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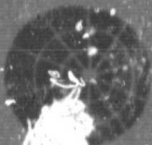
COMSAT Laboratories

NASA CR-168284

THIN N-I-P RADIATION-RESISTANT SOLAR CELLS

Submitted to

NASA Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Under Contract NAS3-22245

July 1983

Final Report

THIN N-I-P RADIATION-RESISTANT SOLAR CELLS

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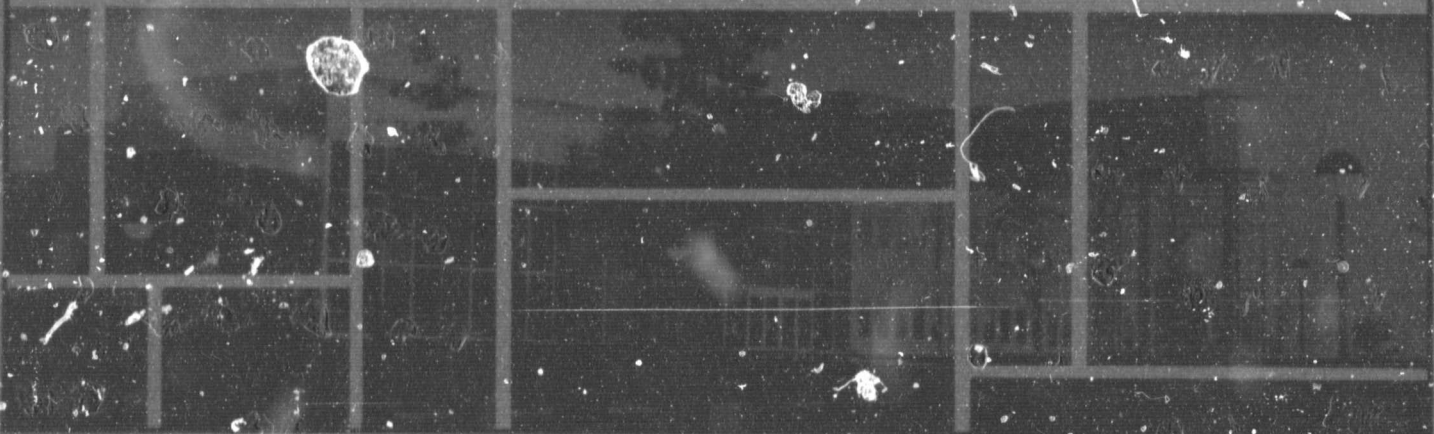

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16. Abstract

Several sets of N-I-P solar cells were fabricated from high resistivity silicon to test the effectiveness of various methods for hardening these devices against radiation. Different substrate materials were used to provide information on the effects of dopant concentration, silicon type, and the presence of oxygen. In some cells, P-type float-zone refined silicon of 800, 8000 and 15,000 Ω-cm resistivity was used to provide a basis for studying resistivity and purity effects. In other cells, N-type silicon ($\sim$ 800 Ω-cm) was used to allow a comparison of dopant type. Oxygen-rich, crucible-grown, silicon ($\sim$ 100 Ω-cm, p-type) will provide information on purity effects and defect "gettering". Lithium was introduced into different types of silicon to determine if mobile ions can reduce radiation induced defects in high resistivity material. Thin cells (2 mil) were fabricated to study the effects of cell thickness and carrier injection on radiation damage. The electrical characteristics of the different sets of cells were measured, analyzed, and compared prior to shipment of the cells to NASA/Lewis for irradiation.

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1. INTRODUCTION

Results of a previous NASA contract (NAS3-21280) [1] demonstrated that thin (~4 mil), high resistivity (n-i-p) silicon solar cells could be made without sacrificing open circuit voltage. For example, a cell with base resistivity of 1250 Ω cm exhibited ~595 mV open circuit voltage (V_{oc}). However, even though this cell lost only about 1 mA/cm^2 in short circuit current (I_{sc}) after a radiation dose equivalent to 3 x 10^{14} cm^{-2} of 1 Mev electrons, the V_{oc} dropped to 480 mV and the fill factor decreased significantly. The purpose of the present contract was to provide n-i-p cells with structures, modified from those made under NAS3-21280, with which to test methods of radiation hardening that were proposed on the basis of the earlier radiation results.

This report describes:

a. the basis for the modifications to harden n-i-p cells,

b. the modifications themselves,

c. the two tasks of cell fabrication and testing that covered two proposed approaches to the problem, and

d. conclusions and recommendations based upon the results and an analysis of the results.

2. TECHNICAL BACKGROUND

2.1   GENERAL

As a result of our first n-i-p contract [1], thin, high-resistivity solar cell output has been raised to levels expected from lower resistivity cells. Subsequent electron irradiation and analysis performed at Lewis Research Center [2],[3] and COMSAT Laboratories has resulted in modeling of these cells to predict where gains can be made both before and after irradiation. Since cells for the present contract were designed for maximum output after extended exposure to the space radiation environment, the major effort was on improvements that will not degrade under irradiation.

Three effects are responsible for the majority of the observed radiation-induced degradation in high resistivity solar cells. The first is a reduction of photo-generated, carrier-modulated conductivity as the bulk lifetime is reduced by irradiation. The second is the loss of voltage generation at the back junction (opposite from the junction nearest the illuminated surface) as a consequence of reduced minority carrier concentration in this region. The third effect is the loss of voltage generated at the front junction, the value of which is dependent on the diffusion length and acceptor concentration in the bulk of the cell.

In addition to these effects, questions have arisen as to the effects of photo-injected carrier level on diffusion length and on the interpretation of diffusion length measurements, radiation damage coefficients, and Fermi levels in the

device. Another aspect, about which little is known, is whether proton damage in high resistivity cells is significantly different from that in lower resistivity cells where strong injection effects are observed. The goal is to investigate and understand these effects and to use this understanding to predict the dependence of cell output under irradiation in the space environment.

The incentive for investigating high resistivity solar cells can be seen from the relationship between minority carrier diffusion length, L, and the radiation fluence, ϕ

$$\frac{1}{L^2} = \frac{1}{L_0^2} + K_L\phi \qquad\qquad (2\text{-}1)$$

where L_0 is the value of L before irradiation and K_L is the damage coefficient. As the bulk resistivity increases, approaching intrinsic conditions, the value of K_L decreases. Since the value of I_{sc} is directly dependent on the value of L, a high resistivity cell should exhibit a decrease in I_{sc} with fluence that is less than that observed in low resistivity cells. Further, it was expected that the portion of V_{oc} developed across the back junction (or, in the present case, the i-p junction) would be preserved if L were preserved. (The voltage developed across the i-p junction is that which boosts the V_{oc} to levels observed in lower resistivity n-p cells.) The value of L also affects the voltage developed across the n-i junction as well as the carrier concentration which, in turn, affects the cell conductivity.

