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**SILICON MATERIALS TASK OF THE LOW COST
SOLAR ARRAY PROJECT (PART 2)**

Fourth Quarterly Report, July 1 1976—September 30, 1976

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**Westinghouse Research Laboratories
Pittsburgh, Pennsylvania**

**Dow Corning Corporation
Pittsburgh, Pennsylvania**

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

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FOURTH QUARTERLY REPORT

1 July 76 - 30 Sept 76

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Contract No. 954331

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TECHNICAL CONTENT STATEMENT

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NEW TECHNOLOGY

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

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SILICON MATERIALS TASK OF THE LOW COST
SOLAR ARRAY PROJECT (PART 2)

Fourth Quarterly Report
1 July 76 - 30 Sept 76
Contract No. 954331

1. SUMMARY

The objective of this program, Part 2 of the Silicon Materials Task, is to develop and define purity requirements for solar grade silicon by exploring the effects of metal impurities on the performance of terrestrial silicon solar cells. During this quarter we have completed the growth of all contract-required Czochralski and silicon dendritic web crystals. The chemical analysis of all the Czochralski ingots is also finished. Preliminary mass spectroscopic evaluation of metal-doped web samples grown at 1.3 cm/min indicates that the effective distribution coefficients for Cu, Ni and Cr all increase with growth rate as anticipated. For chromium the increase is almost 100 fold compared to the effective k for Czochralski ingots grown at 7.5 cm/hr.

PCD lifetime measurements have been completed on 46 ingots. The correlation between solar cell performance (I_{sc}) and PCD lifetime appears valid for all processed wafers except those containing Ti which give lower cell efficiency than would be predicted on the basis of lifetime alone.

Solar cell measurements have been completed in all but a few of the ingots grown during the contract. In particular, data has now been obtained on the second set of multiply-doped samples containing the impurity combinations Zr/Ti, Cr/Ni and Cr/Cu/Ni. As in the case of

ingots containing only Ti, the Zr/Ti sample shows severely degraded cell efficiency, only about 26% of the baseline. The Cr/Ni and Cr/Cu/Ni samples show efficiencies of 81 and 72% of baseline efficiency reflecting the small effects of Cu and Ni on cell performance and the stronger effect of Cr.

2. INTRODUCTION

2.1 Program Objectives

Our objective in Part 2 of the Silicon Materials Task (LCSSAP) is to develop and define purity requirements for solar cell grade silicon material. In a broader sense we are developing a data base which delineates the effects of various impurities and impurity levels on the performance of terrestrial silicon solar cells and which can subsequently be used for material cost-tradeoff analyses.

2.2 Program Approach

The basic approach we have taken is to establish, as unambiguously as possible, what concentrations of the impurities commonly found in silicon starting material (metallurgical grade silicon) can be tolerated in silicon wafers produced by (a) standard Czochralski pulling and (b) rapid sheet growth (dendritic-web) without degrading solar cell performance. Other impurities, e.g., those entering the material via particular purification or sheet growth processes could also be examined within the framework of our methodology as they are identified. Our experimental methods have been described extensively in previous reports,¹⁻³ and will not be repeated here. Instead we briefly describe the pertinent experimental results developed during the last quarter.

2.3 Program Personnel

This program is being conducted by a team of scientists from the Westinghouse Electric Corporation and Dow Corning Corporation whose technical responsibilities are identified below.

Westinghouse Research Laboratories

Dr. R. H. Hopkins -- Technical Manager and Dendritic Web Studies

Dr. J. P. McHugh -- Web Growth

Dr. P. Rai-Choudhury -- Device Diffusion

Mr. J. R. Davis -- Solar Cell Testing and Analysis

Mr. P. D. Blais -- Lifetime Studies, Photolithography and
Metallization.

Dow Corning Corporation

Dr. J. R. McCormick -- Czochralski Ingot Preparation and Evaluation.

Dr. R. Mazelsky, Westinghouse, has administrative responsibility
for the program.

3. TECHNICAL PROGRESS

3.1 Impurity Matrix

Figure 1 depicts the impurity matrix we have used in this program to evaluate the effects of impurities on silicon solar cells, and the status of the doubly-doped Czochralski ingots which contain those impurities. All doubly-doped ingots (metal plus 3.5×10^{15} at/cm³ boron) required for this program have now been grown and most fabricated into solar cells. Several of these ingots remain to be cell-tested. Doubly-doped silicon web samples have been grown using each impurity in the matrix except Zn and Mg which because of their high volatility are difficult to keep in the melt during growth.

Besides the doubly-doped ingots and webs, a number of multiply-doped samples have been prepared in order to assess possible synergistic effects between impurities. For the Czochralski ingots the combinations so far examined are Mn/Cu, Cr/Cu, Cr/Mn, Zr/Ti, Cr/Ni, Ni/Cr/Cu, Fe/Ti, Cr/Fe/Ti, Fe/V, Cu/Ni/Zr, Ti/V and Cu/Ti. Multiply-doped webs include specimens containing Cr/Cu, Mn/Cu, Cr/Mn, Ni/Mn, Zr/Ti and Cu/Ti.

3.2 Silicon Ingot Preparation and Evaluation

3.2.1 Preparation

The details regarding ingot preparation and characterization are discussed in previous project reports.^{2,3} Dopant elements, and their characteristics are summarized in Table 1. The segregation coefficients of elements used as dopants in ingots prepared to date are shown in the last column. The values shown in parentheses in the last column are the best estimate of effective segregation coefficient

INGOT STATUS

G - Grown
F - Fabricated
T - Tested

Concentration Range (At/cm³)

Impurity Element	$< 10^{13}$	1×10^{13} To 1×10^{14}	1×10^{14} To 1×10^{15}	1×10^{15} To 5×10^{15}	5×10^{15} To 1×10^{16}	$> 10^{16}$
Cr		G, F, T	G, F, T	G, F, T		
Mn		G, F, T	G, F, T	G, F, T		
Cu			G, F, T	G, F, T		G, F, T
Ni			G, F, T	G, F, T	(2) G, F, T	
Fe		G, F	(2) G, F, T			
Ti	G	(2) G, F, T	G, F, T			
V	G	G, F	G, F, T			
Mg	G, F, T	G, F, T	G, F, T			
Zn	G, F, T					
Zr			G, F, T	G, F, T		
Al				G, F, T	G, F, T	

Fig. 1. Impurity Matrix.

Table 1. Characteristics of Dopant Impurities

Dopant	Form	Purity %	Melting Point (°C)	Temperature For 1 mm Vapor Pressure (°C)	Segregation Coefficient*
Aluminum ⁺	Wire	99.99	659	1284	1.6×10^{-3} ($2.8 \times 10^{-3}/3 \times 10^{-2}$)
Chromium	Pellets	99.999	1900	1504	10^{-5} ($.95 \times 10^{-5}$)
Copper	Zone Refined Ingot	99.9997	1083	1628	4×10^{-4} (4×10^{-4})
Iron	Sponge/ Ingot	99.999/ 99.999	1535	1783	0.8×10^{-5} (--)
Magnesium	Ingot	99.99	651	605	10^{-3} (1×10^{-5})
Manganese	Flake	99.99	1244	1251	10^{-5} (1.35×10^{-5})
Nickel	Sponge/ Wire	99.999/ 99.97	1455	~1884	0.8×10^{-5} (3.2×10^{-5})
Titanium	Crystal	99.95	1668	~2500	10^{-5} ($.36 \times 10^{-5}$)
Vandium	Dendrite	99.9	2190	2550	10^{-5} ($.45 \times 10^{-5}$)
Zinc	Rod	99.999	419	487	10^{-5} (--)
Zirconium	Foil	99.99	2127	2450	10^{-5} ($<.45 \times 10^{-5}$)

* The segregation coefficients shown are best values obtained from a review of the literature on impurities in silicon. The quantity in parentheses represent calculated segregation coefficients based on this work.

⁺ Two segregation coefficients are shown for aluminum. The first value is based on electrically active aluminum determined by resistivity measurements while the second value is based on total aluminum content in the ingot as determined by mass spec.

based on data collected during this program. For the preparation of a number of ingots this latter coefficient has been used. For aluminum the value of 2.8×10^{-3} relates to the electrically active species only (that which affects resistivity). The effective segregation coefficient of magnesium is more than two orders-of-magnitude smaller than the value previously found in the literature while the effective segregation coefficients for titanium, vanadium, and zirconium are significantly smaller than previously published values.

During this reporting period fourteen ingots were prepared. The status of these ingots is summarized in Table 2. The letter designation indicates whether the ingot has been grown (G), sliced (S), and analyzed (A). Doped ingots for which analysis is not yet complete include W045, W047, W048, W049, W050, W051, and W052. Also remaining to be analyzed are four undoped evaluation ingots.

Difficulties previously encountered in the preparation of multiply-doped ingots were alleviated when total melt doping concentration was reduced to a maximum of 0.5 percent. In general, melt concentrations in the range of 1 percent or greater have made single crystal growth difficult to achieve.

3.2.2 Evaluation

Ingot evaluation is discussed in Section 3.2.2.1 which is devoted to resistivity measurements, defects, and carbon/oxygen evaluation, and Section 3.2.2.2 in which the analysis of ingots for the intentionally added impurities is discussed.

3.2.2.1 Resistivity, Defect Density, and Carbon/Oxygen Analysis

With the exception of carbon and oxygen determination for ingots W048 through W053, this phase of the analytical effort is complete; the results are summarized in Table 3. Resistivity values are within the acceptable range for all ingots although a large longitudinal variation was observed in ingot W043 which was doped with iron and titanium.

