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

Effect of Impurities and Processing on Silicon Solar Cells

Tenth Quarterly Report, January 1—March 31, 1978

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Pittsburgh, Pennsylvania

and

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Midland, Michigan

MASTER

U.S. Department of Energy

Solar Energy

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1 January 1978 - 31 March 1978

Contract No. 954331

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NEW TECHNOLOGY

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

1. SUMMARY

The objective of Phase II of this program is to investigate and define the effects of impurities, processing, and impurity-process interactions on the performance of terrestrial silicon solar cells so that silicon producers, wafer manufacturers and cell fabricators can develop appropriate cost-benefit relationships for the use of Solar Grade Silicon. The major efforts this quarter were on crystal and thermal processing, impurity-grain boundary interactions, measurement of impurity trap levels and concentrations by Deep Level Transient Spectroscopy and improvement of the analytical and solar cell data base for n and p-type silicon.

Ingots doped with Mn were grown at two widely disparate rates (1.9 and 15 cm/hr) which roughly bracket practical Czochralski growth conditions. Despite the nearly eightfold growth rate difference cell performance decreased only by about 13% at the higher growth rate. Ingot doping was targeted at about $6 \times 10^{14} \text{ cm}^{-3}$ for each experiment but increased segregation produced a higher Mn doping level ($\sim 1 \times 10^{15} \text{ cm}^{-3}$) at the 15 cm/hr rate. This resulted in the observed decrease in cell efficiencies relative to material grown more slowly. A tendency to cellular structure reduced the yield of device quality material at the higher growth rate and this problem, rather than reduced cell performance, will probably be the critical factor determining the tolerable impurity content if very high growth rates are employed.

A variety of cleaning procedures were tested in order to minimize wafer surface contamination and subsequent impurity drive-in during high temperature annealing and gettering cycles. Cycles which involved extended deionized water rinses (rather than complicated acid treatments) coupled with small amounts of HCl in the gas phase during heat treatment provided the best capability for recombination lifetime

retention at temperatures up to 1000°C. Without such treatment contamination during wafer handling can easily mask any beneficial efforts of annealing and gettering.

Solar cells were fabricated on pairs of single crystal and polycrystalline ingots doped with either Ti or Mn. Preliminary indications are that Ti produces a similar degree of degradation in cell performance for both the single and polycrystalline material due to the well-documented reduction in bulk lifetime for this element. Cell performance for the Mn-doped polycrystalline material was considerably poorer than obtained on wafers cut from similarly-doped single crystal ingots. Shunting by grain-boundary precipitates is a potential degradation mechanism.

We have demonstrated that Deep Level Transient Spectroscopy (DLTS) can be utilized to evaluate the impurity trap levels, trap concentrations and capture cross sections of as-processed solar cells. The measured trap energy level provides a reliable method for qualitative analysis of the impurities present in silicon solar cells. Electrically active impurity concentration and capture cross section data are more difficult to analyze without ambiguity but if the DLTS method can be refined further it should provide answers to key questions such as 1) Is there a fixed relation between the metallurgical and electrically active impurity concentration in an ingot? 2) Why do some impurities degrade n- and p-base devices differently? 3) How uniform is the impurity distributions in a silicon ingot and solar cell? and 4) What is the nature of impurity-process interactions?

Recent Neutron Activation Analysis (NAA) Data are in excellent agreement with the targeted impurity concentrations for ingots doped with Mn, Cr, Fe, and Cu. However, the NAA results indicate that the segregation coefficients of Mo and Zr in silicon are considerably lower than originally estimated. The revised value for Mo is 4.5×10^{-8} and for Zr $< 1.6 \times 10^{-8}$. Thus significantly less Mo is required to degrade solar cell performance than was first believed; the Mo data are now consistent with earlier results for Ti and V rather than Mn and Cr.

2. INTRODUCTION

The objective of this program is to determine how various processes, impurities and impurity-process interactions affect the properties of silicon and the performance of terrestrial solar cells made from silicon. The development of this data base permits the definition of the tolerable impurity levels in a low-cost Solar Grade Silicon, and identifies processes which mitigate or enhance impurity effects in silicon. The data further provides the silicon manufacturer with a means to select materials of construction which minimize product contamination and permit the cost effective selection of chemical processes for silicon purification. For the silicon ingot, sheet or ribbon manufacturer the data suggest what silicon feedstock purity must be selected to produce wafers suitable for cell production and what furnace materials minimize wafer contamination. The cell manufacturer may use the data to define an acceptable wafer purity for cell processing or to identify processes which minimize impurity impact on efficiency. In short the data provides a basis for cost-benefit analysis to the producers and users of Solar Grade Silicon.

During this quarter the focus of the experimental activity has been in the following four areas: 1) effects of crystal growth rate and thermal processing of silicon on impurity distribution and electrical activity 2) Impurity-grain boundary interactions in polycrystalline silicon 3) preliminary measurements of impurity trap levels, trap concentrations and capture cross sections by Deep Level Transient Spectroscopy of purposely contaminated solar cells and 4) improvement of the solar cell-impurity concentration data base for n and p-type silicon for subsequent modeling studies.

3. TECHNICAL RESULTS

3.1 Silicon Ingot Preparation and Evaluation

Czochralski and float zone silicon crystals purposely contaminated with controlled amounts of metal impurities are the major test vehicles in this study to assess impurity effects in silicon. The impurities, concentration ranges and base doping so far evaluated are depicted in Table 1. The crystal preparation and analytical techniques are noted elsewhere.¹ Below we describe the highlights of recent growth experiments with particular emphasis on the chemical analysis results. Compilations of resistivity, etch pit density, carbon and oxygen analyses, and metal impurity analyses for all ingots grown to date appear in Appendices 7.1 to 7.3. Impurity segregation coefficients are tabulated in Appendix 7.4.

3.1.1 Ingot Preparation

A total of fifteen Czochralski and two float zone ingots were prepared this quarter:

- 1 p-type multiply doped (4 ohm-cm)*
- 1 n-type low resistivity baseline (0.2 ohm-cm)
- 1 p-type baseline (4 ohm-cm)
- 2 p-type singly-doped (4 ohm-cm) for process studies
- 2 p-type singly-doped (0.2 ohm-cm)
- 2 p-type FZ singly-doped (4.0 ohm-cm)
- 3 p-type singly-doped (4.0 ohm-cm)
- 5 n-type singly-doped (1.5 ohm-cm)

* target resistivity shown in parenthesis

We have now completed growth of all scheduled n-base ingots, low resistivity ingots and float zone ingots. Some special procedures regarding the doping of the float zone material should be noted. Elemental chromium was used as the chromium dopant source with no difficulties

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 - 50**		3 - 50
Boron*			
Calcium	0.1		
Carbon	20 - 500 ⁺		47 - 83
Chromium	0.1 - 1.1	0.5	0.3 - 1.0
Copper	0.4 - 60	2.3	2.5 - 10
Iron	0.02 - 1.5	0.8	0.3 - 1.0
Magnesium	0.003 - 0.03		
Manganese	0.01 - 1.3	0.7	1.0
Molybdenum	0.0009 - 0.0042		
Nickel	0.4 - 4.0		2.3
Oxygen	500 - 1700 ⁺		
Phosphorus*	1.0 - 140	100	
Sodium			
Titanium	0.00036 - 0.36	0.2	0.07 - 0.36
Tantalum	~ 0.01		
Vanadium	0.0004 - 0.4	0.4	0.4
Zinc	<0.001		
Zirconium	<0.0007		<0.0007

* 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.

encountered in the growth process. However, loss of elemental titanium from the molten zone as the RF coil approached the titanium dopant required that a silicon-titanium dopant source (90%-2%) be prepared. Using this as the titanium dopant then permitted easy growth of the titanium-bearing FZ ingot.

3.1.2 Ingot Evaluation

Ingot evaluation procedures have been discussed in previous quarterly progress reports.¹ In general, there was no deviation from the norm for either ingot resistivity or etch pit density, Appendix 7.1. The phosphorus compensated, boron-doped ingots (W-116 and W-118) exhibit resistivities which are higher by up to a factor of two than anticipated based on dopant concentration added to the melt. Ingot W-118 was so highly compensated that a p-n junction formed at the tang end of the ingot.

Carbon and oxygen concentrations, Appendix 7.2, are typical of concentrations found in ingots grown by Czochralski pulling. Carbon and oxygen concentrations in all float zone grown ingots, however, have been below the limits of detection as expected.

Target metal concentrations, calculated concentrations based on melt analysis, measured impurity concentration based spark source mass spectrographic analysis, and measured concentrations by neutron activation and electrical resistivity are tabulated in Appendix 7.3. SSMS results for Mn-bearing ingots produced during the last six months show a consistently higher measured concentration than targeted. (W-090, W-091, W-093, W-094, and W-095). During the next quarter a more thorough analysis of selected slices from these ingots is planned. Neutron activation analysis results are in good agreement with targeted values. No other anomalous SSMS results were encountered.

A considerable amount of neutron activation analysis was completed this quarter. (Impurity values determined by NAA are shown in parentheses in the last column of the tables in Appendix 7.3). Some interesting results are apparent. For example, in one set of samples

taken from the seed and tang ends of ingots W*-090, W-093, and W-096, manganese concentrations were:

	10^{15} Seed Mn Atoms/cm ³	10^{15} Tang Mn Atoms/cm ³
W-090	0.69	1.08
W-093	0.77	1.02
W-096	0.62	0.99

These slices were taken from the extreme ends of the ingots prior to slicing for solar cell wafers so they represent the outside limits of impurity variation along the samples. The concentration variation is small and within the range expected from impurity partitioning.

Care must be taken in such measurements, particularly with regard to material taken from the tang end of heavily doped ingots. Ingot W-095 is an example where crystal breakdown occurred at a position above the tang end slice. The resulting seed and tang manganese concentrations for this ingot were:

seed 0.98×10^{15} atoms/cm³; tang 645×10^{15} atoms/cm³

Clearly, if tang end slices are to be used for any analytical purposes great care must be exercised to select single crystal material free from cellular structure.

Neutron activation analysis and SSMS were both sufficiently sensitive to detect variations in impurity concentration related to differences in ingot pull speed. Mn-doped ingot W-095 was grown at 15 cm/hr while ingot W-096 was grown from a melt of approximately the same composition but at a rate of 1.88 cm/hr. Target manganese concentrations (assuming the same effective segregation coefficient applied to both cases), as well as values determined by NAA and SSMS are shown below.

	Tgt. Conc. $\times 10^{15}$ atoms/cm ³	NAA Conc. $\times 10^{15}$ atoms/cm ³	SSMS Conc. $\times 10^{15}$ atoms/cm	Pull Speed cm/hr
W-095	0.5	1.0	2.75	15.0
W-096	0.63	0.6	0.25	1.88

As expected, segregation is enhanced at the higher pull speed.

Neutron activation analyses have been performed on samples taken from fifteen ingots to assess the degree of correlation between target and measured metal impurity concentrations. NAA measurements were made at two different laboratories. The ingots were either singly or multiply doped with the impurities Cr, Cu, Fe, and Mn. When the target impurity values are normalized to 1.0, the mean measured value is 0.96 with a standard deviation of 0.27. Actual target and measured values are shown in Table 2. The correlation is quite good and suggests the degree of accuracy to which impurity concentrations may be predicted if adequate analytical data is available. Development of a similar data base for impurities such as nickel, vanadium, titanium, molybdenum, and zirconium is highly desirable.

SSMS and NAA have been used to update the impurity segregation coefficient data, Appendix 7.4. The values for molybdenum (4.5×10^{-8}) and zirconium ($< 1.6 \times 10^{-8}$) now appear to be considerably lower than originally estimated. Further analyses are necessary to verify this point.

Besides the chemical analyses for specifically added impurities, a small amount of survey analysis has also been conducted to search for the presence of unintentional contaminants. Impurities detected in essentially all ingots examined by Kraftwerk Union A.G. were arsenic (4×10^{11} atoms/cm³ - 1.2×10^{13} atoms/cm³), antimony (3×10^{10} atoms/cm³ - 1.2×10^{12} atoms/cm³), and copper (1×10^{12} - 8.7×10^{12} atoms/cm³). These concentrations are consistent with the impurity levels found in typical Czochralski grown material. There is no pattern regarding the presence of these impurities in specific ingots. Their occurrence can be attributed to their presence as trace elements in either the dopant

Table 2 Comparison of Target Concentrations and Concentrations Measured by Neutron Activation Analysis*

<u>Ingot #</u>	<u>Impurity</u>	<u>Target Conc. x 10¹⁵ atoms/cm³</u>	<u>Measured Conc. x 10¹⁵ atoms/cm³</u>
W-016	Fe	1.0	1.0
W-018	Fe	2.0	2.0
W-045	Fe	0.66	0.64
	Cr	0.5	0.26
N-061	Cr	1.1	1.1
W-064	Mn	1.0	0.61
W-067	Cr	0.44	0.25
	Mn	0.50	0.66
W-068	Cr	1.0	0.44
W-069	Fe	0.98	1.1
W-083	Fe	1.0	1.0
W-089	Cu	2.3	2.5
W-090	Mn	0.7	0.69
W-093	Mn	0.66	0.77
W-094	Mn	0.9	1.07
W-096	Mn	0.63	0.62
W-100	Cu	1.0	1.31

* Neutron Activation Analysis performed at Kraftwerk Union A.G. and General Activation Analysis

material, or in the polysilicon charge material (at a sub-ppb level).

Iron was detected in trace quantities in ingots purposely doped with large amounts of chromium, manganese, and molybdenum. The residual iron concentration varied from 2.8×10^{13} to 5.3×10^{13} atoms/cm³. These concentrations are near the iron detection limit of 2.7×10^{13} atoms/cm³. A relatively large iron concentration (1.1×10^{14} - 1.7×10^{14} atoms/cm³) was observed in ingots heavily doped with nickel. For these ingots the iron concentration is approximately one order of magnitude higher than specified. While this iron concentration is not high enough to influence solar cell performance characteristics and thereby, introduce ambiguity into the results, an effort is underway to eliminate the problem.

As in the past, a best estimate has been made of impurity concentrations in all ingots prepared to date. These estimates are shown in Table 3. Significant changes in impurity concentrations have been made for ingots W-011, W-036, W-037, W-064, W-077, W-085, W-095, W-098, and W-112 as a result of the analytical data collected this past quarter. These changes should be incorporated into all data relating to solar cell performance.

On the basis of our analytical results we make two recommendations with respect to ingot sampling and future analytical activity:

1. Selection of ingot tang material for analytical application must be made with extreme care due to the possibly large impurity fluctuations introduced by cellular breakdown. It is recommended that this material not be used for analytical purposes due to the high potential of generating impurity data which does not represent the remainder of the ingot. To avoid these large impurity fluctuations in the tang end material from the heavily doped ingots would require doubling the melt volume and significantly increasing ingot cost without generating data of great value.

Table 3 Best Estimate of Impurity Concentrations

<u>Ingot Identification</u>	<u>Best Estimate of Impurity Conc. (10¹⁵ atoms/cm³)</u>	
W-001-00-000	--	
W-002-00-000	--	
W-003-00-000	--	
W-004-Cr-001	1.0	(1.0)**
W-005-Mn-001	1.3	(1.3)
W-006-Ni-001	0.5	
W-007-Cu-001	2.0	(1.8)
W-008-Ti-001	0.36	(0.36)
W-009-V-001	0.4	(0.4)
W-010-Ni-002	3.0	(4.0)
W-011-Zr-001	0.0007	(<0.015)
W-012-Cr-002	0.2	--
W-013-Mn-002	0.25	--
W-014-00-000	--	--
W-015-Zn-001	<0.001	(<0.3)
W-016-Fe-001	0.85	(0.9)
W-017-Cu-002	19	(32)
W-018-Fe-002	1.7	(1.7)
W-019-Cu-003	0.4	(0.4)
W-020-00 000	--	--
W-021-Mg-001	0.003	--
W-022-00-000	--	--
W-023-00-000	--	--
W-024-Mg-002	0.03	--
W-025-00-000	--	--
W-026-Mn-003	0.012	--
W-027-Mn/Cu-001	1.3/1.7	(1.0/1.0)
W-028-Al-001	26	(26)
W-029-Cr-003	0.012	--
W-030-Cr/Cu-001	1/1.7	(1.0/1.0)

<u>Ingot Identification</u>	<u>Best Estimate of Impurity Conc. (10¹⁵ atoms/cm³)</u>	
W-031-Cr/Mn-001	1.0/1.3	(1.0/2.5)
W-032-Mg-003	0.32	(0.32)
W-033-Ti-002	0.0036	--
W-034-00-000	--	--
W-035-V-002	0.004	--
W-036-Zr-002	<0.0007	(<0.025)
W-037-Zr/Ti-001	0.0014/ 0.40	(<0.015/0.36)
W-038-Al-002	60	(34)
W-039-Ni-003	8	(4)
W-040-Cr/Ni-001	0.8/2.4	(1.0/3.5)
W-041-Ni/Cr/Cu-001	2.4/0.8/1.7	(3.0/1.7/2.3)
W-042-Ti-003	0.07	--
W-043-Fe/Ti-001	0.56/0.06	--
W-044-Fe-003	0.017	--
W-045-Cr/Fe/Ti-001	0.65/0.43/0.06	(0.2/0.5/0.06)
W-046-Fe/V-001	0.57/0.07	--
W-047-Cu/Ni/Zr-001	2.0/1.0/<0.015	(<2.4/<1/<1)
W-048-Ti-004	0.00036	--
W-049-V-003	0.0004	--
W-050-Ti/V-001	0.00036/0.0004	
W-051-Cu/Ti-001	2.0/0.36	(4/0.36)
W-052-Ni-004	4.5	(4.0)
W-053-Poly	--	--
W-054-00-000	--	--
W-055-Cu-004	0.05	(<1)
W-056-Cu-005	65	(70)
W-057-00-000	--	--
W-058-00-000	--	--
W-059-00-000	--	--
W-060-00-000	--	--
W-061-Cr/Ti-001	1.0/.02	(1.0/<1)
W-062-N/Cu-001	1.7	(2.0)
W-063-N/Cr-001	0.8	(1.0)
W-064-N/Mn-001	1.0	(2.0)

