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DETERMINATION OF A DEFINITION OF SOLAR GRADE SILICON

Second Quarterly Report, January 1—March 31, 1976

D. E. Hill

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Monsanto Research Corporation
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Division of Solar Energy

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DETERMINATION OF A DEFINITION OF
SOLAR GRADE SILICON

Second Quarterly Report

by

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

for

JET PROPULSION LABORATORY
Pasadena, California

1 January - 31 March 1976

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MONSANTO RESEARCH CORPORATION

P. O. Box 8

St. Peters, Missouri 63376

NEW TECHNOLOGY

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

ABSTRACT

Solar device fabrication and evaluation are the key elements of this contract. Test devices from sixteen experimental crystals have been processed to date. A 12-chip LED, specifically developed for this project, now provides ten times more light than the standard lamp and allows meaningful measurements of the minority carrier lifetime in the substrate before processing. A clear relationship between τ and solar cell efficiency η is indicated. Certain trends are beginning to crystallize. For example, oxygen seems to be an undesirable secondary impurity. All Low-Oxygen (i.e., Float-Zone) crystals investigated in this contract not only have better τ values before and after processing but also make a more efficient solar cell. It also seems that nickel, manganese, magnesium, and even carbon may actually enhance solar cell performance. These trends require confirmation through additional experimentation. It is clear, however, that one element, titanium, literally kills solar cell performance.

In Czochralski crystal growth thirteen acceptable single crystals resulted from 23 runs. The most difficult dopants were Cr and Zr. Cr-doping caused persistent slag formation; Zr-doping so far has not given any useable single crystal. The presence of C, Fe, Cr, Mn, Ni, V, Al and oxygen in their respective matrices was confirmed by mass spectrometric analysis. Mg and Ti were not detected in the first two crystals so doped, and second generation crystals were grown with larger amounts of these impurities. A detailed study to confirm or correct the available data for solubility and segregation is underway.

All but one of the originally scheduled float-zone crystals and two second-generation crystals have been grown. The missing crystal will contain a combination of compatible secondary impurities. So far we have found four "compatible" elements: C, Mn, Ni, and Mg. What if a synergistic effect could be found! Compared to equivalent devices fabricated on Czochralski material, nearly all solar cells on float-zone crystal are about 22% more efficient.

All material prepared has been characterized and has been found to deviate considerably from semiconductor silicon standards. Typically 95% of a given series of standard P-type crystals targeted for 0.5 ohm cm would read 0.42 - 0.58. The experimental crystals had minority carrier lifetimes under 20 microseconds, well below standards. The structures of the contract samples also deviated from standard. Although zero-D crystal growth was achieved in all crystals, most metallographic tests showed etchpit formations and distributions.

The analytical technique used to date for the physical-chemical analysis is mass spectroscopy which has a superb sensitivity for

nearly all elements. Only titanium and magnesium have not been detected in the first series of samples analyzed. Emission spectroscopy is in progress now to complement the mass spectroscopic results. For the determination of C and O, IR absorption is used. Here the high carrier concentration in the "contaminated" silicon has resulted in zero transmittance in many samples. Thinner samples are now being used, trading detection limits for visibility.

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1. SUMMARY

1.1 PURPOSE AND OBJECTIVE OF WORK

The purpose of studying the influence of impurities and impurity content on the properties of single crystal silicon is to find maximum impurity concentrations that still make acceptable solar cell devices for terrestrial application.

The overall objective is to determine a definition of solar-grade silicon from the data obtained during the course of this study. This definition will be in the form of specifications for polycrystal silicon suitable as starting material for single crystal sheet, ribbon, or slice preparation for the high volume manufacture of terrestrial solar cells with efficiency equal to or greater than 12%.

1.2 APPROACH

Both Czochralski (Cz) and float-zone (Fz) technology are being employed in growing experimental single crystals to study the influence of commonly found impurities on solar cell performance against high- and low-oxygen background in silicon. To investigate thoroughly the effectiveness of a sawed surface, solar cell pairs are to be prepared on blanks with backside damage and on blanks which are completely damage free. All crystals are being characterized by electrical, metallographic, and chemical-physical analysis. A slice-locating system has been devised to correlate, without error, material characterizations with device performance. A simple solar cell manufacturing process is used which generates devices of reproducible efficiency from baseline, i.e., standard semiconductor grade 1-4 ohm cm P-type Czochralski silicon. Precise information on impurity content of the material and device performance data will permit definition of maximum allowable impurity levels in "solar-grade" silicon.

1.3 TECHNICAL STATUS

With 24 of the 27 crystals in the original experimental matrix grown and processed into samples and solar device blanks, the materials preparation phase of this contract is 90% complete. The material characterization is also 90% complete. Spark source mass spectroscopic analyses have been performed on samples of 21 crystals; this part of the contract is 78% complete. Solar devices have been fabricated on blanks from 16 crystals making this key phase of the experimental part of the contract ~60% complete at this time.

2. TECHNICAL PROGRESS

2.1 LOW-OXYGEN CRYSTALS - Kedar P. Gupta

All float-zoned crystals were prepared using a Monsanto zone refiner. The crystal growth process was described in the first quarterly report (October 1 - December 31, 1975). A flow diagram is given in Figure 1.

Crystal growth is generally carried out to result in 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., are maintained at the same values for each crystal as close as possible. A growth rate (zone travel rate) of 4.0 mm/min is maintained to avoid swirls (vacancy clusters) in the crystals which are formed at low growth rates.¹ Other growth parameters have been chosen to produce low radial resistivity gradient crystals.

The amount of impurity added in each run is calculated from the literature segregation coefficients. It has been assumed that normal segregation takes place during the crystallization ($k_{\text{eff}} = K_0$).

This may not be completely valid in some cases but the scarcity of data in the literature in this area makes it very difficult to apply any correction factor. The situation is further complicated due to many experimental problems, including:

- (a) In general, the segregation coefficients of most metals in silicon are very small, and their reliability is questionable.
- (b) The secondary impurity must be added during the last pass. Since the zone volume in the neck region is very small compared to the volume in the crystal body, the impurity must be added in the body of the crystal. This means at least 6-8 cm above the seed junction.
- (c) The secondary impurity must be dissolved and homogenized in the molten pool in a relatively short period - about 2-5 minutes in most cases.

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 indicates incomplete homogenization of the impurity. The quantity of impurities added in all successful runs were between one and two orders of magnitude below the solubility limit.

Figure 1. Flow Diagram for the Float-Zone Silicon Crystal Growth.

Carbon-doping of N-type and P-type crystals was done using an Ar/CH₄ gas mixture containing 1010 ppm of CH₄. This doping gas was mixed with the purge gas in the chamber. The effective CH₄ concentration in the chamber was close to 115 ppm.

Except for aluminum, the impurities did not noticeably affect the resistivity of the crystal. In the case of the aluminum-doped crystal, the rod resistivity was lowered from 0.48 ohm cm P-type to 0.36 ohm cm P-type. This corresponds to an aluminum concentration of 2.2×10^{16} atoms/cc as an electrically active impurity. Aluminum added in the crystal is 1.1×10^{17} atoms/cc (theoretical calculation). It is clear that only a fraction of the aluminum atoms are electrically active, which is in agreement with the results on Al-doped Cz crystals studied at the Westinghouse Research Laboratories in Pittsburgh.²

Table 1 summarizes the results on all float-zoned crystals prepared so far. It also includes results of the mass spectrographic analyses which will be described in detail in subsequent sections of this report.

A total of 20 float-zoned crystals have been prepared including all but one of the originally scheduled crystals, and a few make-up crystals. About 12 more crystals have to be prepared as part of the extended program. Owing to an unavoidable shutdown of the ZR machine, the crystal preparation will take a longer period than anticipated. It is now expected that all crystals will be completed by the end of next quarter (June 1976).

2.2 CZOCHEWSKI CRYSTAL GROWTH - HIGH OXYGEN CRYSTALS - W. F. Tucker

During the first quarter of 1976, some 23 attempts were made to grow the high oxygen crystals doped with the selected impurities. Of these attempts fifteen resulted in useable crystals. The results of all tries at pulling Czochralski crystals are given in Table 2.

The crystals were grown in an RF-powered puller under argon at 0.5 psig pressure. The crystal grown at 63 mm diameter on the [1-0-0] plane was rotated at 15 RPM while the crucible was rotated in the opposite direction at 10 RPM. The system used to control diameter used both temperature and pull rate changes to accomplish this. The silicon charge weight used was 3.0 kg except where noted in the table. Crystals were grown dislocation-free [i.e., < 500 etch pits/cm², by Sirtl (etch)] except for the nickel-doped crystal.

