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SUMMARY

An investigation of the characteristics and behavior of 10 Ω-cm silicon cells having abnormally high open-circuit voltages was made. The cells studied were made by a new, highly simplified, contact fabrication process which creates both a contact and a thin electric field region at the cell back surface without the need for phosphorus layer removal. These cells had open-circuit voltages of about 0.58 V and their performance as a function of thickness, temperature, and 1 MeV electron irradiation is detailed. The study showed that 10 Ω-cm back-surface-field cells can have the high initial efficiencies and desirable temperature behavior of low resistivity cells. Thin back-surface-field cells were made and showed, in addition, much greater radiation damage resistance. A mechanism is proposed to explain the results.

INTRODUCTION

A comprehensive theoretical treatment of field effects in silicon solar cells has been presented by Wolf (1). The theory predicts that increases in long wavelength response of cells are attainable by incorporation of electric field regions into the cell bulk. More recently, there have been reports of the achievement of unusually high open-circuit voltages and short-circuit currents in 10 Ω-cm cells (2, 3). These results were attributed to a gettering process which removes detrimental impurities from the cell bulk, increasing the minority carrier diffusion length to hitherto unattained values (2, 3). The gettering process was not disclosed.

Wolf extended his calculations (4) to show that the presence of a thin electric field region at a cell back surface could produce significant increases in long-wavelength response. However, the refined analysis made by Wolf did not show a relationship of such a field to cell open-circuit voltage.

Extensive experimental work at the Lewis Research Center has shown that the open-circuit voltage of 10 Ω-cm cells saturates at a maximum value of about 0.55 V. It therefore was questionable that increase of minority carrier diffusion length by a gettering process resulted in the 0.585 V open-circuit voltages reported for 10 Ω-cm cells (2, 3). A study was made of the effects of back surface p$^+$-p electric fields on cell behavior because it was surmised that such fields were most likely responsible for the high open-circuit voltages reported.

EXPERIMENTAL PROCEDURES

Cell Fabrication

Silicon solar cells were fabricated using a new back surface contacting process which hereafter will be referred to as the alloy-through process. Cell fabrication was carried out as shown in figure 1.

Phosphorus was diffused into "p" type 1 × 2 cm silicon wafers at a temperature of 840° C for a time of one-half hour from a phosphorus oxychloride vapor source. Following diffusion, surface oxides on the wafers were removed by immersing them in a 0.5 percent hydrofluoric acid solution. The wafers were then inserted into metal masking jigs which were positioned in a vacuum system. Silver was evaporated over the top surface of the wafers in a ten grid-finger contact pattern (5) and several micrometers of aluminum were evaporated over the entire back surface of the wafers. After removal from the masking jigs, the wafers were immediately heated in a furnace at 800° C for a time of four hours in an argon atmosphere. This heating cycle did not have any adverse effects on either the properties of the Ag front contact or on the n$^+$-p junction below it. During the heating cycle, aluminum first alloys through the phosphorus diffused region on the wafer back surface forming a low resistance contact to the bulk. The alloyed region then serves as a source of aluminum which diffuses into the bulk to an estimated depth of approximately one micrometer during the four-hour 800° C heating cycle. It is thus possible to form a thin electric field region and a low resistance contact at the back of the cell and to simplify the contact fabrication process by use of the alloy-through process. Cell fabrication is completed by masking the top and bottom surfaces of the wafer with wax and etching to remove the phosphorus diffused region from the cell edges.

All cells made had a ten grid finger contact pattern (5) and an active area of 1.7 cm^2. This value of active area is 3 percent less than that of commercial five grid finger cells. The series resistance of the cells, as measured by a two-level illumination method (6), was 0.25 ohms. This compares with values of 0.5 ohms measured for 1 × 2 cm commercial cells. Sheet resistances of all cells made were similar to those of commercial cells and ranged from 60 to 90 ohms/sq., and cell short wavelength responses were similar to those measured for high quality commercial cells. Fill factors of field cells were above 75 percent, ranging up to 78 percent, well above fill factors of commercial cells.