Ingot Identification	Best Estimate of Impurity Conc. (10^{15} atoms/cm ³)		
W-065-N/Ti-001	0.36	(0.75)	
W-066-Ti-005	0.06	(<0.2)	(0.09)
W-067-Cr/Mn/Ti-001	0.4	(0.3)	(0.25)
	0.5	(0.7)	(0.66)
	0.006	(<0.2)	(<0.2)
W-068-Cr-004	1.0	(1.0)	(0.44)
W-069-Fe-004	1.0	(<1.5)	(1.1)
W-070-Al-003	50	(100)	(3)***
W-071-00-000	--	--	
W-072-Cr-005	0.4	0.25	(0.28)
W-073-Cr/Mn/Ni/Ti/V-001	0.5	(0.28)	(0.17)
	0.5	(0.80)	(0.28)
	2.0	(2.0)	(10)
	0.004	(<0.35)	(<0.3)
	0.004	(<0.35)	
W-074-Cr/Mn/Ni/Ti/V-002	0.08	(<0.25)	
	0.08	(<0.25)	
	0.5	(<2.0)	
	0.0006	(<0.25)	
	0.0006	(<0.25)	
W-075-Ti/V-002	0.1	(<0.25)	
	0.1	(<0.25)	
W-076-Poly-2	--	--	
W-077-Mo-001	0.0042	(<0.3)	(0.0042)
W-078-00-000	--	--	
W-079-00-000	--	--	
W-080-Ph-001	0.7	(0.7)***	
W-081-N/Ni-001	1.7	(<2.0)	(15)
W-082-N/V-001	0.4	(0.85)	
W-083-N/Fe-001	1	(<1.5)	(1.0)
W-084-N/Al-001	50	(40)	(4)***
W-085-N/Zr-001	0.0007	(<0.015)	(<0.011)
W-086-C-001	400	(300-500)	150
W-087-Ca-001	?	?	
W*-088-Cr-001	0.5	(3.3)	
W*-089-Cu-001	2.0	0.5	(2.5)

<u>Ingot Identification</u>	<u>Best Estimate of Impurity Conc. (10^{15} atoms/cm³)</u>		
W*090-Mn -001	0.7	(2.75)	(0.69)
W-091-Cr/Mn-002	0.5/0.3	(1/2.75)	(-10.5)
W-092-Ph-002	28	(27-30)***	
W-093-Mn-004	0.66	(2.75)	(0.75)
W-094-Mn-005/Poly	0.9	(2.75)	(1.3)
W-095-Mn-006(F)	1.0	(2.75)	(1.0)
W-096-Mn-007(S)	0.63	(0.25)	(0.6)
W-097-00-000	--	N/A	
W-098-Mo-002	0.00092	(<.3)	
W-099-FZ-001	--	N/A	
W-100-Cu/Ti-002	1.0/0.06	(0.5/0.3)	
W-101-FZ-002	--	N/A	
W-102-Ti-006/Poly	0.2	(0.25)	
W*-103-Ti-001	0.3	(0.25)	
W-104-Cu/Ti-003	2.0/0.25	(4.0/0.25)	
W*105-V-001	0.4	(0.35)	
W-106-N/Al-002	10	(8.3)	(0.7)***
W-107-FZ/Al-001	30	(128)	(12)***
W-108-NV-002	0.08	(<0.2)	
W 109-C-002	<20-140	(<20-140)	
W*-110-Fe-001	0.8	(<2.0)	
W-111-Cu/V-001	2.5/0.3	(2.6/0.25)	
W-112-Ta-001	0.01		
W-113-FZ/Cr-001	0.8		
W-114-00-200	--	N/A	
W-115-N/Cu-002	10		
W*-116-Ph-001	100	(100)***	
W-117-00-000	--	N/A	
W-118-Ph-003	140	(140)***	
W-119-N/FE-002	0.3		
W-120-N/CR-002	0.3		
W-121-N/TI-002	0.07		

<u>Ingot Identification</u>	<u>Best Estimate of Impurity Conc. (10^{15} atoms/cm³)</u>
W-122-Ti -007	0.30
W-123-Ti -008	0.188

* Low resistivity p-type ingot identification.

** Quantity in first set of parenthesis for ingots W-001 through W-054 represents an average value as determined by all applicable measurements (SSMS, NAA, IR, RESTIVITY). Quantity in first parenthesis for ingots W-055 through W-123 represent SSMS value while value in second set of parenthesis has been determined by NAA.

*** Impurity concentration determined by electrical resistivity measurements.

2. A more detailed analysis of heavily-doped ingots containing Mo, Ni, Ta, Ti, V, and Zr should be conducted. This requires preparation of ingots primarily for analytical use or at best duplicates of heavily-doped samples for solar cell evaluation. Such an effort would greatly increase the validity of the data particularly in lightly doped ingots where direct impurity measurement is now impossible.

3.2. Processing Studies

Since crystal growth and subsequent thermal processing each may influence the distribution and electrical activity of impurities in silicon, we undertook as part of this program to evaluate (1) crystal growth rate effects on cell performance and (2) the role of thermochemical treatments in determining the performance of impurity-doped solar cells. Recent results are reported below.

3.2.1 Crystal Processing: Czochralski Growth

In the first of two scheduled experiments to test for the effects of crystal pulling rate on impurity segregation and cell performance. Mn-doped ingots were grown at two widely disparate rates, 15cm/hr and 1.88 cm/hr. The ingots were wafered and processed to solar cells via our standard POCl_3 diffusion cycle.¹ The relative solar cell efficiencies were then compared for devices fabricated on each ingot:

Ingot	Growth Speed	Target Doping (10^{-15} cm^{-3})	Measured Doping (10^{-15} cm^{-3})	η/η_B
W095Mn	15cm/hr	0.5	1.0	.83
W096Mn	1.88cm/hr	0.63	0.6	.96

At a given position in the ingot the crystal grown more rapidly shows the greater depression in cell performance and the observed relative efficiencies are consistent with the measured manganese content. The difference in cell performance for the two ingots is only about 13%,

however, despite the fact that ingot W095 was grown nearly eight times more rapidly than W096. As previously suggested¹ the promotion of cellular breakdown is likely to pose a greater problem at very high growth rates while the reduction in cell performance will limit the tolerable impurity level under normal growth conditions.

3.2.2 Thermal Processing

We demonstrated previously that the principal effect of impurities on solar efficiency is due to a reduction of the minority carrier recombination lifetime¹. Impurities introduce localized discrete levels in the silicon. An impurity atom is said to be "electrically active" if the energy level is created within the forbidden energy gap. Effective recombination occurs only when the trap level is near the center of the forbidden gap so that both holes and electrons have a reasonable probability to achieve the required thermal energy for recombination. Generally, such levels are created by isolated impurity atoms located at substitutional sites. Clustered impurities or those on interstitial sites most probably produce energy levels outside of the band gap. Axiomatically, the number of electrically active impurities will be smaller than the metallurgical concentration.

As part of this study we are exploring methods to reduce the number of electrically active impurities present in the silicon thus mitigating their harmful effects on cell performance. Thermal treatments to promote impurity clustering or precipitation appear to be one effective way to achieve this end. Precipitation/clustering is promoted when the equilibrium solute concentration of a given temperature is less than that at the growth temperature. Precipitates may form homogeneously in the bulk silicon during annealing or may be nucleated heterogeneously on defects. Some control over the process may be exercised by creating such defects purposely, e.g. at a wafer surface. Simple annealing provides less control over precipitation but is potentially a low cost process. Gettering via high concentration phosphorus diffusion or damage (abrasion or ion implantation) are common methods to control impurity reduction and provide a mechanism to remove the impurities from the silicon e.g. by subsequent etching procedures.

Practical precipitation rates are achieved by heating the silicon to elevated temperatures where impurities can move by diffusion to the nucleation sites. Since under some conditions high temperature treatments may also be detrimental³ such effects must be known and controlled in order to discern the lifetime improvements due to precipitation. Preliminary results on the effects of sample cooling rate from 1000°C were described earlier.³ In those studies we found that other factors such as sample contamination reduced recombination lifetime retention during subsequent thermal treatment. A summary of the results of these experiments is presented in Table 4. The silicon samples, with the exception of A and B, were from Ingot W078. The specimens were sawn extra thick and etched to $0.115 \pm .001$ cm (45-46 mils) to minimize higher mode errors in PCD measurements.³ Samples A and B were from a second boron doped ingot with 4 Ω cm resistivity. These samples were sawn following the heat treatment to determine whether the lifetime was adversely effected by propagation of saw damage during the annealing cycle. The initial lifetimes listed for these samples is that typical of 4 Ω cm ingots we have studied previously since PCD measurements cannot be performed without saw preparation. Comparing the data for samples A and B, with that from samples 19 and 20, we conclude that some saw damage does propagate during the anneal cycle but that this is only one of the factors contributing to lifetime degradation. A significant increase in sample lifetime was noted whenever HCl was added to the furnace atmosphere. Sample 21a was processed in oxygen, but the furnace was precleaned with HCl to determine whether the lifetime improvement stemmed from furnace decontamination or silicon surface cleaning. The data indicate that most of the improvement was obtained from HCl etching/cleaning of the silicon surface not furnace cleanup. The results of the experiments on sample 21b corroborate the initial postulate that sample contamination, not thermal damage, is responsible for the degradation of lifetime. The results for sample 22 clearly show that cleaning procedures which minimize contamination strongly effect lifetime. Moreover, controlled final rinsing in DI water is more effective for cleaning than complicated and expensive acid techniques.

TABLE 4
Retention of Recombination Lifetime
Anneal 15 Min. at 1000°C
Cooling Rate, dT/dt = 1°C/Min.

SAMPLE	WAFER CLEANING PROCEDURE (1)	FURNACE ATMOSPHERE	τ_i (μsec) INITIAL	τ_f (μsec) FINAL	τ_f/τ_i	
14	Clean 1	N ₂	52.8	0.45	0.009	
17	Clean 2	N ₂	52.1	1.7	0.033	
18	Clean 3	O ₂	52.6	2.6	0.049	
19	Clean 3	95% O ₂ + 5% HCL (2)	52.6	6.9	0.131	
20 ⁽³⁾	Clean 3	95% O ₂ + 5% HCL (2)	52.3	9.0	0.172	
A	Clean 3	95% O ₂ + 5% HCL	62.7 ⁽⁷⁾	4.9	0.078	
B	Clean 3	95% O ₂ + 5% HCL	62.7 ⁽⁷⁾	10.4	0.166	
21a	Clean 3	O ₂ ⁽⁵⁾	52.1	5.9	0.113	
21b	-	See Note 5	52.1	13.5	0.259	
22	Clean 3 ⁽⁶⁾	95% O ₂ + 5% HCL (2)	52.1	18.8	0.361	
23	Clean 4	95% O ₂ + 5% HCL (2)	52.0	9.3	0.179	
24	Clean 5	95% O ₂ + 5% HCL (2)	51.5	6.6	0.128	
25	Clean 6	95% O ₂ + 5% HCL (2)	58.4	6.7	0.115	

1. Procedure details in Appendix 7.
2. Furnace precleaned 3 hrs. with 95% O₂ + 5% HCL.
3. Edge of specimen etched 2-3 mils to remove saw damage.
4. Furnace precleaned 3 hrs @ 1200°C with 95% O₂ + 5% HCL.
5. 21 a gettered 45 min. POCl₃ @ 950°C.
6. DI Rinse = 2 min., Final rinse = 5 min., H₂O resistivity = 18 Megohm.
7. Average initial value

Additional experiments are being conducted to determine the optimum cleaning procedure necessary for the retention of recombination lifetime, since this type of study is conspicuously absent from the literature and can contribute significantly to solar cell performance.

In parallel with the cleaning studies experiments have been started to determine the optimum precipitation techniques to be used in mitigating the effects of contaminated silicon. POCl_3 gettering will be initially evaluated because of the advantages of surface precipitation and the benefits of adding chlorine. These experiments will utilize the results of our wafer cleaning studies to control base specimen lifetime.

3.3 Impurity/Grain Boundary Interactions

Polycrystalline ingots or forms of silicon sheet containing grain boundaries are potential low cost substrates for terrestrial solar cells. Thus a small part of this program is directed at elucidating the response of solar cells made on polycrystalline silicon to controlled additions of metal contaminants. Preliminary cell data for two impurities, Mn and Ti, are tabulated below. The ingots were grown from small-grained polycrystalline silicon seeds so the microstructure of ingots W094 and W102 is similar to that reported for the uncontaminated polycrystalline baseline ingot W076.²

Ingot	Impurity	Metal Concentration (10^{15}cm^{-3})	η/η_{BP}	η/η_{BS}
W094	Mn	0.9	.29	.80
W102	Ti	0.2	.38	.35

$$\eta_{\text{poly}}/\eta_{\text{single (no impurities)}} = .71$$

The last two columns of the table compare the relative efficiency of cells made on impurity-doped polycrystalline material (η/η_{BP}) and cells made on single crystal material containing the same amount of impurity (η/η_{BS}). For Ti which drastically reduces cell performance via minority carrier recombination, the single and polycrystalline material behave very similarly. That is, Ti produces severe degradation in cell performance regardless of the nature of crystal microstructure. For Mn on the other hand the cell efficiency of the polycrystalline material is generally much poorer than that exhibited in the single crystal ingot. A few of the individual polycrystalline cells from ingot W094 exhibit relative efficiencies close to 0.80, or about equal to the Mn-doped single crystal cells. However, the majority of cells show significant reductions in Voc. Thus unlike the Ti-doped ingots where recombination effects due to metal contamination apparently swamp out grain boundary effects, Mn (possibly as precipitates in the grain boundaries) seems to induce

a far greater deterioration in cell performance in the polycrystalline material than in similarly-doped single crystal cells.

3.4 Quantitative Analysis of Impurity Effects in Silicon and Silicon Solar Cells

3.4.1. Deep Level Transient Spectroscopy (DLTS)

Deep Level Transient Spectroscopy provides some significant advantages over standard thermally stimulated current and capacitance techniques³ as a means to evaluate the type and concentration of electrically active contaminants in silicon ingots and silicon solar cells. We describe below the preparation of specimens for DLTS, how the technique may be performed, data analysis methods and some recent data on the impurities purposely introduced into the solar cells studied as part of this program.*

3.4.1.1 The DLTS Technique

The DLTS measurements were performed with the help of a double-boxcar integrator. In most cases a 100 μ sec pulse ranging from 8 volts reverse bias to 2 volts forward bias was used to fill the minority and the majority traps in the reverse biased depletion region. In some cases where the minority and the majority trap peaks showed a considerable overlap, only a reverse bias pulse (-8 to -2 volts) was used to study the majority traps. At the end of each pulse a capacitance transient is observed as the filled traps start to empty by thermal emission. The sample was continuously pulsed while being heated from liquid N₂ temperature to 50°C at a rate of 1°C/sec. As a result of heating the time constant of the capacitance transient on the emission rate ($e=1/\tau$) changes monotonically. The double boxcar integrator processes the capacitance transient to give an output which corresponds to the average difference of the capacitance amplitude at sampling times t_1 and t_2 .

* We gratefully acknowledge the use of facilities at the Carnegie-Mellon University to take data used for these studies.

The boxcar output reaches a maximum when the time constant of the capacitance transient, which is changing continuously with the temperature, passes through the rate window ($t_2 - t_1$). Changing the rate window shifts the peak to a different temperature, Figure 1. The rate window was varied by changing the boxcar time base t_B from 0.5 to 100 m secs and setting the gate delays t_1 and t_2 at 10% and 90% of the time base. Thus $t_1 = 0.1 t_B$ and $t_2 = 0.9 t_B$.

3.4.1.2 Analysis of the DLTS Data

Figure 1 shows a typical DLTS output for a majority trap which was obtained from the sample P-Ti-008 (P indicates p-type, N represents n-base material in this discussion). Minority traps show up with the inverted peak above the zero level. The DLTS data was analyzed using Lang's approach⁴ in which the capacitance transient is assumed to be exponential

$$C(t) = \Delta C(o) e^{-t/\tau} \quad (3.1)$$

where $\Delta C(o)$ is the capacitance change due to pulse at $t = 0$, and the normalized DLTS output signal at any temperature is given by

$$S(T) = \frac{C(t_1) - C(t_2)}{\Delta C(o)} \quad (3.2)$$

The time constant at the peak temperature is determined by solving for the following condition

$$\frac{d S(T)}{d\tau} = 0 \quad (3.3)$$

$$\text{which gives } \tau_{\max} = (t_1 - t_2) (\ln t_1/t_2)^{-1} \quad (3.4)$$

The emission rate (e) at the peak temperature is obtained from

$$e = \frac{1}{\tau_{\max}} = \frac{1}{(t_1 - t_2) (\ln t_1/t_2)^{-1}} \quad (3.5)$$

since

$$t_1 = 0.1 t_B \text{ and } t_2 = 0.9 t_B$$

FIGURE 1 Typical Experimental DLTS Spectra for Hole Trap in p-type Silicon with Ti Impurity.

$$e = 2.75/t_B$$

Thus each peak gives an emission rate at the peak temperature. The emission rate, in general, is given by⁵

$$e = \frac{\sigma V_{th} N_c}{g} \exp(-E/kT) \quad (3.6)$$

where σ is the capture cross section of the trap, V is the thermal velocity, N_c is the density of the states in the band to which the thermal emission takes place, g is the degeneracy of the trap level, E is the energy level of the trap with respect to the band edge to which thermal emission occurs, k is the boltzman constant and T is the absolute temperature. Using the following expressions

$$V = (3kt/m^*)^{1/2} \quad (3.7)$$

$$N_c = 2M \left(\frac{2\pi m^* kT}{h^2} \right)^{3/2} \quad (3.8)$$

the appropriate values of the parameters for Si, and assuming $g = 1$ leads to

$$e = C \sigma T^2 \exp(-E/kT) \quad (3.9)$$

where $C = 6.4 \times 10^{25}$ for the conduction band

and $C = 1.0 \times 10^{25}$ for the valence band

Assuming the capture cross section to be temperature independent one gets

$$e = C \sigma_o T^2 \exp(-E/kT) \quad (3.10)$$

or
$$\ln \left(\frac{e}{T^2} \right) = \ln C + \ln \sigma_o - E/kT \quad (3.11)$$

Thus the energy level can be obtained from the slope of $\ln (e/T^2)$ vs $1/T$ and the intercept gives the cross section. Figure 2 shows such plots for titanium and vanadium hole traps. When Arrhenius plots are made, they are scaled to the conventional plotting variables $y = \ln \left(\frac{\sigma_0}{T} \right)^2 \cdot e$ and $x = 1000/T$. A computer program was used to calculate these variables from the input data and then plot them as shown in Figure 2. The program also finds the slope (B) and intercept (A) for the best linear fit to give the energy level and the cross section. The confidence limits for the estimated energy and the cross section are calculated using the goodness of fit parameter S;

$$S = \frac{\sum (Y-A-BX)^2}{N-2} \quad (3.12)$$

where N is the number of data points. The error limits for the energy are given by

$$\Delta E = \frac{S \cdot t(N-2, 1-L)}{(\sum (x-x_m)^2)^{1/2}} \quad (3.13)$$

where t is the distribution parameter for N-2 degrees of freedom and fractional error L and x_m is the mean value of x.

