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DETERMINATION OF A DEFINITION OF SOLAR GRADE SILICON

Final Report, October 1975—September 1976

By
M. H. Christ
K. P. Gupta
H. W. Gutsche
D. E. Hill
W. F. Tucker
M. S. Wang

Work Performed Under Contract No. NAS-7-100-954338

Monsanto Research Corporation
St. Peters, Missouri

U.S. Department of Energy

Solar Energy

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for

JET PROPULSION LABORATORY

Pasadena, California

Contract No. 954338

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MONSANTO RESEARCH CORPORATION
P. O. Box 8
St. Peters, Missouri 63376

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NEW TECHNOLOGY

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

ABSTRACT

This final report gives the results of work performed by Monsanto Research Corporation to inquire into the effects of the impurities Al, C, Cr, Cu, Fe, Mg, Mn, Na, Ni, O, Ti, V, and Zr on the performance of silicon solar cells. A series of experimental silicon crystals were prepared containing controlled amounts of these impurities in otherwise semiconductor-grade silicon single crystals. Using these crystals, solar cells were prepared and the solar energy conversion efficiencies of these devices were measured against a standard cell provided by Jet Propulsion Laboratory. As expected, cell efficiency was found to be degraded in various degrees by most of the impurities under investigation. Surprisingly, degradation of efficiency was most severe in the presence of titanium and vanadium. For a $\geq 10\%$ device the concentration of Ti must be kept below $\sim 6 \times 10^{13}$ atoms/cm³ and that of V below $\sim 1.2 \times 10^{14}$ atoms/cm³. On the other hand, silicon solar cell material may contain as much as 10^{17} atoms/cm³ of aluminum or carbon, 10^{16} atoms/cm³ of nickel, but only about 10^{15} atoms/cm³ of manganese, chromium, iron, copper, zirconium, and magnesium to yield a solar device of acceptable performance.

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1. SUMMARY AND CONCLUSIONS

The primary objectives of this project were:

- (1) To prepare a series of silicon crystals containing predetermined concentrations of dopants, that are necessary to render the crystal semiconducting, and impurities, that would be inadvertently present if the crystal came from a melt less pure than current semiconductor-grade polycrystalline silicon.
- (2) To detect and determine as accurately as possible the actual concentrations of dopants and impurities in silicon by physical-chemical analyses.
- (3) To prepare a series of experimental solar cells by a reproducible laboratory process.
- (4) To correlate material preparation and characterization data with the analytical results and with solar cell performance.
- (5) To establish limits of tolerance for the investigated impurities in silicon for solar devices with antireflection (AR) coating of $\geq 12\%$ efficiency.

Approach

Objective (1) was met by using established technology for single crystal growth of semiconductor-grade silicon by (a) the Czochralski method, i.e. pulling from a melt in a container, and by (b) the float zone technique, i.e. growing single crystal without a container. Controlled amounts of impurities were introduced into the melt prior to solidification. Elements studied were those that are the major impurities present in metallurgical-grade silicon, which is the source material for most processes leading to high purity silicon. In addition, the Czochralski-grown crystals have an oxygen content of about 10^{18} atoms/cc, which arises from the use of the quartz container used for the melt from which the crystals are pulled; float zone crystals which are grown without a container typically have oxygen contents about two orders of magnitude lower. Impurities effects in silicon crystals with high and low oxygen contents were examined from comparisons of the data for these different growth processes.

Objective (2) was met by measuring the resistivity and its radial and axial uniformity to obtain the effective dopant concentration and distribution. Spark source mass spectrometry was the primary method used to determine impurity concentrations. These measurements were supplemented by emission and infrared absorption spectroscopy measurements.

Objective (3) was met by demonstrating the close control of the diffusion process such that solar cells fabricated from baseline material were produced with η -values reproducible to $\pm 2.8\%$ within runs and $\pm 7\%$ from run to run.

To meet objective (4) the following parameters were evaluated.

- (a) Crystal growth data
- (b) Segregation coefficients
- (c) Solubility limits
- (d) Electrical resistivity values
- (e) Impurity concentrations as determined by mass spectrometry, emission spectroscopy and infrared absorption
- (f) Solar cell efficiency results
- (g) Minority carrier lifetime measurements before and after device processing.

Finally, objective (5) was met by developing a model that allows both a comparison of all experimental data on the basis of similar impurity concentrations in the material and the prediction of allowable impurity levels in solar cells. For example, for a 10% efficient solar cell; the equation derived from the model is:

$$N_{(10\%)} = \frac{1}{B} \left(1.77 - \frac{1}{\tau_b} \right)$$

N = impurity concentration (atoms/cm³)

B = proportionality factor

τ_b = minority carrier lifetime in "baseline" crystal

Results and Conclusions

- (1) It was found that in some cases the experimentally determined concentration values did not agree with values calculated from the data for segregation coefficients obtained from the literature. Effective segregation coefficients were calculated based upon the data obtained in these experiments; in some cases, no previous values were available. The segregation coefficients used in these studies and the corresponding solubility limits are given as follows:

<u>Impurity</u>	<u>Segregation Coefficient</u>	<u>Solubility Limit (atoms/cc)</u>
Al	5×10^{-3}	2×10^{19}
C	7×10^{-2}	9×10^{17}
Cr	1×10^{-5}	5×10^{15}
Cu	4×10^{-4}	1×10^{17}
Fe	8×10^{-6}	3×10^{16}
Mg	2×10^{-3}	5×10^{18}
Mn	1×10^{-5}	4×10^{16}
Na	2×10^{-3}	9×10^{18}
Ni	1×10^{-4}	1×10^{17}
Ti	1×10^{-5}	1×10^{15}
V	1×10^{-5}	5×10^{15}

- (2) In general, the resistivities of crystals containing impurities were those expected on the basis of the boron or phosphorus dopant concentration alone.
- (3) The minority carrier lifetime measurements indicate that lifetime and device efficiency are closely related and that quality changes do occur during the diffusion and processing steps for silicon containing certain impurities; hence, some of the results obtained are process dependent. For example, the minority carrier lifetime was found to increase during the diffusion step in silicon containing Fe, Cr and Mn.
- (4) The effects of the following impurities in silicon on solar cell performance were investigated.

Al, C, Cr, Cu, Fe, Mg, Mn, Na, Ni, O, Ti, V, Zr

Solar cell efficiency was found to be degraded in various degrees by most of these elements. Specifically, the permissible impurity concentrations in silicon that allow the preparation of 10% efficient solar cells are estimated as follows:

PERMISSIBLE IMPURITY CONCENTRATION

<u>Impurity</u>	<u>In Czochralski Si</u> <u>(10^{15} atoms/cm³ silicon)</u>	<u>In Float Zone Si</u> <u>(10^{15} atoms/cm³ silicon)</u>
	<u>For P-on-N Cells</u>	
Ti	0.04	0.02
V	0.1	0.2
Na	0.2	0.3
Mg	1.0	0.1
Zr	0.1	2.0
Cu		1.5
Cr		5.0
Fe	1.2	6.0
Mn	12.0	2.0
Ni	7.0	20.0
B	6.0	100.0
C	80.0	80.0
Al	150.0	50.0
	<u>For N-on-P-Cells</u>	
Ti	0.2	0.15
P	100.0	60.0
C	300.0	500.0

- (5) Surprisingly, degradation of solar cell efficiency was greatest for V and Ti, and the least for Ni. In fact, both "Fz" and "Cz" solar cells with relatively high concentrations of Ni as secondary impurity had a somewhat higher efficiency than solar cells made with baseline materials. Typical concentration levels and the corresponding solar cell efficiencies are given for these particular impurities for Czochralski and float zone grown crystals as follows for 0.5 ohm-cm boron doped silicon:

Czochralski-grown crystals:

<u>Impurity</u>	<u>Concentration (atoms/cc)</u>	<u>Efficiency (%) Without AR Coating</u>
Baseline	None	8.4
V	7×10^{14}	5.2
Ti	3.6×10^{14}	3.4
C	1×10^{16}	8.8
Ni	7×10^{17}	8.9

Float Zone-Grown crystals

Baseline	None	9.3
V	5×10^{14}	5.8
Ti	1.1×10^{14}	4.4
C	3×10^{16}	8.8
Ni	1.5×10^{16}	9.6

The presence of oxygen - approximately 10^{18} atoms/cm³ in Czochralski silicon and $<10^{16}$ atoms/cm³ in float zone material - seems to affect the fill factor which was found to be on the average 8% higher in devices made with low-oxygen float zone crystal. One explanation could be reduced TiC and TiO₂ formation under the metal-silicon contacts on the low-oxygen material which also contains only about 4.4×10^{15} carbon atoms/cm³ versus 2.2×10^{16} atoms/cm³ in Cz silicon. Auger electron spectroscopy results point in that direction.

Recommendations

Further inquiry is recommended for a more complete understanding of the effects of impurities on solar cell performance including the following:

- (1) Effects of processing on silicon materials.
- (2) Effects of oxygen on impurities in silicon.
- (3) More precise measurement of impurities in the ppba region.
- (4) More work on the effects of impurities on N base materials.
- (5) Extension of work to silicon crystals with multiple impurities.

2. INTRODUCTION

During the past three years public interest has been renewed in direct solar energy conversion. The disappearance of the gasoline shortage of the winter of 1973-74 notwithstanding, concern over the rapidly diminishing supplies of the "easy" fossil fuels in the U.S. and elsewhere, and the mainly media-generated fear of nuclear energy, persists in giving rise to at least some rational national planning for the future. The LSSA project is a step in the right direction.

Of all the proposed devices to convert the practically inexhaustible but highly diffuse solar energy into a concentrated, more usable form (preferably electricity), the silicon solar cell is the logical choice for a major effort towards providing an alternative energy source for a wide range of applications. The technology of the silicon solar cell device is reasonably well understood. Its raw material is the only element on earth the cost of which will not go up because of a dwindling supply.

There is little argument within the community about the previous statement. But because of the high cost of presently commercial solar devices, the large scale application of solar energy conversion by means of such devices does not make much business sense at this time. The LSSA project's main goal is therefore to attack the high cost of silicon solar cells by stimulating volume production and reducing the cost of the material, which at present is semiconductor-grade silicon. The original plan of the LSSA project called for the development of a cheap process for making solar-grade silicon. It now acknowledges the fact that the silicon solar cell is a semiconductor device and as such will probably always require both a "semiconductor grade" material and a semiconductor device process. The cost of the device processing can be reduced by the economy of scale and the learning curve factor. The cost of the material does not necessarily follow that rule. As we will see from the results of our work, which was confirmed by a joint research effort by Westinghouse and the Dow Corning Corporation, certain minimum purity requirements must be met for solar cell material. Such purity requirements actually may be more difficult to meet when operations are scaled up. Certainly, without a thorough knowledge of these purity requirements, i.e., what can and what cannot be tolerated in the silicon crystal substrate and still allow the fabrication of solar devices exhibiting an acceptable efficiency, all efforts to develop a less expensive process to make "solar silicon" must be futile. We hope that our research work, as described in this report, will help define the material requirements for the silicon solar cells of the future.

3. DESCRIPTION OF PROGRAM

Work on this program was begun in October 1975 and was concluded in September 1976.

The purpose of the work covered by this contract was to determine by material analysis and device evaluation which, and what quantities of, the impurities most commonly found in metallurgical-grade silicon may be present in the material and still allow the preparation of silicon solar cell devices with acceptable solar energy conversion efficiency. The objective was to define maximum concentrations for these impurities in the single crystal substrate as well as in the polycrystalline material that is presumably employed as the starting material for the single crystal preparation process under consideration.

The objective of the experimental part of the program included the preparation of two series of silicon single crystals each containing predetermined, precisely controlled amounts of specific impurities. One series was made up of crucible-grown, (i.e. Czochralski) silicon single crystal with an oxygen content of about 10^{18} atoms/cc. These crystals are referred to as Hi-Oxygen crystals hereafter. The other series consisted of float-zoned single crystals with an oxygen content of 10^{16} atoms/cc; these are referred to as Lo-Oxygen crystals hereafter.* Besides oxygen the impurities to be incorporated into the crystal lattice were boron, carbon, manganese, nickel, iron, magnesium, zirconium, titanium, aluminum, vanadium, chromium, and sodium. The objective also included the full characterization of the experimental crystals with respect to resistivity, resistivity uniformity, minority carrier lifetime, and crystallographic structure, and the quantitative determination of all impurities present in the material to be used as a substrate for solar cell fabrication.

The objective further included the development and consistent execution of a stable and highly reliable diffusion process for the preparation of the solar cells and development of a reproducible method for the measurement of the solar energy conversion efficiency of the device.

The main result expected from this research work was a statement as to which impurities and how much of them may be present, and which impurities must be essentially absent, in silicon suitable for the manufacture of solar cells with > 12% efficiency.

* All float-zone silicon crystals were made by the Monsanto Company Mon-X (trade name) process.

The program plan is shown in Figure 1 in the form of a milestone chart. This chart outlines the major activities and events that had to occur to bring the project to a successful and timely conclusion.

Figure 1. Program plan.

4. TECHNICAL ACCOMPLISHMENTS

4.1 EXPERIMENTAL CRYSTAL GROWTH

4.1.1 Low Oxygen - Float Zoned Silicon Crystals

4.1.1.1 Experimental Procedures

This program required an investigation of effects of some of the impurities in float-zone silicon crystals for solar cells. Most previous studies on solar cells of silicon crystals have been made on Czochralski-grown material. The very nature of Czochralski pulling makes it comparatively easier to incorporate desired impurities through addition to the melt pot. Float-zoned crystals, on the other hand, are more difficult from the standpoint of incorporating external impurities, especially metallic ones, since segregation coefficients of metals in silicon are quite low. In many cases, the impurities must be added during the final pass. The zone volume in the neck region is much smaller than the zone volume in the crystal body. This necessitates addition of the impurity somewhere in the middle of the run. Also, the secondary impurity must be dissolved and homogenized in the molten pool in a relatively short period, about 2-5 minutes in most cases.

The poly feed rods selected for the study had low base levels of less than 0.3 ppb N-type impurities (effective value, i.e. $N_D - N_A$). The rods were 50 cm long, and 26 to 28 mm in diameter. Special care was taken in handling the rods to avoid any surface contamination.

The poly rod was set up in a Monsanto zone refiner which has a chamber approximately 15 cm in diameter (I.D.) and 110 cm long. An r-f heating coil concentric to the top rod and the bottom seed is located in the center of the chamber. The coil used was a one-turn copper loop with silver plating. Its dimensions were 28 mm I.D. and 62 mm O.D. The generator used for the r-f power operated at 2.2 to 3.0 MHz and was capable of delivering up to 50 kW power.

The first pass was started by preheating the poly rod and by forming a molten drop on the bottom of the rod. The seed was brought in contact with the molten drop. By individually controlling the rate that the poly rod was fed into the coil and the rate at which the seed was pulled away from the coil, a taper was established on the rod gradually increasing to the desired diameter.

After the first pass the rod was prepared for "contamination" with the metallic impurity. Since the zone volume increases steadily in the taper and becomes nearly constant only in the body, metallic impurities were added at about 1 in. above the end of the taper.

Three notches of 1 mm width and 7' mm length were sawed in the rod at about 1/2 in. apart. The rod was then etched and thoroughly cleaned. The weighed amount of the metal was inserted in these notches and the rod was set up for the final pass.

Boron doping was done by allowing a diborane/argon gas mixture to flow continuously around the molten zone. The various parameters used in the first and the final pass are listed in Table 1. A flow diagram for the crystal preparation is given in Figure 2.

Table 1. PROCESS SPECIFICATION

A.	Poly feed rod	diameter	~ 2.6 cm
		length	~ 50 cm
		bulk resistivity	~ 300 ohm-cm
B.	Seed crystal	diameter	~ 0.6 cm
		length	4.0 cm
		orientation	<100>
C.	Machine setup	atmosphere	Argon
		purging rate	250 cc/min.
		chamber O ₂ content	<8 ppm
		setup time	45 min
		cooling time	30 min
D.	Crystal growth parameters	1st pass	final pass
		Zone travel, mm/min	4.0 3.2
		Bottom rotation, rpm	6.0 6.0
		Top rotation, rpm	2.0 2.0
		Diameter, cm	3.0 3.1
		Orientation	none <100> (dislocation free)

Crystal growth experiments were generally carried out to grow a single crystal rod at least 150 mm in length and 32 mm in diameter. All growth parameters, such as zone travel rate, bottom rotation, top rotation, purge rate, etc., were maintained at the same values for each crystal as close as possible. A growth rate (zone travel rate) of 4.0 mm/min was maintained to avoid swirls (vacancy clusters) in the crystals which are formed at low growth rates. Other growth parameters have been chosen such as to produce low radial resistivity gradient crystals.

The amount of impurity added in each run was calculated from the literature segregation coefficients. It has been assumed the equilibrium segregation takes place during the crystallization ($k_{eff} = K_o$).

Figure 2. Flow diagram for float-zone silicon crystal growth

Amount of Metal Impurity to be Added

$$= \frac{C_s \times V_e \times A_w}{N_o \times K_o} \text{ (grams)} \quad (1)$$

V_e = Zone volume, cc

A_w = Atomic wt of the metal, g

N_o = Avogadro's number

C_s = Amount of impurity (atoms/cc) desired in the solid

K_o = Equilibrium segregation coefficient

In many cases, the secondary impurity was added in a quantity close to the solid-solubility limit, but such experiments were not successful. The "pulled-apart" portions revealed the presence of metallic precipitates at the liquid/solid interface which indicated incomplete homogenization of the impurity. The quantities of impurities added in all successful runs were between one and two orders of magnitude below the solubility limit.

Carbon-doping of N-type and P-type crystals was done using Ar/CH₄. This doping gas was mixed with the purge gas in the chamber.

4.1.1.2 Results

Table 2 gives a complete list of all the float zone crystals prepared for the study. No difficulties were encountered in incorporating the elements Fe, Mn, Ni, V, Al, C, Cr, Cu and P into the silicon lattice. The spark source mass spectrometric analysis indicated that elements like Fe, Cu and Cr, however, were not detectable in the silicon lattice, probably because their concentrations were below the anticipated values. There were also problems with impurities like Zr, Mg, Ti and Na. One of the problems was flushing, i.e a chemical reaction or boil up observed when the molten zone reached these impurities. Except for aluminum, the impurities did not noticeably affect the resistivity of the crystal.

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.

4.1.1.3 Discussion

The inherent superiority of float-zoned silicon for solar cells may lie in the fact that the float zoned crystals contain much lower concentration of oxygen, about 6×10^{16} atom/cc, compared to that of Czochralski growth crystals which have about 200×10^{16} atom/cc oxygen concentration. For the most part carbon does not seem to be detrimental unless added in excessive amounts.

Table 2. SUMMARY OF FLOAT-ZONE SILICON CRYSTALS PREPARED FOR THE CONTRACT

Crystal No.	Secondary Impurity	x_o Used for Calculation	Conc. Range Req. 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}	$10^{15} - 10^{16}$	--	$\sim 1.0 \times 10^{16}$	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	7×10^{-2}	$10^{15} - 10^{16}$	--	--	1.0×10^{16}	Lost ZD due to C-saturation
M2B (1)	Fe	8×10^{-6}	$10^{14} - 10^{16}$	42.0	1.5×10^{15}	N.D.	
M5B (1)	V	10^{-5}	$10^{14} - 10^{15}$	51.0	2.6×10^{15}	4.6×10^{14}	
M32B	Cr	10^{-5}	$10^{14} - 10^{15}$	54.0	2.7×10^{15}	2.6×10^{15}	
M31B	Cu	4×10^{-4}	$10^{14} - 10^{16}$	24.0	3.9×10^{16}	N.D.	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} rerun	7.2×10^{17} 1.0×10^{18}	Cannot prepare crystal with aluminum higher than 10 mg
M16B	P	--	$10^{15} - 10^{18}$	Gas	1.1×10^{16}	1.6×10^{16}	Phosphorus doping during the second first pass
M11B	Ni	10^{-4}	--	16.0	7.1×10^{15}	1.8×10^{16}	
	Mn	10^{-5}	--	14.0	6.6×10^{14}	2.4×10^{15}	
	Mg	2×10^{-3}	--	2.0	4.2×10^{15}	1.1×10^{14}	
M14B (1)	C	--	$10^{15} - 10^{16}$	Gas	--	1.1×10^{17}	
M8B (1)	Ti	10^{-5}	$10^{15} - 10^{16}$	20.0	1.0×10^{15}	N.D.	Boron doped
M19B (2)	Al	5×10^{-3}	$10^{16} - 10^{17}$	5.5	2.6×10^{17} rerun	5.6×10^{17} 6.9×10^{17}	
M19B (1)	Al	5×10^{-3}	$10^{16} - 10^{17}$	1.0	4.0×10^{16}	5.1×10^{16}	
M17B	Ti	10^{-5}	$10^{15} - 10^{16}$	20.0	1.0×10^{15}	N.D.	Phosphorus doped
M15B	Na	2×10^{-3}	$10^{15} - 10^{17}$	11.0	9.6×10^{16}	3.3×10^{14}	NaCl powder used for Na doping
M15B1	Na	2×10^{-3}	$10^{15} - 10^{17}$	31.0	2.7×10^{17}	3.1×10^{14}	NaCl powder used for Na doping

 C_s = Concentration in solid

Another advantage of the float-zone process over Czochralski is that most of the metallic impurities can be swept out through multipass zone refining, or through vacuum reining in some cases. The float-zone method does have the potential for being less expensive if feed rod charge could be increased and a "one-pass" process could be developed.

Out of four aluminum-doped crystals studied, 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 was the only doping impurity and which contained no boron, did not exhibit as high a solar cell efficiency as crystal M10B. This indicates that aluminum by itself is not necessarily the cause for the high efficiency. Table 3 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 (above 3%) lower than the average of samples M3B, M4B, and M7B (9.38% vs avg. 9.67%). A detailed discussion on the solar cell efficiency is given in the subsequent sections of this report.

Table 3. 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) (at/cc)	Al atoms ionized (%)
M10B	2.3	Boron	0.36	1.1×10^{17}	2.2×10^{16}	0.20
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
19B(b)	1.0	--	1.88	0.48×10^{17}	0.75×10^{16}	0.16

4.1.2 High Oxygen (Czochralski) Crystals (W. R. Tucker)

4.1.2.1 Introduction

The Czochralski method of growing silicon crystals utilizes a quartz crucible for containing the molten silicon during the growth process. The liquid silicon dissolves the quartz during the entire crystal growth process and at the same time oxygen is evolved from the melt in the form of SiO (ca. 10 mm Hg vapor pressure at 1400°C). Crystals grown in this manner contain 15 to 35 ppm oxygen (or $1-2 \times 10^{18}$ atoms/cc) depending upon conditions such as the pressure inside the puller chamber, purge gas flow rates, and temperature profile in the crucible.

4.1.2.2 Description of Crystal Puller

The high-oxygen crystals were grown in an rf-powered puller with a water-cooled quartz jacket (see Figure 3). Materials inside the puller were water-cooled stainless steel (ends), the carbon susceptor, the carbon susceptor support, the silica heat shield, and the water-cooled quartz jacket. The charge size was 3 kg except for crystals C1A, C1C, C2A, C2C, and C3B at 4 kg and C8B at 0.5 kg.

4.1.2.3 Crystal Growth Conditions

The puller was purged with argon at 19 liters/min cold for 15 minutes, for 10 minutes on low power, and during melt down. Purge was then reduced to 13 liters/min for the rest of the run. The pressure in the chamber was 103.4 to 104.8 kPa (0.3 to 0.5 psi) above atmospheric pressure.

The seed rotation rate was 15 rpm for all runs, and the crucible was contrarotated at 10 rpm.

The growth rate in the crystal body was 8.9 cm/hr (3.5 in./hr) with the diameter control system adding or subtracting 2.54 cm/hr (1 in./hr) as necessary to maintain the diameter.

Crystals were grown with zero dislocation structure (i.e. < 500 etch pits/cm² by Sirtl etch) at 63 mm diameter on <100> orientation in 140 mm I.D. crucibles.

Crystals were terminated by 1) separating them from the melt quickly after good structure was lost, or 2) tapering them to a point where roughly 90% of the melt was incorporated in the crystal when good structure was maintained. The crystal was then pulled to 50-60 mm above the melt level, the power was shut off, and the crystal was allowed to cool for 30 minutes before it was removed from the puller.

Figure 3. Schematic of crystal puller.

4.1.2.4 Heat Treatment of Crystal

No heat treatment on the crystals was done after they were removed from the puller. There could be a difference in donor (= active) oxygen content from seed end to the tang end of the crystal because of difference in thermal history, particularly for the longer crystals. In any case, these effects would be wiped out in the thermal cycling done in solar cell preparation.

4.1.2.5 Raw Materials and Raw Material Preparation

Silicon - The feed material for the high oxygen crystals consisted of the seed end section of dislocation free, float-zoned silicon crystals. Each piece was zoned at least twice, and the seed end piece was selected because at this point the zone was increasing in volume and not yet in equilibrium with the feed rod, insuring a very low level of impurities except for those, such as phosphorus and boron, having a fairly high segregation coefficient. Arsenic, if present, would be reduced by more than 50% by volatilization, and with zone loading in the two passes (≈ 0.32) it was estimated that less than 10% of the original arsenic would be present.

The actual analysis of silicon used was a simple conductivity type and resistivity measurement. Only dislocation-free N-type float-zone (Fz) tapers with >50 ohm cm resistivity were selected for feed material for the high oxygen crystals.

Cleaning Silicon Feed - The silicon used as feed for the high oxygen process was cleaned by using the acid peroxide and basic peroxide etches tested by RCA.¹ The silicon was washed with distilled demineralized water until the resistivity of the outflowing water was at least 1.0 megohm. The material was then dried in a positive-flow, filtered-air hood using heat radiated from a quartz tube lamp to assist the drying process. The silicon was sealed in polyethylene and transferred without further contamination.

Seeds - The seeds used were dislocation free (i.e. <500 pits/cm² by Sirtle etch), $<100>$ orientation, and 5.5 mm in diameter. The seeds were produced by a modified float zone process using virgin poly with resistivity typically >180 ohm cm N-type or >500 ohm cm P-type.

Seeds were cleaned by CP-4 etching.

Quartz Crucibles - Crucibles used were translucent fused quartz made by G. E. They were removed from their polyethylene bags in a filtered-air hood and were rinsed with electronic-grade isopropanol immediately before use.

Argon - The argon used to purge the puller during heat up and crystal growth was 99.999% argon with typically 1 ppm oxygen and 3 ppm nitrogen.

Carbon - Crucible holders (susceptors) were Airco Speer 873 RL grade graphite. These were heated for at least four hours at 1400 to 1600°C in a stream of argon prior to use.

Doping Materials - The primary dopants, boron and phosphorus, were used in the form of silicon alloys made from the elements which were purchased in 99.999% purity. The purity of the secondary dopants used is given in Table 4 below.

Table 4. DOPANTS USED FOR CZOCHRALSKI WORK

Dopant	Purity (%)	Supplier
Al	99.999	Ventron
C	Spectrograde	Hitachi
Cr	99.99	Ventron
Fe	99.99	Materials Research Corp.
Mg	99.99	Ventron
Mn	99.9	Ventron
NaCl	Ultrapure	Ventron
Ni	99.99	Ventron
Ti	99.9	Materials Research Corp.
Zr	99.99	Ventron

4.1.2.6 Crystal Growth Problems Peculiar to the Secondary Impurity

Considerable difficulty was experienced in getting single crystal growth for both the group IVB elements zirconium and titanium. The problem arose from their great affinity for oxygen and nitrogen, causing slag formation during melt-down. For titanium the problem was made much less severe by using a long seed into the melt at the seeding temperature. For zirconium, the wire failed to stay in place on the seed, and attempts at using tube doping after the silicon was molten were only moderately successful. In one instance where the silicon melt was somewhat above seeding temperature when the zirconium was entered, there was some "thermite" type reaction at the silicon-quartz crucible interface. In all, four attempts were made for each of the group IVB elements.

For chromium four growth attempts were made (with the last being successful), but here the value used for the segregation coefficient was apparently too low (1×10^{-7} vs 1×10^{-4} measured) and the solubility limit was exceeded. This was indicated in the first two attempts when only micro-crystalline structure was obtained even at the seed. Once the adjustment was made for the segregation coefficient, no growth problems were encountered.

4.1.2.7 Correlation of Predicted versus Measured Secondary Impurity Content

Examination of Table 5 shows that for the most part there is poor agreement between the anticipated secondary impurity level and that measured by mass spectrography. The reasons for this only fair correlation are 1) concentration gradients, 2) the assumption that all of the impurity added actually was dissolved by the melt and reacted only with the silicon, 3) limitations of the mass spectrographic analysis, particularly at the extremely low concentrations being measured, and 4) the use of segregation coefficients that were not always accurate. These reasons are individually discussed in the following paragraphs.

Table 5. SUMMARY OF PREDICTED VS. MEASURED IMPURITY CONCENTRATION FOR CZOCHRALSKI (HIGH-OXYGEN) CRYSTALS

Crystal Number	Charge Wt. (Kg)	Primary Dopant			Secondary Dopant				
		Element	Target Cryst. Conc. (A/cc)	Measured Cryst. Conc. (A/cc)	Element	g. Dopant per Kg of Si	Predicted Melt Conc.	Predicted Cryst. Conc.	Measured Cryst. Conc.
C1A	4.0	B	4.2×10^{16}	0.62×10^{16}	None				
C1C	4.0	B	1.2×10^{19}	0.11×10^{19}	None				
C2A	4.0	B	4.2×10^{16}	0.68×10^{16}	C	0.043	5.0×10^{18}	4.5×10^{17}	7.4×10^{16}
C2B	3.0	B	4.2×10^{16}	0.76×10^{16}	C	0.004	3.9×10^{17}	3.5×10^{16}	6.7×10^{16}
C2B1(1)		B	4.2×10^{16}	1.4×10^{16}	C	0.047	5.7×10^{18}	5.3×10^{17}	1.0×10^{17}
C2C	4.0	B	1.2×10^{19}	0.12×10^{19}	C	0.043	5.0×10^{18}	4.47×10^{17}	6.5×10^{16}
C3B	4.0	B	4.2×10^{16}	0.97×10^{16}	Fe	0.77	1.9×10^{19}	1.54×10^{15}	2.1×10^{15}
C4B	3.0	B	4.2×10^{16}	0.92×10^{16}	Cr	1.85	5.0×10^{19}	5×10^{12}	4.1×10^{15}
C5B	3.0	B	4.2×10^{16}	1.1×10^{16}	Mn	0.72	1.8×10^{19}	1.8×10^{14}	1.2×10^{16}
C6B	0.5	B	4.2×10^{16}	0.76×10^{16}	Ni	1.67	4.0×10^{19}	4.0×10^{15}	5.0×10^{16}
C7B	3.0	B	4.2×10^{16}	0.93×10^{16}	V	0.91	2.5×10^{19}	2.5×10^{14}	7.0×10^{14}
C8B	3.0	B	4.2×10^{16}	1.1×10^{16}	Zr	1.00	1.5×10^{19}	1.5×10^{14}	$< 1 \times 10^{14}$ (2)
C8B1	3.0	B	4.2×10^{16}	0.88×10^{16}	Zr	0.96	1.5×10^{19}	1.5×10^{14}	$< 1 \times 10^{14}$ (2)
C9B	3.0	B	4.2×10^{16}	0.97×10^{16}	Hg	0.043	2.5×10^{18}	5.0×10^{16}	$< 1 \times 10^{14}$ (2)
C9B1	3.0	B	4.2×10^{16}	1.1×10^{16}	Hg	1.67	9.6×10^{19}	1.9×10^{18}	1.2×10^{15}
C10B	3.0	B	4.2×10^{16}	1.1×10^{16}	Al	0.963	5.02×10^{19}	2.5×10^{17}	8.3×10^{18}
C10B1	3.0	B	4.2×10^{16}	0.92×10^{16}	Al	0.480	2.5×10^{19}	1.3×10^{17}	2.0×10^{18}
C11B	3.0	B	4.2×10^{16}	1.2×10^{16}	Ti	0.603	3.39×10^{18}	3.3×10^{14}	$< 1 \times 10^{14}$ (4)
C11B1	3.0	B	4.2×10^{16}	1.1×10^{16}	Ti	1.67	8.67×10^{19}	8.7×10^{14}	6.0×10^{14}
C12B	3.0	B	4.2×10^{16}	0.97×10^{16}	C	0.0033	3.87×10^{17}	3.5×10^{16}	2.9×10^{16}
					Ni	1.67	4.0×10^{19}	4.0×10^{16}	4.7×10^{16}
C13A	3.0	P	5.4×10^{15}	5.0×10^{15}	None				
C13B	3.0	P	9.0×10^{16}	4.7×10^{16}	None				
C13C	3.0	P	5.4×10^{18}	2.7×10^{18}	None				
C14A1	3.0	P	1.2×10^{16}	4.4×10^{16}	C	0.0043	5.1×10^{17}	4.6×10^{16}	5.3×10^{16}
C14A2(3)	3.0	P	1.2×10^{16}	2.8×10^{16}	C	0.0043	5.1×10^{17}	$> 4.6 \times 10^{16}$	7.5×10^{16}
C15B	3.0	B	4.2×10^{16}	0.94×10^{16}	Na	0.20 (4)	5.0×10^{18}	1.0×10^{16}	$2.2.1 \times 10^{14}$ (5)
C16B	3.0	B	4.2×10^{16}	1.0×10^{16}	P	Alloy	3.8×10^{16}	1.4×10^{16}	0.57×10^{16}
C16B1	3.0	B	5.3×10^{17}	1.9×10^{17}	P	Alloy	1.3×10^{18}	5.0×10^{17}	2.2×10^{17}
C17B	3.0	P	1.2×10^{16}	0.46×10^{16}	Ti	1.67	4.9×10^{19}	4.9×10^{14}	5.0×10^{14}

(1) C2B and C2B1 are parts of the same crystal sampled at two different points.

(2) Below the detection limit for mass spec analysis

(3) C14A1 and C14A2 are the same crystal sampled at two different points.

(4) Wt. of NaCl/Kg. of silicon

(5) This value is about average for all crystals so it must be presumed that NaCl was not absorbed by the silicon.

Concentration Gradients - The predicted values for secondary impurity content were obtained using the segregation coefficients furnished by JPL and these values would apply to the initial part of the crystal. No correction was applied for the pull rate to estimate what the effective segregation coefficient would be. The crucible and crystal rotation rates were not optimized to give the lowest radial concentration gradient, particularly for those impurities having a very low segregation coefficient. Therefore, we expected the center of the rod to have a 25% higher concentration of the secondary impurity. The axial concentration follows the formula:

$$C_s = k C_o (1-g)^{k-1} \quad (2)$$

where C_s = concentration of impurity being grown into the crystal at point g

g = the fraction of the total melt frozen in the crystal

k = the effective segregation coefficient

and C_o = concentration of impurity in the melt before any crystal was grown.

This gives axial concentrations as shown below in Table 6 for two values of k .