When a crystal failed, the cause for failure was determined by examination of both the portion of the crystal pulled and the residue left in the crucible. When slag particles caused twinning, no change in dopant level was made for the following attempt: however,

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

Crystal No.	Secondary Impurity	k_o	Conc. Range Req'd. by JPL (atoms/cc)	Amount added (mg)	Theoretical C_s (atoms/cc)	Experimental C_s (SSMS) (atoms/cc)	Comments
M-1-A	--	--	--	--	--	--	Boron doped - baseline
M-1-B	--	--	--	--	--	--	Boron doped - baseline
M-1-C	--	--	--	--	--	--	Boron doped - baseline
M-2-B	Fe	8×10^{-6}	$10^{14} - 10^{16}$	20.7	7.6×10^{14}	Not Detected	
M-3-B	Mn	$\sim 10^{-5}$	$10^{15} - 10^{16}$	14.0	6.6×10^{14}	1.5×10^{15}	In powder form
M-4-B	Ni	$\sim 10^{-4}$	$10^{15} - 10^{17}$	16.1	7.1×10^{15}	1.5×10^{16}	
M-5-B	V	$\sim 10^{-5}$	$10^{14} - 10^{15}$	11.0	5.6×10^{14}	4.0×10^{14}	
M-6-B	Zr	NA	$10^{14} - 10^{15}$	15.0	--	N.D.	
M-7-B	Mg	2×10^{-3}	$10^{15} - 10^{17}$	2.5	5.3×10^{16}	N.D.	Flashing Observed
M-8-B	Ti	10^{-5}	$10^{14} - 10^{15}$	10.0	5.2×10^{14}	N.D.	Flashing Observed
M-9-B	C	7×10^{-2}	$10^{15} - 10^{16}$	--	$\sim 1.0 \times 10^{16}$	3.1×10^{16}	Lost ZD due to C-saturation
M-10-B	Al	5×10^{-3}	$10^{16} - 10^{17}$	2.3	1.1×10^{17}	4.0×10^{17}	Lowered the crystal resistivity
M-13-A	--	--	--	--	--	--	Phosphorus doped - baseline
M-13-B	--	--	--	--	--	--	-do-
M-13-C	--	--	--	--	--	--	-do-
M-14-B	C	7×10^{-2}	$10^{15} - 10^{16}$	--	$\sim 1.0 \times 10^{16}$	Not Completed	Lost ZD due to C-saturation
Make-up							
M-2-B (a)	Fe	8×10^{-6}	$10^{14} - 10^{16}$	42.0	--	N.C.	
M-5-B (a)	V	$\sim 10 \times 10^{-5}$	$10^{14} - 10^{15}$	51.0	--	N.C.	

C_s = concentration in solid

Table 2. CZOCHELSKI CRYSTALS PULLED JAN. 1 - MARCH 31, 1976

Crystal Number	Primary Dopant			Secondary Dopant			Results of Growth Attempt
	Element	p Target	Actual ohm cm	Element	g/kg of Si	Melt Conc.	
C3 (011)	Boron	0.50	0.45	Fe	0.765	0.192×10^{20}	79.9% DF*
C4 (013)	Boron	0.50	0.45	Cr	62.5	16.86×10^{20}	Failed; Sol. Limit
C4 (022)	Boron	0.50	0.45	Cr	16.58	4.47×10^{20}	Failed; Sol. Limit
C4 (024)	Boron	0.50	0.45	Cr	1.85	0.499×10^{20}	Failed; Slag
C4 (024)	Boron	0.50	0.55	Cr	1.85	0.499×10^{20}	58% DF
C5 (018)	Boron	0.50	0.55	Mn	9.67	2.47×10^{20}	Failed; Sol. Limit
C5 (021)	Boron	0.50	0.44	Mn	0.717	0.183×10^{20}	87.8% DF
C6 (030)	Boron	0.50	0.52	Ni	1.674	0.392×10^{20}	Single Only
C7 (015)	Boron	0.50	0.52	V	0.910	0.251×10^{20}	71% DF
C8 (016)	Boron	0.50	--	Zr	9.76	1.50×10^{20}	Mach. Problem & Sol. Limit
C8 (029) 3/8	Boron	0.50	--	Zr**	0.957	0.147×10^{20}	<16% DF; Failure
C9 (019)	Boron	0.50	0.52	Mg	0.0043	0.0025×10^{20}	97.8% DF
C10 (012)	Boron	0.50	0.14	Al	0.963	0.501×10^{20}	55% DF
C11 (014)	Boron	0.50	--	Ti	0.683	0.200×10^{20}	<5% DF; Slag
C11 (017)	Boron	0.50	0.56	Ti	0.683	0.200×10^{20}	83.5% DF
C11 (027) 3/8	Boron	0.50	--	Ti**	1.667	0.488×10^{20}	<5% DF; Slag
C11 (027) 3/24	Boron	0.50	0.53	Ti**	1.667	0.488×10^{20}	67% DF
C13A (025)	Phos.	1.0 ohm	0.97	None	--	--	67% DF
C13B (025)	Phos.	0.1 ohm	0.15	None	--	--	91% DF
C13C (025)	Phos.	0.01 ohm	0.011	None	--	--	88% DF
C14 (028)	Phos.	0.01 ohm	0.125	C	0.00433	0.0152×10^{20}	77% DF

*Percent of total charge contained in the crystal as dislocation free material.

**These crystals were grown because the initial crystal showed no secondary dopant in the mass spec analysis.

when the crystal (and/or the residue) showed microcrystalline structure, it was judged that the solubility limit had been exceeded and the impurity level was reduced for the next try. The adjustment was made assuming that the impurity solubility limit given in the literature was correct and had been equalled at the point at which microcrystallinity had been initiated and a new segregation coefficient was estimated. The concentration of impurity in the liquid was adjusted to allow at least 50% of the melt to be incorporated in the crystal before precipitation would occur.

Estimates of the effective segregation coefficient have been made based on the amount of secondary impurity placed into the melt and that measured by mass spectroscopy at a point in the crystal. Since most of these impurities have very low theoretical coefficients, it is expected that the effective coefficients will be considerably higher at the growth rates used (i.e., 2.9 to 3.7 inches/hr).

Table 3. ESTIMATED EFFECTIVE SEGREGATION COEFFICIENTS

<u>Impurity</u>	<u>C_O</u>	<u>C_S @ % Frozen</u>	<u>k_{eff.}</u>	<u>k_{theo.}</u>
Fe	0.192 x 10 ²⁰	2.1 x 10 ¹⁵ 59	4.5 x 10 ⁻⁵	0.8 x 10 ⁻⁵
Cr	0.4999 x 10 ²⁰	4.1 x 10 ¹⁵ 32	5.6 x 10 ⁻⁵	1 x 10 ⁻⁷
Mn	0.183 x 10 ²⁰	1.2 x 10 ¹⁶ 66	2.3 x 10 ⁻⁴	1 x 10 ⁻⁵
V	0.251 x 10 ²⁰	7.0 x 10 ¹⁴ 44	1.6 x 10 ⁻⁵	1 x 10 ⁻⁵
Al	0.501 x 10 ²⁰	8.3 x 10 ¹⁸ 42	0.096	5 x 10 ⁻³

As expected, the effective k is higher than the theoretical k furnished by JPL but with chromium and aluminum the difference is greater than anticipated. These variances may be resolved by further mass spectroscopic (or emission spectroscopic) analyses.

2.3 MATERIAL CHARACTERIZATION - Mike Christ

Material was analyzed in crystal and slice form for electrical and metallographic properties. Table 4 shows the status of analysis to date. Actual analysis data has been published in monthly reports. A summary of this data along with test methods used and conclusions drawn to date are included here.