The trap density was determined by increasing the pulse width until no change in the peak amplitude was observed, indicating the saturation of the trap. The trap density was then obtained from

$$N_T = 2 \frac{\Delta C(o)}{C} (N_D - N_A) \quad (3.14)$$

where

N_T is the trap density

C is the junction capacitance at the reverse bias

$N_D - N_A$ is the net doping density $\approx 5 \times 10^{15} \text{ cm}^{-3}$

$$\Delta C(o) = \frac{C(t_1) - C(t_2)}{S(T)} = \frac{\text{Peak amplitude in capacitance units}}{\frac{t_1}{e \tau_{\max}} - \frac{t_2}{e \tau_{\max}}}$$

FIGURE 2 Arrhenius plot of trap levels in p-type silicon containing Ti or V.

since $t_1 = 0.1 t_B$, $t_2 = 0.9 t_B$ and $\tau_{\max} = \frac{t_B}{2.75}$

$$\Delta C(o) = 1.48 \text{ Peak Amplitude}$$

3.4.1.3 Sample Preparation

To perform the DLTS measurements requires sample devices with sufficiently low capacitance to permit balancing the measurement bridge. The device should also have relatively low surface leakage current. The 1x1 cm solar cells we have used to study impurity effects exhibit too high a capacitance and high leakage current ($I_{sh}|_V = 8 \text{ volts} \sim 100 \mu A$) in the as processed state to facilitate DLTS measurements. Therefore, small areas were mesa etched from the original solar cells for the DLTS purpose. First the front metal contact (Ti-Pd-Ag-grid) was removed while the back contact was preserved. This was followed by Ti-Au evaporation on the front surface. Electron beam evaporation was used first to evaporate 300 Å Ti and then 2000 Å Au on top of it. 30 mil dots were then mesa etched using the photoresist technique. The smaller junction thus obtained had reasonable leakage current of the order of 10-100 nA at approximately 8 volts reverse bias. A set of three 30 mil dots was scribed from each cell and mounted on a T05 header, as shown in Fig. 3. The sapphire was used to isolate the sample from the header.

3.4.1.4 DLTS Evaluation of Impurity-Contaminated Solar Cells

Impurity-induced hole and electron trap levels, their densities and capture cross sections obtained from DLTS measurements are tabulated in Table 5. The spectrum of the energy levels obtained for various impurities, e.g. Ti, V, Mo, Ni, Mn, Fe, Cr, and Al in Si, is shown in Fig. 4. The last column in Table 5 gives the correlation factor for the best linear fit to the data, Fig. 2. Considerations of the energy levels reported by various investigators^{3,4,5,6,7} for some of these impurities in Si indicates some agreement and some disagreement with respect to our data. For example three electron traps (Ec-.28, Ec-.35 and Ec-.41) and

FIGURE 3 Schematic diagram of the sample arrangement used for DLTS measurements.

TABLE 5

TRAP LEVEL, CONCENTRATIONS AND CAPTURE CROSSSECTIONS
FOR IMPURITY-DOPED SOLAR CELLS

Sample ID	Metallurgical Conc. cm^{-3}	Trap Level	Trap Conc. cm^{-3}	Capture Cross section (σ_0) cm^{-2}	Correlation Coefficient
P-Mo-077	6.5×10^{14}	EV + 0.32 EV + 0.20 EC - 0.41	4.90×10^{13} 3.96×10^{13} 3.30×10^{13}	1.5×10^{-15} 1.6×10^{-19} 2.6×10^{-17}	0.990 0.998 0.997
P-Ti-008 (Schottky barrier)	3.6×10^{14}	EV + 0.29 EV = 0.34	7.0×10^{13} 3.0×10^{14}	4.7×10^{-14} 4.0×10^{-16}	0.996 0.999
P-Ti-008 (p-n junction)	3.6×10^{14}	EV + 0.29 EC - 0.26	2.6×10^{13} 1.5×10^{13}		
P-Ti-033	3.6×10^{12}	EC - 0.27	4×10^{12}	4.5×10^{-17}	0.999
N-Ti-065	2.8×10^{14}	EV + 0.25 EV + 0.45	3.0×10^{13} 3.6×10^{13}	1.2×10^{-15} 3.6×10^{-16}	0.999 0.999
N-V-082	4.0×10^{14}	EC - 0.29 EC - 0.50	2.87×10^{13} 2.87×10^{13}	8.1×10^{-13} 1.4×10^{-13}	0.994 0.999
P-V-009	4×10^{14}	EV + 0.42	-	-	-
P-V + Ti-075	$1 \times 10^{14} + 1 \times 10^{14}$	EV + 0.64 EV + 0.31	1.13×10^{13} 2.26×10^{13}	4.1×10^{-13} 8.2×10^{-7}	0.999 0.997
P-Mn-005	1.3×10^{15}	EV + 0.40 EC - 0.25 EC - 0.64	1.6×10^{13} 2.1×10^{13} 2.7×10^{13}	5.5×10^{-16} 3.9×10^{-18} 2.9×10^{-12}	1.0 0.999 0.999
P-Mn-013	2.5×10^{14}	EV + 0.25 EV + 0.43 EC - 0.35 EC - 0.50	6.67×10^{13} 1.28×10^{14} 5.3×10^{13} 9.3×10^{12}	8.8×10^{-14} 1.4×10^{-15} 2.7×10^{-15} 3.9×10^{-16}	0.987 0.999 1.0 0.999
P-Cr-004	1.0×10^{15}	EV + 0.53 EC - 0.26 EC - 0.55	5.0×10^{13} 4.4×10^{13} 1.47×10^{13}	1×10^{-16} 5.9×10^{-18} 9.8×10^{-14}	0.999 0.993 0.998
P-Cr + Mn-031	$1 \times 10^{15} + 1 \times 10^{15}$	EV + 0.44 EV + 0.51 EC - 0.69	2.4×10^{13} 2.6×10^{13} 6.4×10^{12}	3.1×10^{-15} 2.8×10^{-17} 2.3×10^{-12}	0.992 0.836 0.978
P-Fe-018	1.7×10^{15}	EV + 0.29 EV + 0.31 EC - 0.40	3.1×10^{13} 1.9×10^{13} 1.1×10^{13}	4.7×10^{-15} 1.2×10^{-17} 3.4×10^{-17}	0.999 0.999 1.0
N-Ni-081	1.5×10^{15}	EV - 0.31 EC - 0.31	6.7×10^{13} 1.38×10^{13}	5.3×10^{-13} 2.9×10^{-13}	0.997 0.999
P-Al-038	3.4×10^{16}	EC - 0.57	4.5×10^{13}	6.5×10^{-13}	0.99

FIGURE 4 Trap levels determined by DLTS in impurity-doped solar cells.

two hole traps ($E_V \pm .22$ and $E_V + .35$) have been reported for Ni and we see only one hole trap at $E_V + .31$ and one electron trap at $E_C - .31$. In some cases, like V, Fe, and Mn, we see some trap levels which are not reported by others but others which are in agreement with the literature. This is perhaps not very surprising because energy levels depend on the method of impurity incorporation and also the heat treatment used to process the device. For example P-Ti-008 showed two majority traps when a Schottkey barrier diode was fabricated and only one majority trap when p-n junction was used. This tends to indicate that one majority trap disappeared due to phosphorous diffusion, a gettering step. However, this is a preliminary result and needs further investigation as nonuniformity on the wafer doping might also explain the observation.

The P-Ti-008 sample which had $3.6 \times 10^{14} \text{ cm}^{-3}$ Ti showed one majority trap ($E_V + 0.29$) and one minority trap ($E_C - 0.264$) but P-Ti-033 which contained $3.6 \times 10^{12} \text{ cm}^{-3}$ Ti showed only one minority trap ($E_C - .267$). The disappearance of the majority trap in sample P-Ti-033 is not clearly understood. It could result from impurity anisotropy or the low Ti concentration may fail to reveal that trap. Similar results were observed in Mn-doped samples. This point needs further investigation.

The DLTS data on Ti-doped n and p base devices show only one level ($\approx E_V + 0.29$) is common to both. The $E_C - 0.26$ electron trap is not seen in n-base device. Instead a hole trap at $E_V + 0.45$ is observed. Since the DLTS spectrum is not simply inverted in n and p-base devices this and suggests that Ti may be interacting or reacting with the dopant. Our solar cell data, however, do not show any compulsive evidence of such interaction because solar cell efficiency does not change appreciably when the donor or acceptor concentration is varied by an order of magnitude for the same added impurity level. No minority traps were observed in the N-Ti-065 sample although the solar cell data indicates that Ti in n-base devices also hurt the cell performance. The solar cell data shows that Ti hurts the p-base devices more than the n-base devices. This is consistent with the DLTS observation which shows a large distinct minority trap in p-base and no observable minority trap in n-base. This area also

needs further investigation by using n and p-base devices containing different impurities.

Limited data on multiply-doped cells show a weak evidence of mutual interaction again among the impurities although the cell performance data show no compelling evidence of interaction. For example P-V/Ti . 075 sample showed one hole trap ($E_v + 0.31$) which matches with the Ti hole trap within the experimental accuracy. However, it also showed another hole trap ($E_v + 0.64$) which is neither observed in Ti nor in V individually. Substantial electron trapping was observed in the P-Ti-V sample but the electron traps could not be resolved due to considerable overlapping of the peaks. P-Cr/Mn-031 sample showed one hole trap and two electron traps which can be matched with the traps observed in Cr and Mn individually within the experimental error. However some more levels, which we expected to see in the Cr + Mn sample were not observed. Thus this area also requires further analysis.

The capture cross sections listed in Table 4 should be used with some caution because they are estimated by assuming temperature independence of the cross section. This may not necessarily be true and can result in as much as one or two orders of magnitude difference. The DLTS technique can be used to determine the cross sections more accurately² and this will be one of the tasks of future DLTS measurements.

The trap concentrations listed in Table 4 should also be used carefully and with some caution. Especially the analysis of minority trap concentration and its cross section is very poorly understood. The minority trap concentration was determined by increasing the width of the injecting pulse in an attempt to saturate the traps. However, one may receive a false indication of saturation for the following reasons: 1) if $\sigma_{\min}$ is not much larger than $\sigma_{\max}$ for the observed minority trap then some of the trapped minority carriers will recombine with the majority carriers during the injection, 2) If the minority and the majority peaks are quite close then the overlap may affect the peak amplitude. The above ambiguities can be removed for the majority trap by using a reverse bias pulse instead of the injecting pulse. Most of the data quoted in

this report were taken by the injecting pulse because the main purpose of these first experiments with the DLTS technique was to identify levels in the processed solar cells. Thus the absolute trap concentrations and the cross sections listed in Table 4 may be questionable but the energy levels are quite reliable.

It is clear from the above discussion that the preliminary DLTS data is not in total agreement with the cell performance data. It is important to recognize that the DLTS samples are only a 30 mil dot while the cell performance represents the whole 1 cm^2 cell area. Lifetimes ($\tau_U =$

$\frac{1}{N_T \sigma_{th} v_{th}}$) calculated from the trap density (N_T) and the capture cross

section (σ) in Table 4 are not consistent with the OCD lifetime and this could be largely due to the a) error in the estimated cross section b) assumption that $\tau = \tau_0$ which is true only for low level injection with $E_T \sim E_i$ and $\sigma_{maj} [\text{Maj}] \gg \sigma_{min} [\text{Min}]$. Future studies will be directed toward resolving the apparent discrepancies in data and improve our understanding of impurity effects on cell performance.

We have successfully demonstrated that our shallow solar cell junctions can be used for the DLTS measurements. Our preliminary data indicate that the DLTS technique can be used to explore a number of interesting areas related to the impurity affects in silicon and silicon solar cells. More careful and accurate determination of the trap concentration and the cross section will help us answer the following important questions: 1) Is electrically active concentration a fixed fraction of the metallurgical concentration of the impurity in the Si and if yes, how different is this fraction for different impurities? 2) Why do some impurities degrade n-base devices more than the p-base devices or vice versa? 3) Do the impurities interact in a multiply-doped cell? 4) How uniform is the impurity distribution in the silicon? 5) What is the nature of process and impurity interaction, e.g during gettering and annealing etc.

3.4.2 Numerical Analysis of Detailed I-V Data

The detailed analysis of solar cell I-V characteristics was described recently.² Briefly the method involves fitting the experimental IV data to the double exponential model of the solar cell; i.e:

$$I = I_{01}(\exp(V-IR_S)/V_T) - 1) + I_{02}(\exp(V-IR_S)/nV_T)-1) + \frac{V}{R_{SH}} \quad (3.15)$$

$$\text{or for notational convenience: } I = I_B + I_j + \frac{V}{R_{SH}} \quad (3.16)$$

where: R_S and R_{SH} are the cell series and shunt resistances.

V_T is the Thermal voltage, 0.026 volts at room temperature

I_{01} is the saturation current associated with generation/recombination in the cell base.

I_{02} is saturation current associated with the junction and top surface regions.

n is the ideality factor, theoretically $n=2$ but experimentally $n>2$ in most cases.

The graphical method of accomplishing the data reduction is time consuming and tedious. We have therefore developed the following numerical method which is readily amendable to solution by computer or hand calculator.

In the low current range of the IV data ($0.1 \leq v \leq 0.3$) the contribution of I_B and R_S can be neglected providing:

$$I = I_j + \frac{V}{R_{SH}} \quad (3.17)$$

$$\text{or} \quad I = I_{02} \exp (V/(nV_T)) + \frac{V}{R_{SH}} \quad (3.18)$$

which can be rewritten:

$$\ln\left(I - \frac{V}{R_{SH}}\right) - \frac{V}{nV_T} = \ln(I_{02}) \quad (3.19)$$

Eliminating I_{02} gives:

$$\ln\left(I_1 - \frac{V_1}{R_{SH}}\right) - \frac{V_1}{nV_T} = \ln\left(I_2 - \frac{V_2}{R_{SH}}\right) - \frac{V_2}{nV_T} \quad (3.20)$$

$$\frac{V_T}{V_1 - V_2} \ln \left(\frac{I_1 - \frac{V_1}{R_{SH}}}{I_2 - \frac{V_2}{R_{SH}}} \right) = \frac{1}{n} \quad (3.21)$$

By including a third data point we can eliminate n :

$$\frac{V_T}{V_1 - V_2} \ln \left(\frac{I_1 - \frac{V_1}{R_{SH}}}{I_2 - \frac{V_2}{R_{SH}}} \right) - \frac{V_T}{V_1 - V_3} \ln \left(\frac{I_1 - \frac{V_1}{R_{SH}}}{I_3 - \frac{V_3}{R_{SH}}} \right) = 0 \quad (3.22)$$

Solving Eq. 3.22 for R_{SH} using a computer or calculator routine (Appendix 7.6) gives R_{SH} which substituted in Eq. 3.21 gives n and in turn Eq. 3.19 provides I_{02} . With these parameters we can examine the high current behavior ($V \geq \sim 0.50$). In the high current segment we define a transformed current, I' which with Eqs. 3.15 and 3.16 gives

$$I' = I - \left(I_1 + \frac{V}{R_{SH}}\right) = I_{01} \exp\left(\frac{V - IR_S}{V_T}\right) \quad (3.23)$$

Using transformed data points from the high current segment we can write

$$\ln(I'_4) = \ln(I_{01}) + \frac{V_4 - I_4 R_S}{V_T} \quad (3.24)$$

and with I'_5 we can eliminate I_{01}

$$\ln(I'_4) - \frac{V_4 - I_4 R_S}{V_T} = \ln(I'_5) - \frac{V_5 - I_5 R_S}{V_T} \quad (3.25)$$

which rearranged yields R_S :

$$R_S = \frac{(V_4 - V_5) - V_T \ln(I'_4 / I'_5)}{I_4 - I_5} \quad (3.26)$$

Then substituting R_S in 3.25 give I_{01} .

From I_{01} we can determine the effective minority carrier diffusion length and lifetime in the cell base. However, the calculation differs in form for BSF as compared to conventional ohmic back devices. For a p-base conventional cell:

$$I_{01} = \frac{q A n_i^2}{N_A} \frac{D}{L_n} \coth\left(\frac{W_B}{L_n}\right) \quad (3.27)$$

While for a p-base backfield cell:

$$I_{01} = \frac{q A n_i^2}{N_A} \frac{D}{L_n} \left(\tanh\left(\frac{D}{L_n}\right) \right) \quad (3.28)$$

where A = cell area

W_B = the basewidth of the cell

N_A = the acceptor concentration in the base

L_n, D = the diffusion length and diffusivity of electrons in the base.

n_i = the intrinsic carrier concentration, for silicon at 300°K $n_i = 1.45 \times 10^{10} / \text{cm}^3$

q = the electronic charge 1.6×10^{-19}

The program LTAU-III(Appendix 7.6) solves 3.27 or 3.28 for L_n . And since $\tau_n = L_n^2 / D_n$ we can obtain the electron lifetime.