Table 2. Ingot Status

<u>Ingot Identification</u>	<u>Status</u>	<u>Ingot Identification</u>	<u>Status</u>
W-001-00-000	G,S,A	W-028-Al-001	G,S,A
W-002-00-000	G,S,A	W-029-Cr-003	G,S,A
W-003-00-000	G,S,A	W-030-Cr/Cu-001	G,S,A
W-004-Cr-001	G,S,A	W-031-Cr/Mn-001	G,S,A
W-005-Mn-001	G,S,A	W-032-Mg-003	G,S,A
W-006-Ni-001	G,S,A	W-033-Ti-002	G,S,A
W-007-Cu-001	G,S,A	W-034-00-000	G,S,A
W-008-Ti-001	G,S,A	W-035-V-002	G,S,A
W-009-V-001	G,S,A	W-036-Zr-002	G,S,A
W-010-Ni-002	G,S,A	W-037-Zr/Ti-001	G,S,A
W-011-Zr-001	G,S,A	W-038-Al-002	G,S,A
W-012-Cr-002	G,S,A	W-039-Ni-003	G,S,A
W-013-Mn-002	G,S,A	W-040-Cr/Ni-001	G,S,A
W-014-00-000	G,S,A	W-041-Ni/Cr/Cu-001	G,S,A
W-015-Zn-001	G,S,A	W-042-Ti-003	G,S,A
W-016-Fe-001	G,S,A	W-043-Fe/Ti-001	G,S,A
W-017-Cu-002	G,S,A	W-044-Fe-003	G,S,A
W-018-Fe-002	G,S,A	W-045-Cr/Fe/Ti-001	G,S
W-019-Cu-003	G,S,A	W-046-Fe/V-001	G,S
W-020-00-000	G,S	W-047-Cu/Ni/Zr-001	G,S
W-021-Mg-001	G,S,A,P	W-048-Ti-004	G,S
W-022-00-000	G,S	W-049-V-003	G,S
W-023-00-000	G,S	W-050-Ti/V-001	G,S
W-024-Mg-002	G,S,A	W-051-Cu/Ti-001	G,S
W-025-00-000	G,S	W-052-Ni-004	G,S
W-026-Mn-003	G,S,A		
W-027-Mn/Cu-001	G,S,A		

Table 3. Ingot Analysis (Resistivity, Dislocation Density, and Carbon/Oxygen Concentration)

<u>Ingot Identification</u>	<u>Resistivity Seed/ Resistivity Tang (ohm-cm)</u>	<u>Etch Pit Density of Seed End (Etch Pits/cm²)</u>	<u>Carbon Conc./ Oxygen Conc. (10¹⁶ atoms/cm³)</u>
W-001-00-000	2.8/3.2	0	7.5/94
W-002-00-000	3.0/4.0	0	8.3/57
W-003-00-000	3.1/3.6	0	12.5/94
W-004-Cr-001	4.6/4.3	500	6/88
W-005-Mn-001	3.6/3.1	600	6/126
W-006-Ni-001	4.1/3.5	300	7.3/96
W-007-Cu-001	5.2/3.7	0	7.5/49
W-008-Ti-001	4.2/3.1	1800	14/150
W-009-V-001	4.1/3.4	0	18/100
W-010-Ni-002	3.9/3.4	200	12.5/140
W-011-Zr-001	4.4/3.6	400	8/87
W-012-Cr-002	4.1/3.9	400	5/170
W-013-Mn-002	4.3/3.2	200	5/160
W-014-00-000	4.3/3.2	1000	5/160
W-015-Zn-001	3.9/3.6	500	9/100
W-016-Fe-001	4.6/5.2	0	5.5/95
W-017-Cu-002	3.8/3.6	2200	5.5/78
W-018-Fe-002	5.9/5.0	500	7/80
W-019-Cu-003	3.8/3.5	200	4.2/96
W-020-00-000	4.0/2.9	0	3.2/160
W-021-Mg-001	3.8/3.4	500	8/110
W-022-00-000	4.1/3.2	500	7/140
W-023-00-000	0.15/0.15	2500	N/A
W-024-Mg-002	3.8/3.6	3750	8.8/46
W-025-00-000	5.1/4.7	2000	9.6/96
W-026-Mn-003	4.5/3.9	1000	9.4/140
W-027-Mn/Cu-001	8.4/6.3	1250	<2.5/110
W-028-Al-001	2.9/2.4	750	17/80
W-029-Cr-003	5.2/4.6	0	2.5/150
W-030-Cr/Cu-001	7.3/6.9	500	3.8/140
W-031-Cr/Mn-001	8.8/4.7	1250	11/110

Table 3. Ingot Analysis (Resistivity, Dislocation Density,
and Carbon/Oxygen Concentration) (cont.)

<u>Ingot Identification</u>	<u>Resistivity Seed/ Resistivity Tang (ohm-cm)</u>	<u>Etch Pit Density of Seed End (Etch Pits/cm²)</u>	<u>Carbon Conc./ Oxygen Conc. (10¹⁶ atoms/cm³)</u>
W-032-Mg-003	4.5/4.1	0	9/90
W-033-Ti-002	4.5/4.2	0	10/100
W-034-00-000	4.4/4.2	0	2.9/130
W-035-V-002	4.4/3.9	1500	5.1/135
W-036-Zr-002	4.4/4.1	500	5.5/137
W-037-Zr/Ti-001	5.1/4.5	500	8.3/190
W-038-Al-002	2.2/1.55	0	63/143
W-039-Ni-003	5.2/4.3	Multi Xtal	2/170
W-040-Cr/Ni-001	5.3/4.0	1000	3/150
W-041-Ni/Cr/Cu-001	5.1/4.7	2000	9/115
W-042-Ti-003	3.75/3.7	1500	13/150
W-043-Fe/Ti-001	5.7/2.8	750	7.3/159
W-044-Fe-003	3.8/3.8	0	2.4/135
W-045-Cr/Fe/Ti-001	5.3/4.3	500	10/118
W-046-Fe/V-001	5.7/5.3	500	7.7/166
W-047-Cu/Ni/Zr-001	4.8/4.4	1500	2.3/140
W-048-Ti-004	4.5/3.75	500	
W-049-V-003	4.4/3.9	0	
W-050-Ti/V-001	4.6/4.4	500	
W-051-Cu/Ti-001	5.0/4.4	500	
W-052-Ni-004	4.2/3.8	4000	

As noted, great difficulty was encountered in obtaining single crystal growth from melts heavily doped with one or more impurity elements. In the case of ingots W039 and W052, both melts doped to a concentration of 0.75 percent nickel, either multi-crystalline growth occurred or a high density of structural defects and/or precipitates were observed. For example, W039 was actually a $\langle 111 \rangle$ - $\langle 321 \rangle$ bicrystal. Structure tended to degrade rapidly as crystal growth proceeded in these cases. Limiting the initial melt impurity concentration to less than 0.5 atomic percent seems to have alleviated these problems.

Carbon and oxygen concentrations found in all ingots were nominal with the exception of W038 and are representative of undoped ingots prepared in the same equipment. Neither impurity is present in sufficient concentration to adversely affect crystal growth. Whether or not these impurities form complexes with other impurities and what impact higher or lower concentrations would have on solar cell performance has not been investigated.

3.2.2.2 Metal Impurity Analysis

The primary objective of the ingot analysis effort is to establish the concentration of the intentionally introduced metal impurities. The spark source mass spectrometer has been the primary tool employed for ingot analysis supplemented as required with neutron activation analysis. The performance characteristics of the spark source mass spectrometer used in this program are compiled in Table 4 for those dopants for which sufficient data has been collected. In the table column two indicates the limit of detection of the impurity element while the third column contains the mean value (ppba) obtained from the analysis of several samples doped to a particular impurity concentration. The standard deviation (1σ) of the measurement appears in the fourth column. In the third column the quantity in parentheses is the number of samples analyzed. Relatively good results have been obtained for all impurities except iron and zirconium. The relatively low concentration of the latter impurities which can be accommodated in

Table 4. Performance Characteristics Achieved with
Spark Source Mass Spectrometer

<u>Impurity Element</u>	<u>Limit of Detection (ppba)</u>	<u>Mean (ppba)</u>	<u>Standard Deviation (ppba)</u>
Cr	3	26(13)	10
Cu	3	32(9)	19
Fe	30	ND	-
Mn	3	29(6)	16
Ni	30	64(10)	19
Ti	3	8.5(6)	1.6
V	3	8.8(5)	6.2
Zr	10	12.3(6)	5.4

Table 5. Ingot Analysis (Intentionally Added Impurity)

Ingot Identification	Target Conc. (10^{15} atoms/cm ³)	Calc. Conc. (10^{15} atoms/cm ³)	Mass Spec Conc. (10^{15} atoms/cm ³)	NAA Conc. (10^{15} atoms/cm ³)
W-001-00-000	-	-	-	-
W-002-00-000	-	-	-	-
W-003-00-000	-	-	-	-
W-004-Cr-001	1	0.82	0.95	<4 ¹
W-005-Mn-001	1	0.82	1.35	0.6
W-006-Ni-001	1	0.17 ²	<0.5	NA
W-007-Cu-001	1	1.18	1.0	1.65
W-008-Ti-001	1	0.82	0.36	NA
W-009-V-001	1	1.19	0.31	NA
W-010-Ni-002	1	0.56	4.0	NA
W-011-Zr-001	1	2.67 ³	0.45	Incomp
W-012-Cr-002	0.2	0.18	<0.5	NA
W-013-Mn-002	0.2	0.15	<0.5	NA
W-014-00-000	-	-	ND	-
W-015-Zn-001	1	<0.0006 ⁴	<0.5	NA
W-016-Fe-001	1	0.75	<3.0	NA
W-017-Cu-002	10	7	40	25
W-018-Fe-002	2	1.6	<3	NA
W-019-Cu-003	0.2	0.53	<0.5	-
W-020-00-000	-	-	-	-
W-021-Mg-001	1.0	0.59 ⁵	<0.5	NA
W-022-00-000	-	-	-	-
W-023-00-000	-	-	-	-
W-024-Mg-002	10	7.3	<0.5 ⁶	NA
W-025-00-000	-	-	-	-
W-026-Mn-003	0.01	0.0089	<0.5	NA
W-027-Mn/Cu-001	1/1	0.73/0.64	1/1.4	1.1/2.2
W-028-Al-001	1	-	26	NA
W-029-Cr-003	0.01	0.0083	<5 x 10	NA
W-030-Cr/Cu-001	1/1	0.82/0.75	1/1.4	0.5/2.5

Table 5. Ingot Analysis (Intentionally Added Impurity) (cont.)

