.79	-.18	.712	6.58	.78	.00	.00
2T	17.50	.497	15.67	-6.404	1.79	-.18	.712	6.54	.78	.00	.00
3T	17.30	.498	15.61	-6.871	1.63	.30	.716	6.52	.91	.00	.00
4T	17.30	.498	15.48	-6.343	1.82	-.28	.712	6.48	.91	.00	.00
5T	17.10	.496	15.35	-6.526	1.74	-.10	.714	6.40	.52	.00	.00
6T	17.20	.494	15.11	-5.662	2.12	-.66	.690	6.20	.52	.00	.00

AVERAGES: 70609B BASELINE W054 00 000

	22.72	.555	20.97	-7.936	1.47	-.05	.761	10.15	4.94	.00	.00
STD	.04	.001	.04	.068	.01	.07	.002	.04	.22	*	*
	70609B W073CR-MN-NI-TI-V001 (5E14-5E14-2E15-4E12-4E12)										
	17.61	.500	15.66	-6.149	1.93	-.37	.704	6.55	.69	.00	.00
STD	.31	.004	.31	.504	.23	.41	.016	.23	.15	*	*
PERCENT OF BASELINE											
	77.5	90.1	74.7	122.5	131	*****	92.5	64.6	14.0	*****	*****
STD%	1.5	.9	1.6	7.1	17	*****	2.4	2.5	3.8	*****	*****

characteristics, namely: (1) The maximum radiation wavelength is 940 nm, where the absorption coefficient for silicon is too large ($1/e$ depth is only 40 μm); (2) The radiation intensity is too low for significant modulation of low resistivity and/or low lifetime silicon; and (3) The radiation decay time is approximately 200 ns which precludes measurements below this value. The shallow penetration produces a gradient in the minority carriers which in turn causes a diffusion current away from the silicon surface. The mathematical model used³ to correct the measurements for surface recombination assumes uniform generation throughout the silicon sample, and the error which results from this variance can be significant. The low radiation intensity and slow decay time limit the range of silicon resistivity for which accurate measurements may be obtained.

To alleviate these difficulties we have assembled a new PCD apparatus which employs a Nd:YAG laser as the excitation source. The monochromatic radiation wavelength is 1.06 μm , a spectral location for which the absorption coefficient, α , for high purity silicon is 11.70 cm^{-1} at 298°K.⁴ The $1/e$ depth for intrinsic silicon is, therefore, 0.85 mm (34 mils) and the internal radiation after passing through a 10 mil wafer is 75 percent of that at the incident surface. Absorption due to free carriers is small at 1.06 μm and may be neglected for resistivities greater than 0.07 ohm-cm.⁵ The absorption coefficient does, however, increase with temperature.

A schematic diagram of the laser excited PCD apparatus is shown in Fig. 1. The system arrangement is quite similar to that employed for the LED source.³ The most significant change involves the trap light. The maximum intensity of the trap light has been increased approximately ten fold to insure that all traps remain filled even for Mn or V impurity concentrations as large as 10^{15} cm^{-3} . The trap light source is a 300 watt quartz iodine incandescent lamp (General Electric Type ELH-120 volt) powered by a dc regulated power supply. A photograph of the new system is shown in Fig. 2.

Fig. 1. Schematic diagram of laser excited photoconductive decay lifetime measurement apparatus.

Fig. 2. Nd:YAG laser excited PCD apparatus.