Table 6. AXIAL CONCENTRATION GRADIENTS IN CZOCHRALSKI SILICON FOR TWO VALUES OF THE SEGREGATION COEFFICIENT

Amt Melt Frozen (%)	C_s @ % Frozen/ C_s @ $\approx 0\%$ Frozen	
	$k = 10^{-2}$	$k = 10^{-2}$
0	1.00	1.00
10	1.11	1.11
20	1.25	1.25
30	1.42	1.43
40	1.66	1.67
50	1.99	2.00
60	2.48	2.50
70	3.29	3.33
80	4.92	5.00
90	9.77	10.00

From this relative axial concentration gradient and the radial concentration gradient it can be seen that the sampling position makes a significant difference in the level to be expected.

Secondary Impurity Deviation from Ideal Behavior in the Crystal Growth Process - The secondary impurities were added to the silicon by either placing them in the bottom of the silicon charge before meltdown or by adding them to the melt after the silicon had cooled to near the seeding temperature. In either case materials with low boiling points (as Na and Mg) were partially volatilized and incompletely absorbed into the melt. Those elements with a high affinity for oxygen (such as Ti, Zr and V) may react with the quartz crucible and with oxygen that the silicon has dissolved from the crucible and thereby become available to participate as the dissolved element. (This property of these scavenging elements also offers a means of removing them from the silicon melt as slag.)

Accuracy of Impurity Analysis - It is, of course, obvious that the precision of the analytical method has considerable influence on the relationship between the "predicted" and "measured" secondary impurity concentration in the crystals. A full discussion of the limitations of mass spectrographic analysis is given in the analytical section of this report.

Segregation Coefficients - Segregation coefficients for many of the elements in silicon are fairly well documented; however, in some cases the experimental values did not agree with the reported ones, and for zirconium no data has been reported in the literature. Since titanium belongs to the same group a value of 10^{-5} was used for k in estimating the zirconium to be expected in the crystal.

The value of 10^{-7} given for chromium should have been nearer 10^{-4} based on the amount put into the melt and that measured by mass spectrography in the crystal. Supporting this evidence were two unsuccessful attempts to grow a crystal targeted for 1×10^{15} atoms/cc of chromium using 10^{-7} and 10^{-5} for the values of k. Even when the value of 10^{-5} was used for k, the solubility limit was exceeded before more than 1% of the total melt was contained in the crystal.

4.1.3 Material Characterization (M. E. Christ)

4.1.3.1 Description of Procedures

The Czochralski and float-zoned silicon produced under this contract was characterized by electrical, mechanical and metallographic analysis. The evaluation techniques were those commonly used in the industry for production and transfer of material from vendor to customer.

Crystal Analysis - The prime parameters of interest in as-grown crystal are: conductivity type, diameter, structure and resistivity. When the as-grown crystal is received in the laboratory the seed end is cropped where the taper profile intersects the target diameter (See Figure 4). The sawn face of the seed end taper section is then etched to a bright shiny finish in a 57:18:25 solution of nitric, hydrofluoric, and acetic acids. This taper section and the opposite end of the crystal are then decorated in Sirtl etch according to ASTM procedure F47-70. After rinsing and drying the cut end of the taper section is inspected by phase contrast microscope at 100X for dislocations and preferential etching in a swirl pattern characteristic of oxygen vacancy clusters. The outer surface of the crystal at the opposite end is inspected by unaided-eye for structure degradation such as slip. It is then cropped about 6 mm from the farthest extremity of this bad structure toward the seed end or at the target diameter, whichever is farthest from the bad structure. The length and weight of the remaining body of the crystal are then taken and recorded.

Figure 4. Cropping as-grown crystal for diameter and structure.

The next measurement is resistivity. A four-point probe with 1.59 mm point spacing in a collinear array is used. The test set consists of a constant current power supply, a digital voltmeter and a programmer of Monsanto design which allows direct readout of resistivity in ohm-cm. A strip approximately 6 mm wide is abraded down the side of the crystal. The axial resistivity profile is then determined by taking readings at one-centimeter increments along the abraded strip. Next resistivity readings are taken on the cut face of the crystal at each end. These readings are taken at the center, one-half radius, and at

3 mm from the edge on each of four equally spaced radii. (See Figure 5). All resistivity readings are recorded on a data sheet which accompanies the crystal through processing.

Figure 5. Measuring resistivity variability on crystal face and slices.

Next, conductivity type by hot probe (ASTM procedure F42-69) is tested at each end of the crystal at approximately 25 mm increments along the crystal axis.

Slice Analysis - The crystal measurements indicate the suitability for further processing. Structure, conductivity type and diameter data do not vary from original values. However, resistivity characteristically varies both axially and radially in the crystal. Therefore, it is necessary to further characterize the silicon in slice form to better understand the resistivity variability in the crystal. This is done in as-sawn form.

There are also more subtle forms of structure deviations which can better be detected in the polished slice form.

To make the slice analysis meaningful in terms of crystal processing we determined it was necessary to know the location of the slice relative to the bulk crystal. This was accomplished by grinding two notches in the (1-1-0) orientation flat which had been ground on the crystal. These notches diverge from each other from the origin at one end of the crystal in a linear fashion (See Figure 6). In this way one can determine the location of the slice by the distance between the two notches given the angle and original spacing.

Figure 6. Notch configuration for slice location determination.

Slices are accumulated by crystal identity after cleaning and sampled for thickness, bow, taper and resistivity. Thickness and taper are measured with a non-contact probe of the capacitance proximity sensor type. Bow is measured by electronic transducer with the slice supported on a three point jig. Slice resistivity is read with a four point probe with spacing of 0.64 mm between points arranged in a collinear array. The test set design is basically the same as that described for crystal resistivity testing. Readings are taken at center, one-half radius, and at 3 mm from the slice edge on each of four equally space radii. These values are used to calculate radial gradient. (See Figure 5). The readings were taken on a minimum of two slices each from the seed and opposite ends of each crystal. In addition a minimum of one slice from each crystal section was characterized by reading resistivity at 3 mm increments from center to 3 mm from the slice edge on four equally spaced radii. These readings are used to calculate band resistivities. The latter provides a more detailed idea of resistivity variation across a slice than the former. The former is the technique ordinarily used for the exchange of material between vendor and customer.

Radial gradient is calculated from the following equation:

$$\rho_{RG} = \frac{\text{Edge } \rho - \text{Center } \rho}{\text{Center } \rho} \times 100 \quad (3)$$

where edge resistivity is the average of four resistivity readings taken at either the one-half radius or the 3 mm from the edge points shown in Figure 5.

A frequency distribution is developed from this data and resistivity variability on each slice is reported as percent sigma.

4.1.3.2 Discussion of Results

The addition of secondary impurities in material produced under this contract had no impact on conductivity type. In some crystals the added impurity apparently had an effect on ability to target resistivity. Figure 7 illustrates this effect. The typical curve is the distribution expected when crystals are doped with phosphorus or boron only. The Cz section and Fz section curves represent distributions from crystals doped solely on the basis of phosphorus or boron but which have the added secondary impurities specified under this contract. The typical result is a resistivity variability of about 8% sigma. The float-zoned crystal doped with secondary impurities had about 10% sigma when the Czochralski crystals with secondary impurities exhibited over 40% sigma. The impurities causing most of the variability in the Czochralski material was magnesium (C9B), aluminum (C10B, C10B1), and phosphorus compensation (C16B1).

The analysis of rod and slice gradients (Figures 8 and 9) 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 typically somewhat higher than Cz gradients.

Four-point-probe resistivities, taken at approximately 3 mm intervals across four equally spaced radii of a silicon slice were previously referred to as "band" resistivities. Analysis of the variability of these readings indicate macro variations in the dopant profile. The variability among all of the resistivity readings taken in bands (32 readings for a 50 mm slice) is calculated as a percent sigma. The results from two slices per section are plotted in Figure 10 to indicate probability of occurrence. The results are typical of standard material and indicate no significant effect of secondary impurities.

Figures 11 and 12 show the relationship of electrical and metallographic analysis to solar cell efficiency. The graph reference is a plot of solar cell efficiencies for single-side-polished cells in ascending order from left to right. Section profile resistivity nearest the cell and average section gradients at half radius are also plotted. There appears to be no significant correlation between resistivity or resistivity variability and cell efficiency over the range of resistivities produced and tested.

After electrical analysis the slices were polished. A minimum sample of three slices per crystal was analyzed for metallographic defects. One slice was etched in a 1:1 Sirtl solution for 5 minutes. A second slice was etched in a 2:1 Sirtl solution for 10 minutes. The third slice was oxidized at 1100°C until a 12000 Å oxide layer was formed. This oxide was stripped with concentrated

Figure 7. Crystal section end center resistivity probability.

Figure 8. Crystal section end gradient probability.

Figure 9. Slice radial gradient probability.

Figure 10. Slice resistivity variability probability.

Figure 11. Electrical and metallographic properties of float-zone silicon vs cell efficiency.

Figure 12. Electrical and metallurgical properties of Czochralski silicon vs cell efficiency.

hydrofluoric acid. The slice was then Sirtl-etched in a 2:1 solution for 10 minutes. Analysis of the three slices consisted of microscope and unaided-eye inspection for defects.

All crystals except for C2B, C6B and C12B were determined by metallographic analysis to be within the zero dislocation specification of 500 dislocations per square centimeter. The exceptions were considered to be primarily due to the stress caused during termination of crystal growth that was not entirely removed prior to slicing. Figure 13 is a photomicrograph of the defects found in sections C6B and C12B. These defects are known as high angle grain boundaries. An analysis of the data in Figures 11 and 12 shows no correlation between material found to have dislocations and the efficiency of cells made from such material.

Figures 11 and 12 also indicate those slices exhibiting swirls and or fog. Here again there appears to be no correlation between these features and cell efficiency.

Figure 13. Photomicrograph of high angle grain boundaries, 50X.

4.1.4 Physical Methods of Chemical Analysis (M. S. Wang)

4.1.4.1 Introduction

The purpose of this project was to study the effect of varying types and amounts of impurities on the properties of single crystal silicon and to define the maximum impurity concentrations that still yield acceptable solar cell devices for terrestrial application. In other parts of this report, methods of growing crystals doped with various impurities and solar cell fabrication and characterization are discussed. The chemical analysis using physical methods for determination of intentionally doped or accidentally introduced impurities are discussed in this portion of the report.

4.1.4.2 Background

There are many kinds of analytical techniques applicable to semiconductors and some of these are discussed in the literature.^{2,3} Each of these techniques has advantages and some unavoidable disadvantages. In order to obtain the best overall view of impurities in the material, the spark source mass spectrometry (SSMS) technique was our first choice for this project. SSMS is known to have superb sensitivity to nearly all of the elements in the periodic table. Infrared spectroscopy (IR) was chosen for the determination of interstitial oxygen and substitutional carbon in silicon because this technique is widely accepted by silicon manufacturers and consumers. Another technique, emission spectroscopy (ES), was also used in some cases to complement SSMS. At a later point in the project, Auger electron spectroscopy (AES) was also employed as a means of analysis because carbon and oxygen, the major impurities in silicon, were suspected of causing peculiar behavior in the contact metalization process.

Each technique and the instrumentation involved are described here. The interpretation of the data obtained from each method is discussed. The results, including some conclusions and recommendations are then covered.

4.1.4.3 Sampling

The samples for analytical work were obtained from the center of the crystal remaining after the elimination of the seed and opposite ends. Table 7 summarizes the sample requirement for the analytical work.

All of these samples were obtained from all crystals except for a few small crystals for which the 3 mm IR sample was not available.

Table 7. SUMMARY OF SAMPLE REQUIREMENT

Anal. Tech.	Sample Thickness (mm)	No. of Specimens	Polishing	Remarks
IR	3	1	yes	Both surfaces should be parallel
SSMS	0.5	1	no	
SSMS	0.75	1	no	
ES	0.3	2	no	

4.1.4.4 Spark Source Mass Spectrometry (SSMS)

In recent years the growth and development of SSMS as an analytical tool has been stimulated because of the great increase of interest in ultra-trace impurities in electronic materials. Since 1945, the sensitivity of the technique has been extended from the low ppm range to the low ppb range of impurities in many solid samples. As pointed out by Roboz,⁴ the technique is based on four basic assumptions: (1) solid samples break up completely and evenly in the spark, (2) ionization efficiency is essentially the same for all elements and there is no matrix effect, (3) definite identification of the lines can be accomplished from their positions on the photoplate, and (4) the blackening of the photographic emulsion is proportional to ion exposure. Although none of these assumptions has been completely established to be 100% correct, all practitioners of SSMS analyze their results according to these assumptions with only relatively minor modifications or corrections.

The technique has been widely used because of (1) the superb detection limits to low ppb level, and (2) the sensitivity to all of the elements in the periodic table. However, it suffers from (1) high initial instrument cost, (2) relative slowness of the technique, (3) possibility of cross contamination at the low ppm level when the matrix is changed, and (4) lack of practical standards at the ppb level. It is not suitable for process control where analytical time is an important factor. The high initial cost also inhibits the use of this technique in smaller laboratories.

SSMS was our first choice as an analytical tool because of its ability to detect low ppb impurities for practically all of the elements of interest.

Instrument Used - The instrument used was a CEC Model 110 spark source mass spectrometer. This instrument was modified and upgraded to improve the quality of analytical work. The diffusion pumps in the source and analytical sectors were replaced with ion pumps. This modification allows an ultimate vacuum in the 10^{-9} mm Hg region and provides other improvements as follows:

- a) Minimized interference from hydrocarbons.
- b) Improved determination of carbon, oxygen, and nitrogen
- c) Reduced photographic emulsion fogging, thus improving detection limits.
- d) Simplified spectra by reducing charge exchange lines.

A multiple sample holder was built that allows up to eight electrode pairs to be mounted in the source. This reduced the time of source conditioning and increased the analytical efficiency.

An electronic spark gap control system was built to attain better reproducibility. The modified system also reduces the fatigue of the operator, an important factor for successful operation.

Sample Preparation - Samples obtained as specified in Table 2 were cut to approximately 1.5 mm x 10 mm size. Two each of these samples were used for the sparking. No counter electrode made from other material was used. The samples cut to the desired size were etched in a mixture of nitric acid and hydrofluoric acid [3 parts HNO_3 (70%) + 1 part HF (48%)] for 30 to 40 seconds. After rinsing in deionized water, the samples were etched in a hydrofluoric acid bath (HF 48%) for about 10 seconds to remove the silicon oxide from the surface of the sample. The samples were then again rinsed with running deionized water for 10 minutes or longer before drying. After the samples were completely dry, the eight pairs of electrodes were mounted on the multiple specimen holder under a laminar-air-flow, clean hood to avoid contamination.

Sparking Procedure and Photographic Exposure - The sample holder with samples mounted was then inserted to the source chamber of the SSMS and it was evacuated to approximately 1×10^{-9} mm Hg before initiating sparking. Because of increasing vapor pressure during the sparking some change in degree of vacuum is observed. In any case, the vacuum was kept below 1×10^{-7} mm Hg during the sparking of the samples. Generally, some pre-sparking was done to mechanically clean the sample surface, but our experience has indicated that the exact duration, etc. of this process is not of critical importance to the success of the analysis.

For impurities in the low parts-per-billion range 300-nanocoulomb exposures were used for most of the samples. Lower exposures were made for carbon and oxygen analyses or when there were higher concentrations of doped impurities.

An effort was made to keep the parameters of sparking, such as repetition rate, pulse width, gap distance, etc. as constant as possible. Some modifications were necessary because of the different electrical properties of some of the samples.

Photographic Process - In all cases Ilford Q-2 plates were used as the ionsensitive photographic medium. The photographic process is as follows:

Development	3 minutes in D-19 at 20°C
Stopping	10 seconds in used fixer
Fixing	5 minutes in Kodak fixer
Washing	6 minutes in running water.

Data Reduction - A Jarrell-Ash Model 23-100 microdensitometer was used to measure percent absorbance of the lines recorded on the photographic plates. The data obtained were then transferred to computer punch cards and the calculations were carried out by computer. An example of an SSMS report was shown in Table 8. The report is calculated and printed out in three forms: ppm (weight), ppm (atomic), and numbers of atoms per cc. When the elements sought were not detected, the computer printout shows the theoretical detection limits for that element. The emulsion calibration is also computerized. The basic equation used in the calculation of concentration is:

$$C_i = \frac{E_s}{E_i} \times \frac{I_s}{I_i} \times \frac{Int_i}{Int_s} \times 0.7 \frac{M_i}{M_s} \times \frac{RSF_s}{RSF_i} \times C_s \quad (4)$$

where E_s and E_i = ion exposure, coulombs

I_s and I_i = isotopic abundances

Int_s and Int_i = ion intensity interpolated on the emulsion calibration curve.

M_i and Int_i = isotopic masses

RSF_i and RSF_s = relative sensitivity factors

Mass lines were measured with respect to standard lines; the subscript "s" refers to the standard line, while the subscript "i" refers to the line in question.

The relative sensitivity factors (RSF) were determined experimentally for correction of analytical data whenever necessary. The RSF may show considerable variation from one instrument to another, but a detailed discussion of these effects seems inappropriate for this report.

Analytical Data from SSMS - The analytical results for all of the Czochralski (Cz) samples and the float-zone (Fz) samples are summarized later in Tables 21 and 22. Except for some rounding off, the data were taken directly from the computer output. One should not be misled by the number of significant figures given in the computer printout of results. For example, boron for crystal ClA reads 0.62×10^{16} atoms/cc. The two significant figures are strictly a computer printing phenomenon and do not necessarily mean that the SSMS can be relied upon to that degree.

Table 8. SAMPLE SSMS REPORT

SAMPLE SILICON MRC-JPL CONTRACT C-1-A PL-1909 02/02/76

ELEMENT		PPM/A		PPM/W		A/CC	NO. OF DETN.
B		1.2E-01		4.8E-02		6.2E+15	2
C		9.6E-02		4.1E-02		4.8E+15	2
N		INTERFERENCE		INTERFERENCE		INTERFERENCE	
O		4.9E+01		2.8E+01		2.4E+18	2
F		2.4E-02		1.6E-02		1.2E+15	1
NA		6.4E-03		5.2E-03		3.2E+14	2
MG	ND	1.9E-03	ND	1.6E-03	ND	9.2E+13	1
AL	ND	2.3E-02	ND	2.2E-02	ND	1.2E+15	1
P	ND	1.7E-02	ND	1.9E-02	ND	8.5E+14	1
S		1.5E-02		1.7E-02		7.4E+14	1
CL		1.1E-02		1.4E-02		5.6E+14	1
K		2.3E-03		3.2E-03		1.1E+14	1
CA	EST	8.6E-03	EST	1.2E-02	EST	4.3E+14	1
TI	ND	2.1E-03	ND	3.6E-03	ND	1.0E+14	1
V	ND	1.4E-03	ND	2.5E-03	ND	6.8E+13	1
CR		6.6E-03		1.2E-02		3.3E+14	1
MN	ND	1.9E-03	ND	3.8E-03	ND	9.7E+13	1
FE	ND	2.9E-02	ND	5.8E-02	ND	1.5E+15	1
NI	ND	4.0E-02	ND	8.3E-02	ND	2.0E+15	1
CU	ND	3.9E-03	ND	8.9E-03	ND	2.0E+14	1
ZN	ND	1.4E-03	ND	3.2E-03	ND	6.8E+13	1
GA	ND	9.8E-04	ND	2.4E-03	ND	4.9E+13	1
GE	ND	2.5E-03	ND	6.5E-03	ND	1.3E+14	1
MO	ND	6.4E-03	ND	2.2E-02	ND	3.2E+14	1
AG	ND	3.1E-03	ND	1.2E-02	ND	1.6E+14	1

ND = NOT DETECTED - VALUE REPORTED IS THE DETECTION LIMIT
BASED ON EXPERIMENTAL CONDITIONS FOR THIS SAMPLE

EST - ESTIMATED VALUE ONLY - INTERFERENCE

The most significant difference between float-zone (Fz) and Czochralski materials is the oxygen and carbon content, if the intentional dopants are excluded from the comparison. Table 9 shows a statistical comparison of oxygen and carbon in both types of material. The carbon- and oxygen-doped materials were not included in this calculation.

Table 9. COMPARISON OF CARBON AND OXYGEN
IN CZ AND FZ MATERIAL

[(atoms/cc) x 10¹⁶]

	Carbon		Oxygen	
	Cz	Fz	Cz	Fz
N	24	32	24	35
Mean	2.227	0.4499	255.791	5.085
Std. Deviation	2.96	0.4509	134.377	2.401

Note: Does not include carbon data from carbon-doped samples.

Problems with Boron Data - In reviewing the analytical data on boron discrepancies were noticed between electrical results and the analytical data. As previously described, there are no primary reference samples for silicon with trace or ultratrace impurities 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 using electrical results. Consequently, in these cases the SSMS data are 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 be reported in the various tables directly as determined from the SSMS analysis. However, our data can be treated or calibrated with reference to electrical results. The results are shown in Tables 7 and 8 and are discussed below.

Treatment of Boron Data obtained by SSMS - Using boron or arsenic, the resistivity of silicon as a function of impurity concentration was studied by Irvin,⁵ 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. This 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 using 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 quartz⁶ was involved in the 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 concentrations, 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 some good reasons to repeat Irvin's work, especially since the results 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 practice⁷ for converting carrier concentration to resistivity for both N and P type silicon. Method D in that document is based on Irvin's work.⁴ The relationship is expressed as follows:

$$R = \frac{1}{aN^b} \quad (5)$$

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 Tables 10 and 11 are data obtained from the ASTM-recommended practice.⁷ 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 14. Figure 14 was prepared from independent data by analyzing a series of samples of wide range of resistivities. The SSMS data for these samples were plotted against the boron concentration obtained

Table 10. COMPARISON OF BORON DATA FROM SSMS AND VALUES CALCULATED FROM RESISTIVITY FOR CZOCHRALSKI SILICON

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

Crystal	Boron (SSMS)	Boron Correlated * SSMS	Boron from Resistivity **	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

* Converted from Figure 14

** Converted by Method D of Reference (7)

Table 11. COMPARISON OF BORON DATA FROM SSMS AND VALUES CALCULATED FROM RESISTIVITY FOR FLOAT-ZONE SILICON

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

Crystal	Boron (SSMS)	Boron Correlated* SSMS	Boron From Resistivity**	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

* Converted from Figure 14

** Converted by Method D of Reference 7.

Figure 14. Relationship between boron concentrations by SSMS and Irvin's value⁵ converted from resistivities.

from resistivities according to Irvin's original report.⁵ We note that the slope of the line in Figure 14 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 14, 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. Our boron data are reported with theoretical and experimental corrections made in our laboratory.

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 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), since the aluminum concentration was about 830×10^{16} atoms/cc aluminum, which gives a calculated resistivity of 0.07 ohm cm. It is fairly safe to assume that aluminum affected the resistivity and also that the element is, at least partially, electrically inactive.

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 12 and 13. Aluminum results are about one order of magnitude higher in our analysis. Boron was not reported by Westinghouse; we detected it in every sample.

In most cases we have found higher carbon and oxygen values than Westinghouse. The source of discrepancy can be from many factors such as:

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

The problems remain unsolved. We must recognize and emphasize again the needs for a primary standard in this field. Our analysis of sample C10B was repeated, and the results reported in Table 12 are in fair agreement with the original values. This leads us to believe that the reproducibility is as good as desired and that nonuniformities may exist over only a relatively small volume of the sample.

Table 12. 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 12. IMPURITIES DETERMINED BY SPARK SOURCE MASS SPECTROSCOPY
(atoms/cc) $\times 10^{16}$

Crystal Number	Primary Impurities	Secondary Impurities	Resistivity Ohm cm	B	C	H	O	F	Na	Mg	Al	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Ga	Cd	Zr	Nb	Ag
M108 MONS RERUN	B	Al 11	0.37	1.3	0.29	INT	5.8	0.33	0.063	N.D. 0.011	31	N.D. 0.22	N.D. 0.12	0.19	0.012	N.D. 0.0098	N.D. 0.011	N.D. 0.0077	N.D. 0.0097	N.D. 0.0095	N.D. 0.16	N.D. 0.33	N.D. 0.023	N.D. 0.0073	N.D. 0.0055	N.D. 0.013	N.D. 0.048	N.D. 0.015	N.D. 0.017
M108 WESTH	B	Al 11	0.37	0.93	0.18	INT	3.7	0.18	0.062	N.D. 0.0082	22	N.D. 0.096	N.D. 0.049	N.D. 0.021	0.019	N.D. 0.0089	N.D. 0.0096	N.D. 0.0062	N.D. 0.0084	N.D. 0.0086	N.D. 0.14	N.D. 0.19	N.D. 0.019	N.D. 0.0065	N.D. 0.0045	N.D. 0.013	N.D. 0.045	N.D. 0.033	N.D. 0.017
C108 MONS RERUN	S	Al 1.0 $\times 10$	0.15	1.5	1.6	INT	270	0.63	0.020	N.D. 0.012	420	N.D. 0.14	N.D. 0.086	0.28	N.D. 0.0029	N.D. 0.013	N.D. 0.011	N.D. 0.0078	N.D. 0.010	N.D. 0.011	N.D. 0.13	N.D. 0.23	N.D. 0.023	N.D. 0.0076	N.D. 0.0052	N.D. 0.014	N.D. 0.051	N.D. 0.038	N.D. 0.017
C108 WESTH	S	Al 1.0 $\times 10$	0.15	0.48	0.53	INT	55	0.66	0.097	N.D. 0.011	80	N.D. 0.076	N.D. 0.050	N.D. 0.021	0.023	N.D. 0.0098	N.D. 0.011	N.D. 0.0071	N.D. 0.0089	N.D. 0.010	N.D. 0.15	N.D. 0.19	N.D. 0.019	N.D. 0.0065	N.D. 0.0049	N.D. 0.013	N.D. 0.049	N.D. 0.035	N.D. 0.018
W02BAL001 WESTH				0.13	5.0	INT	67	0.94	0.040	N.D. 0.015	5.4	N.D. 0.11	N.D. 0.062	N.D. 0.033	0.024	EST 0.095	N.D. 0.013	N.D. 0.0087	N.D. 0.012	N.D. 0.015	N.D. 0.23	N.D. 0.22	N.D. 0.022	N.D. 0.0074	N.D. 0.0052	N.D. 0.014	N.D. 0.050	N.D. 0.038	N.D. 0.018
DC-C-01-16 AL-WESTH				0.034	3.3	INT	55	0.51	0.015	N.D. 0.013	1000	N.D. 0.089	N.D. 0.045	0.10	N.D. 0.0030	N.D. 0.013	N.D. 0.016	N.D. 0.0098	N.D. 0.013	INT	N.D. 0.24	N.D. 0.30	0.21	N.D. 0.011	N.D. 0.0074	N.D. 0.020	N.D. 0.073	N.D. 0.053	N.D. 0.27

Remarks: MONS RERUN = Run of Monsanto Sample
WESTH = Westinghouse

Values given are computer outputs. Not expressions of accuracy.

INT = Interference

EST = Estimated

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

4.1.4.5 Infrared Spectroscopy (IR) for Oxygen and Carbon Determination

IR technique is used to determine oxygen and carbon. This technique is widely used among producers and consumers of silicon wafers. The American Society for Testing and Materials, Committee F-1, which is actively studying the technique, considers it to be a standard technique for determination of oxygen and carbon in silicon wafers.

Infrared Determination of Interstitial Oxygen - The interstitial oxygen content of single crystal silicon can be determined by infrared spectroscopy. The useful range of oxygen content measurable by this technique is 50 ppba to 63 ppma (2.5×10^{15} to 3×10^{18} atoms/cc). The method uses the relationship between the oxygen content and the absorption coefficient of the $9 \mu\text{m}$ infrared absorption band of interstitial oxygen in silicon.

Interstitial oxygen in the form of the nonlinear Si-O-Si unit exhibits three infrared active bands at 1205 cm^{-1} , 1106 cm^{-1} , and 515^{-2} cm^{-1} . These bands have been assigned by Hrostowski and Kaiser⁸ to the symmetric stretching, asymmetric stretching, and bending modes of the Si_2O unit. Only the 1106 cm^{-1} ($9 \mu\text{m}$) band is intense enough to be useful in quantitative analysis.

Infrared Determination of Substitutional Carbon - Newman and Willis investigated infrared spectra of carbon-doped monocrystalline silicon.⁹ Isotopic substitution of the carbon dopant revealed that the impurity band at 607 cm^{-1} ($16.47 \mu\text{m}$) is due to substitutional C^{12} in the silicon lattice. Silicon doped with C^{14} exhibited the same type of impurity band but shifted to 572 cm^{-1} , and the absorption coefficient of this band was found to be proportional to the C^{14} concentration as determined by radioactivity analysis. The maximum concentration of substitutional carbon in crystalline silicon was found to be 24 ppma, and this is assumed to also be true for the normal C^{12} impurity band at 607 cm^{-1} .

The primary equipment used was a Beckman-IR4 infrared spectrophotometer. A Beckman-IR12 was also used when a more precise measurement was required. The sample used was 3 mm thick and was polished on both sides as mentioned in Table 7. The standards were originally supplied by ASTM Committee F-1 when this laboratory was involved in a round-robin test.

Analytical Data from IR - Data obtained from infrared spectroscopy for carbon and oxygen are summarized in Tables 14 and 15 along with the value obtained from SSMS for comparison. Some samples transmitted no IR light. Such samples are indicated in these tables as zero percent transmission (0%T). This is probably caused by the high concentrations of dopants. Also, there are some discrepancies between data obtained from IR and SSMS. In order to get more information about the problems associated with

Table 14. COMPARISON OF IR AND SSMS DATA FOR CARBON
AND OXYGEN IN CHOCHRALSKI SILICON
[All data expressed as (atoms/cc) $\times 10^{16}$]

Sample No.	Carbon		Oxygen	
	SSMS	IR	SSMS	IR
C1A	0.48	0%T	240	160
C1C	0.93	0%T	310	0%T
C2A	7.4	0%T	260	140
C2A1	10	0%T	390	137
C2B	6.7	0%T	120	130
C2B1	10	0%T	390	151
C2C	6.5	0%T	220	0%T
C3A	0.52	0%T	140	110
C4B	0.82	0%T	270	145
C5B	1.0	0%T	160	135
C6B	0.28	0%T	260	192
C7B	0.72	0%T	240	135
C8B	1.2	0%T	100	95
C8B1	1.2	0%T	100	170
C9B	1.1	9	89	165
C9B1	3.1	0%T	410	115
C10B	1.1	0%T	280	0%T
C10B1	2.7	0%T	390	0%T
C11B	1.5	0%T	220	135
C11B1	1.2	0%T	390	135
C12B	2.9	0%T	200	166
C13A	1.5	11	200	170
C13B	2.9	16	690	163
	1.4		320	
C13C	2.8	0%T	320	0%T
C14A	5.3	0%T	310	160
C14A1	4.7	--	380	--
C14A2	7.5	--	220	--
C15B	3.4	0%T	180	171
C16B	2.4	0%T	120	161
C16B1	5.5	0%T	330	0%T
C17B	15	62	270	174

Table 15. COMPARISON OF IR AND SSMS DATA FOR
CARBON AND OXYGEN IN FLOAT-ZONE
SILICON

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

Sample No.	Carbon		Oxygen	
	SSMS	IR	SSMS	IR
M1A	2.8	15	6.5	<3.0
M1B	0.34	0%T	3.2	0%T
M1C	0.38	0%T	6.0	0%T
M2B	0.52	--	8.5	--
M2B1	0.47	0%T	5.6	<3
M2B2	0.23	0%T	4.1	<3
M2C	0.65	--	9.4	--
M3B	0.20	0%T	2.9	<3
M4B	0.21	0%T	2.7	<3
M4B1	0.44	0%T	4.6	<3
M5B	0.31	0%T	2.7	<3
M5B1	0.50	0%T	8.5	15.
M6B	0.25	0%T	2.6	<3
M7B	0.35	0%T	5.8	<3
M8B	0.21	0%T	4.5	<3
M8B1	0.27	0%T	4.5	<3
M9B	3.1	0%T	2.2	<3
M10B	0.34	0%T	3.4	<3
M11B	0.68	0%T	4.6	<3
M13A	0.46	3	3.4	13.
M13B	0.42	3	4.9	<3
M13C	0.46	12	5.1	4.5
M14B	8.6	56	14	8.5
M14B1	11	0%T	3.2	<3.
M15B	0.35	0%T	8.2	<3
M15B1	0.21	0%T	5.4	<3
M16B	0.58	0%T	6.1	<3
M17B	0.55	5.5	5.6	6.5
M19B	0.33	0%T	3.3	<3
	0.29		3.9	
M19B1	0.58	4.7	2.8	6.5
M19B2	0.46	0%T	3.3	<3
	0.30		4.8	
M31B	0.43	0%T	6.1	<3
M32B	0.35	0%T	5.6	<3

such a discrepancy, five samples were taken to Dow-Corning at Midland, Michigan. The data obtained for carbon in Fz and oxygen in Cz silicon showed fairly good agreement (see Table 16). The values for oxygen in Fz and carbon in Cz silicon showed some disagreement and a need for more data. Except for crystal C9B, however, the discrepancy was not really serious and we have continued to use the oxygen data obtained from the IR technique.

Since the IR technique for determination of oxygen and carbon was basically developed using the data determined by a vacuum fusion technique, one sample (C2C) was selected and sent to Leco Corp. in St. Joseph, Michigan for such an analysis. The data from the vacuum fusion technique are compared with SSMS data in Table 17. The IR analysis for sample C2C showed zero percent transmission for both carbon and oxygen. Sample C2C was doped with carbon; thus, the value obtained from the vacuum fusion technique might be closer to the correct one. The extra sample for the vacuum fusion analysis was obtained in a manner different from the others. It was taken from the opposite end of the crystal which might have contained more carbon doping. SSMS consumed only 1 to 2 mg of sample so that the properties of the local region of sampling might also have affected the results. The SSMS result for carbon in sample C2C and the estimated added value differ by about two orders of magnitude; this was the only exception in the Cz series of crystals. All other carbon-doped samples showed fairly good agreement with analytical results, as shown in Table 18.

4.1.4.6 Emission Spectroscopy (ES)

Emission spectroscopy (ES) was used as a supplemental analytical technique to complement SSMS. The technique is widely used for analysis of electronic materials because of the multielement information it provides and the accuracy and the speed of the operation. The technique however, suffers from some disadvantages: (1) it lacks sensitivity to some elements; and (2) more than one condition has to be selected to excite or record the spectral lines desired.

A Jarrell-Ash 3.4 m Ebert spectrograph was used for emission spectroscopic analysis. The technique used is similar to that reported earlier,^{10,11} with some modifications. The sample was ground to powder and loaded on an electrode, which was pre-arc'd in an argon atmosphere to minimize contamination from the electrode. The samples were then arc'd in a controlled atmosphere and recorded using a photographic emulsion. The photographic plates were racked during the arcing in order to maximize the signal-to-noise ratio. The technique is called the sequential exposure technique and is known to be a powerful technique for the determination of trace and ultra-trace impurities in samples where selective volatilization is severe in the spark or arc excitation.