The diffusion length in the high resistivity, or intrinsic, part of the cell is the critical factor in n-i-p cell performance. Radiation tests have shown that the value of L

dropped too rapidly with radiation fluence for most n-i-p cells to be effective in the space radiation environment. Further, the beginning-of-life (BOL) values under one-sun AM0 conditions were lower than predicted. These low BOL values are attributed to high injection level effects [4] which lower the base diffusion length. As has been implied, methods were sought to alter the nature of radiation damage in high resistivity cells and to reduce the effects of such damage on cell output.

2.2   TASK I

This task was designed to test the dependence of cell damage coefficient, K_L, on resistivity as the base of the cell approaches intrinsic conditions. This work extends the results of contract NAS3-21280, where cells were fabricated from material of 10, 83, 800, and 1200 Ω cm resistivity. The 83 Ω cm cells were found to perform better after irradiation than the 800 and 1200 Ω cm cells [2] because of increased series resistance in the higher resistivity cells stemming from loss of bulk conductivity. However, if the dependence of L on ϕ, or K_L on ρ [equation (2-1)] breaks down at very low doping levels, there would be nothing to gain by using very pure silicon. In order to check this possibility, cells were made from 800, 8,000, and 15,000 Ω cm silicon. Most of these cells were ~10 mils (250 μm) thick so that processing would be simpler and measurements of diffusion length would not be as affected by conditions of carrier recombination at the back surface. A few 2-mil thick cells were made from 800 and 8,000 Ω cm material to test the impact of increased carrier concentration in general and the resulting higher carrier concentration at the i-p junction.

2.3   TASK II

       This task was designed to investigate the viability of
two proposals made by COMSAT for hardening n-i-p cells against
radiation-induced degradation. One of these utilizes silicon
with a high oxygen concentration and the other incorporates
lithium ions in the silicon. In the first of these, when oxygen
combines with radiation-generated vacancies, A-centers are formed
with an energy level 0.18 eV below the conduction band. These
centers act as deep donors to provide carriers to replace photo-
carriers reduced by recombination centers formed during irradia-
tion. Not only does oxygen form A-centers but, since it competes
with dopant atoms and other impurities for vacancies, it reduces
the formation rate of recombination centers. The use of oxygen
should also be compatible with the use of lithium since it sta-
bilizes Li (i.e., keeps it from drifting) in the lattice.

       Although, at one time, lithium was used as an n-type
dopant in solar cells, its use was given up for the following
four reasons: 1) as the Li was used up in healing defects, it
was no longer a donor, and the bulk resistivity would rise; 2) Li
did not adequately heal point defects, such as those generated by
electron irradiation; 3) Li-doped cells made from float-zone
silicon were unstable due to a drifting of the ions to precipita-
tion sites; and 4) n-type silicon is innately more sensitive to
radiation than is p-type.

       Lithium was considered for use in this contract to
study n-i-p cells because, in part, it would not be introduced as
a donor. In fact, it was intended that the lithium be "stored"
in precipitate form to provide a low level source of ions for
neutralizing recombination centers and/or defect clusters gen-
erated by proton irradiation. Thus, the instability of Li in

float-zone silicon would not be a handicap since, in the i-region
of an n-i-p cell, the low doping level does not affect the cell
voltage as long as the diffusion length is large compared to the
base thickness. Some preliminary work with Li [5] in heavily
doped n^+-p cells indicated that Li in an n-i-p structure would be
beneficial. Also, thin solar cells with thin coverslides, a
recent trend, will be more heavily damaged by protons (relative
to electrons) than thicker cells with thick coverslides in the
same environment. Since Li is better for healing proton damage
than it is for healing electron damage and is not needed as a
donor (in thin cells), all things point to the need to reexamine
its use in modern cells.

3. TECHNIQUES AND RESULTS

The fabrication processes for the cells of Task I and Task II are sufficiently different that they will be addressed separately.

3.1   TASK I

Six solar cells, each of 800, 8,000, and 15,000 Ω cm, p-type, float-zone (FZ) silicon were fabricated by using a spin on dopant (Emulsitone N250C) for the n-i junction and evaporated aluminum ($\sim$1 μm) for the i-p junction. Both junctions were formed simultaneously at a temperature of 830°C for 30 minutes. It was recognized that the aluminum alloyed junction is not ideal, but the gettering properties of Al were considered more important. This is because the cells were thick ($\sim$10 mils) and the purpose was to examine diffusion lengths after irradiation. The Al alloying during formation of the n-layer diffusion has reliably provided the best results for achieving long diffusion lengths.

Results of I-V measurements on all 18 cells under one-sun, AMO illumination and low-level gamma cell currents (for diffusion length determination) are summarized in Table 3-1. In addition, one cell from each resistivity group was illuminated at 0.3 and 3.0 suns. An I-V analysis [6] was performed on each of these; the results are shown in Appendix A.

The results of the electrical measurements were quite similar for all three resistivities. The gamma cell current, I_γ, increased slightly with resistivity, as might be expected from purer material and a higher back junction potential. (Variations

in wafer thickness were too small to account for observed differences in I_γ.) The opposite trend is observed in the I_{SC}. The conclusion is that the base diffusion length and/or back junction are better at low injection for the higher resistivity but are poorer at high injection. The poor V_{OC} of the 8K Ω cm cells is unexplained, but the higher fill factor of the 800 Ω cm cells is attributed to a higher base conductivity in these wafers.

Table 3-1. Average Values of Three Sets of n-i-p Cells (~10 mil Thick)

Resistivity (Ω cm)	I_{SC} (mA)	V_{OC} (mV)	Fill Factor	I_γ^* (μA)	I_b^{**} (mA)
800	154.2	540.3	0.694	13.5	36.7
8,000	153.9	527.2	0.676	14.0	34.6
15,000	150.7	540.4	0.690	15.8	34.0

*The short circuit current generated in the cells by uniform gamma radiation from a Co^{60} source.
**The short circuit current measured with a blue transmitting, broadband filter and AMO illumination.