When employing the laser-excited system for PCD measurements, concern must be given to the effects of the higher modes in the spacial distribution of minority carriers, the phenomenon pictorially illustrated in Fig. 3. Initially, at $t = 0$, the distribution of carriers is uniform throughout the sample so long as the pulse width is much less than the lifetime of the carriers (especially at the surface). The spacial distribution approaches a single cosine function with increasing time due to surface recombination and diffusion of the carriers. Mathematically, the excess carrier concentration, δ_n (equal to $n - n_0$), is equal to,^{3,6}

$$\delta_n(x,y,z,t) = \sum_{i,j,k=0}^{\infty} G e^{-t/\tau_{ijk}} \cos(a x) \cos(b y) \cos(c z) \quad (3.5.1)$$

where

$$\frac{1}{\tau_{ijk}} = \frac{1}{\tau_r} + D \left[\frac{\epsilon_i^2}{l^2} + \frac{\eta_j^2}{\omega^2} + \frac{\zeta_k^2}{d^2} \right] \quad (3.5.2)$$

and ϵ_i , η_j , and ζ_k are defined by the transcendental equations.

$$\begin{aligned} \frac{s l}{D} &= \epsilon_i \tan \epsilon_i \\ \frac{s \omega}{D} &= \eta_j \tan \eta_j \\ \frac{s d}{D} &= \zeta_k \tan \zeta_k \end{aligned} \quad (3.5.3)$$

The tangent function repeats in the first and third quadrants, so that solutions for Eq. (3.5.3) exist for intervals $n\pi$ to $(n + 1/2)\pi$, where $n = 0, 1, 2, 3, \dots$, and the value of n is used as subscripts on i, j , and k . An infinite series of time constants is generated through Eq. (3.5.3) with the result that the value of Eq. (3.5.2) varies with time. The net result is that the photoconductivity decay is not characterized by a single time constant. The accepted procedure for determining the fundamental time constant, τ_{000} , is to wait for all the higher modes to

Fig. 3. Changes in minority carrier distribution during PCD measurements due to surface recombination.

decay to insignificance. The time required to establish the fundamental mode can be calculated provided that the diffusivity, D , and the surface recombination velocity, s , are known. Table 17 lists the time constant, γ , associated with the term

$$\left[D \left(\frac{\epsilon_i^2}{l^2} + \frac{\eta_j^2}{\omega^2} + \frac{\zeta_k^2}{d^2} \right) \right]^{-1}$$

for various values of i , j , and k . The dominance of the k series is illustrated. The dominance of the k series vanishes when the specimen thickness approaches the width and length (0.5 cm). It is also apparent that the higher modes decay much more rapidly than the fundamental mode. The most troublesome i , j , k modes all decay with a time constant of approximately 0.32 μsec . The amplitude of these modes will decay to only 0.2% of the initial value if a determination of τ_{ooo} is delayed for 2 μsec after the carrier generation is terminated. The error in the calculated value of τ_r is, however, much larger and increases rapidly with τ_r , due to the differential nature of Eq. (3.5.2). Blakemore and Nomura⁷ have calculated the error in measuring τ_r if it is assumed that

Table 17. Time Constants of Higher Modes

$$s = 8990 \text{ cm/s}; D_n = 32.9 \text{ cm}^2/\text{s}$$

$$2l = 0.5 \text{ cm}, 2\omega = 0.5 \text{ cm}, 2d = 0.0254 \text{ cm}$$

Mode (i,j,k)	γ (μsec)
0,0,0 (Fundamental)	3.216794
1,1,1	0.324496
2,2,2	0.106623
3,3,3	0.051076
1,1,0	3.020686
0,0,1	0.326635
0,0,2	0.107316

the surface rate is only $1/\gamma_{000}$ when the amplitude has decayed to a given fraction of its peak value. The results of Blakemore and Nomura's calculations are reiterated for reference in Table 18 for the case of a square cross-section, when generation is very brief and spatially uniform.

