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**DETERMINATION OF A DEFINITION OF
SOLAR GRADE SILICON**

Third Quarterly Report, April 1—June 30 1976

**H. W. Gutsche
D. E. Hill**

1976

Work Performed Under Contract No. NAS7-100

**Monsanto Research Corporation
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ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Division of Solar Energy

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1 April - 30 June 1976

by

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W. F. Tucker, M. S. Wang

for

JET PROPULSION LABORATORY
Pasadena, California

Contract No. 954338

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NEW TECHNOLOGY

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

ABSTRACT

All scheduled experimental crystals have been grown. Probably, when all analytical data are in, a few make-up crystals will have to be grown in addition. Analysis is about 75% complete; solar cell work is about 50% complete. Minority carrier life-time measurements are 90% done. From the results we conclude not only do solar cells tolerate certain impurities but cells built in silicon containing controlled amounts (up to one ppm) of magnesium, manganese and nickel, singly or combined, have actually higher-than-baseline performances. On the other hand, iron, chromium, vanadium and particularly titanium, reduce conversion efficiency from slightly to catastrophically. The influence of carbon is perhaps only marginal but no doubt is left about oxygen. Oxygen levels about 50 ppm, i.e., about 10^{18} atoms/cc reduce device performance definitely.

Our electrical and physical-chemical analyses have provided very good data. We are particularly pleased with our choice of method for trace analysis. The spark source mass spectrometric analysis continues to provide information about impurity concentration in the ppb range with a high degree of confidence. The accuracy of sequential analyses is $\pm 25\%$.

Our solar cell process continues to give baseline devices with reproducible efficiency values. Here the accuracy is $\pm 2.8\%$ within each diffusion run and $\pm 7\%$ overall from run to run. Cause/effect relationships between specific impurity contamination and change in efficiency have been satisfactorily visible. We believe they are meaningful.

With three more months to go, we feel fairly confident that we will know at the end of the contract which and how much of the investigated impurities may or may not be present in silicon to allow it to be defined as "Solar Grade".

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1. SUMMARY

1.1 INTRODUCTION

This is the Third Quarterly Report of Contract 954338 which began in October 1975. The purpose of this program is to determine a definition for solar-grade silicon and specifically to determine whether and in what quantities certain impurities common in metallurgical-grade silicon can be tolerated in single crystal silicon, i.e. still allow the preparation of solar devices exhibiting 12% efficiency or better.

By using semiconductor-grade material and processing methods that are capable of producing crystals of nearly perfect structure, it is intended to demonstrate mainly the singular effect of these impurities against a uniform background boron doping concentration of 3×10^{16} atoms per cm^3 of silicon (~ 0.5 ohm cm). Since both crucible-grown (Czochralski) and float zone (Mon-X) silicon are being investigated, the effects of two levels of oxygen, 10^{18} atoms per cm^3 Cz versus 10^{16} atoms per cm^3 Mon-X silicon, can be studied.

The Second Quarterly Report of this contract was issued in April 1976. It described the method of preparing the experimental crystals, their characterization, and analysis. It also described solar device work. Based on analytical and the device evaluation results then available the following tentative conclusions were drawn:

1. Solar devices made from high-oxygen (Cz) silicon have efficiencies $\sim 20\%$ lower than devices made from low-oxygen (Mon-X) material.
2. About 10^{14} atoms/ cm^3 Si of Ti and V suffice to reduce solar energy conversion efficiency significantly.
3. Some of the impurities under investigation may have a beneficial effect on device performance.

1.2 TECHNICAL STATUS

All experimental crystals scheduled to date have been completed. A few may have to be repeated, however, because mass spectrographic analysis failed to detect the impurities added. In particular, the sodium-doped and the copper-doped crystals failed to show evidence of these dopants. The absence of sodium in the material is explained by our choice of a volatile doping substance, sodium chloride; the absence of copper in an experimental Fz crystal has not yet been explained. Whatever traces of copper did enter the lattice

during metalization caused the cells manufactured from this material to have a slightly reduced efficiency, i.e., 8.9% versus 9.2% baseline Fz. Of the three Al-doped Fz crystals (Al instead of boron as the P-type dopant) one has been processed all the way through a set of solar cells. The hoped-for high efficiency has not been demonstrated on this first try: 8.3% versus 9.2% baseline.

One Fz crystal was prepared containing three metal impurities. All three (Mg, Mn, and Ni) had been found to have a beneficial effect on solar cell performance when investigated singly. Together, they did not produce a synergistic effect. Nevertheless, it is probably significant that all three impurities can be present in Fz silicon and still allow solar cell efficiencies to be slightly higher than the baseline values. We found 9.4% versus 9.2% baseline.

The characterization of the experimental crystals grown to date is complete and efforts were expended toward finding cause-effect relationships between the material characterization results and the device performance data. No relationship between structure data and solar cell performance could be detected. Also more meaningful ways of presenting our results are being investigated to highlight significance.

Physical-chemical analysis (mainly mass spectrometry, IR absorption and emission spectroscopy) are about 75% complete. Only minor, usually explainable, discrepancies appeared when samples were exchanged between Dow, Westinghouse, and our laboratory.

Solar cell fabrication and evaluation is complete on all single-side polished blanks. We are finding Cz silicon more difficult to process than Fz material. The metalization process in particular was found to be much easier on Fz material. The previously reported result that Fz material always gives better solar devices has been confirmed without exception by additional work. Lifetime measurements are about 90% complete. The expected correlation between open-circuit lifetime in the device and the efficiency of the device has been established.

2. TECHNICAL PROGRESS

2.1 LOW-OXYGEN CRYSTALS - Kedar P. Gupta

The float-zone (Fz) silicon crystals made during this quarter were prepared in the same way as described in the previous quarterly report. All crystals scheduled under the original program as well as under the extended program have been grown, along with many make-up crystals. Table 1 describes the preparation and make-up of all the crystals.

None of the Fz crystals showed structural defects when observed under a microscope after Sirtl etching. All wafers examined were free from any dislocation pattern, grain boundary or lineage. Recently, examination at JPL revealed some possibility "high-angle grain boundaries," and some dislocation structures which were found in Fe and Ni-doped crystals. The etchant used was not Sirtl etch. Although a ZD (zero dislocation) crystal should also be free from other structural defects, there is a distinct possibility of impurity precipitation when a contaminated crystal is being cooled. We are re-examining the slices in question.

Four aluminum-doped crystals have been grown. The first crystal, M10B also contained boron along with the aluminum. This crystal yielded devices with very high solar cell efficiencies. Another crystal, M19B, in which aluminum is the only doping impurity and which contains no boron, does not exhibit as high a solar cell efficiency as crystal M19B. This indicates that aluminum by itself is not necessarily the cause for the high efficiency. A definite conclusion will be made after examining two more crystals, M19B(a) and M19B(b). Table 2 shows the percent of total aluminum as ionized atoms for the above four samples when put into the silicon lattice. On the average only 20% of the total aluminum atoms appear ionized.

Of particular interest is crystal M11B. This crystal has more than one metal impurity, containing Ni, Mg and Mn along with boron. All three of these metal impurities had been found earlier to be not detrimental to solar cell efficiency. Rather, in each case, the efficiency was actually higher than the "baseline" efficiency. The amount of each impurity in crystal M11B was chosen to correspond closely to the levels at which they were added individually in their respective crystals. There seems to be no synergistic effect of the multi-impurity doping. The solar cell efficiency for sample M11B is just slightly (about 3%) lower than the average of samples M3B, M4B, and M7B (9.38% vs avg. 9.67%).

The compensated crystal, M16B, was prepared by adding phosphorus during the first pass, and boron during the last pass. The respective concentrations based on the resistivity readings after each pass are 1.15×10^{16} atom/cc boron (calculated). Thus an effective

Table 1. SUMMARY OF FLOAT-ZONED
SILICON CRYSTALS PREPARED FOR THE CONTRACT

Crystal No.	Secondary Impurity	k_0 Used for Calculation	Conc. Range Req'd. by JPL (atoms/cc)	Amount added (mg)	Theoretical C_S (atoms/cc)	Experimental C_S (SSMS) (atoms/cc)	Comments
M1A	--	--	--	--	--	--	Boron doped - baseline
M1B	--	--	--	--	--	--	Boron doped - baseline
M1C	--	--	--	--	--	--	Boron doped - baseline
M2B	Fe	8×10^{-6}	$10^{14} - 10^{16}$	20.7	7.6×10^{14}	Not Detected	
M3B	Mn	10^{-5}	$10^{15} - 10^{16}$	14.0	6.6×10^{14}	1.5×10^{15}	In powder form
M4B	Ni	10^{-4}	$10^{15} - 10^{17}$	16.1	7.1×10^{15}	1.5×10^{16}	
M5B	V	10^{-5}	$10^{14} - 10^{15}$	11.0	5.6×10^{14}	4.0×10^{14}	
M6B	Zr	NA	$10^{14} - 10^{15}$	15.0	--	N.D.	
M7B	Mg	2×10^{-3}	$10^{15} - 10^{17}$	2.5	5.3×10^{16}	N.D.	Flashing Observed
M8B	Ti	10^{-5}	$10^{14} - 10^{15}$	10.0	5.2×10^{14}	N.D.	Flashing Observed
M9B	C	7×10^{-2}	$10^{15} - 10^{16}$	--	1.0×10^{16}	3.1×10^{16}	Lost ZD due to C-saturation
M10B	Al	5×10^{-3}	$10^{16} - 10^{17}$	2.3	1.1×10^{17}	4.0×10^{17}	Lowered the crystal resistivity
M13A	--	--	--	--	--	--	Phosphorus doped-baseline
M13B	--	--	--	--	--	--	-do-
M13C	--	--	--	--	--	--	-do-
M14B	C	1×10^{-1}	$10^{15} - 10^{16}$	--	1.0×10^{16}	--	Lost ZD due to C-saturation
M2B (a)	Fe	8×10^{-6}	$10^{14} - 10^{16}$	42.0	1.3×10^{16}	N.D.	
M5B (a)	V	10^{-5}	$10^{14} - 10^{15}$	51.0	2.6×10^{15}	4.6×10^{14}	
M31B	Cr	10^{-5}	$10^{14} - 10^{15}$	54.0	2.7×10^{15}	1.5×10^{15}	
M32B	Cu	4×10^{-4}	$10^{14} - 10^{16}$	24.0	3.86×10^{16}	Not completed	Tendency to lose ZD when Cu goes into the melt
M19B	Al	5×10^{-3}	$10^{16} - 10^{17}$	10.0	4.8×10^{17}	Not completed	Can not prepare crystal with aluminum higher than 10 mg
M16B	P	--	$10^{15} - 10^{16}$	Gas	1.1×10^{16}	Not completed	Phosphorus doping during the first pass
M11B	Ni	10^{-4}	--	16.0	7.1×10^{15}	Not completed	
	Mn	10^{-5}	--	14.0	6.6×10^{14}		
	Mg	2×10^{-3}	--	2.0	4.2×10^{15}		
M9B (a)	C	--	$10^{15} - 10^{16}$	Gas	--	Not completed	
M14B (a)	C	--	$10^{15} - 10^{16}$	Gas	--	Not completed	
M8B (a)	Ti	10^{-5}	$10^{15} - 10^{16}$	20.0	1.0×10^{15}	Not completed	Boron doped
M19B (a)	Al	5×10^{-5}	$10^{16} - 10^{17}$	5.5	2.6×10^{16}	Not completed	
M19B (b)	Al	5×10^{-3}	$10^{16} - 10^{17}$	1.0	4.8×10^{16}	Not completed	
M17B	Ti	10^{-5}	$10^{15} - 10^{16}$	20.0	$1. \times 10^{15}$	Not completed	Phosphorus doped

C_S = Concentration in solid

Table 2. ALUMINUM-DOPED SAMPLES

Sample No.	Amount of Al added (mg)	Any other Impurity	Electrical Resistivity (ohm-cm)	Conc. of Al (Theo) (atom/cc)	Conc. of Al ions (electrical) resistivity data	Al atoms ionized (%)
M10B	2.3	Boron	0.36	1.1×10^{17}	2.2×10^{16}	0.20
5 M19B	10.0	-----	0.30	4.8×10^{17}	8.6×10^{16}	0.18
M19B(a)	5.5	-----	0.40	2.6×10^{17}	6.4×10^{16}	0.24
M19B(b)	1.0	-----	1.88	0.48×10^{17}	0.75×10^{16}	0.16

carrier concentration of 4.80×10^{16} atom/cc P-type (or 0.45 ohm cm approximately) was established. The solar cell efficiency measured on this crystal (9.27%) is the same as the baseline efficiency, indicating that 20% phosphorus compensation does not have any significant effect on the efficiency.

All scheduled crystals under the contract have been prepared. However, additional crystals may have to be grown after evaluating all analytical results and solar cell data.

2.2 HIGH-OXYGEN CRYSTALS - W. F. Tucker

The scheduled high-oxygen crystals (=Cz) were completed during the third period of the contract. Some, now failing to show by mass spectrometry the desired levels of secondary impurity, may have to be regrown. The prime candidate for a repeat performance is the sodium-doped crystal too. Table 3 gives the make-up of the material grown during the past three months. The table lists the dopants, their melt concentration and their calculated concentration in the solid crystal after freezing. Most of these crystals have not yet been processed all the way through to the solar devices.

The first magnesium-doped crystal failed because of a Themit reaction whereby the inner parts of the crystal puller were destroyed. This reaction did not occur in the subsequent run. Here the silicon melt temperature was much lower at the quartz-silicon interface than in the first attempt. The second run was successful.

The level of sodium for the NaCl-doped crystal was shown by mass spectrometry to be lower than in all other crystals that were not doped with sodium. This is probably due to a poor choice of doping vehicle. We thought that the escaping tendency of SiCl_4 would allow the sodium to be incorporated in the liquid Si, but did not do that. An odor indicative of silicon tetrachloride was noticed at the doping port of the crystal puller when the doping tube was withdrawn, but the results of the analysis - absence of sodium - proved once again that sodium reduces SiCl_4 at the temperature of molten silicon. The observed odor probably stemmed from a reaction between NaCl and SiO. Another sodium compound will have to be considered for the next attempt to incorporate this element into the charge.