To properly evaluate the behavior of the field cells, control cells (conventional n^+-p geometry) were fabricated from the same region of the silicon ingots as the field cells and measurements were made sequentially on both cell types. Variations in control cell processing were made to obtain equivalent sheet resistances in both field and control cells and to ensure that the control cells had no field region at the back contact.

Table I compares the alloy-through process with a normal process used for forming a back surface field. Field cells made by either process were identical in their performance. The use of the alloy-through process permits elimination of steps 4, 5 and 6 as shown.

A significant economic advantage consisting of savings in labor, materials, and facilities, and reduction of thin cell handling breakage is attainable by use of the alloy-through process. In addition, it becomes possible to evaporate contacts on wafer surfaces untouched by the masking materials and cleaning solvents used in steps 4, 5 and 6. Therefore, more reliable and adherent contacts may be realized as a result of alloy-through processing.

Analysis and Discussion

Table II compares the characteristics of 10 Ω-cm alloyed-through-and-diffused back surface field cells with those of control cells made from the same region of a silicon ingot but having non-alloyed back contacts. The efficiencies shown in the table are calculated by assuming an antireflection coating with a coating factor of 1.4 has been applied to all the cells; the fill-factor and open-circuit voltage values used were those shown in the table. The field cell characteristics are very similar to those of the unusual cells previously reported (2, 3). It should be noted that 0.004-inch-thick field cells can have efficiencies equal to those of the thickest 10 Ω-cm conventional structure cells.

Several experiments were performed to determine whether the high open-circuit voltages of alloyed-through field cells were due to the presence of the field at the cell back surface. In the simplest experiment, 0.002 inch of silicon was removed from the back surface of a 0.012-inch-thick field cell by abrasion and was replaced by a rhodium contact (7) plated on at room temperature. The cell open-circuit voltage dropped from 0.573 to 0.537 volt, a normal value for a 10 Ω-cm 0.010-inch-thick cell. In another experiment, a p^+-p field was created at the back surface of several cells by diffusion of boron into the back surface. Cells so made had the characteristics and behavior of the alloyed and diffused-aluminum field cells, proving that gettering by means of a molten alloy on the cell back surface was not required to achieve unusually high open-circuit voltages in 10 Ω-cm cells.

Cells were also made which had either of the two back surface contact configurations shown in figure 2. Cells having the Type 1 (window contact) back surface contact configuration depicted had low contact resistance and good diode characteristics. However, their open-circuit voltages were the same as for the control cells in Table II. This contrasted with the results for cells having the Type 2 (full coverage) contact configuration. These Type 2 back contact cells had the characteristics of back surface field cells as shown in Table II. Evidently the n^+ window frame surrounding the p^+-p region in the Type 1 configuration acts as a shunt which destroys the effectiveness of the p^+-p window region. Since the same alloying and heating steps were used with both contact geometries, it can be concluded that impurity gettering by the molten alloy was not responsible for the high voltages.

Further experiments elucidated the mechanism by which the back surface field increases the open-circuit voltage of cells. Table III presents the measured temperature behavior of field cells. Analysis of this behavior indicates that field cells behave like conventional cells which are made from much lower resistivity silicon than the field cells. Further confirmation of this analysis was obtained by determining the junction characteristics by measuring short-circuit current and open-circuit voltage at several illumination levels. Table IV shows the junction characteristics of 10 Ω-cm field effect cells to be very similar to those of cells made from much lower resistivity silicon and to differ appreciably from the characteristics of conventional structure 10 Ω-cm cells.

It was evident that the field at the back surface affected the n^+-p barrier in a manner equivalent to that of increasing the majority carrier density of the p-type bulk. The mechanism postulated to create the effects discussed is presented in figure 3.