Table 18. Errors in Measurement of Bulk Recombination Lifetime

Ratio of Bulk Rate to the Surface Rate of the Fundamental Mode ($1/\tau_r/1/\gamma_{000}$)	Percentage Error in Measurement of τ_r			
	Measured when $N(t)/N(o) = 0.75$	Measured when $N(t)/N(o) = 0.50$	Measured when $N(t)/N(o) = 0.25$	Measured when $N(t)/N(o) = 0.10$
0.1	1250%	270%	27%	1.0%
1	160%	50%	12%	2.1%
10	33%	17%	8.9%	5.3%
100	9.5%	5.6%	3.8%	2.7%

The value of $1/\gamma_{000}$ is given in Table 17 as 3.1087×10^5 and the ratio $1/\tau_r/1/\gamma_{000}$ is equal to 0.1 when $\tau_r = 32 \mu\text{sec}$. Thus, accurate measurements for $\tau_r = 32 \mu\text{sec}$ require that the apparent lifetime, τ_r' , be measured after the amplitude has decayed to less than 10% of its initial value. Consideration of these higher modes was found to be unimportant when using the LED source.⁷ This observation resulted from the fact that the LED was pulsed for 10 μsec and the higher modes were all but eliminated by spacial redistribution during the long generation period. In contrast, the laser source is characterized by a very brief pulse and the effects of higher modes must be considered.

A surface recombination velocity, s , equal to 8990 cm/s was used to calculate, τ_r with the LED source. The value was obtained by

obtaining a best fit with experimental data over a very limited thickness range. Actually, the best fit value represented a compromise between minority carriers diffusing toward the surface due to surface recombination and away from the surface due to non-uniform carrier generation. Carrier generation with the Nd:YAG laser is nearly uniform and a true value for the surface recombination must be determined for calibration purposes. Equation (2) can be satisfied for the measured parameter, τ_{ooo} , by an infinite combination of s and τ_r values. In theory, s can be determined by measuring τ_{ooo} for two different thicknesses, $2d$. The accuracy in determining s can, however, be improved by increasing the number of data points so that a curve can be generated. The results obtained from such a set of data for n type silicon is shown in Fig. 4. The correct value of s is one which yields a bulk lifetime, τ_r , which is independent of thickness. Considerable scatter is evident in the data and is a result of the fact that the bulk lifetime for this specimen (21.3 μ sec) was too large for the thickness range utilized. The result is that the correction factor ($-D_p \epsilon_o^2/d^2$) is comparable to $1/\tau_{ooo}$ and small errors in determining τ_{ooo} and small variation in s due to perturbations in the etching techniques are magnified many-fold. Linear regression analysis was used to find the value of s (7640 cm/sec) which minimized the standard deviation. The population (9 measurements) standard deviation, σ , for this sample was equal to 2.99 and the probable error is ± 2.02 μ sec. The apparatus is now considered reasonably calibrated for PCD measurements on n-type silicon, but improved accuracy and confidence will be sought with another calibration series. Calibration for p-type silicon will then be initiated promptly.

Fig. 4. Determination of surface recombination velocity, s for n-type silicon from PCD measurements performed with a Nd:YAG laser.

3.5.2 Thermally Stimulated Measurements

Solar cell performance is strongly influenced by the nature and concentration of centers such as chemical contaminants or lattice defects which act as sites for carrier recombination. In our studies we have related cell performance to total measured impurity content although in fact the impurities may be present in a variety of forms such as precipitates or complexes of differing electrical character. To improve our understanding of impurity effects and to strengthen our modeling we plan to employ thermally stimulated measurements as a means for developing some of the data which cannot be found by our present phenomenological approach.

In principle, the methods of thermally stimulated current and capacitance measurements are capable of giving all the important recombination center parameters. These parameters include, e.g., trap density and energy level, spatial distribution of traps, carrier capture rates and carrier emission rates. In these measurements, the current or capacitance of a p-n junction or of an MOS structure is measured as a function of temperature.

To make such measurements an apparatus consisting of a stage probes, voltage supplies, temperature controller, capacitance meter, electrometer, and X-Y recorder, constructed on a Westinghouse internal program, has been modified recently for our use. The stage is cooled with liquid nitrogen and electrical heating is used to provide the required temperatures and temperature changes. A window at the top of the test chamber permits viewing the specimen under test as well as illuminating the cell with ionizing radiation.