Crystals for analysis are received in as-grown form from both Czochralski and float-zone (Mon-X) processes. Material characterization begins with the cropping of the seed end taper section from the crystal at the point where the required diameter

Table 4. STATUS - ELECTRICAL/METALLOGRAPHIC ANALYSIS

<u>Electrical</u>	<u>Crystal Sections</u>		<u>Slices</u>	
	C1A	M1A	--	M1A
	C1C	M1B	C1C	M1B
	C2A	M1C	C2A	M1C
	C2B1	M2B1	C2B1	M2B1
	C2B2	M2B2	C2B2	M2B2
	C2C	M2C	C2C	M2C
	C3A	M3B	C3A	M3B
	C4B	M4B1	C4B	M4B1
	C5B	M4B2	C5B	M4B2
	C6B	M5B	C6B	M5B
	C7	M6B	C7	M6B
	C9B	M7B	C9B	M7B
	C10B	M8B	C10B	M8B
	C11	M9B	C11	M9B
	C13A	M10B	C13A	M10B
	C13B	M13A	C13B	M15B
	C13C	M13B	C13C	M13A
	C9 (3-8)	M13C	C9 (3-8)	M13B
	C11 (3-23)	M14B	C14A	M13C
	C14A	M15B		M14B
		M16B		M16B
<u>Metallographic</u>	C1A	M1A	C2A	M1A
	C1C	M1B	C2B1	M1B
	C2A	M1C	C3A	M1C
	C2B1	M2B1	C5B	M2B1
	C2B2	M2B2	C6B	M2B2
	C2C	M2C	C7	M3B
	C3A	M3B	C9B	M4B1
	C4B	M4B1	C10B	M4B2
	C5B	M4B2	C11	M5B
	C6B	M5B	C2B2	M6B
	C7	M6B	C4B	M7B
	C9B	M7B	C13A	M8B
	C10B	M8B	C13B	M9B
	C11	M9B	C13C	M10B
	C13A	M10B		M13A
	C13B	M13A		M13B
	C13C	M13B		M14B
	C9 (3-8)	M13C		M15B
	C11 (3-23)	M14B		M16B
	C14A	M15B		
		M16B		

specification is reached. This taper section is then etched in a solution of 57% nitric, 18% hydrofluoric, and 25% acetic acids until the cut surface has a bright finish. The taper and the opposite end of the crystal are then etched in a standard 1:1 Sirtl solution for 7 minutes. The taper is inspected microscopically for defects and by unaided-eye for preferential etching in a swirl pattern. The outer surface of the opposite end of the crystal is also inspected by unaided-eye for freeze-out damage. The opposite end of the crystal is then cropped approximately 6 mm from this damage. The length and weight of the cropped section are then measured.

Resistivity is then measured with a 4-point probe of 1.59 mm point spacing. Axial resistivity profile is determined by taking readings at 1 cm increments along the axis of the crystal. End readings are then taken at the center, at 1/2 radius and at 3 mm from the edge on each of four equally spaced radii on both ends of each crystal. Electrical conductivity type by hot probe technique is checked on each end and at approximately 25 mm increments along the axis of each crystal.

Crystals are then flatted on the 1-1-0 plane to provide crystallographic orientation for solar cell fabrication. They are also notched with two notches of increasing spacing from seed end to opposite end for slice identification with respect to approximate location from a crystal.

After slices have been cut from these crystals and cleaned, resistivity is read with a 4-point probe of 0.64 mm point spacing at center, at 1/2 radius and at 3 mm from the edge on each of four equally spaced radii. These readings are taken on a minimum of two slices from each end of each crystal. Readings are also taken at 3 mm increments from center to edge on four equally spaced radii on a minimum of one slice from each section. These readings are termed slice band resistivities.

Radial gradients are calculated from crystal end resistivities and slice resistivities according to the following equation.

$$\text{Radial Gradient (\%)} = \frac{\text{Edge } \rho - \text{Center } \rho}{\text{Center } \rho} \times 100$$

where edge ρ is the average of four resistivity readings taken at the intersections of four equally spaced radii with a circle of half the radius of the crystal ($R/2$), and with a circle with a radius of 3 mm less than the radius of the crystal section.

Resistivity variability in percent sigma is also calculated from the readings obtained from slice band resistivities. A value is calculated for each slice measured.

Distributions of the probability of occurrence of results of electrical analysis on all material processed to date are shown in Figures 2-5. These include average end center resistivities of crystals (Figure 2), crystal and slice radial gradients (Figures 3 and 4), and resistivity variability on a slice in percent sigma (Figure 5).

Electrical analyses of type and resistivity have not shown a detectable difference between experimental material with added secondary impurities and standard doped silicon. No significant deviations in radial gradient due to the added secondary impurities were detected. In some cases, however, the added secondary impurity did appear to have an effect on the ability to hit a resistivity target calculated solely on the basis of phosphorus or boron dopant. This is shown by the end center resistivity distribution in Figure 2, which, in addition to the results of Mon-X and Cz crystals from this test, shows a typical distribution for standard material.

After electrical analysis, slices are polished. A minimum sample of three slices per crystal is analyzed for metallographic defects. One slice is etched in a 1:1 Sirtl solution for 5 minutes. A second slice is etched in a 2:1 Sirtl solution for 10 minutes. The third slice is oxidized at 1100°C until a 12000 Å oxide layer has formed. This oxide is stripped with concentrated hydrofluoric acid. The slice is then Sirtl etched in a 2:1 solution for 10 minutes. Analysis of the three slices consists of microscope and unaided-eye inspection for defects.

Structural analysis after oxidation and Sirtl etch has revealed several interesting shapes of etching anomalies. The photos in Figures 6 and 7 show examples of these in comparison to a "normal" oxidized and Sirtl etched surface showing a single etch pit (Figure 8). A more thorough description of these etching anomalies is planned.

2.4 PHYSICAL AND CHEMICAL ANALYSIS - M. S. Wang

The analytical techniques used for impurity analysis are spark source mass spectrometry (SSMS), infrared absorption spectrophotometry (IR), and emission spectroscopy (ES). SSMS has inherently superb sensitivities for almost every element in the periodic table.

When the sample is received, SSMS is first used to investigate the elements and their concentrations present in the crystal. The

Figure 2. Crystal Section End Center Resistivity Probability.

Figure 3. Rod Gradient Probability

Figure 4. Slice Gradient Probability

Figure 5. Slice Resistivity Variability Probability

Figure 6. Photomicrograph of Sirtl-Etched Iron-Doped Crystal (M2B) (200X)

Figure 7. Photomicrograph of Sirtl-Etched Titanium-Doped Crystal (C11B) (200X)

Figure 8. Photomicrograph of Sirtl-Etched Standard Semiconductor-Grade Silicon Crystal (1 ohm cm N-Type) (200X)

second step is IR determination of interstitial oxygen and substitutional carbon because the technique is well accepted throughout the semiconductor industry. Emission spectroscopy is used as the third step to selectively determine some of the elements of interest as a complementary technique to confirm SSMS results.

Although work using all three techniques is in process, some of the data are not complete enough for meaningful presentation. Mainly, the data obtained to date from SSMS are presented in this report and some details concerning the technique will be discussed here. The IR and ES methods will be discussed in subsequent quarterly reports.

2.4.1 Sample Requirement for Analysis

The samples for analytical work are taken from the center of the crystal ingots. In the early stages of the work the samples were taken from three sections (such as M1A, M1B, and M1C or C1A, C1B, and C1C). We hoped to find that the impurities would be in these sections in different concentrations. This approach was found to be impractical and, later, doping was aimed to give the crystal one particular concentration only. The sample thicknesses obtained from slicing and polishing are as follows:

(1) Infrared Absorption Spectrophotometry (IR)

For the best results, $3\text{mm} \pm 1\%$ after polishing was selected. Both surfaces were required to be as parallel as possible. However, this thickness was found to be not ideal as the work progressed. The subject will be discussed in a later report.

(2) Spark Source Mass Spectrometry (SSMS)

For most samples a 0.5mm thickness was used, however, some analyses were done using a 0.75mm thick sample. The samples for SSMS received etching and cleaning just prior to use. Polishing was not required here.

(3) Emission Spectroscopy (ES)

The sample will be etched, cleaned, and then ground into a powder. Polishing is not required and thickness is not critical.

2.4.2 SSMS Instrumentation

A C.E.C. Model 110B spark source mass spectrometer is used for analysis. The original equipment has been modified and updated in many respects to improve the quality and efficiency of the instrument. The diffusion pumps in the source and in the analytical

sectors had been replaced with ion pumps. This conversion allows one to reach the ultimate vacuums in a relatively short time and reduce the undesirable background for determination of carbon and oxygen.

Another major improvement is a multiple specimen holder³ which allows up to eight electrode pairs of the same matrix to be mounted in the source. This not only improves the sample handling efficiency by changing the sample without vacuum fluctuation but stabilizes the conditions for oxygen and carbon determination by SSMS.

Whenever necessary, a strip of aluminum foil is used to cover the matrix lines on the photographic plate to reduce background so that detection of a weak signal is possible by improving signal-to-noise ratio.

A Jarrell-Ash Model 200 microphotometer is used to record the line intensity by reading percent absorption. The data then are processed through a computer (CDC 6600) to obtain parts per million by weight (ppmw), parts per million atomic (ppma), and number of atoms per cc.

The details of sample cleaning, source conditions, data processing through the computer, and others are more appropriate for the final report. This report will be limited to a description of those details necessary for the data presented to date.