The aluminum diffused p^+ region at the cell back results in injection of holes into the back of the p bulk, creating a high density of holes at this boundary of the bulk. The n^+ phosphorus-diffused region at the cell front constitutes a barrier to movement of holes to the front contact. Conversely, the n^+ region at the front of the bulk injects electrons into the bulk while the p^+ region at the back constitutes a barrier to movement of electrons to the back contact. The injection of a high concentration of majority carriers at the back of the bulk while not permitting them to leave freely at the front results in transfer of the majority carrier disturbance from the back to the front. There is, consequently, an increase in hole density at the front of the bulk p region. This, in turn, raises the n^+-p barrier height and gives the cell the characteristics of a cell made from lower resistivity silicon. It was expected, based upon the mechanisms outlined, that the open-circuit voltage of a field cell would show a dependency on minority carrier lifetime in the bulk because the hole concentrations at both the front and back of the bulk as well as the current flow within the bulk are functions of the bulk minority carrier lifetime. A dependency on cell thickness should also exist based upon the mechanism postulated.

The dependence of cell open-circuit voltage on minority carrier diffusion length in the bulk and cell thickness was investigated by irradiating both field effect and control cells of various thicknesses with selected fluences of 1-MeV electrons. The variation of bulk minority carrier diffusion length with fluence in such irradiations, compiled from measurements made over many years on conventional cells, is shown in figure 4. Table V compares the open-circuit voltage of conventional (n^+-p) cells and alloyed-through field cells after irradiation. The open-circuit voltages of the field cells show a marked dependence on cell thickness, with the thinner cells retaining their voltage superiority (compared to conventional cells) to greater fluences. The effect of back surface field on the open-circuit voltage apparently vanishes when the post-bombardment minority carrier diffusion length, L_B, decreases to values less than 0.4 W, where W is the cell thickness. As long as $L_B \geq 0.7$ W the open-circuit voltage of field cells is significantly higher than that of conventional cells.

The results obtained for some samples of field and control cells of different thicknesses bombarded to a dose of 3×10^{14} 1-MeV electrons are shown in Table VI. For this dose, only the 0.004-inch-thick cells meet the criterion $L_B \geq 0.7$ W, and these cells have very little loss of current and have open-circuit voltages well above those of the other cells shown in Table VI.

Based upon the criteria that $L_B \geq 0.7$ W and the values of L_B shown in figure 4, it can be calculated that thicknesses of field cells, i.e., the distance from the front junction to the thin electric field region in the bulk, will have to be 0.004 inches or less, in order to retain advantages of back surface fields over the entire lifetime of most space missions. Small values of W are attainable in physically rugged thick cell structures by the design and approach depicted in figure 5. The resistivity of the epitaxially deposited silicon layer shown in figure 5 should be in the 10-20 Ω-cm range to avoid carrier removal damage (8).

CONCLUSIONS

Back surface field effect cells can be made by simplified processing using a new alloy-through back contact process. Cells so made have unusually high open-circuit voltage, vastly improved temperature behavior, and, if made with antireflection coatings, would have AMO efficiencies as high as 12 percent. Alloy-through processing should permit savings in labor, materials, and facilities necessary for field cell fabrication and should result in more reliable and adherent solar cell contacts.

Thin 10 Ω-cm alloy-through cells can be made with unusually high open-circuit voltages, short-circuit currents, and fill factors. AMO efficiencies of 11 percent (based on assumed coating factors), the desirable temperature behavior of 2 Ω-cm cells, and increased radiation damage resistance were attained in 0.004-inch-thick alloyed-through cell structures.

Several experiments performed indicate that the novel characteristics and behavior of alloyed-through cells are caused solely by the presence of the electric field region at their back surfaces. A mechanism proposed for the behavior of alloyed-through cells predicted that bulk minority carrier diffusion length and cell thickness play a vital role in the effectiveness of the back surface electric field. Results of irradiations of field cells corroborated the prediction. It is further predicted that creation of better quality p^+-p junctions at the cell back surface and preservation of higher minority carrier lifetimes in the p region adjacent to the back contact after fabrication will lead to much better field cells than those reported upon to date.