Because the p-n junction in solar cells is not capable of blocking a sufficiently large voltage for these measurements, we expect to make measurements on MOS structures. Fabrication of these structures with low temperature deposited insulators should yield useful devices without changing the density or characteristics of recombination centers

present in finished solar cell material. This facilitates correlation of trap parameters and solar cell performance.

The sensitivity of thermally stimulated measurements depends upon the nature of the particular parameter to be measured, the resistivity of the material, and the details of the measurement procedure. In general, any parameter which affects device performance can be detected or measured with the thermally stimulated measurement technique.

The particular measurement technique -- current or capacitance -- employed also depends upon the parameter to be measured. Usually, a measurement is made by first imposing a suitable voltage across the sample to fill the traps. The specimen is next cooled to a temperature at which the thermal emission rate for carriers is conveniently slow and the traps then are allowed to empty by imposing a different voltage across the device. The rate at which traps empty is then related to the rate at which the current or capacitance varies. The total number of traps is related to the total amount of charge released.

The carrier capture rate is similarly measured by first emptying all traps, then measuring the rate at which the traps are refilled.

It is expected that measurements with this equipment will begin during the next quarter.

3.6 Data Synthesis and Modeling

In the Fifth Quarterly Report² we began the development of a mathematical model for the behavior of a silicon solar cell in the presence of one or more metal impurities. That preliminary treatment included a description of the short circuit current and open circuit voltage behavior of the device, but cell efficiency was not explicitly considered. The discussion of V_{oc} was also somewhat incomplete and predicated on the assumption that the open circuit voltage is wholly dependent on the lifetime in the junction depletion layer which, as we

show below, is not strictly the case. In this section we take up the development of the model by clarifying and completing the description of V_{oc} behavior and then proceeding to consider how the efficiency of the solar cell behaves with respect to the kind and amount of metallic contaminants present. Some material from the previous report² has been repeated here for the sake of completeness or where new data have been added.

3.6.1 Open Circuit Voltage Behavior

The open circuit voltage for the single exponential model is given by:

$$V_{oc} = n V_T \ln\left(\frac{I_{sc}}{I_o}\right) \quad (3.6.1)$$

where n is the ideality factor

$V_T = kT/q$ is the thermal voltage

I_{sc} is the short circuit current

and I_o is the saturation current.

If we define the normalized variables:

$$V_n = \frac{V_{oc}}{V_{oc_o}} \quad (3.6.2)$$

$$I_n = \frac{I_{sc}}{I_{sc_o}}$$

where V_{oc_o} and I_{sc_o} are the open circuit voltage and short circuit current of baseline devices. We can now write Eq. (3.6.1) as:

$$V_n = \frac{nV_T}{V_{oc_o}} \ln\left(\frac{I_n I_{sc_o}}{I_o}\right) \quad (3.6.3)$$

In order to apply Eq. (3.6.3) to the experimental data, we need a value of, or an expression for, the saturation current, I_o . It is difficult to

* Eq. (3.3.5) of Ref. 2.

obtain accurate measured values of the saturation current in a solar cell, but an implicit value exists which depends on two generation-recombination processes, one in the junction depletion region, the other in the base layer of the device. The component of the saturation current associated with the junction depletion region, denoted I_{o2} , varies inversely with lifetime.

$$I_{o2} = \frac{W A q n_i}{2 \tau_{dep}} \quad (3.6.4)$$

The component controlled by the base region is inversely proportional to the square root of lifetime.

$$I_{o1} = \frac{q A n_i^2 \sqrt{D}}{N_A \sqrt{\tau_{base}}} \quad (3.6.5)$$

Thus, the effective saturation current is proportional to τ^{-m} with m lying between 1 and 2, depending on the relative importance of the two mechanisms. An examination of the data of Figs. 13 and 14 of the Fifth Quarterly Report² shows that the open circuit voltage point (~ 0.556 volts) lies on the high current segment which is controlled by I_{o1} . So, from Eq. (3.6.5) we assume $I_o \sim 1/\sqrt{\tau}$ and Eq. (3.6.1.) becomes