Figure 5 shows experimental dark I-V data for cell SOLSEP-108-1. The numbered data points were used with the calculator program of Appendix 7.6 to obtain the following:

FIGURE 5 Example of treatment for typical dark I-V data.
(SOLEP Run 108-1).

SOLEP 108-1 2 Ω cm P-base Backfield Cell

J_{01}	$1.16 \times 10^{-11} \text{ A/cm}^2$
J_{02}	$5.4 \times 10^{-6} \text{ A/cm}^2$
n	4.8
R_S	0.38 Ohms cm^2
R_{SH}	$6.8 \times 10^{-5} \text{ ohms}$
N_D	$7 \times 10^{15} / \text{cm}^3$
D_n	$30 \text{ cm}^2/\text{s}$

This data reduction technique requires only five measurements and provides good agreement with cell performance parameters. The most critical requirement for successful application is that data points 1, 2, and 3 be well into the low current segment; $V_2, V \leq .3$ volts and data points 4 and 5 lie well above the I-V knee; $V \geq 0.4$ volts.

3.4.3 Impurity Behavior in N-Base Cells

In the p-base studies most impurity induced cell degradation was found to be a result of increased carrier recombination in the cell base-region. When impurity atoms are incorporated in the silicon lattice they induce discrete energy states in the forbidden gap which are characteristic of each specific impurity. The degree to which these energy states act as recombination centers depends on their energy position in the band and on their relative position with respect to the Fermi level which depends on doping type and concentration. Thus while the states associated with a given impurity should be the same in p and n-type material, the degree of recombination activity should in general be different because the relative position of the fermi level will be different. A possible exception may exist if a trap level is produced by

a complex of the impurity and the majority dopant.

The data for n-base cells are compared with data in Figure 6. Of particular interest is the fact that the performance degradation in n-base devices is less than in the corresponding p-base devices but in both cases is the result of diffusion length loss. Exceptions are copper and nickel. Copper appears to have little effect in either case except at very high concentrations. Nickel, however, exhibits an entirely different behavior. The efficiency of the nickel doped n-base cells was severely reduced while their short circuit currents were only slightly diminished. This indicates that the base diffusion length is not the controlling parameter but rather the effect of excessive junction dark current or contact degradation. Since these latter effects are acutely sensitive to minor variations in processing, it is necessary to repeat this experiment. It is apparent, however, that nickel does not produce large recombination effects in either n or p-base material.

The I-V data for some of these experiments as well as other recently processed ingots appear in Appendix 7.7.

FIGURE 6 Normalized solar cell efficiency as a function of substrate metal impurity concentration. Experimental data and model derived curves - Foreground shows N-base data, Background is for P-base.

4. CONCLUSIONS

Increased pulling speed during Czochralski growth (1.9 to 15 cm/hr) enhances the segregation of Mn to the growing ingot. Solar cells processed on material grown at high rates give lower efficiencies (by about 13%) than those made from the slowly-pulled ingot. Cellular structures promoted in silicon by rapid growth also reduce the yield of cell quality material.

Wafer cleaning is critical to retain high recombination lifetime when subsequent high temperature annealing or gettering treatments are to be employed. Good DI-wafer rinses appear to be more effective than complicated chemical cleaning.

Solar cells fabricated on polycrystalline material respond differently depending on what impurity is present in the poly ingot. For example, Ti produces similar degradation in cell performance on both poly and single crystalline substrates. Mn doped poly, however, produces considerably poorer cells than achieved for the same Mn level in single crystal material.

Deep Level Transient Spectroscopy appears to be a powerful tool for evaluating the effects of impurities on silicon and silicon solar cells. The method when calibrated gives direct evidence of which contaminants are present in a cell with suitable refinements the amount of electrically active impurity should be measurable as well.

5. PROGRAM STATUS

5.1 Present Status

The program, as Figure 7 illustrates, is on schedule. We expect all elements to be completed by the end of Phase II, May 1978. During this quarter we have:

- Completed the growth of 17 Czochralski and float zone ingots. Ingot growth for Tasks 1, 2, 3, 5 and 6 is now finished.
- Completed Neutron Activation Analysis of almost all ingots. The data show good agreement with previous results and targeted ingot values except for Mo and Zr. (Here the data suggest that the original estimated segregation coefficients for these impurities must be revised downward).
- Developed cleaning procedures to minimize wafer contamination during thermal processing and gettering so that adequate minority carrier lifetime can be maintained during high temperature treatments.
- Applied Deep Level Spectroscopy directly to impurity-bearing solar cells to detect impurity trapping levels and electrically active impurity concentrations in the devices.
- Demonstrated the effects of ingot growth rate on subsequent impurity partitioning and solar cell performance.
- Completed preliminary measurements of impurity-grain boundary interactions.
- Completed solar cell fabrication and analysis on 15 impurity-doped n and p type ingots.

Program
MILESTONE CHART

Fig. 7

5.2 Future Activity

During the next quarter we will complete all elements comprising Phase II of this program. We will report at that time a summary of all pertinent results to date.

6. REFERENCES

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7. APPENDICES

Appendix 7.1 Ingot Resistivity and Etch Pit Density Data

<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 (F)	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 (F)	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-C70-Al-003	4.0 (B)	2.2 - 1.1	0 - 1 K
W-071-Co-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)

Appendix 7.1 Ingot Resistivity and Etch Pit Density (cont.)

<u>Ingot Identification</u>	<u>TGT Resistivity (ohm-cm)</u>	<u>Actual Resistivity (ohm-cm)</u>	<u>Etch Pit Density (/cm)</u>
W-077-Mo-001	4.0 (B)	4.3 - 3.8	0 - Gross Lineage
W-078-00-000	4.9 (B)	4.3 - 3.3	0 - 80 K
W-079-00-000	1.5 (P)	2.3 - 1.1	1 K - 10 K
W-080-Ph-001	4.0 (B)	6.3 - 3.8	0 - 5 K
W-081-N/Ni-001	1.5 (P)	2.2 - 1.4	1 K - 4 K
W-082-N/V-001	1.5 (P)	1.8 - 1.5	0 - 6 K
W-083-N/Fe-001	1.5 (P)	2.1 - 1.3	1 K - Gross Lineage
W-084-N/Al-001	1.5 (P)	7.5 - 1.9	1 K - 80 K
W-085-N/Zr-001	1.5 (P)	2.4 - 1.5	1 K - 20 K
W-086-C-001	4.0 (B)	4.0 - 3.5	0 K - 20 K ⁺
W-087-Ca-001	4.0 (B)	3.8 - 3.4	0 ⁺⁺
W*-088-Cr-001	0.2 (B)	0.2 - 0.18	1 K - 20 K
W*-089-Cu-001	0.2 (B)	0.21 - 0.19	0 - 20 K
W*-090-Mn-001	0.2 (B)	0.21 - 0.20	1 K - 3 K
W-091-Cr/Mn-002	4.0 (B)	5.5 - 3.5	0 - Gross Lineage
W-092-Ph-002	4.0 (B)	1.7 - 5.6	0 - 1 K
W*-093-Mn-004	4.0 (B)	4.9 - 5.3	1 K - 5 K
W-094-Mn-005 (Poly)	4.0 (B)	2.8 - 4.2	N/A
W-095-Mn-006 (F)	4.0 (B)	4.2 - 4.9	0 - 12 K
W-096-Mr-007 (S)	4.0 (B)	4.6 - 4.6	0 - 2 K
W-097-00-000	4.0 (B)	3.2 - 4.2	0
W-098-Mo-002	4.0 (B)	3.6 - 4.3	0 - 10 K
W-099-FZ-001	4.0 (B)	4.2 - 4.4	5 K - 20 K
W-100-Cu/Ti-002	4.0 (B)	3.4 - 5.2	0 - Gross Lineage

Appendix 7.1 Ingot Resistivity and Etch Pit Density (cont.)

Ingot Identification	TGT Resistivity (ohm-cm)	Actual Resistivity (ohm-cm)	Etch Pit Density (/cm)
W-101-FZ-002	4.0 (B)	4.4 - 4.9	3 K - 20 K
W-102-Ti-006 (Poly)	4.0 (B)	3.8 - 6.4	N/A
W*-103-Ti-001	0.2 (B)	0.23 - 0.25	0 - 30 K
W-104-Cu,Ti-003	4.0 (B)	3.8 - 4.2	2 K - Gross Lineage
W*-105-V-001	0.2 (B)	0.23 - 0.26	3 K - Gross Lineage
W-106-N/Al-002	1.5 (P)	2.1 - 2.9	0
W-107-VZ,Al-001	2.0 (B)	1.0 - 2.2	6 K - 15 K
W-108-N/V-002	1.5 (P)	2.3 - 1.4	0
W-109-C-002	4.0 (B)	4.6 - 3.6	0 - 3 K
W-110-FE-001	0.2 (B)	0.16 - 0.15	1 K
W-111-Cu,V-001	4.0 (B)	4.6 - 4.3	1 K
W-112-Ta-001	4.0 (B)	3.5 - 2.9	0 - Gross Lineage
W-113-FZ,CR-001	4.0 (B)	5.6 - 4.9	8 K - Twin
W-114-00-000	0.2 (B)	0.19 - 0.10	0 - 4 K
W-115-N/Cu-002	1.5 (P)	2.2 - 1.4	2 K - 10 K
W*-116-Ph-001	0.2 (B)	0.44 - 0.50	0 - 50 K
W-117-00-000	4.0 (B)	4.1 - 3.7	0 - Gross Lineage
W-118-Ph-003	4.0 (B)	1.17 -	0 - 1 K
W-119-N/FE-002	1.5 (F)	3.1 - 1.5	1 K - Gross Lineage
W-120-N/CR-002	1.5 (F)	1.9 - 1.6	0 - Gross Lineage
W-121-N/TI-002	1.5 (F)	2.2 - 1.4	2 K - 40 K
W-122-TI-007	4.0 (B)	4.1 - 4.5	10 K - Gross Lineage
W-123-TI-008	4.0 (B)	3.8 - 3.6	0 - 20 K

* Use of asterisk indicates low resistivity p-type ingot.

** 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.

+ Twinning due to high carbon concentration occurred after approximately three inches of crystal growth.

++ Multiple crystal growth due probably to Ca O formation.

Appendix 7.2 Carbon and Oxygen Concentration Data

<u>Ingot Number</u>	<u>Carbon Concentration x 10¹⁶ atoms/cm³</u>	<u>Oxygen Concentration x 10¹⁶ atoms/cm³</u>
W-055-Cu-004	11.3	118
W*-057-00-000	**	**
W*-059-00-000	**	**
W-061-Cr/Ti-001	<2	181
W-063-N/Cu-001	4.4	164
W-065-N/Ti-001	<2	176
W-067-Cr/Mn/Ti-001	<2	226
W-069-Fe-004	<2	146
W-071-00-000	7.6	115
W-073-Cr/Mn/Ni/Ti/V-001	4.2	145
W-075-Ti/V-002	11.6	194
W-077-Mo-001	2.5	134
W-079-00-000	<2	157
W-081-N/Ni-001	5	216
W-083-N/V-001	5.5	136
W-085-N/Zr-001	<2	96
W-087-Ca-001	4.5	69
W*-089-Cu-001	**	**
W-091-Cr/Mn-002	20	111
W-093-Mn-004	7	161
W-095-Mn-005	4.2	151
W-097-00-000	13.2	142
W-099-FZ-001	<2	<5
W-101-FZ-002	<2	<5
W*-103-Ti-001	**	**
W*-105-V-001	**	**
W-107-FZ/Al-001	< 2	< 5
W-109-C-002	< 8 - 14	190 - 44

** Due to free carrier absorption infrared methods cannot be used for carbon and oxygen determination in these samples.

Appendix 7.2 Carbon and Oxygen Concentrations (cont.)

<u>Ingot Number</u>	<u>Carbon Concentration x 10¹⁶ atoms/cm³</u>	<u>Oxygen Concentration x 10¹⁶ atoms/cm³</u>
W-111-Cu/V-001	12.1	86
W-113-FZ/CR-001	< 2	< 5
W-115-N/Cu-002	8.3	112
W-117-00-000	4.9	160
W-119-N/FE-002	5.0	125
W-121-N/TI-002	4.7	121
W-123-TI-008	2.7	137

** Due to free carrier absorption infrared methods cannot be used for carbon and oxygen determination in these samples.

Appendix 7.3 Ingot Metal Impurity Concentration Data

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	0.1	0.06	<1
W-056-Cu-005	60	90	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: 1.1	Cr: 1.0	Cr: 1.0
	Ti: 0.02	Ti: 0.017	Ti: <1.0
W-062-N/Cu-001	2.5	2.0	2.0
W-063-N/Cr-001	0.83	0.88	1.0
W-064-N/Mn-001	1.0	0.64	2.0
W-065-N/Ti-001	0.37	0.30	0.75**
W-066-Ti-005	0.06	0.048	<0.2 (0.09)
W-067-Cr/Mn/Ti-001	Cr: 0.44	Cr: 0.3	Cr: 0.3 (0.075)
	Mn: 0.50	Mn: 0.36	Mn: 0.7 (0.066)
	Ti: 0.006	Ti: 0.0039	Ti: <0.2 (<0.2)
W-068-Cr-004	1.0	1.0	1.0 (0.44)
W-069-Fe-004	0.98	0.92	<1.5 (1.1)
W-070-Al-003	50 (4.75)	20 (1.9)	100 (3.0)
W-071-00-000	None	N/A	N/A
W-072-Cr-005	0.4	0.21	0.28
W-073-Cr/Mn/Ni/Ti/V-001	Cr: 0.48	Cr: 0.34	Cr: 0.28 (0.17)
	Mn: 0.46	Mn: 0.31	Mn: 0.8 (0.28)
	Ni: 2.0	Ni: 1.3	Ni: <2.0 (10)
	Ti: 0.004	Ti: 0.005	Ti: <0.35 (<0.3)
	V: 0.004	V: 0.007	V: <0.35

Appendix 7.3 Ingot Metal Impurity Concentration Data (Cont.)

Ingot Identification	Target Concentration 10^{15} atoms/cm ³	Calc. Concentration 10^{15} atoms/cm ³	Measured Concentration 10^{15} atoms/cm ³
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: 0.64 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	0.0042	0.0027	<0.3 (0.0042)
W-078-00-000	None	N/A	None
W-079-00-000	None	N/A	None
W-080-Ph-001	0.6	0.7	0.8 **
W-081-N/Ni-001	2.3	0.65	<2
W-082-N/V-001	0.4	0.475	0.85
W-083-N/Fe-001	1.0	0.86	<1.5 (1.0)
W-084-N/Al-001	50 (4.7)**	22 (2.1)**	40 (<2.5)**
W-085-N/Zr-001	0.0007	0.0005	<0.015 (<0.011)
W-086-C-001	300	N/A	200 - 300
W-087-Ca-001	1.0	0.13	?
W*-088-Cr-001	0.5	0.62	3.3
W*-089-Cu-001	2.3	2.13	0.5 (2.5)
W*-090-Mn-001	0.7	0.52	2.75 (0.69)
W-091-Cr/Mn-002	Cr: 0.5 Mn: 0.3	0.3 0.3	1.0 (--) 2.75 (0.5)

Appendix 7.3 Ingot Metal Impurity Concentration Data (Cont.)

Ingot Identification	Target Concentration 10 ¹⁵ atoms/cm ³	Calc. Concentration 10 ¹⁵ atoms/cm ³	Measured Concentration 10 ¹⁵ atoms/cm ³
W-092-Ph-002	28	N/A	27-30 **
W-093-Mn-004	0.66	0.46	2.75 (0.75)
W-094-Mn-005 (Poly)	0.9	0.63	2.75 (1.07)
W-095-Mn-006 (F)	0.5	0.42	2.75 (1.0)
W-096-Mn-007 (S)	0.63	0.55	0.25 (0.6)
W-097-00-000	None	N/A	N/A
W-098-Mo-002	0.00092	0.00042	<0.3
W-099-FZ-001	None	N/A	N/A
W-100-Cu/Ti-002	Cu 1.0	1.25	0.5
	Ti 0.06	0.07	<0.3
W-101-FZ-002	None	N/A	N/A
W-102-Ti-006 (Poly)	0.2	0.18	0.25
W*-103-Ti-001	0.3	0.25	0.25
W-104-Cu/Ti-003	Cu 2.0	2.2	4.0
	Ti 0.25	0.12	0.25
W*-105-V-001	0.4	0.7	0.85
W-106-N/Al-002	6.6	2.3	8.3 (0.7)**
W-107-FZ/Al-001	30	25	128 (12)**
W-108-N/V-002	0.08	0.098	<0.2
W-109-C-002	<20 - 140	N/A	<20 - 140
W*-110-FE-001	0.8	0.67	<2.0
W-111-Cu/V-001	2.5/0.3	2.5/0.34	2.6/0.25
W-112-Ta-001	0.01	0.0068	
W-113-FZ/CR-001	0.8	0.48	
W-114-00-000	---	N/A	N/A

Appendix 7.3 Ingot Metal Impurity Concentration Data (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-115-N/Cu-002	10		
W*-116-Ph-001	35		(100)**
W-117-00-000	--	N/A	NA
W-118-Ph-003	70		(140)**
W-119-NFE-002	0.3		
W-120-N/CR-002	0.3		
W-121-N/TI-002	0.67		
W-122-TI-007	0.15		
W-123-TI-008	0.188		

** Value based on resistivity measurement.

*** High Ti value possibly due to vacuum leak in M.S.

+ Value in parenthesis based on Neutron Activation Analysis

Appendix 7.4 Segregation Coefficient Data

<u>Element</u>	<u>Segregation Coefficient</u>
Al	3×10^{-2} (2.8×10^{-3})
B	0.8
C	0.05
Ca	?
Cu	8.0×10^{-4}
Cr	1.1×10^{-5}
Fe	6.4×10^{-6}
Mg	3.2×10^{-6}
Mn	1.3×10^{-5}
Mo	4.5×10^{-8}
Ni	3.2×10^{-5}
Ph	0.35
Ta	$\sim 10^{-7}$
Ti	3.6×10^{-6}
V	4×10^{-6}
Zn	10^{-5}
Zr	$< 1.6 \times 10^{-8}$

Appendix - 7.5

WAFER CLEANING PROCEDURES

Clean 1

- a. Strip aluminum^{*}
- b. Rinse in deionized water, 30 sec.
- c. Etch silicon, CP-4A (metal tweezers)
- d. Rinse in deionized water, 30 sec.
- e. N₂ blow dry.