2.3 MATERIAL CHARACTERIZATION - M. H. Christ

The second quarterly report under this contract indicated the probabilities that various parameters such as section and slice resistivities and gradients would meet given specifications. The main purpose of this study was to show the capability of electrical measurements to detect any differences between material with standard impurities and material with secondary impurities added. Also included in the second quarterly report were several photomicrographs of defects after Sirtl etching.

Table 3. SUMMARY OF HIGH OXYGEN CRYSTALS GROWN IN THE 3RD QUARTER

<u>Crystal No.</u>	<u>Identity No.</u>	<u>Dopants</u>	<u>Melt Conc.</u> <u>(C_O, atoms/cc)</u>	<u>C_S Target*</u> <u>(atoms/cc)</u>	<u>C_S Meas.</u> <u>(atoms/cc)</u>
4959	C8B	Zr	1.47×10^{19}	2.45×10^{14}	$<10^{15}$
4962	C8B1	Zr	1.47×10^{19}	2.5×10^{14}	Incomplete
4960	C9B	Mg	9.6×10^{19}	9.6×10^{14}	-
4961	C9B1	Mg	9.6×10^{14}	9.6×10^{14}	1.2×10^{15}
4964	C12B	Ni	4.0×10^{19}	4.5×10^{15}	Incomplete
		C	3.9×10^{17}	3.5×10^{16}	
		B	3.9×10^{16}	3.3×10^{16}	
4961	C15B	Na	5.0×10^{18}	1×10^{16}	Incomplete
4963	C16B1	P	3.8×10^{16}	1.4×10^{16}	Incomplete
4964	C16B2	P	1.3×10^{18}	5.0×10^{17}	Incomplete
4968	C17B	Ti	4.9×10^{19}	4.9×10^{14}	Incomplete

*This value is that targeted for in the crystal at the seed end, (i.e. the minimum concentration.)

This report will again treat these subjects but with more detail. In addition, the relationship of electrical and metallographic characteristics to solar cell efficiency will be examined.

The probability that the crystal sections made under this contract would meet the 0.5 ohm cm target resistivity is shown in Figure 1. The Fz probability appears very near typical while the Cz probability is poorer. The major causes of the Cz results were section C9B at 1.47 ohm cm, C10B at 0.12 ohm cm, and section C16Ba at 0.19 ohm cm.

The analysis of rod and slice gradients, Figures 2 and 3, shows results typical of material with no added secondary impurities. Resistivities at 3 mm from the edge are typically higher than at half radius and Fz gradients are normally slightly higher than Cz gradients.

Four-point probe resistivities, taken at approximately 3 mm intervals across 4 equally spaced radii of a silicon slice, yield what has been termed "band" resistivities. Analysis of the variability of these readings will indicate macro variations in the dopant profile. Such an analysis is presented in Figure 4. The variability among all of the resistivity readings taken in bands, 32 for a 50-mm slice, is calculated as a percent sigma. The results from two slices per section are included in Figure 4. These plots indicate no detectable effect of secondary impurities.

Figures 5 and 6 show the relationship of electrical and metallographic analysis to solar cell efficiency. The graph reference is a plot of solar cell efficiencies in ascending order from left to right. Average section resistivity and average section gradients are also plotted. With the exception of several low resistivities corresponding to low efficiencies and the high resistivity of the most efficient Cz cell, no apparent correlation exists between the electrical and detected metallographic properties and solar cell efficiency.

Presented in the second quarterly report were photomicrographs of Sirtl-etched slugs from crystal section M2B and C11B. They were noted to have a high level of preferentially etched pits. Photos have since been taken of Sirtl-etched slugs from most of the sections processed to date. Etch anomalies of the same nature were noted to a lesser degree on most of the samples. These have been determined to be caused by surface contamination present during Sirtl etch.

True crystallographic defects were, however, found in section C12B. They were determined to be high angle grain boundaries. A photomicrograph is shown as Figure 7.

During the next quarter material characterization will be completed. Results of our analysis will be presented in updated tables in future monthly reports. A more thorough evaluation of these results will also be made.

Figure 1. Crystal Section End Center Resistivity Probability

Figure 2. Crystal Section End Gradient Probability

Figure 3. Slice Radial Gradient Probability

Figure 4. Slice Resistivity Variability Probability

Figure 5. Cz Electrical and Metallographic Properties vs. Cell Efficiency

Figure 6. Fz Electrical and Metallographic Properties vs. Cell Efficiency

Figure 7. C12B, High-Angle Grain Boundary (50X)

2.4 PHYSICAL AND CHEMICAL ANALYSIS - M. S. Wang

During the third quarter, all three analytical techniques (SSMS, IR,ES) were utilized for analysis. Dow Corning and Westinghouse were contacted in order to be sure that agreement exists on the analytical technique involved. Also, some samples were exchanged for comparison of the data obtained from different laboratories. Advantages of intra-laboratory information exchange was apparent and obviously benefited all of the individual laboratories concerned.

2.4.1 Problems with Boron Data

In the Second Quarterly Report of this program, some analytical data from spark source mass spectrometry (SSMS) were presented. Additional analytical results have been added in this report. In reviewing the analytical data on boron there were discrepancies noticed between electrical results and the analytical data presented. As previously described, there are no primary reference samples of silicon for trace or ultratrace impurities determination such as the ones offered by the National Bureau of Standards for other matrix systems. As far as we know, most of the laboratories with SSMS have their own data reduction techniques, and usually the values for boron are calibrated with electrical results. Consequently, in these cases the SSMS data is forced to correlate with electrical resistivity measurements.

The National Bureau of Standards has an effort underway to establish some type of references for these measurements but none are yet available. We believe in the validity of our technique for presentation of SSMS data. Our boron data will remain the way we have presented them in the past. The details of the calibration technique will be described in our final report.

Our data can be treated or calibrated with reference to electrical results. The results are shown in Tables 4 and 5 and are discussed below.

2.4.2 Treatment of Boron Data Obtained by SSMS

Using boron or arsenic, the resistivity of silicon as a function of impurities concentration was studied by Irvin¹ and most of the workers in silicon technology have used his data in the calculation of boron or arsenic concentrations in silicon from resistivity values. The information and its application has been extremely valuable and used extensively. However, with modern technology and knowledge, repetition of his experiments has been considered timely and appropriate by many investigators with newer techniques and purer materials. Other impurities such as oxygen concentration were not determined in Irvin's work. Oxygen concentration can be enormous when the crystal is grown in a quartz crucible. Boron

and aluminum are also known impurities in regular quartz crucibles used for growing crystals.

A hydrothermal recrystallization of quartz² was involved in separation of boron as borate in the presence of sodium hydroxide in the method used in Irvin's work. The preparation of pure quartz is known to be difficult, and occlusion of boron in the precipitate is possible, especially in higher concentration, during this rapid process. Since sodium hydroxide, even in low concentration, was used in the reaction, the formation of some sodium silicate could not be avoided. Boron has a high affinity for this compound. These observations are not conclusive without further experiments but they are extremely important for silicon technology where boron plays a major role in the electrical behavior of silicon.

ASTM Committee F-1 has recommended a practice³ for converting carrier concentration to resistivity for both N and P type silicon. Method D in this document is based on Irvin's work.¹ The relationship is expressed as follows:

$$R = \frac{1}{aN^b}$$

where: R = resistivity, ohm cm
N = carrier concentration/cm³
a, b = constants dependent on N and on the material type and given in a table.

The third columns of Table 4 and 5 are data obtained from the ASTM-recommended practice.³ The boron concentrations obtained directly from SSMS data are in the first column. The resistivity-calibrated concentrations of boron derived from SSMS results are shown in the second column as obtained from Figure 8. Figure 8 was prepared from independent data from analyzing a series of samples of wide range of resistivities. The SSMS data for these samples were plotted against the boron concentration obtained from resistivities according to Irvin's original report.¹ We note that the slope of the line in Figure 8 indicates that a concentration dependence of the calibration must be taken into account in a detailed picture of the behavior of boron.

Using the results of Figure 8, the boron concentration derived from two slightly different sources showed excellent agreement with few exceptions. This might mean that the analytical results for boron by SSMS can be reasonably calibrated using resistivity measurements. For the time being, our boron data will be reported with theoretical and experimental corrections made in our laboratory as we have been doing previously.

Some noticeable boron concentration difference was observed in crystal C10B. Boron values obtained from SSMS indicate the resistivity should be about 0.5 ohm cm. The actual determined

Table 4. COMPARISON OF BORON DATA FROM SSMS
AND VALUES CALCULATED FROM RESISTIVITY (Cz)

[All data expressed as (atoms/cc) $\times 10^{16}$]

Crystal	Boron (SSMS)	Boron (Correlated) ¹ SSMS	Boron from (Resistivity) ²	Resistivity (ohm/cm)
C1A	0.62	2.5	3.6	0.52
C1C	110.	525.	660.	0.105
C2A	0.68	2.8	3.2	0.56
C2B	0.76	3.1	3.4	0.55
C2C	120	575.	660.	0.015
C3A	0.97	4.0	4.0	0.49
C4B	0.92	3.8	3.2	0.56
C5B	1.1	4.5	4.4	0.46
C6B	0.76	3.1	4.2	0.47
C7B	0.93	3.8	3.4	0.55
C9B	0.30	1.2	0.87	1.6
C10B	1.1	4.5	25.	0.15
C11B	1.2	5.0	3.4	0.54

¹Converted from Figure 1

²Converted by Method D of Reference (3)

Table 5. COMPARISON OF BORON DATA FROM SSMS AND
VALUES CALCULATED FROM RESISTIVITY (Fz)

[All data expressed as (atoms/cc) $\times 10^{16}$]

Crystal	Boron (SSMS)	Boron (Correlated) ¹ SSMS	Boron from (Resistivity) ²	Resistivity (ohm/cm)
M1A	0.59	2.4	1.3	1.1
M1B	3.9	17.	2.4	0.015
M1C	34.	160.	190.	0.04
M2B1	1.2	5.0	3.9	0.05
M2B2	1.6	6.6	5.5	0.40
M2C	30.	140.	110.	0.058
M3B	1.2	5.0	4.7	0.44
M4B	0.55	2.2	3.0	0.59
M4B1	0.88	3.7	4.1	0.48
M5B	0.75	3.1	3.9	0.50
M6B	1.1	4.5	4.1	0.48
M7B	1.2	5.0	4.4	0.46
M8B	1.1	4.5	4.1	0.48
M9B	0.60	2.4	4.4	0.46
M10B	1.4	5.8	6.2	0.37

¹Converted from Figure 1

²Converted by Method D of Reference (3)

Figure 8. Relationship Between Boron Concentrations by SSMS and Irvin's Value¹ Converted from Resistivities

resistivity (0.15 ohm cm) was probably the result of aluminum doping, however, if all the aluminum were electrically active, the resistivity should have been much lower (~ 0.012 ohm cm): about 830×10^{16} atoms/cc aluminum. Analysis of C10B returned from Westinghouse gave 80×10^{16} atoms/cc aluminum, which gives a calculated resistivity of 0.07 ohm cm. It is fairly safe to assume that aluminum has affected the resistivity and also that the element is at least partially, electrically inactive.

2.4.3 Oxygen Determination with Infrared Spectrophotometry

In the March Monthly Report, some difficulties in oxygen determination by infrared spectrophotometry were reported to be mainly due to high free carrier concentration caused high doping by levels. In order to be sure of the instrumentation, technique, and standards involved, a trip was made to Dow Corning at Midland, Michigan. In discussions with Dow Corning scientists, no apparent problems were discovered. Five of our samples were left for cross checking by them. As shown in the May Monthly Report, the agreement was fair and our work on infrared spectrophotometry had been continued.

As previously mentioned, infrared spectrophotometry for oxygen and carbon determinations is quite popular and in most of the laboratories this is the only instrument available for such analyses.

Table 6 shows a compilation of the data for the Cz crystals. All of the crystals showed oxygen concentrations in the expected ranges determined by this technique. The lowest oxygen concentration was found in C8B which was 95×10^{16} atoms/cc and the highest value was shown in C16B, 180×10^{16} atoms/cc. The average value was 142.5×10^{16} atoms/cc.

Similar data on the Fz material are on hand. Oxygen determination with this technique for the Fz material is difficult because of the sloping background due to high level of doping. Changing to a more appropriate reference specimen in the double beam infrared spectrophotometer might minimize the problem. Additional data, including the Fz data, will be reported in the next report.

2.4.4 Samples Exchanged with Westinghouse

As repeatedly stated, there are no primary or secondary standards available for trace or ultratrace analysis of silicon. The problems are unsolved, especially in the field of spark source mass spectrometry, when dealing with the question of accuracy. Some of our samples were delivered to Westinghouse for analysis and then returned to us for re-examination. The results are summarized in Tables 7 and 8. Aluminum results are about one order of magnitude higher in our analysis. Boron was not detected by Westinghouse, but we detected it in every sample.

Table 6. OXYGEN CONCENTRATION BY INFRARED (Cz)
 (atoms/cc $\times 10^{16}$)

C1A	160
C2A	140
C2B	130
C3A	110
C4B	145
C5B	135
C6B	100
C8B	95
C7B	135
C9B	165
C11B	135
C13A	170
C13B	165
C14A	160
C15B	155
C16B	180

Table 7. INTER-LABORATORY COMPARISON OF
SSMS DATA ON ALUMINUM DOPED SILICON

(atoms/cc)

Sample	DC-C-01-16	C10B	M10B	W028AL001
<u>Aluminum</u>				
Westinghouse	4.1×10^{17}	4.5×10^{17}	3.6×10^{16}	1.5×10^{15}
Monsanto	1.0×10^{19}	8.3×10^{18}	4.0×10^{17}	5.4×10^{16}
<u>Boron</u>				
Westinghouse	N.D.	N.D.	N.D.	N.D.
Monsanto	3.4×10^{14}	1.1×10^{16}	1.4×10^{16}	1.3×10^{15}
<u>Oxygen</u>				
Westinghouse	3.5×10^{16}	1.5×10^{17}	3.6×10^{17}	7.0×10^{15}
Monsanto	5.5×10^{17}	2.5×10^{18}	3.4×10^{16}	6.7×10^{17}
<u>Carbon</u>				
Westinghouse	3.3×10^{16}	3.5×10^{16}	3.7×10^{16}	7.6×10^{15}
Monsanto	3.3×10^{16}	1.1×10^{16}	3.4×10^{15}	5.0×10^{16}

Table E. IMPURITIES DETERMINED BY SPARK SOURCE
MASS SPECTROSCOPY

NT = Interference
EST = Estimated
N.D. = Not detected. Value reported is the
detection limit based on the conditions
used for the sample.

