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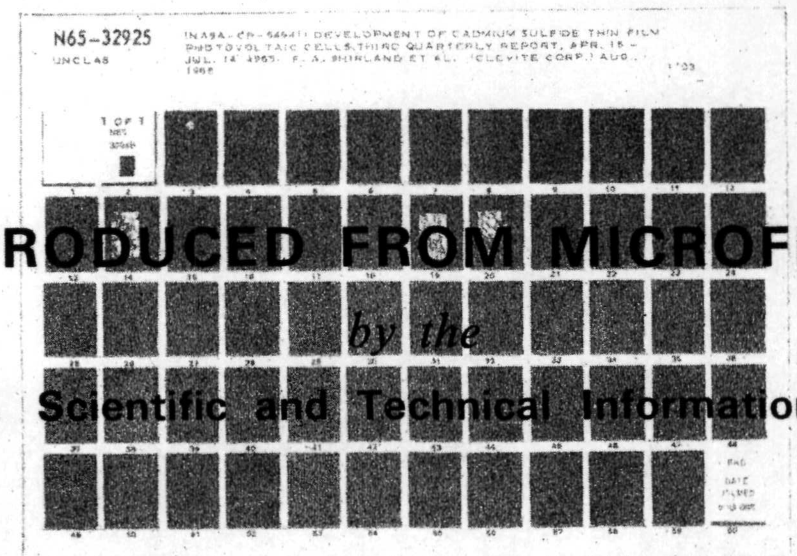

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ROUGH DRAFT

COMPARISON OF N-ON-P CELLS AND LITHIUM CONTAINING P-ON-N CELLS

by Joseph Mandelkorn

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

The evaluation and comparison of radiation damage resistance of solar cells requires that valid methods of measurement be used and proper allowances be made for differences among cells which exist because of fabrication variables.

Slide 1 illustrates a common method of evaluation still used extensively today. In this method a cell, which has been subjected to specific environmental conditions, i.e. bombardment or annealing at high temperatures, is illuminated and its current measured. The measured current is then related to the radiation damage resistance of the cell. When used for comparing cells, the method illustrated has several severe limitations as shown on the slide. If the bulk resistance or contact resistance of an evaluated cell is high, the current of that cell as read by the meter will be low. This low reading may be attributed by the investigator to a low minority carrier diffusion length within the cell. Actually, the low current is due to the fact that the cell resistances are too high to permit the maximum available cell current to flow in the circuit. Cell surface reflectance also has an important influence on the current which a cell manifests under illumination, and surface reflectance can vary considerably among cells. Thus reliance on

[redacted]

illuminated cell currents to determine and compare cell radiation damage is foolhardy because the environmental condition the cell is subjected to could degrade the cell's contacts, change its bulk resistance, or alter its surface reflectance.

The lithium-doped p-on-n cell serves as a good illustration of how misinterpretations and erroneous conclusions were made because reliance was placed upon illuminated cell current as an indicator of radiation damage.

Slide II shows the chemical impurity structure of a lithium cell. As is known, lithium acts as a donor in silicon. Thus the diffusion of lithium from the back surface of the cell throughout the bulk of the cell silicon creates a resistivity profile as shown in the slide. It will be noted that the lowest concentration region (highest bulk resistivity region) occurs adjacent to the junction of the cell. Research on the lithium p-on-n cell was started at Lewis in September 1966. It soon became evident that there was an extremely high rate of carrier removal damage in the lithium cell. This had not been reported by other investigators of lithium cells (refs. 1, 2, and 3). Furthermore, other investigators had drawn many conclusions and made many interpretations from measurements of illuminated cell currents. The high carrier removal rate in lithium cells makes it invalid to relate illuminated cell current to cell radiation damage.

Slide III shows that as a lithium cell is bombarded with 1 MeV electrons, the resistivity profile within the bulk is altered. The most

[redacted]

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Slide III shows that as a lithium cell is bombarded with 1 MeV electrons, the resistivity profile within the bulk is altered. The most drastic change takes place adjacent to the junction since the bulk resistivity is highest near the junction. The little table on the slide shows how, for any one of three different resistivity profiles, sufficient bombardment makes the region near the junction become very high in resistance. As bombardment proceeds further, the high resistance region spreads outward from the junction towards the back contact. Eventually at a dose of 1.5×10^{16} 1 MeV electrons, the entire bulk or body of the cell becomes high resistance material.