Three wafers of 800 and 8,000 Ω cm material were fabricated into 2-mil thick cells. In order to optimize the EOL efficiency, the p-layer face was made the illuminated face. This provides higher V_{OC} because of Dember effects and better fill factors because of the more uniform distribution of photo-injected carriers. To achieve a transparent p+ layer, B rather than Al was used as the dopant. The electrical characteristics of the cells are shown in Table 3-2. Again, the low-injection diffusion lengths (indicated by I_γ) are longer for the 8 kΩ cm cells but the I_{SC} and V_{OC} values are lower. Even though illumination is from the p+ side in these cells, the explanation of the data appears identical with that for Table 3-1.

Table 3-2. Average Values for Two Sets of
Thin Cells (~2 mil Thick)

Resistivity (Ω cm)	I_{SC} (mA)	V_{OC} (mV)	Fill Factor	I_γ (μA)	I_b (mA)
800	138.4	550.1	0.676	4.8	26.6
8,000	132.2	533.5	0.656	5.2	27.0

3.2 TASK II

The solar cell materials in this task were selected to test techniques of hardening cells against radiation. The rationale for the various methods has already been discussed. Oxygen-rich, crucible grown, CG, silicon of ~100 Ω cm p-type and ~1000 n-type FZ silicon were added to the 800 Ω cm p-type FZ silicon for the study of Li doping effects. As an initial step, base materials and processes were examined by making n-i-p cells with the 800 Ω cm p-type and ~1000 Ω cm n-type wafers by using a boron doped p+ surface. A comparison between the electrical characteristics of these cells (Table 3-3) indicates the effects of processing on the two types of material and the effect of shifting the n-i junction from the illuminated to the non-illuminated side. A comparison of Table 3-3 with Table 3-1 indicates that the boron diffusion reduces the base minority carrier diffusion length in p-type substrates, L_e, relative to aluminum. In the n-type substrate, much better results are obtained for L_h. This is probably due to the location of the intrinsic defect energy levels relative to the Fermi level in the n-type and p-type materials and the lower doping level in n-type material than in p-type material for the same resistivity.

Table 3-3. Average Values for Two Types of
n-i-p Cells (~10 mil Thick)

Type	Illuminated Face	I_{SC} (mA)	V_{OC} (mV)	Fill Factor	I_γ (µA)	I_b (mA)
800 Ω cm	n	146.6	525.4	0.601	6.4	34.1
p-type	p	113.1	522.1	0.677		17.4
1,000 Ω cm	n	136.9	552.7	0.642	12.3	30.4
n-type	p	148.0	553.1	0.620		28.6

The B doped p^+ layer is not as good as the phosphorous doped n^+ layer in terms of collecting photo-generated carriers (see I_b column of Table 3-3). This is in spite of the n^+ layer being thicker than normal (therefore reducing the blue response) to assure that no emitter problems interfere with a study of the base material. The higher V_{OC} values of the n-type cells indicate that the L values of the n-material are still better under illumination than those of the p-material.

The major difficulty encountered in the contract was the introduction of Li into these cells. Because of the high mobility of Li in silicon, high temperature steps subsequent to the introduction of Li had to be avoided. Further, because of the high mobility of Li, the tendency of the Li to precipitate made the determination of the ratio of active concentration to inactive very difficult. This difficulty was compounded by the requirement that only low levels of active lithium were desired so as not to raise the Fermi level too high into the upper part of the forbidden band (n-type silicon has higher radiation degradation). Chemical analysis was attempted for determining the total Li content but, in general, the levels were too low for reliable measurements. Measurement of sheet resistance in high

resistivity material was found to be less than perfect (even with no Li present); however, it was decided that such measurements still provided the best indication of active Li concentration. These measurements, coupled with the results of a study on Li precipitation [7], were used to determine a minimum Li content.

The technique used to introduce Li was to dope the silicon at a high temperature and quench the material to freeze-in a level equivalent to 30-100 Ω cm n-type silicon. A subsequent, low temperature heat treatment was then used to precipitate most of the active Li. Several methods of applying this basic technique were attempted to arrive at reproduceable results. One of these was the use of a spin-on source. However, the temperature required to free the Li from the source (>850°C) was too high and, because of the high mobility of Li, the concentration remaining in the silicon was too low. Stacking wafers in close proximity improved the results, but not sufficiently. When a higher concentration of Li in the spin-on dopant was tried, the formation of Li-Si alloys damaged the surface to the extent that photolithography was not possible.

The method that evolved was to use a closed quartz crucible that had been coated with LiCl. The wafers were put into the crucible, which was then raised to 750°C. The coating of LiCl acted as a source of Li atoms. All other high temperature processing was done prior to the introduction of Li. Attempts to determine the quantity of Li in the silicon did not yield very precise values; the results and possible explanations for the results are given in Appendix B. Because of the uncertainty in the Li concentration, doping levels high enough to yield an n^+-n-n^- structure (and therefore more reliable resistivity measurements) were chosen for the Li doped cells of

Task II.* This concentration raises the Fermi level too far into the upper region of the forbidden band and therefore increases the radiation sensitivity of the devices. However, the resultant cells should provide a more clear cut test of the properties of Li in high resistivity solar cells.

The total concentration of Li (electrically active and inactive) should be the critical factor in long-term healing of radiation damage. This was determined in some test wafers by atomic absorption and the results were not inconsistent with values expected from the resistivity measurements. When the cells have been on the shelf for ≥ 6 months, C-V measurements of the cell junction should be able to show the equilibrium distribution of the electrically active Li. However, the results for a cell under illumination and loaded near the maximum power point for a similar period might be different, since electric fields from the junction extend deep into the base for high resistivity cells under these conditions.

Another consequence of the thermal instability of Li in the high resistivity FZ material was seen in the use of evaporated Al_2O_3 AR coatings, rather than the normal COMSAT coating of thermally oxidized Ta_2O_5. This Al_2O_3 coating does not provide as low surface recombination velocity as does Ta_2O_5, as seen in a poorer blue response. This effect will not alter the radiation degradation of diffusion length, but will increase the power degradation of the Al_2O_3 coated cells relative to Ta_2O_5 coated cells.

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*Here, n^+, n, and n^- refer to heavy doping, moderate doping, and low doping, respectively. Dopant could be P or Li for n-type material.