2.4.3 Analytical Data from SSMS

The analyses of 14 Czochralski (Cz) samples and 16 Float-Zone (Fz) samples have been completed by SSMS. The data are summarized in Tables 5 and 6. Although some rounding off was done on the numbers, the data are basically the output of the computer. One should not be misled by the accuracy expressed by the computer printout of results. As an example, boron for ClA reads $0.62 \text{ atoms/cc} \times 10^{16}$. 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. The number is subject to the limitation of accuracy and precision of the technique used. Since the correlation study of the kind and concentration of impurity elements with performance of the solar cells is still in an early stage and data from SSMS might need more investigation, Tables 5 and 6 are left as the computer expressed the results.

As stated in the Second Monthly Technical Progress Report of this program Cz crystal is always high in oxygen and the data in Tables 5 and 6 really show the difference in oxygen content between the two types of crystals. Some statistical treatment will be done on the oxygen content upon the completion of all of the samples.

Table 5. IMPURITIES DETERMINED BY SPARK SOURCEMASS SPECTROMETRY (CZ)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	N.D. 0.09	0.14	0.09	0.01	EST 0.044	N.D. 0.01	N.D. 0.007	0.082	N.D. 0.009	0.43	N.D. 0.20	N.D. 0.02	N.D. 0.007	N.D. 0.006	N.D. 0.013		N.D. 0.032	N.D. 0.016
C2A	B	C 0.1~1	0.68	7.4	INT	250	0.31	0.03	N.D. 0.01	N.D. 0.17	N.D. 0.1	0.20	N.D. 0.03	0.004	EST 0.13	N.D. 0.01	N.D. 0.007	N.D. 0.009	N.D. 0.01	N.D. 0.15	N.D. 0.21	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.036	N.D. 0.016
C2B	B	C 0.1~1	0.76	6.7	INT	120	0.25	0.05	N.D. 0.01	N.D. 0.13	N.D. 0.11	N.D. 0.04	0.23	0.04	EST 0.2	N.D. 0.01	N.D. 0.008	N.D. 0.05	N.D. 0.01	N.D. 0.17	N.D. 0.22	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.036	N.D. 0.017
C2C	B	C 0.1~1	120	6.5	INT	220	2.2	0.06	N.D. 0.01	N.D. 0.16	N.D. 0.16	N.D. 0.21	0.13	0.06	EST 0.09	N.D. 0.01	N.D. 0.008	0.034	N.D. 0.01	N.D. 0.16	N.D. 0.24	N.D. 0.02	N.D. 0.008	N.D. 0.005	N.D. 0.013	N.D. 0.05	N.D. 0.036	N.D. 0.018
C3A	B	Fe 0.01~1	0.97	0.52	INT	140	1.3	0.09	N.D. 0.01	N.D. 0.22	N.D. 0.15	N.D. 0.04	0.16	0.04	EST 0.033	N.D. 0.01	N.D. 0.007	N.D. 0.008	N.D. 0.009	0.21	N.D. 0.20	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013		N.D. 0.036	N.D. 0.018
C4B	B	Cr 0.01~1	0.92	0.82	INT	270	0.42	0.03	N.D. 0.01	N.D. 0.12	N.D. 0.11	N.D. 0.03	N.D. 0.03	0.014	EST 0.072	N.D. 0.01	N.D. 0.008	0.41	N.D. 0.01	N.D. 0.17	N.D. 0.22	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.036	N.D. 0.017
C5B	B	Mn 0.1~1	1.1	1.0	INT	160	0.30	0.05	N.D. 0.01	N.D. 0.18	N.D. 0.11	0.22	0.15	0.03	N.D. 0.011	N.D. 0.011	N.D. 0.007	N.D. 0.01	1.2	N.D. 0.18	N.D. 0.22		N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.033	N.D. 0.017
C6B	B	Ni 0.1~1	0.76	0.28	INT	260	0.16	0.03	N.D. 0.01	N.D. 0.14	N.D. 0.10	N.D. 0.03	N.D. 0.02	0.01	N.D. 0.010	N.D. 0.012	N.D. 0.008	N.D. 0.01	N.D. 0.01	7.1	N.D. 0.16	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 0.01~0.1	0.93	0.72	INT	240	1.3	0.09	N.D. 0.01	N.D. 0.19	N.D. 0.11	0.17	0.15	0.04	N.D. 0.010	N.D. 0.011	0.07	0.28	N.D. 0.01	1.2	N.D. 0.22	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014		N.D. 0.036	N.D. 0.018
C9B	B	Mg 0.1~10	0.30	1.1	INT	69	0.88	0.03	N.D. 0.01	N.D. 0.17	N.D. 0.12	N.D. 0.04	N.D. 0.03	0.05	EST 0.1	N.D. 0.013	N.D. 0.008	N.D. 0.01	N.D. 0.01	N.D. 0.17	N.D. 0.23	N.D. 0.02	N.D. 0.008	N.D. 0.005	N.D. 0.015	N.D. 0.05	N.D. 0.034	N.D. 0.018
C10B	B	Al 1.0~10	1.1	1.1	INT	280	1.3	0.08	N.D. 0.01	83C	N.D. 0.12	0.26	0.10	0.04	N.D. 0.01	N.D. 0.011	N.D. 0.007	N.D. 0.009	N.D. 0.01	N.D. 0.15	N.D. 0.20	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014		N.D. 0.037	N.D. 0.014
C11	B	Ti 0.01~0.1	1.2	1.5	INT	220	0.87	0.02	0.01	N.D. 0.18	N.D. 0.11	N.D. 0.05	0.15	0.02	EST 0.05	N.D. 0.012	N.D. 0.008	N.D. 0.009	N.D. 0.01	N.D. 0.16	N.D. 0.20	N.D. 0.03	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.036	N.D. 0.018
C13C	P		N.D. 0.01	2.8	INT	320	0.27	0.04	N.D. 0.01	N.D. 0.27	270	N.D. 0.03	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

Table 6. IMPURITIES DETERMINED BY SPARK SOURCE
MASS SPECTROMETRY (F2)