The effect does not reverse itself if the cell is left at room temperature after bombardment for any amount of time, i.e. there is no room temperature annealing. The increase in resistance is cumulative with added bombardment doses. The overall behavior is similar to that of carrier removal effects in n-on-p cells. The difference is that, whereas increases in bulk resistance sufficient to alter electrical characteristics occur in 10 ohm-cm n-on-p cells at doses exceeding 1×10^{16} 1 MeV electrons, they occur in lithium cells at doses as low as 5×10^{14} 1 MeV electrons. The electrical characteristics of bombarded 10 ohm-cm n-on-p cells are compared with those of bombarded lithium cells in slide IV. It will be noted that the two electrical symptoms of an increase in bulk resistivity during bombardment are an appreciable decrease in open circuit voltage and curve power factor. Both of these electrical characteristics degrade because their values vary inversely with bulk resistivity of the cell silicon. The higher the bulk resistivity, the lower is the open circuit voltage and curve power factor of a cell. The lithium cell starts with a low bulk resistivity and good open circuit voltage and curve power factors. As bombardment of the cell proceeds, carrier removal increases the bulk resistivity and degrades the electrical behavior of the cell as shown. Similar degradation takes place for the n-on-p cell but at dosage exceeding 1×10^{16} 1 MeV electrons. The effects of carrier removal become severe only when the bulk resistivity of a cell exceeds 20 ohm-cm. The chart in slide V shows how for a given rate of carrier removal, the severity of the damage can be delayed to higher doses by adding more lithium to the cell bulk. Thus, it requires a higher dose to make the resistivity of the bulk exceed 20 ohm-cm when the original starting resistivity is made very low. However, a price is paid for adding more lithium to the cell; it is degradation of the original characteristics of the lithium cell.

Slide VI shows the original electrical characteristics of three categories of lithium cells. Cells in each one of the categories have a specific lithium concentration near the junction. They are, therefore, classified as lightly doped, medium doped, and heavily doped lithium cells. It is apparent that heavily doped lithium cells suffer from short minority carrier diffusion lengths. This means that such cells will have low efficiencies before bombardment because currents and open circuit voltages of cells depend directly upon diffusion length. As shown the open circuit voltages of all three categories of cells are fairly similar despite the differences in their diffusion lengths.

This situation arises because open circuit voltage also depends on resistivity, the lower the resistivity, the higher the open circuit voltage. The heavier doped lithium cell categories have lower diffusion lengths but their bulk resistivities are low enough to make their open circuit voltages equivalent to the lightly doped lithium cells. The advantage of the lightly doped cell lies in a higher short circuit current, whereas the advantage of the more heavily doped cells lies in their having a low bulk resistance and, therefore, better curve power factor. All three categories of cells show the effects of extremely high carrier removal rate after bombardment as shown in slide VII. The differences are that the carrier removal damage does not have a severe effect on the electrical characteristics of the more heavily doped cells until higher bombardment dosages. The electrical characteristics of the three categories of lithium cells can be compared with those of 10 ohm-cm n-on-p cells shown at the bottom of the slide. In no case does the power available from any category of lithium cell exceed the power available from the 10 ohm-cm n-on-p cell. The values for the 10 ohm-cm n-on-p cell are those obtained from five years of analysis and evaluation of commercial cells carried out at the Lewis Research Center. The diffusion length values shown for the lithium cells are the values obtained after bombardment and room temperature annealing of the cells until no further change in diffusion length could be detected. They are the stable room temperature values.