$$I_o = \frac{C \left(\frac{1}{I_n} - C_1 \right)}{C_2} \quad (3.6.6)$$

where C is a proportionality constant. Combining Eqs. (3.6.3) and (3.6.4) gives:

$$V_n = \frac{nV_T}{V_{oc_o}} \ln \left(\frac{I_n}{\frac{1}{I_n} - C_1} \right) + \frac{nV_T}{V_{oc_o}} \ln \left(\frac{C_2 I_{sc_o}}{C} \right) \quad (3.6.7)$$

or defining two functional parameters E and F , we have:

$$V_n = E \ln \left(\frac{I_n}{\frac{1}{I_n} - C_1} \right) + F \quad (3.6.8)$$

C_1 has the value 0.9368 as determined by applying Eq. (3.25) of Ref. 2 to the data shown in Fig. 15 of that reference.

A least squares fit of experimental data to Eq. (3.6.8) provides $E = 0.0472$ and $F = 0.8747$. As defined in Eq. (3.6.7), $E = n V_T / V_{oc0}$ and $V_{oc0} = 0.556$ volts. Therefore, we obtain n equal to 1.02. Sah-Noyce-Shockley⁸ theory predicts n equal to one in this region of the I-V curve. Had we assumed that V_{oc} was governed by the lifetime in the depletion region, the curve fit procedure results in $n = 0.5$, a value for which there is no experimental or theoretical basis.

The curve representing Eq. (3.6.8) is shown in Fig. 5 with the experimental data.

3.6.2 Efficiency Behavior

In order to obtain an expression for efficiency, we begin with the single exponential solar cell equation:

$$I = I_{sc} - I_o \exp(V/nV_T) , \quad (3.6.9)$$

and again normalize the variables with the baseline values of I_{sc0} and V_{oc0} :

$$\frac{I}{I_{sc0}} = \frac{I_{sc}}{I_{sc0}} - \frac{I_o}{I_{sc0}} \exp \left(\frac{V}{V_{oc0}} \cdot \frac{V_{oc0}}{nV_T} \right) . \quad (3.6.10)$$

Defining $I_{nv} \triangleq I/I_{sc0}$ and $V_{nv} \triangleq V/V_{oc0}$ we have:

$$I_{nv} = I_n - \frac{I_o}{I_{sc0}} \exp \left(V_{nv} \cdot \frac{V_{oc0}}{nV_T} \right) \quad (3.6.11)$$

Following the same arguments in the discussion of open circuit voltage, we use the base controlled expression for I_o (Eq. 3.6.6).

$$I_{nv} = I_n - C' \left(\frac{1}{I_n} - C_1 \right) \exp \left(V_{nv} \cdot \frac{V_{oc0}}{nV_T} \right) . \quad (3.6.12)$$

The proportionality constant C' can be found from the boundary requirement that if $I_n = 1$ and $I_{nv} = 0$, then $V_{nv} = 1$.

Fig. 5. Variation of normalized open circuit voltage with normalized short circuit current for metal-doped solar cells. Data fit to model indicated in the inset.

$$C' = \left\{ (1 - C_1) \exp(V_{oc_0}/nV_T) \right\}^{-1} . \quad (3.6.13)$$

From the V_{oc} analysis $V_{oc_0} = 0.556$ volts, $n = 1.02$, $V_T = 0.026$ volts and $C_1 = 0.9368$ which gives $C' = 9.71 \times 10^{-9}$.