Crystal Number	Primary Impurities	Secondary Impurities	Resistivity Ohm cm	B	C	N	O	F	Na	Mg	Al	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Ga	Ge	Zr	Mo	Ag
M108 MONS RERUN	B	Al	1i	.37	1.3	.29	INT	5.8	33	.063	N.D. .011	N.D. .22	N.C. .12	.19	.012	N.D. .0098	N.D. .011	N.D. .0077	N.D. .0097	N.D. .0055	N.D. .16	N.D. .23	N.C. .023	N.D. .0073	N.D. .0055	N.D. .013	N.D. .048	N.D. .035	N.D. .017
M108 WESTH	B	Al	1i	.37	.93	.18	INT	3.7	18	.062	N.D. .0082	N.D. .036	N.C. .049	N.D. .021	.019	N.D. .0089	N.D. .0096	N.D. .0062	N.D. .0084	N.D. .0056	N.D. .14	N.D. .19	N.D. .019	N.D. .0065	N.D. .0046	N.D. .013	N.D. .046	N.D. .033	N.D. .017
C108 MONS RERUN	P	Al	1.0x10	.15	1.5	1.6	INT	270	63	.020	N.D. .012	N.D. .14	N.D. .086	.28	N.D. .0029	N.D. .013	N.D. .011	N.D. .0078	N.D. .010	N.D. .011	N.D. .17	N.D. .23	N.D. .023	N.D. .0076	N.D. .0052	N.D. .014	N.D. .051	N.D. .038	N.D. .017
C108 WESTH	B	Al	1.0x10	.15	.48	.53	INT	55	66	.097	N.D. .011	N.D. .076	N.D. .020	N.D. .021	.023	N.D. .0098	N.D. .011	N.D. .0071	N.D. .0089	N.D. .010	N.D. .15	N.D. .19	N.D. .019	N.D. .0065	N.D. .0049	N.D. .013	N.D. .049	N.D. .035	N.D. .018
W028AL001 WESTH				.13	5.0	INT	67	94	.040	N.D. .015	N.D. .14	N.D. .11	N.D. .082	N.D. .033	.024	EST .095	N.D. .013	N.D. .0087	N.D. .012	N.D. .015	N.D. .23	N.D. .22	N.D. .022	N.D. .0074	N.D. .0052	N.D. .014	N.D. .050	N.D. .038	N.D. .018
DC-C-01-1E AL-WESTH				.034	3.3	INT	55	51	.015	N.D. .013	N.D. .030	N.D. .089	N.D. .025	.10	N.D. .0030	N.D. .013	N.D. .016	N.D. .0098	N.D. .013	INT	N.D. .24	N.D. .30		N.D. .011	N.D. .0074	N.D. .020	N.D. .073	N.D. .053	N.D. .027

Remarks: MONS RERUN = Re-run of Monsanto Sample

WESTH = Westinghouse

Values given are computer outputs. Not expressions of accuracy.

In most cases we have reported higher carbon and oxygen values. The sources of discrepancy can be from many factors such as:

- 1) Sampling position
- 2) Segregation of the impurities
- 3) Differences in data reducing process, and others

The problems remain unsolved but one should recognize and emphasize the needs for a primary standard in this field. The analysis of sample C10B was repeated, and the results reported in Table 8 are in fair agreement with the original values. This leads us to believe that the reproducibility is as good as desired and nonuniformities may exist over only a relatively small volume of the sample.

2.4.5 Additional Data from SSMS

The spark source mass spectrometer is playing the major role in the impurity analysis for this contract. The analytical results for phosphorus doped M13 series showed high concentrations of P as expected. The magnesium doped (C9B1), titanium doped (C11C1), and vanadium doped (M5B1) crystals were all found to contain measurable quantities of the specific doped element in the crystal. Carbon was also detected in higher-than-normal amounts in all carbon-doped samples. Tables 9 and 10 contain updated data.

2.4.6 Concluding Remarks

The work has progressed along in all phases. Copper contamination in manganese-doped samples was observed previously and the crystal should be defined as a Cu-Mn doped crystal. Segregation anomalies of aluminum and other impurities might be present as evidenced in some observations. It is too early to reach a firm conclusion but the problem is worthy of all the attention we can focus on it.

There was no apparent discrepancy in infrared data on oxygen and carbon checked by Dow Corning and MRC. Some samples exchanged with Westinghouse for SSMS analysis showed some disagreement. Because of lack of suitable standards, the problems are left unsolved. It was found to be extremely beneficial to have an intra-laboratory exchange of information.

There was no serious discrepancy between SSMS and Emission Spectrometric (ES) results, and SSMS exhibited good reproducibility. Since SSMS is reproducible, and sensitive for almost every element, some meaningful interpretation should be able to be derived from the analytical results. The total analysis of the crystal is the only way to obtain the most valuable and meaningful information on impurities in the crystals.

Good primary standards for silicon analysis are needed urgently for accurate interpretation of analytical results. The standards

Table 9. IMPURITIES DETERMINED BY SPARK SOURCE
MASS SPECTROMETRY (CZ)
Expressed as (Atoms/cc) $\times 10^{16}$

INT = Interference
EST = Estimate
N.D. = Not Detected. Value reported is
the detection limit based on the
conditions used for the samples.

Crystal Number	Primary Impurity	Secondary Impurities Added	B	C	N	O	F	Na	Mg	Al	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Ga	Ge	Zr	Mo	Ag
C1A	B	--	0.62	0.48	INT	240	0.12	0.03	N.D. 0.009	0.12	0.085	0.074	0.056	0.011	EST 0.043	N.D. 0.01	N.D. 0.007	0.033	N.D. 0.01	N.D. 0.15	N.D. 0.20	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013		N.D. 0.032	N.D. 0.016
C1C	B	--	110	0.93	INT	310	0.3	0.04	N.D. 0.008	N.D. 0.13	N.D. 0.09	0.14	0.09	0.01	EST 0.044	N.D. 0.01	N.D. 0.007	0.082	N.D. 0.003	0.43	N.D. 0.20	N.D. 0.02	N.D. 0.007	N.D. 0.006	N.D. 0.013		N.D. 0.032	N.D. 0.016
C2A	B	C 0.1~1	0.68	7.4	INT	260	0.31	0.03	N.D. 0.01	N.D. 0.17	N.D. 0.1	0.20	N.D. 0.03	0.004	EST 0.13	N.D. 0.01	N.D. 0.007	N.D. 0.009	N.D. 0.01	N.D. 0.15	N.D. 0.21	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.036	N.D. 0.016
C2B	B	C 0.1~1	0.76	6.7	INT	120	0.25	0.05	N.D. 0.01	N.D. 0.13	N.D. 0.11	N.D. 0.04	0.23	0.04	EST 0.2	N.D. 0.01	N.D. 0.008	N.D. 0.05	N.D. 0.01	N.D. 0.17	N.D. 0.22	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.036	N.D. 0.017
C2C	B	C 0.1~1	120	6.5	INT	220	2.2	0.06	N.D. 0.01	N.D. 0.16	N.D. 0.15	N.D. 0.21	0.13	0.06	EST 0.09	N.D. 0.01	N.D. 0.008	0.034	N.D. 0.01	N.D. 0.16	N.D. 0.24	N.D. 0.02	N.D. 0.008	N.D. 0.005	N.D. 0.013	N.D. 0.05	N.D. 0.036	N.D. 0.018
C3A	B	Fe 0.01~1	0.97	0.52	INT	140	1.3	0.09	N.D. 0.01	N.D. 0.22	N.D. 0.15	N.D. 0.04	0.16	0.04	EST 0.033	N.D. 0.01	N.D. 0.007	N.D. 0.008	N.D. 0.003	0.21	N.D. 0.20	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013		N.D. 0.036	N.D. 0.018
C4B	B	Cr 0.01~1	0.92	0.82	INT	270	0.42	0.03	N.D. 0.01	N.D. 0.12	N.D. 0.11	N.D. 0.05	N.D. 0.03	0.014	EST 0.072	N.D. 0.01	N.D. 0.008	0.41	N.D. 0.01	N.D. 0.17	N.D. 0.22	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.036	N.D. 0.017
C5B	B	Mn 0.1~1	1.1	1.0	INT	160	0.30	0.05	N.D. 0.01	N.D. 0.18	N.D. 0.11	0.22	0.15	0.03	N.D. 0.011	N.D. 0.011	N.D. 0.007	N.D. 0.01	1.2	N.D. 0.18	N.D. 0.22	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.033	N.D. 0.017
C6B	B	Ni 0.1~1	0.76	0.28	INT	260	0.16	0.03	N.D. 0.01	N.D. 0.14	N.D. 0.15	N.D. 0.05	N.D. 0.02	0.01	N.D. 0.010	N.D. 0.012	N.D. 0.008	N.D. 0.01	N.D. 0.01	7.1	N.D. 0.02	N.D. 0.013	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.038	N.D. 0.017	
C7B	B	V 0.01~0.1	0.93	0.72	INT	240	1.3	0.09	N.D. 0.01	N.D. 0.19	N.D. 0.11	0.17	0.15	0.04	N.D. 0.010	N.D. 0.011	N.D. 0.011	0.07	0.28	N.D. 0.01	1.2	N.D. 0.22	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.036	N.D. 0.018
C9B	B	Hg 0.1~10	0.30	1.1	INT	89	0.88	0.03	N.D. 0.01	N.D. 0.17	N.D. 0.12	N.D. 0.04	N.D. 0.03	0.05	EST 0.1	N.D. 0.013	N.D. 0.008	N.D. 0.01	N.D. 0.01	N.D. 0.17	N.D. 0.23	N.D. 0.02	N.D. 0.008	N.D. 0.005	N.D. 0.015	N.D. 0.05	N.D. 0.034	N.D. 0.018
C10B	B	Al 1.0~10	1.1	1.1	INT	280	1.3	0.08	N.D. 0.01	830	N.D. 0.12	0.26	0.10	0.04	N.D. 0.01	N.D. 0.011	N.D. 0.007	N.D. 0.009	N.D. 0.01	N.D. 0.15	N.D. 0.20	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014		N.D. 0.037	N.D. 0.014
C11B	B	Ti 0.01~0.1	1.2	1.5	INT	220	0.87	0.02	N.D. 0.01	N.D. 0.18	N.D. 0.11	N.D. 0.05	0.15	0.02	EST 0.06	N.D. 0.012	N.D. 0.008	N.D. 0.009	N.D. 0.01	N.D. 0.16	N.D. 0.20	N.D. 0.03	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.036	N.D. 0.018
C13C		P	N.D. 0.01	2.8	INT	320	0.27	0.04	N.D. 0.01	N.D. 0.27	N.D.	270	N.D. 0.02	N.D.	EST 0.034	N.D. 0.011	N.D. 0.007	N.D. 0.009	N.D. 0.01	N.D. 0.15	N.D. 0.22	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.037	N.D. 0.017
C2B1	B	C	1.4	10.	INT	390	0.46	0.05	N.D. 0.01	N.D. 0.11	N.D. 0.036	0.05	0.042	0.04	EST 0.055	N.D. 0.01	N.D. 0.007	N.D. 0.009	N.D. 0.01	N.D. 0.16	N.D. 0.22	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.035	N.D. 0.018
C9B1	B	Mg	1.1	3.1	INT	410	0.24	0.06	N.D. 0.11	N.D. 0.038	N.D.	0.03	0.057	0.07	EST 0.040	N.D. 0.01	N.D. 0.006	N.D. 0.008	N.D. 0.009	N.D. 0.15	N.D. 0.20	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013	N.D. 0.05	N.D. 0.036	N.D. 0.018
C11B1	B	Ti	1.1	1.2	INT	390	0.33	0.09	N.D. 0.01	N.D. 0.12	N.D. 0.035	0.08	0.037	0.020	N.D. 0.089	N.D. 0.06	N.D. 0.006	N.D. 0.02	N.D. 0.01	N.D. 0.16	N.D. 0.21	N.D. 0.02	N.D. 0.007	N.D. 0.007	N.D. 0.014	N.D. 0.05	N.D. 0.035	N.D. 0.018
C13A	P		N.D. 0.014	1.5	INT	200	1.1	0.06	N.D. 0.01	N.D. 0.17	N.D.	0.50	0.05	0.027	EST 0.043	N.D. 0.01	N.D. 0.006	N.D. 0.008	N.D. 0.01	N.D. 0.16	N.D. 0.20	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.035	N.D. 0.017
C14A	P	C	N.D. 0.018	5.3	INT	310	0.19	0.05	N.D. 0.009	N.D. 0.11	N.D.	4.4	N.D. 0.026	0.021	N.D. 0.091	N.D. 0.01	N.D. 0.006	N.D. 0.008	N.D. 0.009	N.D. 0.14	N.D. 0.19	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013	N.D. 0.05	N.D. 0.035	N.D. 0.017
C13B	P		N.D. 0.015	2.9	INT	690	0.54	0.04	N.D. 0.009	N.D. 0.16	N.D.	4.7	N.D. 0.030	0.020	N.D. 0.087	N.D. 0.01	N.D. 0.006	N.D. 0.008	N.D. 0.009	N.D. 1.4	N.D. 1.9	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013	N.D. 0.05	N.D. 0.034	N.D. 0.017

Table 10. IMPURITIES DETERMINED BY SPARK SOURCE

MASS SPECTROMETRY (F2)
Expressed as (Atoms/cc) $\times 10^{16}$

INT = Interference

EST = Estimated

N.D. = Not Detected. Value reported is
the detection limit based on the
conditions used for the samples.