Expressed as (Atoms/cc) x 10¹⁶

INT = Interference

EST = Estimated

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

Crystal Number	Primary Impurity	Secondary Impurities Added	B	C	N	O	F	Na	Mg	Al	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Ga	Ge	Zr	Mo	Ag	
M1A	B	--	0.56	2.8	INT	6.5	1.3	0.03	N.D. 0.01	N.D. 0.13	N.D. 0.12	0.26	0.16	0.014	EST 0.09	N.D. 0.01	N.D. 0.007	0.06	N.D. 0.01	N.D. 0.17	N.D. 0.22	N.D. 0.05	N.D. 0.007	N.D. 0.007	N.D. 0.013		N.D. 0.01	N.D. 0.018	
M1B	B	--	3.9	0.34	INT	3.2	0.19	0.03	N.D. 0.0009	N.D. 0.15	N.D. 0.11	N.D. 0.033	N.D. 0.025	9.7	N.D. 0.01	N.D. 0.01	N.D. 0.007	N.D. 0.009	N.D. 0.01	N.D. 0.17	N.D. 0.22	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.014	N.D. 0.05	N.D. 0.04	N.D. 0.02	
M1C	B	--	34	0.38	INT	6.0	0.59	0.04	N.D. 0.009	N.D. 0.24	N.D. 0.16	0.39	0.15	0.016	N.D. 0.009	N.D. 0.01	N.D. 0.007	0.04	N.D. 0.009	N.D. 0.15	N.D. 0.21	N.D. 0.02	N.D. 0.006	N.D. 0.005	N.D. 0.013	N.D. 0.05	N.D. 0.035	N.D. 0.016	
M2B	B	Fe	0.06	1.2	0.47	INT	5.6	0.21	0.07	N.D. 0.01	N.D. 0.24	N.D. 0.12	0.051	0.085	0.022	N.D. 0.01	N.D. 0.01	N.D. 0.007	N.D. 0.009	N.D. 0.009	N.D. 0.14	N.D. 0.2	N.D. 0.02	N.D. 0.0065	N.D. 0.005	N.D. 0.012		N.D. 0.034	N.D. 0.017
M2B2	B	Fe	0.08	1.4	0.52	INT	8.5	0.25	0.06	N.D. 0.009	N.D. 0.22	N.D. 0.12	0.056	0.15	0.027	EST 0.06	N.D. 0.01	N.D. 0.007	N.D. 0.009	N.D. 0.009	N.D. 0.16	N.D. 0.21		N.D. 0.007	N.D. 0.005	N.D. 0.014		N.D. 0.036	N.D. 0.018
M2C	B	Fe	0.06	3.0	0.65	INT	9.4	4.0	0.03	N.D. 0.008	N.D. 0.33	N.D. 0.14	N.D. 0.07	N.D. 0.025	N.D. 0.0024	EST 0.03	N.D. 0.01	N.D. 0.0065	N.D. 0.009	N.D. 0.009	N.D. 0.14	N.D. 0.20	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013		N.D. 0.036	N.D. 0.017
M3B	B	Mn	0.07	1.2	0.20	INT	2.9	0.15	0.045	N.D. 0.008	N.D. 0.22	N.D. 0.11	N.D. 0.027	N.D. 0.022	0.01	N.D. 0.009	N.D. 0.01	N.D. 0.006	0.06	0.15	N.D. 0.13	N.D. 0.17	N.D. 0.02	N.D. 0.006	N.D. 0.004	N.D. 0.01	N.D. 0.04	N.D. 0.026	N.D. 0.013
M4B	B	Ni	0.07	0.55	0.21	INT	2.7	0.16	0.05	N.D. 0.009	N.D. 0.11	N.D. 0.11	0.05	N.D. 0.028	0.016	N.D. 0.01	N.D. 0.01	N.D. 0.007	0.15	N.D. 0.01	0.96	1.5	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013		N.D. 0.034	N.D. 0.017
M4B2	B	Ni	0.07	0.88	0.44	INT	4.6	0.37	0.045	N.D. 0.01	N.D. 0.22	N.D. 0.11	0.36	0.19	0.033	N.D. 0.01	N.D. 0.01	N.D. 0.007	0.02	N.D. 0.009	N.D. 0.14	0.62	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013		N.D. 0.032	N.D. 0.016
M5B	B	V	0.06	0.75	0.31	INT	2.7	0.17	0.056	N.D. 0.01	N.D. 0.2	0.21	0.12	N.D. 0.03	0.025	N.D. 0.01	N.D. 0.01	0.01	0.025	N.D. 0.01	N.D. 0.15	N.D. 0.21	N.D. 0.02	N.D. 0.007	N.D. 0.005	N.D. 0.013		N.D. 0.034	N.D. 0.017
M6B	B	Zr	1.1	0.25	INT	2.6	0.16	0.034	N.D. 0.01	N.D. 0.16	N.D. 0.13	N.D. 0.038	N.D. 0.028	0.011	N.D. 0.012	N.D. 0.01	N.D. 0.007	N.D. 0.008	N.D. 0.008	N.D. 0.14	N.D. 0.15	N.D. 0.015	N.D. 0.005	N.D. 0.004	N.D. 0.008	N.D. 0.03	N.D. 0.02	N.D. 0.09	
M7B	B	Mg	5.	1.2	0.35	INT	5.8	0.29	0.05	N.D. 0.01	N.D. 0.2	N.D. 0.15	N.D. 0.064	N.D. 0.03	0.024	N.D. 0.011	N.D. 0.01	N.D. 0.007	N.D. 0.008	N.D. 0.009	N.D. 0.14	N.D. 0.22	N.D. 0.022	N.D. 0.0075	N.D. 0.005	N.D. 0.013	N.D. 0.045	N.D. 0.032	N.D. 0.016
M8B	B	Ti	0.05	1.1	0.21	INT	4.5	0.20	0.074	N.D. 0.01	N.D. 0.27	N.D. 0.27	N.D. 0.1	N.D. 0.04	0.054	N.D. 0.012	N.D. 0.01	N.D. 0.007	N.D. 0.009	N.D. 0.009	N.D. 0.14	N.D. 0.16	N.D. 0.015	N.D. 0.0052	N.D. 0.0036	N.D. 0.009	N.D. 0.03	N.D. 0.02	N.D. 0.009
M9B	B	C	0.6	3.1	INT	2.2	1.8	0.035	N.D. 0.009	N.D. 0.17	N.D. 0.1	N.D. 0.03	N.D. 0.022	0.01	EST 0.016	N.D. 0.01	N.D. 0.008	0.01	0.01	0.17	0.23	0.05	0.008	0.0057	0.015	0.054	0.03	N.D. 0.013	
M10B	B	Al	11	1.4	0.34	INT	3.4	0.57	0.07	N.D. 0.01	N.D. 0.14	N.D. 0.24	0.21	0.037	N.D. 0.01	N.D. 0.01	N.D. 0.007	N.D. 0.002	N.D. 0.009	N.D. 0.15	N.D. 0.22	N.D. 0.022	N.D. 0.007	N.D. 0.005	N.D. 0.015	N.D. 0.05	N.D. 0.035	N.D. 0.017	
M15B	B	Fe	1.6	0.92	0.23	INT	4.1	0.24	0.023	N.D. 0.013	N.D. 0.2	N.D. 0.12	N.D. 0.04	N.D. 0.03	0.05	EST 0.04	N.D. 0.01	N.D. 0.007	N.D. 0.06	N.D. 0.01	N.D. 0.14	N.D. 0.17	N.D. 0.017	N.D. 0.006	N.D. 0.004	N.D. 0.011	N.D. 0.037	N.D. 0.027	N.D. 0.013

The carbon content of both the Cz and Fz crystals is fairly low, and statistical treatment will also be carried out at the completion of the program. Unfortunately nitrogen (N^{14}) is interfered with by multiply charged ions of the matrix element Si^{28} , and its determination has not been possible.

Boron is heaviest in the C section of the crystal as shown in ClC, C2C, and M1C. Boron was not detected in ClC crystal, which is doped only with phosphorus. The concentration of boron in the oxygen crystal varies to some degree. The reason is not known.

Two elements from the alkali group, sodium and potassium, are detected in low concentrations in every crystal. Fluorine is also consistently detected, albeit in low concentrations. The occasional appearance of sulfur and chlorine in both processes is also evident. Calcium is not consistently present in the crystals. SiC occasionally interferes with the Ca line. Therefore, values given in the Table are estimates only.

In all cases, when the crystals are carbon-doped, the SSMS-determined C concentration increased accordingly.

Iron doping in Cz crystal was successful. A significant amount of iron was detected in the C3 crystal. However, iron was not detected in the Fz material (M2 series). The concentration of iron present was apparently below the detection limit. Iron was detected in crystals ClC, C7, and M4B even though the element was not intentionally added to these crystals. This unexpected contaminant in the crystals may be difficult to avoid because iron is a major component of stainless steel which is a major construction material of the source chamber. Another element in the stainless steel is chromium which is frequently seen in the analysis.

Manganese is easy to detect in all Mn-doped crystals. However, a usually undesirable and unexpected element, copper, was detected in the C5B crystal. From our experience in the field of trace or ultra-trace element study, this type of mishap, contamination, is possible even when ultimate care has been taken to avoid the contamination.

Nickel is another element which is readily detectable in the crystal after doping with this element. Chromium showed up inadvertently in some crystals as mentioned previously. Vanadium behaved similarly to nickel.

Magnesium doping created considerable problems and will be discussed in the section on crystal growing. In spite of a large amount of the element added, the dopant was not detected in the final product. Magnesium-doped crystals will be investigated with emission

spectroscopy because this technique is extremely sensitive to the presence of Mg.

Aluminum, on the other hand, was detected in much higher concentrations than expected in both Al-doped ingots. This might be evidence of a "segregation in the crystal" problem since only 2 to 3 mg of sample is consumed during the spark excitation and the particular portion consumed may not be representative of the entire sample in question. This element will also be carefully studied by emission spectroscopy to clarify some of the questions.

The detection of titanium and zirconium are also difficult. The reason is not well understood at this time.

2.4.4 Remarks

The preceding section contains some observations based on the SSMS data available now. They are not to be taken as the final conclusions or results of our work. In most cases of trace or ultra-trace analysis, some problems of contamination are inevitable. In other cases, segregation problems can yield nonrepresentative data. SSMS is currently being used to analyze additional samples of this program, and repeated analyses of some samples will be performed if necessary to clarify the results. IR analysis will be discussed in the next quarterly report. Samples which are suitable for emission spectroscopy will be analyzed to investigate segregation and contamination problems. All of these three techniques, SSMS, IR, and ES, will supplement one another, and the final analytical results will be used to correlate the performance of solar cell fabricated in our laboratory with material properties as determined by analyses.

2.5 SOLAR CELL FABRICATION AND TESTING

2.5.1 Summary

Tables 7 and 8 summarize the results of this work thus far, including crystal preparation, analyses, and solar cell evaluations. Details of the various types of information are found later in the report. All samples from each ingot were taken from very close to the same location as verified by noting the similar notch spacing.