The average electrical characteristics of the various type Li-doped solar cells are displayed in Table 3-4. The differences between the n-i-p cells on n and p type substrates are remarkably small. This would indicate that Li dominates the initial substrate dopant. The differences between the cells fabricated from FZ and CZ material are more significant. The biggest difference is in V_{OC}, where Li is seen to reduce the voltage generated in FZ material at the p^+ junction (compare with Tables 3-1 and 3-3). In the CG material, this effect is reduced and the difference betwen FZ and CG must be attributed to the difference in Li mobility in the two materials. The higher low-injection diffusion lengths (indicated by I_γ) of the FZ over the CG material appears to be washed out or even reversed at high carrier injection levels (indicated by I_{SC} and perhaps V_{OC}). It would appear that, at least at BOL, oxygen reduces the negative impact of Li on cell characteristics. Perhaps annealing the cells to reduce the electrically active Li would also reduce this problem. However, EOL characteristics are the crucial factor in this task, so changes to improve BOL characteristics are not called for unless they also improve EOL results.

Table 3-4. Average Values for Different Type
Cells Doped With Li (~10 mil Thick)

Cell Type	I_{SC} (mA)	V_{OC} (mV)	Fill Factor	I_γ (μA)	I_b (mA)
800 Ω cm, p, FZ	146.6	473.3	0.638	14.0	32.5
800 Ω cm, n, FZ	144.4	484.0	0.635	13.7	32.2
~100 Ω cm, p, CZ	147.0	506.5	0.645	12.1	32.9

3.3   FERMI LEVEL, LIFETIME, AND n-i-p CELL BEHAVIOR

The INTELSAT-V analysis (Appendix A), comparison of the various cell configurations in Task II, and some preliminary radiation data on n-i-p cells have increased our understanding of the electrical behavior of high resistivity cells.

The Fermi and quasi-Fermi levels play an important part in the cell open circuit voltages and diffusion lengths. Under illumination the Fermi level in an n-i-p cell will shift toward midgap. At short circuit conditions, the quasi-Fermi levels coincide with the Fermi level, E_f. Under applied voltages, the quasi-Fermi levels diverge from the short-circuited cell Fermi level in the regions of non-zero electric field. (At high illumination, the volume between the n^+ and p^+ layers or, if these layers are shallow, the whole cell has electric fields throughout.) As illumination is increased in p type cells, E_f rises and electrons begin to fill (and neutralize) deep, positively charged recombination centers. The neutralized centers have a much lower recombination capture cross-section and, therefore, the diffusion length increases. After E_f reaches midgap and most of these centers are neutralized, a further increase in illumination will lower L, because the number of holes and electrons will continue to increase; the holes help to empty the centers and the electrons help to refill them. The turnover point, where L stops increasing with illumination, is where the free electrons and holes are nearly equal. This is the definition of high-injection, and the corresponding illumination level depends on the doping concentration and lifetime of the material.

With this background, it can be readily seen that the diffusion lengths in a high resistivity cell can rise and fall, depending upon the illumination levels and internal electric

fields in the bulk of the cell. This effect complicates the prediction of the cell I_{SC} and V_{OC}, because uniform values of L are assumed for the normally used equations, and because the applied forward voltage provides an increased carrier concentration in the junction region which can extend through the base of an n-i-p cell. High injection is the reason for a diode factor of n = 2 (assuming no series resistance effects), but the reduction of L with applied voltage can reduce V_{OC} to below that predicted on the basis of L values measured at I_{SC}. The consequences are a value of n < 2 and a slope on the INTELSAT-V curve at the V = 0 axis which would appear to be a result of shunt resistance.

If the dominant defect in n-type n-i-p cells is the same as in p-type, then the low injection minority carrier lifetime τ would be longer for n-type cells. However, τ and L should decrease uniformly with increasing illumination in this case. At the same high injection level, τ should be the same for both n- and p-type material, but the carrier concentration profiles will differ because of the different collection junction in n-i-p cells.

The addition of Li into solar cells will make them more n-type and should increase τ, unless the Fermi level is raised above another defect energy level. However, Li gradients in the cell bulk and interference with the p$^+$ junction could offset any effects of the increased τ.

Radiation damage will take the form of defect centers which should lower L and τ regardless of injection levels. At low injection levels, some of these defect centers can alter the Fermi level and actually increase L in the same manner that injection can in p-type silicon. In some preliminary irradiation

tests, one Li-doped cell was irradiated and annealed; the measured L value was higher after the test than before. The INTELSAT-V characteristics did not show a full recovery from the irradiation, so that negative injection level effects were observed to increase with gamma and electron irradiation on some n-i-p cells. The A-center (Appendix A) could act in just this manner even though the oxygen concentration in FZ material is low ($<10^{16}/cm^3$).

Cluster defects created by proton irradiation will affect local volumes and, hopefully, will not alter the electrical characteristics in such a confused manner as the point defects generated uniformly throughout the cell volume by gamma or electron irradiation. Protons also generate point defects so that this initial radiation test can provide a warning that, at least to some extent, analysis of proton irradiation of the contract cells may not be completely straightforward.

4. <u>CONCLUSIONS AND RECOMMENDATIONS</u>

Several sets of high resistivity (n-i-p) cells have
been fabricated to test the radiation sensitivity and annealing
capability of various configurations. A set of high-purity, FZ,
refined, p-type, thick, silicon, solar cells (800, 8,000, and
15,000 Ω cm) will provide a test for radiation damage coeffi-
cients in this extreme purity range. Some of these cells should
be irradiated by 1 MeV electrons and a few by 40-60 MeV protons
(preferably in a simulated isotropic fluence). Diffusion length
measurements after various fluences would establish the damage
coefficients. For an optimum test, the cells should be irradi-
ated under AMO illumination and loaded near maximum power.

A set of 800-1,000 Ω cm, FZ, n- and p-type cells,
capable of being illuminated from either side, can provide a
baseline for a set of similar resistivity cells with Li present
in the bulk. The latter set of Li doped cells include some CG
material for high oxygen content. Both of these sets of cells
should be irradiated in the same manner as the first set; part
with electrons and part with protons.

Further comparisons provided by these sets of cells in-
clude: Al vs B p^+ layers (Table 3-1 vs Table 3-3); Li in CZ vs
FZ material (Table 3-4); and injection level effects in various
portions of a solar cell (Table 3-3). These comparisons have al-
ready been made for the cells prior to irradiation; they should
also be made after irradiation.

High resistivity solar cells have an easily altered
Fermi energy level, E_f. Small changes in illumination, doping,
bias, or irradiation can raise or lower E_f. Cell diffusion
lengths will change with E_f; the direction and extent depends

upon defect energy levels near E_f. From analysis of the unir-
radiated cells, primary defects are observed just below midgap
and at $E_c - 0.2$ eV. The deep centers are predominantly posi-
tively charged for E_f below the defect level and neutral when E_f
is above this level. The shallow level, observed under forward
bias, is neutral until the Fermi level or electron quasi-Fermi
level rises above the defect level. This defect is assumed to be
the A-center, which becomes negative (and therefore a more active
recombination center) at high Fermi levels.