Clean 2

- a. Strip aluminum^{*}, DI rinse, 30 sec.
- b. Etch silicon 10 sec, CP-4A, DI rinse
- c. Rinse with 4 parts H₂SO₄ + 1 part H₂O₂ @ 87°C
- d. Repeat step b.
- e. KMnO₄ etch⁺, 10 sec, DI rinse
- f. NH₄OH + H₂O₂, DI rinse 30 sec.
- g. H₂O₂ + HCL + H₂O, DI rinse 30 sec.
- h. N₂ blow dry.

Clean 3

- a. Strip aluminum^{*}, DI rinse 30 sec.
- b. Etch silicon CP-4A 10 sec, DI rinse 30 sec.
- c. Repeat step b.
- d. Rinse in deionized water 1 minute
- e. H₂O₂ + NH₄OH + H₂O, 10 min. @ 80°C
- f. Rinse in deionized water 30 sec.
- g. H₂O₂ + HCL + H₂O, 10 min @ 80°C.
- h. Rinse in deionized water, 30 sec.
- i. Blow dry.

Clean 4

- a. Strip aluminum^{*}, DI rinse 30 sec.
- b. Ultrasonic clean 5 min 17% sol FL70 @ 25°C.
- c. Rinse in deionized water 3 min.
- d. Repeat steps b and c.
- e. Ultrasonic DI water @ 90°C for 5 min.
- f. Rinse in DI for 3 min.
- g. H₂O₂ + NH₄OH + H₂O, 10 min @ 80°C. DI rinse 30 sec.
- h. H₂O₂ + HCL + H₂O, 10 min. @ 80°C, DI rinse 30 sec.
- i. Repeat steps g and h
- j. DI rinse 30 sec. N₂ blow dry.

^{*} Aluminum etch solution = 750 ml H₃PO₄, 140 ml H₂O, 30 ml HNO₃, and 150 ml CH₃COOH

+ Stain removal solution = 2 parts HF, 1 part 0.038M KMnO₄

Appendix - 7.5

WAFER CLEANING PROCEDURES

Clean 5

- a. Strip aluminum^{*}, DI rinse 30 sec.
- b. $\text{H}_2\text{O}_2 + \text{NH}_4\text{OH} + \text{H}_2\text{O}$, 10 min. @ 80°C, DI rinse 30 sec.
- c. $\text{H}_2\text{O}_2 + \text{HCL} + \text{H}_2\text{O}$, 10 min. @ 80°C, DI rinse 30 sec.
- d. Repeat steps b and c.
- e. DI rinse 30 sec.
- f. Rinse 5% HF solution 15 sec. DI rinse.
- g. Ultrasonic clean 10 sec. in quartz double distilled H_2O , 5 times
- h. Chelate^{**} ultrasonically 1 min., 5 times.
- i. Repeat step g.

Clean 6

- a. Strip aluminum^{*} DI rinse 30 sec.
- b. Rinse 3 min tetrachloroethylene ultrasonically, 3 times
- c. Rinse 1 minute in acetone ultrasonically.
- d. Rinse in distiller water 3 times.
- e. Ultrasonic 5% KOH 3 minutes
- f. Ultrasonic distille H_2O 2 min. 10 times.
- g. 50% KOH @ 50°C for 10 min.
- h. Distilled water rinse 1 min, 3 times.
- i. Rinse 1 min. 0.3% HCL ultrasonically
- j. Rinse distilled water 1 min, 6 times.
- k. Rinse 1 min propanol, 2 times.
- l. Dry wafers in vacuum oven 20 min.

^{**} Chelate solution = 1000 ml quartz distilled H_2O + 15 ml NH_4OH +
5 gr Ethylenediaminetetracetic Acid (EDTA)

Appendix 7.6

The program DEXP-V listed in Table 7.6.1 written for an HP67/97 calculator and five unknown parameters of the double exponential model for a silicon solar cell.

$$J \doteq J_{01} \exp \frac{V - JR_S}{V_T} + J_{02} \exp \frac{V - JR_S}{V_T} + \frac{V}{R_{SH}}$$

The required data consists of five dark current-voltage points, three in the low current segment and two in the high current segment. The IV data is stored in the secondary registers R_{10} through R. Data is entered or altered via subroutine f_b as follows. Press f_b , a cue will appear indicating the register index $(10)^b$, then enter J_1 press R/S, the cue will show 11, enter V_1 followed by R/S...continue in this manner to the last entry, V_5 in R_{19} . Alternatively, to review or edit the data press f_b followed by R/S, R/S....if no data is entered from the key board the display will show the index cues and corresponding data as it is stored. To change any displayed number, enter the new value followed by R/S.

With all the IV data entered press A to find R_{SH} (This will take 1 minute plus).

Then in order B, C, D, E will find N , I_{02} , R_S , and I_{01} respectively. These data are stored for review or later use as follows:

$$\begin{aligned} \text{Register E} &= J_{01} \text{ (A/cm}^2\text{)} \\ \text{" C} &= J_{02} \text{ (A/cm}^2\text{)} \\ \text{" B} &= n \\ \text{" D} &= R_S \text{ ohm cm}^2 \\ \text{" A} &= R_{SH} \text{ ohms} \end{aligned}$$

This five point algorithm generally gives reliable answers provided the three low current points, (I_1 , I_2 , and I_3) lie below the knee of $\log I$ vs V (typically for $.2 \leq V \leq .3$) and the high current points (I_4 and I_5) well above ($V > .4$).

An example from experimental data is given in the text, see section 3.4.2.

A second program LTAU-III, listed in Table 7.6.2, is used to determine the base diffusion length and lifetime from the saturation current I_{01} found and stored in register E by DEXP. These calculations require additional data, entered using f_b . Key N_A (the base acceptor concentration/cm³) press ENTER, key W_E (the base width in microns) press ENTER, key D_n (the base diffusion constant in cm²/s) press R/S. These are stored in registers R_0 , R_1 , and R_2 respectively.

The equation to be solved depends on the boundary conditions imposed by the device structure. For a back surface with zero surface recombination velocity, corresponding approximately to a back-surface-field device the equation is:

$$\frac{q n_i^2 D_n}{N_A L_n} \tanh\left(\frac{W_B}{L_n}\right) - J_{01} = 0$$

Subroutine A solves this equation for L_n ; ie, the BSF case. For a device without back field; $s \neq \infty$, the hyperbolic tangent is replaced by the hyperbolic cotangent. Subroutine B finds L_n for this case, that of a conventional ohmic back device.

You will find if you use the wrong boundary case that the value obtained may be unreasonably large or small. The internal algorithm places an upper bound on L_n of approximately 9922 μ m. If this value occurs it implies that the input IV data and the boundary case are inconsistent. An example of this is the data given in section 3.4.2 for the back-field device SOLEP-108. Solved using the $s = 0$ (BSF) routine gives $L_n = 472\mu$ m and a lifetime, $\tau_n = 67\mu$ s; but using the $s = \infty$

(ohmic) routine, L_n is given the impossible value of $9921\mu\text{m}$ and $\tau_n = 29800\mu\text{s}$.

The lifetime, τ_n is found using subroutine C using the usual relationship

$$\tau_n = (L_n^2)/D_n$$

The five parameters of the IV equation found using DEXP-V are not altered during execution of the routines of LTAU-III. So that the routine D can be used to calculate the current given a voltage from the curve-fit parameters. Key the desired voltage and press D. Remember the IV equation is algebraically irreducible in I if R_s is significant it is necessary to use an iterative algorithm; it takes about one minute per point. If the device is known to have negligible series resistance; store 0 in R_1 , the desired voltage in R_2 , press GSB₆. This one pass approximation is very fast.

001	*LBLA	057	-	113	3	169	STO2
002	1	058	+	114	3	170	ISZ1
003	STO7	059	RTN	115	CHS	171	RCL1
004	.	060	*LBL1	116	STO1	172	ST-0
005	0	061	1	117	STO1	173	ISZ1
006	1	062	STO0	118	*LBLB	174	RCL1
007	0	063	4	119	RCL2	175	ST-1
008	STO3	064	2	120	1/X	176	GSEa
009	F03	065	CHS	121	STO6	177	-
010	EEA	066	STO1	122	R/S	178	RCL2
011	0	067	GSE1	123	*LBLC	179	XZY
012	RCL1	068	STO2	124	1	180	+
013	RCL0	069	5	125	4	181	LN
014	+	070	STO0	126	STO1	182	RCL5
015	F03	071	5	127	RCL1	183	X
016	STO3	072	3	128	ISZ1	184	ST-1
017	.	073	CHS	129	RCL1	185	RCL0
018	STO3	074	STO1	130	RCLH	186	ST+1
019	STO4	075	GSE1	131	+	187	RCL1
020	GSE1	076	RCL2	132	-	188	STO0
021	X/01	077	-	133	RCL1	189	RTN
022	GSE2	078	RTN	134	RCL5	190	*LBLB
023	RTN	079	*LBL2	135	+	191	1
024	R/S	080	RCLH	136	RCLB	192	0
025	*LBL0	081	EEA	137	+	193	STO1
026	1	082	2	138	e^X	194	RCL1
027	0	083	+	139	+	195	RCL0
028	STO1	084	RCL2	140	STO0	196	X
029	RCL1	085	+	141	R/S	197	ISZ1
030	ISZ1	086	RCL3	142	*LBLA	198	RCL1
031	RCL1	087	RCL6	143	STO4	199	-
032	STO1	088	+	144	RCL2	200	RCL5
033	RCLH	089	2	145	+	201	+
034	+	090	+	146	RCL5	202	RCL2
035	-	091	STO4	147	+	203	LN
036	RCLC	092	XZY	148	e^Y	204	+
037	+	093	RTN	149	1	205	e^X
038	RCL0	094	3	150	+	206	STO6
039	RCL1	095	0	151	RCLC	207	RTN
040	+	096	CHS	152	X	208	*LBLB
041	STO1	097	STO1	153	RCL4	209	1
042	XZY	098	GSE1	154	RCLH	210	0
043	RCL1	099	RCL7	155	+	211	STO1
044	ISZ1	100	+	156	+	212	+
045	RCL1	101	X/01	157	RTN	213	F03
046	RCLH	102	STO3	158	*LBLC	214	STO1
047	+	103	RCLH	159	1	215	0
048	-	104	STO6	160	0	216	STO0
049	RCLC	105	3	161	STO1	217	*LBLC
050	+	106	0	162	RCL1	218	RCL1
051	-	107	LAS	163	STO6	219	F03
052	LN	108	STO1	164	ISZ1	220	RCL1
053	RCL5	109	STO1	165	RCL1	221	R/S
054	+	110	*LBL9	166	STO1	222	STO1
055	RCL1	111	RCLH	167	GSEa	223	ISZ1
056	RCL1	112	STO5	168	-	224	STO3

TABLE 7.6.1 Program DEXP-V for Determining I_{O1} , I_{O2} , n , R_S and R_{SH} from IV data using an HP67/97 calculator.

001	*LBL1	057	ST05	113	ROLB	169	ST05
002	ROL2	058	GT02	114	+	170	3
003	ROL3	059	*LBLA	115	e ^x	171	8
004	+	060	CF0	116	1	172	CHS
005	2	061	*LBL5	117	-	173	ST01
006	+	062	1	118	ROL0	174	GT01
007	e	063	ST05	119	+	175	R/S
008	ENT1	064	CHS	120	ROL0		
009	ENT1	065	ST07	121	e ^x		
010	+	066	EEN	122	1		
011	-	067	4	123	-		
012	XZV	068	ST06	124	ROL0		
013	1	069	GS02	125	+		
014	+	070	RTN	126	+		
015	+	071	*LBL6	127	ROL0		
016	FD1	072	SF0	128	ROL9		
017	1	073	GS03	129	+		
018	ROL3	074	RTN	130	ROLA		
019	+	075	*LBL0	131	+		
020	ROL1	076	ROL3	132	+		
021	+	077	1	133	ROL1		
022	ROL0	078	0	134	-		
023	+	079	+	135	RTN		
024	3	080	ENT1	136	*LBL7		
025	0	081	+	137	ROL1		
026	EEN	082	ROL1	138	2		
027	4	083	+	139	5		
028	+	084	RTN	140	+		
029	ROL0	085	*LBLB	141	ROL5		
030	-	086	ST02	142	+		
031	RTN	087	RJ	143	ROL5		
032	*LBL2	088	ST01	144	ROL6		
033	ROL3	089	RJ	145	+		
034	EEN	090	ST00	146	2		
035	2	091	R/S	147	+		
036	+	092	*LBLD	148	ST01		
037	ROL5	093	ST02	149	XZV		
038	+	094	0	150	RTN		
039	ROL7	095	ST05	151	5		
040	ROL3	096	1	152	1		
041	+	097	0	153	CHS		
042	2	098	ST00	154	ST01		
043	+	099	1	155	GS01		
044	ST03	100	CHS	156	ROL7		
045	XZV	101	ST07	157	+		
046	RTN	102	GS07	158	XZV		
047	GS01	103	RTN	159	ST00		
048	ROL7	104	*LBL6	160	ROL1		
049	+	105	ROL2	161	ST00		
050	XZV	106	ROL1	162	3		
051	GT01	107	ROL0	163	0		
052	ROL3	108	+	164	CHS		
053	ST06	109	-	165	ST01		
054	GT02	110	ROL5	166	ST01		
055	*LBL4	111	+	167	*LBL8		
056	ROL3	112	ST00	168	ROL1		

TABLE 7.6.2 Program LTAU-III for Determining Diffusion Length and Lifetime using an HP67/97 Calculator.

Appendix 7.7

7.7 Photovoltaic Characteristics of Solar Cells Fabricated on Impurity Doped Czochralski Ingots

Test Conditions: no AR coatings, cell area 1 cm^2 and illumination 91.6 mn/cm^2

Abbreviations: R - calibrated reference device
C - wafers from ingot center
T - wafers from ingot tary and
S - wafers from ingot seed and
B - wafers from uncontaminated baseline ingots

71101 W092PH002 (2.8E16) W078 00 000
 *SOL6 4 /20/78 AM1: PO=91.60MW/CM*2 NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD	PCDA	PCDP
1R*	22.50	.555	20.11	-6.138	2.06	-.40	.713	9.41	.00	.00	.00
1B	22.40	.550	20.05	-6.113	2.06	-.69	.721	9.39	4.55	.00	.00
2B	22.10	.553	20.00	-6.600	1.87	-.74	.742	9.59	4.55	.00	.00
3B.*	22.30	.550	19.85	-5.724	2.26	-1.37	.724	9.40	3.90	.00	.00
4B.*	21.80	.545	17.69	-3.556	4.79	-5.61	.650	8.16	3.12	.00	.00
5B.*	22.40	.547	19.13	-4.490	3.22	-2.71	.684	8.86	2.60	.00	.00
1C	22.30	.566	19.52	-5.144	2.71	-1.91	.706	9.43	3.51	.00	.00
2C	22.10	.561	19.05	-4.751	3.03	-2.29	.690	9.04	3.12	.00	.00
3C	22.30	.550	18.66	-4.275	3.50	-2.18	.648	8.40	1.30	.00	.00
4C	22.60	.564	19.78	-5.134	2.70	-1.90	.707	9.53	5.20	.00	.00
5C	22.10	.562	19.22	-4.960	2.84	-2.13	.700	9.19	2.73	.00	.00
6C	22.40	.565	19.60	-5.136	2.71	-1.86	.705	9.43	3.90	.00	.00
7C	22.60	.562	19.78	-5.104	2.71	-1.99	.708	9.51	4.55	.00	.00
8C	21.70	.564	19.30	-5.705	2.33	-1.48	.724	9.37	3.38	.00	.00
9C	22.40	.567	19.89	-5.672	2.35	-1.32	.719	9.66	4.55	.00	.00
10C	22.40	.566	19.51	-4.987	2.83	-2.10	.702	9.41	2.99	.00	.00
11C	22.00	.563	19.08	-4.894	2.91	-2.17	.696	9.12	2.99	.00	.00
12C	22.20	.565	19.64	-5.490	2.46	-1.60	.718	9.52	4.16	.00	.00
1S	22.20	.568	19.85	-5.918	2.23	-1.28	.730	9.73	4.55	.00	.00
2S	21.70	.565	18.85	-4.844	2.97	-2.71	.706	9.16	3.64	.00	.00
3S	22.30	.565	19.56	-5.234	2.63	-1.70	.706	9.40	3.25	.00	.00
4S	22.10	.565	19.45	-5.353	2.55	-1.62	.710	9.38	3.64	.00	.00
5S	22.50	.565	19.81	-5.319	2.57	-1.76	.714	9.59	3.90	.00	.00
1T	21.90	.563	19.43	-5.760	2.29	-.94	.711	9.27	4.16	.00	.00
2T	22.00	.567	19.68	-6.045	2.16	-.93	.724	9.55	3.51	.00	.00
3T	22.30	.562	20.13	-6.467	1.95	-.66	.734	9.73	4.68	.00	.00
4T	22.10	.561	19.93	-6.445	1.96	-.59	.731	9.58	4.55	.00	.00
5T	22.50	.559	19.80	-5.435	2.47	-1.19	.703	9.35	3.90	.00	.00