Table 16. COMPARISON OF MONSANTO AND DOW-CORNING IR DATA

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

Sample	Carbon		Oxygen	
	Dow Corning	Monsanto	Dow Corning	Monsanto
C9B	5.0	47	170	165
C13B	27	70	180	165
M1A	19	14	ND	<1.5
M13A	8.0	6.0	ND	12
M14B	41	55	ND	8.4

ND = Not Detected

Table 17. COMPARISON OF VACUUM FUSION, SSMS, AND IR DATA FOR CARBON AND OXYGEN ANALYSIS ON SAMPLE C2C

[(atoms/cc) $\times 10^{16}$]

	Carbon	Oxygen
Vacuum Fusion Avg. of Quadruplicate	870	127
SSMS	6.5	220
IR	0%T	0%T
Expected	497	Unknown

Table 18. CARBON ADDED AND DETERMINED BY SSMS

[(atoms/cc) $\times 10^{16}$]

Sample	Estimated (added) C _s	SSMS C _s
C2A	16	7.4
C2B	39	6.7
C2C	497	6.5
C2B1	3.5	10
C2B1 (R)	3.5	6.1
C14A	4.6	5.3
C14A1	4.6	4.7
C14A2	1.2	7.5

Since emission spectroscopy was intended to be used as a supplemental technique for SSMS, some samples which exhibited unexpected results were selected to check the data reported. Table 19 summarizes the ES results and compares them to the data from SSMS.

Samples M2B1 and C5B showed copper contamination by SSMS, and ES confirmed these results. The intentional dopants were not detected in M6B, M7B, M8B, and M31B; and this was again the case with ES. In magnesium-doped sample C9B the data from both techniques are in good agreement. In aluminum-doped samples C10B and M10B the aluminum values determined by ES were somewhat lower than those found by SSMS. In any case considering the range of impurities sought for, the discrepancy of results from SSMS and ES was not considered serious.

The aluminum concentration obtained from the second analysis of sample M10B (Table 19) is considerably lower than originally reported. The aluminum concentration obtained by ES from sample M10B is in fair agreement with that obtained by Westinghouse (see Table 12). However, aluminum results from sample C10B agreed well with the re-run by SSMS reported in Table 13. These observations led to the belief that the aluminum local segregation problem must be serious and therefore the inhomogeneity of sample may be considerable.

The aluminum-doped M19B series was then selected for investigation. Table 20 compares the results of SSMS and ES with the theoretical aluminum concentration derived from resistivity data. Theoretical doping concentrations of aluminum are also shown for comparison. The data for the M19B series in Table 20 is rather interesting. The theoretical aluminum concentration obtained from the resistivity data came within about a factor of two of the results from emission spectroscopy. The theoretical concentration (C_s), calculated from the doping, considering solubility and segregation, agreed with the results of spark source mass spectrometry within a factor of two. Yet the discrepancies between ES and SSMS are about one order of magnitude. If we disregard the problem of inhomogeneity of the samples, these theoretical calculations based on presently available knowledge regarding solubilities or segregation coefficient should be carefully re-studied. Undoubtedly, the theoretical calculations depend on the analytical technique used.

4.1.4.7 Auger Electron Spectroscopy (AES)

Auger electron spectroscopy (AES) was not originally planned to be used in this project. After observations of analytical results from both Cz and Fz series, however, a distinct difference in carbon and oxygen content was observed. These two elements are to be considered as major impurities and have been suspected as possible causes of poor contacts in Ag-Ti-Si layers described

Table 19. IMPURITIES DETERMINED BY EMISSION SPECTROSCOPY

Sample	Dopant	Element Determined	Es [ppm (w/w)]	SSMS [ppm (w/w)]
M2B1	Fe	Cu	0.24	0.6
M6B (OE) ¹	Zr	Zr	ND ²	ND
M7B	Mg	Mg	ND	ND
M8B (OE)	Ti	Ti	ND	ND
M10B	Al	Al	2.4 0.9	7.8
M31B	Cu	Cu	ND	ND
C5B	Mn	Cu	0.18	0.15
C9B	Mg	Mg	0.02	ND
C9B (3/8)	Mg	Mg	0.04	0.02
C10B	Al	Al	40	160

¹OE = Opposite End²ND = Not DetectedTable 20. COMPARISON OF Al DATA FROM SSMS AND ES
(atoms/cc)

Sample	Resistivity (ohm/cm)	Al Concentration from Table 22	SSMS	ES	Theoretical
M19B	0.31	8.0×10^{16}	7.2×10^{17}	5.46×10^{16}	4.0×10^{17}
M19B1	1.85	7.5×10^{15}	5.2×10^{16}	5×10^{15}	4.8×10^{16}
M19B2	0.43	4.8×10^{16}	5.6×10^{17}	10×10^{16}	2.6×10^{17}

in other parts of this report. The technique is new, compared to the other three techniques used in this project. In order to clarify the data presented in this report a brief discussion of the technique is included here.

Auger electron spectroscopy is described in different publications.^{12,13} The common notation for the electron shells K, L, M, ... correspond to a principal quantum numbers $n = 1, 2, 3, \dots$. The subscripts for each shell above K, i.e., L_1, L_2, L_3 , denote energy levels for different azimuthal and electronic spin terms.

Electron bombardment, X-ray irradiation, or other methods can create a vacancy in an inner or K shell. A de-excitation can occur in two different ways. In the case of X-rays, the vacancy is filled by an electron from an outer shell, such as L_3 , and the energy is emitted as an X-ray quantum. In the case of the Auger process, the electron vacancy is filled by an electron from a less energetic outer shell, such as the L_1 shell. The energy released by this transition is transferred to another electron in one of the outer shells, such as L_3 , this electron is then ejected with a precisely determined energy that is uniquely related to the atom from which it is ejected.

The equipment used was the Auger electron spectrometer (AES) made by Physical Electronics Industries, Inc. of Edina, Minnesota. The instrument uses an electron beam for the excitation of Auger electrons. It incorporates an electron energy analyzer, an inert gas ion beam for sputter-etching, controlling electronics, and associated vacuum equipment. The escape depth of the Auger electrons is about $10\text{\AA}$, and this limits the depth of the analysis. In AES the electrons are energy analyzed, and the occurrence of the peak in the Auger spectrum at particular energies indicates the presence of specific elements at the specimen surface. The "Auger spectrum" is commonly expressed as $dN(E)/dE$, the derivatives of the secondary electron energy distribution. This curve is known to have a lower background and more pronounced Auger peaks than $N(E)$, the electron energy distribution.

In our solar cell fabrication process Ti/Ag contacts are used. The processes used are discussed in other parts of this report. Previously we reported that poor adhesion of these contacts sometimes caused peeling of the metals. It was thought that AES could be used to study the profile of the Si-Ti-Ag system, especially the movement of oxygen and carbon in these layers. Oxygen and carbon, as major impurities in silicon and other metals, migrate or transfer between different metals, particularly when the samples are heat treated. In addition, these two elements may even be added unintentionally during the fabrication process.

Some silicon wafers were coated with a thinner Ti/Ag film. Then the surface and profile were studied with AES. The technique detects elements in the top $\sim 20\text{\AA}$ layer and detection limits are about 0.1% of the concentration in the layer.

Some Auger electron spectra from silicon wafer M1A with a Ti/Ag coating are shown in Figures 14 to 18. Figure 14 shows the results when the sample was not heat treated. C, O, and Ag with contamination of Cl were observed. After heat treatment (Figure 16) Ti was observed to have diffused to the Ag surface.

Ti/Ag was then coated on a different sample using an ion pump vacuum system (Figure 17). The sample was not heat treated. Oxygen concentration was less than that found in Figure 14 because of the better vacuum system.

Then the sample coated with Ti/Ag using the ion pump vacuum system was heat treated (Figure 18). The heat treatment caused an increase of O, and Ti also diffused to the surface.

AES was also used simultaneously with argon ion sputtering for removing surface layers. Figures 19 to 22 show the profiles obtained from sample M1A with the Ti/Ag coating. The surface Auger spectra of the C1A samples are shown in Figure 27. At the Ag/Ti interface, less silver, more titanium, and the two contaminants (C and O) are still observed. Ion gun interference, and the argon used for ion etching was also recorded. Silicon did not appear in this interface. At the Ti/Si interface, as shown in Figure 18, significantly less silver and strong titanium, oxygen, carbon, and argon are observed. Silicon is now present rather strongly. The carbon peak is a typical carbide peak which is not indicative of a graphitic carbon. Silicon is an elemental silicon rather than an oxide form. If SiO_x were present a peak at 87 eV would show up. When the titanium^x layer was completely removed, only Si, O, Ar, and possible SiO_x were observed.

From these observations, it is easily derived that titanium forms carbide and oxide at the Ti/Si interface and the distribution is more to the titanium side.

Figures 28 and 29 are profile studies of sample C1A which had a relatively thin Ti/Ag layer. The results are quite similar to those from the M1A series; the heat treatment diffuses the metals interchangeably. Oxygen, again, was pushed to the left, closer to the Ag/Ti interface.

4.1.4.8 Discussion and Conclusions

In the Cz series of samples, the intentional dopant is not detected by SSMS for seven samples. The detection of magnesium in sample C9B was a difficult problem. Titanium and zirconium were other dopants which were not easily detected even when the runs

Figure 15. Auger spectrum of contact metallization surface, sample M1A, not heat treated.

Figure 16. Auger spectrum of contact metallization surface, sample M1A, heat treated.

Figure 17. Auger spectrum of contact metallization surface, sample M1A, not heat treated, ion pump.

Figure 18. Auger spectrum of contact metallization surface, sample M1A, heat treated, ion pump.

Figure 19. Profile study of the Ti/Ag contact, sample M1A, not heat treated.

Figure 20. Profile study of the Ti/Ag contact, sample M1A, heat treated.

Figure 21. Profile study of the Ti/Ag contact, sample M1A, not heat treated, ion pump.

Figure 22. Profile study of the Ti/Ag contact, sample M1A, heat treated, ion pump.

Figure 23. Profile study of the Ti/Ag contact. Sample ClA. Heat treated.

Figure 24. Auger spectrum of the contact metallization surface. Sample ClA. Heat treated. Before ion etching.

Figure 25. Auger spectrum of the contact metallization surface. Sample ClA. Heat treated at Ag/Ti interface.

Figure 26. Auger spectrum of the contact metallization surface. Sample ClA. Heat treated at Ti/Si interface.

Figure 27. Auger spectrum of the contact metallization surface. Sample ClA. Heat treated after removal of the Ag/Ti layer.

Figure 28. Profile study of the Ti/Ag contact. Sample ClA. Not heat treated.

Figure 29. Profile study of the Ti/Ag contact. Sample ClA. Heat treated.

were repeated several times. These two elements were probably segregated. It was possible to detect the intentional dopants for 23 samples by SSMS, but there were some discrepancies in both directions probably caused by segregation problems.

In the Fz series the dopants were not detected in 12 samples and the dopants were detected in 20 samples. The reasons for the discrepancies are probably the same as for the Cz series. In some cases unexpected elements were detected in the samples. These are not uncommon and the knowledge of all of the elements present in the sample can only be considered as advantageous even if it is difficult to understand the exact reason for their presence or what effect they may have in the use of the silicon.

Some samples were exchanged with other laboratories. Comparison of data shows both some discrepancies and some good agreement. Sampling might have caused some problems but the most inherent difficulty is lack of STANDARD or reference material which are not available. A silicon standard for SSMS is urgently needed for this type of project.

Overall, SSMS furnished some meaningful data for this project in spite of the existence of some difficulties, which were mentioned previously.

The IR technique, in spite of its popularity in the field, was found to be rather useless because of the high doping level which caused a high free carrier concentration that made the measurement extremely difficult. For low-grade silicon it is not the most useful technique for this purpose.

Emission spectroscopy has some edge in detection limits for some elements but requires different conditions for the detection of different elements. For silicon analysis, it is an excellent supplemental tool for SSMS.

Auger electron spectroscopy demonstrated useful application for noting movement of carbon and oxygen on the surface and at different depths in the Ag/Ti contact system. The heat treatment tended to diffuse metals into adjacent areas. Some carbide formation and oxide formation of titanium metal were observed. Oxygen and carbon have a tendency to accumulate in the interface area. Also, oxygen was found to move to the titanium layer.

In using all four techniques, a considerable amount of data were obtained and it is not possible at present to develop a complete understanding of the problems, or connect all the various pieces of data. Analytical work of this type provides a big step towards the success of the low-cost solar cell project, but additional work will probably be necessary to help complete our understanding of the problems.

4.1.4.9 Recommendations

The same approach would be recommended for analysis of low cost silicon material if the project were to be done again. Spark source mass spectrometry is the best tool available for this particular type of matrix and problem. However, some improvements would be necessary to enhance progress:

- 1) Standard or reference material for silicon in the low ppm to ppb range is urgently needed. The National Bureau of Standards and the American Society for Testing and Materials should accelerate this program.
- 2) The only meaningful analytical approach for this type of project is total analysis. Partial information about the material does not provide a complete enough picture of the problems. SSMS should really be used for the detection of every possible element in the material.
- 3) Auger electron spectroscopy should be more involved in the surface analysis of material. Surface, thin layer, movement of elements in the contact profile, contact failure, etc. are impurity problems. Knowledge on these problems should assist in understanding and finding solutions more quickly and efficiently.
- 4) Impurities are not always homogeneously distributed. The problem of segregation, occlusion, inclusion, and precipitation are often the source of misunderstanding of impurity problems. Unless more analytical work is done, some aspects of the problem will not be clarified.

4.1.5 Solar Cell Fabrication and Evaluation (D. E. Hill)

The principal aim of the present work is the comparison of solar cell performance between cells fabricated from high quality "semi-conductor grade" silicon wafers containing one purposely added doping impurity and those fabricated from silicon which has, in addition to the primary doping impurity, a secondary dopant whose effect we wish to study. In order to achieve this aim with the assurance that the results will be meaningful and applicable to the current solar cell industry, the processing used to fabricate the solar cells must be as stable and reproducible as possible and capable of producing a solar cell of reasonably high efficiency. Stability and reproducibility were designed into the process to as high a degree as possible and were monitored in all cases by processing "baseline" wafers along with all samples as controls. For the purpose of this contract, "reasonably high" has been defined as greater than 12% efficiency at 100 mW/cm².

Table 21. IMPURITIES DETERMINED BY SPARK SOURCE MASS SPECTROMETRY (C2)

Expressed as (Atoms/cc) x 10¹⁶

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	0.09	0.14	0.09	0.01	EST 0.044	N.D. 0.01	N.D. 0.007	0.082	N.D. 0.009	N.D. 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	16	0.68	7.4	INT	260	0.31	0.03	N.D. 0.01	N.D. 0.17	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	39	0.76	6.7	INT	120	0.25	0.05	N.D. 0.01	N.D. 0.13	0.11	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
C2B1	B	C	3.5	1.4	10.	INT	390	.46	.05	N.D. .01	N.D. .11	.096	.05	.042	.04	EST .055	N.D. .01	N.D. .007	N.D. .009	N.D. .01	N.D. .16	N.D. .22	N.D. .02	N.D. .007	N.D. .005	N.D. .014	N.D. .05	N.D. .035	N.D. .018
C2B1(R)	B	C	3.5	1.6	6.1	INT	420	.34	.20	N.D. .015	N.D. .092	.13	N.D. .044	.050	.046	EST .081	N.D. .012	N.D. .0074	N.D. .0094	N.D. .011	N.D. .17	N.D. .20	N.D. .020	N.D. .0070	N.D. .0051	N.D. .014	N.D. .048	N.D. .036	N.D. .017
C2C	B	C	497	120	6.5	INT	220	2.2	0.06	N.D. 0.01	N.D. 0.16	0.16	N.D. 0.21	0.13	0.06	EST 0.09	N.D. 0.01	N.D. 0.008	N.D. 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	.154	0.97	0.52	INT	140	1.3	0.09	N.D. 0.01	N.D. 0.22	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. 0.009	N.D. 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	.0005	0.92	0.82	INT	270	0.42	0.03	N.D. 0.01	N.D. 0.12	0.11	N.D. 0.03	0.03	0.014	EST 0.072	N.D. 0.01	N.D. 0.008	N.D. 0.01	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	.018	1.1	1.0	INT	160	0.30	0.05	N.D. 0.01	N.D. 0.18	0.11	N.D. 0.22	0.15	0.03	N.D. 0.011	N.D. 0.011	N.D. 0.007	N.D. 0.01	N.D. 1.2	N.D. 0.18	N.D. 0.22	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	0.4	0.76	0.28	INT	260	0.16	0.03	N.D. 0.01	N.D. 0.14	0.10	N.D. 0.03	0.02	0.01	N.D. 0.010	N.D. 0.012	N.D. 0.008	N.D. 0.01	N.D. 0.01	N.D. 0.16	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	.025	0.93	0.72	INT	240	1.3	0.09	N.D. 0.01	N.D. 0.19	0.11	N.D. 0.17	0.15	0.04	N.D. 0.010	N.D. 0.011	N.D. 0.07	N.D. 0.28	N.D. 0.01	N.D. 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
C8B(R1)	B	Zr	.01	.98	1.9		110	.29								EST	N.D.	N.D.	INT	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	
C8B(R2)	B	Zr	.01	1.1	INT	INT	INT	.99	.16	N.D. .014	N.D. .21	N.D. .15	N.D. .079	.24	.046	EST .089	N.D. .013	N.D. .0087	N.D. .014	N.D. .014	N.D. .21	N.D. .25	N.D. .025	N.D. .0082	N.D. .0062	N.D. .016	N.D. .059	N.D. .042	N.D. .020
C8B(R3)	B	Zr	.01	.73	1.2	INT	100	.33	.026	N.D. .010	N.D. .28	N.D. .095	N.D. .050	.13	.018	EST .041	N.D. .012	N.D. .0076	N.D. .0097	N.D. .014	N.D. .17	N.D. .25	N.D. .027	N.D. .0080	N.D. .0060	N.D. .016	N.D. .057	N.D. .042	N.D. .021
C8B1	B	Zr	0.01*	.88	INT	INT	INT	.35	.069	N.D. .013	N.D. .35	N.D. .16	N.D. .087	.20	.039	EST .045	N.D. .014	N.D. .0087	N.D. .014	N.D. .21	N.D. .24	N.D. .024	N.D. .0082	N.D. .0062	N.D. .017	N.D. .060	N.D. .043	N.D. .021	
C8B1(R1)	B	Zr	0.01*	.80	1.2	INT	100	.61	.037	N.D. .010	N.D. .15	N.D. .15	N.D. .059	.17	.022	EST .044	N.D. .012	N.D. .0077	N.D. .010	N.D. .014	N.D. .19	N.D. .23	N.D. .026	N.D. .0079	N.D. .0061	N.D. .017	N.D. .061	N.D. .044	N.D. .021
C9B	B	Mg	5.	0.30	1.1	INT	89	0.88	0.03	N.D. 0.01	N.D. 0.17	0.12	N.D. 0.04	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
C9B1	B	Mg	192.	1.1	3.1	INT	410	.24	.06	N.D. .11	N.D. .088	.03	N.D. .057	.07	.07	EST .040	N.D. .01	N.D. .006	N.D. .008	N.D. .009	N.D. .15	N.D. .20	N.D. .02	N.D. .007	N.D. .005	N.D. .013	N.D. .05	N.D. .036	N.D. .018
C10B	B	Al	--	1.1	1.1	INT	180	1.3	0.08	N.D. 0.01	N.D. 0.12	0.06	N.D. 0.26	0.10	0.04	EST 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. 0.057	N.D. 0.014	
C10B1	B	Al	20.	.92	2.7	INT	390	.25	.044	N.D. .011	N.D. .13	.062	N.D. .044	.017	.017	EST .033	N.D. .013	N.D. .0081	N.D. .010	N.D. .013	N.D. .19	N.D. .23	N.D. .023	N.D. .0079	N.D. .0058	N.D. .015	N.D. .055	N.D. .041	N.D. .020
C11B	B	Ti	.0355	1.2	.15	INT	220	0.87	0.02	N.D. 0.01	N.D. 0.18	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
C11B1	B	Ti	.087	1.1	1.2	INT	390	.33	.09	N.D. .01	N.D. .12	.085	N.D. .08	.037	.020	EST .089	N.D. .06	N.D. .006	N.D. .02	N.D. .01	N.D. .16	N.D. .21	N.D. .02	N.D. .007	N.D. .007	N.D. .014	N.D. .05	N.D. .035	N.D. .018
C12B	B	C	3.5 .45	.93	2.9	INT	200	.44	.023	N.D. .011	N.D. .15	.13	N.D. .057	.018	.0021	EST .017	N.D. .011	N.D. .0076	N.D. .0098	N.D. .0096	N.D. .15	N.D. .24	N.D. .024	N.D. .0082	N.D. .0057	N.D. .016	N.D. .057	N.D. .042	N.D. .020
C13A	P	--	N.D. .014	1.5	INT	200	1.1	.06	N.D. .01	N.D. .17	N.D. .50	.05	.027	.03	EST .043	N.D. .01	N.D. .006	N.D. .008	N.D. .01	N.D. .16	N.D. .20	N.D. .02	N.D. .007	N.D. .005	N.D. .014	N.D. .05	N.D. .035	N.D. .017	
C13B	P	--	N.D. .015	2.9	INT	690	.54	.04	N.D. .009	N.D. .16	N.D. .47	N.D. .030	N.D. .020	.01	N.D. .0087	N.D. .01	N.D. .006	N.D. .008	N.D. .009	N.D. 1.4	N.D. 1.9	N.D. .02	N.D. .007	N.D. .005	N.D. .013	N.D. .05	N.D. .034	N.D. .017	
C13B(R1)	P	--	N.D. .016	1.4	INT	320	.27	.022	N.D. .011	N.D. .15	N.D. .25	N.D. .065	N.D. .10	.015	N.D. .010	N.D. .013	N.D. .0083	N.D. .011	N.D. .012	N.D. .19	N.D. .27	N.D. .027	N.D. .0082	N.D. .0062	N.D. .017	N.D. .056	N.D. .041	N.D. .020	
C13C	P	--	N.D. 0.01	2.8	INT	320	0.27	0.04	N.D. 0.01	N.D. 0.27	N.D. 0.03	N.D. 0.02	N.D. 0.02	0.02	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	
C14A	P	C	4.6 .018	N.D.	5.3	INT	310	.19	.05	N.D. .009	N.D. .11	.44	N.D. .026	N.D. .021	.02	N.D. .0091	N.D. .01	N.D. .006	N.D. .008	N.D. .009	N.D. .14	N.D. .19	N.D. .02	N.D. .007	N.D. .005	N.D. .013	N.D. .05	N.D. .035	N.D. .017
C14A1	P	C	4.6 .017	N.D.	4.7	INT	380	.27	.018	N.D. .011	N.D. .18	.5	N.D. .011	.067	N.D. .023	EST .043	N.D. .011	N.D. .0075	N.D. .0094	N.D. .011	N.D. .16	N.D. .23	N.D. .022	N.D. .0078	N.D. .0056	N.D. .014	N.D. .057	N.D. .042	N.D. .020
C14A2	P	C	1.2 .012	N.D.	7.5	INT	220	.26	.014	N.D. .011	N.D. .13	.28	N.D. .068	N.D. .021	N.D. .023	EST .050	N.D. .014	N.D. .0093	N.D. .011	N.D. .011	N.D. .18	N.D. .27	N.D. .027	N.D. .0090	N.D. .0066	N.D. .018	N.D. .057	N.D. .042	N.D. .021
C15B	B	Na	1.0	.94	3.4	INT	180	.35	.021	N.D. .0092	N.D. .16	.15	N.D. .074	.019	.012	EST .026	N.D. .010	N.D. .0070	N.D. .030	N.D. .0096	N.D. .15	N.D. .21	N.D. .021	N.D. .0073	N.D. .0055	N.D. .015	N.D. .057	N.D. .041	N.D. .020
C16B	B	P	1.4	1.0	2.4	INT	120	.21	.051	N.D. .0088	N.D. .069	.57	N.D. .052	.039	.019	EST .038	N.D. .010	N.D. .0075	N.D. .0094	N.D. .010	N.D. .007	N.D. .16	N.D. .22	N.D. .022	N.D. .0055	N.D. .015	N.D. .055	N.D. .041	N.D. .021
C16B1	B	P	50.	19.	5.5	INT	330	.33	.077	N.D. .010	N.D. .098	.22	N.D. .072	N.D. .025	.024	EST .075	N.D. .012	N.D. .0080	N.D. .010	N.D. .011	N.D. .17	N.D. .23	N.D. .023	N.D. .0079	N.D. .0060	N.D. .016	N.D. .058	N.D. .043	N.D. .021
C17B	P	Ti	0.05	.022	15.	INT	270	.69	.047	N.D. .016	N.D. .35	1.7	N.D. .12	.29	.015	EST .12	N.D. .011	N.D. .014	N.D. .016	N.D. .23	N.D. .32	N.D. .033	N.D. .011	N.D. .0082	N.D. .021	N.D. .067	N.D. .044	N.D. .020	

Table 22. IMPURITIES DETERMINED BY SPARK SOURCE MASS SPECTROMETRY (FZ)

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

Crystal Matrix	Primary Impurity	Secondary Impurity Added	B	C	H	O	F	Na	Mg	Al	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Ga	Ge	Zr	Mo	Hg
N1A	B	--	0.56	2.8	INT	6.5	1.3	0.03	W.D.	W.D.	W.D.	0.26	0.16	0.014	EST	W.D.	W.D.	0.06	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N1B	B	--	3.9	0.34	INT	3.2	0.19	0.03	W.D.	W.D.	W.D.	W.D.	W.D.	9.7	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N1C	B	--	34	0.39	INT	6.0	0.59	0.04	W.D.	W.D.	W.D.	0.39	0.15	0.016	W.D.	W.D.	W.D.	0.04	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N2B	B	Fe 0.00	1.4	0.52	INT	0.5	0.25	0.06	W.D.	W.D.	W.D.	0.056	0.15	0.037	EST	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	1.3	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N2D1	B	Fe 0.06	1.2	0.47	INT	5.6	0.21	0.07	W.D.	W.D.	W.D.	0.051	0.085	0.022	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N2B2	B	Fe 1.6	0.92	0.33	INT	4.1	0.24	0.023	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N2C	B	Fe 0.06	30.	0.65	INT	9.4	4.0	0.03	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N3B	B	Nb 0.07	1.3	0.30	INT	2.9	0.15	0.045	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N4B	B	Ni 0.07	0.55	0.11	INT	2.7	0.16	0.05	W.D.	W.D.	W.D.	0.05	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N4B1	B	Ni 0.07	0.00	0.44	INT	4.6	0.37	0.045	W.D.	W.D.	W.D.	0.36	0.19	0.033	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N5B	B	V 0.06	0.75	0.31	INT	2.7	0.17	0.056	W.D.	W.D.	W.D.	0.12	W.D.	0.025	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N5B (R)	B	V .06						.053	W.D.	W.D.	W.D.		W.D.	0.01	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N5B1	B	V .50	1.1	.50	INT	6.5	.30	.05	W.D.	W.D.	W.D.	.22	.13	.029	EST	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N6B	B	Zr	1.1	0.25	INT	2.6	0.16	0.034	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N7B	B	Hg 5.	1.2	0.35	INT	5.0	0.29	0.05	W.D.	W.D.	W.D.	W.D.	W.D.	0.024	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N8B	B	Ti 0.05	1.1	0.21	INT	4.5	0.20	0.074	W.D.	W.D.	W.D.	W.D.	W.D.	0.054	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N8B	B	Ti .010	1.1	.27	INT	4.5	.55	.061	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N9B	B	C	0.6	3.1	INT	2.2	1.8	0.035	W.D.	W.D.	W.D.	W.D.	W.D.	0.01	EST	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N10B	B	Al 11	1.4	0.34	INT	3.4	0.57	0.07	W.D.	W.D.	W.D.	0.24	0.21	0.037	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N11B	B	Ni .71 Pb .006 Hg .42	1.6	.66	INT	4.6	.48	.048	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N11A	P	--	W.D.	.46	INT	3.4	.69	.03	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N11B	P	--	W.D.	.42	INT	4.9	.77	.06	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N11C	P	--	W.D.	.46	INT	5.1	.45	.07	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N11D	P	C ~1.0	W.D.	8.6	INT	14.	.87	.06	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N11D1	P	C ---	W.D.	11.	INT	3.2	.25	.032	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N15B	B	Na	.90	.35	INT	6.2	.34	.033	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N15B1	B	Na	1.2	.21	INT	5.4	.26	.031	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N16B	B	P 1.1	3.4	.58	INT	6.1	.32	.020	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N17B	P	Ti .01	.14	.55	INT	5.6	.30	.038	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N18B	-	Al 48.	W.D.	.33	INT	3.3	.13	.038	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N19B (R)	-	Al 48.	W.D.	.29	INT	3.9	.24	.022	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N19B1	-	Al 2.6	W.D.	.050	INT	2.8	1.5	.024	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N19B2	-	Al 4.8	W.D.	.46	INT	3.3	.14	.071	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N19B2 (R)	-	Al 4.8	W.D.	.30	INT	4.8	.31	.029	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N31B	B	Cu .27	1.3	.43	INT	6.1	.51	.044	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.
N32B	B	Cr 3.06	1.4	.35	INT	5.6	.33	.033	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.	W.D.

INT = Interference

EST = Estimated

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

Features like antireflection (AR) coatings and, to some extent, drift field back contacts are independent of the inner workings of the cell and add a constant factor to the performance of all cells. For this reason practically all comparisons in this work were carried out using cells without AR coatings or drift field back contacts. Some cells were examined with and without AR coatings, however, to provide assurance that a "reasonable" efficiency could be obtained and that the observed efficiency would increase in the usual fashion with AR coating. The latter item insures that the effects observed are not complicated by the presence of accidental AR coatings as a result of processing which could conceivably differ for silicon containing various dopants.

It was recognized from the inception of this work that the processing procedures, heat treatments, etc, would very likely play a role in determining the behavior of some of the impurities in silicon under study. For that reason, among others, the fabrication procedures are described in some detail in the following sections.

4.1.5.1 Solar Cell Fabrication Procedure

A general outline of the fabrication procedure is given below. Some of the steps will be described in more detail in the following sections. The composition of the cleaning solutions and etches are described in Appendix I. The wafers used for solar cell fabrication and those used for analytical purposes were selected from as near the same position of the crystal as possible. This was facilitated by the notch encoding system described earlier. Appendix IV lists the notch spacing for the analytical samples and the spread of the notch spacings for the wafers used for solar cell fabrication.

Fabrication Procedure

- 1) Scribe identification on wafers and measure notch spacing.
- 2) Clean wafers with HF dip, soap solution scrub, A and B baths.
- 3) Diffuse wafers.
- 4) Mask front of wafer with black wax.
- 5) Remove oxide from back of slice in 10% HF.
- 6) Remove diffused layer from back of slice in CP4.
- 7) Solvent clean and rinse in distilled water.
- 8) Remove oxide from front of cell in 0.5% HF, rinse and spin dry.
- 9) Rinse in H_2O_2 - NH_4OH solution.
- 10) Evaporate 500-800 Å Ti followed by 10,000 Å Ag on the front of the wafer and then on the back of the wafer.
- 11) Heat treat at 500°C for 15 minutes.
- 12) Photoresist and etch junction-side contact pattern. Protect backside metallization with photoresist and remove photoresist after etching.
- 13) Saw into 2 x 2 cm cells.
- 14) Solder dip.
- 15) Coat selected cells with antireflection coating.

Phosphorus Diffusion - The quality of the diffused junction is of prime importance to the efficiency of solar cells that can be fabricated from a wafer of silicon. It provides both the voltage and the charge separation that permits current to flow when the cell is illuminated. The diffusion process usually used to form this junction has been and is the subject of much research and development. The usual goals of this activity are the development of "record high" efficiencies and simple or low cost processes.

The present work does not require "record high" efficiencies, but does require an overall process which is reproducible and is capable of producing solar cells with greater than 12% efficiency. The following process fills these requirements.

The phosphorus diffusions in this work employed phosphine as a diffusant source. The diffusions were carried out at 850°C in a gas stream consisting of 800 cc/min. of 1% PH₃ in Ar, 45 cc/min. O₂, and 300 cc/min of N₂. The wafers were given a 3-minute preheat in the hot zone in O₂ and N₂, and a 15-minute diffusion in the full gas stream, followed by a 10-minute oxidation and flushing operation in O₂ and N₂ and a 5-minute slow cool in N₂ in the end of the furnace tube.

To obtain the best reproducibility,¹⁴ diffusion runs were spaced 30 minutes apart with a N₂ flow through the furnace during this period. A run without wafers was performed prior to each series of diffusions to condition the diffusion tube. Diffusion run size and wafer location were maintained as constant as possible. Reproducibility of the sheet resistance resulting from this diffusion was checked by examining wafers at random from nearly all the different diffusions and found to have a standard deviation of 9%.

The diffusion was optimized by making runs with various diffusion times. The results are shown in Table 23.

Table 23. SOLAR CELLS FABRICATED USING PHOSPHORUS DIFFUSION AT 850°C 100 mW/cm²; NO ANTIREFLECTION COATINGS

Diffusion Time (min)	Sheet Resistance (ohms/)	V _{oc} (volts)	I _{sc} (mA/cm ²)	Fill Factor	Efficiency (%)
10	59	0.586	20.32	0.712	8.48
15	55	0.594	20.38	0.733	8.86
20	50	0.589	20.19	0.729	8.75
30	44	0.585	20.11	0.719	8.44

Some effort was expended to determine the junction depths using the following technique. Starting with a diffused Monsanto polished wafer which was optically flat and scratch free, a 2° angle bevel was lapped onto the surface using levigated alumina on a glass plate. The junction was stained using ~ 1 drop of HNO₃ in 100 cc of HF under a bright light. The edge of the bevel was not easy to observe and was often visible only as the place where the lapping scratches terminated. The lack of precision of the 2° angle lap and other difficulties limited the accuracy of these results to somewhat better than 0.1 μm. The results indicate that the junction depth for the 10-minute diffusion was a little greater than 0.2 μm. For the 15-, 20-, and 30-minute diffusions the depths were, respectively, slightly less than 0.3 μm, somewhat larger than 0.3 μm, and about 0.4 μm.

A limited examination of lower diffusion temperatures (825°C) was carried out. These showed little or no advantage in resultant cell efficiency over the 850°C diffusion used. Further optimization of the 825°C diffusion may have resulted in slightly higher efficiencies, but the 850°C diffusion used was more than adequate for this contract.

Boron Diffusion - The criteria for the choice of a boron diffusion were the same as those applied to the phosphorus diffusion.

The boron diffusion employed for this work made use of Combat¹⁵ boron nitride (BN) discs as the boron source. This method of diffusion has been investigated by Goldsmith¹⁶ of RCA and others¹⁷ and has some advantages over other boron diffusion methods.

The BN disc system as described here results in a sheet resistance reproducibility of 19% as sampled at random from most of the runs. In addition, this system should be expandable to larger wafers and large numbers of wafers without the difficulties encountered in flow systems. Grade "A" BN wafers were primarily used in this work after it was found that grade "M" BN resulted in solar cells that suffered from shorts.

The diffusions were carried out in the following manner. Before the initial oxidation the BN discs were solvent-cleaned, rinsed and etched, then rinsed again, dried, and placed in a diffusion boat. These discs were then thoroughly baked in flowing N₂ in the entrance of the furnace tube and then slowly pushed into the center zone of the furnace at 920°C. At this point the N₂ was turned off and the discs were oxidized in a flow of 1000 cc/min of O₂ for 30 minutes. Then the discs were stabilized at the same temperature in 1000 cc/min of N₂ for 1 hour. It was necessary to store the discs after oxidation in a dry N₂ atmosphere at a temperature of 200°C or greater. This was done in a diffusion tube extension near the entrance of the furnace. The discs were reoxidized every week.