Ingot Identification	Target Conc. (10^{15} atoms/cm ³)	Calc. Conc. (10^{15} atoms/cm ³)	Mass Spec Conc. (10^{15} atoms/cm ³)	NAA Conc. (10^{15} atoms/cm ³)
W-031-Cr/Mn-001	1/1	0.85/0.82	1/2.5	-
W-032-Mg-003	1	0.24	0.3	NA
W-033-Ti-002	0.01	0.011	<0.3	NA
W-034-00-000	-	-	-	-
W-035-V-002	0.01	0.013	<0.2	NA
W-036-Zr-002	2	1.74	<0.45	NA
W-037-Zr/Ti-001	1/1	0.95/0.97	<0.45/0.35	NA
W-038-Al-002	3.4	1.84	34	NA
W-039-Ni-003	8	6.6	3.6	NA
W-040-Ni/Cr/Cu-001	0.8	0.73	1	NA
W-041-Ni/Cr/Cu-001	3/0.8	3/0.8	3.5/1.4	NA
W-042-Ti-003	0.07	0.038	NA	NA
W-043-Fe/Ti-001	0.8/0.07	0.65/0.06	ND	NA
W-044-Fe-003	0.02	0.0167	NA	NA
W-045-Cr/Fe/Ti-001	0.65/0.5/ 0.06	0.47/0.37/ 0.048	Incomp	NA
W-046-Fe/V-001	0.65/0.06	0.37/0.056	NA	NA
W-047-Cu/Ni/Zr-001	1/1/ 0.3	1.1/0.47 0.35	Incomp	NA
W-048-Ti-004	0.00035	0.00067	NA	NA
W-049-V-003	0.00030	0.00078	NA	NA
W-050-Ti/V-001	0.00035/ 0.0003	0.0035/ 0.0041	NA	NA
W-051-Cu/Ti-001	1/0.35	0.85/0.2	Incomp	NA
W-052-Ni-004	10	5.4	Incomp	NA

1. NAA indicated impurity concentration of less than 4×10^{15} atoms/cm³ which represents the limit of detection.
2. Nickel powder used as dopant. Dopant partially lost during furnace evacuation. Figure of 0.17×10^{15} atoms/cm² indicative of actual impurity concentration.
3. The high Zr concentration is obviously in error since it greatly exceeds the amount added to the melt.
4. Zinc loss from the melt by evaporation was essentially complete.
5. Modest loss of magnesium occurred due to evaporation.
6. No Mg detected indicating much smaller segregation coefficient than suspected. Best estimate is a concentration of 1×10^{13} atoms/cm³ for W-021 and 1×10^{14} atoms/cm³ for W-024.

in silicon without polycrystalline growth complicates the analysis. (Neutron activation analysis is now being used to obtain measurements for these elements.) Since samples have been selected from more than one ingot (doped to the same concentration and grown in the same manner) the deviation may be partially due to the growth process as well as sample processing and the actual measurement. Insufficient data has been collected for the impurities aluminum, magnesium, and zinc to permit a meaningful analysis.

The overall results support use of the spark source mass spectrometer as a primary analytical tool in ingot analysis.

The analytical results for all ingots produced in the program are summarized in Table 5. Calculated impurity concentration based on melt analysis is in good agreement with targeted values for all ingots except W048, W049, and W050. The differences for these ingots range from a factor of two to an order-of-magnitude for ingot W050. In these very lightly doped melts, the concentration of impurities is approaching the detection limit of the atomic absorption measurement process used for melt analysis. In future work, more ingot will be grown to further concentrate the impurities in the melt for analysis purposes. For the three ingots noted, the actual concentration is believed to be closer to the targeted value than the concentration calculated from crucible remains analysis.

Mass spectrographic analysis is not applicable to many ingots produced this quarter due to the relatively low impurity concentrations being investigated. It is being used to screen these ingots for possible contamination and in the development of data to establish segregation coefficients and thereby improve our predicative capabilities for all impurities under investigation.

As in the past we have provided a compilation of the best estimates of impurity concentration for all ingots produced on this program, viz., Table 6.

Table 6. Best Estimate of Impurity Concentration

<u>Ingot Identification</u>	<u>Best Estimate of Impurity Conc. (10¹⁵ atoms/cm)</u>	<u>Ingot Identification</u>	<u>Best Estimate of Impurity Conc. (10¹⁵ atoms/cm)</u>
W-001-00-000	--	W-028-Al-001	26
W-002-00-000	--	W-029-Cr-003	0.01
W-003-00-000	--	W-030-Cr/Cu-001	1.0/1.0
W-004-Cr-001	0.95	W-031-Cr/Mn-001	1.0/1.0
W-005-Mn-001	1.0	W-032-Mg-003	0.3
W-006-Ni-001	0.5	W-033-Ti-002	0.0035
W-007-Cu-001	1.0	W-034-00-000	--
W-008-Ti-001	0.36	W-035-V-002	0.003
W-009-V-001	0.31	W-036-Zr-002	<0.45
W-010-Ni-002	4.0	W-037-Zr/Ti-001	<0.25/0.36
W-011-Zr-001	<0.25	W-038-Al-002	34
W-012-Cr-002	0.2	W-039-Ni-003	8
W-013-Mn-002	0.2	W-040-Cr/Ni-001	0.8/3.5
W-014-00-000	--	W-041-Ni/Cr/Cu-001	3/0.8/1.0
W-015-Zn-001	.0001-.1	W-042-Ti-003	0.07
W-016-Fe-001	<1.5	W-043-Fe/Ti-001	<1/0.07
W-017-Cu-002	10	W-044-Fe-002	0.02
W-018-Fe-002	<3	W-045-Cr/Fe/Ti-001	0.65/0.5/0.06
W-019-Cu-003	0.1-0.5	W-046-Fe/V-001	0.5/0.06
W-020-00-000	10	W-047-Cu/Ni/Zr-001	1/0.75/0.3
W-021-Mg-001	0.003	W-048-Ti-004	0.00035
W-022-00-000	--	W-049-V-003	0.0003
W-023-00-000	--	W-050-Ti/V-001	0.00035/0.0003
W-024-Mg-002	0.03	W-051-Cu/Ti-001	1/0.35
W-025-00-000	--	W-052-Ni-004	7.5
W-026-Mn-003	0.01		--
W-027-Mn/Cu-001	1.0/1.0		

3.3 Silicon Dendritic Web Preparation and Evaluation

3.3.1 Preparation

To evaluate the effects of rapid growth rate on the incorporation of impurities in silicon and subsequent solar cell performance, we have undertaken the examination of metal-doped silicon dendritic web crystals. Dendritic web growth produces silicon in a ribbon form at rates comparable to those proposed for other silicon sheet growth techniques.

The web crystals for this study were grown in the modified Czochralski furnace depicted in Fig. 2. The melts, about sixty grams in weight, were held in quartz crucibles heated by means of an inductively coupled molybdenum susceptor, Fig. 3. Melt doping was achieved with the same materials used in the Czochralski work and listed in Table 1. During a run the furnace was purged by a constant argon flow which entered at the bottom of the quartz-encased chamber and exited through a duct at the top.

Since our intent was to examine impurity effects, we made no effort to produce wide sheets. Rather we fixed the growth conditions to give material of fairly reproducible characteristics. Web widths were typically one cm (including dendrites) and often as large as 1.3 cm, this dimension being limited by the size of the melt pool. The webs ranged up to 74 cm in length, the limit of the travel mechanism. Usually several strips were grown during a given run as indicated by the examples in Fig. 4.

The melt temperature could be controlled to 0.1°C via a light pipe detector in the susceptor wall and the feedback controller indicated in Fig. 2. The actual system temperature was monitored with a Pt/Rh thermocouple at a position on the susceptor axis within one mm of the quartz crucible bottom. During a run, a thin clean dendrite seed⁴ is equilibrated with the liquid silicon so that the dendrite neither grows nor melts. The liquid is then supercooled (about 4°C in our experiments). Growth from the seed spreads laterally across the melt to form a "button"

Fig. 2. Modified Czocharalski puller and control unit used for web growth.

Fig. 3. Left to right: Susceptor heat shields, susceptor containing frozen silicon melt and quartz crucible used to grow web.

(a)

(b)

(c)

(d)

Fig. 4. Representative web samples grown in specific runs: (a) Run 28 (Cr/Mn-doped); (b) Run 29 (Ni/Mn-doped); (c) Run 30 (Al-doped); (d) Run 31 (Zr/Ti-doped).

as the temperature falls. Growth is begun by withdrawing the seed upward so that dendrites propagate into the melt from each end of the button as illustrated in Fig. 5. A thin silicon sheet, or web, crystallizes between the dendrites. For our experiments the growth rate was fixed at 1.3 cm/min, about an order of magnitude faster than the rates we employed to grow the Czochralski crystals.

To compare the web and Czochralski material it is desirable to obtain similar metal concentrations in the two types of crystals. While the segregation coefficients for metals in Czochralski crystals are well known no such information on web growth exists. Calculations by Swartz et al.⁵ suggest that when growth rates approach 2.5 cm/min effective segregation coefficients as large as 10^{-2} may be encountered for solutes with equilibrium segregation ratios of 10^{-5} in silicon. To achieve metal concentrations in the solid of 10^{15} atoms/cm³ this implies melt concentrations in the 10^{17} to 10^{18} atoms/cm³ range. We chose the latter value to assure detectable impurity levels in our webs. For multiply-doped webs the sum of the impurity contents was fixed at about 10^{18} atoms/cm³. The web runs, intentionally added impurity(ies) and a brief description of the web characteristics are compiled in Table 7. Each web also contains about 4×10^{15} atoms/cm³ boron.

3.3.2 Web Evaluation

3.3.2.1 Metallographic Characteristics

The crystallographic features of silicon web crystals have been described in detail in a number of previous papers, e.g., Refs. 6-9. Undoped webs as well as webs doped with electrically active impurities such as boron exhibit complicated arrays of dislocations formed by slip and by Lomer-Cottrell reactions between slip dislocations.⁶⁻⁸ The dislocations arise from two primary sources: (1) the freezing of liquid droplets trapped during growth along ridges in the dendrites or (2) by dendrite side branches which form below the liquid surface and eventually contact the growing web.⁶ Both of these situations are promoted by large undercoolings which favor dendrite thickening and branching.

Dwg. 6256A82

Fig. 5. Depiction of growing silicon dendritic web illustrating web nomenclature.