AVERAGES: 71101 BASELINE W078 00 000

	22.25	.552	20.04	-6.361	1.96	-.71	.732	9.49	4.55	.00	.00
STD	.15	.002	.01	.248	.10	.03	.011	.10	.00	*	*
	71101 W092PH002 (2.8E16)										
	22.21	.563	19.52	-5.367	2.58	-1.65	.709	9.38	3.73	.00	.00
STD	.25	.004	.36	.528	.36	.54	.017	.28	.83	*	*
PERCENT OF BASELINE											
	99.8	102.2	97.4	115.6	132	-32.0	96.9	98.8	82.1	*****	*****
STD%	1.8	.9	1.9	11.9	26	87.4	3.8	4.0	18.2	*****	*****

71108 W093MN004 (6.6E14) W078 00 000
 *SOL6 4 /20/78 AM1: P0=91.60MW/CM:2 NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD	PCDA	PCDP
1R*	22.50	.556	20.08	-6.076	2.10	-.46	.712	9.42	.00	.00	.00
1B	22.40	.548	20.32	-6.899	1.74	-.08	.731	9.50	5.85	.00	.00
2B.	22.50	.548	19.88	-5.637	2.29	-.84	.704	9.17	4.29	.00	.00
3B*	21.40	.525	15.56	-3.164	5.82	-2.36	.506	6.01	.65	.00	.00
4B.*	22.50	.539	18.74	-4.255	3.45	-1.86	.639	8.19	1.95	.00	.00
5B.*	22.40	.545	19.37	-4.989	2.73	-1.27	.679	8.76	3.64	.00	.00
1B	21.90	.551	19.71	-6.363	1.96	-.62	.729	9.30	4.55	.00	.00
2B	21.90	.549	19.70	-6.346	1.96	-.62	.728	9.26	4.16	.00	.00
3B	22.20	.547	19.59	-5.547	2.35	-1.05	.705	9.05	3.90	.00	.00
4B	22.20	.549	19.84	-6.007	2.11	-.88	.722	9.31	3.90	.00	.00
1C	21.00	.536	18.17	-5.056	2.65	-1.24	.679	8.08	1.30	.00	.00
2C	20.70	.538	18.12	-5.287	2.49	-1.43	.698	8.22	1.04	.00	.00
3C	20.70	.531	17.49	-4.558	3.09	-1.61	.652	7.58	.91	.00	.00
4C	20.50	.531	17.84	-5.145	2.57	-1.44	.689	7.93	.91	.00	.00
5C	20.80	.529	17.85	-5.031	2.64	-.57	.657	7.65	1.04	.00	.00
6C	20.90	.533	18.16	-5.193	2.53	-1.05	.682	8.03	1.30	.00	.00
7C	20.70	.534	18.04	-5.174	2.56	-1.48	.693	8.10	1.30	.00	.00
8C	20.90	.534	18.23	-5.224	2.52	-1.31	.691	8.16	1.30	.00	.00
9C	20.60	.534	18.18	-5.545	2.31	-1.24	.707	8.23	1.30	.00	.00
10C	20.40	.528	17.58	-4.884	2.76	-1.76	.680	7.75	.78	.00	.00
11C	20.80	.534	18.50	-5.941	2.09	-.64	.710	8.33	1.30	.00	.00
12C	21.00	.539	19.08	-6.973	1.70	-.16	.735	8.80	2.08	.00	.00
1S	20.70	.536	18.11	-5.296	2.48	-1.32	.695	8.16	1.30	.00	.00
2S	21.00	.543	19.09	-6.959	1.72	-.26	.738	8.90	1.95	.00	.00
3S	21.20	.540	19.01	-6.248	1.97	-.59	.722	8.74	1.82	.00	.00
4S	20.60	.533	17.55	-4.816	2.84	-.95	.653	7.58	.91	.00	.00
5S	21.20	.544	19.35	-7.241	1.63	-.11	.743	9.06	2.21	.00	.00
1T	20.30	.532	17.82	-5.381	2.41	-1.43	.703	8.02	.91	.00	.00
2T	20.90	.535	18.55	-5.801	2.17	-.90	.711	8.41	1.96	.00	.00
3T	20.40	.528	17.63	-4.947	2.71	-1.72	.684	7.79	.91	.00	.00
4T	20.40	.529	17.79	-5.142	2.56	-1.70	.696	7.95	1.04	.00	.00
5T.*	20.40	.424	17.36	-3.334	4.28	*****	.852	7.79	.78	.00	.00
6T.*	20.40	.424	17.07	-3.159	4.78	*****	.825	7.54	.65	.00	.00

AVERAGES: 71108 BASELINE W078 00 000
 22.40 .548 20.32 -6.899 1.74 -.08 .731 9.50 5.85 .00 .00
 STD .00 .000 .00 .000 .00 .00 .000 .00 .00 * *
 71108 W093MN004 (6.6E14)
 20.75 .534 18.20 -5.516 2.40 -1.09 .696 8.16 1.31 .00 .00
 STD .25 .004 .54 .732 .38 .51 .025 .41 .43 * *
 PERCENT OF BASELINE
 92.6 97.5 89.5 120.0 138 ***** 95.2 86.0 22.4 ***** *****
 STD% 1.1 .8 2.6 10.6 22 627.5 3.4 4.4 7.3 ***** *****

71109 W094 MN 005 (9E14) (SINTERED) POLY INGOT W078 00 000
 *SOL6 4 /20/78 AM1: PQ=91.60MW/CM*2 NO AP COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDB
1R*	22.50	.555	20.22	-6.379	1.96	-.33	.721	9.52	.00	.00	.00
1E	22.00	.551	19.79	-6.222	2.02	-1.00	.735	9.43	4.29	.00	.00
2R.*	22.10	.547	18.95	-4.621	3.08	-2.40	.684	8.74	2.86	.00	.00
3E.*	21.80	.544	19.22	-5.379	2.44	-1.67	.714	8.95	3.25	.00	.00
4B.	22.10	.546	19.45	-5.389	2.44	-1.41	.707	9.02	3.25	.00	.00
1C.	17.90	.304	10.67	-5.784	1.26	10.60	.316	1.82	.00	.00	.00
2C.	18.00	.315	10.96	-5.153	1.54	9.80	.328	1.97	.00	.00	.00
3C.	17.10	.245	10.23	-7.391	.73	9.76	.312	1.38	.00	.00	.00
4C.	13.70	.193	7.88	-7.422	.58	10.13	.299	.84	.00	.00	.00
5C.	13.30	.155	7.74	-15.404	.19	9.29	.296	.64	.00	.00	.00
6C.	17.10	.265	10.49	-6.421	.95	9.63	.325	1.56	.00	.00	.00
7C	20.30	.515	17.49	-5.137	2.50	-.49	.661	7.31	.00	.00	.00
8C.	17.70	.328	10.66	-5.854	1.34	11.41	.320	1.96	.00	.00	.00
9C.	15.40	.170	9.24	-12.255	.27	8.27	.307	.85	.00	.00	.00
10C.	16.60	.234	9.77	-6.584	.81	9.47	.309	1.27	.00	.00	.00
11C.	18.30	.360	10.90	-4.797	1.97	10.94	.322	2.24	.00	.00	.00
1S.	18.50	.394	11.39	-5.064	1.98	11.53	.334	2.57	.00	.00	.00
2S.	18.50	.393	11.33	-5.316	1.83	12.02	.330	2.54	.00	.00	.00
3S	19.90	.522	17.45	-5.504	2.29	-.81	.691	7.59	.00	.00	.00
4S.	20.10	.523	16.79	-4.159	3.55	-3.31	.658	7.32	.00	.00	.00
5S.	18.30	.424	11.30	-5.932	1.69	13.76	.330	2.70	.00	.00	.00
1T.	15.70	.172	9.38	-9.419	.38	7.92	.309	.88	.00	.00	.00
4T.	16.30	.189	13.43	-13.220	.28	5.32	.458	1.49	.00	.00	.00

AVERAGES: 71109 BASELINE W078 00 000

	22.00	.551	19.79	-6.222	2.02	-1.00	.735	9.43	4.29	.00	.00
STD	.00	.000	.00	.000	.00	.00	.000	.00	.00	*	*
	71109 W094 MN 005 (9E14) (SINTERED) POLY INGOT										
	20.10	.519	17.47	-5.320	2.40	-.65	.676	7.45	.00	.00	.00
STD	.20	.004	.02	.184	.10	.16	.015	.14	.00	*	*
PERCENT OF BASELINE											
	91.4	94.1	88.3	114.5	119	135.2	91.9	79.0	.0	*****	*****
STD%	.9	.6	.1	3.0	5	16.3	2.0	1.5	.0	*****	*****

71208 W095MN006(F) (1E15) W097 00 000
 *SOL6 4 /20/78 AM1: P0=91.60MW/CM² NO AP COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDR
1R*	22.50	.555	20.19	-6.332	1.98	-.30	.718	9.48	.00	.00	.00
1B.	22.80	.551	20.36	-5.951	2.14	-.90	.722	9.59	3.90	.00	.00
2R*	20.40	.525	17.65	-5.209	2.49	-.61	.669	7.58	.65	.00	.00
3B	22.70	.550	20.66	-7.009	1.71	-.21	.740	9.77	.49	.00	.00
4B.	22.40	.546	19.87	-5.754	2.22	-.87	.710	9.19	3.25	.00	.00
5B.	22.90	.543	19.73	-4.774	2.89	-1.87	.684	9.00	2.60	.00	.00
6B.*	22.70	.543	19.52	-4.862	2.82	-1.28	.671	8.75	3.77	.00	.00
1C	20.50	.534	18.17	-5.632	2.26	-1.47	.718	8.32	.91	.00	.00
2C	20.50	.534	18.47	-6.373	1.90	-.85	.734	8.50	1.17	.00	.00
3C	20.50	.524	17.46	-4.579	3.03	-2.24	.671	7.62	.65	.00	.00
4C	20.50	.531	18.01	-5.354	2.42	-1.59	.706	8.13	.91	.00	.00
5C	20.20	.526	17.56	-5.003	2.66	-2.11	.698	7.85	.91	.00	.00
6C	20.50	.529	17.98	-5.268	2.47	-1.77	.707	8.10	1.04	.00	.00
7C	20.30	.537	18.13	-5.911	2.13	-1.33	.728	8.39	1.17	.00	.00
8C	20.40	.533	17.66	-4.954	2.73	-1.87	.688	7.91	.91	.00	.00
9C	20.40	.528	17.60	-4.868	2.78	-1.98	.685	7.81	.78	.00	.00
10C	20.40	.528	17.46	-4.649	2.98	-2.34	.679	7.73	.78	.00	.00
11C.*	20.30	.525	16.91	-4.119	3.61	-3.28	.654	7.37	.65	.00	.00
1S	20.70	.536	18.17	-5.262	2.50	-1.89	.710	8.33	.91	.00	.00
2S	20.70	.534	18.04	-5.050	2.65	-2.05	.701	8.20	.91	.00	.00
3S	21.00	.539	18.81	-5.984	2.09	-1.34	.733	8.78	1.30	.00	.00
4S	21.00	.535	18.34	-5.110	2.60	-1.95	.704	8.36	1.17	.00	.00
5S	20.80	.535	18.48	-5.791	2.17	-1.09	.716	8.42	1.17	.00	.00
6S	20.80	.535	18.48	-5.791	2.17	-1.09	.716	8.42	1.17	.00	.00
1T.*	20.30	.523	16.81	-4.009	3.77	-3.62	.651	7.31	.52	.00	.00
2T	20.50	.527	17.65	-4.778	2.85	-2.22	.686	7.84	.65	.00	.00
3T	20.70	.526	17.65	-4.561	3.05	-2.40	.675	7.77	.52	.00	.00
4T.*	20.30	.525	17.09	-4.285	3.38	-3.06	.666	7.50	.65	.00	.00
5T	20.30	.531	17.95	-5.519	2.32	-1.68	.718	8.19	1.04	.00	.00
6T	20.60	.526	17.74	-4.789	2.83	-2.13	.685	7.85	.65	.00	.00

AVERAGES: 71208 BASELINE W097 00 000

	22.70	.550	20.66	-7.009	1.71	-.21	.740	9.77	.49	.00	.00
STD	.00	.000	.00	.000	.00	.00	.000	.00	.00	*	*

71208 W095MN006(F) (1E15)

	20.57	.531	17.99	-5.261	2.53	-1.77	.703	8.13	.94	.00	.00
STD	.22	.004	.38	.506	.33	.44	.019	.31	.21	*	*

PERCENT OF BASELINE

	90.6	96.6	87.1	124.9	148	*****	95.0	83.2	189.5	*****	*****
STD%	.9	.8	1.8	7.2	19	210.4	2.5	3.1	42.9	*****	*****

71213 W096MN007 (6.3E14) W097 00 000
 *SOL6 4 /20/78 AM1: P0=91.60MW/CM:2 NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDF
1R*	22.50	.553	20.18	-6.285	1.99	-.39	.719	9.46	.00	.00	.00
1B.	22.50	.549	19.79	-5.289	2.52	-1.73	.712	9.31	4.16	.00	.00
2B.	22.30	.545	19.85	-5.809	2.19	-1.04	.718	9.23	3.77	.00	.00
3F	22.20	.548	19.88	-6.100	2.06	-.82	.725	9.32	4.03	.00	.00
4F	22.20	.548	20.13	-6.626	1.84	-.79	.745	9.59	3.90	.00	.00
1C	22.50	.547	19.78	-5.315	2.49	-1.55	.708	9.22	3.64	.00	.00
2C	22.70	.548	20.21	-5.809	2.20	-1.05	.720	9.47	3.90	.00	.00
3C	22.60	.539	19.14	-4.490	3.17	-1.85	.660	8.50	2.21	.00	.00
4C	22.60	.543	19.15	-4.380	3.32	-2.54	.670	8.70	2.60	.00	.00
5C	22.30	.546	19.57	-5.228	2.55	-1.74	.708	9.12	3.25	.00	.00
6C	22.60	.548	20.09	-5.717	2.25	-1.18	.719	9.42	3.77	.00	.00
7C	22.30	.549	20.04	-6.176	2.03	-.99	.734	9.50	4.55	.00	.00
8C	22.30	.547	19.76	-5.587	2.32	-1.36	.717	9.25	4.42	.00	.00
9C	22.50	.546	19.77	-5.327	2.48	-1.45	.706	9.17	2.99	.00	.00
1S	22.40	.548	20.04	-5.990	2.11	-1.05	.728	9.44	3.38	.00	.00
2S	22.30	.546	19.80	-5.684	2.26	-1.24	.719	9.25	3.90	.00	.00
3S	22.60	.548	20.17	-5.885	2.16	-1.08	.724	9.48	4.55	.00	.00
4S	22.50	.541	19.88	-5.530	2.33	-1.23	.711	9.15	4.29	.00	.00
5S	22.40	.546	20.14	-6.220	2.00	-.90	.733	9.48	3.64	.00	.00
6S	22.40	.546	19.81	-5.482	2.38	-1.50	.716	9.27	3.64	.00	.00
1T	21.60	.541	19.16	-5.748	2.21	-.94	.711	8.78	1.95	.00	.00
2T	21.90	.535	18.88	-4.885	2.77	-1.56	.679	8.42	1.30	.00	.00
3T	22.00	.542	19.76	-6.332	1.94	-.44	.722	9.10	2.60	.00	.00
4T	22.10	.536	19.21	-5.122	2.58	-1.20	.685	8.58	1.69	.00	.00
5T	22.10	.543	20.14	-7.239	1.62	.18	.734	9.31	2.99	.00	.00
6T	22.00	.536	19.04	-4.997	2.68	-1.36	.681	8.50	1.69	.00	.00

AVERAGES: 71213 BASELINE W097 00 000

	22.20	.548	20.01	-6.363	1.95	-.81	.735	9.45	3.97	.00	.00
STD	.00	.000	.12	.263	.11	.01	.010	.13	.06	*	*
	71213 W096MN007 (6.3E14)										
	22.32	.544	19.69	-5.578	2.37	-1.24	.709	9.10	3.19	.00	.00
STD	.27	.004	.41	.632	.38	.52	.021	.36	.97	*	*
PERCENT OF BASELINE											
	100.5	99.2	98.4	112.3	122	46.1	96.5	96.3	80.4	*****	*****
STD%	1.2	.8	2.7	14.0	28	68.0	4.2	5.2	26.2	*****	*****