ACKNOWLEDGEMENT

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Table I

FABRICATION OF Al ALLOYED AND DIFFUSED FIELD EFFECT CELLS

Process	Alloy-Through	Normal
1 Etch wafers	✓	✓
2 Diffuse phosphorus	840°C, 30 min.	840°C, 30 min.
3 Remove surface oxides	✓	✓
4 Mask front, etch back	-	✓
5 Clean	-	✓
6 Evaporate Al on back	-	✓
7 Heat	-	800°C, 4 hrs.
8 Evaporate contacts	✓	✓
9 Heat	800°C, 4 hrs.	600°C, 5 min.
10 Etch edges	✓	✓

Table II

CHARACTERISTICS OF FIELD EFFECT AND CONTROL CELLS
10 Ω-cm, bare

Thickness, in.		.004	.006	.008	.012	.020
V_{oc}[1], volts	Control	0.50	0.525	0.535	0.55	0.555
	Field	0.58	0.58	0.58	0.58	--
I_{sc}[2], ma	Control	44	47	49	52.5	53.5
	Field	50.5	51.5	52.5	53	--
F.F.[3], %	Control	←———		74-75		———→
	Field	←———		75-78		———→
Eff.[4], %	Control	8.25	9.25	10.3	11	11.3
	Field	11.25	11.6	11.8	12	--

[1] V_{oc} measured at 25°C for I_{sc} = 65 ma.

[2] I_{sc} as measured under xenon simulator and Lewis filter wheel simulator (NASA TND-2562, 1965).

[3] Fill Factor at 25°C for I_{sc} = 65 ma.

[4] Efficiency calculated for 136 mw/cm^2 AMO equivalent illumination and if cells had antireflection coating with coating factor of 1.4.

Table III

TEMPERATURE BEHAVIOR OF FIELD EFFECT AND CONTROL CELLS

ρ Ω-cm	Type	Thick. in.	T, °C		T. Coeff. mv/°C	F.F. T=160°C %
			60	160		
			V_{oc}, volts			
10	Control	.006	0.436	0.193	2.43	47
	Field	.006	0.482	0.267	2.15	54.5
	Field	.015	0.481	0.264	2.17	50
	Control	.022	0.465	0.235	2.3	47.5
1	Control	.020	0.485	0.275	2.1	55

Table IV

COMPARISON OF JUNCTION CHARACTERISTICS OF FIELD EFFECT AND CONTROL CELLS

Cell Description				
Type	Field	Field	Control	Control
Thickness, in.	0.008	0.008	0.015	0.015
Resistivity, Ω-cm	10	10	2	10
I_{sc}, ma	V_{oc}, V			
	Temperature, 58° C			
5	0.412	0.410	0.412	0.402
10	0.445	0.443	0.445	0.425
20	0.474	0.469	0.471	0.446
70	0.515	0.513	0.512	0.479
	Temperature, 25° C			
70	0.584	0.583	0.583	0.554

Table V

OPEN CIRCUIT VOLTAGE AS A FUNCTION OF THICKNESS AND BULK DIFFUSION LENGTH, L_B, AFTER IRRADIATION

10 Ω-cm cells

1 MeV Fluence, e/cm^2		0	3×10^{13}	9×10^{13}	3×10^{14}
Estimated L_B, µm			125-140	80-110	60-75
Thick Control Cells, V_{oc}, Volts		0.555	0.540	0.535	0.520
Field Effect Cells Thickness in.	µm	V_{oc}, Volts			
.015	375	0.573	0.540	0.535	0.520
.012	300	0.573	0.560	0.535	0.520
.008	200	0.576	0.565	0.547	0.520
.006	150	0.573	0.565	0.550	0.526
.0042	105	0.572	---	---	0.542

Table VI

IRRADIATION RESULTS FOR FIELD EFFECT AND CONTROL CELLS

FLUENCE: 3×10^{14} 1-MeV electrons/cm^2;
10 ohm-cm bare cells; estimated
bulk diffusion length[1]: 60-75 µm

	Thickness, in.	.004	.006	.008-.012
Control Cells	V_{oc}[2], volts	.5	.520	.523
	I_{sc}[3], ma	44	47	47
	F.F.[4], %	⟵ 74-75 ⟶		
	Eff.[5], %	8.2	9.2	9.2
Field Cells	V_{oc}[2], volts	.545	.526	.522
	I_{sc}[3], ma	50	47	47
	F.F.[4], %	⟵ 75-77 ⟶		
	Eff.[5], %	10.5	9.3	9.2

[1] L_B, post bombardment minority carrier diffusion length.