Table 7. Metal-Doped Silicon Dendritic Webs
 Growth Rate 1.3 cm/min, $\Delta T \sim 4^\circ\text{C}$,
 Boron Concentration (TGT

<u>Web Run Number</u>	<u>Dopant</u>	<u>Target Melt Conc.</u>	<u>Comment</u>
DW 017	Cr		Occasional breakdown and thirds
DW 018	Cr		Cellular structure, thirds
DW 019	Cu		Smooth, flat web
DW 020	Mn		Short web
DW 021	Ni		Smooth, flat web
DW 022	Ti		Tended to breakdown, thirds
DW 023	V		Breakdown, thirds
DW 024	Fe		Occasional breakdown, thirds
DW 025	Cr/Cu		Smooth, flat web
DW 026	Mn/Cu		Smooth, flat web
DW 027	Zr		Occasional breakdown, thirds
DW 028	Cr/Mn		Some flat areas, thirds
DW 029	Ni/Mn		Smooth, flat web
DW 030	Al		Smooth, flat web
DW 031	Zr/Ti		Breakdown, thirds
DW 032	Cu/Ti		Occasional breakdown

The generation of dislocations at pockets of trapped then frozen liquid is clearly visible in the (220) topograph taken from one of our boron-doped webs, Fig. 6a. This structure can be minimized by keeping the dendrites thinner, e.g., Fig. 6b. When dislocations spread from the strain centers (bright), they migrate into the web to form occasional shallow tilt boundaries normal to the web surface. A group of boundaries formed near the web center is shown in Fig. 7a, a Sirtl etched cross-section of the web which also illustrates the twin plane structure (horizontal line) inherent to web growth. Assuming the boundaries are pure tilt, we calculate misorientation of less than 0.01° from the dislocation spacing. The heavy concentration of dislocations generated by the frozen liquid droplets in the dendrites is apparent in Fig. 7b, a section again normal to the growth direction and twin planes. Typical dislocation web densities lie in the range $10^4/\text{cm}^2$ while reaching much higher values in the dendrites. Solar cells fabricated on past web samples¹⁰ show efficiencies essentially the same as Czochralski material so the low angle boundaries are apparently not particularly harmful.

No major differences between the boron-doped web we grew and that reported previously have been discovered. However, with the addition of metal dopants to the web, this picture changes as can be ascertained from the qualitative descriptions in Table 7. In that table we have used the term "smooth, flat" web to indicate material comparable to the baseline webs. "Breakdown" is used here to describe the formations of irregular ridged patches along the web surface, e.g., the Ti-doped web shown in Fig. 8. The figure also indicates a feature related to the breakdown, the formation of an extra dendrite or "third" in close proximity to the ridged structure.

We note from Table 7 that "breakdown" is most prevalent in webs grown with V, Ti, Zr, Cr, Mn, and Fe at 10^{18} atoms/cc melt concentration, while Cu, Ni or Al doped webs rarely showed such structure. The former impurities are those with relatively small segregation coefficients and solid solubilities, suggesting that the surface structure we see may represent the precursor to true breakdown of the solid-liquid interface.

(a)

(b)

Fig. 6. (220) X-ray diffraction topographs of boron-doped silicon dendritic web crystals. Ag k_{α} radiation, $\sim 10\times$. (a) Bright spots are strained regions formed when liquid freezes in the dendrites which bound the web. Dislocations generated at these regions often wander toward the center of the web where they form low angle boundaries. (b) Web grown with thin dendrites which are nearly free of strained regions.

(a)

(b)

Fig. 7. Syton polished, sirtl-etched sections of silicon web 017-1 cut normal to the $\langle 211 \rangle$ growth direction. Horizontal line is etched twin plane region. (a) Low angle boundaries near web center; rest of web is essentially free of dislocations ($\sim 200X$). (b) High dislocation density at the edge of a bounding dendrite where trapped liquid was frozen-in ($\sim 100X$).

Fig. 8. Macrograph of web sample DW022-1 illustrating the irregular patches of surface structure (arrow) we call breakdown. Note the onset of a third dendrite near one of these patches ($\sim 3X$).

A cellular structure much like that observed in doped Ge crystals¹¹ was, in fact, detected in Sample DW 018 grown from a melt containing $\sim 10^{19}$ atoms/cm³ Cr.

Figures 9 and 10 depict the structures observed in topographs of a Cu-doped sample free from surface structure and the Ti-doped sample of Fig. 8. The structure in the Cu-doped material is reminiscent of the baseline web but precipitation along dislocation lines and near the dendrites is evident. In the Ti-doped material strain fields surrounding several large inclusions can be discerned.

3.3.2.2 Chemical Analysis

The first analyses of silicon web samples and the crucible remains from the web preparation have just been completed. Analysis of five crucible remains was conducted for the specific impurity added while a survey analysis of impurities of interest was carried out for two of these samples to determine if any gross contamination existed. These results are summarized in Tables 8 and 9. All values shown are in wt. percent. Based on target melt concentrations of 0.2 percent for DW 018 and approximately 0.02 percent for DW 019 through DW 022, agreement between targeted value and crucible remains analysis is adequate. No significant contamination is apparent although a trace of iron was observed in sample DW 019. Since the quartz crucible must be broken away from the crucible remains, it is possible that the iron was introduced in sample processing.

Mass spectrographic analysis of web samples was conducted on samples cut from the central web region after removal of the dendrites. The results for the first three samples analyzed are as follows.

<u>Web Identification</u>	<u>Impurity/Concentration (atoms/cm³)</u>
DW 017	Cr/ 1.2×10^{16}
DW 019	Cu/ 8×10^{17}
DW 021	Ni/ 3.5×10^{15}

Fig. 9. (111) X-ray topograph of Cu-doped web DW018-1 Mo k_{α} radiation, $\sim 10\times$. Besides the dislocations and low angle boundaries seen in other webs, the singular point images and bright spots aligned along dislocations (arrow) indicate that precipitation occurs in the fillet region of the web. The high contrast in the dendrites suggests that Cu may also segregate there.

Fig. 10. (111) X-ray topograph of Ti-doped web DW022-1, Mo k_{α} radiation, $\sim 10\times$. The large bright spots indicate the position of several inclusions and strings of inclusions in the web. These were also detected by infrared microscopy.

Table 8. Survey Analysis of Crucible Remains
for Web Crystal Growth

<u>Elements in Determined %</u>	<u>Sample No. DW-019</u>	<u>Sample No. DW-021</u>
Al	<0.001	<0.001
Cr	<0.001	<0.001
Cu	0.024	<0.0005
Fe	0.003	<0.001
Mn	<0.001	<0.001
Mo	<0.001	<0.001
Ni	<0.001	0.023
Ti	<0.001	<0.001
V	<0.001	<0.001
Zr	<0.001	<0.001

Table 9. Analysis of Crucible Remains for
Specific Dopant for Web Samples

<u>Elements in Determined %</u>	<u>Sample No. DW-018</u>	<u>Sample No. DW-019</u>	<u>Sample No. DW-020</u>	<u>Sample No. DW-021</u>	<u>Sample No. DW-022</u>
Cr	0.20	----	----	----	----
Cu	----	0.024	----	----	----
Mn	----	----	0.015	----	----
Ni	----	----	----	0.023	----
Ti	----	----	----	----	0.031

The concentration of chromium and copper are significantly higher, at least an order-of-magnitude, than concentrations found in ingots prepared by the Czochralski process. The concentration found in the nickel doped sample is approximately the same as that found in the most heavily doped samples prepared by the Czochralski process. Trace amounts of chromium and copper were detected in sample DW 021 while trace amounts of vanadium, chromium and manganese were detected in sample DW 019. Due to the limited amount of material available all of these results must be considered as semi-quantitative at best.

The higher concentrations found in web grown from relatively lightly doped melts (as compared to those used in the Czochralski ingot preparation) indicates definite differences in the effective segregation coefficients for the two processes. Using the measured melt concentrations for DW 018 and 021 and assuming that the melt concentration for DW 017 is close to the target value, we can estimate very approximately the effective k values for Cu, Ni and Cr; these are indicated below.

<u>Impurity</u>	<u>k_{czo}</u>	<u>k_{web}</u>	<u>k_{web}/k_{czo}</u>
Cr	1 x 10 ⁻⁵	~10 ⁻³	~10 ²
Ni	3 x 10 ⁻⁵	~10 ⁻³	~.3 x 10 ²
Cu	4 x 10 ⁻⁴	~8 x 10 ⁻²	~2 x 10 ²

Clearly, segregation to the crystal is significantly increased during web growth compared to Czochralski pulling.

3.4 Wafer Evaluation

3.4.1 Recombination Lifetimes Measured by Photoconductive Decay (PCD)

3.4.1.1 Lifetime Measurements on Czochralski Wafers

The recombination lifetimes measured by the photoconductive decay method for all ingots up to W046 are listed in Table 10. In addition to the new data for ingots W035 to W046, the table includes

Table 10. Bulk Lifetime, τ_r (PCD Measurements)

Lot No.	Impurity Type	Concentration (cm^{-3}) (Note 1)	Lifetime (As-Grown)		Lifetime (Diffused)	
			$\tau(\mu\text{sec})$	σ (Note 2)	$\tau(\mu\text{sec})$	σ (Note 2)
W001	Baseline	N/A	7.1	1.1(5)	6.9	0.5(3)
W002	Baseline	N/A	6.3	0.6(2)	8.6	1.6(2)
W003	Baseline	N/A	11.6	2.3(2)	8.4	0.7(2)
W004	CR001	0.92×10^{15}	0.35	0.2(3)	1.1	0.2(4)
W005	MN001	1.35×10^{15}	1.8(3)	--	0.3	0.0(5)
W006	NI001	1.7×10^{14}	11.3	2.7(2)	7.7	0.2(2)
W007	CU001	1.0×10^{15}	6.9	0.9(4)	6.6	3.2(3)
W008	TI001	3.6×10^{14}	2.0	0.5(3)	0.6	0.1(4)
W009	V001	3.1×10^{14}	0.4	0.1(3)	<2.2(3)	1.8(5)
W010	NI002	4×10^{15}	6.8	2.6(3)	3.4	3.3(4)
W011	ZR001	4.5×10^{14}	2.6	0.2(2)	2.4	0.7(4)
W012	CR002	1.8×10^{14} *	<0.4	0.1(2)	4.9	1.0(5)
W013	MN002	1.5×10^{14} *	1.2(3)	1.0(3)	10.5(3)	4.7(5)
W014	Audit	N/A	7.5	0.4(2)	8.3	0.1(2)
W015	ZN001	1×10^{15} *	7.2	0.6(2)	5.3	0.4(4)
W016	FE001	1×10^{15} *	0.5	0.0(2)	3.8	1.5(4)
W017	CU002	4×10^{16}	8.8	0.1(2)	7.1	0.7(2)
W018	FE002	2×10^{15} *	8.1	5.5(2)	0.6	0.3(4)
W019	CU003	2×10^{14} *	4.3	3.3(2)	5.7	0.5(2)
W020	Audit	N/A	7.0	1.7(2)	7.3	1.2(2)
W021	MG001	1×10^{15} *	8.2	0.8(2)	7.7	0.1(2)
W022	Audit	N/A	7.8	1.0(2)	9.1	0.2(2)
W023	Audit	N/A	Note (4)		Note (4)	
W024	MG002	1×10^{13}	7.5	0.9(2)	10.2	0.9(2)
W025	Audit	N/A	7.6	0.0(2)	12.7	1.0(2)
W026	MG003	1×10^{13} *	5.1	0.2(2)	9.3	0.0(2)
W027	MN/CU001	$1/1.4 \times 10^{15}$	22.3(3)	2.3(2)	0.5	0.2(3)
W028	AL001	1×10^{15} *	2.9	0.2(2)	1.9	0.0(2)
W029	CR003	8.3×10^{12}	1.1	0.6(2)	6.2	0.4(4)