If the A-center is an active recombination center in a
high resistivity cell under high injection, then the implication
for radiation damage and cell configuration must be considered.
Radiation will increase the number of A-centers by creating them
from inactive oxygen present within the cell. The result is a
drop in I-V characteristics well beyond that predicted on the
basis of any change in I_γ measured at low injection. Reducing
cell thickness will increase the injection level; but it might
also reduce the recombination volume if the high injection region
is thicker than the bulk of a thinned cell. Injection of light
from the p^+ side, rather than n^+ side will increase the average
electron quasi-Fermi level, but it may also reduce the maximum
value to below the level of the A-center. Which effect is more
important must depend upon the individual cell (L and geometry).
Other variations in cell structure or material must also be con-
sidered in this light. Such variations could include:

a. nonreflective surfaces, which concentrate carriers
closer to the illuminated surface;

b. CZ vs FZ material, where the oxygen concentration might
be much more important than previously thought;

c. counter-doping, where Li could reduce A-center effects and boron could lower the quasi-Fermi levels; and

d. concentrator cells, which, with higher injection levels, could be less advantageous than otherwise expected, unless this defect site is removed.

As has been observed throughout this report, n-i-p cell operation is more complicated to analyze and predict than that of low resistivity cells, because Fermi level variations in high purity material are dramatic and dependent upon many factors. These cells should be most useful (particularly in the Li-doped case) for a proton environment. If the electron environment or point defect generation from protons is too intense, the n-i-p cell characteristics will degrade too fast for this structure to be useful. Proton irradiation of these cells is necessary to determine the worth of future work in high resistivity solar cells for space power. Undoubtedly, the results will be as difficult to interpret as prior results, but this complexity is a result of a richness and diversity that makes the n-i-p cell an important tool for studying radiation damage, but not a good candidate as a radiation-hardened structure.

5. REFERENCES

[1] J. F. Allison, R. A. Arndt, and A. Meulenberg, Jr., "Thin n-i-p Radiation Resistant Solar Cell Feasibility Study," Final Report, NASA CR-159871, June 1980.

[2] I. Weinberg et al., "Performance of High Resistivity n^+pp^+ Silicon Solar Cells Under 1 MeV Electron Irradiation," 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, pp. 484,489.

[3] C. Garadia, I. Weinberg, and C. Baraona, "A Theory of the n-i-p Silicon Solar Cell," 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, pp. 855-860.

[4] O. L. Curtis, J. R. Srour, and R. B. Rauch, "Recombination Studies on Gamma-Irradiated n-Type Silicon," J. Applied Physics, Vol. 43, No. 11, November 1972, pp.4638-4646.

[5] A. M. Hermann et al., "Radiation Damage in Lithium-Counterdoped N/P Silicon Solar Cells," 14th IEEE Photovoltaic Specialists Conference, San Diego, California, January 7-10, 1980, pp. 840-846.

[6] E. S. Rittner, A. Meulenberg, and J. F. Allison, "Dependence of Efficiency of Shallow Function Silicon Solar Cells on Substrate Doping," Journal of Energy, Vol. 5, No. 1, January-February, 1981, pp. 9-14.

[7] E. M. Pell, "Interactions Between Li and O in Si," Solid State Physics in Electronics and Telecommunications, Vol. 1, Part 1, <u>Proc. of the International Conference</u>, Brussels, June 2-7, 1958, Ed. by M. Désirant and J. R. Michiels, Academic Press, London, 1960, pp. 261-276.

APPENDIX A.   I-V ANALYSIS OF n-i-p CELLS

Three cells from the group of cells sent to NASA/Lewis, as deliverables for Phase I of Contract NAS-3-22245, were measured at three different levels of solar intensity. Each of the three cells represents the average of I-V characteristics for 800, 8,000, and 15,000 Ω-cm n-i-p cells, respectively. These cells were fabricated with evaporated aluminum used to create the p^+ layer during the formation of a 0.3 μm n^+ layer with N250C at 850°C for 30 minutes. The I-V measurements were made at 0.3, 1, and 3 suns AMO from the X-25L solar simulator. Analysis of these data was carried out using the COMSAT INTELSAT-V analysis program [6]. This program does not correct for resistive voltage drops within the I layer of a cell, and errors therefore result in the low voltage region. The results for the dark current components, J_D and J_R, however, are essentially unaffected since they are determined by data in the high voltage region of the INTELSAT-V plot.

Table A-1 gives the open circuit voltages and short circuit currents of the three cells at the three intensities. Included in Table A-1 are the gamma cell current measurements (I_γ) and the cell thicknesses (W) necessary to indicate diffusion lengths L.* The 8K Ω-cm cells do not have as high V_{OC} as the 800 or 15K Ω-cm cells. The diffusion lengths, determined from the I_γ's, which are measured at low injection, do not explain the difference. Differences in V_{OC} (for the same cell) between the different illumination levels are midway between the 28 mV expected for n = 1 cells and the 56 mV expected for n = 2 cells, when the illumination is varied by 3X.

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*Assuming a perfect p^+ back surface, I_γ = L tanh (W/L).

Table A-1. Cell Parameters for Illumination
Levels of 0.3, 1, and 3 x AM0

Resistivity (Ω-cm)	V_{OC} (mV)			I_{SC} (mA)			I γ (μA)	W* (mils)
	0.3	1	3	0.3	1	3		
800	496	537	576	52	155	461	13.6	11.0 ± 0.3
8,000	482	529	571	47	152	459	14.3	11.1 ± 0.3
15,000	498	541	581	49	154	458	15.8	11.6 ± 0.1

*The average values of W are provided from measurements of
other cells made from the same material.

Results of the INTELSAT-V analysis are presented in
Table A-2. The analysis curves for 800, 8,000, and 15,000 Ω-cm
cells are displayed in Figure A-1 through A-3, respectively. The
major trends observed are a reduction in J_D and an increase in J_R
with increasing illumination (0.3, 1, and 3 suns) for all resis-
tivities. These trends fit with the change to higher injection
levels (and more of the cell in high injection) with increased
illumination. High injection conditions are modeled with n = 2
(J_R dominant) and low injection with n = 1 (J_D dominant). How-
ever, with thick cells, it is probable that the N-I junction
regions is in high injection, but the I-P junction region is in
low injection. The open circuit voltage is a sum of both junc-
tion voltages; therefore, the increase in V_{OC} with increasing
illumination will reflect both n = 1 and n = 2 regimes.