The silicon wafers were placed in the diffusion boat back to back, with the front surfaces facing BN discs. The wafer surfaces were parallel to the BN discs and spaced about 1/8 in. apart. The BN discs used had a diameter at least 1/4 in. greater than the silicon wafers. The wafer and disc surfaces were perpendicular to the axis of the furnace tube and the diffusion was carried out in a 1000 cc/min N₂ flow.

After deposition the wafers were cleaned. A drive-in diffusion and oxidation could be used if desired to obtain a deeper junction with lower boron concentration. This work employed the deposition diffusion only.

The diffusion was optimized by varying both temperature and time to obtain a fairly large range of sheet resistances. This is summarized in Table 24. We see that the optimum sheet resistance is on the order of 200 ohms/□. This is contrary to our experience with phosphorus diffusions in which case the optimum sheet resistance is about 55 ohms/□.

Table 24. SOLAR CELLS FABRICATED FROM BORON-DIFFUSED N-TYPE SILICON, 100 mW/cm² INCIDENT INTENSITY

(No Antireflection Coatings)

Diff.	Temp. (°C)	Time (min.)	Sheet Resistance (ohms/)	V _{oc} (volts)	I _{sc} (mA/cm ²)	Fill Factor	Efficiency (%)
B1	900	30	163	0.555	19.87	0.772	8.51
B2	920	30	130	0.549	18.96	0.754	7.84
B3	940	40	71	0.552	18.05	0.631	6.36
B4	900	30	165	0.574	19.80	0.768	8.73
B5	875	30	280	0.565	20.03	0.756	8.55
B6	875	45	200	0.584	20.94	0.771	9.43
B7	860	25	380	0.577	20.44	0.758	8.94

The proper interpretation of the observation of high efficiency for high sheet resistance is not certain, but may be related to bulk lifetime changes caused by the generally higher temperatures used for boron diffusions. Thus, there could be a balance between increased efficiency due to increased lifetime at lower diffusion temperatures and decreasing efficiency caused by the sheet resistance becoming too high to be properly contacted by the metal pattern used.

Metalization - The solar cells fabricated in this contract were metalized with Ti and Ag as described earlier. This was carried out by vacuum evaporation from a filament and boat, respectively. This method of coating was used primarily because of the availability of the equipment. Several Ti sources were tried before a satisfactory one was found. Initially, pieces of Ti "sponge" were evaporated from a tungsten basket. The poor thermal contact between the sponge and basket required over-heating of the basket in order to melt the Ti. Consequently, the evaporation occurred almost instantaneously, creating difficulties in timing the shutter opening to avoid contamination of the solar cells from the hot filament while still allowing the Ti to reach the silicon surface.

Titanium-loaded filaments of the kind used in sputtering pumps were also evaluated as possible evaporation sources for Ti. These worked very well in a vacuum system which was pumped with Ti sputtering pumps. However, the system used for solar cell metalization was pumped by a liquid nitrogen trapped oil diffusion pump. The Ti-loaded filaments evaporated the Ti so slowly that it was deposited in a partially oxidized condition in this system.

The Ti source used for the evaporations overcame these difficulties to a reasonable degree. It was a simple tungsten filament, the center of which was wrapped with a measured length of Ti wire. In this case it was possible to melt the Ti on the filament in a controlled manner, open the shutter, and evaporate the Ti fast enough so that there was no evidence of oxidation.

It was also found to be advantageous to modify the metallization system in the following manner. A heat shield was constructed for the alumina-coated molybdenum boat used for Ag evaporation so that the wafers "saw" only the molten silver and did not "see" the rest of the hot boat and leads directly. In addition, a second Ti filament was installed in a shielded position in the vacuum chamber. This filament was used as a sputtering pump to "getter" oxygen, etc. prior to and during the early stages of metal evaporation onto the wafers. The net effect of these changes was to enable the evaporations to take place at a vacuum of about 3×10^{-7} torr, which is 10 times better than that possible before the modifications.

Metal Contact Geometry - The metal contact patterns for the solar cells fabricated in this work were defined by standard photolithographic and etching techniques. The mask used for all cells is shown in Figure 30. These are test patterns along the edge of the mask which are useful for contact and sheet resistance measurements and the small circular contacts can be etched into mesa diodes for capacitance measurements etc. This pattern has 14.1% metal coverage, which is a little more than necessary for this type of cell. However, for the purposes of this contract such a

Figure 30. Solar cell metallization mask No. C71, 2cm x 2cm
 Dimensions: buss bar - 0.040" x 0.771"; vertical
 arms, segment 1-0.012" x 0.222"; segment 2-0.010"
 x 0.300"; segment 3-0.080" x 0.205"; horizontal
 fingers, inner segment - 0.005" x 0.060"; outer
 segment - 0.003" x 0.050"

pattern was perfectly satisfactory since the comparison between cells fabricated from wafers with secondary impurities and baseline ingots was the important item.

Solder Dipping - After sawing and breaking, the solar cells were solder dipped to make the Ag/Ti contacts permanent by sealing them off from the atmosphere. In addition this increased the conductance of the metalized areas, which improved the performance of the cells.

The solder consisted of 62% Sn, 36% Pb, and 2% Ag and was used at a temperature near 210°C. Immediately before solder dipping the cells were dipped in Kester #1544 soldering flux¹⁸ to promote wetting between the solder and the Ag. The flux residue was removed with toluene, trichlorethylene, and isopropyl alcohol, used sequentially. The latter two solvents were sufficient for one bottle of flux, but a second batch required the use of toluene to eliminate some cell shorting caused by the flux residue.

The average improvement for the various parameters of a series of solar cells measured both before and after solder dipping are given below. The fill factor and efficiency improve much more

than V_{oc} and I_{sc} as one would expect. The degree of improvement depends on the thickness of silver present originally, and the results apply for about 1000Å of Ag and our standard metallization pattern.

Ratio	V_{oc}	I_{sc}	Fill Factor	Efficiency
Value after solder dip	1.001	1.004	1.050	1.053
Value before solder dip				

Antireflection Coating - Silicon has a very high index of refraction for visible light ($n_{Si} \sim 4$), which causes a silicon surface to have a relatively high reflectivity (> 30%). An antireflection coating is commonly used to reduce this reflectivity and thus permit more light to be absorbed by the solar cell, increasing its output.

The ideal single layer antireflection coating should be formed of a material with a refractive index¹⁹ equal to $\sqrt{n_{Si}}$. This leads to a preferred index value of ~ 2 . It can be shown¹⁹ that the refractive index of the reflection coating can differ a fair amount from this value, however, and still yield satisfactory results.

We chose silicon nitride (Si_3N_4) as a material that can be reliably formed as thin films in our laboratory with very nearly the optimum refractive index. Silicon nitride could be deposited in transparent thin film form with a refractive index of about 2.0 in an existing rf sputtering apparatus. An additional advantage of this technique occurred because sputtering is a low temperature process. These coatings would be applied to cells that had been solder-dipped and tested, and the cells could be re-tested without the necessity of any photoresist or etching processes.

The thickness of the antireflection coating should be equivalent to an optical path length of 1/4 wavelength of the light in question. Since the solar cell is not subjected to a single wavelength of light but rather to the spectrum of the sun, this thickness is also a compromise which is usually determined experimentally. A thickness in the neighborhood of 600Å, corresponding to a deep blue-purple color, resulted from our optimization experiments. Table 25 shows the ratio of the short circuit voltage and fill factor changed very little with antireflection coating.

The actual values for the solar cell parameters have been listed in Table 26 for three groups of cells with Si_3N_4 antireflection coatings. These efficiencies would increase by about a factor of 1.1 if a proper mask with less metal coverage were used.

Table 25. THE EFFECT OF SPUTTERED Si_3N_4 ANTIREFLECTION COATING ON SOLAR CELL PERFORMANCE

Sputtering Conditions: 6 in. Si_3N_4 target,
1-1/2 in. spacing,
250 watts RF power,
sputtered in N_2 at
30 micron pressure.

Sputtering Time	$\frac{I_{sc} \text{ with AR Coating}}{I_{sc} \text{ Without}}$	$\frac{\text{Eff with AR Coating}}{\text{Eff Without}}$
8	1.247 ± 0.006	1.257 ± 0.006
10	1.327 ± 0.006	1.343 ± 0.045
11	1.348 ± 0.012	1.323 ± 0.012
12	1.320 ± 0.010	1.323 ± 0.021

Table 26. AVERAGE PERFORMANCE VALUES FOR SOLAR CELLS WITH 11 MINUTE Si_3N_4 ANTIREFLECTION COATING, MEASURED AT $100\text{mW}/\text{cm}^2$ WITHOUT DRIFT FIELD BACK CONTACTS

Sample No.	V_{oc} (volts)	$\frac{I_{sc}}{A}$ (mA/cm^2)	Fill Factor	Efficiency (%)
M1BD	0.587 ± 0.001	27.06 ± 0.24	0.770 ± 0.004	12.20 ± 0.12
M3BS	0.590 ± 0.003	27.45 ± 0.25	0.785 ± 0.006	12.71 ± 0.20
M4BS	0.586 ± 0.004	27.49 ± 0.17	0.782 ± 0.007	12.56 ± 0.20

4.1.5.2 Evaluation

Solar Cell Parameter Evaluation Method - The solar cell I-V characteristic was evaluated using the usual four-contact method, i.e. two current leads and two voltage leads, to eliminate the effects of lead resistance and contact problems between the metal probes and the metalized regions of the solar cells. A Spectrolab Heliotek type HTB-171 water-cooled solar cell test fixture was used for these measurements connected as shown in Figure 31.

The open circuit voltage, V_{OC} , and short circuit current, I_{SC} , were measured in the expected fashion by first adjusting the power supply until the current meter read zero and then reading V_{OC} on the digital volt meter, or vice versa. The maximum power point was found with the aid of a series of constant power curves on the graph paper of the X-Y recorder, and the voltage and current values at maximum power were read from the digital meters. This allowed us to quickly find the maximum power point to an accuracy of a fraction of 1%. The dark I-V characteristics of the cells could be measured on the same apparatus by excluding all light with black cloths. All measurements were made at $27^\circ \pm 1^\circ\text{C}$.

The light source employed for all solar cell measurements was the same one used in the Air Mass 2 Simulator developed at Lewis Research Center for NASA.²⁰ The lamps designated Quartzline ELH, are composed of a tungsten halogen bulb with an axial filament and quartz envelope.

This bulb was set in a stippled reflector which had a front surface dichroic coating to reduce the infrared content of the reflected radiation. The lamp had a beam angle of 20° , a color temperature of 3350°K , and an average life of 35 hours.

The calibration of our lamp was verified during the latter portion of the contract period using standard solar cell No. TSS006 received from JPL. Our calibration was found to agree with the JPL cell to better than 6 parts in 1000. The spectral distribution of the lamp is described in the NASA work.²⁰

Open Circuit Decay Minority Carrier Lifetime Determination Method- The open circuit decay technique can be used to determine the excess carrier lifetime and the series resistance in a fabricated P/N junction device. In this type of measurement the device is forward biased for a time at least long enough for steady state operation to be reached. Then the bias is removed and the decay of the voltage across the junction is monitored under open circuit conditions. In the case where $V \gg kT/q$ the initial voltage decay is linear with a slope of $kT/q\tau$, where τ is the excess carrier lifetime, k is the Boltzmann constant, T is the absolute temperature, and q is the charge of an electron.²¹ This linear slope is preceded by an abrupt decrease in voltage which is related to the series resistance of the device in the simplest case.

Figure 31. Solar cell evaluation equipment.

The circuit diagram for this measurement and the actual equipment used is shown in Figure 32.

Using a 2 x 2 cm solar cell fabricated from 1-2 ohm cm material, curves of the type shown in Figure 33 were obtained. Obviously, the level of injection must be high enough so that the linear portion of the decay can be observed. For these devices the slope is essentially unchanged for forward bias values of 0.1 to 1 A. Values of 0.5 to 1.0 A were used in this work to permit an easier determination of the slope. The initial drop in Figure 33 corresponds to a series resistance of about 0.2 ohm, which is a reasonable value for these cells. These series resistance values are tabulated in Appendix V for the cells fabricated in this program.

Unfortunately, the open circuit decay of most cells examined in this work did not have such a distinctive form. The lower resistivity cells particularly seemed to yield curves that look more like Figure 34 with a much less pronounced distinction between the linear and non-linear regions. This shape difference is related to the relative values of cell impedance and shunt resistance. Figure 35 shows the same cell as Figure 34 at 900 mA with external shunt values of 50 ohms, 270 ohms, and ∞ . This technique of observing the effect of shunt resistance increased our confidence that the proper interpretation of these curves was being made.

Photoconductive Decay Minority Carrier Lifetime Determination

Method - The lifetime-measuring equipment used in the routine evaluation of silicon ingots (xenon flash lamp - photoconductive decay method) has a lower limit of lifetime detectability of 20 microseconds. For the usual commercial types of silicon this is more than adequate. For this program, however, the interest centered on relatively low-resistivity silicon (~ 0.5 ohm cm) which had been doped in addition with certain specified materials that further decreased the lifetime. In practically all cases this brought the area of interest well below the limit of detectability.

The simplest extrapolation of this method would involve the use of a lamp which has a faster turn-off time. A GaAs light emitting diode (LED) was an obvious candidate for the job. Various commercial infrared LED's of the epitaxially grown junction type (e.g. Monsanto type ME7140) were investigated. These have turn-off times from 0.5 to 0.2 microsecond and are generally the most efficient GaAs LED's available. These LED's result in satisfactory measurements for samples with resistivities of about 1 ohm cm or greater when used with small samples. However, when dealing with resistivities of 0.5 ohm cm and below, the modulation available is decreased to such a degree by both the higher carrier concentration and the accompanying lower lifetimes that satisfactory measurements are impossible.

Figure 32. Open circuit decay apparatus.

Figure 33. Open circuit decay waveform. Vertical scale 0.2V/div., horizontal scale 20 μ sec/div., current pulses of 2, 5, 30, 100, 500 and 900mA. 1-2 ohm cm base material 2cm x 2cm solar cell.

Figure 34. Open circuit decay waveform. Vertical scale 0.1V/div., voltage zero is 2 div below bottom of reticule. Horizontal scale 20 μ sec/div., current pulses of 2, 5, 30, 100, 500, and 900mA. M4B 2cm x 2cm solar cell.

Figure 35. Open circuit decay waveform. Vertical scale 0.2V/div., horizontal scale 20 μ sec/div., 900mA pulse. shunt resistance of 50 ohms, 270 ohms, and ∞ . M4B-3 2cm x 2cm solar cell.

For this reason a special LED was fabricated which provided essentially one order of magnitude more light in about the same size package without increasing the turn-off time. This enabled us to measure lifetimes down to 0.5 microsecond on the low resistivity samples used in this program. Signal averaging techniques could probably be used to extend this method or to achieve similar results with commercial LED's. These were not investigated.

The apparatus used in this work is shown in Figure 36. The trap light was a type EJY-80 watt tungsten-halogen, quartz envelope lamp with an associated focusing reflector.

Figure 36. Photoconductive decay apparatus.

Samples for photoconductive decay measurements were fabricated from 330-micron thick silicon wafers which were polished on both sides. These were cut into strips about 3 mm wide, and two Al contacts were placed on either end with an active region about 6 mm long in the center. For phosphorus-doped samples, Au-As contacts are used. The contacts were shielded from direct exposure to the light source and the sample was illuminated from the side opposite to the contacts. The sample absorption provided a large degree of additional shielding of the contacts from the light. Samples with resistivities of 0.5 ohm cm and lower of the size described had resistances of about 50 ohms or lower so it was advantageous to use amplifiers etc. with 50-ohm impedance in the measuring systems. This minimized the effects of stray capacitance and facilitated interconnecting the various components without degrading the response time.

The interpretation of these measurements in terms of bulk lifetime is not simple. One problem that is encountered is minority carrier trapping. Traps are centers that capture the excess carriers quickly and then release them at a much slower rate than would have occurred in their absence, resulting in a decay time that is not related to carrier lifetime. The trap population can be changed by a steady light while the lifetime decay is not, so that this phenomenon can be used to decide when trapping is involved. If the trap light is intense enough, the traps can be saturated and a true lifetime can be measured. All samples in this investigation were measured with and without a trap light. Most samples showed no evidence of trapping, but silicon with the secondary impurity Mn in particular, exhibited strong trapping and the application of a strong trap light reduced the decay time to less than 0.5 microsecond.

In the absence of trapping effects, the observed decay times would be a lower limit for the bulk lifetimes. Recombination can occur very rapidly at sample surfaces, however, and the proper accounting for this is a second major obstacle to the interpretation of these decays in terms of bulk lifetimes. If a sample is uniformly excited through the bulk in a direction perpendicular to the surfaces, the relationship between the effective photoconductive decay lifetime, τ_{eff} and the bulk lifetime τ can be given by²²

$$\tau_{\text{eff}}/\tau = 1 - \frac{(sL/DT) \sinh(T/L)}{(1/L) \sinh(T/L) + (s/D) \cosh(T/L)} \quad (6)$$

where s is the surface recombination velocity, L is the minority carrier diffusion length, D is the diffusivity, and $2T$ is the sample thickness. This expression is evaluated using appropriate parameters in Figure 37. We see that for lifetimes ranging from 0.5 to a few microseconds, which is the range of interest in this work, the value of the surface recombination velocity can have considerable influence on the interpretation of the results.

A difficulty with the application of this equation in addition to the necessity of knowing the surface recombination velocity, is the requirement of uniform excitation through the volume of the sample. To obtain some indication about the uniformity of the excitation, the relative emission spectra of two types of GaAs LED's²³ have been plotted in Figure 38 along with the absorption coefficient for silicon.²⁴ We see that the absorption length (i.e., that depth at which $\sim 63\%$ of the light has been absorbed) corresponding to the peak of the LPE emission curve is about 45 μm or about 1/8 of the sample thickness. This type of nonuniform excitation is bound to increase the effect of surface recombination on the results and essentially move the curves in Figure 37 for various s values to the left. Furthermore, the application of the above equation to a specimen with such nonuniform illumina-

Figure 37. Relationship between τ and τ_{eff} for uniformly illuminated sample 300 μm total for various bulk diffusion lengths with the surface recombination velocity as a parameter.

Figure 38. Absorption coefficient, α and absorption length $L_\alpha = 1/\alpha$ for silicon. Compared to emission spectra for diffused junction and liquid phase epitaxially (LPE) grown junction infrared emitting diodes. Dashed curve shows the effect of a 0.001 in. silicon filter on the emission spectra of the diffused emitter.

tion seems questionable at best. Thus, one might have considerable uncertainty about the validity of corrections that can be obtained from this equation.

One technique commonly used with broad-band sources (such as xenon flash tubes) to make surface effects less important is the use of a silicon filter between the light source and the sample. This does a good job of removing the visible component from a xenon light source, but does little but reduce the intensity of the emission for a GaAs LED, as seen from the dashed curve in Figure 38. It has been experimentally observed that a silicon filter does not change the observed decay time although it does reduce the signal amplitude considerably.

A second possibility for minimizing the effect of the surface is to observe only the last portion (perhaps 10%) of the decay curve. Unfortunately, our modulation amplitude was not sufficiently large to enable use of this method for most samples. The best we could hope to do with this type of measurement was to maintain fixed sample conditions and interpret the decay times only in a relative way. The use of a high recombination surface such as a sand-blasted one seems attractive since the sensitivity to variation of s is small for $s \geq 10^4$ (see Figure 38). However, sandblasting the sample surface reduces the sensitivity to too large a degree to be tolerated. For this reason we standardized on the Monsanto polished surface for our photoconductive lifetime samples. The post diffusion samples must have the p-n junction removed before the measurements can be made; this was done with a brief etch in CP4.

An interesting treatment of surface recombination for higher resistivity silicon samples can be found in the reports of Westinghouse contracts²⁵ which ran concurrently with this work.

4.1.5.3 Solar Cell Evaluation Results

All the data for individual solar cells and summaries of the averages and standard deviations are given in Appendix II and III. Data relating the sample number, polish, dopants, and resistivity are also included. The following sections treat the solar cell results in several related groups.

Phosphorus-Diffused Boron-Doped Silicon with Secondary Impurities- Table 27 includes the efficiency, short circuit current and fill factor results along with their standard deviations for Fz and Cz samples with secondary impurities which either leave the solar cell unchanged or show some potential for improving its performances. It is useful to consider the I_{sc} along with the efficiency since it is possible to have small variations in fill factor that

Table 27. SOLAR CELLS EXHIBITING POSSIBLE IMPROVEMENT
WITH THE ADDITION OF SECONDARY IMPURITIES

Material - Czochralski and Float Zone
Polish - Single Sided
Illumination - 100 mW/cm²
Temperature - 27°C
AR Coating - None
Drift Field Contact - None

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Sample	Dopant		Sec Imp Conc (atoms x 10 ¹⁶)	Eff (%)	ISC/A (mA/cm ²)	Fill Factor
	Pri	Sec				
M1A	B	None	---	9.25 ± 0.24*	20.66 ± 0.22	0.774 ± 0.018
M1B	B	None	---	9.23 ± 0.25	19.88 ± 0.30	0.777 ± 0.017
M3B	B	Mn	0.15	9.74 ± 0.06	20.56 ± 0.03	0.797 ± 0.003
M4B	B	Ni	1.5	9.60 ± 0.11	20.65 ± 0.08	0.790 ± 0.006
M4B1	B	Ni	0.62	9.51 ± 0.20	20.52 ± 0.13	0.784 ± 0.019
M7B	B	Mg	0.01	9.69 ± 0.17	20.82 ± 0.14	0.787 ± 0.013
M9B	B	C	3.1	8.32 ± 0.69	19.28 ± 0.97	0.748 ± 0.047
M9B1	B	C	---	8.75 ± 0.33	19.89 ± 0.16	0.757 ± 0.025
M10B	B	Al	40.	9.32 ± 0.25	20.31 ± 0.08	0.779 ± 0.018
M11B	B	Ni/Mn/Mg	---	9.38 ± 0.63	20.84 ± 0.11	0.762 ± 0.045
M15B1	B	Na	0.03	9.40 ± 0.38	20.87 ± 0.23	0.763 ± 0.026
C1A	B	None	---	8.41 ± 0.24	19.90 ± 0.18	0.736 ± 0.021
C2A	B	C	7.4	8.76 ± 0.32	19.76 ± 0.23	0.764 ± 0.024
C2B	B	C	6.7	8.78 ± 0.38	19.92 ± 0.10	0.762 ± 0.032
C2B1	B	C	10.	8.56 ± 0.27	20.21 ± 0.16	0.733 ± 0.023
C4B	B	Cr		8.94 ± 0.19	19.63 ± 0.10	0.791 ± 0.013
C5B	B	Mn	1.2	7.73 ± 0.34	18.74 ± 0.09	0.723 ± 0.027
C6B	B	Ni	7.1	8.89 ± 0.27	19.70 ± 0.22	0.780 ± 0.023
C9B	B	Mg	0.01	9.15 ± 0.42	20.87 ± 0.16	0.768 ± 0.032
C9B1	B	Mg	0.12	8.50 ± 0.37	19.37 ± 0.12	0.762 ± 0.030
C10B	B	Al	830.	2.74 ± 0.17	7.58 ± 0.32	0.729 ± 0.034
C10B1	B	Al	200.	4.23 ± 0.74	11.95 ± 0.06	0.669 ± 0.107
C12B	B	C/Ni	---	7.95 ± 0.44	19.51 ± 0.04	0.708 ± 0.035

* Quantities listed after the ± sign are the standard
deviations for these measurements.

affect the efficiency more than the I_{sc} . If both show the same trend, one has more confidence in the results. Also, the I_{sc} tends to have a smaller standard deviation and this may give a better measure of how small a change is significant.

All of the samples considered in this section are boron doped with resistivities between 0.15 and 1.6 ohm cm, and all but seven have resistivities between 0.4 and 0.6 ohm-cm.

Comparing the entries in Table 27 for the baseline samples, i.e., those with boron doping only, we see that the Fz solar cells are somewhat better than the samples. This will be discussed further in a later section. For Mon-X crystals M1B was taken as the baseline crystal. M1A is higher in resistivity, giving it a higher I_{sc} and power V_{oc} but essentially the same efficiency.

Before going further with this discussion it might be well to warn the reader that all the improvements in efficiency etc. to be discussed in the next few paragraphs are small enough (i.e. on the order of the standard deviation of a single set of data) that they would have to be considered marginally significant when viewed as comparison of two sets of data only. More significance is added to the data when the same results occur a number of times, so that it is felt that these results have some real meaning. However, there may not be general agreement on this subject so that the reader may wish to conclude at this point that these impurities simply cannot be tolerated in the concentrations noted without degrading solar cell performance.

Carbon is a secondary impurity of interest, since it has direct bearing on processes such as ribbon growth that use carbon components in contact with the melt. It is interesting to note that two of the three carbon-doped Cz samples showed a small, probably significant improvement compared to baseline samples. In contrast, both carbon-doped Fz samples showed small but probably significant decreases in efficiency, even though the carbon concentrations in the Cz samples were larger than in the Fz crystals. Thus, the behavior of carbon in Fz and Cz crystals seems really different. One might suspect that the carbon interacts with the oxygen in Cz samples since this is the principal difference between the two different types of crystals, and somehow improves the quality of the resultant solar cell. The impurities Ni, Mn, Mg, Cr and Al also seem to improve the solar cells slightly if they are not present in too high a quantity. It is interesting to note that in each case in which the efficiency improved, the fill factor improved. This could be interpreted to mean that series resistance improved a small amount in each case. Alternatively, it could mean that the generation-recombination contribution or

other less ideal diode term decreased slightly. At present it is not possible to determine exactly which of these possibilities is more likely, but if the latter were the case, it might be worthwhile to pursue this type of investigation further.

Tables 28 and 29 contain efficiency and short circuit current data for solar cells fabricated from the boron-doped Cz and Fz samples. We see that the secondary impurities Fe, V, Zr, Ti, C, Cr, Mn and Al can reduce the efficiency of the solar cell. This is accompanied by a reduction in short circuit current, indicating that the lifetime in these solar cells is shorter than that in the baseline samples. These data are combined with the analytical results of impurity concentration in a later section of this report to estimate the tolerance limit for each impurity.

Phosphorus-Diffused Aluminum-Doped Silicon - The solar cell results for phosphorus diffused aluminum-containing silicon solar cells are listed in Table 30 along with the baseline data. The only case in which the presence of aluminum does not degrade the cell performance is for sample M10B, which has a small quantity of Al along with the usual boron doping. In all other cases, including those samples doped only with aluminum, the efficiency is lower than that of the corresponding baseline samples.

From the analytical data it seems that much of the aluminum present is not in the usual acceptor site. This "electrically inactive" aluminum could be present as precipitates or agglomerates or perhaps associated with the oxygen in the crystal forming a defect that degrades the lifetime. In any case it seems that aluminum-doped Si will not produce solar cells that are intrinsically better than boron-doped ones.

Boron-Diffused Phosphorus-Doped Silicon with Secondary Impurities - In considering the tolerance of silicon solar cells to the presence of impurities there is no a priori reason why one would expect P/N and N/P cells to have the same degree of tolerance for all impurities. In fact one might assume that an impurity could exhibit a different charge state in N and P type material because of the large difference in the position of the Fermi level and therefore affect the performance of the solar cell in a different manner. For this reason a number of samples of phosphorus-doped material containing secondary impurities were boron-diffused and fabricated into solar cells. These data are summarized in Tables 31 and 32.

The first pertinent observation of this data might be that none of the efficiencies are as high as the best observed when the diffusion was optimized (see Table 24). The reason for this is not understood at the present. The diffusion was optimized using wafers from a silicon crystal different from any of those reported

Table 28. RESULTS FOR SOLAR CELLS FABRICATED FROM PHOSPHORUS-DIFFUSED, BORON-DOPED FLOAT-ZONE SILICON WAFERS

MATERIAL - MON-X (FLOAT ZONE)
 POLISH - SINGLE SIDED
 ILLUMINATION - 100 MW/CM²
 TEMPERATURE - 27 C
 AR COATING - NONE
 DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		RHO	VOC	ISC/A	EFF	FF
	PRI	SEC	OHM-CM	VOLTS	MA/CM ²	%	
M1A	B	NONE	1.060	0.578	20.663	9.250	0.774
M1B	B	NONE	0.150	0.598	19.885	9.235	0.777
M2B1	B	FE	0.380	0.581	19.341	8.926	0.794
M2B2	B	FC	0.400	0.570	18.410	0.107	0.768
M3B	B	MN	0.440	0.595	20.562	9.747	0.797
M4B	B	NI	0.590	0.589	20.651	9.609	0.790
M4B1	B	NI	0.500	0.592	20.521	9.513	0.784
M5B	B	V	0.490	0.551	14.996	6.416	0.776
M5B1	B	V	0.480	0.537	13.917	5.793	0.774
M6B	B	ZR	0.480	0.582	19.795	8.940	0.776
M7B	B	MG	0.450	0.592	20.823	9.694	0.787
M8B	B	TI	0.490	0.521	13.382	3.938	0.565
M8B1	B	TI	0.490	0.519	13.168	4.810	0.707
M9B	B	C	0.480	0.577	19.289	8.320	0.748
M9B1	B	C	0.460	0.581	19.892	8.752	0.757
M10B	B	AL	0.370	0.589	20.313	9.323	0.779
M11B	B	NI/MN/MG	0.490	0.590	20.843	9.380	0.762
M15B	B	NA	0.480	0.586	20.980	9.112	0.742
M15B1	B	NA	0.460	0.591	20.872	9.406	0.763
M16B	B	P COMP	0.420	0.588	20.476	9.269	0.770
M31B	B	CU	0.470	0.585	20.879	8.914	0.729
M32B	B	CR	0.470	0.578	19.509	8.180	0.725

Table 29. RESULTS FOR SOLAR CELLS FABRICATED FROM PHOSPHORUS-DIFFUSED, BORON-DOPED CZOCHRALSKI SILICON WAFERS

MATERIAL - CZOCHRALSKI
 POLISH - SINGLE SIDED
 ILLUMINATION - 100 MW/CM²
 TEMPERATURE - 27 C
 AR COATING - NONE
 DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		RHO	VOC	ISC/A	EFF	FF
	PRI	SEC	OHM-CM	VOLTS	MA/CM ²	%	
C1A	B	NONE	0.550	0.575	19.900	8.412	0.736
C2A	B	C	0.530	0.581	19.767	8.767	0.764
C2B	B	C	0.550	0.578	19.922	8.783	0.762
C2B1	B	C	0.440	0.578	20.217	8.562	0.733
C3A	B	FE	0.490	0.558	19.012	7.294	0.687
C4B	B	CR	0.550	0.576	19.629	8.941	0.791
C5B	B	MN	0.470	0.570	18.745	7.734	0.723
C6B	B	NI	0.530	0.579	19.702	8.896	0.780
C7B	B	V	0.555	0.526	14.303	5.156	0.683
C8B	B	ZR	0.630	0.570	19.419	7.764	0.701
C8B1	B	ZR	0.570	0.570	19.338	7.273	0.660
C9B	B	MG	1.600	0.571	20.874	9.150	0.768
C9B1	B	MG	0.530	0.576	19.378	8.509	0.762
C10B	B	AL	0.152	0.497	7.581	2.746	0.729
C10B1	B	AL	0.215	0.528	11.953	4.231	0.669
C11B	B	TI	0.540	0.505	10.808	2.564	0.469
C11B1	B	TI	0.560	0.512	11.734	4.426	0.737
C12B	B	C/NI	0.550	0.575	19.519	7.952	0.708
C15B	B	NA	0.570	0.574	19.727	8.449	0.745
C16B	B	P-COMP	0.470	0.576	19.492	8.295	0.738
C16B1	B	P-COMP	0.180	0.573	19.096	7.779	0.711

Table 30. RESULTS FOR SOLAR CELLS FABRICATED FROM SILICON CONTAINING ALUMINUM

MATERIAL - CZ AND MON-X
POLISH - SINGLE SIDED
ILLUMINATION - 100 MW/CM²
TEMPERATURE - 27 C
AR COATING - NONE
DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		RHO	VOC	ISC/A	EFF	FF
	PRI	SEC	OHM-CM	VOLTS	MA/CM ²	%	
C1A	B	NONE	0.550	0.575	19.900	8.412	0.736
C10B	B	AL	0.152	0.497	7.581	2.746	0.729
C10B1	B	AL	0.215	0.528	11.953	4.231	0.669
M1B	B	NONE	0.150	0.598	19.885	9.235	0.777
M10B	B	AL	0.370	0.589	20.313	9.323	0.779
M19B		AL ONLY	0.310	0.579	18.996	8.299	0.755
M19B1		AL ONLY	1.850	0.564	20.760	8.586	0.733
M19B2		AL ONLY	0.540	0.581	20.357	8.337	0.705

Table 31. RESULTS FOR SOLAR CELLS FABRICATED FROM BORON DIFFUSED, PHOSPHORUS DOPED FLOAT-ZONE SILICON WAFERS

MATERIAL - MON-X (FLOAT ZONE)
POLISH - SINGLE SIDED
ILLUMINATION - 100 MW/CM²
TEMPERATURE - 27 C
AR COATING - NONE
DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		RHO	VOC	ISC/A	EFF	FF
	PRI	SEC	OHM-CM	VOLTS	MA/CM ²	%	
M13A	P	NONE	0.750	0.562	20.187	8.605	0.758
M13B	P	NONE	0.460	0.568	19.738	8.213	0.733
M13C	P	NONE	0.270	0.571	19.969	8.629	0.757
M14B	P	C	0.440	0.570	20.315	8.942	0.773
M14B1	P	C	0.110	0.556	18.412	7.735	0.756
M17B	P	TI	0.540	0.557	18.581	7.704	0.745

Table 32. RESULTS FOR SOLAR CELLS FABRICATED FROM BORON-DIFFUSED, PHOSPHORUS-DOPED CZOCHRALSKI SILICON WAFERS

MATERIAL - CZOCHRALSKI
POLISH - SINGLE SIDED
ILLUMINATION - 100 MW/CM²
TEMPERATURE - 27 C
AR COATING - NONE
DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		RHO	VOC	ISC/A	EFF	FF
	PRI	SEC	OHM-CM	VOLTS	MA/CM ²	%	
C13A	P	NONE	1.050	0.568	20.708	8.761	0.745
C13B	P	NONE	0.170	0.581	20.224	8.640	0.735
C14A	P	C	0.126	0.545	19.622	6.137	0.567
C14A1	P	C	0.126	0.577	20.049	8.473	0.732
C14A2	P	C	0.080	0.584	19.259	8.229	0.731
C17B	P	TI	0.600	0.548	18.363	6.914	0.687

in Table 31 or 32, but of the same dopant and resistivity range. More likely the changes are related to some unintentional process change that occurred between the optimization and the running of the actual samples of interest.

The most important consideration in all this is that one should not conclude that P/N cells are inherently less efficient than N/P cells. We have produced P/N cells of 9.4% efficiency in the optimization studies. This efficiency is essentially equivalent to that of the best N/P cells we have produced. The problems with the boron diffusion mentioned above do not hamper our efforts to determine the effects of secondary impurities, since performance relative to baseline solar cells is the important feature.