Table 10 (con't)

Lot No.	Impurity Type	Concentration (cm ⁻³) (Note 1)	Lifetime (As-Grown)		Lifetime (Diffused)	
			τ (μ sec)	σ (Note 2)	τ (μ sec)	σ (Note 2)
W030	CR/CU001	$1/1.4 \times 10^{15}$	<0.3	0.0(2)	0.4	0.1(2)
W031	CR/MN001	$1/2.5 \times 10^{15}$	Note (5)	--	<0.3	0.0(2)
W032	MG003	3×10^{14}	7.2	1.1(2)	7.1	1.1(2)
W033	TI002	$1 \times 10^{13*}$	3.1	0.0(2)	2.9	0.1(2)
W034	Audit	N/A	21.8	4.2(2)	1.7	0.1(2)
W035	V002	$1 \times 10^{13*}$	1.2	0.0	1.5	0.2(2)
W036	ZR002	$\leq 4.5 \times 10^{14}$	1.2	0.0(2)	1.0	0.0(2)
W037	ZR/TI001	$\leq 4.5/\leq 3.5 \times 10^{14}$	0.5	0.1(2)	0.4	0.1(2)
W038	AL002	4×10^{16}	0.7	0.2(2)	<0.1	0.0(2)
W039	NI003	6.6×10^{15}	2.0	0.1(2)	6.5	1.5(2)
W040	CR/NI001	$1/3.5 \times 10^{15}$	<0.2	0.0(2)	1.4	0.4(2)
W041	CR/CU/NI001	$2.5/3/18 \times 10^{15}$	<0.2	0.0(2)	0.4	0.3(2)
W042	TI003	3.9×10^{13}	0.8	0.1(2)	0.7	0.1(2)
W043	FE/TI001	$6.7/0.7 \times 10^{14}$	0.9	0.0(2)	0.5	0.0(2)
W044	FE003	1.7×10^{13}	1.3	0.2(2)	6.6	0.1(2)
W045	CR/FE/TI001	$3.6/5.7/0.6 \times 10^{14}$	0.1	0.0(2)	0.1	0.0(2)
W046	FE/V001	$4.7/0.6 \times 10^{14}$	<0.1	0.0(2)	<0.1	0.0(2)
W047						
W048	TI004	7×10^{11}				
W049	V003	7.8×10^{11}				

Note 1. Impurity concentration measured by Mass Spec or crucible remains unless marked by * to indicate a target value. For best estimate of impurity concentration, see Table .

Note 2. Sample size shown in parentheses.

Note 3. Lifetime measurements subject to large errors due to extreme shallow trap density.

Note 4. Lifetime measurements not practical due to low resistivity.

Note 5. Lifetime measurements not possible due to very low lifetime (Δv too small).

minor corrections to earlier data on W035 resulting when additional samples were processed and measured.

3.4.1.2 Correlation of Recombination Lifetime and Cell Short Circuit Current

The characterization of impurity effects on solar cells requires establishing a correlation between cell performance and the concentration of the contaminant impurities. In addition to fabricating cells and measuring cell parameters, it is desirable to use minority carrier lifetime as an indicator of cell performance. Lifetime can be observed as a function of process parameters and under proper circumstances correlates fairly well with cell performance. A plot of the measured values of τ_r and I_{sc} is shown in Fig. 11 for data from up through ingot W041. A curve was drawn through the data points using a linear regression (least squares) curve fitting technique with an assumed form, $I_{sc} = I_o \tau^n$.

While considerable scatter in the data is evident, the curve clearly establishes a relationship between I_{sc} and τ . The origin of deviations for two of the points is an artifact of the measurement as indicated by the arrows. The point at $\tau = 2.2 \mu\text{sec}$ is for vanadium at 3.1×10^{14} was characterized by severe shallow trapping. The incandescent trap filling light source was marginally intense at maximum output and the traps were often only partially filled. The measurement data ranges from 0.32 to 5.0 μsec . The second arrowed data point at $\tau = 0.3 \mu\text{sec}$ is also shifted from the curve for the same reason. Here the sample has a manganese concentration of 2.5×10^{15} and also exhibits severe shallow trapping. The two data points at $I_{sc} = 7.7 \text{ mA}$ show the largest departure from the overall trend of the data, but no definite reasons can be given at present for the behavior. We note that both of these data points are from wafers doped with titanium at high concentrations; it is possible that this element also exhibits shallow trapping. A second, although unlikely, possibility is that titanium severely decreases the mobility of the minority carriers. The diffusivity of the carriers, related to the

Fig. 11. Correlation between bulk recombination lifetime, τ_r , and short circuit output current, I_{SC} , of metal impurity-doped solar cells.

mobility by Einstein's relationship, $D_n = (kT/q)\mu_n$, is used to correct for the effects of surface recombination on τ_r . A diffusivity of $32.9 \text{ cm}^2/\text{sec}$ was assumed for all ingots regardless of impurity concentration, and a reduction of this value due to the high titanium concentration would produce the observed error.

The value of the exponent n obtained from the curve in Fig. 11 is 0.145. A slope closer to $1/2$ was initially expected since the diffusion length is proportional to $\tau^{1/2}$. A very simple model assuming a uniform electron-hole pair generation rate throughout the sample would therefore yield a slope of $1/2$. A more refined model was developed which indicates that the form $I_{sc} = I_o \tau^{1/2}$ is inappropriate and that the observed slope is in agreement with the more refined model. The derivation of the newer model and a comparison of its predictions with experimental data is included in the next section.

3.4.1.3 Modeling Solar Cell Short Circuit Current, I_{sc}

To reveal the relationship between the solar cell short circuit current, I_{sc} , and the bulk recombination lifetime, τ_r , we developed the theoretical model outlined below. The purpose for developing this theoretical relationship is to verify that the shape of the experimentally determined curve shown in Fig. 11 is valid. In addition, the model may be used to extend the range beyond the available experimental data.

For the model we assume that τ_r is a constant throughout the silicon wafer. The error due to this assumption is probably small since significant variations in τ_r are only expected near the heavily doped diffused phosphorus layer. A second assumption is that the electric fields present in an operating cell are negligible in determining the minority carrier distribution. Again, this assumption is generally valid except in the immediate vicinity of the p-n junction. The junction and the back side ohmic contact are assumed to be infinite sinks for minority carriers so that only electron-hole pairs generated in the upper

half of the wafer are collected by the p-n junction. The effects of surface recombination on the top surface are neglected.

The absorption coefficient, α , for an optical medium is defined as

$$dE = -\alpha E dx \quad (1)$$

where E is the irradiance (light intensity) in W/cm^2 and dx is an incremental thickness perpendicular to the path of the optical radiation. The units of the absorption coefficient are cm^{-1} , and the magnitude is a function of the wavelength. The functional variation with wavelength will be initially omitted for brevity. Equation (1), when integrated for monochromatic radiation, is simply Lambert's (more properly Bouguer's) Law.

$$E(x) = E_0 e^{-\alpha x} \quad (2)$$

where E_0 is the internal irradiance at the incident surface ($x = 0$), and x is the depth into the optical medium. Reflection at the solar cell surface is neglected in this derivation since it can be simply added later as a multiplying factor. The absorbed energy in the incremental thickness dx is

$$dE = \alpha E_0 e^{-\alpha x} dx \quad \text{W/cm}^2 \quad (3)$$

The conversion from watts/cm^2 to quanta/sec/cm^2 results in

$$dN = \frac{\alpha E_0 \lambda}{hc} e^{-\alpha x} dx \quad \text{s}^{-1} \text{cm}^{-2} \quad (4)$$

where h is Planck's constant (6.62×10^{-34} Joule-sec), c is the velocity of light, and λ is the wavelength in cm. It is further assumed that each quantum absorbed results in the generation of an electron-hole pair with an electronic charge, q . The probability that the minority carrier electron in the p base will survive the random walk to the p-n junction is

$$p = e^{-(x-x_j)/L_n} \quad (5)$$

where L_n is the diffusion length of electrons in the p-type base and is equal to $\sqrt{D_n \tau_r}$. As a practical matter, the junction depth x_j is very small compared to L_n for all but extremely low lifetime material, and the x_j term can be neglected. The external current produced by the incremental depth, dx , in the silicon is

$$dI(x) = \frac{q \alpha E_o \lambda}{hc} \left[e^{-(\alpha x + x/L_n)} \right] dx \quad \text{Amps} \quad (6)$$

The total external current for monochromatic radiation is simply Eq. (6) integrated over one-half the solar cell thickness, d .

$$I(\lambda) = \int_0^d \frac{q \alpha E_o \lambda}{hc} \left[e^{-(\alpha + 1/L_n)x} \right] dx \quad \text{Amps} \quad (7)$$

or

$$I(\lambda) = \frac{q E_o \lambda}{hc} \left(\frac{\alpha L_n}{1 + \alpha L_n} \right) \left[1 - e^{-d(\alpha + 1/L_n)} \right] \quad \text{Amps} \quad (8)$$

The total short circuit external current for a solar cell with an arbitrary spectral radiation $E_o(\lambda)$ is

$$I_{sc} = \frac{q}{hc} \int_{\lambda_1}^{\lambda_2} E_o(\lambda) \lambda \left(\frac{\alpha(\lambda) L_n}{1 + \alpha(\lambda) L_n} \right) \left[1 - e^{-d(\alpha(\lambda) + 1/L_n)} \right] d\lambda \quad (9)$$

The functional relationships $E_o(\lambda)$ and $\alpha(\lambda)$ are not simple functions and Eq. (9) is best integrated by means of a computer with digital values of E_o and α manually entered into the program.