High resistivity material (the bulk of the n-i-p cell)
will display an IR drop in the regions of low injection. This
voltage drop is between the two junctions; being internal to the
cell, it is included in the junction characteristics. The de-
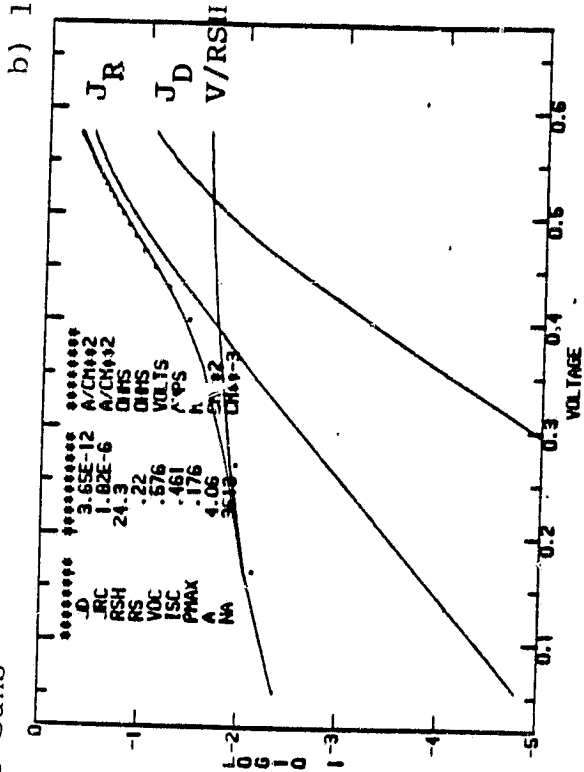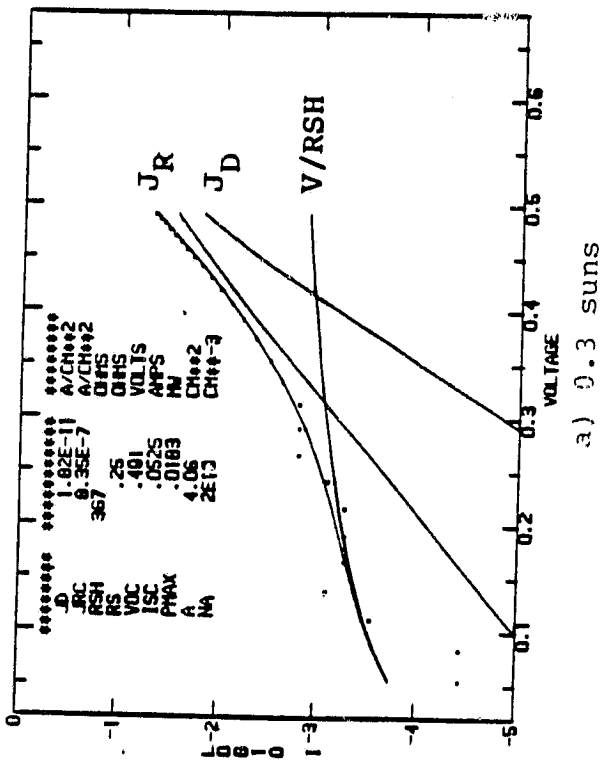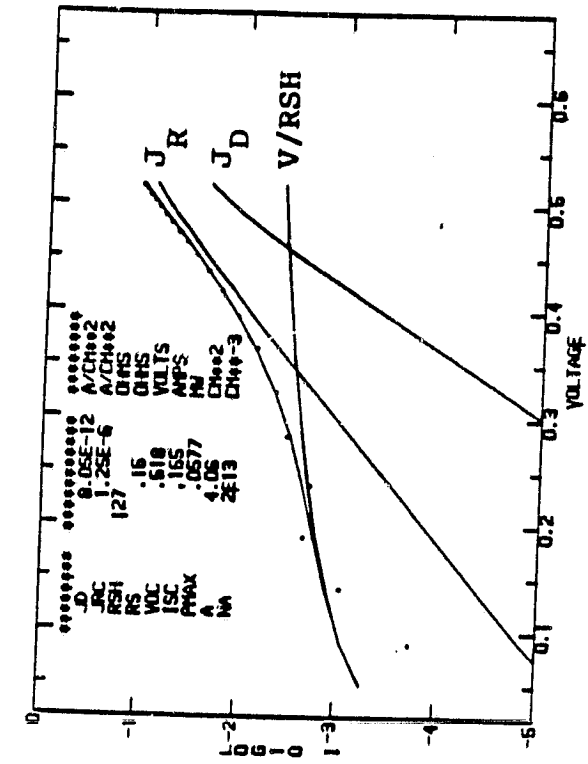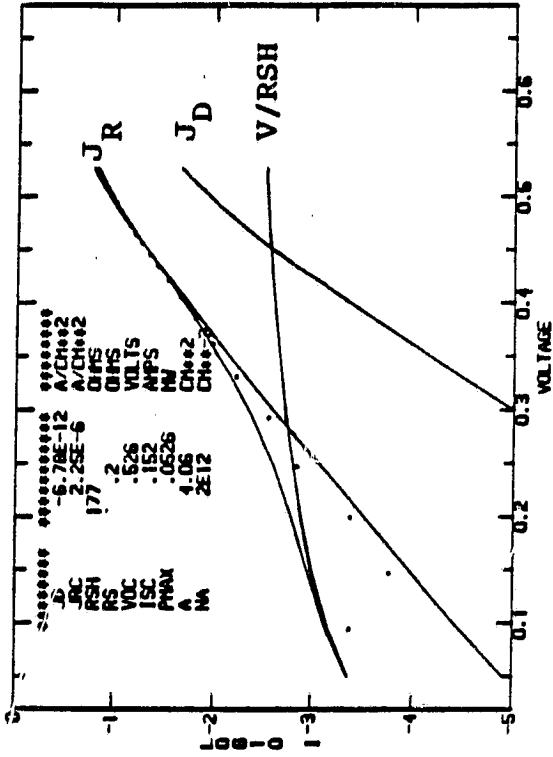crease in R_{SH} in Table A-2 with increasing illumination is an