Again the effect of carbon is small. There is some evidence of the possibility of improving the behavior of Fz material by adding carbon but none for any improvement of the Cz. This would be a reversal of the behavior observed with boron-doped silicon. This evidence is too meager to form any real conviction and would have verified by further work.

The evidence here seems to indicate that phosphorus-doped silicon may have a somewhat higher tolerance for Ti as compared to boron-doped Si. This will be dealt with further when the tolerance is estimated in a later section.

Solar Cell Results for Si with Low Base Resistivities - Solar cells were fabricated from a few samples with resistivities less than 0.1 ohm cm. These results are given in Table 33. In general, the deleterious effects of higher carrier concentrations masked the effects of any secondary impurities. The poor efficiency of sample C1C with respect to C2C is caused by a low fill factor. This is probably not a basic problem of solar cell behavior since the short circuit currents are almost identical, but it may indicate a fabrication difficulty.

This data does emphasize that too much B or P in the silicon can be just as bad as the presence of a secondary impurity. This also will be treated further in the section where tolerance levels are estimated.

Table 33. RESULTS FOR SOLAR CELLS FABRICATED FROM HEAVILY DOPED SILICON

			MATERIAL - CZ AND MON-X POLISH - SINGLE SIDED ILLUMINATION - 100 MW/CM ² TEMPERATURE - 27 C AR COATING - NONE DRIFT FIELD CONTACT - NONE				
SAMPLE	DOPANT		RHO	VOC	ISC/A	EFF	FF
-----	PRI	SEC	OHM-CM	VOLTS	MA/CM ²	%	---
C1C	B	NONE	0.015	0.225	9.467	0.848	0.391
C2C	B	C	0.016	0.550	9.471	3.340	0.639
C13C	P	NONE	0.011	0.413	13.347	3.150	0.572
M1C	B	NONE	0.040	0.584	17.696	7.105	0.687
M2C	B	FE	0.060	0.585	17.205	7.174	0.713

Comparison of Double-Side-Polished with Single-Side-Polished Wafers - At the outset of this work it was anticipated that the fabrication procedures, processing, etc. could play a significant role in the behavior of impurities and the manner in which they affect solar cell performance. It was also suspected that "gettering" might play a similar important role. In addition, a sawed surface is known to be a good "gettering" agent. Thus, it was decided to fabricate solar cells from a representative set of wafers that were polished on both sides for comparison with cells fabricated from wafers polished on one side with the second side remaining as a sawed surface.

The results of this experiment are summarized in Table 34. The detailed data are given in Appendix III. It is evident that this set of experiments turned out to be a verification of the reproducibility of the diffusions and fabrication processes rather than a study of gettering. Ratios of the other parameters also averaged close to unity, with somewhat larger standard deviations scaled roughly according to the standard deviations of the individual parameters.

Comparison of Results Using Float-Zone and Czochralski Silicon - Study of the results of the phosphorus diffused solar cells fabricated from Cz and Fz silicon given in Tables 27, 28, and 29 makes it obvious that the cells fabricated from Fz silicon are in general more efficient than those fabricated from Cz silicon. If the averages for the improved Fz and Cz samples listed in Table 27 are compared, one obtains 9.45% and 8.94%, respectively. Similar comparisons can be made from the data contained in the other two tables, but one must use more care in the comparison since the secondary impurity concentration in corresponding samples may not be the same.

The principal difference in the impurity content between the two types is that Cz crystals have about 100 times more oxygen and about 3 times more carbon than the Fz crystals. One is tempted to put the blame on the oxygen, since it is really present in much larger quantities in the Cz crystal. However, it is not certain that one can separate the effects of these two impurities since carbon seems to improve Cz crystals and degrade Fz crystals. Thus, the resultant differences are very similar at a level of 3 to 6×10^{16} atoms carbon/cc. Therefore, it is not possible to conclude definitely whether the carbon or the oxygen is to blame for the difference in performance.

In the case of the phosphorus-doped, boron-diffused wafers, it is not obvious from the data available, given in Tables 31 and 32 that there is a difference between Cz and Fz crystals. Further study would be necessary to confirm this finding. If it should be confirmed, it would be an important factor to consider in deciding what kind of crystal growth and device fabrication process to consider for low-cost solar cells.

Table 34. COMPARISON OF I_{sc} FOR SINGLE- AND DOUBLE-SIDE-POLISHED WAFERS

Type of Crystal	No. of Runs	Avg $\left(\frac{I_{sc} \text{ Single Side}}{I_{sc} \text{ Double Side}} \right)$	Std. Dev.
Float-Zone			
B doped	16	0.987	0.014
P doped	5	0.993	0.013
Czochralski			
B doped	11	1.022*	0.111*
P doped	6	1.001	0.024

* One sample, C16B1, had a ratio of 1.35. Without this sample the average ratio would be 0.989 ± 0.024 .

Table 35. COMPARISON BETWEEN FLOAT-ZONE AND CZOCHRALSKI

	Float-Zone	Czochralski
Average Fill Factor	0.750	0.695
Average of Std. Dev. of FF	0.043	0.043
Average Std. Dev. of Eff	0.344	0.463
Average Std. Dev. of I_{sc}	0.282	0.179
Average Std. Dev. of V_{oc}	0.0038	0.0095

There has been a vague feeling in this work that Fz silicon is a little easier to contact or fabricate than Cz silicon. This has been very hard to quantify, however. One attempt is contained in Table 35. One might expect that if the above were true, that the fill factor, or the standard deviations of the cell properties would be different. Although there are some differences in these quantities as given in Table 35, they are not large enough or consistent enough to be convincing. Thus, we have no direct evidence that there is a difference between Cz and Fz in terms of ease of fabrication.

4.1.5.4 Minority Carrier Lifetime Results

Measurements of the minority carrier lifetime have been carried out by the photoconductive decay method before (τ_{PDB}) and after (τ_{PDA}) diffusion and using the open circuit decay method (τ_{OCD}) on the fabricated solar cells. These have been carried out on both boron- and phosphorus-doped Fz and Cz material and are discussed below.

Minority Carrier Lifetime for Boron Doped Silicon - Minority carrier lifetimes measured by photoconductive decay both before and after diffusion and by the open circuit decay technique after diffusion are listed in Tables 36 and 37 for Fz and Cz crystals. The lifetimes designated $< 0.5\mu\text{sec}$ are those that show some modulation but that have decay constants between $0.5\mu\text{sec}$ and that of the light source (about $0.2\mu\text{sec}$). The "dash" entries in the table indicate no modulation for the photoconductive decay measurements and a nonstandard decay for the open-circuit decay measurements. Since the magnitude of the modulation is proportional to the lifetime for these short-lifetime samples, the lifetime for these samples is almost certainly considerably smaller than $0.5\mu\text{sec}$.

Samples C1C and C2C should be considered separately since they are much more heavily boron doped than the other samples. This accounts for the low lifetimes observed. Similarly M1C and M2C are considerably lower in resistivity than the other crystals so that the observed lifetimes are low for that reason.

From the data in these two tables it can be definitely concluded that the minority carrier lifetime for silicon with Fe, Cr, and Mn as the secondary impurity, increases after the wafers are diffused. This is evidence for some kind of rearrangement, precipitation, or gettering that occurs during the diffusion process. The data are particularly clear for sample M2B1 where the lifetime increases by more than fourfold after diffusion.

It is much more difficult to try to ascertain in more detail what is occurring for these three impurities. All three have been found to have deep donor levels associated with them.²⁶ However, the diffusion coefficients are so high that the impurities are

mobile at room temperature and the donor levels are only observed in quenched samples.²⁷ In addition, it has been established that these three elements form pairs with boron and other acceptors with sufficient binding energy that no unassociated ions exist in an equilibrium at room temperature for samples which contain an excess of acceptor impurities.²⁸ Since these samples are slow-cooled after crystal growth, diffusion, and heat treatment, one would expect that approximately room temperature equilibrium conditions prevail in the samples at all steps in the process. These samples contain roughly 10 times more boron than iron, so all the iron should be paired with boron. Under these conditions there is no obvious reason that the lifetime should increase after diffusion. However, the lifetime does change, so something additional must be occurring. This line of reasoning has been pursued to show that even when we have some information about the complex behavior of these impurities in silicon, the explanation of their observed behavior may require knowledge and information we do not yet possess.

The changes in minority carrier lifetime after diffusion for the other samples are smaller and generally indicate a decrease in lifetimes. As long as the final lifetime is over a microsecond or two, these changes will have only a small effect on the solar cell performance.

Lifetimes were also measured for the double-side-polished wafers. One fairly consistent observation is that the open circuit decay lifetimes were lower than those observed for single-side-polished wafers. This general lowering trend was not reflected, however, in the photoconductive decay measurements for the double-sided wafers after diffusion. These results were not significantly different from those for single-sided wafers. Thus it seems likely that the open circuit decay measurements for the double-sided wafers are somehow affected, perhaps by different contact properties of the back surface, relative to measurements on the single-sided wafers.

Minority Carrier Lifetime for Phosphorus-Doped Silicon - Table 38 lists the lifetimes determined for the N-type samples. Sample Cl3C has a much lower resistivity than the rest, which accounts for the low lifetimes observed for this sample. We note that in general, the lifetimes are higher than those observed for the P-type samples. At least part of this longer lifetime must be due to lower doping level required to obtain 0.5 ohm cm material in N-type material compared to P-type because of the higher mobility. In addition the surface recombination may be lower for this material.

After diffusion the photoconductive measurements show some decrease in lifetime but the open circuit decay values are much lower. This is reminiscent of similar phenomena discussed in the last section. Again it is possible that the contacting may be

Table 36. MINORITY CARRIER LIFETIME RESULTS FOR BORON-DOPED
FLOAT-ZONE CRYSTALS

Sample	Secondary Impurity	Minority Carrier Lifetime(μ sec)			Solar Cell Efficiency (%)
		Photoconductive Decay		Open Circuit Devices	
		Before Diff.	After Diff.		
M1A	---	3.4	2.6	6.1	9.25
M1B	---	4.6	2.3	2.4	9.24
M1C	---	---	---	0.4	7.10
M2B1	Fe	0.5	2.6	2.3	8.93
M2B2	Fe	<0.5	1.4	1.1	8.11
M2C	Fe	---	---	0.4	7.17
M3B	Mn	---	2.8	5.1	9.75
M4B	Ni	4.2	2.7	4.6	9.61
M4B1	Ni	4.3	3.6	4.3	9.51
M5B	V	<0.5	<0.5	0.3	6.42
M5B1	V	<0.5	<0.5	0.4	5.79
M6B	Zr	4.0	2.6	2.4	8.94
M7B	Mg	4.0	2.9	4.6	9.69
M8B	Ti	<0.5	<0.5	---	3.94
M8B1	Ti	<0.5	<0.5	---	4.81
M9B	C	4.6	2.3	2.5	8.32
M9B1	C	2.8	2.8	2.9	8.75
M10B	Al	3.2	1.5	2.9	9.32
M11B	Ni/Mn/Mg	---	3.8	4.1	9.38
M15B	Na	3.9	3.2	2.7	9.11
M15B1	Na	3.7	2.6	4.1	9.41
M16B	P-comp	3.6	4.5	3.8	9.27
M19B	Al only	1.4	1.7	1.2	8.30
M19B1	Al only	3.1	2.9	4.7	8.59
M19B2	Al only	2.6	1.4	1.4	8.33
M31B	Cu	4.0	2.6	3.9	8.91
M32B	C	---	1.6	1.3	8.18

NOTE: All dashed entries indicate no modulation visible (lifetime almost certainly very small) or open circuit decay has non-standard shape (again very short lifetime).

Table 37. MINORITY CARRIER LIFETIME RESULTS
FOR BORON-DOPED CZOCHRALSKI CRYSTALS

Sample	Secondary Impurity	Minority Carrier Lifetime (μ sec)		Open Circuit Devices	Solar Cell Efficiency (%)
		Photoconductive Decay Before Diff.	Photoconductive Decay After Diff.		
C1A	--	2.9	1.9	1.4	8.41
C1C	--	<0.5	<0.5	0.1	.67
C2A	C	3.7	3.2	2.2	8.77
C2B	C	3.1	3.2	2.5	8.78
C2B1	C	3.7	2.4	1.7	8.56
C2C	C	--	<0.5	0.4	3.34
C3A	Fe	<0.5	<0.5	0.7	7.29
C4B	Cr	--	<0.5	1.8	8.94
C5B	Mn	<0.5	1.1	0.6	7.73
C6B	Ni	3.2	2.3	2.5	8.90
C7B	V	<0.5	<0.5	0.3	5.16
C8B	Zr	3.5	1.9	1.4	7.76
C9B	Mg	3.2	2.9	4.0	9.15
C9B1	Mg	3.2	2.8	1.3	8.51
C8B1	Zr	2.9	1.0	1.1	7.72
C10B	Al	--	<0.5	0.2	2.75
C10B1	Al	--	--	0.4	4.23
C11B	Ti	<0.5	<0.5	--	2.56
C11B1	Ti	<0.5	<0.5	--	4.43
C12B	C/Ni	2.9	2.0	1.4	7.95
C15B	Na	2.8	1.4	1.7	8.45
C16B	P-comp	3.5	1.7	1.0	8.29
C16B1	P-comp	<0.5	1.6	0.9	7.78

Note: All dashed entries indicate no modulation visible (lifetime almost certainly very small) or open circuit decay has nonstandard shape (again very short lifetime).

different for these devices. For example, for samples containing Ti as the secondary impurity, the efficiency and short circuit are noticeably reduced, but not to the extent observed for the boron-doped crystals. This will be confirmed when we estimate the tolerance of N- and P-type silicon to Ti.

Table 38. MINORITY CARRIER LIFETIME RESULTS
FOR PHOSPHORUS DOPED SILICON

Sample	Secondary Impurity	Minority Carrier Lifetime (μ sec)			Solar Cells Efficiency (%)
		Photoconductivity Decay		Open Circuit Devices	
		Before Diff.	After Diff.		
M13A	--	9.1	4.6	1.3	8.61
M13B	--	7.2	6.0	1.0	8.21
M13C	--	10.5	4.2	0.8	8.63
M14B	C	7.2	4.8	1.3	8.48
M14B1	C	7.2	3.8	0.8	7.74
M17B	Ti	2.1	1.4	0.8	7.70
C13A	--	10	3.2	1.2	8.76
C13B	--	12	7.2	0.8	8.64
C13C	--	--	--	0.4	3.15
C14A	C	12	2.4	0.4	6.14
C14A1	C	12	7.2	0.6	8.47
C14A2	C	10.1	4.3	0.6	8.23
C17B	Ti	0.9	0.8	0.4	6.91

Note: All dashed entries indicate no modulation visible (lifetime almost certainly very small) or open circuit decay has nonstandard shape (again very short lifetime).

Correlation of Efficiency and Short Circuit Current with Lifetime - There are probably few people who would doubt that there is a correlation between lifetime and efficiency or short circuit current, but we will pursue it a little to see how our data fits a specific model for the relationship. We will concentrate on the open circuit decay measurements on the solar cells themselves since it turns out that these data exhibit less scatter.

Figures 39 and 40 show the solar cell efficiency and the short circuit current plotted as a function of the square root of the open circuit decay lifetime. Both Fz and Cz data are included in this curve. A regular dependence is 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 Fz and Cz crystals.

Figure 39. Efficiency vs. $\sqrt{\tau}$ for float-zone Czochralski silicon. Efficiency measured without AR coating.

Figure 40. Short circuit current density vs. $\sqrt{\tau}$ for float-zone Czochralski silicon. I_{sc} measured without AR coating.

To see if a very simplified model can explain the observed behavior let us first assume that the behavior of a solar cell with minority carriers having a single effective diffusion length or lifetime can be represented. 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 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:

$$\frac{1}{\tau_C} = \frac{1}{\tau} + \frac{1}{\tau_L} \quad (7)$$

or

$$\tau_C = \frac{\tau}{1 + \tau/\tau_L} \quad (8)$$

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:

$$L_C = \sqrt{D} \sqrt{\frac{\tau}{1 + \tau/\tau_L}} \quad (9)$$

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

$$\text{Eff} = A \sqrt{\frac{\tau}{1 + \tau/\tau_L}} \quad (10)$$

The solid lines on Figures 39 and 40 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 Cz 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 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 by²⁹

$$\frac{1}{\tau} = \sigma v_{th} N = N\sigma \quad 1.168 \times 10^7 \sqrt{\frac{T}{300^\circ\text{K}}} \sqrt{\frac{M}{M_{eff}}} \quad (11)$$

$$\text{or} \quad \sigma = \frac{1}{\tau N 2.7 \times 10^7} \quad (12)$$

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 geometric²⁹ value of $\sim 10^{-15}$. 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. If this were attained, it would provide a basis for extrapolating results to different impurity concentrations.

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

4.1.5.5 Estimation of Tolerable Impurity Concentration

The main goal of all this work is the determination of the concentration of various impurities that can be tolerated in silicon and still allow a reasonable solar cell to be fabricated from it. We have a considerable amount of experimental data on efficiencies that can be obtained with certain silicon wafers on the concentrations of impurities in these wafers. However, we do not have a

convenient method to compare all this information on an equal basis. We need to be able to answer the question, how much of "X" can silicon contain and still be able to be fabricated into a 10% (or some other fixed value) efficient solar cell. The following will provide one way to carry out this comparison.

Equation (10) can be rewritten as:

$$\text{Eff} = 12.58 \sqrt{\frac{1}{\frac{1}{\tau} + 1.621}} \quad (13)$$

We can express τ as

$$\frac{1}{\tau} = \frac{1}{\tau_{BL}} + \frac{1}{\tau_{SI}} \quad (14)$$

where τ_{BL} is the lifetime for the baseline sample and τ_{SI} is the lifetime representative of the secondary impurity. In addition let us assume that τ_{SI} can be related to the number of secondary impurities, N_{SI} by

$$\frac{1}{\tau_{SI}} = BN_{SI} \quad (15)$$

where B is a constant of proportionality. Now we can rewrite equation (13) as

$$\text{Eff} = 12.58 \sqrt{\frac{1}{BN_{SI} + \frac{1}{\tau_{BL}} + 1.621}} \quad (16)$$

Now with solar cell information for baseline silicon we can find an effective value for τ_{BL} by solving equation (16) with $N_{SI} = 0$. We can calculate the constant B for a certain secondary impurity using appropriate solar cell data and a measurement or estimate of the concentration of that secondary impurity. Let us decide that we would like to know what concentration of secondary impurity would yield 10% efficiency (~7.52% without AR coating) on this model. This can be found by substituting 7.52 for the left hand side of equation (16) and solving for N_{SI} (10%):

$$N_{SI}(10\%) = \frac{1}{B} \left(1.177 - \frac{1}{\tau_{BL}} \right) \quad (17)$$

It must be admitted that some of the above assumptions may not be true for all secondary impurities. However, at present we do not have any better information and this formality at least gives a way of treating all our data on a more or less equal basis.

The above calculation has been applied to all our experimental data and the results are displayed as a bar graph in Figures 41 and 42. In cases for which the impurity was not detected by SSMS, the detection limit was used in the calculation. The impurity level which would yield a 10% (with AR coating) efficient cell is represented by data points on these curves for all impurities which were found to decrease the impurity level. The impurity level present for those impurities that leave the cell performance unchanged, or which improve it, are plotted directly.

The results for the Ti-doped samples are fairly well established, since the solar cells were very measurably degraded with the Ti was detected by SSMS in one of the four samples. The permissible concentration for Ti is very likely in the mid- 10^{13} /cc range.

The results for the secondary impurity V are quite believable, since the solar cells were definitely degraded and V was detected by SSMS in two samples. The permissible concentration is around 10^{14} atoms/cc and if one believes the data explicitly, the Fz samples may have a slightly higher tolerance than the Cz samples.

The interpretation of the results for Na are very uncertain. Even though Na was detected by SSMS in these crystals, it was also detected in the non-Na-doped crystals at about the same level. It could be that this is roughly the saturation concentration of Na in Si. It is also possible that the Na detected is an artifact of the analytical method. The efficiencies of the "Na doped" solar cells turn out to be not very different from the baseline samples. If the Na detected by the SSMS is related to real Na in Si, then the mid 10^{15} atom/cc range is a tolerable level, but this interpretation is subject to some doubt.

The concentration of Mg was measurable by SSMS for one of the Cz samples, and the solar cell performance was not degraded at that level. The Mg concentrations was below the detection limit for the Fz cells, which seemed to be improved by the presence of the Mg. Thus a little more than 10^{15} atoms/cc seems to be about the tolerance level for Mg in Si based on SSMS results. Based on the segregation coefficient, the concentrations would be about three orders of magnitude higher, so if these coefficients are correct the tolerance limits must be appropriately adjusted.

The Zr-doped samples degrade the cells somewhat, but this impurity was undetected by SSMS. Furthermore, there are no estimates available for the segregation coefficient. In this case then, the

Figure 41. Permissible secondary impurity concentrations for a 10% efficient solar cell fabricated by phosphorus diffusion into 0.5 ohm cm boron-doped silicon.

Figure 42. Permissible secondary impurity concentrations for a 10% efficient solar cell fabricated by boron diffusion into 0.5 ohm cm phosphorus-doped silicon.

limits shown in Figure 41 are upper limits for the tolerable concentration and the permissible levels must be below 10^{14} atoms/cc. Lacking better information, one might assume that the tolerable concentration may be about the same as for Ti.

Cu was not detected by SSMS and seemed to degrade the solar cell performance slightly, so the permissible level must be below 10^{15} atoms/cc. Again, if the segregation coefficient estimate of concentration is correct, the tolerable level may be 100 times greater.

Iron was present at a level detectable by SSMS in the Cz sample and the solar cells were noticeably degraded. Therefore, the permissible concentration is probably about 10^{15} atoms/cc.

The Cr level was measurable by SSMS in the Fz sample and the solar cells were degraded. Therefore the tolerable Cr level is very likely in the mid 10^{15} atoms/cc range.

In a similar manner the Mn concentration was measurable by SSMS for the Cz sample and the solar cell was degraded. These measurements lead to a tolerable level of about 10^{16} atoms/cc.

The presence of Ni in every case slightly improved the solar cell performance, and the concentration was determinable by SSMS. Therefore the levels shown are lower estimates to the tolerable concentrations which may be in the mid 10^{16} atom/cc range.

The tolerance to boron was calculated from the heavily doped samples. In this case the resistivity of the Si was lowered and the efficiency became smaller also. The Fz samples seemed to be able to tolerate about 10^{17} atoms/cc boron, while the permissible level for Cz silicon may be about 10 times smaller. These limits may need to be 4 or 5 times higher if we calibrate against resistivity values.

Carbon behaves differently in Fz and Cz silicon as discussed earlier. This leads to the conclusion that Cz silicon has a permissible level somewhat greater than 10^{17} atoms/cc while the value for Fz is less than 10^{17} atoms/cc.

There is considerable scatter in the data for aluminum-doped silicon, but the permissible level is probably in the mid 10^{17} atom/cc range whether it is considered in combination with boron or as the only dopant.

Titanium was detected by SSMS for the Cz phosphorus-doped crystal, and the tolerance level is in the mid 10^{14} atom/cc range, about 10 times greater tolerance than exhibited by boron-doped silicon.

Phosphorus can be tolerated to nearly the 10^{17} atom/cc level in N-type material. The level is about the same for Fz and Cz in contrast to the differences observed for boron in P-type crystals.

Permissible levels of carbon are in the mid 10^{17} atom/cc range for N-type silicon, which may be a little higher than for boron-doped Si.

5. GENERAL CONCLUSIONS AND RECOMMENDATIONS

The results of our work leave little doubt that the manufacture of solar silicon must meet purity requirements that are not much different from those established for semiconductor silicon. This should not be surprising. The solar cell is, after all, very much a semiconductor device.

In fact, it seems that the presently slightly more expensive float zone (Fz) method of preparing single crystal silicon may be preferred over the more generally used Czochralski (Cz) method. Fz silicon contains about 1 to 2 orders of magnitude fewer impurities, particularly less oxygen and carbon. In our work baseline Fz material (boron-doped only) devices were about 12% more efficient than equivalent baseline Cz devices, and Fz devices made with material containing secondary impurities were, on the average, about 18% more efficient than the equivalent Cz devices. The difference in efficiency was related to differences in the fill factor of the devices measured. Now, the fill factor (FF) is influenced significantly by the quality of the metal-silicon contact, and the Fz devices showed an 8% higher FF than the Cz cells. Therefore it may be concluded that this difference in performance is related to the difference in the oxygen and the carbon content in the two types of crystal. Auger electron spectroscopy results show that indeed TiO_2 and TiC are formed at the interface between the silicon and the Ti-Ag metal contacts.

Mass spectrometry was found to be the best analytical tool for the determination of trace elements in the ppm and the ppb range, albeit a lack of standards hampered the generation of absolute data in some cases. Some discrepancies remained unresolved at the end of the contract but were related mostly to difficulties in sample taking. The results, in general, were meaningful and were confirmed by sample exchange with other laboratories. Infrared absorption proved of limited use in the determination of trace elements in silicon mainly because of the low resistivity (~ 0.5 ohm cm) of the experimental crystals. Emission spectroscopy, the third analytical tool applied, also found limited use only because of lack of sensitivity for many of the elements under investigation as stated above. Auger electron spectroscopy, on the other hand, was found highly useful and successful in contributing a first step to the solution to the age old problem of poor contact adherence in silicon solar cells.

The minority carrier lifetime measurements indicate that lifetime and device efficiency are closely related and that quality changes do occur during the diffusion and processing steps for silicon containing certain impurities; hence, some of the results obtained are process dependent. For example, the minority carrier lifetime was found to increase during the diffusion step in silicon containing Fe, Cr and Mn.

The effects of the following impurities in silicon on solar cell performance were investigated.

Al, C, Cr, Cu, Fe, Mg, Mn, Na, Ni, O, Ti, V, Zr

Solar cell efficiency was found to be degraded in various degrees by most of these elements. Specifically, the permissible impurity concentrations in silicon that allow the preparation of 10% efficient solar cells are estimated as follows:

Table 39. PERMISSIBLE IMPURITY CONCENTRATION

Impurity	In Czochralski for P-on-N Cells	In Float Zone Si for P-on-N Cells
	(10^{15} atoms/cm ³ silicon)	(10^{15} atoms/cm ³ silicon)
Ti	0.04	0.02
V	0.1	0.2
Na	0.2	0.3
Mg	1.0	0.1
Zr	0.1	2.0
Cu		1.5
Cr		5.0
Fe	1.2	6.0
Mn	12.0	2.0
Ni	7.0	20.0
B	6.0	100.0
C	80.0	80.0
Al	150.0	50.0

<u>For N-on-P Cells</u>		
Impurity	In Czochralski for N-on-P Cells	In Float Zone Si for N-on-P Cells
	(10^{15} atoms/cm ³ silicon)	(10^{15} atoms/cm ³ silicon)
Ti	0.2	0.15
P	100.0	60.0
C	300.0	500.0

Surprisingly, degradation of solar cell efficiency was greatest for V and Ti, and the least for Ni. In fact, both Fz and Cz solar cells with relatively high concentrations of Ni as secondary impurity had a somewhat higher efficiency than solar cells made with baseline materials. Typical concentration levels and the corresponding solar cell efficiencies are given for these particular impurities for Czochralski and float-zone grown crystals as follows for 0.5 ohm-cm boron-doped silicon:

Czochralski grown crystals:

<u>Impurity</u>	<u>Concentration (atoms/cc)</u>	<u>Efficiency (%)</u>
Baseline	none	8.4
V	7×10^{14}	5.2
Ti	3.6×10^{14}	3.4
C	1×10^{16}	8.8
Ni	7×10^{17}	8.9

Float Zone grown crystals:

Baseline	none	9.3
V	5×10^{14}	5.8
Ti	1.1×10^{14}	4.4
C	3×10^{16}	8.8
Ni	1.5×10^{16}	9.6

The presence of oxygen - approximately 10^{18} atoms/cm³ in Czochralski silicon and $< 10^{16}$ atoms/cm³ in float zone material - seems to affect the fill factor, which was found to average 8% higher in devices made with low-oxygen float zone crystal. One explanation could be reduced TiC and TiO₂ formation under the metal-silicon contacts on the low-oxygen material, which also contains only about 4.4×10^{15} atoms/cm³ versus 2.2×10^{16} atoms/cm³ in Cz silicon. Auger electron spectroscopy results point in that direction.

Further inquiry is recommended for a more complete understanding of the effects of impurities on solar cell performance, including the following:

- (1) Effects of processing on silicon materials.
- (2) Effects of oxygen on impurities in silicon.
- (3) More precise measurement of impurities in the ppba region.

- (4) More work on the effects of impurities on N base materials.
- (5) Extension of work to silicon crystals with multiple impurities.

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APPENDIX I

CLEANING SOLUTIONS AND ETCHES

HF Dip 10%

1800 ml H₂O
200 ml HF (48%)
Room Temp.

Triton Solution

3 ml Triton-X 100
1 ml Formaldehyde
4.55 liters H₂O
Room Temp.

A-Bath

950 ml H₂O
150 ml NH₄OH
Heat to 70°C
Add 150 ml H₂O₂ (30%)
Re-heat to 70°C to 80°C
Immerse wafers for 10 min.

B-Bath

900 ml H₂O
150 ml HCl
Heat to 70°C
Add 150 ml H₂O₂ (30%)
Re-heat to 70°C to 80°C
Immerse wafers for 10 min.

Process

10% HF
H₂O rinse
Triton scrub
H₂O rinse
A-Bath
H₂O rinse
B-Bath
H₂O rinse

CP4 Etch

210 ml HF (48%)
350 ml HNO₃
210 ml CH₃COOH
Immerse wafers 20 to 30 sec
Room Temp.

H₂O₂ - NH₄OH Solution

500 ml H₂O₂
500 ml NH₄OH
Room Temp.
Immerse wafers for 3 min.

Siler Etch

200 ml Fe(NO₃)₃
400 ml H₂O
Immerse wafers 30 to 60 sec
Room Temp.

Ti Etch

60 ml HCl (30%)
30 ml NH₄F (40%)
150 cc H₂O
Room Temp.
Immerse wafers 4 to 6 sec

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APPENDIX II

SOLAR CELL DATA SUMMARY

MATERIAL - CZOCHRALSKI
 POLISH - SINGLE SIDED
 ILLUMINATION - 100 MW/CM²
 TEMPERATURE - 27 C
 AR COATING - NONE
 DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		RHO	VOC	ISC/A	EFF	FF
	PRI	SEC	OHM-CM	VOLTS	MA/CM ²	%	
C1A	B	NONE	0.550	0.575	19.900	8.412	0.736
C1C	B	NONE	0.015	0.225	9.467	0.848	0.391
C2A	B	C	0.530	0.581	19.767	8.767	0.764
C2B	B	C	0.550	0.578	19.922	8.783	0.762
C2B1	B	C	0.440	0.578	20.217	8.562	0.733
C2C	B	C	0.016	0.550	9.471	3.340	0.639
C3A	B	FE	0.490	0.558	19.012	7.294	0.687
C4B	B	CR	0.550	0.576	19.629	8.941	0.791
C5B	B	MN	0.470	0.570	18.745	7.734	0.723
C6B	B	NI	0.530	0.579	19.702	8.896	0.780
C7B	B	V	0.555	0.526	14.303	5.156	0.683
C8B	B	ZR	0.630	0.570	19.419	7.764	0.701
C8B1	B	ZR	0.570	0.570	19.338	7.273	0.660
C9B	B	MG	1.600	0.571	20.874	9.150	0.768
C9B1	B	MG	0.530	0.576	19.378	8.509	0.762
C10B	B	AL	0.152	0.497	7.581	2.746	0.729
C10B1	B	AL	0.215	0.528	11.953	4.231	0.669
C11B	B	TI	0.540	0.505	10.808	2.564	0.469
C11B1	B	TI	0.560	0.512	11.734	4.426	0.737
C12B	B	C/NI	0.550	0.575	19.519	7.952	0.708
C13A	P	NONE	1.050	0.568	20.708	8.761	0.745
C13B	P	NONE	0.170	0.581	20.224	8.640	0.735
C13C	P	NONE	0.011	0.413	13.347	3.150	0.572
C14A	P	C	0.126	0.545	19.622	6.137	0.567
C14A1	P	C	0.126	0.577	20.049	8.473	0.732
C14A2	P	C	0.080	0.584	19.259	8.229	0.731
C15B	B	NA	0.570	0.574	19.727	8.449	0.745
C16B	B	P-COMP	0.470	0.576	19.492	8.295	0.738
C16B1	B	P-COMP	0.180	0.573	19.096	7.779	0.711
C17B	P	TI	0.600	0.548	18.363	6.914	0.687

MATERIAL - CZOCHRALSKI
 POLISH - DOUBLE-SIDED
 ILLUMINATION - 100 MW/CM²
 TEMPERATURE - 27 C
 AR COATING - NONE
 DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		RHO	VOC	ISC/A	EFF	FF
	PRI	SEC	OHM-CM	VOLTS	MA/CM ²	%	
C1A	B	NONE	0.550	0.578	20.037	8.658	0.748
C2B1	B	C	0.440	0.582	19.943	8.767	0.755
C3A	B	FE	0.490	0.574	19.176	8.430	0.766
C4B	B	CR	0.550	0.576	19.542	8.513	0.757
C5B	B	MN	0.470	0.574	19.103	8.233	0.751
C6B	B	NI	0.530	0.577	19.863	8.460	0.739
C7B	B	V	0.555	0.535	14.284	5.747	0.751
C8B1	B	ZR	0.570	0.575	19.271	8.118	0.733
C9B1	B	MG	0.530	0.578	19.930	8.577	0.744
C10B	B	AL ONLY	0.152	0.494	8.144	2.794	0.694
C10B1	B	AL	0.215	0.529	11.788	4.234	0.677
C11B1	B	TI	0.560	0.507	11.904	4.597	0.761
C12B	B	C/NI	0.550	0.578	19.406	8.462	0.755
C13A	P	NONE	1.050	0.565	20.807	8.630	0.735
C13B	P	NONE	0.170	0.579	19.860	8.748	0.761
C13C	P	NONE	0.011	0.528	13.304	4.280	0.608
C14A	P	C	0.126	0.587	20.120	8.431	0.714
C14A1	P	C	0.126	0.575	19.527	7.380	0.653
C15B	B	NA	0.570	0.576	20.053	8.768	0.759
C16B1	B	P-COMP	0.180	0.563	14.097	5.466	0.688
C17B	P	TI	0.600	0.554	18.309	7.385	0.728