The power produced by the cell in normalized variables is:

$$P_n = I_{nv} V_{nv} . \quad (3.6.14)$$

The peak power output results when $dP_n/dV_{nv} = 0$ or:

$$\frac{dI_{nv}}{dV_{nv}} + I_{nv} = 0 . \quad (3.6.15)$$

From Eq. (3.6.12) we obtain:

$$I_n - \left[C' \left(\frac{1}{I_n} - C_1 \right) \exp \left(V_{nv} \frac{V_{oc_0}}{nV_T} \right) \right] \left[\frac{V_{oc_0}}{nV_T} V_{nv} + 1 \right] = 0 , \quad (3.6.16)$$

Solving Eq. (3.6.16) for V_{nv} with the normalized short circuit current, I_n , as a parameter gives the peak power voltages, V_{np} , and using Eq. (3.6.11), the peak power currents, I_{np} , as functions of I_n . The cell efficiency is defined in terms of the light energy input, P_L .

$$\eta = I_p V_p / P_L , \quad (3.6.17)$$

which normalized by the baseline values becomes:

$$\eta/\eta_0 = \frac{I_{np} V_{np}}{I_{np_0} V_{np_0}} \quad (3.6.18)$$

where the zero subscript denotes baseline quantities.

The behavior of efficiency as a function of short circuit current calculated using (3.6.16) and (3.6.18) is shown as the curve in Fig. 5. The agreement with experimental data for singly-doped ingots is quite good.

Fig. 6. Normalized short circuit current, $I_n = I_{\text{sc}}/I_{\text{scBaseline}}$

Because Eq. (3.6.16) has no closed form solution, the curve is computer generated using an iterative technique. However, in order to calculate the behavior of efficiency as a function of impurity species and concentration, it is convenient to obtain a closed-form expression for this curve. A least-square procedure provides an excellent approximation.

$$\eta/\eta_o = 0.964 I_n^{1.239} + 0.036 I_n^{12} . \quad (3.6.19)$$

We are now in a position to calculate the cell efficiency as a function of metal concentration. The short circuit current model described earlier² provides the relationship between short circuit current and metal concentration:

$$I_n = I_{n\infty} \left[(C_1 + C_{2x} N_x)^{1/2} + 1 \right]^{-1} \quad (3.6.20)$$

where $I_{n\infty} = 1.10$.

Table 19 (reproduced from Ref. 2) tabulates the values obtained for C_1 and C_{2x} for samples containing single metal additives.

These data in Eqs. (3.6.19) and (3.6.20) provide the calculated efficiency curves shown in Fig. 7. Agreement with the measured efficiencies is generally within the range of experimental errors. One exception is the behavior of iron for which neither the short circuit current (see Fig. 8) nor efficiency curves fit well. It would appear from the experimental data that the degradation due to iron increases superlinearly with iron concentration. At present we know of no physical mechanism to account for such behavior; however, it is possible to include non-linear dependence on concentration in the model and this plus further experimental study will be carried out in the future.

A second case of poor agreement is for nickel. Here the experimental data points have the same functional trend as predicted but are displaced downward in efficiency. This suggests that nickel

$$I_n = I_{n\infty} \left\{ (C_1 + C_{2x} N_x)^{1/2} + 1 \right\}^{-1}$$

$$I_{n\infty} = 1.10$$

Table 19. Calculated Coefficients of Equations (3.31) and (3.32) of Ref. 2 for the Short Circuit Current Behavior with Single Metal Additions. See also Fig. 10, Ref. 2.

	Coefficient of Fit R^2	C_1	C_{2x}	N_{ox}
Cu	.98	0.0120	7.301×10^{-19}	1.265×10^{14}
Ni	.69	0.0192	3.271×10^{-18}	3.644×10^{15}
Cr	.81	0.0037	7.843×10^{-17}	4.76×10^{13}
Fe	.58	0.0019	1.48×10^{-16}	1.28×10^{13}
Mn	.98	0.00966	6.099×10^{-17}	1.60×10^{14}
Zr	.86	0.0130	1.841×10^{-15}	7.36×10^{12}
V	.70	0.0106	5.4×10^{-15}	1.96×10^{12}
Ti	.95	0.0105	6.98×10^{-15}	1.51×10^{12}

Fig. 7. Normalized solar cell efficiency as a function of substrate metal impurity concentration. Experimental data and model derived curves.