The first two columns of data list the measured resistivity of the silicon and the boron concentration as determined by spark source mass spectroscopy (SSMS). If we average the resistivity and the boron content for all samples between 0.4 and 0.6 ohm cm we find that a resistivity of 0.49 ± 0.5 ohm cm corresponds to a SSMS boron concentration of $0.96 \pm 0.25 \times 10^{16}$ atoms/cc. Using the standard conversion this resistivity corresponds to about 4×10^{16} acceptors/cc. Thus the SSMS boron concentration is about four times too low

Table 7. SUMMARY OF EXPERIMENTAL RESULTS FOR BORON DOPED MON-X CRYSTALS

<u>Crystal Number</u>	<u>ρ (ohm cm)</u>	<u>Boron Conc. $\times 10^{16}$</u>	<u>Secondary Impurity</u>	<u>Target Conc. $\times 10^{16}$</u>	<u>SSMS* Measurement Conc. $\times 10^{16}$</u>	<u>Relative** Solar Cell Efficiency</u>
M1A	1.1	0.56	--	--	--	
M1B	0.15	3.9	--	--	--	1.00
M1C	0.04	34	--	--	--	
M2B	0.50	1.2	Fe	0.06	<0.16	
M2B2	0.40	1.4	Fe	0.08	<0.16	0.89
M2C	0.058	3.0	Fe	0.06	<0.14	
M3B	0.44	1.2	Mn	0.07	0.15	1.05
M4B	0.59	0.55	Ni	0.07	1.5	1.05
M4B2	0.48	0.88	Ni	0.07	0.62	1.08
M5B	0.50	0.75	V	0.06	0.01	0.69
M6B	0.48	1.1	Zr	--	<0.03	0.96
M7B	0.46	1.2	Mg	5	<0.01	1.09
M8B	0.48	1.1	Ti	0.05	<0.01	0.33
M9B	0.46	0.6	C	--	3.1	
M10B	0.37	1.4	Al	11	40	
M15B	0.48	0.9	Fe	1.6	<0.14	0.88

*SSMS = Spark source mass spectroscopic analysis

**Solar cell efficiency of crystal in question divided by solar cell efficiency of baseline crystal.

Table 8. SUMMARY OF RESULTS FOR BORON DOPED CZOCHRALSKI CRYSTALS

<u>Crystal Number</u>	<u>ρ (ohm cm)</u>	<u>Boron Conc. $\times 10^{16}$</u>	<u>Secondary Impurity</u>	<u>Target Conc. $\times 10^{16}$</u>	<u>SSMS* Measurement Conc. $\times 10^{16}$</u>	<u>Relative** Solar Cell Efficiency</u>
C1A	0.52	0.62	--	--	--	(0.93)***
C1C	0.015	110	--	--	--	0.087
C2A	0.56	0.68	C	0.1-1	7.4	
C2B	0.55	0.76	C	0.1-1	6.7	(1.04)
C2C	0.015	120	C	0.1-1	6.5	
C3A	0.49	0.97	Fe	0.01-1	0.21	(0.85)
C4B	0.56	0.92	Cr	0.01-1	0.41	
C5B	0.46	1.1	Mn	0.1-1	1.2	
C6B	0.47	0.76	Ni	0.1-1	7.1	(1.08)
C7B	0.55	0.93	V	0.01-0.1	0.07	(0.63)
C9B	1.6	0.30	Mg	0.1-10	<0.01	
C10B	0.15	1.1	Al	1-10	830	0.28
C11	0.54	1.2	Ti	0.01-0.1	<0.01	0.24

*SSMS = Spark source mass spectroscopic analysis

**Solar cell efficiency of crystal in question divided by solar cell efficiency of baseline crystal.

***Results based on limited samples; reruns of these samples are under-way.

compared with resistivity results for these samples. This serves to emphasize that while the SSMS results are correct in order of magnitude, they may need calibration factors if detailed comparisons are considered.

The second, third, and fourth columns list the secondary impurity added, the target concentration range for this impurity and the level of the impurity detected by SSMS. The final column lists the relative solar cell efficiency, i.e., the solar cell efficiency of cells made from the sample in question divided by the efficiency of cells made from the baseline silicon.

Iron was detected in one sample (Cz) of the two in which it was expected to exceed the detection limits. However, the solar cell efficiency was reduced in each iron-doped sample, indicating that some iron was probably incorporated into the Si in each case.

The presence of Mn, Ni, Mg, and C in the degree of doping attained in this silicon seems to have improved the solar cell performance slightly. In all cases except Mg the impurities were detected by SSMS so there can be little doubt about their presence. Some sort of "gettering" action could explain these results.

Vanadium degrades the solar cells and the higher V concentration sample exhibits somewhat more efficiency reduction.

The effect of Zr is in question since the element is not detected analytically and the solar cell performance is very near that of the baseline samples.

Titanium is not detected by SSMS but severely reduces the solar cell efficiency. In this case either Ti is not detected by SSMS for some unknown reason, or else the solar cell is degraded by less than 10^{14} Ti atoms/cc.

The Czochralski Al-doped ingot yielded an Al concentration of 8.3×10^{18} atoms/cc, which did not affect the resistivity very much. The fact that the Mon-X (Fz) ingot also has a large Al concentration makes it less likely that the results are caused by a large Al precipitation in the region analyzed. It seems likely then, that the aluminum is rendered inactive electrically (perhaps by combination with oxygen) but fairly well dispersed throughout the samples. These aluminum complexes may be a recombination center, however, so that the lifetime and thus the solar cell performance is severely degraded as was noted experimentally. Lower aluminum concentrations or Al in Mon-X (Fz) crystals, where much less oxygen is present, will very likely behave differently.

2.5.2 Solar Cell Fabrication

2.5.2.1 Diffusion

The solar cell diffusions are carried out as described previously except that the standard diffusion time has been decreased from 20 to 15 minutes. The sheet resistances for 10, 15, 20, and 30 minute diffusions are respectively about 59, 55, 50 and 44 ohms/ $\square$.

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

A limited examination of lower diffusion temperatures (825°C) was carried out. These show little or no advantage in resultant cell efficiency over the 850°C diffusion presently in use. In addition, the appearance of some surface haze indicated that the details of the gas flows etc. would have to be re-optimized. Since our base-line efficiency is satisfactory, and only limited time is available, and the main aim of this work is to obtain relative results between various secondary dopants, the decision was made to use 850°C, 15 minute diffusion as described earlier for our standard diffusion.

2.5.2.2 Fabrication

The Ti and Ag metalization system has been upgraded in the following ways. First, all unused fixturing was removed from the vacuum system. In addition, a heat shield was constructed for the Ag boat so that the wafers see only the molten silver and not the rest of the hot boat and leads. Finally, additional electrical "feed-through's" were incorporated in the vacuum system so that a second Ti filament could be installed in a shielded position of the vacuum chamber. This filament is 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 10 times better than that previously possible.

The masks used to determine the solar cell metalization patterns have been remade for the following reasons. First, difficulties were encountered while attempting to align small wafers (all M series wafers) using a four-cell mask designed for larger wafers. Thus a one-cell mask is needed. In addition, it was desired to have some diagnostic patterns for contact resistance, sheet resistance, and small-area diodes fabricated on each wafer along with the solar cell. Finally, the buss bar contact on the mask was larger than necessary so it was reduced in width from 0.060 in. to 0.040 in.

Both four-cell and one-cell masks have been fabricated with these changes using the basic design of masks C-71 and C-72 (see Figure 2 and Figure 3 in 1st quarterly report). This reduces the metal coverage to 14.1% for C73 and C75 (similar to C71) and to 9.9% for C74 and C76 (similar to C72).

2.5.2.3 Lifetime Measurements

a. Photoconductive Decay Lifetime Determinations

The existing lifetime-measuring equipment used in 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 centers on relatively low resistivity silicon (~ 0.5 ohm cm) which has been doped in addition with certain specified materials that further decrease the lifetime. In practically all cases this brings 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) is an obvious candidate for the job. A Monsanto ME7140 is among the most efficient infrared emitters commercially available. This type of liquid epitaxially grown junction can have a turn-off time of up to about 0.5 microsecond, but individual units may be found with values closer to 0.2 microsecond.

Experience has shown that this LED results in satisfactory measurements for samples with resistivities of about 1 ohm cm or greater. However, when one is dealing with resistivities of 0.5 ohm cm and below, the modulation available is decreased both by the higher carrier concentration and the accompanying lower lifetimes. For this reason a special LED has been fabricated using existing Monsanto facilities. This LED has 12 chips connected in series mounted on an insulating substrate on a TO-18 header (same size as ME7140), providing roughly one order of magnitude more light without increasing the decay time. This source has extended the range of our lifetime

capabilities, but decay times of less than about 0.5 microsecond are still a problem.