Crystal Number	Primary Impurity	Secondary Impurities Added	B	C	N	O	F	Na	Mg	Al	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Ga	Ge	Zr	Mo	Ag
M1A	B	--	0.56	2.8	INT	6.5	1.3	0.03	N.D. 0.01	N.D. 0.13	N.D. 0.12	0.26	0.16	0.014	EST 0.09	N.D. 0.01	N.D. 0.007	0.06	N.D. 0.01	N.D. 0.17	N.D. 0.22	N.D. 0.05	N.D. 0.007	N.D. 0.007	N.D. 0.013		N.D. 0.01	N.D. 0.018
M1B	B	--	3.9	0.34	INT	3.2	0.19	0.03	N.D. 0.0009	N.D. 0.15	N.D. 0.11	N.D. 0.033	N.D. 0.025	9.7	N.D. 0.01	N.D. 0.01	N.D. 0.007	N.D. 0.009	N.D. 0.01	N.D. 0.17	N.D. 0.22	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.04	N.D. 0.02
M1C	B	--	34	0.38	INT	6.0	0.59	0.04	N.D. 0.009	N.D. 0.24	N.D. 0.16	0.39	0.15	0.016	N.D. 0.009	N.D. 0.01	N.D. 0.007	0.04	N.D. 0.039	N.D. 0.15	N.D. 0.21	N.D. 0.02	N.D. 0.006	N.D. 0.005	N.D. 0.013	N.D. 0.05	N.D. 0.035	N.D. 0.016
M2B1	B	Fe	0.06	1.2	0.47	INT	5.6	0.21	0.07	N.D. 0.01	N.D. 0.24	N.D. 0.12	0.051	0.085	0.022	N.D. 0.01	N.D. 0.01	N.D. 0.007	N.D. 0.009	N.D. 0.039	N.D. 0.14	0.2	0.02	N.D. 0.0065	N.D. 0.005	N.D. 0.012	N.D. 0.034	N.D. 0.017
M2B	B	Fe	0.08	1.4	0.52	INT	8.5	0.25	0.06	N.D. 0.009	N.D. 0.22	N.D. 0.12	0.056	0.15	0.027	EST 0.06	N.D. 0.01	N.D. 0.007	N.D. 0.009	N.D. 0.009	N.D. 0.16	0.21	1.3	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.036	N.D. 0.018
M2C	B	Fe	0.06	3.0	0.65	INT	9.4	4.0	0.03	N.D. 0.008	N.D. 0.33	N.D. 0.14	N.D. 0.07	N.D. 0.025	N.D. 0.0024	EST 0.03	N.D. 0.01	N.D. 0.0065	N.D. 0.009	N.D. 0.009	N.D. 0.14	N.D. 0.20	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013	N.D. 0.036	N.D. 0.017
M3B	B	Mn	0.07	1.2	0.20	INT	2.9	0.15	0.045	N.D. 0.008	N.D. 0.22	N.D. 0.11	N.D. 0.027	N.D. 0.022	0.01	N.D. 0.009	N.D. 0.01	N.D. 0.006	0.06	0.15	N.D. 0.13	N.D. 0.17	N.D. 0.02	N.D. 0.006	N.D. 0.004	N.D. 0.01	N.D. 0.04	N.D. 0.026
M4B	B	Ni	0.07	0.55	0.21	INT	2.7	0.16	0.05	N.D. 0.009	N.D. 0.11	N.D. 0.11	0.05	N.D. 0.028	0.016	N.D. 0.01	N.D. 0.01	N.D. 0.007	0.15	N.D. 0.01	0.96	1.5	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013	N.D. 0.034	N.D. 0.017
M4B1	B	Ni	0.07	0.88	0.44	INT	4.6	0.37	0.045	N.D. 0.01	N.D. 0.22	N.D. 0.11	0.36	0.19	0.033	N.D. 0.01	N.D. 0.01	N.D. 0.007	0.02	N.D. 0.009	N.D. 0.14	0.62	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013	N.D. 0.032	N.D. 0.016
M5B	B	V	0.06	0.75	0.31	INT	2.7	0.17	0.056	N.D. 0.01	N.D. 0.2	N.D. 0.21	0.12	N.D. 0.03	0.025	N.D. 0.01	N.D. 0.01	0.01	0.025	N.D. 0.01	N.D. 0.15	N.D. 0.21	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013	N.D. 0.034	N.D. 0.017
M6B	B	Zr	1.1	0.25	INT	2.6	0.16	0.034	N.D. 0.01	N.D. 0.16	N.D. 0.13	N.D. 0.038	N.D. 0.028	0.011	N.D. 0.012	N.D. 0.01	N.D. 0.007	N.D. 0.008	N.D. 0.008	N.D. 0.14	N.D. 0.15	N.D. 0.015	N.D. 0.005	N.D. 0.004	N.D. 0.008	N.D. 0.03	N.D. 0.02	N.D. 0.09
M7B	B	Hg	5.	1.2	0.35	INT	5.8	0.29	0.05	N.D. 0.01	N.D. 0.2	N.D. 0.15	N.D. 0.064	N.D. 0.03	0.024	N.D. 0.011	N.D. 0.01	N.D. 0.007	N.D. 0.008	N.D. 0.009	N.D. 0.14	N.D. 0.22	N.D. 0.022	N.D. 0.0075	N.D. 0.005	N.D. 0.013	N.D. 0.045	N.D. 0.032
M8B	B	Ti	0.05	1.1	0.21	INT	4.5	0.20	0.074	N.D. 0.01	N.D. 0.27	N.D. 0.27	0.1	N.D. 0.04	0.054	N.D. 0.012	N.D. 0.01	N.D. 0.007	N.D. 0.009	N.D. 0.009	N.D. 0.14	N.D. 0.16	N.D. 0.015	N.D. 0.0052	N.D. 0.0036	N.D. 0.009	N.D. 0.03	N.D. 0.02
M9B	B	C	0.6	3.1	INT	2.2	1.8	0.035	N.D. 0.009	N.D. 0.17	N.D. 0.1	N.D. 0.03	N.D. 0.022	0.01	EST 0.016	N.D. 0.01	N.D. 0.008	N.D. 0.01	N.D. 0.01	N.D. 0.17	N.D. 0.23	N.D. 0.05	N.D. 0.008	N.D. 0.0057	N.D. 0.015	N.D. 0.054	N.D. 0.03	N.D. 0.013
M10B	B	Al	11	1.4	0.34	INT	3.4	0.57	0.07	N.D. 0.01	40	N.D. 0.14	0.24	0.21	0.037	N.D. 0.01	N.D. 0.01	N.D. 0.007	N.D. 0.005	N.D. 0.009	N.D. 0.15	N.D. 0.22	N.D. 0.022	N.D. 0.007	N.D. 0.005	N.D. 0.015	N.D. 0.05	N.D. 0.035
4232	B	Fe	1.6	0.92	0.23	INT	4.1	0.24	0.023	N.D. 0.013	N.D. 0.2	N.D. 0.12	N.D. 0.04	N.D. 0.03	N.D. 0.05	EST 0.04	N.D. 0.01	N.D. 0.007	N.D. 0.06	N.D. 0.01	N.D. 0.14	N.D. 0.17	N.D. 0.017	N.D. 0.006	N.D. 0.004	N.D. 0.011	N.D. 0.037	N.D. 0.027
413A	P		N.D. .C13	0.46	INT	3.4	0.69	0.03	N.D. 0.014	N.D. .095	N.D. 0.58	N.D. 0.03	N.D. 0.071	0.011	EST 0.036	N.D. 0.02	N.D. 0.01	N.D. 0.01	N.D. 0.015	N.D. 0.24	N.D. 0.35	N.D. 0.03	N.D. 0.012	N.D. 0.009	N.D. 0.02	N.D. 0.09	N.D. 0.066	N.D. 0.031
413B	P		N.D. .C11	0.42	INT	4.9	0.77	0.06	N.D. 0.009	N.D. .095	1.4	N.D. 0.03	N.D. 0.020	0.015	N.D. 0.008	N.D. .009	N.D. 0.006	0.03	N.D. 0.008	N.D. 0.13	N.D. 0.19	N.D. 0.02	N.D. 0.006	N.D. 0.005	N.D. 0.012	N.D. 0.04	N.D. 0.034	N.D. 0.016
413C	P		N.D. .C13	0.46	INT	5.1	0.45	0.07	N.D. 0.011	N.D. 0.15	2.6	N.D. 0.07	N.D. 0.024	0.018	N.D. 0.01	N.D. 0.01	N.D. 0.007	N.D. 0.009	N.D. 0.01	N.D. 0.16	N.D. 0.21	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013	N.D. 0.05	N.D. 0.035	N.D. 0.017
414B	P	C	1.0 .026	8.6	INT	14.	0.37	0.08	N.D. 0.015	N.D. 0.19	1.3	N.D. 0.07	0.28	0.024	EST 0.08	N.D. 0.01	N.D. 0.008	N.D. 0.01	N.D. 0.01	N.D. 0.20	N.D. 0.22	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.035	N.D. 0.017
4531	B	V	.58	1.1	.50	INT	8.5	0.30	0.05	N.D. .0096	N.D. 0.15	N.D. .096	0.22	0.13	0.029	EST 0.04	N.D. 0.09	0.05	N.D. 0.008	N.D. 0.009	N.D. 0.15	N.D. 0.20	N.D. 0.02	N.D. 0.007	N.D. 0.007	N.D. 0.014	N.D. 0.05	N.D. 0.037

will furnish more uniform or standardized data for more meaningful interpretation of the results of several laboratories.

Overall, we have been taking advantage of total impurity analysis of material with different analytical techniques. Also these advantages are enhanced by intra-laboratory communications. In most of our doped samples the elements in question were determined as our analytical data have demonstrated.

2.5 SOLAR CELL FABRICATION AND TESTING - D. E. Hill

2.5.1 Solar Cell Fabrication

2.5.1.1 Metalization of Solar Cells

Solar cells are being diffused and fabricated in the manner described in earlier reports. The only portion of the process where trouble is encountered periodically is in the metalization of the wafers. Lack of good adhesion is the main symptom and in many cases it can be traced to vacuum problems. In a few instances the causes are not so clear but these have usually followed a period in which the metalization system was idle. The problem then decreased in severity as the system was operated under metalization conditions.

In view of these problems it seemed wise to have available a back up metalization system to prevent delays which might occur in the case of breakdowns of the Ti and Ag evaporator. Since some time is available on a Materials Research Corp. turret head sputtering system in this laboratory, appropriate Ag and Ti targets were procured. Sputtering conditions were established and initial tests yielded cells with good metal adherence, and which etch and solder-dip well. It would appear that the sputtered metal is at least as good as that obtained with the evaporator when it is running properly. However, the throughput and availability of this machine at the present would make it difficult to process all cells in this manner.

2.5.1.2 Solar Cells Fabricated Using Boron Diffusion

A series of solar cells have been fabricated using the BN-type boron diffusion described in an earlier report.⁴ The fabrication procedures are the same as those used for the N/P cells including the Ti-Ag metalization. The diffusion temperatures and times and the resultant sheet resistances are tabulated along with the solar cell results in Table 11.

Table 11. RESULTS FOR SOLAR CELLS FABRICATED FROM BORON-DIFFUSED 1-2 OHM CM PHOSPHORUS-DOPED SILICON

<u>Diffusion</u>	<u>Temp (°C)</u>	<u>Time (Minutes)</u>	<u>Sheet Resistance (ohms/□)</u>	<u>No. of Cells</u>	<u>V_{oc} (volts)</u>	<u>I_{sc}/A (mA)</u>	<u>FF</u>	<u>Eff. (%)</u>
1	900	30	163	9	0.555	19.87	0.772	8.51
2	920	30	130	7	0.549	18.96	0.754	7.84
3	940	40	71	2	0.552	18.05	0.631	6.36

2.5.2 Solar Cell Evaluations

2.5.2.1 Apparatus Calibration

Standard Solar Cell No. TSS006 was received from JPL to be used in establishing the calibration of our solar cell evaluation apparatus. Previous calibration was obtained using several of our solar cells which were evaluated at both MRC and JPL. The standard solar cell indicates that the intensity which we have been using as 100 milliwatts/cm² is 3% to 5% too low. Since this is a small correction, since the results obtained between baseline crystals and those with secondary impurities will be unchanged, and since numerous cells have been measured with the previous calibration, the new calibration will not be instituted with our equipment.

2.5.2.2 Comparison of MRC and Westinghouse (Dow) Baseline Silicon and Device Fabrication

Since MRC and Westinghouse contracts have parallel efforts in part, it is natural to compare results. The question of the importance of the differences in fabrication processes and baseline material properties needs to be addressed. With the kind cooperation of Westinghouse we have obtained some Westinghouse baseline silicon and a copy of their metalization pattern and etching masks to run through our process. Likewise, we have supplied Westinghouse with some of our baseline material and a metalization mask. The results of our diffusion and fabrication of the Westinghouse material is discussed below.

Westinghouse baseline material, designated W-002, is Czochralski-grown, boron-doped, <111> oriented silicon with a resistivity of 2.9-4.0 ohm cm and a dislocation count of less than 5000/cm². MRC baseline Czochralski material is zero dislocation, <100> oriented and boron-doped to a resistivity of 0.5 ohm cm. MRC wafers are finished with a special polish resulting in a low damage mirror finish, while Westinghouse wafers are used with a chemically polished surface which is less flat. Experiments using these two different surfaces shows that they have very little if any effect on the solar cell quality using our diffusion and fabrication process.

In order to establish a comparison of baseline materials, fabrication processes, and the effects of the different metalization patterns, one-half of the cells were fabricated using a metalization mask supplied by Westinghouse⁵ (cell area of ~1 cm²) while the usual MRC mask (cell area of 4 cm²) was used on the rest of the cells. All cells were cleaned, diffused, metalized and processed, etc. together in a single lot.

2.5.2.3 Metalization Pattern Comparison

Table 12 summarizes the results of this experiment. The data in the first two rows shows that the Westinghouse metalization pattern yields a higher efficiency than the MRC pattern by a factor of 1.19. The most obvious differences in the metal patterns are that the Westinghouse cell is a 1 cm² , mesa-defined cell with a 5.4% metal coverage⁴ while the Monsanto cell is a 4 cm² cell which is cleaved or sawed to shape and has 14.1% metal coverage.