71214 W098 M0 002 (9.2E11) W097 00 000
 *SOL6 4 /20/78 AM1: P0=91.60MW/CM:2 NO AR COATING

ID	ISC	VOC	IP	LOG(I/O)	N	R	FF	EFF	OCD	PCDA	PCDR
1R*	22.50	.555	20.25	-6.493	1.91	-.18	.720	9.51	.00	.00	.00
1B.*	22.70	.546	19.94	-5.328	2.48	-1.37	.704	9.23	3.51	.00	.00
2B	22.40	.547	20.20	-6.440	1.91	-.60	.732	9.48	4.29	.00	.00
3B.	22.70	.547	19.89	-5.251	2.53	-1.41	.701	9.20	3.64	.00	.00
4B.	22.60	.550	20.18	-5.901	2.16	-1.08	.725	9.53	3.77	.00	.00
1C	20.80	.522	18.13	-5.161	2.51	-1.46	.693	7.95	1.04	.00	.00
2C	21.10	.524	18.61	-5.632	2.21	-.79	.700	8.18	1.43	.00	.00
4C	21.00	.524	18.88	-6.413	1.85	-.37	.722	8.40	1.30	.00	.00
5C	20.80	.518	18.14	-5.214	2.45	-1.28	.691	7.87	.78	.00	.00
6C	20.80	.514	17.62	-4.631	2.91	-1.33	.651	7.37	1.04	.00	.00
7C	20.80	.521	18.37	-5.551	2.25	-1.28	.710	8.14	1.04	.00	.00
8C	20.80	.519	18.18	-5.186	2.47	-1.68	.701	8.00	1.04	.00	.00
9C	20.80	.517	18.00	-4.998	2.60	-1.53	.684	7.78	1.04	.00	.00
10C	21.00	.520	18.54	-5.529	2.26	-1.28	.710	8.19	1.04	.00	.00
11C	21.10	.519	18.38	-5.279	2.41	-.84	.682	7.90	1.04	.00	.00
1S	20.90	.527	18.65	-6.040	2.02	-.68	.716	8.34	1.30	.00	.00
2S	20.90	.527	18.58	-5.964	2.05	-.48	.706	8.22	1.17	.00	.00
3S	21.30	.526	18.82	-5.578	2.25	-1.17	.709	8.40	1.30	.00	.00
4S	21.00	.525	18.65	-5.786	2.13	-.97	.713	8.32	1.04	.00	.00
5S	20.80	.525	18.48	-5.787	2.14	-1.05	.715	8.26	1.30	.00	.00
6S	20.80	.522	18.31	-5.470	2.30	-1.23	.704	8.09	.91	.00	.00
1T	21.30	.524	18.60	-5.321	2.40	-.94	.688	8.12	1.04	.00	.00
2T	20.90	.525	18.73	-6.256	1.92	-.50	.719	8.35	1.43	.00	.00
3T	20.90	.521	18.22	-5.283	2.42	-.98	.686	7.90	.91	.00	.00
4T	20.80	.523	18.38	-5.729	2.16	-.65	.700	8.05	1.30	.00	.00
5T	20.80	.523	18.54	-5.962	2.04	-.78	.715	8.23	1.04	.00	.00

AVERAGES: 71214 BASELINE W097 00 000

	22.40	.547	20.20	-6.440	1.91	-.60	.732	9.48	4.29	.00	.00
STD	.00	.000	.00	.000	.00	.00	.000	.00	.00	*	*

71214 W098 M0 002 (9.2E11)

	20.92	.522	18.42	-5.560	2.27	-1.01	.701	8.10	1.12	.00	.00
STD	.16	.003	.29	.421	.24	.36	.016	.24	.17	*	*

PERCENT OF BASELINE

	93.4	95.5	91.2	113.7	119	29.9	95.7	85.4	26.1	*****	*****
STD%	.7	.6	1.4	6.5	13	59.7	2.2	2.6	4.0	*****	*****

71216 W100CU-TI002 (1E15-6F13) W097 00 000
 *SOL7 4 /21/78 AM1: P0=91.60MW/CM12 NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDP
1R*	22.50	.555	20.25	-6.561	1.89	.01	.717	9.46	.00	.00	.00
1R.	22.70	.547	20.00	-5.490	2.38	-1.05	.703	9.23	3.64	.00	.00
2R.*	22.80	.540	19.07	-4.320	3.37	-1.73	.642	8.36	2.08	.00	.00
3R.	22.70	.546	19.80	-5.136	2.61	-1.43	.694	9.10	3.25	.00	.00
4R	22.70	.550	20.46	-6.378	1.94	-.70	.733	9.68	4.42	.00	.00
5P	22.70	.552	20.50	-6.413	1.93	-.82	.739	9.79	4.55	.00	.00
1C	15.40	.488	13.57	-6.009	1.94	.21	.682	5.42	.91	.00	.00
2C	15.60	.486	13.59	-5.625	2.13	-.06	.670	5.37	.91	.00	.00
3C	15.50	.486	13.66	-6.016	1.93	.20	.682	5.44	1.04	.00	.00
4C	15.70	.484	13.63	-5.513	2.18	-.14	.666	5.35	.91	.00	.00
5C	15.90	.488	13.94	-5.822	2.03	.08	.677	5.55	.78	.00	.00
6C	15.60	.484	13.61	-5.659	2.10	-.09	.672	5.37	.78	.00	.00
7C	15.40	.484	13.45	-5.679	2.09	-.10	.673	5.30	.91	.00	.00
8C	16.20	.486	14.00	-5.337	2.29	-.42	.663	5.52	.91	.00	.00
9C	16.20	.485	14.00	-5.329	2.29	-.42	.663	5.51	.91	.00	.00
10C	15.20	.483	12.95	-5.027	2.51	-.71	.648	5.03	.91	.00	.00
11C	15.60	.489	13.69	-5.803	2.04	-.14	.681	5.49	.91	.00	.00
12C	15.70	.486	13.64	-5.561	2.16	.01	.665	5.36	.52	.00	.00
1S	15.70	.490	13.81	-5.861	2.02	-.11	.683	5.56	1.04	.00	.00
2S	15.50	.486	13.61	-5.870	2.00	.11	.678	5.40	.91	.00	.00
3S	16.00	.489	13.93	-5.564	2.17	-.23	.671	5.55	.91	.00	.00
4S	15.80	.487	13.75	-5.550	2.17	-.25	.671	5.46	.91	.00	.00
5S	15.80	.489	13.85	-5.766	2.06	-.17	.680	5.56	1.04	.00	.00
6S	15.50	.487	13.67	-6.102	1.90	.49	.679	5.42	1.04	.00	.00
1T	15.30	.486	13.14	-5.256	2.36	-.30	.654	5.14	.91	.00	.00
2T	15.40	.489	13.52	-5.913	1.99	.27	.676	5.38	1.04	.00	.00
3I	15.70	.491	13.81	-5.870	2.02	-.11	.684	5.57	.65	.00	.00
4T	15.50	.488	13.65	-6.052	1.92	.52	.676	5.41	.91	.00	.00
5T	15.60	.489	13.75	-6.029	1.93	.25	.682	5.50	.91	.00	.00

AVERAGES: 71216 BASELINE W097 00 000

	22.70	.551	20.48	-6.395	1.94	-.76	.736	9.74	4.49	.00	.00
STD	.00	.001	.02	.017	.00	.06	.003	.05	.06	*	*
	71216 W100CU-TI002 (1E15-6F13)										
	15.64	.487	13.66	-5.705	2.10	-.05	.673	5.42	.90	.00	.00
STD	.25	.002	.24	.277	.15	.29	.009	.13	.12	*	*
PERCENT OF BASELINE											
	68.9	88.4	66.7	110.8	108	193.6	91.4	55.7	20.0	*****	*****
STDZ	1.1	.5	1.2	4.6	8	40.9	1.6	1.6	3.0	*****	*****

80106 W102T1006 POLY (2E14) W097 00 000
 *SOL7 4 /21/78 AM1: P0=91.60MW/CM12 NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDR
1R*	22.50	.552	20.24	-6.402	1.94	-.36	.723	9.49	.00	.00	.00
1R	22.80	.547	20.54	-6.381	1.93	-.58	.730	9.63	3.90	.00	.00
2B.	22.70	.545	20.08	-5.582	2.31	-1.13	.711	9.30	3.51	.00	.00
3B.	23.30	.548	20.36	-5.156	2.60	-1.45	.698	9.42	3.25	.00	.00
4B	23.30	.549	20.88	-6.144	2.03	-.64	.722	9.77	4.29	.00	.00
1C	14.00	.457	11.77	-4.810	2.58	-.87	.633	4.28	.39	.00	.00
2C	13.90	.450	11.34	-4.207	3.20	-2.58	.614	4.06	.39	.00	.00
3C.	13.00	.382	8.77	-4.180	2.78	8.61	.398	2.09	.26	.00	.00
4C.	13.60	.420	9.68	-3.377	4.60	-1.25	.480	2.90	.26	.00	.00
5C.	13.60	.433	9.89	-3.231	5.23	-5.34	.519	3.23	.26	.00	.00
6C.	13.50	.528	9.42	-4.795	3.01	13.44	.407	3.06	.26	.00	.00
7C	13.10	.421	9.78	-3.933	3.42	1.88	.497	2.90	.26	.00	.00
8C.	13.60	.429	10.31	-3.577	4.17	-3.16	.544	3.36	.26	.00	.00
9C	13.60	.451	11.37	-4.706	2.65	-1.15	.629	4.08	.78	.00	.00
10C.	13.30	.442	10.49	-3.758	3.91	-4.55	.592	3.68	.39	.00	.00
11C	13.70	.445	10.99	-4.056	3.39	-2.51	.595	3.83	.52	.00	.00
1S	14.10	.462	12.25	-5.667	2.02	.29	.661	4.56	.91	.00	.00
2S	13.10	.446	10.89	-4.574	2.77	-1.67	.626	3.87	.65	.00	.00
3S.	14.20	.438	10.45	-3.217	5.27	-6.08	.536	3.53	.39	.00	.00
1T.	13.70	.453	10.91	-3.845	3.81	-4.26	.601	3.94	.91	.00	.00
2T.	13.20	.439	9.97	-3.465	4.59	-4.94	.551	3.38	.39	.00	.00
3T	13.50	.453	11.27	-4.622	2.75	-1.68	.633	4.09	.91	.00	.00
4T.	13.80	.456	11.53	-4.655	2.72	-1.39	.631	4.20	.91	.00	.00
5T.	13.30	.432	9.81	-3.433	4.60	-3.29	.520	3.16	.26	.00	.00
6T.	13.20	.445	10.26	-3.726	4.01	-3.71	.570	3.54	.52	.00	.00

AVERAGES: 80106 BASELINE W097 00 000

	23.05	.548	20.71	-6.263	1.98	-.61	.726	9.70	4.10	.00	.00
STD	.25	.001	.17	.118	.05	.03	.004	.07	.19	*	*

80106 W102T1006 POLY (2E14)

	13.64	.449	11.24	-4.581	2.83	-1.08	.613	3.99	.64	.00	.00
STD	.34	.011	.64	.482	.42	1.32	.044	.43	.24	*	*

PERCENT OF BASELINE

	59.2	81.9	54.3	126.8	143	23.9	84.4	41.1	15.5	*****	*****
STD%	2.1	2.2	3.6	9.2	25	233.3	6.5	4.8	6.9	*****	*****

80110 W104CU-TI003 (2E15-2.5E14) W097 00 000
 *SOL7 4 /21/78 AM1: PO=91.60MW/CM:2 NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDR
1P*	22.50	.552	20.15	-6.231	2.01	-.36	.716	9.40	.00	.00	.00
1P.*	23.20	.546	20.51	-5.629	2.28	-.85	.705	9.45	3.90	.00	.00
2P	23.30	.551	21.30	-7.293	1.63	-.04	.743	10.09	5.20	.00	.00
3E	23.00	.552	21.10	-7.473	1.58	-.16	.753	10.11	4.94	.00	.00
4P*	22.70	.542	19.48	-4.672	2.99	-2.07	.682	8.87	2.99	.00	.00
5E*	23.10	.547	19.65	-4.777	2.91	-.68	.648	8.66	3.51	.00	.00
1C	14.50	.472	12.48	-5.310	2.27	-.38	.657	4.76	1.04	.00	.00
2C	14.60	.473	12.73	-5.639	2.08	-.19	.672	4.91	1.04	.00	.00
3C	14.70	.470	12.64	-5.229	2.31	-.67	.659	4.82	.78	.00	.00
4C	14.50	.471	12.73	-5.876	1.95	.01	.679	4.91	1.17	.00	.00
5C	14.70	.471	12.86	-5.773	2.00	.00	.674	4.94	1.04	.00	.00
6C	14.50	.469	12.64	-5.593	2.09	-.39	.674	4.85	.91	.00	.00
7C	14.70	.475	12.81	-5.614	2.10	-.28	.673	4.97	1.04	.00	.00
8C	14.50	.471	12.67	-5.729	2.02	-.10	.674	4.87	1.04	.00	.00
9C	14.90	.473	12.91	-5.441	2.19	-.39	.666	4.96	.91	.00	.00
10C	14.70	.469	12.79	-5.603	2.08	-.12	.668	4.87	.91	.00	.00
11C	14.70	.470	12.73	-5.402	2.20	-.57	.668	4.88	1.04	.00	.00
1S	14.70	.474	12.84	-5.739	2.03	.02	.672	4.95	1.30	.00	.00
2S	14.60	.469	12.71	-5.572	2.10	-.35	.672	4.87	1.04	.00	.00
3S	14.30	.471	12.46	-5.636	2.07	-.18	.671	4.78	1.04	.00	.00
4S	14.40	.469	12.54	-5.645	2.06	-.06	.669	4.78	1.04	.00	.00
5S	14.80	.471	12.85	-5.499	2.14	-.34	.668	4.92	1.17	.00	.00
6S	14.60	.468	12.68	-5.480	2.14	-.49	.670	4.84	1.04	.00	.00
1T	14.10	.467	12.38	-5.979	1.89	.44	.674	4.69	.91	.00	.00
2T	14.60	.466	12.55	-5.248	2.28	-.55	.658	4.73	.91	.00	.00
3T	14.20	.466	12.36	-5.595	2.08	-.26	.670	4.69	1.04	.00	.00
4T	14.80	.469	12.84	-5.483	2.14	-.34	.667	4.90	.91	.00	.00
5T	15.80	.472	13.11	-5.243	2.30	-.82	.665	5.05	1.17	.00	.00
6T	14.40	.465	12.50	-5.504	2.12	-.35	.668	4.73	.91	.00	.00

AVERAGES: 80110 BASELINE W097 00 000

	23.15	.552	21.20	-7.383	1.60	-.10	.748	10.10	5.07	.00	.00
STD	.15	.000	.10	.090	.02	.06	.005	.01	.13	*	*

80110 W104CU-TI003 (2E15-2.5E14)

	14.60	.470	12.69	-5.558	2.11	-.28	.662	4.85	1.02	.00	.00
STD	.23	.003	.18	.191	.11	.26	.005	.09	.11	*	*

PERCENT OF BASELINE

	63.0	85.2	59.8	124.7	132	-74.2	89.4	48.1	20.1	*****	*****
STD%	1.4	.5	1.1	3.5	9	568.9	1.3	.9	2.8	*****	*****

80116 W106N-AL002 (1F16) W079 00 000
 *SOL7 4 /21/78 AM1: P0=91.60MW/CM12 NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDP
1R	22.50	.553	20.24	-6.443	1.93	-.27	.721	9.49	.00	.00	.00
1E	22.10	.558	20.24	-7.353	1.64	-.22	.750	9.79	9.75	.00	.00
2E.*	21.60	.552	18.90	-5.250	2.57	-1.45	.698	8.80	4.16	.00	.00
3E	22.00	.561	20.45	-8.602	1.35	.12	.771	10.07	11.05	.00	.00
4E.*	22.00	.547	19.22	-5.102	2.65	-1.86	.703	8.95	5.85	.00	.00
1C	22.00	.551	20.04	-6.940	1.74	-.52	.747	9.58	8.45	.00	.00
2C.*	21.70	.539	18.32	-4.244	3.49	-3.30	.675	8.35	5.20	.00	.00
3C	21.60	.548	19.45	-6.262	1.99	-1.03	.737	9.23	6.50	.00	.00
4C	21.70	.549	19.39	-5.845	2.19	-1.47	.732	9.22	7.80	.00	.00
5C	22.20	.547	19.45	-5.163	2.60	-1.88	.708	9.10	8.06	.00	.00
6C	22.20	.538	18.96	-4.577	3.07	-2.20	.676	8.54	5.20	.00	.00
7C	21.90	.541	18.72	-4.479	3.20	-2.95	.688	8.62	6.50	.00	.00
8C	21.90	.550	19.70	-6.192	2.03	-1.06	.736	9.37	9.78	.00	.00
9C	21.80	.550	19.93	-7.215	1.65	-.34	.750	9.51	11.70	.00	.00
10C	22.00	.544	18.98	-4.735	2.95	-2.39	.693	8.77	6.50	.00	.00
11C	22.10	.546	20.22	-7.249	1.63	-.34	.751	9.59	10.80	.00	.00
1S	22.10	.547	19.93	-6.402	1.92	-.72	.734	9.38	8.45	.00	.00
2S	22.20	.541	19.98	-6.372	1.92	-.54	.727	9.24	8.84	.00	.00
3S.*	21.90	.536	18.36	-4.145	3.60	-3.27	.666	8.26	6.50	.00	.00
4S	22.00	.545	19.88	-6.508	1.88	-.66	.736	9.33	9.75	.00	.00
1T	22.30	.548	20.04	-6.222	2.00	-.81	.730	9.43	8.45	.00	.00
2T	21.90	.549	19.77	-6.437	1.92	-.78	.737	9.37	9.75	.00	.00
3T	21.70	.543	19.23	-5.591	2.31	-1.44	.718	8.95	7.80	.00	.00

AVERAGES: 80116 BASELINE W079 00 000

	22.05	.560	20.34	-7.977	1.49	-.05	.761	9.93	10.40	.00	.00
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STD	.05	.002	.11	.625	.14	.17	.010	.14	.65	*	*
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80116 W106N-AL002 (1F16)

	21.98	.546	19.60	-6.012	2.19	-1.20	.725	9.20	8.40	.00	.00
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STD	.20	.004	.44	.853	.49	.76	.022	.31	1.66	*	*
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PERCENT OF BASELINE