Samples for photoconductive decay measurements are fabricated from 330 microns thick silicon wafers which are polished on both sides. This is cut into strips about 3 mm wide, and two Ti/Ag or Al contacts are placed on either end with an active region about 6 mm long in the center. The contacts are shielded from direct exposure to the light source and the sample is illuminated from the side opposite to the contacts. The sample absorption provides a large degree of additional shielding of the contacts from the light. Two- and four-contact measurements have been compared and found to give essentially the same results. Samples with resistivities of 0.5 ohm cm and lower of the size described have resistances of about 50 ohms or lower so it is advantageous to use amplifiers etc. with 50-ohm impedance in the measuring systems. This minimizes the effects of stray capacitance and facilitates interconnecting the various components without degrading the response times. A schematic circuit for the photoconductive decay measurements is shown in Figure 9 and includes information on the various components used.

The results of the photoconductive decay measurements are tabulated along with the solar cell results in Table 9. The detailed interpretation of these decay times is not clear. In the absence of trapping effects, which may be less prevalent in material of this resistivity, the decay times would be a lower limit for the bulk lifetime. 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 by⁴

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

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 10.

The most limiting condition on the application of this expression is that of uniform excitation. To obtain some indication about the uniformity of the excitation, the relative emission spectra of two types of GaAs LED's⁵ has been plotted in Figure 11 along with the absorption coefficient for silicon.⁶ 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

Figure 9a. Photoconductive Decay Apparatus

Figure 9b. , Open Circuit Decay Apparatus

Table 9. EVALUATION OF PHOSPHORUS DIFFUSED BORON DOPED SOLAR CELLS
WITH SOME SECONDARY IMPURITIES. NO ANTIREFLECTION COATING OR DRIFT
FIELD BACK CONTACT 100 mW/cm² INCIDENT ENERGY DENSITY.

<u>Sample</u>	<u>Impurity</u>	<u>ρ</u> <u>(ohm cm)</u>	<u>V_{oc}</u> <u>Volts</u>	<u>I_{sc}/A</u> <u>mA/cm²</u>	<u>Eff.</u> <u>%</u>	<u>F.F.</u>	<u>I_{OCD}</u> <u>(μsec)</u>	<u>I_{PD}</u> <u>(μsec)</u>
10 Min Diff	--	1-2	0.571	19.20	7.77	0.709	2.0	--
15 Min Diff	--	1-2	0.578	19.31	8.25	0.738	1.9	--
20 Min Diff	--	1-2	0.575	18.98	7.99	0.733	1.5	--
30 Min Diff	--	1-2	0.572	18.88	7.67	0.710	1.4	--
C1A*	--	0.52	0.567	19.07	7.64	0.706	2.2	--
C1C	--	0.015	0.18	9.60	0.67	0.363	0.2	<0.5
C2B*	C	0.56	0.575	19.60	8.61	0.763	3.3	2.0
C3A*	Fe	0.49	0.554	18.32	7.05	0.695	0.9	<0.5
C6B*	Ni	0.47	0.578	19.83	8.88	0.775	2.3	3.2
C7B*	V	0.55	0.527	13.31	5.19	0.740	0.7	<0.5
C10B	Al	0.152	0.497	7.58	2.75	0.729	0.8	--
C11B	Ti	0.54	0.505	10.81	2.56	0.469	--	--
M1B	--	0.15	0.598	19.88	9.24	0.777	2.4	4.6
M2B2	Fe	0.38	0.582	19.38	8.73	0.774	2.3	~0.5
M3B	Mn	0.44	0.595	20.56	9.75	0.797	5.1	--
M4B	Ni	0.59	0.589	20.65	9.61	0.790	4.6	4.2
M4B2	Ni	0.48	0.592	20.52	9.51	0.784	4.3	4.3
M5B	V	0.50	0.551	15.00	6.42	0.776	0.3	<0.5
M6B	Zr	0.48	0.585	19.41	8.89	0.783	2.8	4.0
M7B	Mg	0.46	0.592	20.82	9.69	0.787	4.6	4.0
M8B	Ti	0.48	0.521	13.38	3.94	0.565	--	<0.5
M15B	Fe	0.48	0.573	18.42	8.11	0.768	1.1	~0.5

*Results based on limited samples; reruns of these samples are underway.

Figure 10. Relationship between τ and τ_{eff} for uniformly illuminated sample 330 μm thick for various bulk diffusion lengths with the surface recombination velocity as a parameter.

nonuniform excitation is bound to increase the effect of surface recombination on the results and essentially move the curves in Figure 10 for various s values to the left.

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 11. It has been experimentally observed that a silicon filter does not change the observed decay time although it does reduce the signal amplitude considerably.

It seems that the best we can hope to do with this type of measurement at the present is 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 sandblasted one seems attractive since the sensitivity to variation of s is small for $s \geq 10^4$ (see Figure 10). However, sandblasting the sample surface reduces the sensitivity to too large a degree to be tolerated. For this reason we have standardized on the Monsanto polished surface for our photoconductive lifetime samples.

b. Open Circuit Decay Technique

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.⁷ 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.

Using a 2 x 2 cm solar cell fabricated from 1-2 ohm cm material, curves of the type shown in Figure 12 are obtained. The circuit diagram for this measurement and the actual equipment used is shown in Figure 9. Obviously the level of injection must be high enough to be able to observe the linear portion of the decay. For these devices the slope is essentially unchanged for forward bias values of 0.1 to 1 amp. Values of 0.5 to 1.0 amp will be used in this work to permit an easier determination of the slope.

The initial drop in Figure 12 corresponds to a series resistance of about 0.2 ohm, which is a reasonable value for these cells.

Figure 11. 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.

Figure 12. 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.

Unfortunately, the open circuit decay of most cells examined in this work does not have such a distinctive form. The lower resistivity cells particularly seem to have curves which look more like Figure 13 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 14 shows the same cell as Figure 13 at 900 mA with external shunt values of 50 ohms, 270 ohms, and ∞ . This technique of observing the effect of shunt resistance increases ones confidence that the proper interpretation of these curves is being made. The results of these measurements are tabulated in Table 9 (and in more detail in Appendix I) along with the photoconductive decay measurements and the solar cell results.

2.5.2.4 Solar Cell Evaluations

When a solar simulator is used to test solar cells, there is always a question as to how the results obtained with the simulator are related to operation in actual sunlight. The following measurements were carried out in order to obtain at least some estimate as to the degree of agreement obtained between our simulator and "St. Louis clear-day-late-February" sunlight.

The solar cell and a thermopile were exposed to sunlight through an open window on 2/24/76 when the temperature was near 60°F. The solar cell was mounted on a temperature-stabilized block and the thermopile was in the same plane and as near as possible to the solar cell. Both viewed a rectangular pyramid of radiation coming from the sky through the window with a half-angle of about 9° around the sun. A series of measurements were taken between 3:00 pm and 3:30 pm when the thermopile indicated that the power received from the sun averaged about 83 milliwatts/cm².

The short circuit current measurements on the solar cell (4 cm² area) averaged 0.828 mA/mW with a standard deviation of about 2%. The difference is presumably caused by the different spectral output of the simulator and the sun. This indicates that our simulator evaluations are slightly conservative with respect to the sun performance for this particular day.

The absolute calibration of our simulator is, however, dependent on the thermopile calibration. In order to check this calibration, evaluations of the same cells were carried out at our laboratory and both JPL and Westinghouse. In both cases our efficiency evaluations were somewhat too high. For this reason our simulator was adjusted to agree with that of JPL. Efficiencies given in earlier reports should be multiplied by about 0.92 to agree with the current calibration. All measurements in this report are made with

Figure 13. Open Circuit Decay Waveform. Vertical scale 0.1 volt/div., Voltage zero is 2 divisions 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 14. 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.

the revised calibration. In addition the water filter was eliminated in the simulator since it has so little effect on the spectrum.⁸

Table 9 summarizes the solar cell evaluations and the lifetime determination carried out since the last quarterly report. Data for individual cells are tabulated in Appendix I for the samples which are not being re-run. The diffusion time studies were carried out on Czochralski crystals. The 15-minute diffusion was used for all samples except the 1st, 3rd, and 4th which were diffused as noted.

It is interesting to note that the baseline efficiency seems to be significantly higher for Float-Zone (Mon-X) baseline crystals than for Czochralski. This is being pursued further to determine if this is a truly meaningful result, or whether the particular ingots or processing steps may have been questionable.

It is further interesting to note that the C and Ni Czochralski samples as well as the Ni, Mn, and Mg Mon-X ones are better than the respective baseline ingots. This improvement is caused by increases in I_{sc} as well as in fill factor and may be related to some gettering action. The increases are relatively small, however, and the results will have to be confirmed in order to be sure that they are really significant.

The secondary impurities which degrade the efficiency, Al, V, Ti, and perhaps Fe and Mn are discussed in the summary sections of this report.