The mesa cell has a nominal 1 cm² (actual nearly 0.400 in. x 0.400 in. on the Westinghouse mask used) sensitive area fabricated by etching a few microns off of the front surface of the rest of the wafer. The actual sensitive area of such a cell, however, is somewhat uncertain since it is possible to collect some minority carriers from outside the mesa area within a diffusion length or so of the mesa edge.

To eliminate this area uncertainty, the mesa cells were then sawed to a precise 1 cm² area and re-evaluated. The data are shown in the third row of the table. This reduced the experimental ratio of efficiency improvement between the two metal patterns to 1.12. This value is close to the ratio determined from the relative open area (not metal covered) of the two cells of 1.10. The degree of agreement of these two ratios is probably as good as our knowledge of the actual metal coverage. The coverage areas used were computed from mask design numbers.

A second possibility for the cause of the observed efficiency reduction when the 1 cm² mesa cells were sawed would be the introduction of junction damage and shunt resistance at the saw cut. Such effects would be expected to degrade the fill factor while the observed fill factor increases a little upon sawing. The principal change observed upon sawing is a decrease in short circuit current, which is to be expected if the active area is reduced. In addition, the edges of some sawed cells have been etched with negligible effects on the efficiency. The saw used in this case was a Tempress Model 602 dicing saw capable of sawing 0.020 in. deep with a 0.002 in. kerf loss.

In general then, the different results obtained with the two metalization patterns is essentially what one would expect on the basis of exposed area of the cell.

It is obvious that the MRC metal pattern could be redesigned to yield higher efficiencies by reducing the metal coverage. This is not necessary for the work of this contract, however, since the main result is the relative performance of cells fabricated from silicon with and without secondary impurities added.

Table 12. PROPERTIES OF SOLAR CELLS FABRICATED FROM
WESTINGHOUSE BASELINE MATERIAL (W002)

<u>Metal Pattern</u>	<u>No. Cells</u>	<u>Voc</u> (volts)	<u>I_{sc}/A</u> (mA)	<u>FF</u>	<u>Eff.</u> (%)	<u>Material</u>	<u>Diffusion Fabrication</u>
Monsanto	6	0.555	20.76	0.776	3.92	W002	Monsanto
Westinghouse	6	0.562	25.01	0.755	10.59	W002	Monsanto
Westinghouse, same cells, but sawed to 1 cm ²	6	0.561	23.18	0.768	9.98	W002	Monsanto
Westinghouse*		0.551	22.56	0.775	9.66	W002	Westinghouse
Monsanto	5	0.578	19.31	0.738	8.25	Monsanto 1-2 ohm cm	Monsanto
Monsanto		0.571	20.87	0.768	9.15	Best Czochralski Data to Date**	Monsanto

*See Reference 6

**Secondary Impurity = Mg

2.5.2.4 Diffusion Comparison

To compare results obtained with the Westinghouse diffusion and that of MRC, we need to compare the data in row 2 with the similar data in row 4 obtained by Westinghouse on their baseline material.

The data were obtained by averaging the results on "standard" material in Table 8 in the First Quarterly Report of the Westinghouse contract. Similar results can be obtained from the data in the Second Quarterly Report. We see that the MRC results exceed those of Westinghouse by a factor of about 1.1. This could be a real difference in the diffusion results, but is more likely caused by a difference in simulator calibration.

A final observation, which can be made from the data in Table 12, is the comparison between solar cells fabricated from Westinghouse and MRC baseline materials. Comparing the data in row 1 with that in rows 5 and 6, we see that Westinghouse baseline material may result in slightly better solar cells than the MRC baseline materials. The MRC float-zone baseline material results in a cell which is better than either of the Czochralski materials.

In any case it is clear that there are no important differences between the processes and baseline materials used by Westinghouse and MRC that would cause difficulties in interpreting the results of these contracts. In fact, the results show good agreement thus far, in regions where comparisons are possible. The use of somewhat different boron doping levels, fabrication and diffusion processes by the two laboratories give increased validity to the results obtained.

2.5.2.5 Boron Diffusions

The evaluations of the P/N solar cells produced by boron diffusions into N-type silicon are summarized in Table 11. We see that the highest sheet resistance diffusions used so far of 163 ohms/ $\square$ results in the highest efficiency cells. This is contrary to our experience with phosphorus diffusions where the optimum sheet resistance was on the order of 55 ohms/ $\square$. The average efficiency obtained for cells fabricated from the material diffused at 900°C is 8.51% with a standard deviation of $\pm 0.29\%$.

The proper interpretation of the observation of high efficiency for high sheet resistance is not certain at the present, but may be related to a lower surface recombination rate for these diffusions. It could be that it is necessary to go to higher sheet resistances in the case of boron diffusions to be able to achieve the same surface recombination velocity as is obtained at lower sheet resistance values for phosphorus diffusions. In any case, these results will be confirmed and extended using contract N-type baseline material.

2.5.2.6 Phosphorus Diffusions/Discussion of Results to Date

Tables 13 and 14 list the solar cell results to date on Czochralski and float-zone (Mon-X) wafers polished on one side. Note that more float-zone wafers than Czochralski wafers have been successfully processed into solar cells. In addition fewer float-zone crystals require re-runs. This is partly caused by the size of the Czochralski wafers (≈ 2.3 in. diameter) since the usual wafer size for much of our work is 2 in. This leads to more broken wafers when inappropriate equipment is mistakenly used. In addition to this, however, significantly more difficulties with metalization are experienced with the Czochralski wafers than the float-zone wafers. The reason for this is not clear at the present, but could conceivably be related to the higher oxygen content of Czochralski wafers.

A peculiarity also exists with the solar cells fabricated from both the Czochralski and float-zone crystals with Ti as the secondary impurity. The open circuit decay measurements on both of these groups of solar cells show no linear portion of the decay so that it is not clear how to interpret the decay curve in terms of a lifetime. This may be related to poor junction characteristics, or series or shunt resistance since the fill factor is considerably lower than that found for other cells. The short circuit current is also very low for these cells indicating a lifetime degradation as the major cause of efficiency reduction.

A second group of samples which are different from the majority of those in the tables are ClC, C2C, and, to a lesser extent, M1C and M2C. These ingots have much higher doping levels and need to be considered separately. M2C and M1C both have essentially the same efficiency of about 7.1% which is considerably lower than the baseline values. The efficiency reduction is caused by the increased doping and the presence of Fe in M2C seems to be of little significance. Sample C2C has considerably higher efficiencies (3.3%) than ClC (0.7%) even though both are doped to the same level. This may be related to the presence of the secondary impurity (carbon) in C2C. If so the mechanism is not a simple lifetime improvement since the short circuit currents are nearly the same. It would seem that the junction quality is improved in C2C, since the open circuit voltage (0.55 volt) and fill factor (0.64) are much higher than for ClC (0.18 volt and 0.36 respectively).

The above observations and correlations must be regarded as tentative at this point since the experimental evidence is limited in extent.

The remainder of the results listed in Tables 13 and 14 can be examined together since the principal doping level (boron) of the

Table 13. EVALUATION OF PHOSPHORUS DIFFUSED BORON DOPED SOLAR CELLS
WITH SOME SECONDARY IMPURITIES. NO ANTIREFLECTION COATING OR DRIFT
FIELD BACK CONTACT 100 mW/cm² INCIDENT ENERGY DENSITY

Sample	Secondary Impurity	ρ (ohm cm)	V_{oc} (volts)	I_{sc}/A (mA/cm ²)	Eff. (%)	FF	τ_{OCD} (μ sec)	τ_{PDA} (μ sec)	τ_{PDB} (μ sec)
C1A*	--	0.52	0.572	19.25	8.69	0.787	1.7	--	--
C1C	--	0.015	0.180	9.60	0.67	0.363	0.1	<0.5	<0.5
C2A	C	0.53	0.581	19.77	8.77	0.764	2.2	2.2	--
C2B	C	0.55	0.578	19.92	8.78	0.762	2.5	--	2.0
C2B1*	C	0.46	0.582	19.60	8.77	0.768	1.9	2.4	--
33 C2C	C	0.016	0.550	9.47	3.34	0.639	0.4	<0.5	--
C4B	Cr	0.55	0.576	19.63	8.94	0.791	1.8	<0.5	--
C5B	Mn	0.48	0.572	18.79	7.66	0.713	0.9	--	--
C6B	Ni	0.53	0.579	19.70	8.90	0.780	2.5	2.3	3.2
C7B*	V	0.55	0.525	13.62	5.26	0.736	0.3	<0.5	<0.5
C9B1	Mg	0.53	0.576	19.38	8.51	0.762	1.3	2.0	--
C10B	Al	0.15	0.497	7.58	2.75	0.729	0.2	<0.5	--
C11B	Ti	0.54	0.505	10.81	2.56	0.469	--	<0.5	--
C15B	Na	0.57	0.574	19.73	8.45	0.745	1.7	--	--
C9B	Mg	1.6	0.571	20.87	9.15	0.768	4.0	2.9	--

*Results based on limited samples. Reruns are underway.

Table 14. EVALUATION OF PHOSPHORUS DIFFUSED BORON DOPED SOLAR CELLS
WITH SOME SECONDARY IMPURITIES. NO ANTIREFLECTION COATING OR DRIFT
FIELD BACK CONTACT 100 mW/cm² INCIDENT ENERGY DENSITY

Sample	Secondary Impurity	ρ (ohm cm)	V_{oc} (volts)	I_{sc} (mA/cm ²)	Bff. (%)	FF	τ_{QCD} (μ sec)	τ_{PDA} (μ sec)	τ_{PDB} (μ sec)
M1A	--	1.06	0.578	20.66	9.25	0.774	6.1	2.6	--
M1B	--	0.15	0.598	19.88	9.24	0.777	2.4	2.3	4.6
M1C	--	0.04	0.584	17.70	7.10	0.687	0.4	**	**
M2B1	Fe	0.38	0.581	19.34	8.93	0.794	2.3	2.6	0.5
M2B2	Fe	0.48	0.573	18.42	8.11	0.768	1.1	1.4	<0.5
M2C	Fe	0.056	0.585	17.21	7.17	0.713	0.4	**	**
M3B	Mn	0.44	0.595	20.56	9.75	0.797	5.1	**	**
M4B	Ni	0.59	0.589	20.65	9.61	0.790	4.6	2.7	4.2
M4B1	Ni	0.50	0.592	20.52	9.51	0.784	4.3	--	4.3
M5B	V	0.49	0.551	15.00	6.42	0.776	0.3	<0.5	<0.5
M5B1	V	0.48	0.537	13.92	5.79	0.774	0.4	--	<0.5
M6B*	Zr	0.48	0.585	19.41	8.89	0.783	2.8	2.2	4.0
M7B	Mg	0.45	0.592	20.82	9.69	0.787	4.6	2.9	4.0
M8B	Ti	0.49	0.521	13.38	3.94	0.565	--	<0.5	<0.5
M9B	C	0.48	0.577	19.29	8.32	0.748	2.5	2.3	4.6
M9B1	C	0.46	0.581	19.89	8.75	0.757	2.9	--	--
M10B	Al	0.36	0.589	20.31	9.32	0.779	2.9	1.5	--
M11B	Ni/Mn/Ma	0.49	0.590	20.84	9.38	0.762	4.1	--	**
M15B*	Na	0.48	0.589	20.88	9.21	0.748	3.9	2.9	--
M15B1	Na	0.46	0.591	20.87	9.41	0.763	4.1	2.6	--
M16B	P	0.42	0.588	20.48	9.27	0.770	3.8	--	3.6
M19B	Al Only	0.31	0.579	19.00	8.30	0.755	1.2	--	1.4
M31B	Cu	0.47	0.585	20.88	8.91	0.729	3.9	2.6	4.0
M32B	Cr	0.47	0.578	19.51	8.18	0.725	1.3	1.6	**

* Results based on limited samples Reruns underway.

** No modulation visible and/or trapping problems.

samples is nearly the same and since the solar cells fabricated from those samples all have reasonable fill factors (>0.7) and the differences lie mainly in the short circuit currents and are presumably related mainly to minority carrier lifetime differences. These results reasonably compare using the impurity concentrations determined by the analytical measurements (principally spark source mass spectroscopy).

Our experience tells us that there may be some uncertainties with the interpretation of the various analytical results. The results are reproducible, however, and they are the best answers available at the present. A further problem in the interpretation of these results is that we have very little specific information on the effects of gettering which can greatly change our interpretation of the results we have. The gettering effects may very well depend on the specific processing used. One feature of this dependence, the use of wafer with a polished-vs-as-sawed back, will be examined in the remainder of the contract.

Figure 9 shows the relative efficiencies of solar cells with different secondary impurities compared to the efficiencies of the baseline cells along with the concentration of the secondary impurity. The data for both float-zone and Czochralski wafers are presented.

Titanium is the worst offender in terms of reducing cell efficiency, with a reduction to a value of about 0.3 to 0.5 times that for the baseline material for about $10^{14}/\text{cc}$ of the impurity present. Vanadium is next with a reduction of 0.6 to 0.7 for concentrations of 1 to $7 \times 10^{14}/\text{cc}$. Iron is somewhat less effective with a concentration about $2 \times 10^{15}/\text{cc}$ being required to reduce the efficiency to 0.8 of the baseline value. Zirconium may also be detrimental but to a lesser degree than the preceding three impurities.

Manganese seems not to be detrimental and perhaps even beneficial at the $10^{15}/\text{cc}$ level, although $10^{16}/\text{cc}$ degraded the efficiency of the Czochralski sample.

Similarly, aluminum at the $4 \times 10^{17}/\text{cc}$ level does not decrease the efficiency of the float-zone sample while $8 \times 10^{18}/\text{cc}$ reduces the efficiency of the Czochralski sample severely. The disturbing feature of these samples is the large value of Al determined analytically. If these are correct, then the aluminum is mostly electrically inactive since the resistivity is not strongly affected. The aluminum then, must be present as something other than a simple substitutional atom and these precipitates or other complex impurity groupings are acting to reduce the efficiency. The large difference between the behavior of float-zone and Czochralski silicon leads one to suspect the involvement of oxygen

Figure 9. Relative Efficiency for Various Secondary Impurities Baseline
 Efficiency = 8.6% for Czochralski
 and 9.25% for Mon-X

in the complex. Similar effects may be present in the manganese sample.