Fig. 8. Variation in normalized solar cell short circuit current with metal concentration of the solar cell substrate; see also Ref. 2.

introduces effects in addition to base lifetime degradation on which the model is predicted. Further study of this behavior will also be implemented.

Overall the model, with the exception of iron and nickel, seems to provide satisfactory predictions of the impurity effects. Most of the data discrepancies are believed to be due to experimental errors, particularly of metal concentration. The statistically limited nature of the data also accounts for some of the inaccuracies.

3.6.3 Multiply-Doped Cells

The efficiency and short circuit current calculations can be extended to cells made from crystals containing several metals. The behavior of short circuit current developed in the Fifth Quarterly Report provides:

$$I_n = I_{n\infty} \left[(C_1 + C_{2x}N_x + C_{2y}N_y \dots C_{2z}N_z)^{1/2} + 1 \right]^{-1} \quad (3.6.21)$$

The constants C_{2x} , C_{2y} are taken from Table 19, where x , y , ... z refer to the metal species and N_x , N_y , etc. are the corresponding concentrations. C_1 is assigned the averaged value, 0.012 and $I_{n\infty} = 1.10$.

The data in Table 20 show the impurity concentrations, the measured and calculated short circuit current, and the measured and calculated efficiencies for multiply-doped samples. (Some of the I_n results have been corrected for a minor numerical error in the original calculation.²) The measured data errors are standard deviations of the experiments while the calculated errors are based on the accuracy of the metal concentration measurements, estimated to be within a factor of two. The experimental values are compared to the calculated values in Figs. 9 and 10. These results are generally in agreement. Those data exhibiting disagreement are thought to be a result of limited statistics and as noted earlier, the possible invalidity of assuming that number of recombination centers is linearly dependent on the total metal concentration. Both of these limitations will be dealt with as additional data become available.

The performance of these multiply-doped cells does not, based on present data, show any compelling evidence of either synergic or antisynnergic behavior. However, with some specific ingots these effects may be present; for example, the data from ingot 051 imply that copper reduces the degradation of titanium. In contrast are the results from ingot 027 where it seems that copper makes manganese more damaging. Future experiments are needed to clarify this situation. And it should be kept in mind that synergic behavior, like the effects of single impurities, will, if it exists, be sensitive to processing influences.

$$I_n = I_{sc} / I_{sc0}$$

$$C_1 = 0.012$$

$$I_n = 1.10$$

$$I_n = I_n \left\{ (C_1 + C_{2x} N_x + C_{2y} N_y + \dots C_{2z} N_z)^{1/2} + 1 \right\}^{-1}$$

Table 20. Calculated and Measured Short-Circuit Currents and Efficiencies for Multiple Metal Additions

Ingot No.	Metal Concentration (10^{15} at.cm $^{-3}$)								Measured I_n	Calculated I_n	Measured $\eta/\eta_{baseline}$	Calculated $\eta/\eta_{baseline}$
	Ti	Cu	V	Cr	Fe	Zr	Ni	Mn				
37	0.3					<0.0015			.599 ± .019	.447 ± .186	.446 ± .021	.356 ± .192
43	0.06				0.56				.703 ± .014	.641 ± .162	.564 ± .026	.556 ± .181
51	0.36	1.7							.619 ± .027	.425 ± .186	.498 ± .026	.334 ± .190
50	0.00036		0.0004						.869 ± .013	.974 ± .013	.797 ± .014	.960 ± .019
45	0.06			0.65	0.43				.727 ± .078	.633 ± .164	.616 ± .071	.547 ± .183
47		1.7				<0.0015	0.75		.938 ± .010	.911 ± .054	.897 ± .016	.870 ± .075
27		1.5						1.3	.737 ± .028	.844 ± .089	.689 ± .038	.786 ± .115
41		1.7		0.8			3.0		.828 ± .061	.851 ± .086	.690 ± .081	.794 ± .111
30		1.5		1.0					.761 ± .029	.845 ± .089	.688 ± .044	.787 ± .114
40				1.0			3.5		.868 ± .079	.835 ± .093	.772 ± .112	.776 ± .119
46			0.07		0.56				.769 ± .015	.652 ± .159	.665 ± .025	.567 ± .179
31				1.0				1.0	.543 ± .025	.792 ± .112	.450 ± .032	.724 ± .138
61	0.02			1.0				0.5	.734 ± .038	.728 ± .136	.614 ± .046	.652 ± .160
67	0.006			0.42					.844 ± .021	.850 ± .086	.742 ± .051	.793 ± .112
73	0.005		0.005	0.5			2.0	0.5	.797 ± .015	.901 ± .059	.628 ± .034	.857 ± .081
74	0.0006		0.006	0.08			0.5	0.08	.934 ± .025	.970 ± .013	.890 ± .032	.959 ± .020
75	0.1		0.1						.696 ± .012	.519 ± .183	.566 ± .022	.428 ± .194