It has been suggested in a previous publication (ref. 2) that, if the rate of bombardment of lithium cells were to be extremely slow (such as the rate which would occur in the radiation belts around the earth), the entire radiation damage in lithium cells would anneal out. The author of the publication did not realize the importance of ~~was, at the time, blissfilly unaware of~~ the carrier removal damage in silicon and was basing his speculation on the room temperature diffusion length annealing that he had observed. Experiments at Lewis have shown that the carrier removal damage in lithium cells is stable and does not anneal even at a temperature of 200° C. Other experiments at Lewis were carried out under conditions where all the annealing that could occur in lithium cells actually did occur during the course of bombardment of the cells. The final diffusion lengths in the cells which annealed completely during bombardment were the same as the final diffusion lengths in cells which were bombarded rapidly and then left to anneal at room temperature. The experiments at Lewis were based upon measurement of diffusion length which is a specific characteristic of the silicon material in the cell. Diffusion length measurements identify radiation damage with the minimum possibility of lack of validity of the measurement due to other degradations or variations of cells. It is, therefore, believed that there is nothing magical about a slow rate of bombardment of the lithium cell which would make all damage in the cell disappear. In fact room temperature annealing is known to occur in proton bombarded cells and in bombarded n-on-p cells made from high resistivity material. There is nothing in our knowledge at present which suggests that, if a bombarded cell undergoes room temperature annealing of its diffusion length, it will not be damaged at all if the bombardment rate is slow.

In conclusion research at the Lewis Research Center first identified the cause of rapid degradation of lithium cells after bombardment as an extremely high rate of carrier removal damage. The carrier removal increases the resistance of the body of the cell and, thereby, degrades the open circuit voltage and curve power factor. The carrier removal damage in lithium cells does not anneal at temperatures up to 200^{o} C and is cumulative. Although room temperature annealing of diffusion length occurs in lithium cells, it has not been found possible to utilize this effect to create lithium cells which are more radiation damage resistant than the presently available 10 ohm-cm n-on-p commercial cells. Furthermore the work at Lewis has shown that the lithium cell is extremely difficult to make in reproducible fashion. The long-term reliability of such cells stored or operated above room temperature would be poor because the lithium would change its concentration profile under such conditions in an uncontrollable fashion, (ref. 4).

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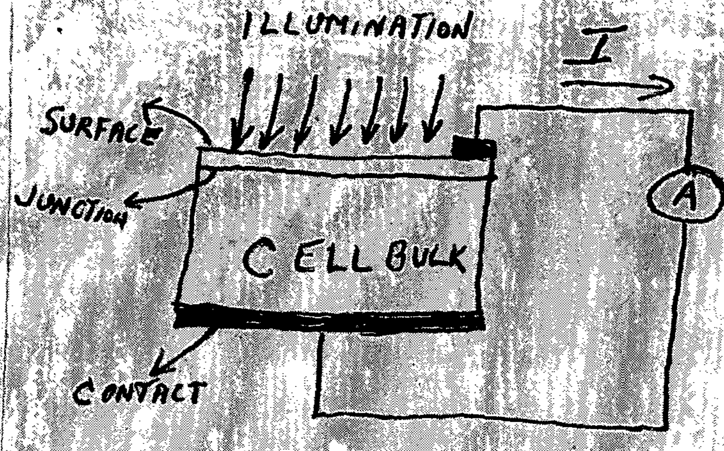
SLIDE I