It is also interesting to compare results of the open circuit decay and the photoconductive decay lifetime determinations with each other and with the solar cell results. We see that the good cells have lifetimes of somewhat greater than about 1.5 microseconds while the slightly degraded cells have lifetimes of close to 1 microsecond and the definitely degraded cells have lifetimes of 0.8 microsecond or less. In this case also the correlations will become clearer as more data are accumulated and more experience is gained with the lifetime measurements.

3. PROJECTED ACTIVITIES FOR NEXT QUARTER

- Complete experimental crystal growth.
- Continue blank preparation and material characterization.
- Continue chemical-physical analysis for impurity content.
- Continue to manufacture solar cells from experimental blanks and measure cell performance.

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APPENDIX I

This Appendix lists results for individual solar cells and life-time samples. Zero's printed in a data column are an artifact of the computer program and indicate a lack of data rather than actual zero values. Standard deviations and averages are included at the bottom of each column.

C-1-C
 SINGLE-SIDED NONE
 RESISTIVITY= 0.015
 DIFFUSION NUMBER= 99
 CONTROL PERCENTAGE= 107.8
 FILE NUMBER= 1

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.189	9.93	0.122	25.43	0.73	0.413	0.200	0.1	0.0
0.130	9.51	0.088	20.55	0.45	0.366	0.200	0.2	0.0
0.049	10.00	0.027	20.62	0.14	0.284	0.300	0.5	0.0
0.043	9.96	0.025	19.09	0.12	0.279	0.300	0.5	0.0
0.384	9.61	0.238	27.50	1.64	3.443	0.600	0.1	0.0
0.189	9.10	0.125	20.14	0.63	0.366	0.600	0.1	0.0
0.173	9.39	0.126	19.78	0.62	0.384	0.400	0.2	0.0
0.282	9.27	0.159	24.50	0.97	0.372	0.800	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

STANDARD DEVIATION AND AVERAGE

0.1138	0.3388	0.0696	3.135	0.489	0.0572	0.2188	0.17	0.00
0.180	9.60	0.114	22.20	0.67	0.363	0.425	0.2	0.0

C-10-B
 SINGLE-SIDED AL
 RESISTIVITY= 0.152
 DIFFUSION NUMBER= 97
 CONTROL PERCENTAGE= 83.6
 FILE NUMBER= 2

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.508	8.03	0.402	29.85	3.00	0.736	0.400	0.8	0.0
0.505	7.90	0.392	28.85	2.83	0.708	0.400	0.8	0.0
0.491	7.10	0.414	25.68	2.66	0.763	0.320	1.0	0.0
0.501	7.68	0.408	28.12	2.87	0.746	0.400	0.8	0.0
0.495	7.55	0.406	28.26	2.87	0.767	0.400	0.8	0.0
0.488	7.41	0.396	25.04	2.48	0.686	0.380	0.6	0.0
0.494	7.23	0.404	26.43	2.67	0.747	0.360	0.8	0.0
0.494	7.76	0.400	26.00	2.60	0.678	0.320	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

STANDARD DEVIATION AND AVERAGE

0.0070	0.3227	0.0069	1.719	0.172	0.0340	0.0354	0.13	0.00
0.497	7.58	0.403	27.28	2.75	0.729	0.373	0.8	0.0

C-11
 SINGLE-SIDED TI
 RESISTIVITY= 0.54
 DIFFUSION NUMBER= 96
 CONTROL PERCENTAGE= 77
 FILE NUMBER= 9

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
0.500	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

M-1-B
 SINGLE-SIDED NONE
 RESISTIVITY= 0.15
 DIFFUSION NUMBER= 90
 CONTROL PERCENTAGE= 100
 FILE NUMBER= 1

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	0.503	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
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

M-2-B-2
 SINGLE-SIDED FE
 RESISTIVITY= 0.385
 DIFFUSION NUMBER= 88
 CONTROL PERCENTAGE= 94.5
 FILE NUMBER= 2

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	4.0
0.586	19.35	0.501	72.19	9.04	0.797	0.200	2.4	4.0
0.582	19.46	0.495	73.10	9.05	0.799	0.200	2.4	4.0
0.583	19.68	0.492	73.62	9.06	0.789	0.250	2.2	4.0
0.578	19.30	0.489	72.00	8.80	0.789	0.160	2.4	4.0
0.580	19.23	0.400	72.21	7.22	0.647	2.000	2.2	4.0
0.582	19.28	0.495	72.41	8.96	0.799	0.180	2.4	4.0
0.583	19.47	0.491	72.79	8.93	0.787	0.200	2.2	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

STANDARD DEVIATION AND AVERAGE

0.0026	0.1439	0.0331	0.543	0.619	0.0516	0.6356	0.15	0.00
0.582	19.38	0.481	72.60	8.73	0.774	0.429	2.3	4.0

M-3-B
 SINGLE-SIDED MN
 RESISTIVITY= 0.44
 DIFFUSION NUMBER= 87
 CONTROL PERCENTAGE= 99.4
 FILE NUMBER= 3

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

M-4-B-1
 SINGLE-SIDED NI
 RESISTIVITY= 0.59
 DIFFUSION NUMBER= 86
 CONTROL PERCENTAGE= 100.6
 FILE NUMBER= 4

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

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

M-4-B-2
 SINGLE-SIDED N1
 RESISTIVITY= 0.5
 DIFFUSION NUMBER= 85
 CONTROL PERCENTAGE= 105.5
 FILE NUMBER= 5

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
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

M-5-B
 SINGLE-SIDED V
 RESISTIVITY= 0.49
 DIFFUSION NUMBER= 84
 CONTROL PERCENTAGE= 0
 FILE NUMBER= 6

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.552	15.02	0.465	55.96	6.51	0.783	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
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

M-6-B
 SINGLE-SIDED ZR
 RESISTIVITY= 0.48
 DIFFUSION NUMBER= 79
 CONTROL PERCENTAGE= 0
 FILE NUMBER= 7

VOC	ISC/A	VM	IM	EFF	FF	RS	TOC	TPC
0.587	19.89	0.496	74.78	9.27	0.794	0.180	3.0	4.0
0.584	19.36	0.492	69.06	8.49	0.751	0.220	2.6	4.0
0.581	18.45	0.488	68.81	8.39	0.783	0.170	2.6	4.0
0.589	19.76	0.499	73.99	9.23	0.793	0.170	3.0	4.0
0.582	19.59	0.494	73.22	9.04	0.793	0.180	3.0	4.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0
0.000	0.00	0.000	0.00	0.00	0.000	0.000	0.0	0.0

STANDARD DEVIATION AND AVERAGE

0.0034	0.5714	0.0041	2.828	0.414	0.0183	0.0207	0.22	0.00
0.585	19.41	0.494	71.97	8.89	0.783	0.184	2.8	4.0

M-7-B
 SINGLE-SIDED MG
 RESISTIVITY= 0.45
 DIFFUSION NUMBER= 89
 CONTROL PERCENTAGE= 104
 FILE NUMBER= 8

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
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

M-8-B
 SINGLE-SIDED TI
 RESISTIVITY= 0.49
 DIFFUSION NUMBER= 83
 CONTROL PERCENTAGE= 78.5
 FILE NUMBER= 9

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
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

M-15-B
 SINGLE-SIDED FE
 RESISTIVITY= 0.48
 DIFFUSION NUMBER= 80
 CONTROL PERCENTAGE= 0
 FILE NUMBER= 10

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

APPENDIX II

Characteristics of Dopant Impurities

	<u>Dopant</u>	<u>Form</u>	<u>Purity (%)</u>	<u>Solid Solubility (atoms/cc)</u>	<u>Donor/ Acceptor Levels (eV)</u>
Primary	Boron (Cz)	Powder	99.99	6×10^{20}	a. 0.045
	Boron (Fz)	Diborane/Ar	99.998	6×10^{20}	
	Phosphorus (Cz)	Lumps	99.9999	1×10^{21}	d. 0.044
	Phosphorus (Fz)	Phosphine/As	99.998	1×10^{21}	
Secondary	Oxygen	From Crucible	--	1×10^{18}	--
	Carbon	Powder	99.999	9×10^{17}	--
	Iron	Wire	99.998	3×10^{16}	d. 0.55
	Chromium	Crystalites	99.998	5×10^{15}	d. 0.11
	Manganese	Powder	99.9	4×10^{16}	d. 0.53
	Nickel	Wire	99.998	1×10^{18}	a. 0.24, +0.37
	Vanadium	Wire	99.995	5×10^{15}	--
	Zirconium	Wire	99.998	t.b.d.	--
	Magnesium	Chips	99.99	5×10^{18}	--
	Aluminum	Wire	99.999	2×10^{19}	a. 0.057
	Titanium	Wire	99.98	1×10^{15}	--
	Sodium	NaCl	U.P.	8×10^{18}	--