MATERIAL - CZOCHRALSKI
 POLISH - SINGLE SIDED
 ILLUMINATION - 100 MW/CM²
 TEMPERATURE - 27 C
 AR COATING - NONE
 DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		VOC	ISC/A	EFF	FF
	PRI	SEC	SIGMA	SIGMA	SIGMA	SIGMA
C1A	B	NONE	0.002	0.189	0.243	0.021
C1C	B	NONE	0.093	0.286	0.424	0.031
C2A	B	C	0.002	0.238	0.326	0.024
C2B	B	C	0.002	0.104	0.386	0.032
C2B1	B	C	0.002	0.165	0.279	0.023
C2C	B	C	0.009	0.482	0.498	0.071
C3A	B	FE	0.017	0.129	0.855	0.069
C4B	B	CR	0.003	0.104	0.192	0.013
C5B	B	MN	0.003	0.093	0.340	0.027
C6B	B	NI	0.003	0.226	0.279	0.023
C7B	B	V	0.009	0.092	0.814	0.095
C8B	B	ZR	0.005	0.041	0.328	0.026
C8B1	B	ZR	0.005	0.080	0.794	0.066
C9B	B	MG	0.003	0.160	0.427	0.032
C9B1	B	MG	0.003	0.127	0.376	0.030
C10A	B	AL	0.007	0.323	0.172	0.034
C10B1	B	AL	0.009	0.060	0.745	0.107
C11B	B	TI	0.003	0.162	0.756	0.135
C11B1	B	TI	0.002	0.071	0.107	0.015
C12B	B	C/NI	0.004	0.044	0.449	0.035
C13A	P	NONE	0.002	0.133	0.364	0.026
C13B	P	NONE	0.003	0.314	0.267	0.017
C13C	P	NONE	0.012	0.120	0.092	0.014
C14A	P	C	0.058	0.170	1.866	0.129
C14A1	P	C	0.006	0.272	0.376	0.030
C14A2	P	C	0.002	0.162	0.483	0.044
C15B	B	NA	0.004	0.132	0.427	0.033
C16B	B	P-COMP	0.003	0.153	0.287	0.022
C16B1	B	P-COMP	0.004	0.127	0.464	0.038
C17B	P	TI	0.005	0.149	0.483	0.041

MATERIAL - CZOCHRALSKI
 POLISH - DOUBLE SIDED
 ILLUMINATION - 100 MW/CM²
 TEMPERATURE - 27 C
 AR COATING - NONE
 DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		VOC	ISC/A	EFF	FF
	PRI	SEC	SIGMA	SIGMA	SIGMA	SIGMA
C1A	B	NONE	0.004	0.194	0.354	0.026
C2B1	B	C	0.001	0.109	0.205	0.015
C3A	B	FE	0.003	0.111	0.406	0.034
C4B	B	CR	0.003	0.123	0.436	0.035
C5B	B	MN	0.002	0.123	0.359	0.031
C6B	B	NI	0.002	0.042	0.478	0.041
C7B	B	V	0.003	0.136	0.420	0.048
C8B1	B	ZR	0.002	0.091	0.520	0.046
C9B1	B	MG	0.002	0.095	0.517	0.041
C10B	B	AL ONLY	0.008	0.233	0.254	0.053
C10B1	B	AL	0.011	0.173	0.781	0.111
C11B1	B	TI	0.003	0.067	0.164	0.024
C12B	B	C/NI	0.003	0.145	0.514	0.042
C13A	P	NONE	0.001	0.343	0.155	0.019
C13B	P	NONE	0.007	0.203	0.212	0.017
C13C	P	NONE	0.025	0.076	0.400	0.037
C14A	P	C	0.004	0.138	0.496	0.039
C14A1	P	C	0.020	0.292	1.833	0.143
C15B	B	NA	0.002	0.095	0.238	0.019
C16B1	B	P-COMP	0.007	0.252	0.717	0.078
C17B	P	TI	0.003	0.239	0.260	0.028

MATERIAL - MON-X (FLOAT ZONE)
 POLISH - SINGLE SIDED
 ILLUMINATION - 100 MW/CM²
 TEMPERATURE - 27 C
 AR COATING - NONE
 DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		RHO	VOC	ISC/R	EFF	FF
	FRI	SEC	OHM-CM	VOLTS	MA/CM ²	%	
M1A	B	NONE	1.060	0.578	20.663	9.250	0.774
M1B	B	NONE	0.150	0.598	19.885	9.235	0.777
M1C	B	NONE	0.040	0.584	17.698	7.105	0.687
M2B1	B	FE	0.380	0.581	19.341	8.926	0.794
M2B2	B	FE	0.480	0.573	18.418	8.107	0.768
M2C	B	FE	0.060	0.585	17.205	7.174	0.713
M3B	B	MN	0.440	0.595	20.562	9.747	0.797
M4B	B	NI	0.590	0.589	20.651	9.609	0.790
M4B1	B	NI	0.500	0.592	20.521	9.513	0.784
M5B	B	V	0.490	0.551	14.996	6.416	0.776
M5B1	B	V	0.480	0.537	13.917	5.793	0.774
M6B	B	ZR	0.480	0.582	19.795	8.940	0.776
M7B	B	MG	0.450	0.592	20.823	9.694	0.787
M8B	B	TI	0.490	0.521	13.382	3.938	0.565
M8B1	B	TI	0.490	0.519	13.168	4.810	0.707
M9B	B	C	0.480	0.577	19.289	8.320	0.748
M9B1	B	C	0.460	0.581	19.892	8.752	0.757
M10B	B	AL	0.370	0.589	20.313	9.323	0.779
M11B	B	NI/MN/MG	0.490	0.590	20.843	9.380	0.762
M13A	P	NONE	0.750	0.562	20.187	8.605	0.758
M13B	P	NONE	0.460	0.568	19.738	8.213	0.733
M13C	P	NONE	0.270	0.571	19.969	8.629	0.757
M14B	P	C	0.440	0.570	20.315	8.942	0.773
M14B1	P	C	0.440	0.556	18.412	7.735	0.756
M15B	B	NA	0.480	0.586	20.980	9.112	0.742
M15B1	B	NA	0.460	0.591	20.872	9.406	0.763
M16B	B	P COMP	0.420	0.588	20.476	9.269	0.770
M17B	P	TI	0.540	0.557	18.581	7.704	0.745
M19B		AL ONLY	0.310	0.579	18.996	8.299	0.755
M19B1		AL ONLY	1.850	0.564	20.760	8.506	0.733
M19B2		AL ONLY	0.540	0.581	20.357	8.337	0.705
M31B	B	CU	0.470	0.585	20.879	8.914	0.729
M32B	B	CR	0.470	0.578	19.509	8.180	0.725

MATERIAL - MON-X (FLOAT ZONE)
 POLISH - DOUBLE SIDED
 ILLUMINATION - 100 MW/CM²
 TEMPERATURE - 27 C
 AR COATING - NONE
 DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		RHO	VOC	ISC/A	EFF	FF
	PRI	SEC	OHM-CM	VOLTS	MA/CM ²	%	---
M1B	B	NONE	0.150	0.596	20.650	9.498	0.772
M2B2	B	FE	0.480	0.571	18.723	8.193	0.765
M3B	B	MN	0.440	0.588	20.960	9.308	0.755
M4B1	B	NI	0.500	0.584	21.066	8.882	0.722
M5B1	B	V	0.480	0.526	14.337	5.958	0.794
M6B	B	ZR	0.480	0.581	20.044	8.547	0.733
M7B	B	MG	0.450	0.584	20.850	9.047	0.742
M8B	B	TI	0.490	0.526	13.582	5.296	0.741
M9B1	B	C	0.460	0.573	19.792	8.631	0.760
M10B	B	AL	0.370	0.579	20.648	8.074	0.674
M11B	B	NI/MN/MG	0.490	0.585	21.044	9.013	0.732
M13A	P	NONE	0.750	0.562	20.204	7.972	0.702
M13B	P	NONE	0.460	0.564	19.806	7.617	0.681
M13C	P	NONE	0.270	0.566	19.730	6.983	0.625
M14B	P	C	0.440	0.568	20.474	8.796	0.756
M15B	B	NA	0.480	0.589	20.795	8.744	0.714
M15B1	B	NA	0.460	0.585	20.955	8.474	0.691
M16B	B	P COMP	0.420	0.589	21.020	9.221	0.744
M17B	P	TI	0.540	0.556	19.123	7.833	0.737
M19B1		AL ONLY	1.850	0.570	20.960	8.863	0.741
M31B	B	CU	0.470	0.590	20.798	9.404	0.767
M32B	B	CR	0.470	0.576	19.393	8.138	0.728

MATERIAL - MON-X (FLOAT ZONE)
 POLISH - SINGLE SIDED
 ILLUMINATION - 100 MW/CM²
 TEMPERATURE - 27 C
 AR COATING - NONE
 DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		WOC	ISC/A	EFF	FF
	PRI	SEC	SIGMA	SIGMA	SIGMA	SIGMA
M1A	B	NONE	0.003	0.222	0.242	0.018
M1B	B	NONE	0.003	0.300	0.258	0.017
M1C	B	NONE	0.006	0.166	0.639	0.055
M2B1	B	FE	0.003	0.089	0.097	0.005
M2B2	B	FE	0.003	0.060	0.258	0.021
M2C	B	FE	0.005	0.859	0.384	0.029
M3B	B	MN	0.002	0.039	0.066	0.003
M4B	B	NI	0.003	0.085	0.112	0.006
M4B1	B	NI	0.002	0.136	0.205	0.019
M5B	B	V	0.002	0.120	0.159	0.015
M5B1	B	V	0.004	0.755	0.374	0.014
M6B	B	ZR	0.003	0.315	0.355	0.028
M7B	B	MG	0.002	0.141	0.173	0.013
M8B	B	TI	0.002	0.208	0.216	0.033
M8B1	B	TI	0.003	0.978	0.247	0.070
M9B	B	C	0.013	0.971	0.693	0.047
M9B1	B	C	0.004	0.166	0.333	0.025
M10B	B	AL	0.004	0.083	0.258	0.018
M11B	B	NI/MN/MG	0.004	0.112	0.633	0.045
M13A	P	NONE	0.002	0.064	0.216	0.018
M13B	P	NONE	0.003	0.345	0.479	0.046
M13C	P	NONE	0.004	0.430	0.203	0.014
M14B	P	C	0.003	0.132	0.112	0.013
M14B1	P	C	0.005	0.258	0.212	0.013
M15B	B	NA	0.007	0.394	0.299	0.029
M15B1	B	NA	0.003	0.233	0.381	0.026
M16B	B	P COMP	0.005	0.147	0.391	0.029
M17B	P	TI	0.002	0.192	0.197	0.023
M19B		AL ONLY	0.003	0.249	0.528	0.043
M19B1		AL ONLY	0.002	0.089	0.342	0.026
M19B2		AL ONLY	0.004	0.447	0.587	0.042
M31B	B	CU	0.007	0.377	0.856	0.060
M32B	B	CR	0.005	0.133	0.837	0.066

MATERIAL - MON-X (FLOAT ZONE)
 POLISH - DOUBLE SIDED
 ILLUMINATION - 100 MW/CM²
 TEMPERATURE - 27 C
 AR COATING - NONE
 DRIFT FIELD CONTACT - NONE

SAMPLE	DOPANT		VOC	ISC/A	EFF	FF
	PRI	SEC	SIGMA	SIGMA	SIGMA	SIGMA
M1B	B	NONE	0.001	0.109	0.183	0.014
M2B2	B	FE	0.004	0.480	0.542	0.034
M3B	B	MN	0.002	0.178	0.509	0.036
M4B1	B	NI	0.005	0.181	0.544	0.037
M5B1	B	V	0.030	0.312	0.244	0.065
M6B	B	ZR	0.004	0.142	0.880	0.071
M7B	B	MG	0.006	0.249	0.691	0.045
M8B	A	TI	0.003	0.035	0.176	0.026
M9B1	B	C	0.009	0.761	0.673	0.048
M10B	B	AL	0.013	0.169	1.744	0.137
M11B	B	NI/MN/MG	0.005	0.310	0.787	0.058
M13A	P	NONE	0.004	0.279	0.497	0.040
M13B	P	NONE	0.010	0.062	1.238	0.102
M13C	P	NONE	0.007	0.145	0.759	0.060
M14B	P	C	0.003	0.331	0.253	0.011
M15B	B	NA	0.003	0.070	0.616	0.047
M15B1	B	NA	0.004	0.136	0.726	0.054
M16B	B	P COMP	0.001	0.291	0.410	0.029
M17B	P	TI	0.003	0.082	0.369	0.031
M19B1		AL ONLY	0.006	0.118	0.990	0.075
M31B	B	CU	0.003	0.093	0.332	0.026
M32B	B	CR	0.004	0.101	0.733	0.062

APPENDIX III

DATA ON SOLAR CELLS FABRICATED DURING FINAL QUARTER

This appendix contains the detailed solar cell data collected since the third 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 [C = Czochralski, M = Mon-X (float zone)].
- Single-Sided = Polished on one side.
- Secondary Dopant = C: Carbon is the secondary impurity.
- Resistivity = 0.55: Silicon resistivity in ohm cm.
- Control Percentage = 96: Relative efficiency (%) of baseline silicon run with this diffusion to the expected value for baseline silicon.

Abbreviations:

VOC = Open circuit voltage, volts.

ISC = Short circuit current density, mA/cm².

VM = Voltage at maximum power point, volts.

IM = Current at maximum power point, mA.

EFF = Solar cell efficiency, %.

FF = Fill factor.

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

TOC = Lifetime, microseconds, from open circuit decay measurement.

TPC = Photoconductive decay lifetime, microseconds, before diffusion.

C1A
SINGLE-SIDED
SECONDARY DOPANT = NONE
RESISTIVITY = 0.55
CONTROL PERCENTAGE = 96

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	----	----	----	----	----	----	----	----
0.573	19.62	0.474	70.24	8.32	0.740	0.160	1.3	2.9
0.577	19.84	0.475	72.00	8.55	0.747	0.180	1.4	2.9
0.573	20.00	0.485	67.54	8.19	0.715	0.160	1.5	2.9
0.573	19.78	0.478	71.38	8.53	0.753	0.160	1.4	2.9
0.575	19.81	0.476	69.59	8.28	0.727	0.160	1.4	2.9
0.576	19.76	0.484	67.55	8.17	0.718	0.200	1.4	2.9
0.575	20.01	0.476	73.56	8.75	0.761	0.180	1.5	2.9
0.572	20.01	0.457	70.43	8.05	0.703	0.180	1.4	2.9
0.578	20.30	0.481	70.98	8.54	0.727	0.200	1.6	2.9
0.574	19.86	0.481	72.62	8.73	0.766	0.160	1.5	2.9
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

0.0020	0.1895	0.0079	1.983	0.243	0.0210	0.0165	0.08	0.00
0.575	19.90	0.477	70.59	8.41	0.736	0.174	1.4	2.9

C1A
DOUBLE-SIDED
SECONDARY DOPANT = NONE
RESISTIVITY = 0.55
CONTROL PERCENTAGE = 108

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	----	----	----	----	----	----	----	----
0.573	19.95	0.471	68.87	8.11	0.709	0.400	1.0	2.2
0.580	20.20	0.492	69.30	8.52	0.738	0.220	1.2	2.2
0.581	20.11	0.484	74.59	9.03	0.772	0.300	1.1	2.2
0.573	19.94	0.472	71.46	8.43	0.738	1.000	1.2	2.2
0.574	20.06	0.476	70.06	8.34	0.724	1.200	1.1	2.2
0.582	20.13	0.488	75.66	9.23	0.788	0.600	1.2	2.2
0.582	20.36	0.491	72.51	8.90	0.751	0.480	1.2	2.2
0.577	19.69	0.480	72.90	8.75	0.770	0.800	1.2	2.2
0.577	19.90	0.477	72.23	8.61	0.750	0.720	1.2	2.2
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
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0037	0.1936	0.0079	2.301	0.354	0.0256	0.3263	0.07	0.00
0.578	20.04	0.481	71.95	8.66	0.748	0.636	1.2	2.2

C1C
 SINGLE-SIDED
 SECONDARY DOPANT = NONE
 RESISTIVITY = 0.015
 CONTROL PERCENTAGE = 100

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

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

C2A
 SINGLE-SIDED
 SECONDARY DOPANT = C
 RESISTIVITY = 0.53
 CONTROL PERCENTAGE = 100

VOC	ISC/A	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

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

C2B
 SINGLE-SIDED
 SECONDARY DOPANT = C
 RESISTIVITY = 0.55
 CONTROL PERCENTAGE = 97

VOC	ISC/A	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

C2B1
 SINGLE SIDED
 SECONDARY DOPANT = C
 RESISTIVITY = 0.44
 CONTROL PERCENTAGE = 100

VOC	ISC/H	VM	IM	EFF	FF	RS	TOC	TPC
0.576	20.26	0.492	72.69	8.94	0.766	0.180	1.8	3.7
0.578	20.20	0.482	68.40	8.24	0.706	0.100	1.7	3.7
0.578	20.18	0.485	69.15	8.38	0.719	0.200	1.7	3.7
0.577	20.24	0.474	68.25	8.09	0.692	0.170	1.7	3.7
0.581	20.37	0.491	71.95	8.83	0.746	0.160	1.9	3.7
0.578	20.42	0.489	70.93	8.67	0.735	0.190	1.7	0.0
0.578	20.32	0.485	71.55	8.68	0.739	0.180	1.6	3.7
0.575	19.86	0.490	69.48	8.51	0.745	0.180	1.7	3.7
0.577	20.10	0.489	71.26	8.71	0.751	0.200	1.8	3.7
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

0.0017	0.1650	0.0057	1.621	0.279	0.0234	0.0132	0.09	1.23
0.578	20.22	0.486	70.41	8.56	0.733	0.183	1.7	3.3

C2B1
DOUBLE-SIDED
SECONDARY DOPANT = C
RESISTIVITY = 0.44
CONTROL PERCENTAGE = 105

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.584	20.06	0.492	72.58	8.93	0.762	0.820	1.2	2.9
0.580	19.92	0.487	71.70	8.73	0.756	0.400	1.2	2.9
0.582	19.98	0.462	72.67	8.39	0.722	2.000	1.2	2.9
0.582	20.11	0.491	73.21	8.99	0.768	1.000	1.2	2.9
0.582	19.83	0.468	72.53	8.49	0.735	2.000	1.2	2.9
0.580	19.78	0.475	72.23	8.58	0.748	2.200	1.2	2.9
0.584	20.02	0.483	74.09	8.95	0.765	0.500	1.1	2.9
0.583	19.89	0.483	72.33	8.73	0.753	1.900	1.2	2.9
0.583	19.86	0.489	73.24	8.95	0.773	0.280	1.1	2.9
0.584	20.06	0.489	72.95	8.92	0.761	0.400	1.2	2.9
0.583	19.87	0.481	73.06	8.79	0.758	1.100	1.2	2.9
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

0.0014	0.1091	0.0098	0.633	0.205	0.0150	0.7449	0.04	0.00
0.582	19.94	0.482	72.78	8.77	0.755	1.145	1.2	2.9

C2C
SINGLE-SIDED
SECONDARY DOPANT = C
RESISTIVITY = 0.016
CONTROL PERCENTAGE = 79

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

C3A
 SINGLE-SIDED
 SECONDARY DOPANT = FE
 RESISTIVITY = 0.49
 CONTROL PERCENTAGE = 96

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.552	18.79	0.439	62.70	6.88	0.663	0.220	0.7	0.0
0.532	19.11	0.419	63.77	6.68	0.657	0.220	0.4	0.0
0.572	19.03	0.486	67.52	8.20	0.754	0.200	0.9	0.0
0.566	19.10	0.470	55.10	6.47	0.599	0.200	0.7	0.0
0.569	19.03	0.484	68.03	8.23	0.760	0.200	0.8	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

STANDARD DEVIATION AND AVERAGE

0.0165	0.1286	0.0295	5.194	0.855	0.0690	0.0110	0.19	0.00
0.558	19.01	0.460	63.42	7.29	0.687	0.208	0.7	0.0

C3A
 DOUBLE-SIDED
 SECONDARY DOPANT = FE
 RESISTIVITY = 0.49
 CONTROL PERCENTAGE = 108

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.576	19.08	0.487	71.13	8.66	0.788	0.240	0.9	0.0
0.571	19.35	0.474	71.34	8.45	0.765	0.200	1.0	0.0
0.576	19.16	0.487	71.71	8.73	0.791	0.200	1.0	0.0
0.573	19.20	0.480	71.30	8.56	0.778	0.200	0.9	0.0
0.570	19.08	0.475	69.17	8.21	0.755	0.280	0.9	0.0
0.576	19.26	0.482	71.46	8.61	0.776	0.500	0.9	0.0
0.575	19.02	0.483	70.71	8.54	0.781	0.220	1.0	0.0
0.570	19.11	0.455	63.43	7.22	0.663	0.860	0.8	0.0
0.578	19.31	0.479	71.44	8.55	0.766	0.300	1.2	0.0
0.580	19.33	0.486	71.43	8.68	0.774	0.240	1.2	0.0
0.573	19.11	0.475	71.92	8.54	0.780	0.600	0.9	0.0
0.571	19.11	0.468	71.88	8.41	0.771	0.480	0.9	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0033	0.1113	0.0092	2.365	0.406	0.0339	0.2082	0.12	0.00
0.574	19.18	0.478	70.58	8.43	0.766	0.360	1.0	0.0

C4B
 SINGLE-SIDED
 SECONDARY DOPANT = CR
 RESISTIVITY = 0.55
 CONTROL PERCENTAGE = 100

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
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	0.0065	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

C4B
 DOUBLE-SIDED
 SECONDARY DOPANT = CR
 RESISTIVITY = 0.55
 CONTROL PERCENTAGE = 111

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.577	19.65	0.495	72.55	8.98	0.792	0.200	0.8	1.2
0.574	19.43	0.484	66.08	8.00	0.717	0.400	0.7	1.2
0.570	19.47	0.485	66.13	8.02	0.722	0.280	0.7	1.2
0.579	19.58	0.495	72.04	8.91	0.787	0.220	0.8	1.2
0.577	19.66	0.495	72.44	8.96	0.790	0.240	0.8	1.2
0.577	19.72	0.488	68.96	8.41	0.740	0.220	0.7	1.2
0.578	19.34	0.492	71.40	8.78	0.786	0.260	0.8	1.2
0.576	19.49	0.487	70.77	8.62	0.768	0.260	0.8	1.2
0.573	19.56	0.488	65.05	7.94	0.708	0.200	0.8	1.2
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
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0028	0.1227	0.0044	3.016	0.436	0.0347	0.0616	0.05	0.00
0.576	19.54	0.490	69.49	8.51	0.757	0.253	0.8	1.2

C5B
SINGLE-SIDED
SECONDARY DOPANT = MN
RESISTIVITY = 0.47
CONTROL PERCENTAGE = 96

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
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0.572	18.81	0.481	66.66	8.02	0.745	0.180	0.7	0.0
0.568	18.77	0.472	62.33	7.35	0.690	0.200	0.6	0.0
0.571	18.71	0.486	64.56	7.84	0.734	0.200	0.8	0.0
0.568	18.68	0.468	61.58	7.20	0.679	0.200	0.6	0.0
0.569	18.95	0.465	69.04	8.03	0.744	0.200	0.8	0.0
0.566	18.66	0.473	62.53	7.39	0.700	0.200	0.5	0.0
0.568	18.62	0.477	62.73	7.48	0.707	0.200	0.6	0.0
0.575	18.75	0.488	68.28	8.33	0.773	0.200	0.6	0.0
0.572	18.66	0.489	64.09	7.84	0.734	0.200	0.6	0.0
0.572	18.80	0.485	64.29	7.80	0.725	0.200	0.6	0.0
0.572	18.80	0.485	64.29	7.80	0.725	0.190	0.7	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	0.0927	0.0084	2.450	0.340	0.0273	0.0065	0.09	0.00
0.570	18.74	0.479	64.58	7.73	0.723	0.197	0.6	0.0

C5B
DOUBLE-SIDED
SECONDARY DOPANT = MN
RESISTIVITY = 0.47
CONTROL PERCENTAGE = 102

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
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0.571	19.21	0.475	68.87	8.18	0.746	0.200	0.9	0.0
0.576	19.01	0.471	68.42	8.06	0.736	0.240	0.9	0.0
0.573	19.30	0.475	70.17	8.33	0.753	0.200	0.9	0.0
0.574	19.11	0.473	66.24	7.83	0.714	0.220	0.8	0.0
0.577	19.15	0.494	71.23	8.80	0.796	0.200	0.9	0.0
0.570	19.25	0.472	66.63	7.86	0.717	0.200	0.8	0.0
0.573	19.00	0.478	64.70	7.73	0.710	0.200	0.7	0.0
0.575	19.09	0.483	70.91	8.56	0.780	0.200	0.8	0.0
0.577	19.00	0.489	70.12	8.57	0.782	0.200	0.9	0.0
0.575	18.92	0.486	69.15	8.40	0.772	0.200	0.8	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

0.0024	0.1235	0.0079	2.162	0.359	0.0312	0.0135	0.07	0.00
0.574	19.10	0.480	68.64	8.23	0.751	0.206	0.8	0.0

C6B
SINGLE-SIDED
SECONDARY DOPANT = NI
RESISTIVITY = 0.53
CONTROL PERCENTAGE = 106

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

C6B
DOUBLE-SIDED
SECONDARY DOPANT = NI
RESISTIVITY = 0.53
CONTROL PERCENTAGE = 74

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.575	19.89	0.469	69.27	8.12	0.710	0.200	1.4	0.0
0.578	19.83	0.483	72.86	8.80	0.767	0.220	1.6	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

0.0021	0.0424	0.0099	2.539	0.478	0.0406	0.0141	0.14	0.00
0.577	19.86	0.476	71.07	8.46	0.739	0.210	1.5	0.0

C7B
 SINGLE-SIDED
 SECONDARY DOPANT = V
 RESISTIVITY = 0.555
 CONTROL PERCENTAGE = 101

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.529	14.23	0.441	46.20	5.09	0.677	0.280	0.3	0.5
0.534	14.35	0.455	52.96	6.02	0.786	0.280	0.4	0.5
0.514	14.16	0.410	40.26	4.13	0.567	0.280	0.2	0.5
0.516	14.37	0.400	42.48	4.25	0.573	0.260	0.2	0.5
0.532	14.31	0.438	51.17	5.60	0.736	0.260	0.3	0.5
0.533	14.40	0.454	51.47	5.84	0.761	0.260	0.3	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

0.0090	0.0921	0.0229	5.260	0.814	0.0951	0.0110	0.08	0.00
0.526	14.30	0.433	47.42	5.16	0.683	0.270	0.3	0.5

C7B
 DOUBLE-SIDED
 SECONDARY DOPANT = V
 RESISTIVITY = 0.555
 CONTROL PERCENTAGE = 102

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.536	14.33	0.447	52.94	5.92	0.770	0.440	0.3	0.5
0.538	14.30	0.440	51.36	5.65	0.734	2.400	0.3	0.5
0.532	14.44	0.443	52.29	5.79	0.754	0.240	0.2	0.5
0.540	14.49	0.458	53.14	6.08	0.777	0.320	0.2	0.5
0.537	14.29	0.457	52.71	6.02	0.785	0.320	0.3	0.5
0.535	14.11	0.454	50.71	5.76	0.762	0.280	0.3	0.5
0.532	14.15	0.435	48.30	5.25	0.698	0.800	0.2	0.5
0.533	14.19	0.451	47.95	5.41	0.715	0.360	0.3	0.5
0.538	14.46	0.450	53.82	6.05	0.778	0.320	0.3	0.5
0.535	14.31	0.439	57.72	6.33	0.827	0.480	0.3	0.5
0.538	14.28	0.447	52.76	5.90	0.768	0.400	0.3	0.5
0.531	14.07	0.427	44.99	4.80	0.643	0.400	0.2	0.5
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0029	0.1363	0.0093	3.280	0.420	0.0480	0.5961	0.05	0.00
0.535	14.28	0.446	51.56	5.75	0.751	0.563	0.3	0.5

C8B
 SINGLE-SIDED
 SECONDARY DOPANT = ZR
 RESISTIVITY = 0.63
 CONTROL PERCENTAGE = 98

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.577	19.45	0.472	66.95	7.90	0.704	0.160	1.5	3.5
0.571	19.37	0.478	67.25	8.04	0.727	0.200	1.3	3.5
0.571	19.46	0.483	66.40	8.02	0.722	0.180	1.6	3.5
0.569	19.38	0.479	63.41	7.59	0.689	0.180	1.4	3.5
0.564	19.44	0.462	62.95	7.27	0.663	0.220	1.2	3.5
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
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

0.0047	0.0408	0.0082	2.049	0.328	0.0260	0.0228	0.16	0.00
0.570	19.42	0.475	65.39	7.76	0.701	0.188	1.4	3.5

C8B1
 SINGLE-SIDED
 SECONDARY DOPANT = ZR
 RESISTIVITY = 0.57
 CONTROL PERCENTAGE = 100

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.572	19.24	0.476	62.92	7.49	0.680	0.160	1.2	0.5
0.577	19.44	0.491	69.26	8.50	0.758	0.180	1.7	0.5
0.568	19.32	0.471	60.00	7.07	0.644	0.000	0.0	0.0
0.572	19.34	0.484	63.53	7.69	0.695	0.180	1.3	0.5
0.565	19.42	0.473	53.56	6.33	0.577	0.180	1.1	0.5
0.565	19.27	0.459	57.21	6.56	0.603	0.220	1.0	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

0.0047	0.0799	0.0111	5.459	0.794	0.0657	0.0776	0.57	0.20
0.570	19.34	0.476	61.08	7.27	0.660	0.153	1.1	0.4

C881
 DOUBLE-SIDED
 SECONDARY DOPANT = ZR
 RESISTIVITY = 0.57
 CONTROL PERCENTAGE = 103

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.574	19.46	0.477	71.37	8.51	0.762	0.500	1.0	2.1
0.573	19.29	0.479	60.85	7.29	0.659	0.800	0.8	2.1
0.572	19.19	0.471	70.82	8.34	0.760	0.440	1.0	2.1
0.573	19.24	0.472	64.30	7.59	0.688	2.200	0.9	2.1
0.579	19.18	0.490	70.24	8.60	0.775	0.220	1.0	2.1
0.575	19.32	0.469	69.99	8.21	0.739	0.500	1.1	2.1
0.576	19.31	0.479	64.53	7.73	0.695	0.640	0.9	2.1
0.577	19.20	0.488	71.18	8.68	0.784	0.300	1.1	2.1
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

STANDARD DEVIATION AND AVERAGE

0.0024	0.0909	0.0077	4.057	0.520	0.0459	0.6326	0.10	0.00
0.575	19.27	0.478	67.91	8.12	0.733	0.700	1.0	2.1

C98
 SINGLE-SIDED
 SECONDARY DOPANT = MG
 RESISTIVITY = 1.6
 CONTROL PERCENTAGE = 98

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

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

C9B1
 SINGLE-SIDED
 SECONDARY DOPANT = MG
 RESISTIVITY = 0.53
 CONTROL PERCENTAGE = 91

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	1.3	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

C9B1
 DOUBLE-SIDED
 SECONDARY DOPANT = MG
 RESISTIVITY = 0.53
 CONTROL PERCENTAGE = 100

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.581	19.89	0.487	74.39	9.06	0.784	0.320	1.3	2.9
0.578	20.04	0.483	71.31	8.61	0.743	0.360	1.2	2.9
0.574	19.91	0.478	64.35	7.69	0.673	0.280	1.1	2.9
0.580	20.07	0.490	74.29	9.10	0.782	0.440	1.3	2.9
0.577	19.85	0.481	69.65	8.38	0.731	0.360	1.2	2.9
0.577	19.85	0.482	71.62	8.63	0.754	0.360	1.2	2.9
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

0.0025	0.0951	0.0043	3.710	0.517	0.0409	0.0532	0.08	0.00
0.578	19.93	0.484	70.94	8.58	0.744	0.353	1.2	2.9

C108
SINGLE-SIDED
SECONDARY DOPANT = AL
RESISTIVITY = 0.152
CONTROL PERCENTAGE = 84

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

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

C108
DOUBLE-SIDED
SECONDARY DOPANT = AL ONLY
RESISTIVITY = 0.152
CONTROL PERCENTAGE = 84

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.506	8.39	0.409	29.24	2.99	0.704	0.440	0.1	0.5
0.493	7.73	0.395	27.40	2.71	0.710	0.480	0.1	0.5
0.496	8.15	0.407	28.93	2.94	0.729	0.480	0.1	0.5
0.481	8.27	0.374	26.12	2.44	0.614	0.360	0.2	0.5
0.502	8.43	0.412	30.66	3.16	0.746	0.440	0.1	0.5
0.491	8.17	0.396	26.27	2.60	0.649	0.360	0.3	0.5
0.494	7.84	0.405	27.32	2.77	0.714	0.360	0.1	0.5
0.499	8.09	0.407	29.97	3.05	0.756	0.400	0.1	0.5
0.487	8.24	0.393	25.39	2.49	0.622	0.380	0.2	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

STANDARD DEVIATION AND AVERAGE

0.0076	0.2328	0.0118	1.853	0.254	0.0527	0.0501	0.07	0.00
0.494	8.14	0.400	27.92	2.79	0.694	0.411	0.1	0.5

C10B1
 SINGLE SIDED
 SECONDARY DOPANT = AL
 RESISTIVITY = 0.215
 CONTROL PERCENTAGE = 89

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.523	12.01	0.413	38.19	3.94	0.628	0.280	0.4	0.0
0.534	11.96	0.436	43.64	4.76	0.745	0.280	0.4	0.0
0.535	12.03	0.457	44.29	5.06	0.786	0.260	0.4	0.0
0.512	11.88	0.382	30.74	2.94	0.483	0.280	0.3	0.0
0.530	11.91	0.436	40.82	4.45	0.705	0.280	0.4	0.0
0.531	11.94	0.441	38.48	4.24	0.669	0.260	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

0.0087	0.0600	0.0264	4.923	0.745	0.1069	0.0103	0.04	0.00
0.528	11.95	0.428	39.36	4.23	0.669	0.273	0.4	0.0

C10B1
 DOUBLE-SIDED
 SECONDARY DOPANT = AL
 RESISTIVITY = 0.215
 CONTROL PERCENTAGE = 100

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.539	11.87	0.458	43.32	4.96	0.776	0.300	0.4	0.0
0.537	11.95	0.446	42.90	4.78	0.745	0.400	0.4	0.0
0.536	11.86	0.452	41.90	4.73	0.745	0.420	0.2	0.0
0.505	11.90	0.349	31.46	2.74	0.457	0.360	0.3	0.0
0.527	11.80	0.413	37.60	3.88	0.624	0.400	0.1	0.0
0.523	11.40	0.405	34.78	3.52	0.591	0.420	0.1	0.0
0.532	11.71	0.450	39.89	4.49	0.721	0.360	0.1	0.0
0.533	11.82	0.446	42.67	4.76	0.755	0.400	0.1	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

0.0110	0.1725	0.0370	4.349	0.781	0.1107	0.0406	0.13	0.00
0.529	11.79	0.427	39.32	4.23	0.677	0.383	0.2	0.0

C11B
 SINGLE-SIDED
 SECONDARY DOPANT = TI
 RESISTIVITY = 0.54
 CONTROL PERCENTAGE = 77

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	-----	----	----	-----	-----	----	-----	-----
0.504	10.98	0.245	37.29	2.28	0.413	0.000	0.0	0.0
0.507	10.84	0.230	30.63	1.76	0.321	0.000	0.0	0.0
0.503	10.95	0.297	35.34	2.62	0.477	0.000	0.0	0.0
0.504	11.00	0.358	39.29	3.52	0.634	0.000	0.0	0.0
0.502	10.76	0.222	34.70	1.93	0.356	0.000	0.0	0.0
0.499	10.43	0.204	26.45	1.35	0.259	0.000	0.0	0.0
0.509	10.79	0.381	38.39	3.66	0.666	0.000	0.0	0.0
0.508	10.79	0.299	34.88	2.61	0.476	0.000	0.0	0.0
0.501	10.73	0.349	36.67	3.20	0.595	0.000	0.0	0.0
0.508	10.81	0.303	35.82	2.71	0.494	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