Figure A-1. I-V Analysis Results of Cell #1489-2 (800 Ω-cm)
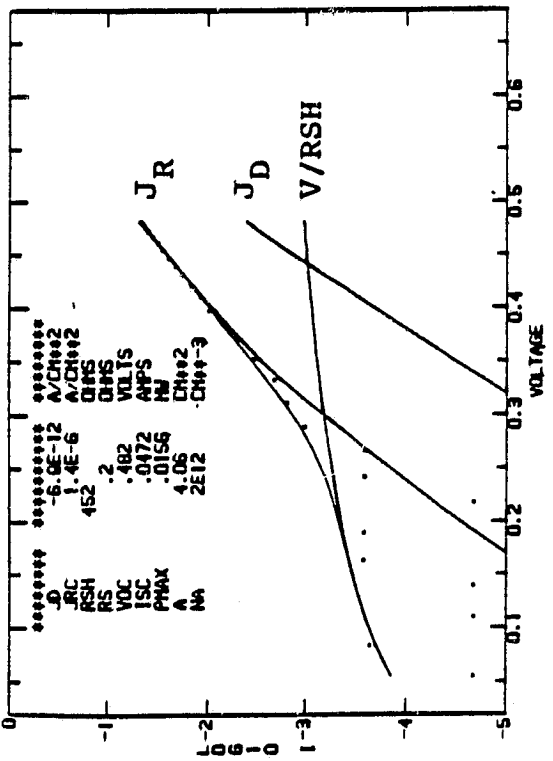
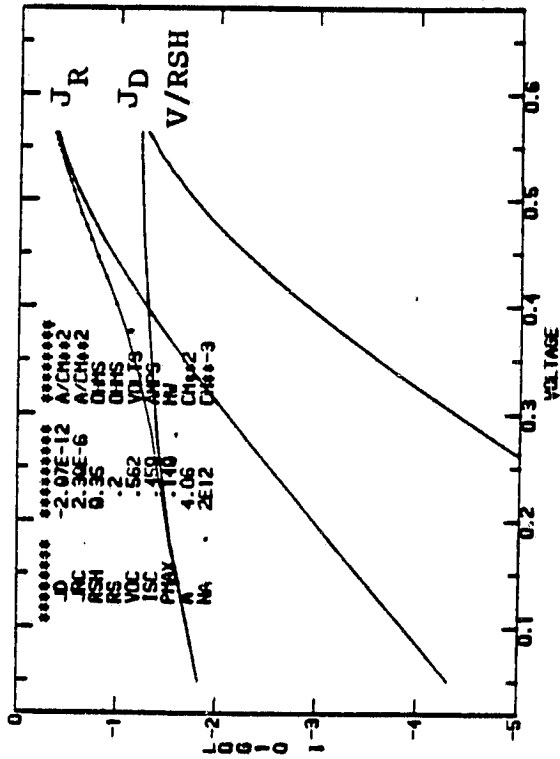Figure A-2. I-V Analysis Results of Cell #1491-3 (8,000 Ω-cm)
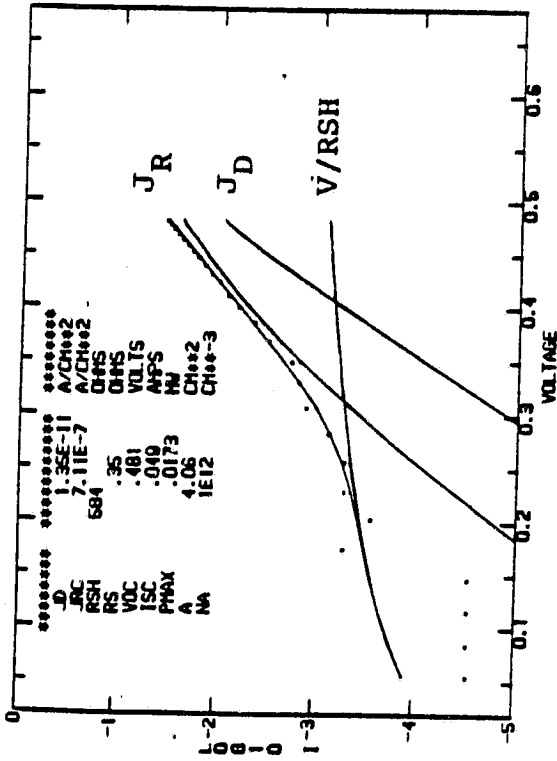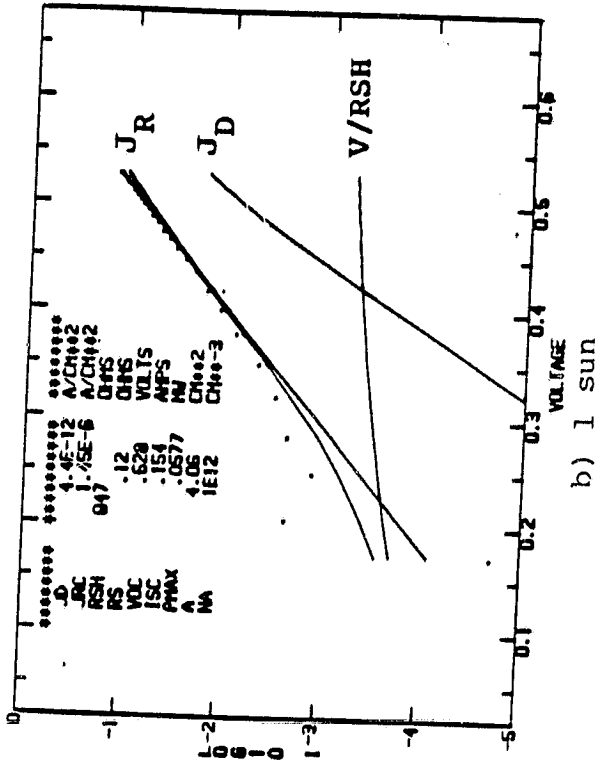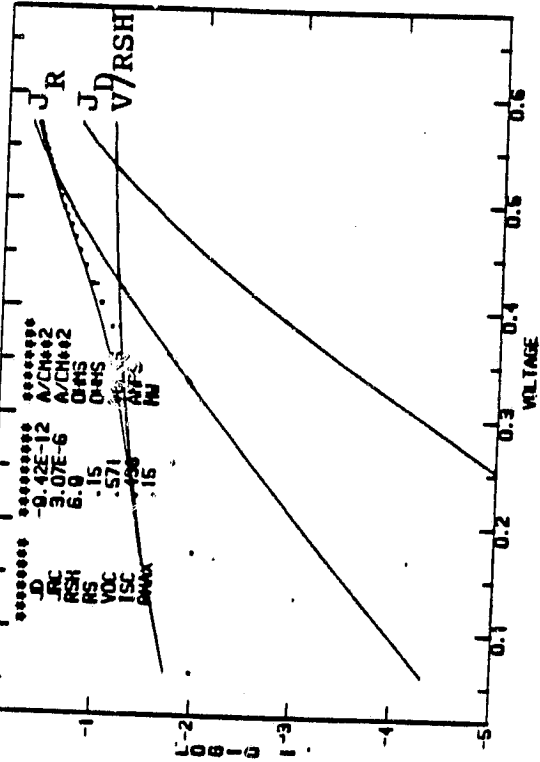
Figure A-3. I-V Analysis Results of Cell #1493-3 (15,000 Ω-cm)