	99.7	97.6	96.4	124.6	147	*****	95.3	92.7	80.7	*****	*****
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STD%	1.1	.9	2.7	17.4	50	*****	4.2	4.5	22.0	*****	*****
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80202 REPEAT RUN OF W107FZ-AL001 (3E16) W101FZ001
 *SOL6 4 /20/78 AM1: P0=91.60MW/CM:2 NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDR
1R	22.50	.551	20.29	-6.560	1.87	-.23	.725	9.50	.00	.00	.00
2CZB.*	22.20	.540	19.43	-5.188	2.55	-1.65	.703	8.92	3.64	.00	.00
3CZB	22.30	.545	20.41	-7.363	1.59	-.09	.746	9.59	4.55	.00	.00
1FZB.	22.50	.543	19.86	-5.512	2.35	-1.20	.709	9.16	4.29	.00	.00
2FZB	22.70	.544	20.29	-5.991	2.09	-.85	.722	9.43	4.29	.00	.00
3FZB.	22.50	.544	19.98	-5.677	2.26	-1.23	.719	9.30	4.29	.00	.00
4FZB.*	22.60	.539	19.57	-4.938	2.73	-1.63	.688	8.86	3.64	.00	.00
1C	21.90	.560	19.24	-5.300	2.57	-1.68	.708	9.19	2.60	.00	.00
2C	22.30	.573	20.18	-6.578	1.94	-.69	.739	9.99	3.25	.00	.00
3C	22.30	.566	19.79	-5.641	2.37	-1.39	.719	9.60	3.25	.00	.00
4C	22.20	.572	20.08	-6.511	1.97	-.77	.739	9.93	3.38	.00	.00
5C	22.40	.575	20.39	-6.875	1.84	-.60	.747	10.18	3.77	.00	.00
6C	22.30	.560	19.50	-5.226	2.62	-1.40	.697	9.20	2.47	.00	.00
7C	22.50	.572	20.43	-6.783	1.86	-.48	.740	10.07	3.64	.00	.00
8C	22.10	.564	19.07	-4.757	3.04	-2.38	.692	9.12	1.95	.00	.00
9C	22.30	.567	20.26	-6.747	1.86	-.73	.747	9.99	1.95	.00	.00
10C	22.20	.559	19.23	-4.923	2.86	-1.84	.690	9.05	2.86	.00	.00
11C	22.20	.567	19.94	-6.191	2.09	-.87	.729	9.71	1.30	.00	.00
12C	22.30	.555	18.63	-4.194	3.65	-2.59	.651	8.52	1.30	.00	.00
13C	22.60	.567	20.33	-6.252	2.06	-.88	.733	9.94	3.90	.00	.00
14C	22.30	.563	19.55	-5.205	2.65	-1.79	.707	9.39	2.21	.00	.00
15C	22.40	.556	19.40	-4.928	2.83	-1.77	.689	9.07	2.21	.00	.00

AVERAGES: 80202 BASELINE W101FZ001

	22.70	.544	20.29	-5.991	2.09	-.85	.722	9.43	4.29	.00	.00
STD	.00	.000	.00	.000	.00	.00	.000	.00	.00	*	*
	80202 REPEAT RUN OF W107FZ-AL001 (3E16)										
	22.29	.565	19.73	-5.741	2.41	-1.32	.715	9.53	2.67	.00	.00
STD	.16	.006	.53	.840	.52	.64	.027	.47	.82	*	*
PERCENT OF BASELINE	98.2	103.9	97.3	104.2	115	44.4	99.1	101.1	62.2	*****	*****
STDZ	.7	1.1	2.6	14.0	25	75.7	3.7	5.0	19.2	*****	*****

80222 W108N/V002 (8E13) W079 00 000
 SOL8 4 /21/78 AM1: PO=91.60MW/CM12 NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD	PCDA	PCDF
1E*	22.50	.552	20.21	-6.386	1.95	-.24	.718	9.43	.00	.00	.00
1E	20.90	.550	18.89	-6.599	1.87	-.55	.734	8.92	6.89	.00	.00
2E.*	21.20	.545	18.62	-5.374	2.46	-1.38	.703	8.59	4.55	.00	.00
3E	21.00	.547	18.83	-6.126	2.05	-.98	.728	8.85	4.55	.00	.00
4E	21.50	.552	19.51	-6.943	1.75	-.05	.731	9.18	7.80	.00	.00
5E.*	20.90	.546	18.69	-6.014	2.10	-1.05	.725	8.75	5.85	.00	.00
1C	18.30	.523	16.37	-6.219	1.95	-.65	.718	7.26	1.95	.00	.00
2C	18.00	.522	16.01	-5.985	2.06	-.80	.711	7.06	1.43	.00	.00
3C	18.30	.523	16.27	-5.925	2.09	-.97	.713	7.22	1.04	.00	.00
4C	18.20	.522	16.21	-6.000	2.05	-.92	.715	7.19	1.30	.00	.00
5C	18.10	.524	16.33	-6.579	1.81	-.57	.730	7.32	1.56	.00	.00
6C	18.40	.525	16.52	-6.220	1.96	-1.11	.731	7.47	1.69	.00	.00
7C	18.10	.515	15.95	-5.773	2.13	-.44	.691	6.81	1.56	.00	.00
8C	17.80	.517	15.66	-5.639	2.22	-.89	.695	6.77	1.82	.00	.00
9C	18.20	.519	16.13	-5.885	2.09	-.70	.704	7.03	1.56	.00	.00
10C	18.90	.528	17.17	-6.892	1.71	-.53	.741	7.82	1.95	.00	.00
11C	18.60	.519	16.12	-5.227	2.48	-.89	.674	6.88	1.56	.00	.00
12C	18.30	.520	16.39	-6.273	1.92	-.57	.718	7.22	2.47	.00	.00
1S	19.00	.527	17.26	-6.842	1.72	-.68	.745	7.88	1.95	.00	.00
2S	19.00	.527	17.26	-6.842	1.72	-.68	.745	7.88	1.56	.00	.00
3S	18.50	.519	16.22	-5.534	2.28	-.82	.690	7.00	.65	.00	.00
4S	18.40	.520	16.37	-6.101	1.99	-.37	.705	7.13	1.30	.00	.00
5S	18.50	.520	16.33	-5.697	2.19	-.95	.702	7.14	1.30	.00	.00
1T	17.90	.527	16.32	-7.225	1.61	-.17	.741	7.39	1.56	.00	.00
2T	17.80	.522	15.76	-5.827	2.14	-.85	.704	6.92	1.95	.00	.00
3T	17.80	.520	15.85	-6.149	1.97	-.37	.706	6.91	1.56	.00	.00
4T	17.90	.518	16.05	-6.562	1.80	.19	.708	6.94	2.08	.00	.00
5T	17.90	.517	15.67	-5.493	2.31	-.95	.689	6.75	1.95	.00	.00

AVERAGES: 80222 BASELINE W079 00 000

	21.13	.550	19.08	-6.556	1.89	-.53	.731	8.98	6.41	.00	.00
STD	.26	.002	.31	.335	.13	.38	.002	.14	1.37	*	*

80222 W108N/V002 (8E13)

	18.27	.522	16.28	-6.131	2.01	-.67	.712	7.18	1.63	.00	.00
STD	.36	.004	.44	.504	.22	.30	.019	.33	.38	*	*

PERCENT OF BASELINE

	86.4	94.9	85.4	106.5	106	73.2	97.4	80.0	25.3	*****	*****
STD%	2.8	1.0	3.7	12.9	19	188.9	3.0	5.0	12.6	*****	*****

80220 W109C002 (3.7E16) W097 00 000
 SOL8 4 /21/78 AM1: P0=91.60MW/CM:2 NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD	PCDA	PCDR
1R*	22.50	.552	20.15	-6.231	2.01	-.36	.716	9.40	.00	.00	.00
1P*	22.70	.538	18.52	-3.768	4.22	-3.65	.637	8.22	2.08	.00	.00
2H.*	22.90	.544	19.57	-4.547	3.13	-2.30	.679	8.95	3.12	.00	.00
3B	22.90	.548	20.59	-6.267	1.98	-.72	.730	9.68	4.94	.00	.00
4B	22.60	.548	20.38	-6.381	1.93	-.72	.734	9.61	5.20	.00	.00
5B*	22.80	.538	18.71	-3.875	4.02	-3.21	.638	8.28	2.21	.00	.00
1C	22.20	.548	19.40	-5.014	2.72	-2.32	.712	9.16	4.16	.00	.00
2C	22.10	.543	19.24	-4.955	2.75	-2.21	.704	8.94	2.86	.00	.00
3C	22.10	.542	19.65	-5.765	2.20	-1.14	.719	9.11	4.42	.00	.00
4C	22.40	.544	19.79	-5.509	2.35	-1.32	.712	9.18	4.55	.00	.00
5C	22.30	.542	19.53	-5.144	2.59	-1.88	.708	9.05	4.42	.00	.00
6C	21.90	.543	19.63	-6.050	2.07	-1.07	.730	9.18	4.42	.00	.00
7C	22.10	.541	19.79	-6.063	2.05	-.90	.726	9.18	4.29	.00	.00
8C	22.50	.540	19.80	-5.366	2.43	-1.42	.708	9.10	3.25	.00	.00
9C.*	21.70	.540	18.56	-4.434	3.26	-3.36	.695	8.61	3.64	.00	.00
10C	22.80	.543	19.76	-4.903	2.78	-1.84	.692	9.06	3.90	.00	.00
1S	22.10	.547	19.59	-5.626	2.30	-1.26	.716	9.15	4.16	.00	.00
2S	22.30	.547	19.90	-5.967	2.12	-.83	.719	9.28	5.85	.00	.00
4S	22.20	.544	19.47	-5.271	2.51	-1.50	.704	8.99	3.90	.00	.00
5S	22.00	.544	19.83	-6.447	1.90	-.50	.728	9.22	4.94	.00	.00
6S	22.00	.546	19.75	-6.169	2.02	-.88	.729	9.26	4.55	.00	.00
1T	22.70	.547	20.00	-5.609	2.30	-.59	.694	9.12	4.16	.00	.00
2T	22.30	.546	19.90	-5.959	2.12	-.83	.719	9.26	4.94	.00	.00
3T	21.90	.541	19.24	-5.367	2.44	-1.35	.704	8.82	4.42	.00	.00
4T	22.40	.543	19.84	-5.630	2.28	-1.11	.712	9.16	4.03	.00	.00
5T	22.30	.543	19.89	-5.911	2.13	-.92	.720	9.22	4.94	.00	.00

AVERAGES: 80220 BASELINE W097 00 000

	22.75	.548	20.49	-6.324	1.96	-.72	.732	9.65	5.07	.00	.00
STD	.15	.000	.11	.057	.02	.00	.002	.04	.13	*	*

80220 W109C002 (3.7E16)

	22.24	.544	19.68	-5.617	2.32	-1.26	.713	9.13	4.32	.00	.00
STD	.24	.002	.21	.430	.26	.50	.011	.11	.63	*	*

PERCENT OF BASELINE

	97.8	99.3	96.1	111.2	119	24.8	97.5	94.6	85.3	*****	*****
STD%	1.7	.4	1.6	7.7	15	69.7	1.8	1.5	14.8	*****	*****

80227 W111CU-V001 (2.5E15-3E14) W097 00 000
 SOL8 4 /21/78 AM1: P0=91.60MW/CM12 NO AR COATING

ID	ISC	VOC	IP	LOG(ID)	N	R	FF	EFF	OCD	PCDA	PCLP
1R*	22.50	.552	19.90	-5.666	2.29	-.84	.705	9.26	.00	.00	.00
1E.*	21.60	.542	18.55	-4.741	2.94	-1.96	.679	8.41	3.51	.00	.00
2E	21.70	.547	19.46	-6.159	2.03	-.83	.726	9.12	4.81	.00	.00
3E.	21.30	.539	18.70	-5.361	2.44	-1.37	.702	8.53	3.90	.00	.00
4E.*	21.40	.540	18.60	-5.675	2.25	.87	.652	7.96	3.64	.00	.00
1C	15.00	.476	13.17	-5.965	1.92	.42	.674	5.09	.52	.00	.00
2C	15.60	.476	13.55	-5.546	2.13	-.06	.665	5.23	.52	.00	.00
3C	15.00	.474	12.98	-5.355	2.24	-.70	.669	5.03	.65	.00	.00
4C.*	14.20	.463	11.34	-3.871	3.81	-3.93	.601	4.18	.65	.00	.00
5C	15.30	.475	13.43	-5.832	1.98	-.05	.679	5.22	.65	.00	.00
6C	15.10	.469	12.97	-5.174	2.34	-.79	.660	4.94	.65	.00	.00
7C	15.20	.476	13.47	-6.141	1.84	-.03	.693	5.31	.78	.00	.00
8C	15.50	.476	13.71	-5.986	1.90	-.33	.694	5.42	.65	.00	.00
9C	15.40	.469	13.07	-4.920	2.52	-.87	.645	4.93	.39	.00	.00
10C	15.40	.474	13.35	-5.427	2.19	-.47	.668	5.16	.65	.00	.00
11C	15.60	.472	13.50	-5.377	2.21	-.48	.666	5.19	.78	.00	.00
12C	15.10	.476	13.39	-6.078	1.87	-.37	.699	5.31	.91	.00	.00
1S	15.60	.481	13.95	-6.393	1.75	-.27	.711	5.64	.91	.00	.00
2S	15.50	.477	13.71	-6.033	1.89	-.18	.693	5.42	.78	.00	.00
3S	15.40	.478	13.64	-6.031	1.89	-.36	.697	5.43	.91	.00	.00
4S	15.10	.478	13.47	-6.315	1.78	-.21	.706	5.39	.91	.00	.00
5S	15.40	.478	13.75	-6.391	1.74	-.05	.705	5.49	.91	.00	.00
1T	15.10	.474	12.88	-4.913	2.56	-1.52	.659	4.99	.91	.00	.00
2T.*	14.80	.462	10.82	-3.980	3.58	4.01	.469	3.39	.39	.00	.00
3T	15.20	.468	12.83	-4.746	2.67	-1.45	.645	4.85	.65	.00	.00
4T	14.90	.469	12.86	-5.257	2.28	-.90	.667	4.93	.65	.00	.00
5T	15.10	.469	13.02	-5.236	2.29	-.87	.666	4.99	.78	.00	.00

AVERAGES: 80227 BASELINE W097 00 000

	21.70	.547	19.46	-6.159	2.03	-.83	.726	9.12	4.81	.00	.00
STD	.00	.000	.00	.000	.00	.00	.000	.00	.00	*	*

80227 W111CU-V001 (2.5E15-3E14)

	15.28	.474	13.34	-5.656	2.10	-.48	.678	5.20	.73	.00	.00
STD	.22	.004	.33	.509	.28	.47	.020	.22	.15	*	*

PERCENT OF BASELINE

	70.4	86.7	68.5	108.2	103	142.3	93.3	57.0	15.1	*****	*****
STD%	1.0	.7	1.7	8.3	14	57.0	2.7	2.4	3.1	*****	*****

80301 W112TA001 (1E13) W097 00 000
 SOL8 4 /21/78 AM1: P0=91.60MW/CM:2 NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD	PCDA	PCDR
1R*	22.50	.553	20.07	-6.052	2.10	-.46	.711	9.36	.00	.00	.00
1E.*	21.70	.536	17.94	-4.038	3.77	-2.87	.641	7.89	1.02	.00	.00
2P.*	22.00	.547	18.90	-4.588	3.12	-2.79	.692	8.81	3.64	.00	.00
3H.*	21.20	.541	16.75	-4.385	3.33	2.36	.535	6.49	2.99	.00	.00
4E	21.40	.544	19.21	-6.176	2.02	-.90	.729	8.97	3.90	.00	.00
5E	22.00	.548	19.92	-6.612	1.85	-.66	.740	9.43	4.42	.00	.00
1C	19.20	.525	16.31	-4.537	3.11	-2.58	.670	7.14	.91	.00	.00
2C	19.20	.528	16.97	-5.736	2.19	-.86	.703	7.53	.91	.00	.00
3C	19.60	.521	16.71	-4.815	2.80	-1.17	.657	7.09	.65	.00	.00
4C	19.60	.534	17.69	-6.734	1.77	-.05	.722	8.00	1.17	.00	.00
5C	19.40	.523	16.80	-5.113	2.57	-1.30	.680	7.30	.91	.00	.00
6C	19.20	.532	16.98	-5.692	2.24	-1.11	.707	7.64	1.04	.00	.00
8C	19.10	.528	16.23	-4.507	3.16	-2.84	.673	7.18	.91	.00	.00
9C	19.50	.533	17.61	-6.732	1.77	-.10	.724	7.96	1.04	.00	.00
10C	19.70	.529	17.45	-5.798	2.16	-.79	.705	7.77	.91	.00	.00
1S	19.10	.529	16.70	-5.287	2.48	-1.57	.697	7.45	1.04	.00	.00
2S	19.70	.529	17.35	-5.633	2.25	-.76	.696	7.67	.91	.00	.00
3S	18.80	.521	16.43	-5.445	2.34	-.81	.685	7.09	.65	.00	.00
4S	20.30	.534	18.20	-6.543	1.84	.30	.705	8.08	1.04	.00	.00
5S	19.90	.532	17.64	-5.875	2.13	-.57	.702	7.86	.91	.00	.00
6S	19.20	.534	17.24	-6.436	1.89	-.32	.719	7.79	1.04	.00	.00
1T	19.30	.527	16.54	-4.764	2.89	-2.08	.676	7.27	.78	.00	.00
2T	19.20	.525	16.65	-5.076	2.61	-1.68	.687	7.32	.65	.00	.00
3T	19.10	.528	16.91	-5.763	2.18	-.99	.708	7.55	.91	.00	.00
4T	19.50	.517	16.34	-4.352	3.27	-2.33	.649	6.92	.52	.00	.00
5T	19.60	.525	17.08	-5.198	2.51	-1.48	.691	7.52	.91	.00	.00

AVERAGES: 80301 BASELINE W097 00 000

	21.70	.546	19.57	-6.394	1.93	-.78	.734	9.20	4.16	.00	.00
STD	.30	.002	.36	.218	.08	.12	.006	.23	.26	*	*

80301 W112TA001 (1E13)

	19.41	.528	16.99	-5.500	2.41	-1.15	.693	7.51	.89	.00	.00
STD	.33	.005	.52	.712	.44	.83	.020	.33	.16	*	*

PERCENT OF BASELINE

	89.4	96.6	86.8	114.0	125	51.8	94.3	81.6	21.4	*****	*****
STD%	2.8	1.2	4.3	14.4	29	145.2	3.5	5.7	5.4	*****	*****