LIMITATIONS OF I_{SC} MEASUREMENT



Variations in Surface Reflection

Effect of Bulk Resistance Variation

Effect of Contact Resistance Variation

Effect of Junction Depth Variation

$I \neq I_{SC}$ if R_B or R_C are High

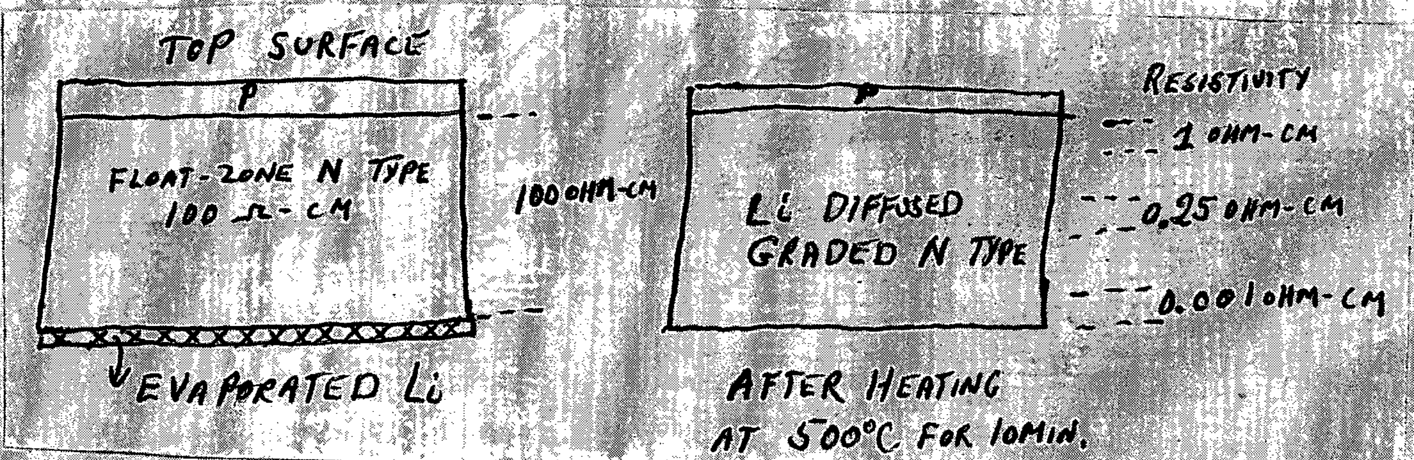
I_{SC} Short Circuit Current

R_B Resistance of Bulk

R_C Resistance of Contact

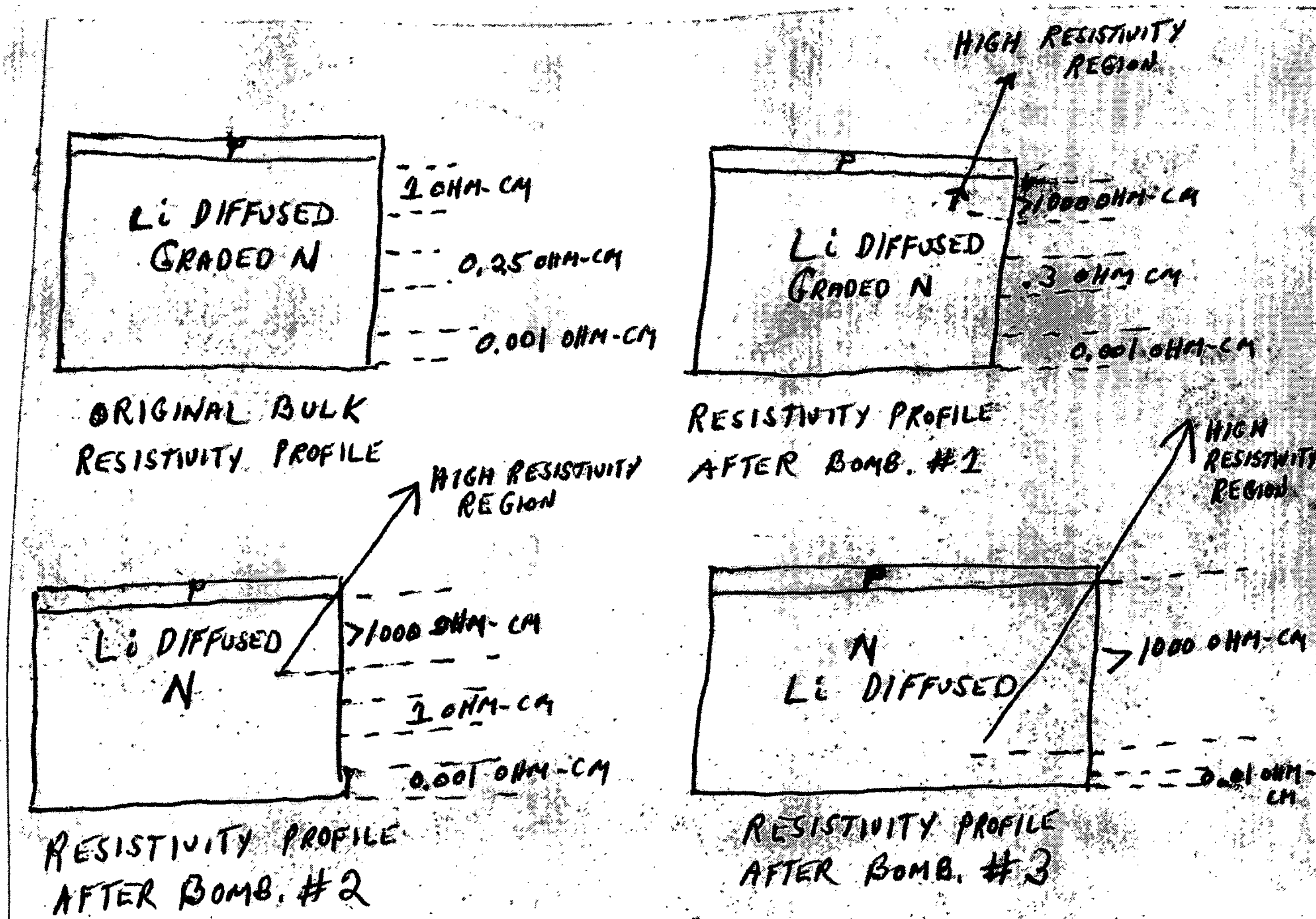
SLIDE II

RESISTIVITY PROFILE IN Li DIFFUSED P ON N CELL



SLIDE III

EFFECT OF BOMBARDMENT ON BULK RESISTIVITY OF Li CELL



SLIDE IV

ELECTRICAL EFFECTS OF BULK RESISTIVITY INCREASING

DURING BOMBARDMENT

ELECTRICAL CHAR., CPF[a] (%)

Dose, 1 MeV e/cm^2	5×10^{14}	1.5×10^{15}	5×10^{15}	1.5×10^{16}
Li Cell*	72	71	67	< 45
10 ohm-cm n/p	72	72	70	66

ELECTRICAL CHAR., V_{OC}[b] (VOLTS)

Dose 1 MeV e/cm^2	5×10^{14}	1.5×10^{15}	5×10^{15}	1.5×10^{16}
Li Cell*	0.5	0.48	0.41	0.3
10 ohm-cm n/p	0.5	0.48	0.47	0.44

[a] CPF is measure of losses in cell

$$CPF = \frac{\text{Maximum Power Obtainable in External Circuit}}{V_{OC}\, I_{SC}}$$

[b] V_{OC} open circuit voltage, I_{SC} short circuit current

*Medium doped Li Cell

SLIDE V

EFFECT OF Li CONC. PROFILE ON BOMB. BEHAVIRO OF Li CELL

Let ϕ = Dose of 1 MeV e/cm^2

C.R.R. = Carrier Removal Rate[a]

C.R.R. X ϕ = Total Carriers Removed