a) 0.3 suns

b) 1 sun

c) 3 suns

artifact of our program which represents the cell internal voltage drop at high currents, generated from the internal series resistance $(\Delta V = R_S \Delta I)$, by a leakage component of the dark current $(\Delta_I = \Delta V / R_{SH})$. A large series resistance creates a large voltage drop ΔV at high currents (near I_{SC}), and this appears as a large ΔI in the calculated dark current at low voltages. Since the program does not distinguish the internal ΔV, it generates a large ΔI to fit the data by providing a low R_{SH}. Therefore, as illumination increases, the series resistance of the low injection region creates a higher internal voltage offset and the program attempts to fit the data with a lower R_{SH}, as seen in Table A-2. The fit-to-data degrades as the cell internal voltage drop increases. If the cell were in high injection throughout, a change in illumination would not have the same effect, since the series resistance (which depends on the photo generated carrier concentration) would decrease with increased illumination (by the same amount as the I_{SC} increases) and no increase in internal voltage drop would result.

Table A-2.   Results of I-V Analysis of
the Cells of Table A-1

Resistivity (Ω-cm)	J_D (pA/cm^2)			J_R (μA/cm^2)			R_{SH} (Ω)		
	0.3	1	3	0.3	1	3	0.3	1	3
800	18	8	1-4	0.8	1.2	2	367	127	24
8,000	*	*	*	~1.4	~2.3	~2.4	452	177	9
15,000	13	4	*	0.7	1.5	~3	584	~500	7

*Values are too low for accuracy, or are negative (a non-real possibility).

The I-V analysis program fits data for the 800 Ω-cm cell very well at all intensities (Figure A-la, b, and c). In the case of the 8,000 Ω-cm cell, the fits (Figure A-2a, b, and c) to the data are not as good (as evidenced by negative values for J_D), but the calculated values for J_R are almost unaffected, since the J_D contribution is quite small. One change in the computer program that helped the fit was the use of dominant recombination center near E_C - 0.2 eV, rather than the normally used mid-gap center (E_C - 0.5 eV). This change has an impact on the correlation of data with theory only in the 0.3 sun case, where its effect is seen in the higher than normal slope (n = 1) of the J_R curve of Figure A-2a at lower voltages.* A similar change was found useful in the 15K Ω-cm cell (Figure A-3a). The E_C - 0.2 eV level is close to the E_C - 0.18 eV level of the A center (vacancy-oxygen defect) which should have no impact on the cell unless the Fermi level or quasi-Fermi level approaches or exceeds this energy. It is possible that the electron quasi-Fermi level associated with high injection conditions of high lifetime, high resistivity cells do exceed the E_C - 0.2 eV level and cause the A-center to be an active recombination site. This could account for an apparent decrease in diffusion length with increased illumination which was directly observed in the previous n-i-p contract (NAS3-21280) and indirectly observed here from the increasing values of J_R (Table A-2) with illumination. This effect could also explain the lower I_{SC} and V_{OC} values of the 8K Ω-cm cell (Table A-1). It would not, however, be observed in the low injection level I_γ measurements.

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*Introduction of the shallow center causes the J_R curve to bend over from an n = 2 slope at high voltages to an n = 1 slope at lower voltages.

In summary, I-V analysis of the n-i-p cells produced under this contract has pointed to:

a. the presence of both high and low injection regimes in thick (~11 mil) cells;

b. an increase in dark current (n = 2) at higher illumination as more of the cell reaches high injection (and possibly associated with a decrase in diffusion length with increased carrier concentration); and

c. a specific defect site that becomes a carrier recombination center at high injection levels.

APPENDIX B.   LITHIUM CONCENTRATION MEASUREMENTS

In the effort to quantify the Li content of the cells fabricated under this task, some unusual effects were noted. Early in the program, wafers heated with the Li spin-on dopant were thought to have some Li present, because the sheet resistivity rose from the 33,000 $\Omega/\square$ of the 800 Ω cm substrates used in this test to over 100,000 $\Omega/\square$. However, in some later tests it was found that all high resistivity substrates (≥ 800 Ω cm) changed resistivity and became more intrinsic during a high temperature step ($> 850°C$). The reason for this change or its consequences was not investigated.

An attempt to profile the Li in a wafer was made by use of C-V techniques. Initial measurements indicated donor levels of $10^{15}/cm^3$ at the surface and rising toward $10^{16}/cm^3$ in the bulk. Since these concentration levels were unrealistic, more careful measurements were made on three wafers with varying degrees of Li content. The result of this study indicated that the surface concentration was less than the acceptor level ($\sim 10^{13}/cm^3$) and then increased in the bulk. In the more heavily Li-doped samples, the Li content is expected to exceed the acceptor concentration and thereby establish a junction which makes the equipment read a low change in capacitance with changing voltage. This would incorrectly indicate a very high carrier concentration. Resistivity probe measurements would show just the opposite. If the probe does not penetrate the junction (unlikely if the Li concentration is very high), only the conductivity of the surface layer would be measured. If the wafer thickness (rather than the surface layer thickness) were used in the resistivity calculation, the results would be orders of magnitude too high. Therefore, C-V measurements give high Li

concentration and sheet-resistivity measurements indicate low Li concentration.

The extremely high mobility of Li in this high purity FZ material is the primary cause of these problems. The surface acts as a precipitation site and Li migrates there until an electron field prevents further net Li^+ transport in that direction. The result is an equivalent n n^- field, except that the field region is probably depleted of Li ions, leaving the original p or i layer in the field region. The result is an n p n^- structure which is very unstable. This instability is reflected in the fact that heat treatments (even low temp ~400°C) or surface etches changed the resistivity readings for up to a day until the Li had an opportunity to return to its equilibrum profile. This problem also prevented "hot probe" measurements from being used to determine type (n or p) of the Li-doped wafers.