[2] V_{oc} measured at 25°C for I_{sc} = 65 ma.

[3] I_{sc} as measured under xenon simulator and Lewis filter wheel simulator (NASA TND-2562, 1965).

[4] Fill Factor at 25°C for I_{sc} = 65 ma.

[5] Efficiency calculated for 136 mw/cm^2 AMO equivalent illumination and if cells had antireflection coating with coating factor of 1.4.

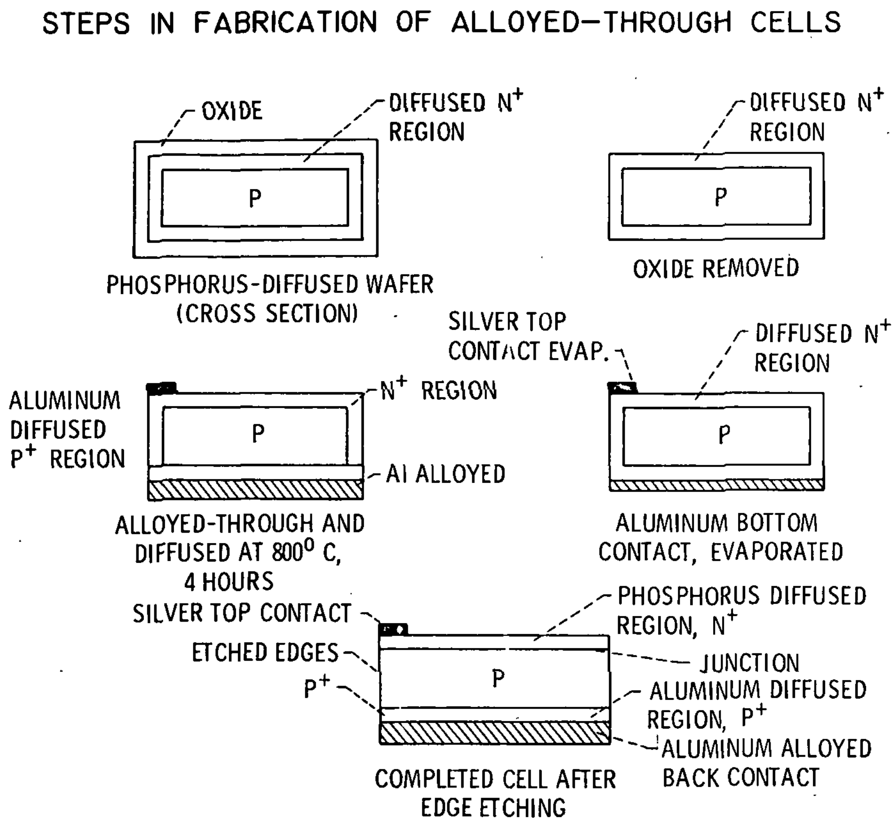

STEPS IN FABRICATION OF ALLOYED–THROUGH CELLS
OXIDE
DIFFUSED N+ REGION
P
PHOSPHORUS-DIFFUSED WAFER (CROSS SECTION)
DIFFUSED N+ REGION
P
OXIDE REMOVED
ALUMINUM DIFFUSED P+ REGION
N+ REGION
P
Al ALLOYED
ALLOYED-THROUGH AND DIFFUSED AT 800° C, 4 HOURS
SILVER TOP CONTACT EVAP.
DIFFUSED N+ REGION
P
ALUMINUM BOTTOM CONTACT, EVAPORATED
SILVER TOP CONTACT
ETCHED EDGES
P+
P
PHOSPHORUS DIFFUSED REGION, N+
JUNCTION
ALUMINUM DIFFUSED REGION, P+
ALUMINUM ALLOYED BACK CONTACT
COMPLETED CELL AFTER EDGE ETCHING

Fig. 1.