IF

Original average Li conc. = 10^{16} and C.R.R. = 7

Then for Dose	5×10^{14}	1.5×10^{15}	5×10^{15}	1.5×10^{16}
Carriers Removed	$7 \times 5 \times 10^{14}$	$7 \times 1.5 \times 10^{15}$	$7 \times 5 \times 10^{15}$	$7 \times 1.5 \times 10^{16}$

Carriers Remaining = 10^{16} − carriers removed

For dose	5×10^{14}	1.5×10^{15}
Carriers Remaining	6.5×10^{15}	0

[a]Carrier is a majority carrier (a free electron in the silicon which helps conduction and thereby lowers the silicon's resistance)

Carrier removal rate is number of carriers removed (trapped) for each incident 1 MeV e/cm^2

SLIDE VI

ORIGINAL CHAR. OF 3 TYPES OF Li CELLS

	V_{OC}	L	CPF
Lightly Doped	0.57 - 0.61	150 - 200	65 - 68
Medium Doped	0.56 - 0.58	60 - 90	69 - 70
Heavily Doped	0.56 - 0.58	30 - 50	72 - 74
10 ohm-cm comm n/p	0.54	150 - 200	70 - 74

V_{OC} Open Circuit Voltage, Volts

L Minority Carrier Diffusion Length, Microns

CPF Curve Power Factor, %

SLIDE VII

BOMB. BEHAVIOR OF 3 CATEGORIES OF Li CELLS

	Dose at which CPF and V_{OC} are so degraded that cell is useless
Lightly Doped	1.5×10^{15}
Medium Doped	5.0×10^{15}
Heavily Doped	1.5×10^{16}
N/P	$> 1.5 \times 10^{16}$

At no point during bombardment does the available power of any Li Cell exceed that of the N/P 10 ohm-cm cell