0.0034	0.1623	0.0617	3.815	0.756	0.1352	0.0000	0.00	0.00
0.505	10.81	0.289	34.95	2.56	0.469	0.000	0.0	0.0

C11B1
 SINGLE-SIDED
 SECONDARY DOPANT = TI
 RESISTIVITY = 0.56
 CONTROL PERCENTAGE = 100

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	-----	----	----	-----	-----	----	-----	-----
0.511	11.74	0.430	40.25	4.33	0.721	0.200	0.0	0.0
0.509	11.73	0.435	40.15	4.37	0.731	0.200	0.0	0.0
0.510	11.81	0.427	41.46	4.43	0.735	0.200	0.0	0.0
0.513	11.71	0.433	40.57	4.39	0.731	0.200	0.0	0.0
0.511	11.69	0.415	41.52	4.31	0.721	0.200	0.0	0.0
0.510	11.74	0.426	40.42	4.30	0.719	0.200	0.0	0.0
0.514	11.59	0.436	40.93	4.46	0.749	0.200	0.0	0.0
0.512	11.72	0.428	41.42	4.43	0.739	0.000	0.0	0.0
0.514	11.70	0.434	41.06	4.46	0.741	0.200	0.0	0.0
0.513	11.79	0.435	42.60	4.63	0.766	0.200	0.0	0.0
0.510	11.86	0.430	42.67	4.59	0.758	0.200	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

0.0018	0.0710	0.0060	0.863	0.107	0.0152	0.0603	0.00	0.00
0.512	11.73	0.430	41.19	4.43	0.737	0.182	0.0	0.0

C11B1
 DOUBLE-SIDED
 SECONDARY DOPANT = TI
 RESISTIVITY = 0.56
 CONTROL PERCENTAGE = 103

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.505	11.98	0.429	43.76	4.69	0.776	0.300	0.3	0.5
0.505	11.93	0.432	42.43	4.58	0.761	0.320	0.3	0.5
0.509	11.88	0.429	43.79	4.70	0.777	0.340	0.3	0.5
0.510	11.76	0.438	42.19	4.62	0.770	0.360	0.3	0.5
0.509	11.94	0.433	42.12	4.56	0.750	0.300	0.3	0.5
0.510	11.81	0.434	43.20	4.69	0.778	0.320	0.3	0.5
0.508	11.97	0.427	43.08	4.60	0.757	0.320	0.3	0.5
0.507	11.93	0.435	41.12	4.47	0.739	0.340	0.3	0.5
0.511	11.93	0.431	44.01	4.74	0.778	0.300	0.3	0.5
0.501	11.84	0.421	39.30	4.14	0.697	0.320	0.3	0.5
0.508	11.96	0.431	43.76	4.72	0.776	0.320	0.3	0.5
0.504	11.93	0.428	43.60	4.67	0.776	0.360	0.3	0.5
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0030	0.0673	0.0044	1.384	0.164	0.0238	0.0211	0.00	0.00
0.507	11.90	0.431	42.70	4.60	0.761	0.325	0.3	0.5

C12B
 SINGLE-SIDED
 SECONDARY DOPANT = C/NI
 RESISTIVITY = 0.55
 CONTROL PERCENTAGE = 93

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.575	19.52	0.476	65.87	7.84	0.698	0.180	1.0	0.0
0.577	19.53	0.483	66.14	7.99	0.709	0.180	1.4	0.0
0.579	19.50	0.494	70.07	8.65	0.766	0.180	1.0	0.0
0.579	19.61	0.476	69.33	8.25	0.727	0.180	1.4	0.0
0.570	19.46	0.469	62.54	7.33	0.661	0.180	1.3	0.0
0.571	19.53	0.459	65.33	7.50	0.672	0.200	1.2	0.0
0.576	19.50	0.489	66.33	8.11	0.722	0.190	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
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	0.0440	0.0119	2.528	0.449	0.0354	0.0079	0.18	0.00
0.575	19.52	0.476	66.52	7.95	0.708	0.184	1.2	0.0

C12B
DOUBLE-SIDED
SECONDARY DOPANT = C/NI
RESISTIVITY = 0.55
CONTROL PERCENTAGE = 106

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.581	19.39	0.490	67.81	8.31	0.737	0.260	1.3	3.4
0.574	19.24	0.474	70.13	8.31	0.752	1.800	1.2	3.4
0.576	19.24	0.489	69.95	8.55	0.772	0.240	1.2	3.4
0.579	19.40	0.494	72.03	8.90	0.792	0.180	1.3	3.4
0.576	19.26	0.493	70.86	8.73	0.787	0.200	1.2	3.4
0.577	19.51	0.485	67.73	8.21	0.730	0.180	1.3	3.4
0.578	19.70	0.496	71.74	8.90	0.781	0.180	1.4	3.4
0.575	19.34	0.493	66.02	8.14	0.732	0.200	1.2	3.4
0.582	19.58	0.496	72.39	8.98	0.788	0.200	1.3	3.4
0.573	19.40	0.476	60.63	7.21	0.649	0.180	1.0	3.4
0.582	19.43	0.493	71.80	8.85	0.783	0.240	1.3	3.4
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

STANDARD DEVIATION AND AVERAGE

0.0031	0.1447	0.0076	3.510	0.514	0.0423	0.4814	0.10	0.00
0.578	19.41	0.489	69.19	8.46	0.755	0.351	1.2	3.4

C13A
SINGLE-SIDED
SECONDARY DOPANT = NONE
RESISTIVITY = 1.05
CONTROL PERCENTAGE = 102

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.567	20.64	0.474	72.89	8.64	0.738	0.200	1.2	3.2
0.565	20.45	0.462	70.31	8.12	0.703	0.180	1.2	3.2
0.571	20.66	0.479	76.11	9.11	0.772	0.180	1.1	3.2
0.568	20.58	0.469	75.59	8.86	0.758	0.160	1.2	3.2
0.566	20.67	0.467	73.76	8.61	0.736	0.180	1.1	3.2
0.566	20.73	0.464	71.08	8.25	0.703	0.180	1.2	3.2
0.567	20.82	0.465	75.55	8.78	0.744	0.200	1.2	3.2
0.568	20.81	0.467	76.68	8.95	0.758	0.200	1.2	3.2
0.571	20.85	0.478	77.28	9.23	0.776	0.180	1.2	3.2
0.571	20.87	0.476	76.03	9.05	0.759	0.180	1.2	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

0.0023	0.1332	0.0062	2.486	0.364	0.0256	0.0126	0.04	0.00
0.568	20.71	0.470	74.53	8.76	0.745	0.184	1.2	3.2

C13A
DOUBLE-SIDED
SECONDARY DOPANT = NONE
RESISTIVITY = 1.05
CONTROL PERCENTAGE = 0

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.566	20.34	0.474	72.23	8.56	0.744	0.800	1.0	0.9
0.566	20.82	0.459	74.42	8.54	0.725	2.000	1.0	0.9
0.564	20.69	0.469	75.15	8.81	0.755	0.440	1.2	0.9
0.563	21.28	0.451	75.06	8.46	0.707	3.600	0.9	0.9
0.565	20.93	0.462	76.00	8.78	0.742	4.000	0.8	0.9
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

0.0013	0.3430	0.0089	1.425	0.155	0.0191	1.6041	0.15	0.00
0.565	20.81	0.463	74.57	8.63	0.735	2.168	1.0	0.9

C13B
SINGLE-SIDED
SECONDARY DOPANT = NONE
RESISTIVITY = 0.17
CONTROL PERCENTAGE = 99

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.582	19.84	0.490	69.95	8.57	0.742	0.200	0.8	7.2
0.581	19.88	0.482	69.16	8.33	0.722	0.200	0.7	7.2
0.584	20.17	0.496	71.46	8.86	0.752	0.180	0.8	7.2
0.581	20.60	0.492	72.22	8.88	0.742	0.180	0.9	7.2
0.581	20.61	0.487	72.19	8.79	0.734	0.180	0.8	7.2
0.586	20.12	0.493	72.27	8.91	0.756	0.180	0.9	7.2
0.580	19.61	0.482	67.53	8.14	0.715	0.200	0.6	7.2
0.578	20.64	0.485	71.71	8.69	0.729	0.180	0.9	7.2
0.579	20.28	0.483	72.23	8.72	0.743	0.180	0.8	7.2
0.579	20.25	0.482	70.79	8.53	0.728	0.200	0.8	7.2
0.579	20.42	0.481	71.28	8.57	0.725	0.180	0.8	7.2
0.586	20.17	0.494	73.10	9.03	0.764	0.180	0.9	7.2
0.578	20.35	0.480	69.07	8.29	0.705	0.180	0.7	7.2

STANDARD DEVIATION AND AVERAGE

0.0028	0.3141	0.0056	1.621	0.267	0.0168	0.0096	0.09	0.00
0.581	20.22	0.487	71.00	8.64	0.735	0.186	0.8	7.2

C13B
DOUBLE-SIDED
SECONDARY DOPANT = NONE
RESISTIVITY = 0.17
CONTROL PERCENTAGE = 100

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	----	----	----	----	----	----	----	----
0.587	19.78	0.490	69.90	8.56	0.737	0.200	0.8	2.9
0.586	19.99	0.483	70.13	8.47	0.723	0.180	0.8	2.9
0.583	19.91	0.491	72.61	8.91	0.768	0.200	0.9	2.9
0.582	20.07	0.496	72.01	8.93	0.764	0.180	0.9	2.9
0.583	19.82	0.500	72.43	9.05	0.784	0.180	0.9	2.9
0.585	20.01	0.497	72.09	8.96	0.765	0.180	0.9	2.9
0.573	19.63	0.480	71.67	8.60	0.765	0.180	0.9	2.9
0.571	19.56	0.475	71.87	8.53	0.764	0.180	0.8	2.9
0.572	19.58	0.483	70.55	8.52	0.761	0.200	0.8	2.9
0.574	20.14	0.486	72.76	8.84	0.765	0.200	0.8	2.9
0.571	19.99	0.481	73.62	8.85	0.776	0.200	0.9	2.9
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

0.0065	0.2026	0.0080	1.157	0.212	0.0168	0.0104	0.05	0.00
0.579	19.86	0.487	71.79	8.75	0.761	0.189	0.9	2.9

C13C
SINGLE-SIDED
SECONDARY DOPANT = NONE
RESISTIVITY = 0.011
CONTROL PERCENTAGE = 95

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	----	----	----	----	----	----	----	----
0.414	13.23	0.297	42.26	3.14	0.573	0.220	0.4	0.0
0.421	13.17	0.303	42.11	3.19	0.575	0.220	0.4	0.0
0.416	13.46	0.290	44.69	3.24	0.579	0.220	0.5	0.0
0.430	13.30	0.300	40.30	3.10	0.543	0.200	0.4	0.0
0.421	13.41	0.311	41.23	3.21	0.568	0.220	0.4	0.0
0.412	13.25	0.301	40.78	3.07	0.562	0.200	0.4	0.0
0.395	13.33	0.285	42.85	3.05	0.580	0.220	0.4	0.0
0.393	13.51	0.285	42.69	3.04	0.573	0.220	0.4	0.0
0.413	13.48	0.283	46.78	3.31	0.595	0.200	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

STANDARD DEVIATION AND AVERAGE

0.0120	0.1198	0.0106	2.023	0.092	0.0142	0.0100	0.03	0.00
0.413	13.35	0.296	42.63	3.15	0.572	0.213	0.4	0.0

C13C
DOUBLE-SIDED
SECONDARY DOPANT = NONE
RESISTIVITY = 0.011
CONTROL PERCENTAGE = 96

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.556	13.40	0.427	43.24	4.62	0.619	0.200	0.6	0.5
0.531	13.30	0.392	44.88	4.40	0.623	0.220	0.6	0.5
0.514	13.25	0.403	43.41	4.37	0.642	0.240	0.6	0.5
0.485	13.23	0.367	41.27	3.79	0.590	0.240	0.5	0.5
0.520	13.23	0.355	41.22	3.66	0.532	0.220	0.5	0.5
0.559	13.40	0.431	43.52	4.69	0.626	0.220	0.6	0.5
0.534	13.33	0.416	42.69	4.44	0.624	0.220	0.5	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

STANDARD DEVIATION AND AVERAGE

0.0255	0.0758	0.0292	1.304	0.400	0.0370	0.0138	0.05	0.00
0.528	13.30	0.399	42.89	4.28	0.608	0.223	0.6	0.5

C14A
SINGLE-SIDED
SECONDARY DOPANT = C
RESISTIVITY = 0.126
CONTROL PERCENTAGE = 0

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.449	19.76	0.264	59.16	3.90	0.440	0.280	0.2	2.4
0.531	19.68	0.339	60.46	5.12	0.490	0.300	0.3	2.4
0.583	19.72	0.482	67.31	8.11	0.705	0.240	0.5	2.4
0.581	19.61	0.473	68.00	8.04	0.706	0.220	0.5	2.4
0.579	19.34	0.428	51.43	5.50	0.492	0.220	0.4	2.4
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

0.0577	0.1698	0.0936	6.777	1.866	0.1286	0.0363	0.13	0.00
0.545	19.62	0.397	61.27	6.14	0.567	0.252	0.4	2.4

C14A
DOUBLE-SIDED
SECONDARY DOPANT = C
RESISTIVITY = 0.126
CONTROL PERCENTAGE = 107

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	-----	----	----	-----	-----	-----	-----	-----
0.590	20.33	0.493	70.44	8.68	0.724	0.200	0.8	2.9
0.582	20.12	0.462	70.81	8.18	0.699	0.200	0.7	2.9
0.591	20.16	0.499	71.16	8.88	0.745	0.200	0.7	2.9
0.590	19.90	0.494	71.57	8.84	0.753	0.200	0.7	2.9
0.585	20.07	0.477	63.49	7.57	0.645	0.200	0.5	2.9
0.584	20.16	0.481	70.15	8.44	0.717	0.200	0.7	2.9
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	0.1383	0.0138	3.037	0.496	0.0390	0.0000	0.10	0.00
0.587	20.12	0.484	69.60	8.43	0.714	0.200	0.7	2.9

C14A1
SINGLE-SIDED
SECONDARY DOPANT = C
RESISTIVITY = 0.126
CONTROL PERCENTAGE = 100

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	-----	----	----	-----	-----	-----	-----	-----
0.580	19.99	0.490	72.56	8.89	0.767	0.200	0.7	7.2
0.580	19.86	0.486	69.81	8.48	0.736	0.200	0.6	7.2
0.574	19.62	0.475	69.99	8.31	0.738	0.220	0.6	7.2
0.571	19.91	0.481	73.13	8.79	0.774	0.200	0.7	7.2
0.565	20.44	0.462	69.64	8.04	0.696	0.220	0.6	7.2
0.581	20.25	0.486	73.26	8.90	0.757	0.200	0.7	7.2
0.579	20.51	0.483	72.93	8.81	0.742	0.220	0.6	7.2
0.581	19.98	0.468	68.31	7.99	0.689	0.200	0.6	7.2
0.587	19.95	0.485	70.45	8.54	0.729	0.200	0.7	7.2
0.572	19.99	0.479	66.51	7.96	0.697	0.200	0.6	7.2
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

0.0064	0.2720	0.0088	2.276	0.376	0.0299	0.0097	0.05	0.00
0.577	20.05	0.480	70.66	8.47	0.732	0.206	0.6	7.2

C14A1
 DOUBLE-SIDED
 SECONDARY DOPANT = C
 RESISTIVITY = 0.126
 CONTROL PERCENTAGE = 99

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.564	19.70	0.399	54.02	5.39	0.485	0.200	0.4	2.6
0.532	19.77	0.319	54.50	4.35	0.413	0.220	0.3	2.6
0.594	19.74	0.495	72.11	8.92	0.761	0.180	0.8	2.6
0.589	19.65	0.488	70.25	8.57	0.741	0.200	0.8	2.6
0.551	19.43	0.402	52.43	5.27	0.492	0.200	0.4	2.6
0.580	19.20	0.468	69.00	8.07	0.725	0.200	0.6	2.6
0.585	19.35	0.484	69.62	8.42	0.744	0.300	0.7	2.6
0.586	19.27	0.490	70.48	8.63	0.765	0.240	0.7	2.6
0.549	18.99	0.364	52.44	4.77	0.458	0.220	0.3	2.6
0.587	19.45	0.476	70.52	8.39	0.735	0.200	0.7	2.6
0.591	19.97	0.494	73.16	9.04	0.766	0.200	0.8	2.6
0.589	19.81	0.490	71.26	8.73	0.748	0.200	0.8	2.6
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0205	0.2918	0.0604	8.678	1.833	0.1425	0.0311	0.20	0.00
0.575	19.53	0.447	64.98	7.38	0.653	0.213	0.6	2.6

C14A2
 SINGLE-SIDED
 SECONDARY DOPANT = C
 RESISTIVITY = 0.08
 CONTROL PERCENTAGE = 104

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.583	19.36	0.438	65.05	7.12	0.631	0.220	0.6	7.2
0.586	19.11	0.488	68.47	8.35	0.746	0.200	0.6	7.2
0.586	19.06	0.481	67.35	8.10	0.725	0.200	0.6	7.2
0.582	19.40	0.493	70.60	8.70	0.771	0.200	0.6	7.2
0.584	19.22	0.491	68.87	8.45	0.753	0.200	0.6	7.2
0.584	19.11	0.478	69.57	8.31	0.745	0.220	0.6	7.2
0.582	19.28	0.477	69.98	8.35	0.744	0.200	0.6	7.2
0.584	19.56	0.486	65.14	7.95	0.696	0.200	0.6	7.2
0.588	19.24	0.502	69.47	8.72	0.771	0.200	0.6	7.2
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
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

0.0020	0.1617	0.0181	1.971	0.483	0.0439	0.0088	0.00	0.00
0.584	19.26	0.482	68.31	8.23	0.731	0.204	0.6	7.2

C15B
SINGLE-SIDED
SECONDARY DOPANT = NA
RESISTIVITY = 0.57
CONTROL PERCENTAGE = 82

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

C15B
DOUBLE-SIDED
SECONDARY DOPANT = NA
RESISTIVITY = 0.57
CONTROL PERCENTAGE = 98

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	----	----	----	----	----	----	----	----
0.578	20.04	0.484	72.60	8.78	0.758	0.440	1.2	2.4
0.575	20.18	0.490	72.42	8.87	0.764	0.300	1.3	2.4
0.575	20.22	0.488	74.48	9.09	0.782	0.280	1.3	2.4
0.574	20.00	0.469	70.89	8.31	0.724	0.760	1.1	2.4
0.574	19.95	0.475	73.67	8.75	0.764	0.500	1.2	2.4
0.579	20.03	0.480	71.48	8.58	0.740	1.220	1.2	2.4
0.574	20.01	0.478	73.63	8.80	0.766	1.200	1.3	2.4
0.577	20.00	0.494	72.61	8.97	0.777	0.260	1.3	2.4
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

STANDARD DEVIATION AND AVERAGE

0.0020	0.0951	0.0083	1.185	0.238	0.0191	0.3983	0.07	0.00
0.576	20.05	0.482	72.72	8.77	0.759	0.620	1.2	2.4

C16B
 SINGLE-SIDED
 SECONDARY DOPANT = P-COMP
 RESISTIVITY = 0.47
 CONTROL PERCENTAGE = 99

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.570	19.52	0.476	64.38	7.66	0.688	0.200	1.0	3.5
0.576	19.66	0.491	70.64	8.67	0.766	0.200	1.0	3.5
0.574	19.29	0.485	65.96	8.00	0.722	0.200	1.0	3.5
0.578	19.42	0.488	69.19	8.44	0.752	0.200	1.0	3.5
0.576	19.35	0.486	66.88	8.13	0.729	0.200	1.0	3.5
0.575	19.81	0.478	69.35	8.29	0.728	0.200	1.1	3.5
0.578	19.63	0.491	69.00	8.47	0.746	0.190	1.1	3.5
0.577	19.46	0.487	67.46	8.21	0.732	0.200	0.9	3.5
0.578	19.48	0.488	68.90	8.41	0.747	0.190	1.1	3.5
0.577	19.40	0.488	68.73	8.39	0.749	0.200	0.9	3.5
0.579	19.41	0.494	69.52	8.59	0.764	0.200	0.8	3.5
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

STANDARD DEVIATION AND AVERAGE

0.0025	0.1525	0.0054	1.825	0.287	0.0220	0.0040	0.09	0.00
0.576	19.49	0.487	68.18	8.29	0.738	0.198	1.0	3.5

C16B1
 SINGLE-SIDED
 SECONDARY DOPANT = P-COMP
 RESISTIVITY = 0.18
 CONTROL PERCENTAGE = 97

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.568	19.04	0.468	59.30	6.94	0.642	0.180	0.8	0.0
0.575	19.36	0.482	66.06	7.96	0.715	0.200	0.9	0.0
0.577	19.09	0.483	68.89	8.32	0.755	0.200	0.9	0.0
0.569	19.13	0.476	63.68	7.58	0.696	0.200	0.8	0.0
0.575	19.07	0.475	64.22	7.63	0.695	0.200	0.9	0.0
0.577	19.24	0.490	67.22	8.23	0.742	0.200	0.9	0.0
0.570	19.04	0.468	62.99	7.37	0.679	0.180	0.8	0.0
0.570	19.03	0.474	63.99	7.58	0.699	0.200	0.9	0.0
0.578	18.88	0.484	69.70	8.43	0.773	0.200	1.0	0.0
0.571	19.09	0.473	65.56	7.75	0.711	0.200	0.9	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	0.1275	0.0072	3.041	0.464	0.0383	0.0084	0.06	0.00
0.573	19.10	0.477	65.16	7.78	0.711	0.196	0.9	0.0

C16B1
 DOUBLE-SIDED
 SECONDARY DOPANT = P-COMP
 RESISTIVITY = 0.18
 CONTROL PERCENTAGE = 104

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.564	14.00	0.481	44.90	5.40	0.684	0.220	0.5	0.5
0.559	13.99	0.467	43.81	5.11	0.654	0.200	0.4	0.5
0.563	13.69	0.472	48.59	5.73	0.744	0.220	0.4	0.5
0.569	14.22	0.485	50.20	6.09	0.752	0.200	0.4	0.5
0.572	14.53	0.483	54.86	6.62	0.797	0.200	0.4	0.5
0.552	13.98	0.430	40.24	4.33	0.561	0.220	0.4	0.5
0.556	14.29	0.449	43.37	4.87	0.613	0.240	0.4	0.5
0.566	14.08	0.451	49.42	5.57	0.699	0.260	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

STANDARD DEVIATION AND AVERAGE

0.0067	0.2515	0.0197	4.688	0.717	0.0777	0.0214	0.04	0.00
0.563	14.10	0.465	46.92	5.47	0.688	0.220	0.4	0.5

C17B
 SINGLE-SIDED
 SECONDARY DOPANT = TI
 RESISTIVITY = 0.6
 CONTROL PERCENTAGE = 72

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.548	18.33	0.451	64.96	7.32	0.729	0.320	0.4	0.8
0.541	18.48	0.437	57.79	6.31	0.632	0.480	0.3	0.8
0.552	18.24	0.446	65.20	7.27	0.722	0.600	0.4	0.8
0.552	18.52	0.449	66.72	7.49	0.733	1.500	0.4	0.8
0.539	18.20	0.419	58.10	6.09	0.620	0.480	0.3	0.8
0.548	18.15	0.440	58.82	6.47	0.651	0.440	0.4	0.8
0.552	18.51	0.444	66.26	7.35	0.720	1.400	0.4	0.8
0.544	18.58	0.414	65.86	6.82	0.674	2.200	0.4	0.8
0.549	18.32	0.428	64.95	6.95	0.691	1.200	0.4	0.8
0.551	18.31	0.435	65.00	7.07	0.701	2.400	0.4	0.8
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

0.0047	0.1488	0.0125	3.597	0.483	0.0413	0.7618	0.04	0.00
0.548	18.36	0.436	63.37	6.91	0.687	1.102	0.4	0.8

C17B
 DOUBLE-SIDED
 SECONDARY DOPANT = TI
 RESISTIVITY = 0.6
 CONTROL PERCENTAGE = 104

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
-----	-----	-----	-----	-----	-----	-----	-----	-----
0.556	18.31	0.451	66.40	7.49	0.735	0.220	0.5	0.9
0.558	18.39	0.422	66.76	7.04	0.686	0.380	0.4	0.9
0.554	18.40	0.425	65.37	6.95	0.681	0.320	0.4	0.9
0.553	18.33	0.443	67.37	7.46	0.736	0.240	0.5	0.9
0.557	18.15	0.462	66.57	7.69	0.761	0.200	0.5	0.9
0.558	18.38	0.459	67.57	7.75	0.756	0.280	0.5	0.9
0.554	18.63	0.441	68.72	7.58	0.734	0.320	0.5	0.9
0.555	18.44	0.451	64.98	7.33	0.716	0.220	0.2	0.4
0.554	17.65	0.460	64.25	7.39	0.756	0.240	0.5	0.9
0.547	18.55	0.420	66.60	6.99	0.689	0.800	0.4	0.9
0.552	18.17	0.457	65.10	7.44	0.741	0.200	0.4	0.9
0.555	18.39	0.440	66.30	7.29	0.715	0.700	0.3	0.9
0.553	18.24	0.460	66.15	7.61	0.754	0.220	0.4	0.9

STANDARD DEVIATION AND AVERAGE

0.0029	0.2394	0.0151	1.200	0.260	0.0279	0.1935	0.09	0.14
0.554	18.31	0.445	66.32	7.38	0.728	0.334	0.4	0.9

M1A
 SINGLE SIDED
 SECONDARY DOPANT = NONE
 RESISTIVITY = 1.06
 CONTROL PERCENTAGE = 100

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

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

M1B
 SINGLE-SIDED
 SECONDARY DOPANT = NONE
 RESISTIVITY = 0.15
 CONTROL PERCENTAGE = 100

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
-----	-----	-----	-----	-----	-----	-----	-----	-----
0.599	19.66	0.503	74.37	9.35	0.794	0.220	2.2	2.9
0.597	19.61	0.505	69.10	8.72	0.745	0.200	2.6	2.9
0.600	20.16	0.503	74.83	9.41	0.778	0.200	3.5	2.9
0.600	19.65	0.510	72.85	9.29	0.788	0.200	1.8	2.9
0.599	19.92	0.508	72.81	9.25	0.775	0.180	2.0	2.9
0.593	20.32	0.500	75.13	9.39	0.779	0.400	2.0	2.9
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	0.2997	0.0037	2.229	0.258	0.0170	0.0826	0.63	0.00
0.598	19.88	0.505	73.18	9.24	0.777	0.233	2.4	2.9

M1B
 DOUBLE SIDED
 SECONDARY DOPANT = NONE
 RESISTIVITY = 0.15
 CONTROL PERCENTAGE = 0

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
-----	-----	-----	-----	-----	-----	-----	-----	-----
0.596	20.78	0.505	76.18	9.62	0.777	0.240	0.8	4.6
0.597	20.53	0.502	76.12	9.55	0.779	0.240	0.8	4.6
0.596	20.60	0.512	74.97	9.60	0.782	0.240	0.8	4.6
0.594	20.69	0.503	73.37	9.23	0.751	0.200	0.9	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
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	0.1088	0.0045	1.317	0.183	0.0145	0.0200	0.05	0.00
0.596	20.65	0.506	75.16	9.50	0.772	0.230	0.8	4.6

M1C
 SINGLE-SIDED
 SECONDARY DOPANT = NONE
 RESISTIVITY = 0.04
 CONTROL PERCENTAGE = 100

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
0.580	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

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
SECONDARY DOPANT = FE
RESISTIVITY = 0.38
CONTROL PERCENTAGE = 94

VOC	ISC/A	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

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

M2B2
SINGLE-SIDED
SECONDARY DOPANT = FE
RESISTIVITY = 0.48
CONTROL PERCENTAGE = 0

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.575	18.50	0.484	68.93	8.34	0.784	0.200	0.8	0.0
0.573	18.42	0.483	65.04	7.85	0.744	0.210	1.0	0.0
0.577	18.47	0.488	69.00	8.42	0.790	0.200	1.2	0.0
0.574	18.35	0.486	65.17	7.92	0.752	0.180	1.2	0.0
0.568	18.45	0.476	66.06	7.86	0.750	0.260	1.1	0.0
0.574	18.40	0.487	68.78	8.37	0.793	0.200	1.1	0.0
0.573	18.34	0.486	65.69	7.98	0.759	0.180	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
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0028	0.0596	0.0040	1.856	0.258	0.0207	0.0270	0.16	0.00
0.573	18.42	0.484	66.95	8.11	0.768	0.204	1.1	0.0

M2B2
 DOUBLE SIDED
 SECONDARY DOPANT = FE
 RESISTIVITY = 0.48
 CONTROL PERCENTAGE = 105

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	----	----	----	----	----	----	----	----
0.570	18.45	0.483	68.91	8.32	0.791	0.200	0.7	0.0
0.573	19.28	0.490	70.74	8.67	0.784	0.200	1.0	0.0
0.570	18.27	0.478	68.01	8.13	0.780	0.200	0.6	0.0
0.565	18.18	0.478	68.17	7.19	0.700	0.200	0.6	0.0
0.577	19.18	0.492	70.40	8.66	0.783	0.200	0.9	0.0
0.573	18.98	0.479	68.44	8.20	0.754	0.240	0.7	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

0.0040	0.4800	0.0063	3.881	0.542	0.0345	0.0163	0.16	0.00
0.571	18.72	0.483	67.78	8.19	0.765	0.207	0.8	0.0

M2C
 SINGLE-SIDED
 SECONDARY DOPANT = FE
 RESISTIVITY = 0.06
 CONTROL PERCENTAGE = 104

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	58.59	6.99	0.657	0.220	0.4	0.0
0.581	16.06	0.487	55.81	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

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

M3B
 SINGLE-SIDED
 SECONDARY DOPANT = MN
 RESISTIVITY = 0.44
 CONTROL PERCENTAGE = 99

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.593	20.57	0.503	77.06	9.69	0.795	0.170	5.0	0.0
0.596	20.54	0.503	77.23	9.71	0.793	0.170	4.8	0.0
0.597	20.58	0.506	77.84	9.85	0.801	0.170	5.0	0.0
0.592	20.55	0.499	77.54	9.67	0.795	0.180	5.5	0.0
0.596	20.65	0.504	77.92	9.82	0.798	0.170	5.2	0.0
0.593	20.53	0.503	77.05	9.69	0.796	0.160	5.0	0.0
0.594	20.55	0.504	77.70	9.79	0.802	0.180	5.0	0.0
0.595	20.53	0.504	77.43	9.76	0.799	0.170	5.4	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

STANDARD DEVIATION AND AVERAGE

0.0018	0.0390	0.0020	0.338	0.066	0.0032	0.0064	0.24	0.00
0.595	20.56	0.503	77.47	9.75	0.797	0.171	5.1	0.0

M3B
 DOUBLE SIDED
 SECONDARY DOPANT = MN
 RESISTIVITY = 0.44
 CONTROL PERCENTAGE = 98

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.588	21.22	0.496	74.72	9.27	0.743	0.180	1.4	0.0
0.585	20.76	0.492	69.06	8.49	0.700	0.200	1.2	0.0
0.586	20.83	0.493	73.01	9.00	0.737	0.200	1.4	0.0
0.590	20.82	0.502	77.60	9.74	0.793	0.220	1.8	0.0
0.591	21.07	0.501	79.33	9.94	0.798	0.240	1.8	0.0
0.589	21.13	0.499	77.64	9.69	0.778	0.200	1.7	0.0
0.585	20.89	0.493	73.31	9.04	0.739	0.200	1.5	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

0.0024	0.1780	0.0041	3.527	0.509	0.0356	0.0190	0.23	0.00
0.588	20.96	0.497	74.95	9.31	0.755	0.206	1.5	0.0

M4B
 SINGLE-SIDED
 SECONDARY DOPANT = NI
 RESISTIVITY = 0.59
 CONTROL PERCENTAGE = 101

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
-----	-----	-----	-----	-----	-----	-----	-----	-----
0.584	20.52	0.496	76.77	9.52	0.794	0.170	4.8	4.0
0.594	20.68	0.499	78.60	9.81	0.798	0.160	4.8	4.0
0.589	20.76	0.497	78.02	9.69	0.793	0.160	4.6	4.0
0.590	20.78	0.496	77.99	9.67	0.789	0.170	5.0	4.0
0.589	20.62	0.497	76.40	9.49	0.782	0.170	4.2	4.0
0.586	20.67	0.498	77.45	9.64	0.796	0.160	4.7	4.0
0.588	20.62	0.492	77.29	9.51	0.784	0.180	4.6	4.0
0.591	20.58	0.499	76.46	9.54	0.784	0.180	4.4	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

STANDARD DEVIATION AND AVERAGE

0.0030	0.0850	0.0023	0.798	0.112	0.0063	0.0083	0.25	0.00
0.589	20.65	0.497	77.37	9.61	0.790	0.169	4.6	4.0

M4B1
 SINGLE-SIDED
 SECONDARY DOPANT = NI
 RESISTIVITY = 0.5
 CONTROL PERCENTAGE = 106

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
-----	-----	-----	-----	-----	-----	-----	-----	-----
0.593	20.76	0.489	77.00	9.41	0.765	0.200	4.0	4.0
0.589	20.42	0.503	75.68	9.52	0.791	0.180	4.4	4.0
0.592	20.57	0.502	76.72	9.63	0.791	0.180	4.4	4.0
0.594	20.40	0.506	76.20	9.64	0.795	0.170	4.2	4.0
0.593	20.39	0.505	76.03	9.60	0.794	0.170	4.4	4.0
0.591	20.50	0.502	77.25	9.69	0.800	0.160	4.8	4.0
0.589	20.61	0.488	74.56	9.10	0.749	0.210	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

STANDARD DEVIATION AND AVERAGE

0.0020	0.1360	0.0075	0.913	0.205	0.0190	0.0177	0.28	0.00
0.592	20.52	0.499	76.21	9.51	0.784	0.181	4.3	4.0

M4B1
 DOUBLE SIDED
 SECONDARY DOPANT = NI
 RESISTIVITY = 0.5
 CONTROL PERCENTAGE = 103

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.587	21.08	0.492	74.31	9.14	0.739	0.440	1.5	4.3
0.587	21.34	0.492	72.23	8.88	0.709	0.200	1.3	4.3
0.583	21.00	0.486	71.02	8.63	0.705	0.200	1.2	0.0
0.587	21.08	0.500	76.83	9.60	0.776	0.820	1.7	8.6
0.575	20.84	0.473	68.95	8.15	0.681	0.800	1.1	4.3
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

0.0052	0.1806	0.0100	3.031	0.544	0.0367	0.3065	0.24	3.04
0.584	21.07	0.489	72.67	8.88	0.722	0.492	1.4	4.3