The primary purpose for this derivation is to determine the theoretical relationship between I_{sc} and τ_r . The relationship can be shown, to a first order accuracy, by plotting Eq. (8) for monochromatic light as a function of τ . The shape of the resulting curve will depend upon the particular wavelength chosen as typical. The sun, a 6000°K source, has a Wiens Displacement Wavelength (maximum output) of 4.83×10^{-5} cm. The absorption coefficient for silicon at this wavelength

is $1.7 \times 10^4 \text{ cm}^{-1}$, and 90 percent of the radiation is absorbed within $1.35 \text{ }\mu\text{m}$. The lifetime necessary for a diffusion length of $1.35 \text{ }\mu\text{m}$ is only 5.0×10^{-10} seconds in p type material with a resistivity of $4 \text{ }\Omega\text{-cm}$ ($D_n = 36.5$). The absorption coefficient at 840 nm is 709 cm^{-1} and $32.5 \text{ }\mu\text{m}$ of silicon is necessary to absorb 90% of the radiation. Equation (8) is plotted for this more reasonable wavelength in Fig. 12. The curve experimentally observed and previously shown in Fig. 11 is also shown for direct comparison.

Reasonable agreement is noted between the experimental and theoretical curves. The shape of the theoretical curve is closely approximated by considering only the factor $(\alpha L_n / (1 + \alpha L_n))$ in Eq. (8), since the exponential term within the brackets is usually negligibly small. The critical diffusion length below which I_{sc} decreases is $150 \text{ }\mu\text{m}$. As expected, this critical value is approximately equal to one-half the wafer thickness. The recombination lifetime corresponding to the critical value of L_n is $6.16 \text{ }\mu\text{sec}$ for silicon with a resistivity of 4 ohm-cm .

3.4.2 Gettering Experiments

We performed some preliminary experiments to assess the effects of high temperature phosphorus gettering and damage gettering on the lifetime of metal-doped silicon wafers. Gettering offers a potential route for improving solar cell performance of impure silicon.

We carried out the experiments on Mn, Ti, and V-doped wafers. Damage gettering was done by lapping the back surface of the polished wafers with $22.5 \text{ }\mu\text{m}$ size particles (600 mesh). Phosphorus gettering was performed at 1200°C using POCl_3 for 20 mins followed by slow cooling (1°C/min to 600°C and then pulled out of the furnace). The phosphorus diffused n^+ -regions were removed by chemical polishing prior to cell fabrication. All cells were fabricated together in one run using control wafers from baseline or audit crystals.

The variation in solar cell parameters with processing is summarized in Table 11. The minority carrier lifetime data have been

Fig. 12. Effect of diffusion length on short circuit current of a silicon solar cell. Theoretical curve was calculated with $\alpha = 709 \text{ cm}^{-1}$, $d = 0.0127 \text{ cm}$ and $D_n = 36.5 \text{ cm}^2/\text{sec}$.

Table 11

Date: 2/27/92

GETTERING - LAPPING EFFECTS COMPARISON TABLE ON BASELINE, W005 MN, W008 TI, W009 V

Identification	V _{oc}	I _{sc}	V _p	I _p	I _o	N	FF	Eff	TAU
Baseline	.536	22.50	.4471	20.94	2.3×10^{-9}	1.341	.7764	9.36	4.875
Normal									
Gettered	.526	20.35	.4370	18.89	4.92×10^{-9}	1.309	.7711	8.26	2.405
Baseline									
% Change	-1.87	-9.56	-2.26	-9.79	43.5	1.61	-.68	-11.75	-50.67
Gettered VS Normal									
Lapped	.536	22.5	.4471	20.94	2.3×10^{-9}	1.341	.7764	9.36	5.85
Baseline									
% Change	—	—	—	—	—	—	—	—	16.67
Lapped VS Normal									
W005-MN-001	.526	18.80	.4392	17.51	1.67×10^{-9}	1.160	.7777	7.69	1.30
Normal									
Gettered	.465	10.40	.3781	9.51	1.98×10^{-8}	1.353	.7437	3.60	.910
W005-MN-001									
% Change	-11.60	-44.68	-13.91	-45.69	91.56	8.25	-4.37	-53.19	-30.0
Gettered VS Normal									
Lapped	.522	18.35	.4315	16.97	8.63×10^{-9}	1.215	.7647	7.32	1.43
W005-MN-001									
% Change	-.76	-2.39	-1.75	-3.08	80.64	7.08	-1.68	-4.81	9.09
Lapped VS Normal									
W008-Ti-001	.445	8.00	.3603	7.29	2.28×10^{-8}	1.281	.7383	2.63	.455
Normal									
Gettered	.480	11.45	.3939	10.55	9.73×10^{-9}	1.302	.7554	4.155	.520
W008-Ti-001									
% Change	7.29	30.13	8.59	30.9	-57.32	-2.38	2.26	36.70	12.5
Gettered VS Normal									
Lapped	.4450	8	.3603	7.29	2.28×10^{-8}	1.281	.7383	2.63	.390
W008-Ti-001									
% Change	—	—	—	—	—	—	—	—	-14.29
Lapped VS Normal									
W009-V-001	.466	10.70	.3868	9.93	2.09×10^{-9}	1.246	.7700	3.84	.130
Normal									
Gettered	.509	15.40	.4190	14.21	8.20×10^{-9}	1.358	.7594	5.96	.975
W009-V-001									
% Change	8.44	30.5	7.68	30.04	74.5	14.26	-1.37	35.57	86.66
Gettered VS Normal									
Lapped	4.66	10.50	.3846	9.70	4.13×10^{-9}	1.341	.7626	3.73	.390
W009-V-001									
% Change	—	-1.86	-.569	-2.31	49.39	4.53	-.961	-2.86	66.6
Lapped VS Normal									

compiled in Table 12 for ease in observing the trends. The degradation of baseline material during high temperature phosphorus gettering may result from the propagation of diffusion-induced crystallographic defects into the p-region of the wafer. Similarly, lifetime in the Mn-doped wafers also decreased after phosphorus gettering. This is contrary to our previous results of low temperature gettering. Both Ti and V doped wafers, however, improved in lifetime after phosphorus gettering. Damage gettering was apparently not effective in improving lifetime, probably because the grit used for lapping was too fine.

Apparently, different impurities react differently to the gettering treatments. Thus, a number of experiments are needed to establish a gettering process that can be applied to all impurities of interest here.

3.5 Solar Cell Characterization

3.5.1 Data Analysis

The overall purpose of this program is to establish quantitative trade-off relationships between silicon purity and the performance of solar cells. It is clear, based on past and present solar cell studies, that cell performance has a strong and complex dependence on all of the following:

- 1) the species of the contaminant and their concentration,
- 2) the method of crystal growth,
- 3) the crystalline character of the substrate,
- 4) the design of the cell
- 5) the fabrication processes and their parameters.

It is necessary, therefore, to control or determine the effects of the above in order that the resulting data be meaningful in the various contexts of the low cost solar cell project. Figure 13 is a schematic illustration of cell fabrication showing some of the observations which can be made at the various stages. Although the most useful correlation

Table 12. Effect of Gettering on Minority Carrier Lifetime

Sample No.	Open Circuit Voltage Decay Lifetime, μ s		
	Normal Process	POCl ₃ Gettered	Back Surface Damage Gettered
W025 (Baseline)	4.86	2.41	5.85
W005 MN	1.30	0.91	1.43
W008 TI	0.46	0.52	0.39
W009 V	0.13	0.98	0.39

Fig. 13. Schematic illustration of silicon processing sequence illustrating analysis that can be performed at each stage of the route from raw material to finished solar cell.

is that between cell performance and impurity concentration, it is desirable to have an indirect parameter which can be observed and followed through the earlier stages of cell fabrication. We have found in our studies that the principal influence of the metallic impurities is to reduce the carrier collection efficiency. This is observed as a reduction in the cell short circuit current. This in turn is closely correlated with the cell lifetime both in theory and experiment, viz. Figs. 11, 12 (Section 3.4.1) and Fig. 14. The actual correlation function is dependent on cell structure and the illumination spectrum. The data in Fig. 14 are open-circuit decay lifetime plotted against the cell short circuit current. The result as expected is similar to the computer prediction. Since different methods of lifetime measurement are being used in our work, it is informative to compare the results. Figure 15 shows reasonable agreement between the two sets of data. The filled data points are subject to some question and additional measurements are being made on those specimens.

It would be most convenient if lifetime of the processed material were related in some predictable way to that of as-grown wafers. Unhappily, this is not the case as the uncorrelated data in Fig. 16 clearly indicate. Some sense emerges when samples containing a single species of contaminant are traced through various processes. Figure 17 illustrates the results of some experiments of this sort. It is apparent that there are major dissimilarities in the process dependent behavior of the different metals impurities.

It is believed at this time that the process dependent changes result mainly from variation in the distribution and the degree of electrical activity of the metallic impurity atoms. That is, how and where they are incorporated in the crystal, as precipitates, clusters, in lattice or interstitial sites, decorating dislocations, etc. In addition, it seems probable that the total amount of contaminant will not change very much during the processing.

Fig. 14. Variation in relative solar cell short circuit current with cell open circuit decay lifetime.

Fig. 15. Correlation of the lifetimes measured on processed wafers by the photoconductive decay and open circuit decay methods.

Fig. 16. Variation in photoconductive decay lifetime measured on wafers after processing compared to that measured on the as-grown material. No correlation is apparent.

Fig. 17. Effect of processing history on photoconductive decay lifetime. Note that impurities may respond in very different ways to the same treatment.

Now if we examine the effect of contaminant concentration on cell performance, we should observe a behavior like that sketched in Fig. 18. The threshold concentrations and the maximum degradation will, of course, be functions of the species of contaminant and the particular processed used. The intrinsic lifetime region corresponds to high purity or baseline material. The solubility limited region may not be observable for some impurities since at high concentration some contaminants cause crystal growth to break down.