Magnesium seems to be non-detrimental or perhaps advantageous at the $10^{14}/\text{cc}$ level and perhaps innocuous even at 10 times that concentration.

Carbon apparently improves Czochralski samples even at the $10^{17}/\text{cc}$ level, but degrades the float-zone samples slightly. Actually, all the carbon-doped samples have very nearly the same efficiency values. The bars representing the float-zone efficiency in Figure 9 are shorter because the baseline efficiency is higher.

Nickel seems to increase the efficiency slightly even at the $7 \times 10^{16}/\text{cc}$ level. Since one might expect Fe and Ni to behave similarly, the possibility that the Ni is "gettered" out and may even assist in the "gettering" of other impurities during processing seems a likely one.

Analytical results are not available for the impurities in the remaining samples so one can not interpret the results with certainty. However, the use of Al instead of B and the addition of Cr as a secondary impurity seem to degrade the performance of the cells somewhat.

2.5.3 Minority Carrier Lifetime Determination

2.5.3.1 Open Circuit Decay Measurements

The values of lifetimes determined to date are listed in Tables 13 and 14. We will concentrate on the Open Circuit Decay Measurements on the solar cells themselves since they form the most complete set of lifetime data we have at the present.

Figures 10 and 11 show the solar cell efficiency and the short circuit plotted as a function of the square root of the open circuit decay lifetime. Both float-zone and Czochralski data are included in this curve. We see a regular dependence displayed without too much scatter except at the smaller values of $\sqrt{\tau}$. This indicates that the lifetime and efficiency are related in the same way for both Mon-X and Czochralski crystals.

To see if a very simplified model can explain the observed behavior let us first assume that we can represent the behavior of a solar cell with minority carriers having a single effective diffusion length or lifetime. When this diffusion length, L , is much smaller than the cell thickness, X , and/or the absorption length reciprocal absorption coefficient, $1/\alpha$, of the light involved, one might expect that the efficiency or short circuit current would be proportional to the effective diffusion length. At the other extreme we would expect that there is a limiting value for

Figure 10. Efficiency vs. $\sqrt{\tau}$ for Mon-X and Czochralski Silicon

Figure 11. Short Circuit Current Density vs. $\sqrt{\tau}$ for Mon-X and Czochralski Silicon

the diffusion length beyond which increases in bulk diffusion length will have little or no effect on the cell efficiency. This limit would very likely be related to the effective absorption length of the light involved but could be related to cell thickness in some cases. In terms of lifetimes one might connect these two limits by expressing an "effective collection lifetime" τ_C as follows:

$$\frac{1}{\tau_C} = \frac{1}{\tau} + \frac{1}{\tau_L} \quad (1)$$

or

$$\tau_C = \frac{\tau}{1 + \tau/\tau_L} \quad (2)$$

where τ is the bulk lifetime and τ_L is the limiting lifetime corresponding to the limiting diffusion length discussed above. This can be converted to an "effective collection diffusion length", L_C as follows:

$$L_C = \sqrt{D} \sqrt{\frac{\tau}{1 + \tau/\tau_L}} \quad (3)$$

The efficiency (or short circuit current) should then be proportional to L_C .

$$\text{Eff} = A \sqrt{\frac{\tau}{1 + \tau/\tau_L}} \quad (4)$$

The solid lines on Figures 11 and 12 represent a fit of the above equation to the data with the parameters as shown. The samples at small $\sqrt{\tau}$ which are furthest from the curve represent the two very heavily doped samples and the Czochralski aluminum-doped sample. Except for these both types of samples fall fairly close to the curves shown. This gives one some confidence that the efficiencies observed are mainly lifetime determined and not influenced too much by more complicated factors.

The value of τ_L from the fit to the efficiency curve corresponds to limiting length of about $25\mu\text{m}$. The absorption length attains that value between $8000\text{\AA}$ and $9000\text{\AA}$ for silicon. One might have expected the correspondence at a shorter wavelength, but this is at least a reasonable result, considering the simplified nature of our model.

Since the minority carrier lifetime is of major importance in determining solar cell performance we can carry out one more simple calculation to obtain some feeling for the reasonableness of our data for lifetimes and impurity concentrations. Let us assume that the secondary impurity is the controlling factor

in determining the lifetime. This should be a reasonable assumption for the samples containing V. The lifetime τ is related to the capture cross-section σ , the thermal velocity, v_{th} , and the impurity concentration by⁸

$$\frac{1}{\tau} = \sigma v_{th} N = N \sigma 1.168 \times 10^7 \sqrt{\frac{T}{300^\circ K}} \sqrt{\frac{M}{M_{eff}}} \quad (5)$$

$$\text{or } \sigma = \frac{1}{\tau N 2.7 \times 10^7} \quad (6)$$

Using the tabulated values for N and τ_{OCD} we obtain cross sections between 1.2×10^{-15} and $1.8 \times 10^{-15} \text{ cm}^2$ for the V-doped samples. We see that these are not too far from the geometric⁵ value of $\approx 10^{-15}$. Although a precise interpretation of the meaning of these values is not possible it is at least a little comforting to see that they are near the expected order of magnitude. One should get the same cross section for different concentrations of a given impurity and if this were attained it would give one a basis for extrapolating results to different impurity concentrations.

In general then we can conclude that we have some evidence that minority carrier lifetime is the predominant factor in determining solar cell performance and that both float-zone and Czochralski ingots exhibit the same relationship between lifetime and performance. Further, the capture cross-section calculated for vanadium is of a reasonable magnitude, giving us some confidence that our lifetimes and impurity concentrations are not unreasonable.

3. TENTATIVE CONCLUSIONS AND RECOMMENDATIONS

- As far as experimental crystal growth work is concerned we conclude at this stage that only a few make-up crystals will have to be grown in order to meet the specific objectives of the contract program plan.
- Tentative conclusions can be drawn from the preliminary results of our attempts to use aluminum instead of the more conventional boron as the P-type doping impurity. The resistivity measurements indicate that only 20% of the aluminum atoms incorporated in the crystal lattice have become ionized to contribute to the conductivity. This is disappointing to say the least. We had assumed the earlier reported low ionization ratio for aluminum in Cz-silicon might have been caused solely by the observed precipitation of aluminum oxides, which are electrically inactive. We had hoped that the two orders of magnitude lower oxygen concentration in Fz silicon would help to obtain the desirable high ionization ratio of the other P-type dopants. This does not seem to happen. The solar cell efficiency of the first series of devices built in aluminum-doped (boron content less than 0.2 ppb!) Fz-silicon crystal was actually lower than the efficiency always observed in Fz-baseline devices. At least two more crystals are to be evaluated, and final conclusions as to the merits of aluminum doping will have to wait until all the data are in. We recommend that additional crystals not be grown at this time.
- The exceptionally high efficiencies observed in devices made from Fz crystals that were contaminated with magnesium, manganese, or nickel made us wish to find out whether a synergistic effect could come from having all three metals present in the same crystal at the same time. From the performance data obtained so far we conclude that if such an effect exists, it is rather insignificant. Of considerable significance, however, for the objectives of Task I and II, should be the fact that all three impurities, Mg, Mn, and Ni, can be present in appreciable concentration, at least in low-oxygen silicon and still allow the construction of solar devices with efficiencies sufficient to meet the goals of the LSSA project.
- From the results of material characterization we are inclined to conclude at this time that no clear relationship exists between the generated resistivity data and the observed solar cell efficiencies. However, it seems that 0.4 ohm cm P-type may be the lower resistivity limit for a satisfactory starting material for N/P devices designed to have a minimum efficiency. Furthermore, one might suspect that the optimum

resistivity value is not exactly 0.5 ohm cm but somewhere above that value for maximum cell performance, everything else staying the same.

- There were no real discrepancies apparent in the infrared data on oxygen and carbon as checked by both Dow and MRC laboratories. Some samples exchanged with Westinghouse for mass spectrometric analysis showed some disagreement because of lack of suitable standards. Overall, it was found to be extremely beneficial to have an inter-laboratory exchange of information. There are not serious discrepancies between mass spectrometric (SSMS) and emission spectrographic results either, and SSMS itself shows good reproducibility. Since SSMS is reproducible and sensitive for almost every element under investigation in this study, meaningful interpretations can be derived from the analytical results. We believe the SSMS-Total Impurities analysis is the best way to obtain meaningful data on the impurities present in the crystals under investigation. Good primary standards for silicon analysis, however, are needed urgently.

- In PN solar cell work we conclude that the proper interpretation of the high efficiency for high sheet resistance is not certain at this time but may be related to a lower surface recombination rate for these diffusions. It could be that it is necessary to go higher in sheet resistance in the case of boron diffusion to achieve the same recombination velocity as is obtained at lower sheet resistance for phosphorus diffusions.

- In NP solar cell work we find that, in general, float-zone (Mon-X) material has been easier to handle than Cz material. In particular, our experience has been that float-zone is much easier to metalize. This could be related to the lower oxygen content in float-zone, but we are not sure of this. We are certain, however, that low-oxygen silicon, i.e., silicon grown without a contaminating container, is a considerably better starting material for solar cells than Cz crystal. Not only does the "baseline" material give better cells but low-oxygen silicon solar cells have shown a considerably higher tolerance toward metallic contaminants than than devices built in Cz crystal.

- We have now more evidence that certain impurities, mainly Mg, Mn, and Ni, have a beneficial effect on solar cell functioning. Even when all three elements are present in the same crystal, no efficiency-reducing effect has been observed. On the other, hand, the hoped-for synergistic effect failed to materialize.

- Of the deleterious impurities, titanium is the worst offender in terms of reducing cell efficiency, with a reduction to a value of about 0.3 to 0.5 times that for the baseline material for about 10^{14} /cc of the impurity present. Vanadium is

next with a reduction of 0.6 to 0.7 for concentrations of 1 to 7×10^{14} /cc. Iron is somewhat less effective with a concentration about 2×10^{15} /cc being required to reduce the efficiency to 0.8 of the baseline value. Zirconium may also be detrimental but to a lesser degree than the preceding three impurities.

The results of our lifetime measurements allow us to conclude that minority carrier lifetime is the predominant factor in determining solar cell performance and that both float-zone and Czochralski ingots exhibit the same relationship between lifetime and performance. Further more, the capture cross-section calculated for vanadium is of a reasonable magnitude, giving us confidence that our lifetimes and impurity concentrations are reasonable.

4. PROJECTED ACTIVITIES FOR NEXT QUARTER

- Complete all experimental work scheduled for the contract.
- Collect and evaluate data.
- Prepare tentative definition of solar-grade silicon.
- Prepare draft of final report.

5. REFERENCES

1. John C. Irvin, The Bell System Technical Journal, 51(2), 887 (1962).
2. C. L. Luke and S. S. Flaschen, Anal. Chem., 30, 1406 (1958).
3. "Recommended Practice for the Conversion of Carrier Concentration to Resistivity for N- and P-Type Silicon," ASTM F-1 Document 6038.
4. First Quarterly Report, this contract. 1 October 1975-31 December 1975, p 9.
5. Mask design described in Res. Rpt. 76-964-SIMAT-R1, 1st Quarterly Report, 1 October 1975 - 31 December 1975, JPL Contract No. 954331, Westinghouse, Dow Corning, Figure 8, p 25.
6. Ref. 5, p 52, Table 8.
7. Ref. 5, p 24.
8. Eberhard Spenke, "Electronic Semiconductors", McGraw Hill Book Co., New York, 1950, p 327.

APPENDIX I

This appendix contains the detailed solar cell data collected since the last quarterly report. Measurements made at 100 mW/cm² incident intensity. The following explains the table headings, with examples:

- Zeros in printed output indicate no value available, rather than actual zero values.
- C2A: Silicon ingot number; *** indicates re-run to be done.
- Single-Sided-C: Polished on one side
Carbon is the secondary impurity
- Resistivity = 0.55: Silicon resistivity in ohm cm
- Diffusion Number = 134: Sequential number assigned to this diffusion.
- Control Percentage = 96: Relative efficiency (in percent) of baseline silicon run with this diffusion to the expected value for baseline silicon.
- File Number = 6: File number where this data is recorded on magnetic tape.

Abbreviations:

VOC = Open circuit voltage in volts.

ISC = Short circuit current density in mA/cm².

VM = Voltage at maximum power point in volts.

IM = Current at maximum power point in mA.

EFF = Solar cell efficiency in %.

FF = Fill factor.

RS = Series resistance in ohms from open circuit decay measurement.

TOC = Lifetime in microseconds from open circuit decay measurement.

TPC = Photoconductive decay lifetime in microseconds before diffusion.