Fig. 9. Normalized short circuit current for multiply doped material.

Fig. 10. Normalized cell efficiency, $\eta/\eta_{\text{baseline}}$, for multiply doped material.

4. CONCLUSIONS

Nearly all the baseline crystals and about a third of the doped crystals have now been grown; the primary effort being concentrated on singly- and multiply-doped p-type ingots and the first generation n-type ingots. Four n-type ingots, doped respectively with Cu, Cr, Mn, and Ti have been processed to solar cells and tested. Cu and Cr affect n-base solar cells in much the same way as they do p-base devices: Cu produces no discernable reduction in efficiency of the n-base cells while Cr reduces cell efficiency to about 80% of baseline (uncontaminated) devices. Mn and Ti, however, appear to be less harmful to the n-base cells than to the p-base counterpart. For example, Mn at about 10^{15} at.cm⁻³ reduces cell efficiency to 71% of baseline in the p-type device but hardly affects the cell performance of the n-type cells. At 3×10^{14} at.cm⁻³ Ti degrades cell performance to 25% of the p-type baseline but reduces the efficiency of the n-type cells to only about 80% of the baseline value.

Mathematical modeling of solar cell behavior has been extended to cover cell efficiency as well as short circuit current and open circuit voltage effects. Overall, the model with the exception of iron and nickel provides very satisfactory predictions of efficiency with metal content of the silicon. Degradation in cell efficiency due to iron appears superlinear in concentration (a violation of the assumptions of the model) and will be examined in further detail later. The nickel data follow the predicted trend with concentration but are displaced downward in efficiency suggesting that nickel introduces effects on the cell in addition to base lifetime degradation. The model has been used to predict with general experimental agreement the short circuit current

and efficiency of seventeen p-type ingots containing two to five metal impurities each. The performance of the multiply-doped ingots shows no compelling evidence for synergic behavior although two ingots in the initial data suggest interaction of the contaminants.

5. PROGRAM STATUS

5.1 Present Status

The program is generally on schedule, Fig. 11, although ingot evaluation lags somewhat the original plan since the contract was only recently signed with JPL.

During this quarter we have:

- Completed growth and initial evaluation of half the ingots for processing studies.
- Completed modifications to the laser-excited PCD measurement apparatus and thermally stimulated measurement apparatus.
- Completed growth and evaluation of half the first generation n-base (phosphorus-doped) ingots.
- Extended the data base on singly- and multiply-doped p-type material to include five more ingots.
- Grew the baseline polycrystalline material for grain boundary studies.
- Extended the mathematic model of the solar cell to include the effects of impurities on cell efficiency.

5.2 Future Activity

During the coming quarter the growth and cell evaluation of all first generation n-base ingots will be completed. Processing studies, including gettering and heat treatment, will be initiated. The first generation low resistivity ingots will be grown and most of the evaluation completed. Carbon and phosphorus doped ingots will be prepared as part of the 4 Ω -cm p-type matrix extension studies.

PROPOSED PROGRAM
MILESTONE CHART

Fig. 11

6. REFERENCES

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