Data for three species of contaminants are shown in Figs. 19, 20, and 21. The concentration values are those obtained from the analysis of the as-grown material and represents total impurity content. It is assumed that the concentration is not significantly changed by the processing. In any case, no concentration data for processed material are available at this time.

The behavior shown in these figures generally follows that predicted by the conceptual model of Fig. 18.

3.5.2 Solar Cell Measurements

Since the last report, we have completed measurements on five ingots from this program plus a number of comparison samples from Monsanto. The processing of samples cut from the dendritic webs has also begun. Wafers from another eight ingots are at various stages of cell fabrication and will be measured shortly.

3.5.2.1 Doubly-Doped Ingots

Data for ingots containing one metal contaminant are depicted in graphical summary form as in the past, Fig. 22. The metal concentrations indicated in the diagram will be revised to reflect new data in the next quarterly report. For the most recent analytical data consult Table 6.

3.5.2.2 Multiply-Doped Ingots

A summary of the solar cell parameters from the second set of multiply-doped ingots appears in Table 13. The impurity combinations

Fig. 18. Expected effects of contaminant concentration on silicon wafer lifetime and hence cell performance.

Fig. 19. Measured variation in silicon wafer lifetime with manganese concentration (before and after processing).

Fig. 20. Measured variation in silicon wafer lifetime with chromium concentration (before and after processing).

Fig. 21. Measured variation in silicon wafer lifetime with titanium concentration (before and after processing).

Effect of Metal Doping on Solar Cell Efficiency (uncoated)

Fig. 22. Variation in solar cell performance with metal doping. No AR coatings, AM1 quartz-iodine illumination.

Table 13. Average Solar Cell Characteristics of Multiply-Doped Ingots

<u>Ingot ID</u>	<u>V_{OC} (V)</u>	<u>I_{sc} (ma)</u>	<u>V_p</u>	<u>I_p</u>	<u>I_o</u>	<u>n</u>	<u>FF</u>	<u>η(%)</u>	<u>τ(μsec)</u>
W037 Zr/Ti	.4419	7.76	.3598	7.10	1.56 E-08	1.278	.745	2.57	0.130
base 020	.5530	22.64	.4635	21.13	1.98 E-09	1.271	.782	9.80	5.07
W040 Cr/Ni	.5164	19.74	.4297	18.33	3.94 E-09	1.272	.7716	7.90	1.018
base 020	.552	22.52	.4644	21.07	1.35 E-09	1.23	.787	9.79	4.576
W041 Cr/Cu/Ni	.5107	18.96	.4145	17.20	1.91 E-05	1.618	.7384	7.15	.615
base 020	.555	22.68	.4684	21.26	7.77 E-10	1.207	.7907	9.96	4.55

include material containing Cr/Cu and Ni and as well ingots with Cr/Ni and Zr/Ti pairings. The complete data are collected in the Appendix.

The rather remarkable depression in cell performance due to Ti is carried over into the multiply-doped ingots. Much less harmful effects due to other impurity combinations are apparent.

3.5.3 Comparison of Float-Zone and Czochralski-Silicon

Experiments were carried out to compare our baseline material (W-Cz) with those grown by Monsanto. With the exception of M1A, which is 1.06 ohm-cm, all Monsanto ingots are about 0.5 ohm-cm in resistivity. The prefix "M" denotes float zoned and "C" denotes Czochralski crystals. Comparison of the baseline materials showing the effect of resistivity, on float zoned and Czochralski material is presented in Table 14. W003 is slightly higher in resistivity (~ 3 ohm-cm) than M1A and the use of float zoned silicon resulted in only 5 percent increase in efficiency. The increase in open circuit voltage due to increased doping in C1A appears to be accompanied with a reduction in the short circuit current, and the net cell efficiency is decreased in comparison to W003.

A comparison of baseline with doped ingots from Monsanto is shown in Table 15. Titanium seems to degrade the cells drastically regardless of the crystal type or resistivity, indicating that complexing with oxygen or carbon may not be a significant contribution to lower lifetime. The effect of carbon in M9B is unexpectedly high, especially when compared with Czochralski material (W003 and C1A) which should contain fairly high carbon. Carbon in Czochralski silicon might be interacting with oxygen producing neutral complexes, whereas in float zoned silicon, carbon is more active and might form deep levels in combination with vacancies. Decrease in the carrier lifetime due to aluminum is also significant. Based on our experience in the use of aluminum in power devices, one would expect a decrease in lifetime through interaction of aluminum with other impurities, especially copper.

Table 14

00021 MONSANTO M1A COMPARED TO W003 00 000

VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
AVERAGES: 00021 BASELINE W003 00 000								
.5540	23.08	.4626	21.49	2.12E-09	1.312	.7776	9.94	5.382
00021 MONSANTO M1A								
.5710	23.18	.4816	21.72	2.60E-09	1.248	.7903	10.46	5.408
PERCENT CHANGE								
3.07	.43	4.11	1.03	22.30	-4.94	1.63	5.18	.48

00022 MONSANTO C1A COMPARED TO W003 00 000

VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
AVERAGES: 00022 BASELINE W003 00 000								
.5540	23.08	.4626	21.49	2.12E-09	1.312	.7776	9.94	5.382
00022 MONSANTO C1A								
.5790	21.65	.4827	20.14	4.78E-09	1.393	.7755	9.72	2.037
PERCENT CHANGE								
4.51	-6.20	4.35	-6.31	125.15	6.16	-.27	-2.23	-62.16

00023 MONSANTO M1A COMPARED TO MONSANTO C1A

VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
AVERAGES: 00023 BASELINE MONSANTO C1A								
.5790	21.65	.4827	20.14	4.78E-09	1.393	.7755	9.72	2.037
00023 MONSANTO M1A								
.5710	23.18	.4816	21.72	2.60E-09	1.248	.7903	10.46	5.408
PERCENT CHANGE								
-1.38	7.07	-.23	7.83	-45.68	-10.46	1.90	7.58	165.53

Table 15

COMPARISON OF MONSANTO BASELINE TO DOPED INGOTS

Sample Identification	V _{oc}	I _{sc}	V _p	I _p	I _o	N	FF	Eff	TAU
MIA Baseline FZ	.5710	23.18	.4816	21.72	2.6×10^{-9}	1.248	.7903	10.46	5.408
Percent Change of Doped Float Zone Ingots Versus Float Zone Baseline									
M6 Zirconium	1.34	-5.09	-.20	-6.01	375.78	15.29	-2.49	-6.17	-49.52
M8B Titanium	-11.27	-58.58	-19.75	-62.17		100.72	-17.02	-69.47	-94.39
M10 Aluminum	.35	-6.38	-3.60	-8.93	8812.61	38.99	-6.53	-12.18	-85.10
M9B Carbon	-6.47	-30.19	-9.55	-31.81	1500.71	23.39	-5.50	-38.24	-94.58
CIA Baseline CZ	.5790	21.65	.4827	20.14	4.78×10^{-9}	1.393	.7755	9.72	2.037
Percent Change of Doped CZ Ingots Versus CZ Baseline									
C11 Titanium	-15.24	-65.36	-17.37	-66.03	3639.78	5.61	-4.37	-71.90	-84.04

4. CONCLUSIONS

The Czochralski-growth phase of the work is now complete. It appears from this work that melt concentrations above about 0.5 wt.% result in the degradation of silicon crystal quality for the pull speeds we use (~ 7.5 cm/hr). For this reason the crystal impurity content is limited for most impurities to less than 10^{15} atoms/cm³. In contrast, silicon webs grown at 1.3 cm/min contain impurity contents in the 10^{15} - 10^{17} range, well in excess of the Czochralski material. This apparently stems from the higher effective segregation coefficients for web growth.

We have developed a model which predicts fairly well the relationship between PCD lifetime and the cell performance (I_{sc}) which we observe experimentally. Data from all processed Czochralski material can be represented by the model except those from Ti-doped ingots. Here the lifetime measured on the processed wafers predicts much better cell behavior than is actually observed.

Preliminary studies of high temperature gettering treatments show that impurities may respond very differently to the same treatment. For example, the lifetime of Ti and V-bearing wafers improves while those containing Mn actually decreased. Further experiments evidently will be required to find a process compatible with a spectrum of contaminants.

Solar cell data from a second set of multiply-doped ingots further illustrate the marked effect of Ti on cell performance. When coupled with Zr, an impurity which has little effect on solar cells, Ti still dramatically degrades cell output. A triply-doped ingot containing Cr/Cu and Ni showed a cell efficiency reduction to about 70% of baseline probably due primarily to the Cr content.

5. PROGRAM STATUS

5.1 Present Status

The program is essentially on schedule, Fig. 23. During this quarter we have:

- Completed the Czochralski-growth of all ingots.
- Completed the growth of all dendritic web samples.
- Completed the chemical analysis of all but a few Czochralski ingots.
- Initiated the chemical analysis of web samples.
- Completed the lifetime measurements on 46 of 52 ingots.
- Completed the solar cell evaluation of the second set of multiply-doped ingots.
- Initiated lifetime measurements and cell preparation of web samples.
- Continued both damage gettering and high temperature phosphorous diffusion studies.

5.2 Future Activity

Within the next quarter all effort on the present program will be completed.

Fig. 23. Program Schedule.

6. REFERENCES

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7. APPENDIX

PHOTOVOLTAIC CHARACTERISTICS OF SOLAR CELLS UNDER AM1-EQUIVALENT QUARTZ-IODINE ILLUMINATION

Test Conditions: No AR coatings, cell area 1 cm^2 and
illumination = 100 mw/cm^2 .