C1A***
 SINGLE-SIDED ---
 RESISTIVITY = 0.55
 DIFFUSION NUMBER = 134
 CONTROL PERCENTAGE = 96

VOC	ISC	VM	IM	EFF	FF	RS	TOC	TPC
0.570	19.63	0.467	73.28	8.56	0.765	0.300	1.4	0.0
0.577	19.55	0.479	71.19	8.53	0.756	0.180	1.4	0.0
0.578	19.49	0.492	72.33	8.90	0.790	0.180	1.5	0.0
0.571	18.20	0.486	72.10	8.76	0.843	0.180	1.6	0.0
0.575	19.40	0.486	71.59	8.70	0.780	0.100	2.8	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.0036	0.5943	0.0096	0.7958	0.152	0.0341	0.0716	0.60	0.00
0.574	19.25	0.482	72.10	8.69	0.787	0.180	1.7	0.0

C2A
 SINGLE-SIDED C
 RESISTIVITY= 0.53
 DIFFUSION NUMBER= 139
 CONTROL PERCENTAGE= 100
 FILE NUMBER= 6

VOC	ISC/E	VM	IM	EFF	FF	RS	TOC	TPC
0.582	19.96	0.494	73.76	9.11	0.784	0.280	2.3	0.0
0.584	19.88	0.489	73.72	9.01	0.776	0.240	2.0	0.0
0.579	19.30	0.489	70.41	8.61	0.770	0.180	2.1	0.0
0.580	19.65	0.486	71.66	8.71	0.764	0.600	1.9	0.0
0.582	19.98	0.490	74.35	9.11	0.783	0.440	2.6	0.0
0.579	19.88	0.471	69.93	8.23	0.716	1.100	2.4	0.0
0.580	19.72	0.473	72.66	8.59	0.751	0.340	1.8	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0019	0.2375	0.0089	1.735	0.326	0.0241	0.3170	0.29	0.00
0.581	19.77	0.485	72.36	8.77	0.764	0.454	2.2	0.0

C1C
 SINGLE-SIDED NONE
 RESISTIVITY= 0.015
 DIFFUSION NUMBER= 99
 CONTROL PERCENTAGE= 100
 FILE NUMBER= 1

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.189	9.93	0.122	25.43	0.78	0.413	0.300	0.2	0.1
0.130	9.51	0.088	20.55	0.45	0.366	0.300	0.2	0.1
0.384	9.61	0.238	27.50	1.64	0.443	0.400	0.1	0.1
0.189	9.10	0.125	20.14	0.63	0.366	0.400	0.1	0.1
0.173	9.39	0.126	19.78	0.62	0.384	0.400	0.1	0.1
0.282	9.27	0.159	24.50	0.97	0.372	0.300	0.1	0.1
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0926	0.2863	0.0517	3.254	0.424	0.0313	0.0548	0.04	0.00
0.225	9.47	0.143	22.98	0.85	0.391	0.350	0.1	0.1

C10B
 SINGLE-SIDED AL
 RESISTIVITY= 0.152
 DIFFUSION NUMBER= 97
 CONTROL PERCENTAGE= 84
 FILE NUMBER= 2

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.508	8.03	0.402	29.85	3.00	0.736	0.400	0.2	0.0
0.505	7.90	0.392	28.85	2.83	0.708	0.400	0.2	0.0
0.491	7.10	0.414	25.68	2.66	0.763	0.320	0.2	0.0
0.501	7.68	0.408	28.12	2.87	0.746	0.400	0.2	0.0
0.495	7.55	0.406	28.26	2.87	0.767	0.400	0.2	0.0
0.488	7.41	0.396	25.04	2.48	0.686	0.380	0.2	0.0
0.494	7.23	0.404	26.43	2.67	0.747	0.360	0.2	0.0
0.494	7.76	0.400	26.00	2.60	0.678	0.320	0.2	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0070	0.3227	0.0069	1.719	0.172	0.0340	0.0354	0.01	0.00
0.497	7.58	0.403	27.28	2.75	0.729	0.373	0.2	0.0

C28
 SINGLE-SIDED C
 RESISTIVITY= 0.55
 DIFFUSION NUMBER= 113
 CONTROL PERCENTAGE= 97
 FILE NUMBER= 7

VOC	ISC/R	VM	IM	EFF	FF	RS	TOC	TPC
0.577	19.93	0.483	67.57	8.16	0.710	0.140	2.2	2.0
0.578	19.85	0.487	69.30	8.44	0.735	0.120	2.4	2.0
0.580	19.95	0.493	74.40	9.17	0.792	0.180	2.6	2.0
0.580	19.98	0.495	73.39	9.08	0.784	0.140	2.5	2.0
0.580	20.12	0.500	73.17	9.15	0.784	0.140	2.7	2.0
0.582	19.98	0.494	74.02	9.14	0.786	0.160	2.6	2.0
0.577	19.89	0.481	69.33	8.34	0.726	0.160	2.2	2.0
0.579	19.98	0.475	71.48	8.49	0.734	0.160	2.4	2.0
0.575	19.78	0.493	72.65	8.95	0.787	0.160	2.7	2.0
0.574	19.78	0.487	73.20	8.91	0.785	0.140	2.6	2.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0025	0.1041	0.0076	2.336	0.386	0.0319	0.0170	0.19	0.00
0.578	19.92	0.489	71.85	8.78	0.762	0.150	2.5	2.0

C281***
 SINGLE-SIDED C
 RESISTIVITY = 0.46
 DIFFUSION NUMBER = 114
 CONTROL PERCENTAGE = 73

VOC	ISC	VM	IM	EFF	FF	RS	TOC	TPC
0.581	19.21	0.459	68.75	7.89	0.707	0.160	1.6	0.0
0.581	19.03	0.492	67.68	8.32	0.753	0.140	2.0	0.0
0.581	19.67	0.431	69.82	7.52	0.658	0.160	1.8	0.0
0.584	19.90	0.501	73.26	9.18	0.790	0.140	2.0	0.0
0.583	19.68	0.500	72.31	9.04	0.788	0.120	2.0	0.0
0.583	19.81	0.503	73.27	9.21	0.798	0.140	2.0	0.0
0.584	19.62	0.502	72.74	9.13	0.797	1.600	2.0	0.0
0.581	19.55	0.503	72.37	9.10	0.801	0.140	2.1	0.0
0.582	19.88	0.496	73.68	9.14	0.790	0.160	2.1	0.0
0.584	19.66	0.501	73.18	9.17	0.798	0.140	1.8	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0013	0.2815	0.0242	2.1424	0.623	0.0484	0.4605	0.16	0.00
0.582	19.60	0.489	71.71	8.77	0.768	0.290	1.9	0.0

C2C
SINGLE-SIDED C
RESISTIVITY= 0.016
DIFFUSION NUMBER= 112
CONTROL PERCENTAGE= 79
FILE NUMBER= 9

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.537	8.99	0.416	27.04	2.81	0.583	0.200	0.4	0.0
0.559	10.21	0.462	34.40	3.97	0.696	0.180	0.4	0.0
0.557	9.61	0.466	32.56	3.79	0.708	0.180	0.4	0.0
0.557	8.92	0.458	30.37	3.48	0.700	0.180	0.4	0.0
0.551	9.71	0.429	29.90	3.21	0.600	0.220	0.3	0.0
0.541	9.39	0.406	27.34	2.78	0.546	0.180	0.4	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0093	0.4817	0.0258	2.880	0.498	0.0708	0.0167	0.04	0.00
0.550	9.47	0.440	30.27	3.34	0.639	0.190	0.4	0.0

C4B
SINGLE-SIDED CR
RESISTIVITY= 0.55
DIFFUSION NUMBER= 119
CONTROL PERCENTAGE= 100
FILE NUMBER= 8

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.571	19.59	0.482	70.78	8.53	0.762	0.120	1.7	0.0
0.578	19.72	0.496	73.54	9.12	0.800	0.140	1.7	0.0
0.578	19.44	0.496	72.46	8.99	0.800	0.120	1.8	0.0
0.578	19.58	0.491	73.72	9.05	0.800	0.140	1.9	0.0
0.578	19.64	0.499	72.34	9.02	0.795	0.140	1.8	0.0
0.573	19.71	0.485	73.70	8.94	0.791	0.160	1.8	0.0
0.573	19.72	0.486	73.60	8.94	0.791	0.140	1.8	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0031	0.1039	0.0005	1.096	0.192	0.0133	0.0138	0.07	0.00
0.576	19.63	0.491	72.88	8.94	0.791	0.137	1.8	0.0

C5B
 SINGLE-SIDED MN
 RESISTIVITY= 0.477
 DIFFUSION NUMBER= 117
 CONTROL PERCENTAGE= 100
 FILE NUMBER= 12

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.568	18.65	0.461	60.46	6.97	0.658	0.340	0.9	0.0
0.573	18.78	0.423	61.64	6.52	0.606	0.220	0.8	0.0
0.575	18.70	0.484	70.08	8.48	0.789	0.140	1.0	0.0
0.574	18.90	0.486	70.30	8.54	0.788	0.140	1.0	0.0
0.564	18.93	0.464	67.30	7.01	0.725	0.160	1.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0031	0.1195	0.0254	4.651	0.902	0.0806	0.0849	0.09	0.00
0.572	18.79	0.464	65.96	7.66	0.713	0.200	0.9	0.0

C6B
 SINGLE-SIDED NI
 RESISTIVITY= 0.53
 DIFFUSION NUMBER= 110
 CONTROL PERCENTAGE= 106
 FILE NUMBER= 11

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.577	19.55	0.494	72.43	8.95	0.793	0.180	2.5	3.2
0.579	20.10	0.475	74.28	8.82	0.758	0.440	2.0	3.2
0.582	19.58	0.501	72.70	9.11	0.799	0.140	2.5	3.2
0.580	19.90	0.496	72.00	8.93	0.774	0.120	2.6	3.2
0.577	19.84	0.456	74.58	8.50	0.743	0.260	2.4	3.2
0.578	19.27	0.498	70.89	8.83	0.792	0.160	2.5	3.2
0.578	19.75	0.494	73.70	9.10	0.798	0.140	2.6	3.2
0.571	19.62	0.474	70.67	8.37	0.748	0.160	2.2	3.2
0.581	19.63	0.500	72.88	9.11	0.799	0.160	2.5	3.2
0.583	19.79	0.504	73.41	9.25	0.802	0.140	2.8	3.2
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0034	0.2263	0.0156	1.312	0.279	0.0231	0.0958	0.22	0.00
0.579	19.70	0.489	72.75	8.90	0.780	0.190	2.5	3.2

C7B***
 SINGLE-SIDED V
 RESISTIVITY = 0.555
 DIFFUSION NUMBER = 118
 CONTROL PERCENTAGE = 105

VOC	ISC	VM	IM	EFF	FF	RS	TOC	TPC
0.528	13.90	0.439	45.51	4.99	0.681	0.210	0.3	0.0
0.522	13.81	0.436	51.22	5.58	0.774	0.240	0.3	0.0
0.526	13.15	0.432	48.25	5.21	0.753	0.240	0.3	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0031	0.4070	0.0035	2.8558	0.298	0.0491	0.0173	0.00	0.00
0.525	13.62	0.436	48.33	5.26	0.736	0.230	0.3	0.0

C9B
 SINGLE-SIDED MG
 RESISTIVITY= 1.6
 DIFFUSION NUMBER= 148
 CONTROL PERCENTAGE= 98
 FILE NUMBER= 5

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.572	20.97	0.473	78.42	9.27	0.773	0.150	3.8	0.0
0.571	20.72	0.482	77.72	9.37	0.792	0.140	3.8	0.0
0.566	20.84	0.477	75.55	9.01	0.764	0.140	3.7	0.0
0.574	21.15	0.485	78.91	9.57	0.788	0.150	3.9	0.0
0.573	20.77	0.479	77.89	9.33	0.784	0.150	4.4	0.0
0.570	20.81	0.470	71.14	8.36	0.705	0.160	4.2	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0028	0.1597	0.0056	2.915	0.427	0.0324	0.0075	0.27	0.00
0.571	20.87	0.478	76.61	9.15	0.768	0.148	4.0	0.0

C981
 SINGLE-SIDED MG
 RESISTIVITY= 0.53
 DIFFUSION NUMBER= 137
 CONTROL PERCENTAGE= 91
 FILE NUMBER= 4

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.572	19.38	0.472	68.33	8.06	0.728	0.200	1.2	0.0
0.571	19.45	0.473	67.21	7.95	0.716	0.200	1.2	0.0
0.577	19.20	0.480	67.82	8.14	0.735	0.160	1.3	0.0
0.579	19.42	0.495	72.23	8.94	0.795	0.160	1.4	0.0
0.579	19.50	0.485	69.87	8.47	0.750	0.160	1.4	0.0
0.580	19.60	0.491	73.40	9.01	0.793	0.180	1.0	0.0
0.573	19.38	0.487	71.78	8.74	0.787	0.160	1.4	0.0
0.578	19.23	0.481	69.25	8.33	0.749	0.160	1.4	0.0
0.575	19.41	0.487	71.77	8.74	0.783	0.160	1.4	0.0
0.580	19.23	0.492	70.88	8.72	0.782	0.160	1.4	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0034	0.1268	0.0078	2.078	0.376	0.0296	0.0170	0.08	0.00
0.576	19.38	0.484	70.25	8.51	0.762	0.170	1.3	0.0

C158
 SINGLE-SIDED NH
 RESISTIVITY= 0.57
 DIFFUSION NUMBER= 136
 CONTROL PERCENTAGE= 82
 FILE NUMBER= 10

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.578	19.68	0.488	72.93	8.90	0.782	0.180	1.8	0.0
0.577	19.66	0.483	70.67	8.53	0.752	0.160	1.8	0.0
0.580	19.91	0.490	72.34	8.86	0.768	0.170	1.8	0.0
0.576	19.45	0.479	67.21	8.05	0.719	0.160	1.6	0.0
0.571	19.78	0.475	70.66	8.39	0.743	0.200	1.7	0.0
0.577	19.88	0.484	73.60	8.91	0.777	0.180	1.8	0.0
0.568	19.84	0.469	65.53	7.68	0.682	0.160	1.5	0.0
0.573	19.61	0.474	67.62	8.01	0.713	0.180	1.7	0.0
0.575	19.69	0.487	70.52	8.59	0.758	0.180	1.7	0.0
0.573	19.72	0.468	69.56	8.14	0.720	0.180	1.6	0.0
0.571	19.79	0.482	73.68	8.88	0.786	0.180	1.8	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0036	0.1319	0.0075	2.714	0.427	0.0333	0.0121	0.10	0.00
0.574	19.73	0.480	70.39	8.45	0.745	0.175	1.7	0.0

M1A
 SINGLE-SIDED -
 RESISTIVITY= 1.06
 DIFFUSION NUMBER= 133
 CONTROL PERCENTAGE= 103
 FILE NUMBER= 18

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.576	20.43	0.476	75.96	9.04	0.768	0.220	6.2	0.0
0.574	20.75	0.481	76.95	9.25	0.777	0.160	5.8	0.0
0.577	20.53	0.481	76.58	9.21	0.777	0.240	6.6	0.0
0.578	20.46	0.484	76.94	9.31	0.787	0.160	6.0	0.0
0.581	20.86	0.484	73.96	8.95	0.739	0.160	5.6	0.0
0.581	20.60	0.485	76.53	9.28	0.775	0.160	6.0	0.0
0.582	21.03	0.491	79.10	9.71	0.793	0.160	6.2	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0030	0.2219	0.0046	1.520	0.242	0.0176	0.0346	0.32	0.00
0.578	20.66	0.483	76.57	9.25	0.774	0.180	6.1	0.0