M5B
 SINGLE-SIDED
 SECONDARY DOPANT = V
 RESISTIVITY = 0.49
 CONTROL PERCENTAGE = 0

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.553	15.02	0.465	55.96	6.51	0.700	0.300	0.3	0.5
0.552	15.03	0.464	56.15	6.51	0.785	0.320	0.3	0.5
0.548	15.17	0.461	56.30	6.49	0.781	0.300	0.4	0.5
0.551	14.86	0.450	54.55	6.14	0.750	0.300	0.3	0.5
0.552	14.91	0.469	54.91	6.44	0.782	0.300	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
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	0.1197	0.0072	0.790	0.159	0.0149	0.0089	0.05	0.00
0.551	15.00	0.462	55.57	6.42	0.776	0.304	0.3	0.5

M5B1
 SINGLE-SIDED
 SECONDARY DOPANT = V
 RESISTIVITY = 0.48
 CONTROL PERCENTAGE = 102

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

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

M5B1
 DOUBLE SIDED
 SECONDARY DOPANT = V
 RESISTIVITY = 0.48
 CONTROL PERCENTAGE = 0

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.542	14.56	0.455	54.57	6.21	0.787	0.240	0.3	0.0
0.535	14.37	0.450	51.77	5.82	0.758	0.240	0.3	0.0
0.532	13.94	0.449	52.12	5.85	0.789	0.240	0.4	0.0
0.542	14.65	0.458	54.67	6.26	0.788	0.240	0.3	0.0
0.452	14.60	0.456	54.83	6.25	0.947	0.240	0.4	0.0
0.535	13.90	0.456	51.49	5.87	0.790	0.280	0.4	0.0
0.538	14.58	0.451	51.02	5.75	0.733	0.240	0.3	0.0
0.528	14.11	0.446	50.64	5.65	0.758	0.260	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

STANDARD DEVIATION AND AVERAGE

0.0301	0.3115	0.0042	1.757	0.244	0.0654	0.0149	0.05	0.00
0.526	14.34	0.453	52.64	5.96	0.794	0.248	0.3	0.0

M6B
 SINGLE-SIDED
 SECONDARY DOPANT = ZR
 RESISTIVITY = 0.48
 CONTROL PERCENTAGE = 98

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.581	19.21	0.494	71.60	8.84	0.792	0.220	2.4	4.0
0.582	19.95	0.496	73.62	9.13	0.786	0.180	2.4	4.0
0.581	19.41	0.487	72.92	8.88	0.787	0.200	2.5	4.0
0.586	19.88	0.501	73.70	9.23	0.792	0.180	2.4	4.0
0.581	19.93	0.483	72.32	8.73	0.754	0.190	2.3	4.0
0.586	20.15	0.497	75.22	9.35	0.792	0.180	2.5	4.0
0.578	19.95	0.482	68.30	8.23	0.714	0.300	2.2	4.0
0.584	19.89	0.495	73.78	9.13	0.786	0.190	2.4	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

STANDARD DEVIATION AND AVERAGE

0.0028	0.3150	0.0070	2.074	0.355	0.0279	0.0407	0.10	0.00
0.582	19.79	0.492	72.68	8.94	0.776	0.205	2.4	4.0

M6B
 DOUBLE SIDED
 SECONDARY DOPANT = ZR
 RESISTIVITY = 0.48
 CONTROL PERCENTAGE = 104

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.578	20.25	0.503	74.90	9.42	0.805	0.200	1.5	4.0
0.581	19.89	0.476	68.62	8.17	0.707	0.200	1.2	4.0
0.580	20.24	0.495	74.16	9.18	0.782	0.200	1.4	4.0
0.585	20.00	####	0.50	7.89	0.671	0.300	1.4	4.0
0.586	19.99	0.498	74.01	9.21	0.787	0.220	0.8	4.0
0.576	19.93	0.435	64.60	7.03	0.612	0.240	0.8	4.0
0.582	20.01	0.494	72.39	8.94	0.768	0.200	1.2	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

STANDARD DEVIATION AND AVERAGE

0.0036	0.1425	####	27.067	0.880	0.0712	0.0157	0.29	0.00
0.581	20.04	9.414	61.31	8.55	0.733	0.209	1.2	4.0

M7B
 SINGLE-SIDED
 SECONDARY DOPANT = MG
 RESISTIVITY = 0.45
 CONTROL PERCENTAGE = 104

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	-----	----	----	-----	-----	----	-----	-----
0.590	20.73	0.501	77.31	9.68	0.792	0.340	5.0	4.0
0.590	20.59	0.501	77.02	9.65	0.794	0.320	5.2	4.0
0.596	20.75	0.503	77.68	9.77	0.790	0.240	4.5	4.0
0.590	21.02	0.497	78.77	9.79	0.789	0.220	4.8	4.0
0.590	20.89	0.491	76.03	9.33	0.757	0.220	3.4	4.0
0.593	20.88	0.506	77.42	9.79	0.791	0.200	4.6	4.0
0.594	20.92	0.504	78.13	9.84	0.792	0.240	4.8	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

STANDARD DEVIATION AND AVERAGE

0.0025	0.1411	0.0050	0.863	0.173	0.0130	0.0538	0.58	0.00
0.592	20.82	0.500	77.48	9.69	0.787	0.254	4.6	4.0

M7B
 DOUBLE SIDED
 SECONDARY DOPANT = MG
 RESISTIVITY = 0.45
 CONTROL PERCENTAGE = 100

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	-----	----	----	-----	-----	----	-----	-----
0.573	20.40	0.476	66.59	7.92	0.678	0.680	1.0	4.0
0.583	20.81	0.468	71.34	8.35	0.688	0.680	1.2	4.0
0.590	21.15	0.498	79.74	9.93	0.795	0.220	1.8	4.0
0.590	21.15	0.468	79.74	9.33	0.748	0.220	1.8	4.0
0.585	20.88	0.503	77.41	9.73	0.797	0.200	1.7	4.0
0.582	20.86	0.483	72.12	8.71	0.717	0.320	1.3	4.0
0.582	20.65	0.492	73.03	8.98	0.748	0.280	1.4	4.0
0.589	20.91	0.497	75.84	9.42	0.765	0.200	1.6	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

STANDARD DEVIATION AND AVERAGE

0.0057	0.2489	0.0139	4.560	0.691	0.0449	0.2078	0.30	0.00
0.584	20.85	0.486	74.48	9.05	0.742	0.350	1.5	4.0

M8B
 SINGLE-SIDED
 SECONDARY DOPANT = TI
 RESISTIVITY = 0.49
 CONTROL PERCENTAGE = 79

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.519	13.49	0.300	48.05	3.60	0.515	0.000	0.0	0.5
0.519	13.36	0.337	46.77	3.94	0.568	0.000	0.0	0.5
0.523	13.66	0.344	46.45	3.99	0.559	0.000	0.0	0.5
0.522	13.28	0.354	47.51	4.20	0.607	0.000	0.0	0.5
0.524	13.12	0.356	44.33	3.95	0.574	0.000	0.0	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
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0023	0.2079	0.0227	1.426	0.216	0.0331	0.0000	0.00	0.00
0.521	13.38	0.338	46.62	3.94	0.565	0.000	0.0	0.5

M8B
 DOUBLE SIDED
 SECONDARY DOPANT = TI
 RESISTIVITY = 0.49
 CONTROL PERCENTAGE = 98

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.525	13.60	0.433	47.64	5.16	0.722	0.500	0.3	0.0
0.526	13.60	0.433	47.64	5.16	0.721	0.300	0.3	0.0
0.530	13.53	0.445	48.07	5.35	0.746	0.260	0.3	0.0
0.524	13.60	0.433	51.03	5.52	0.775	0.320	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

STANDARD DEVIATION AND AVERAGE

0.0026	0.0346	0.0060	1.636	0.176	0.0255	0.1063	0.00	0.00
0.526	13.58	0.436	48.60	5.30	0.741	0.345	0.3	0.0

M8B1
 SINGLE SIDED
 SECONDARY DOPANT = TI
 RESISTIVITY = 0.49
 CONTROL PERCENTAGE = 102

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
-----	-----	-----	-----	-----	-----	-----	-----	-----
0.520	12.65	0.428	44.89	4.80	0.730	0.220	0.0	0.0
0.517	12.81	0.425	44.72	4.75	0.717	0.240	0.0	0.0
0.516	15.38	0.420	41.99	4.41	0.556	0.230	0.0	0.0
0.522	12.84	0.437	46.97	5.13	0.765	0.240	0.0	0.0
0.521	12.90	0.431	45.54	4.91	0.730	0.240	0.0	0.0
0.524	12.86	0.445	45.32	5.04	0.748	0.230	0.0	0.0
0.516	12.74	0.434	42.63	4.63	0.703	0.240	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

0.0032	0.9778	0.0082	1.723	0.247	0.0698	0.0079	0.00	0.00
0.519	13.17	0.431	44.58	4.81	0.707	0.234	0.0	0.0

M9B
 SINGLE-SIDED
 SECONDARY DOPANT = C
 RESISTIVITY = 0.48
 CONTROL PERCENTAGE = 102

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	0.495	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
0.585	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

STANDARD DEVIATION AND AVERAGE

0.0134	0.9705	0.0171	3.456	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
 SECONDARY DOPANT = C
 RESISTIVITY = 0.46
 CONTROL PERCENTAGE = 99

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	0.476	68.26	8.12	0.717	0.160	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

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

M9B1
 DOUBLE SIDED
 SECONDARY DOPANT = C
 RESISTIVITY = 0.46
 CONTROL PERCENTAGE = 101

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.584	20.55	0.498	75.78	9.43	0.786	0.180	1.5	2.8
0.581	19.87	0.495	73.57	9.10	0.789	0.200	1.3	2.8
0.581	19.91	0.492	74.78	9.20	0.795	0.180	1.4	2.8
0.560	20.62	0.457	66.54	7.60	0.659	0.200	1.8	2.8
0.574	19.71	0.480	70.08	8.41	0.743	0.200	0.9	2.8
0.562	18.33	0.470	67.99	7.99	0.776	0.200	0.8	2.8
0.572	19.56	0.486	71.46	8.68	0.776	0.200	1.1	2.8
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

0.0095	0.7607	0.0148	3.471	0.673	0.0480	0.0098	0.35	0.00
0.573	19.79	0.483	71.46	8.63	0.760	0.194	1.3	2.8

M10B
 SINGLE-SIDED
 SECONDARY DOPANT = AL
 RESISTIVITY = 0.37
 CONTROL PERCENTAGE = 103

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

M10B
 DOUBLE SIDED
 SECONDARY DOPANT = AL
 RESISTIVITY = 0.37
 CONTROL PERCENTAGE = 100

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.559	20.88	0.408	52.16	5.32	0.456	0.200	0.5	3.2
0.585	20.43	0.496	72.44	8.98	0.752	0.200	1.2	3.2
0.589	20.58	0.502	75.78	9.51	0.785	0.200	1.4	3.2
0.573	20.61	0.471	62.68	7.38	0.625	0.200	0.9	3.2
0.587	20.74	0.495	74.15	9.18	0.754	0.200	1.3	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
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

0.0126	0.1690	0.0390	9.946	1.744	0.1365	0.0000	0.36	0.00
0.579	20.65	0.474	67.44	8.07	0.674	0.200	1.1	3.2

M118
SINGLE-SIDED
SECONDARY DOPANT = I/MN/MG
RESISTIVITY = 0.49
CONTROL PERCENTAGE = 103

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

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

M118
DOUBLE-SIDED
SECONDARY DOPANT = I/MN/MG
RESISTIVITY = 0.49
CONTROL PERCENTAGE = 95

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.577	21.17	0.479	65.73	7.87	0.645	0.200	1.2	0.0
0.586	21.16	0.500	79.00	9.88	0.797	0.200	1.9	0.0
0.587	20.51	0.498	68.99	8.59	0.713	0.200	1.4	0.0
0.589	21.31	0.502	74.25	9.32	0.742	0.200	1.5	0.0
0.585	21.08	0.493	76.36	9.41	0.763	0.200	1.7	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	0.3099	0.0092	5.424	0.787	0.0575	0.0000	0.27	0.00
0.585	21.04	0.494	72.87	9.01	0.732	0.200	1.5	0.0

M13A
SINGLE-SIDED
SECONDARY DOPANT = NONE
RESISTIVITY = 0.75
CONTROL PERCENTAGE = 105

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.563	20.29	0.465	73.46	8.54	0.748	0.840	1.3	9.1
0.566	20.13	0.479	74.02	8.86	0.778	0.220	1.5	9.1
0.564	20.17	0.463	73.30	8.48	0.746	0.280	1.4	9.1
0.561	20.10	0.466	73.30	8.54	0.757	0.400	1.2	9.1
0.561	20.24	0.464	75.20	8.72	0.768	0.360	1.5	9.1
0.560	20.18	0.453	72.88	8.25	0.730	1.800	1.0	9.1
0.562	20.20	0.472	74.84	8.83	0.778	0.240	1.5	9.1
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

STANDARD DEVIATION AND AVERAGE

0.0021	0.0645	0.0080	0.869	0.216	0.0179	0.5732	0.19	0.00
0.562	20.19	0.466	73.86	8.61	0.758	0.591	1.3	9.1

M13A
DOUBLE-SIDED
SECONDARY DOPANT = NONE
RESISTIVITY = 0.75
CONTROL PERCENTAGE = 0

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.560	20.25	0.427	73.04	7.80	0.688	5.000	1.0	0.0
0.562	20.27	0.460	72.33	8.32	0.730	0.800	1.0	0.0
0.557	19.90	0.452	73.96	8.36	0.754	0.560	1.0	0.0
0.559	19.88	0.415	69.24	7.18	0.647	7.000	1.0	0.0
0.569	20.62	0.467	72.52	8.47	0.722	0.220	1.1	0.0
0.565	20.31	0.448	68.84	7.71	0.672	1.000	0.9	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

0.0044	0.2792	0.0200	2.107	0.497	0.0402	2.8486	0.06	0.00
0.562	20.20	0.445	71.66	7.97	0.702	2.430	1.0	0.0

M138
 SINGLE-SIDED
 SECONDARY DOPANT = NONE
 RESISTIVITY = 0.46
 CONTROL PERCENTAGE = 106

VOC	ISC/R	VM	IM	EFF	FF	RS	TOC	TPC
-----	-----	-----	-----	-----	-----	-----	-----	-----
0.566	19.69	0.471	72.08	8.49	0.762	0.200	1.1	7.2
0.568	19.48	0.470	71.30	8.38	0.757	0.220	1.0	7.2
0.571	20.26	0.453	66.34	7.51	0.650	0.240	1.0	7.2
0.563	19.32	0.454	67.92	7.71	0.709	0.600	0.8	7.2
0.568	19.67	0.469	72.79	8.53	0.764	0.340	1.0	7.2
0.570	20.01	0.473	73.20	8.66	0.759	0.200	1.2	7.2
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
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

0.0029	0.3451	0.0090	2.813	0.479	0.0460	0.1559	0.13	0.00
0.568	19.74	0.465	70.61	8.21	0.733	0.300	1.0	7.2

M138
 DOUBLE-SIDED
 SECONDARY DOPANT = NONE
 RESISTIVITY = 0.46
 CONTROL PERCENTAGE = 111

VOC	ISC/R	VM	IM	EFF	FF	RS	TOC	TPC
-----	-----	-----	-----	-----	-----	-----	-----	-----
0.553	19.86	0.410	60.25	6.27	0.570	0.200	0.7	0.0
0.567	19.82	0.455	69.33	7.89	0.702	0.180	1.0	0.0
0.572	19.74	0.481	72.33	8.70	0.770	0.200	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
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0098	0.0618	0.0327	6.290	1.238	0.1016	0.0115	0.17	0.00
0.564	19.81	0.451	67.30	7.62	0.681	0.193	0.9	0.0

M13C
 SINGLE-SIDED
 SECONDARY DOPANT = NONE
 RESISTIVITY = 0.27
 CONTROL PERCENTAGE = 101

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.574	20.26	0.488	73.69	8.99	0.773	0.240	0.9	10.5
0.567	20.02	0.474	72.15	8.55	0.753	0.240	0.8	10.5
0.564	20.26	0.468	73.63	8.61	0.754	0.480	0.8	10.5
0.572	19.11	0.479	69.50	8.32	0.761	0.260	0.8	10.5
0.576	19.84	0.486	72.49	8.81	0.771	0.340	0.9	10.5
0.573	19.75	0.481	70.70	8.50	0.751	0.300	0.8	10.5
0.572	19.97	0.478	72.72	8.69	0.761	0.380	0.8	10.5
0.572	20.54	0.464	73.78	8.56	0.729	1.400	0.8	10.5
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

STANDARD DEVIATION AND AVERAGE

0.0039	0.4299	0.0083	1.536	0.203	0.0139	0.3904	0.05	0.00
0.571	19.97	0.477	72.33	8.63	0.757	0.455	0.8	10.5

M13C
 DOUBLE-SIDED
 SECONDARY DOPANT = NONE
 RESISTIVITY = 0.27
 CONTROL PERCENTAGE = 106

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.561	19.83	0.417	67.42	7.03	0.632	0.220	0.6	0.0
0.577	19.72	0.478	70.35	8.41	0.739	0.200	0.8	0.0
0.570	19.83	0.462	60.00	6.94	0.614	0.300	0.6	0.0
0.563	19.56	0.434	59.51	6.35	0.577	0.260	0.6	0.0
0.562	19.88	0.424	64.61	6.85	0.613	0.220	0.7	0.0
0.561	19.55	0.422	59.96	6.33	0.577	0.280	0.6	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

0.0065	0.1453	0.0248	4.747	0.759	0.0599	0.0393	0.08	0.00
0.566	19.73	0.440	63.49	6.98	0.625	0.247	0.7	0.0

M14B
SINGLE-SIDED
SECONDARY DOPANT = C
RESISTIVITY = 0.44
CONTROL PERCENTAGE = 113

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.573	20.28	0.484	74.94	9.07	0.780	0.220	1.4	7.2
0.571	20.31	0.490	72.70	8.91	0.768	0.240	1.5	7.2
0.567	20.48	0.480	73.93	8.87	0.764	0.300	1.4	7.2
0.573	20.16	0.484	74.63	9.03	0.782	0.220	1.4	7.2
0.569	20.41	0.486	74.04	9.00	0.775	0.200	1.4	7.2
0.570	20.43	0.477	73.29	8.74	0.751	0.220	1.3	7.2
0.564	20.15	0.483	74.40	8.98	0.791	0.220	1.3	7.2
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
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

0.0033	0.1321	0.0042	0.779	0.112	0.0133	0.0324	0.07	0.00
0.570	20.32	0.483	73.99	8.94	0.773	0.231	1.4	7.2

M14B
DOUBLE-SIDED
SECONDARY DOPANT = C
RESISTIVITY = 0.44
CONTROL PERCENTAGE = 112

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.563	20.67	0.468	74.54	8.72	0.750	0.200	1.0	0.0
0.567	19.84	0.464	72.87	8.45	0.752	0.260	1.0	0.0
0.571	20.73	0.481	75.56	9.09	0.768	0.200	1.2	0.0
0.570	20.46	0.480	73.54	8.82	0.757	0.200	1.2	0.0
0.567	20.49	0.472	72.98	8.61	0.741	0.200	1.0	0.0
0.572	20.67	0.480	75.64	9.08	0.768	0.200	1.2	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

STANDARD DEVIATION AND AVERAGE

0.0033	0.3311	0.0072	1.243	0.253	0.0105	0.0245	0.11	0.00
0.568	20.47	0.474	74.19	8.80	0.756	0.210	1.1	0.0

M14B1
 SINGLE-SIDED
 SECONDARY DOPANT = C
 RESISTIVITY = 0.44
 CONTROL PERCENTAGE = 102

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.550	18.01	0.465	64.77	7.53	0.760	0.240	0.6	7.2
0.553	18.43	0.450	66.55	7.49	0.734	0.440	0.7	7.2
0.562	18.50	0.474	67.26	7.97	0.767	0.260	0.9	7.2
0.555	18.35	0.443	68.34	7.57	0.743	0.500	0.7	7.2
0.561	18.86	0.456	70.14	8.00	0.756	0.500	0.9	7.2
0.550	18.26	0.454	68.16	7.74	0.770	0.320	0.8	7.2
0.558	18.47	0.462	68.06	7.86	0.763	0.220	0.8	7.2
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
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

0.0049	0.2580	0.0102	1.671	0.212	0.0130	0.1231	0.11	0.00
0.556	18.41	0.458	67.61	7.74	0.756	0.354	0.8	7.2

M15B
 SINGLE SIDED
 SECONDARY DOPANT = NA
 RESISTIVITY = 0.48
 CONTROL PERCENTAGE = 98

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.573	21.85	0.462	75.66	8.74	0.698	0.180	2.6	3.9
0.591	21.04	0.503	75.10	9.44	0.760	0.200	2.5	3.9
0.588	20.46	0.505	75.87	9.58	0.796	0.190	2.0	3.9
0.578	20.92	0.492	70.96	8.73	0.722	0.190	2.7	3.9
0.585	20.89	0.492	73.69	9.06	0.742	0.180	2.7	3.9
0.590	20.82	0.502	73.21	9.19	0.748	0.190	3.0	3.9
0.589	21.01	0.494	73.45	9.07	0.733	0.180	2.8	3.9
0.591	20.86	0.482	75.39	9.08	0.737	0.190	3.0	3.9
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

0.0067	0.3938	0.0141	1.666	0.299	0.0286	0.0071	0.32	0.00
0.586	20.98	0.492	74.17	9.11	0.742	0.188	2.7	3.9

M15B
 DOUBLE-SIDED
 SECONDARY DOPANT = NA
 RESISTIVITY = 0.48
 CONTROL PERCENTAGE = 100

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	-----	----	----	-----	-----	----	-----	-----
0.591	20.74	0.496	74.37	9.22	0.753	0.200	3.4	3.9
0.590	20.84	0.502	71.96	9.03	0.735	0.180	3.3	3.9
0.590	20.74	0.498	72.64	9.04	0.739	0.240	3.4	3.9
0.584	20.77	0.487	63.14	7.69	0.634	0.190	2.7	3.9
0.588	20.90	0.495	70.58	8.73	0.711	0.200	3.0	3.9
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	0.0698	0.0055	4.355	0.616	0.0475	0.0228	0.30	0.00
0.589	20.80	0.496	70.54	8.74	0.714	0.202	3.2	3.9

M15B1
 SINGLE-SIDED
 SECONDARY DOPANT = NA
 RESISTIVITY = 0.46
 CONTROL PERCENTAGE = 102

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
0.593	20.88	0.494	78.43	9.69	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

M15B1
 DOUBLE-SIDED
 SECONDARY DOPANT = NA
 RESISTIVITY = 0.46
 CONTROL PERCENTAGE = 97

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	-----	----	----	-----	-----	----	-----	-----
0.588	20.92	0.496	71.50	8.87	0.721	0.200	3.2	3.7
0.585	20.73	0.494	69.29	8.56	0.706	0.190	3.0	3.7
0.588	21.06	0.496	74.49	9.24	0.746	0.190	3.4	3.7
0.587	20.98	0.490	69.33	8.49	0.690	0.210	3.2	3.7
0.584	21.12	0.490	70.13	8.59	0.697	0.180	2.9	3.7
0.577	20.93	0.470	60.45	7.10	0.588	0.180	2.4	3.7
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

0.0042	0.1357	0.0099	4.706	0.726	0.0542	0.0117	0.35	0.00
0.585	20.96	0.489	69.20	8.47	0.691	0.192	3.0	3.7

M16B
 SINGLE SIDED
 SECONDARY DOPANT = P COMP
 RESISTIVITY = 0.42
 CONTROL PERCENTAGE = 101

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	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

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

M16B
 DOUBLE SIDED
 SECONDARY DOPANT = P COMP
 RESISTIVITY = 0.42
 CONTROL PERCENTAGE = 92

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.589	20.87	0.493	72.99	9.00	0.732	0.200	1.1	3.6
0.589	21.32	0.501	74.52	9.33	0.743	0.200	1.3	3.6
0.591	21.21	0.503	74.73	9.40	0.750	0.180	1.5	3.6
0.587	20.72	0.492	71.44	8.79	0.722	0.200	1.5	3.6
0.590	20.68	0.496	70.69	8.77	0.718	0.200	1.2	3.6
0.590	20.93	0.506	78.51	9.93	0.804	0.200	1.7	3.6
0.590	21.41	0.497	75.13	9.33	0.739	0.200	1.3	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
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0013	0.2909	0.0052	2.612	0.410	0.0287	0.0076	0.21	0.00
0.589	21.02	0.498	74.00	9.22	0.744	0.197	1.4	3.6

M17B
 SINGLE-SIDED
 SECONDARY DOPANT = TI
 RESISTIVITY = 0.54
 CONTROL PERCENTAGE = 97

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.560	18.42	0.458	67.61	7.74	0.751	0.800	0.8	2.1
0.556	18.39	0.475	65.42	7.77	0.760	0.340	0.8	2.1
0.555	18.78	0.453	67.20	7.61	0.730	0.580	0.8	2.1
0.554	18.80	0.460	60.15	7.84	0.752	0.260	0.7	2.1
0.558	18.68	0.444	66.28	7.36	0.706	0.560	0.7	2.1
0.558	18.42	0.467	67.74	7.91	0.769	0.240	0.8	2.1
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

STANDARD DEVIATION AND AVERAGE

0.0022	0.1924	0.0108	1.027	0.197	0.0230	0.2203	0.05	0.00
0.557	18.58	0.460	67.07	7.70	0.745	0.463	0.8	2.1

M17B
 DOUBLE-SIDED
 SECONDARY DOPANT = TI
 RESISTIVITY = 0.54
 CONTROL PERCENTAGE = 100

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.557	19.27	0.442	66.87	7.39	0.689	0.320	0.6	0.0
0.553	19.08	0.453	68.80	7.79	0.738	0.220	0.6	0.0
0.554	19.09	0.455	66.59	7.57	0.716	0.240	0.6	0.0
0.559	19.16	0.460	71.53	8.23	0.768	0.200	0.7	0.0
0.549	18.99	0.439	66.60	7.31	0.701	0.240	0.5	0.0
0.558	19.19	0.465	69.82	8.12	0.758	0.220	0.6	0.0
0.559	19.12	0.457	71.41	8.16	0.764	0.220	0.7	0.0
0.556	19.10	0.459	70.57	8.10	0.763	0.200	0.7	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

0.0035	0.0822	0.0090	2.121	0.369	0.0312	0.0385	0.07	0.00
0.556	19.12	0.454	69.02	7.83	0.737	0.233	0.6	0.0

M19B
 SINGLE-SIDED
 SECONDARY DOPANT = AL ONLY
 RESISTIVITY = 0.31
 CONTROL PERCENTAGE = 99

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	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	69.68	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

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

M1931
SINGLE-SIDED
SECONDARY DOPANT = AL ONLY
RESISTIVITY = 1.85
CONTROL PERCENTAGE = 86

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
-----	-----	-----	-----	-----	-----	-----	-----	-----
0.566	20.86	0.477	75.66	9.02	0.764	0.180	4.8	0.0
0.562	20.88	0.471	73.53	8.66	0.738	0.180	4.6	0.0
0.564	20.70	0.471	71.53	8.42	0.722	0.180	4.5	0.0
0.566	20.73	0.473	75.55	8.93	0.762	0.210	5.0	0.0
0.566	20.66	0.472	69.90	8.25	0.705	0.190	4.6	0.0
0.562	20.75	0.456	72.19	8.23	0.706	0.190	4.6	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

0.0020	0.0086	0.0072	2.292	0.342	0.0262	0.0117	0.18	0.00
0.564	20.76	0.470	73.06	8.59	0.733	0.188	4.7	0.0

M19B1
DOUBLE-SIDED
SECONDARY DOPANT = AL ONLY
RESISTIVITY = 1.85
CONTROL PERCENTAGE = 100

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
-----	-----	-----	-----	-----	-----	-----	-----	-----
0.574	21.00	0.475	78.58	9.33	0.774	0.300	2.6	0.0
0.574	20.94	0.478	77.97	9.32	0.775	0.440	2.2	2.2
0.569	20.79	0.456	76.88	8.76	0.741	0.240	2.6	0.0
0.559	20.92	0.452	61.14	6.91	0.591	0.220	2.0	0.0
0.573	20.98	0.480	78.08	9.37	0.780	0.240	3.0	0.0
0.572	21.15	0.481	78.91	9.49	0.784	0.940	2.0	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

0.0058	0.1182	0.0129	6.952	0.990	0.0751	0.2781	0.40	0.90
0.570	20.96	0.470	75.26	8.86	0.741	0.397	2.4	0.4

M19B2
 SINGLE-SIDED
 SECONDARY DOPANT = AL ONLY
 RESISTIVITY = 0.54
 CONTROL PERCENTAGE = 0.659986982

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.583	19.89	0.499	69.91	8.72	0.752	0.190	1.5	0.0
0.575	20.14	0.477	68.35	8.15	0.704	0.190	1.4	0.0
0.580	20.24	0.470	70.62	8.30	0.707	1.000	1.4	0.0
0.578	19.87	0.475	63.13	7.50	0.653	0.190	1.3	0.0
0.586	20.74	0.493	75.30	9.28	0.764	0.200	1.6	0.0
0.585	21.05	0.478	71.65	8.56	0.695	0.210	1.5	0.0
0.578	20.57	0.477	65.81	7.85	0.660	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
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0041	0.4468	0.0105	3.974	0.587	0.0418	0.3037	0.11	0.00
0.581	20.36	0.481	69.25	8.34	0.705	0.311	1.4	0.0

M31B
 SINGLE-SIDED
 SECONDARY DOPANT = CU
 RESISTIVITY = 0.47
 CONTROL PERCENTAGE = 105

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
0.587	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

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

M31B
DOUBLE-SIDED
SECONDARY DOPANT = CU
RESISTIVITY = 0.47
CONTROL PERCENTAGE = 102

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.592	20.75	0.505	75.33	9.51	0.774	0.200	3.4	4.0
0.591	20.70	0.504	76.79	9.68	0.787	0.200	3.5	4.0
0.587	20.91	0.490	72.04	8.82	0.719	0.240	3.2	4.0
0.592	20.86	0.510	76.46	9.75	0.790	0.180	3.6	4.0
0.584	20.64	0.503	73.97	9.30	0.772	0.200	3.4	4.0
0.592	20.83	0.506	74.02	9.36	0.759	0.200	3.3	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

STANDARD DEVIATION AND AVERAGE

0.0034	0.0933	0.0068	1.784	0.332	0.0259	0.0197	0.14	0.00
0.590	20.80	0.503	74.77	9.40	0.767	0.203	3.4	4.0

M32B
SINGLE-SIDED
SECONDARY DOPANT = CR
RESISTIVITY = 0.47
CONTROL PERCENTAGE = 102

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	8.41	0.742	0.300	1.2	0.0
0.578	19.31	0.489	66.54	8.10	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

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

M32B
 DOUBLE-SIDED
 SECONDARY DOPANT = CR
 RESISTIVITY = 0.47
 CONTROL PERCENTAGE = 99

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
----	-----	----	----	-----	-----	----	-----	-----
0.568	19.46	0.465	60.02	6.98	0.631	0.200	1.0	0.0
0.580	19.44	0.493	72.28	8.91	0.790	0.200	1.3	0.0
0.578	19.40	0.492	71.08	8.74	0.780	0.200	1.2	0.0
0.576	19.51	0.476	64.85	7.72	0.687	0.200	1.1	0.0
0.578	19.33	0.495	69.04	8.54	0.765	0.200	1.2	0.0
0.577	19.23	0.486	65.33	7.94	0.716	0.200	1.1	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

0.0042	0.1010	0.0118	4.577	0.733	0.0618	0.0000	0.10	0.00
0.576	19.39	0.485	67.10	8.14	0.728	0.200	1.2	0.0

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX IV

NOTCH SPACING (N.S.) FOR ANALYTICAL AND SOLAR CELL WAFERS

Sample #	Analytical	Single		Double	
	N.S. (mm)	Avg. (mm)	σ (mm)	Avg (mm)	σ (mm)
M1A	10.5	14.1	1.53	--	--
M1B*	7.5	8.8	0.378	7.5	0.535
M1C	11.0	14.1	1.81	--	--
M2B1	8.0	6.8	0.267	--	--
M2B2	16.5	20.9	0.694	18.2	10.3
M2C	9.0	9.7	0.931	--	--
M3B	12.0	15.3	1.73	21.3	4.25
M4B	9.5	13.3	2.31	--	--
M4B1	8.5	10.1	0.904	9.0	1.28
M5B	8.0	9.4	0.694	--	--
M5B1*	13.5	13.3	0.530	13.3	0.378
M6B	12.0	13.3	2.95	15.2	1.45
M7B	19.5	25.3	0.799	22.4	2.72
M8B	18.5	21.4	1.35	21.9	5.25
M8B1	6.5	9.3	1.71	--	--
M9B	18.5	22.0	2.24	--	--
M9D1	10.5	22.8	0.707	23.9	0.821
M10B	7.5	13.7	1.22	9.7	1.36
M11B	12.0	12.7	0.458	10.5	0.463
M13A*	8.5	9.3	1.19	10.0	1.10
M13B	10.0	12.1	0.954	17.6	1.66
M13C	12.0	13.3	0.463	18.3	0.964
M14B	12.5	4.8	1.22	9.9	4.59
M14B1	9.5	4.1	1.08	--	--
M15B	18.5	19.5	0.534	17.2	0.594
M15B1	13.0	14.1	0.417	11.0	1.10
M16B	16.0	16.4	0.496	14.7	0.594
M17B	12.5	15.0	1.36	9.1	0.821
M19B	9.0	9.8	0.463	--	--
M19B1	13.5	14.8	0.530	10.6	0.835
M19B2	13.5	14.9	0.791	--	--
M31B	10.5	11.4	0.417	8.3	1.00
M32B	24.5	25.0	0.417	23.4	0.835
C1A	21.0	25.2	2.08	17.2	0.764
C1B	41.0	21.2	1.15	--	--
C2A	10.0	12.0	--	--	--
C2B	14.5	11.7	0.764	--	--
C2B1	21.0	7.5	3.50	15.0	0.500
C2C	19.5	41.5	0.500	--	--
C3A*	None	--	--	12.1	3.3
C4B	13.0	16.2	1.53	22.8	0.764
C5B	15.5	24.0	6.06	--	--
C6B	15.0	4.0	0.743	--	--
C7B	40.5	46.0	1.00	46.2	1.53
C8B	12.0	13.6	0.535	--	--
C8B1	8.0	3.7	0.764	14.3	0.290
C9B	39.5	38.7	7.77	--	--
C9B1	11.5	18.0	0.500	15.0	0.500
C10B	16.0	17.5	2.62	20.3	1.15
C10B1	13.0	15.6	1.03	6.4	1.18
C11B	44.0	46.8	0.577	--	--
C11B1	10.5	41.0	1.32	12.8	0.577
C12B	11.0	13.7	1.44	9.5	0.500
C13A	15.5	20.6	2.04	24.1	1.38
C13B	18.0	24.8	1.35	33.0	1.22
C13C	15.0	19.2	2.31	23.8	1.04
C14A	10.5	19.6	1.75	14.9	0.479
C14A1	10.5	19.6	0.894	4.1	0.854
C14A2	13.5	13.3	0.500	--	--
C15B	21.5	22.0	0.866	20.2	0.289
C16B	12.5	13.5	0.500	--	--
C16B1	11.0	14.0	1.50	8.8	0.289
C17B	7.0	10.3	1.60	5.6	0.479

*No notches available on wafers. Measurements indicate length of flat on wafers.