Key to Abbreviations:

- R - calibrated reference devices
- C - wafers from ingot center
- T - wafers from tang end
- S - wafers from seed end
- B - baseline wafers
- E or N - end
- * - item deleted from averages

60714 W036ZR002 W025 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5450	23.20	.4547	21.59	2.35E-09	1.301	.7765	9.82	5.200
2B	.5450	23.20	.4547	21.59	2.35E-09	1.301	.7765	9.82	5.200
3B	.5450	23.20	.4547	21.59	2.35E-09	1.301	.7765	9.82	4.160
4B	.5450	23.20	.4547	21.59	2.35E-09	1.301	.7765	9.82	5.200
5B	.5450	23.20	.4547	21.59	2.35E-09	1.301	.7765	9.82	5.200
1C	.5290	18.50	.4312	16.95	2.80E-08	1.518	.7468	7.31	1.300
2C	.5290	18.50	.4312	16.95	2.80E-08	1.518	.7468	7.31	1.300
3C	.5290	18.50	.4312	16.95	2.80E-08	1.518	.7468	7.31	1.040
4C	.5290	18.70	.4293	17.08	4.40E-08	1.570	.7410	7.33	1.040
5C	.5290	18.00	.4364	16.63	7.34E-09	1.383	.7622	7.26	1.040
1S	.5220	17.80	.4311	16.46	6.42E-09	1.353	.7635	7.09	1.040
2S	.5220	17.80	.4311	16.46	6.42E-09	1.353	.7635	7.09	1.170
3S	.5190	17.80	.4230	16.31	2.72E-08	1.490	.7466	6.90	1.040
1T	.5220	18.00	.4319	16.66	5.10E-09	1.332	.7660	7.20	1.040
2T	.5220	18.00	.4319	16.66	5.10E-09	1.332	.7660	7.20	1.040
3T	.5220	18.00	.4319	16.66	5.10E-09	1.332	.7660	7.20	1.040
4T	.5220	18.00	.4319	16.66	5.10E-09	1.332	.7660	7.20	1.040

AVERAGES: 60714 BASELINE W025 00 000

.5450 23.20 .4547 21.59 2.35E-09 1.301 .7765 9.82 4.992

60714 W036ZR002

.5247 18.13 .4310 16.70 1.63E-08 1.419 .7568 7.20 1.094

PERCENT CHANGE

-3.73 -21.84 -5.21 -22.65 595.26 9.06 -2.54 -26.67 -78.08

60803 W038AL002 (4E16) W020 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5530	22.40	.4641	20.93	1.00E-09	1.257	.7840	9.71	4.290
2B	.5530	22.50	.4632	20.99	1.33E-09	1.278	.7815	9.72	4.550
3B	.5530	22.40	.4641	20.93	1.00E-09	1.257	.7840	9.71	4.550
4B	.5530	22.60	.4646	21.13	8.61E-10	1.245	.7854	9.82	4.550
5B	.5530	22.50	.4670	21.10	3.91E-10	1.190	.7921	9.86	4.290
1C	.5200	18.00	.4293	16.64	6.80E-09	1.352	.7630	7.14	.520
2C	.5200	18.00	.4259	16.55	1.64E-08	1.438	.7529	7.05	.390
3C	.5200	18.30	.4268	16.85	1.32E-08	1.415	.7556	7.19	.260
4C	.5200	18.00	.4293	16.64	6.80E-09	1.352	.7630	7.14	.130
1S	.5180	17.70	.4258	16.31	1.06E-08	1.391	.7577	6.95	.130
2S	.5180	18.00	.4309	16.72	2.65E-09	1.266	.7728	7.21	.130
3S	.5180	17.70	.4283	16.38	5.50E-09	1.330	.7651	7.01	.390
1T	.5230	18.20	.4304	16.79	9.84E-09	1.394	.7590	7.22	.260
2T	.5200	17.80	.4244	16.32	2.33E-08	1.476	.7485	6.93	.260
3T	.5200	17.80	.4293	16.45	6.67E-09	1.352	.7630	7.06	.260
4T	.5200	18.00	.4275	16.59	1.07E-08	1.395	.7579	7.09	.390

AVERAGES: 60803 BASELINE W020 00 000

.5530 22.48 .4646 21.02 9.18E-10 1.245 .7854 9.76 4.446

60803 W038AL002 (4E16)

.5197 17.95 .4280 16.57 1.02E-08 1.378 .7599 7.09 .284

PERCENT CHANGE

-6.02 -20.13 -7.88 -21.17 1015.37 10.67 -3.25 -27.37 -93.62

60721 W037ZR-TI001 W020 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5530	22.80	.4695	21.45	1.72E-10	1.137	.7986	10.07	5.200
2B	.5530	22.60	.4635	21.10	1.21E-09	1.271	.7823	9.78	5.200
3B	.5530	22.60	.4635	21.10	1.21E-09	1.271	.7823	9.78	5.200
4B	.5530	22.60	.4578	20.93	6.08E-09	1.406	.7666	9.58	4.550
5B	.5530	22.60	.4635	21.10	1.21E-09	1.271	.7823	9.78	5.200
1C	.4410	8.20	.3574	7.48	2.17E-08	1.321	.7394	2.67	.130
2C	.4410	7.80	.3605	7.16	8.54E-09	1.236	.7507	2.58	.130
3C	.4410	7.80	.3605	7.16	8.54E-09	1.236	.7507	2.58	.130
1S	.4450	7.70	.3635	7.07	9.12E-09	1.254	.7497	2.57	.130
2S	.4450	8.00	.3576	7.25	4.63E-08	1.419	.7284	2.59	.130
3S	.4450	7.70	.3635	7.07	9.12E-09	1.254	.7497	2.57	.130
1T	.4450	8.10	.3647	7.45	6.95E-09	1.225	.7537	2.72	.130
2T	.4370	7.30	.3571	6.70	8.47E-09	1.230	.7500	2.39	.130
3T	.4370	7.50	.3534	6.83	2.46E-08	1.331	.7365	2.41	.130
4T	.4420	7.50	.3599	6.87	1.27E-08	1.279	.7453	2.47	.130

AVERAGES: 60721 BASELINE W020 00 000
.5530 22.64 .4635 21.13 1.98E-09 1.271 .7824 9.80 5.070
60721 W037ZR-TI001
.4419 7.76 .3598 7.10 1.56E-08 1.278 .7454 2.56 .130
PERCENT CHANGE
-20.09 -65.72 -22.37 -66.39 688.49 .59 -4.73 -73.91 -97.44

60811 W040CR-NI001 (1E15-3.5E15) W020 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5520	22.30	.4583	20.69	4.22E-09	1.371	.7703	9.48	4.160
2B	.5520	22.30	.4633	20.84	9.75E-10	1.253	.7842	9.65	4.940
3B	.5520	22.50	.4669	21.12	3.09E-10	1.173	.7939	9.86	4.940
4B	.5520	23.00	.4628	21.47	1.18E-09	1.265	.7827	9.94	4.940
5B	.5520	22.50	.4709	21.23	7.18E-11	1.085	.8049	10.00	3.900
1C	.5260	20.70	.4388	19.27	2.11E-09	1.257	.7764	8.45	1.300
2C	.5380	21.40	.4506	19.97	1.25E-09	1.243	.7816	9.00	1.950
3C	.5260	20.80	.4381	19.34	2.65E-09	1.274	.7743	8.47	1.170
4C	.5260	20.30	.4386	18.89	2.22E-09	1.262	.7758	8.28	1.300
5C	.5180	20.00	.4313	18.59	2.64E-09	1.258	.7739	8.02	.650
1S	.5240	20.30	.4335	18.79	5.94E-09	1.340	.7657	8.14	1.040
2S	.5380	21.40	.4506	19.97	1.25E-09	1.243	.7816	9.00	1.950
3S	.5350	21.40	.4469	19.93	1.85E-09	1.265	.7780	8.91	1.690
1T	.5030	18.50	.4158	17.12	5.92E-09	1.294	.7647	7.12	.390
2T	.4940	17.80	.4085	16.47	5.56E-09	1.268	.7651	6.73	.260
3T	.4900	17.40	.4050	16.10	5.69E-09	1.262	.7645	6.52	.260
4T	.4850	16.90	.3987	15.58	1.02E-08	1.302	.7577	6.21	.260

AVERAGES: 60811 BASELINE W020 00 000
.5520 22.52 .4644 21.07 1.35E-09 1.230 .7872 9.79 4.576
60811 W040CR-NI001 (1E15-3.5E15)
.5169 19.74 .4297 18.33 3.94E-09 1.272 .7716 7.90 1.018
PERCENT CHANGE
-6.36 -12.34 -7.48 -12.99 191.36 3.48 -1.98 -19.23 -77.75

60809 W041CR-CU-NI001 (2.5E15-3E15-1.8E16) W020 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5560	22.50	.4675	21.05	7.58E-10	1.243	.7865	9.84	4.550
2B	.5560	22.90	.4723	21.55	1.51E-10	1.135	.7996	10.18	5.200
3B	.5520	22.40	.4602	20.84	2.49E-09	1.326	.7756	9.59	3.250
4B	.5560	22.80	.4706	21.41	2.79E-10	1.174	.7948	10.08	4.810
5B	.5560	22.80	.4715	21.43	2.09E-10	1.155	.7972	10.11	4.940
1C	.5150	19.00	.4310	17.72	1.23E-09	1.197	.7806	7.64	.650
2C	.5340	20.50	.4478	19.14	1.01E-09	1.221	.7831	8.57	1.300
3C	.5100	18.80	.4199	17.35	9.54E-09	1.353	.7598	7.28	.520
4C	.5050	20.20	.3479	15.34	2.10E-04	4.243	.5231	5.34	.260
1S	.5100	19.00	.4195	17.52	1.07E-08	1.363	.7585	7.35	.520
2S	.5240	20.30	.4343	18.81	4.76E-09	1.320	.7681	8.17	.910
3S	.5180	20.00	.4232	18.35	2.40E-08	1.461	.7497	7.77	.780
1T	.5010	18.00	.4091	16.51	2.23E-08	1.417	.7491	6.76	.390
2T	.5010	18.20	.4075	16.65	3.38E-08	1.460	.7441	6.78	.390
3T	.5010	17.70	.4117	16.31	1.12E-08	1.350	.7572	6.71	.520
4T	.4990	16.90	.4076	15.51	2.03E-08	1.408	.7495	6.32	.520

AVERAGES: 60809 BASELINE W020 00 000

.5552	22.68	.4684	21.26	7.77E-10	1.207	.7907	9.96	4.550
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60809 W041CR-CU-NI001 (2.5E15-3E15-1.8E16)

.5107	18.96	.4145	17.20	1.91E-05	1.618	.7384	7.15	.615
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PERCENT CHANGE

-8.01	-16.39	-11.51	-19.08	*****	34.06	-6.62	-28.16	-86.49
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