M1C
 SINGLE-SIDED --
 RESISTIVITY= 0.04
 DIFFUSION NUMBER= 131
 CONTROL PERCENTAGE= 100
 FILE NUMBER= 15

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.587	17.79	0.491	60.11	7.38	0.707	0.220	0.4	0.0
0.500	17.42	0.446	58.50	6.52	0.646	0.220	0.4	0.0
0.592	17.79	0.497	62.97	7.82	0.743	0.220	0.4	0.0
0.578	17.67	0.459	60.50	6.94	0.680	0.240	0.4	0.0
0.589	17.63	0.490	62.91	7.71	0.742	0.240	0.5	0.0
0.577	17.90	0.454	55.10	6.25	0.606	0.240	0.4	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0063	0.1658	0.0222	2.960	0.639	0.0546	0.0110	0.03	0.00
0.584	17.70	0.473	60.02	7.10	0.687	0.230	0.4	0.0

M2B1
 SINGLE-SIDED FE
 RESISTIVITY= 0.38
 DIFFUSION NUMBER= 88
 CONTROL PERCENTAGE= 94
 FILE NUMBER= 24

VOC	ISC/R	VM	IM	EFF	FF	RS	TOC	TPC
0.579	19.30	0.486	72.45	8.80	0.788	0.240	2.0	0.5
0.586	19.35	0.501	72.19	9.04	0.797	0.200	2.4	0.5
0.582	19.46	0.495	73.10	9.05	0.799	0.200	2.4	0.5
0.578	19.30	0.489	72.39	8.85	0.793	0.160	2.4	0.5
0.580	19.23	0.490	72.21	8.85	0.793	0.200	2.2	0.5
0.582	19.28	0.495	72.41	8.96	0.799	0.180	2.4	0.5
0.583	19.47	0.491	72.79	8.93	0.787	0.200	2.2	0.5
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0027	0.0886	0.0050	0.328	0.097	0.0049	0.0243	0.16	0.00
0.581	19.34	0.492	72.51	8.93	0.794	0.197	2.3	0.5

M2C
 SINGLE-SIDED FE
 RESISTIVITY= 0.056
 DIFFUSION NUMBER= 132
 CONTROL PERCENTAGE= 104
 FILE NUMBER= 16

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.592	18.19	0.494	64.02	7.91	0.734	0.220	0.4	0.0
0.583	16.63	0.487	57.78	7.03	0.726	0.220	0.4	0.0
0.588	16.79	0.489	58.70	7.18	0.727	0.220	0.4	0.0
0.587	18.11	0.477	58.39	6.99	0.657	0.220	0.4	0.0
0.581	16.06	0.487	53.81	6.79	0.728	0.220	0.4	0.0
0.580	17.47	0.483	59.18	7.15	0.705	0.220	0.4	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0046	0.8585	0.0057	2.726	0.384	0.0290	0.0000	0.03	0.00
0.585	17.21	0.486	59.01	7.17	0.713	0.220	0.4	0.0

M581
 SINGLE-SIDED V
 RESISTIVITY= 0.48
 DIFFUSION NUMBER= 155
 CONTROL PERCENTAGE= 102
 FILE NUMBER= 22

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.538	14.11	0.450	52.92	5.95	0.784	0.240	0.4	0.5
0.541	14.37	0.450	53.35	6.00	0.772	0.260	0.4	0.5
0.540	14.31	0.456	53.15	6.06	0.784	0.240	0.4	0.5
0.541	14.28	0.460	52.89	6.08	0.788	0.280	0.4	0.5
0.529	13.56	0.444	48.68	5.40	0.754	0.280	0.4	0.5
0.536	14.19	0.427	53.62	5.72	0.752	0.280	0.4	0.5
0.534	12.17	0.455	44.54	5.07	0.780	0.240	0.4	0.5
0.540	14.36	0.455	53.24	6.06	0.781	0.240	0.4	0.5
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0042	0.7554	0.0104	3.251	0.374	0.0140	0.0198	0.02	0.00
0.537	13.92	0.450	51.55	5.79	0.774	0.258	0.4	0.5

M9B
 SINGLE-SIDED C
 RESISTIVITY= 0.48
 DIFFUSION NUMBER= 130
 CONTROL PERCENTAGE= 102
 FILE NUMBER= 17

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.555	17.89	0.452	65.60	7.41	0.746	0.200	1.0	4.6
0.586	20.02	0.456	66.75	7.61	0.649	0.200	2.8	4.6
0.587	19.66	0.490	72.70	9.00	0.780	0.180	3.4	4.6
0.578	19.78	0.474	72.08	8.54	0.747	0.200	2.8	4.6
0.560	17.94	0.462	67.53	7.80	0.776	0.200	1.3	4.6
0.580	20.26	0.484	74.01	8.96	0.756	0.180	3.0	4.6
0.585	19.48	0.490	72.88	8.93	0.784	0.180	3.4	4.6
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0134	0.9705	0.0171	0.456	0.693	0.0465	0.0107	0.98	0.00
0.577	19.29	0.473	70.22	8.32	0.748	0.191	2.5	4.6

M9B1
 SINGLE-SIDED C
 RESISTIVITY= 0.46
 DIFFUSION NUMBER= 150
 CONTROL PERCENTAGE= 99
 FILE NUMBER= 23

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.585	20.02	0.484	73.47	8.89	0.759	0.160	3.2	0.0
0.574	19.75	0.470	60.20	0.12	0.717	0.100	2.2	0.0
0.583	20.15	0.485	72.29	8.77	0.746	0.160	3.0	0.0
0.581	19.92	0.488	72.00	8.78	0.759	0.160	2.8	0.0
0.581	19.78	0.481	73.50	8.84	0.769	0.300	3.0	0.0
0.583	19.75	0.493	73.94	9.11	0.792	0.160	3.2	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0038	0.1659	0.0058	2.092	0.333	0.0249	0.0572	0.37	0.00
0.581	19.89	0.485	72.24	8.75	0.757	0.183	2.9	0.0

M10B
 SINGLE-SIDED AL
 RESISTIVITY= 0.365
 DIFFUSION NUMBER= 128
 CONTROL PERCENTAGE= 103
 FILE NUMBER= 14

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.590	20.33	0.497	74.56	9.26	0.773	0.160	2.8	0.0
0.592	20.42	0.492	77.41	9.52	0.788	0.160	2.7	0.0
0.585	20.31	0.491	72.50	8.90	0.749	0.160	2.8	0.0
0.586	20.33	0.500	75.32	9.42	0.790	0.160	3.0	0.0
0.594	20.19	0.502	75.80	9.51	0.793	0.160	3.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0038	0.0829	0.0048	1.798	0.258	0.0183	0.0000	0.13	0.00
0.589	20.31	0.496	75.12	9.32	0.779	0.160	2.9	0.0

M11B
 SINGLE NI/MN/MG
 RESISTIVITY= 0.49
 DIFFUSION NUMBER= 151
 CONTROL PERCENTAGE= 103
 FILE NUMBER= 19

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.588	20.65	0.498	70.20	8.74	0.720	0.180	3.4	0.0
0.590	20.91	0.500	76.07	9.51	0.771	0.140	4.2	0.0
0.595	20.94	0.511	78.40	10.02	0.804	0.160	4.5	0.0
0.583	20.90	0.474	70.46	8.35	0.685	0.170	3.6	0.0
0.595	20.93	0.502	79.10	9.93	0.797	0.140	4.5	0.0
0.593	20.73	0.507	77.59	9.83	0.800	0.140	4.4	0.0
0.587	20.86	0.493	75.31	9.28	0.758	0.240	4.4	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0045	0.1122	0.0120	3.636	0.633	0.0451	0.0359	0.45	0.00
0.590	20.84	0.498	75.30	9.38	0.762	0.167	4.1	0.0

M15B***
 SINGLE-SIDED NA
 RESISTIVITY = 0.48
 DIFFUSION NUMBER = 126
 CONTROL PERCENTAGE = 22

VOC	ISC	VM	IM	EFF	FF	RS	TOC	TPC
0.589	20.62	0.500	74.62	9.33	0.768	0.180	4.0	0.0
0.591	21.42	0.503	77.16	9.70	0.766	0.160	4.2	0.0
0.592	20.90	0.503	75.33	9.47	0.766	0.160	4.1	0.0
0.584	20.50	0.480	69.42	8.33	0.693	0.160	3.4	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0036	0.3879	0.0111	3.3189	0.605	0.0367	0.0100	0.36	0.00
0.589	20.88	0.497	74.13	9.21	0.748	0.165	3.9	0.0

M15B1
 SINGLE-SIDED NA
 RESISTIVITY= 0.46
 DIFFUSION NUMBER= 127
 CONTROL PERCENTAGE= 102
 FILE NUMBER= 11

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.592	20.78	0.496	76.96	9.54	0.776	0.200	4.2	0.0
0.595	21.42	0.502	78.21	9.82	0.770	0.200	4.4	0.0
0.503	20.88	0.494	78.43	9.89	0.782	0.200	4.4	0.0
0.588	20.84	0.479	73.03	8.75	0.714	0.200	3.5	0.0
0.590	20.68	0.495	77.79	9.63	0.789	0.180	4.3	0.0
0.588	20.89	0.494	75.86	9.37	0.763	0.160	4.0	0.0
0.588	20.70	0.498	71.59	8.91	0.732	0.160	3.5	0.0
0.590	20.80	0.494	77.30	9.55	0.778	0.200	4.4	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0026	0.2335	0.0067	2.528	0.381	0.0264	0.0377	0.39	0.00
0.591	20.87	0.494	76.15	9.41	0.763	0.198	4.1	0.0

M16B
 SINGLE P-COMP
 RESISTIVITY= 0.42
 DIFFUSION NUMBER= 154
 CONTROL PERCENTAGE= 101
 FILE NUMBER= 20

VOC	ISC/A	VM	IM	EFF	FF	RS	TDC	TPC
0.593	20.64	0.504	77.37	9.75	0.796	0.160	4.2	3.6
0.582	20.43	0.486	74.50	9.05	0.761	0.160	3.4	3.6
0.584	20.64	0.490	71.73	8.79	0.729	0.160	3.5	3.6
0.592	20.29	0.506	74.59	9.44	0.786	0.160	4.0	3.6
0.593	20.49	0.503	76.82	9.66	0.795	0.160	4.1	3.6
0.586	20.46	0.491	75.87	9.31	0.777	0.160	3.9	3.6
0.581	20.60	0.479	72.55	8.69	0.726	0.160	3.3	3.6
0.591	20.27	0.497	76.18	9.47	0.790	0.160	4.1	3.6
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0051	0.1469	0.0096	2.006	0.391	0.0286	0.0000	0.36	0.00
0.588	20.48	0.495	74.95	9.27	0.770	0.160	3.8	3.6

M19B
 SINGLE AL ONLY
 RESISTIVITY= 0.31
 DIFFUSION NUMBER= 153
 CONTROL PERCENTAGE= 99
 FILE NUMBER= 21

VOC	ISC/A	VM	IM	EFF	FF	RS	TDC	TPC
0.581	19.07	0.488	69.18	8.44	0.762	0.180	1.2	1.4
0.577	18.75	0.481	67.50	8.12	0.750	0.200	1.1	1.4
0.579	19.03	0.496	69.60	8.64	0.784	0.180	1.2	1.4
0.576	18.75	0.484	69.69	8.43	0.781	0.180	1.1	1.4
0.583	19.42	0.499	70.76	8.83	0.780	0.220	1.4	1.4
0.577	18.98	0.476	61.65	7.34	0.670	0.180	1.0	1.4
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0027	0.2490	0.0088	3.323	0.528	0.0434	0.0167	0.14	0.00
0.579	19.00	0.487	68.08	8.30	0.755	0.190	1.2	1.4

M31B
 SINGLE-SIDED CU
 RESISTIVITY= 0.47
 DIFFUSION NUMBER= 125
 CONTROL PERCENTAGE= 105
 FILE NUMBER= 12

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.593	20.69	0.501	77.44	9.70	0.791	0.160	4.2	4.0
0.576	20.73	0.478	67.69	8.09	0.677	0.180	3.2	4.0
0.589	21.03	0.495	78.13	9.67	0.781	0.180	4.0	4.0
0.589	20.63	0.502	74.37	9.33	0.768	0.200	4.1	4.0
0.577	20.61	0.458	66.79	7.65	0.643	1.100	3.6	4.0
0.507	21.59	0.495	73.09	9.04	0.714	0.300	4.0	4.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0070	0.3771	0.0171	4.788	0.856	0.0605	0.3691	0.38	0.00
0.585	20.88	0.488	72.92	8.91	0.729	0.353	3.9	4.0

M32B
 SINGLE-SIDED CR
 RESISTIVITY= 0.47
 DIFFUSION NUMBER= 124
 CONTROL PERCENTAGE= 102
 FILE NUMBER= 13

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.578	19.47	0.495	72.05	8.92	0.792	0.160	1.3	0.0
0.584	19.77	0.499	73.62	9.18	0.795	0.160	1.3	0.0
0.581	19.53	0.478	70.40	0.41	0.742	0.300	1.2	0.0
0.578	19.31	0.489	66.54	8.13	0.729	0.180	1.3	0.0
0.579	19.59	0.483	72.07	8.70	0.767	0.180	1.3	0.0
0.570	19.42	0.461	60.48	6.97	0.630	0.180	1.2	0.0
0.569	19.51	0.453	61.21	6.93	0.625	0.200	1.2	0.0
0.582	19.49	0.470	69.70	8.19	0.722	0.200	1.3	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0054	0.1332	0.0163	5.035	0.837	0.0663	0.0450	0.05	0.00
0.578	19.51	0.479	68.26	8.18	0.725	0.195	1.3	0.0

MILESTONE CHART
UPDATED PROGRAM PLAN CONTRACT No. 954338