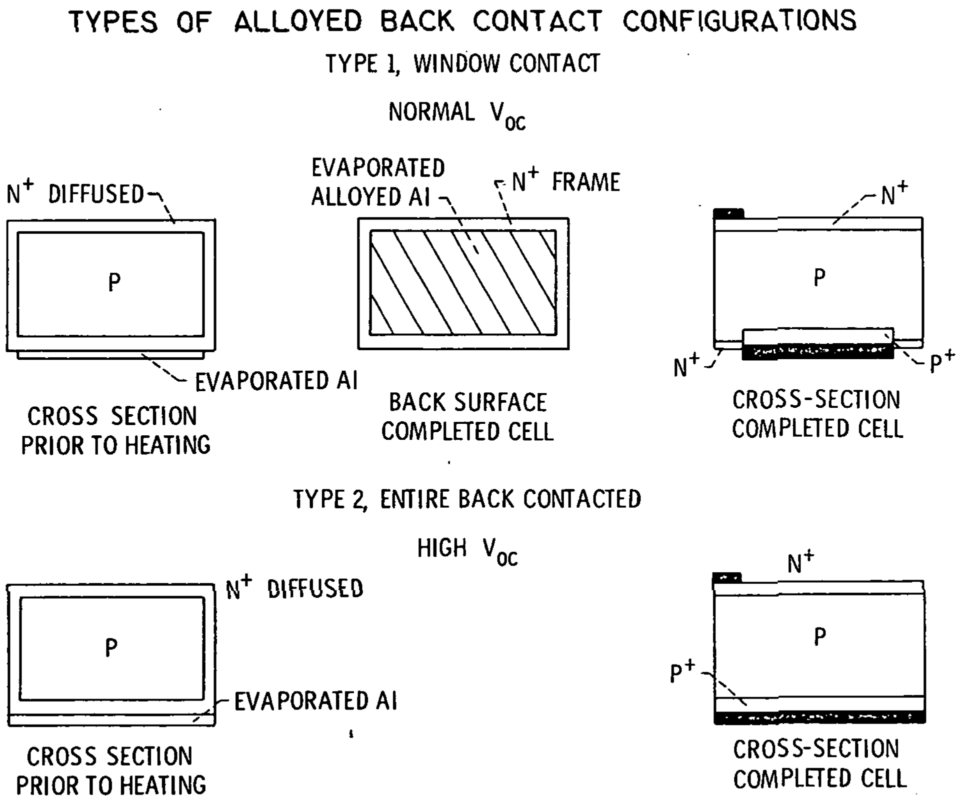
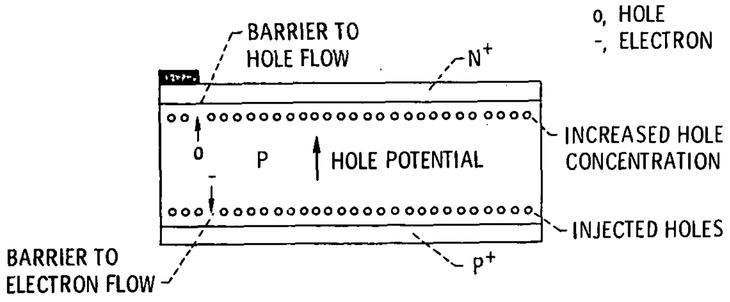

TYPES OF ALLOYED BACK CONTACT CONFIGURATIONS
TYPE 1, WINDOW CONTACT
NORMAL V_{OC}
N+ DIFFUSED
P
EVAPORATED Al
CROSS SECTION PRIOR TO HEATING
EVAPORATED ALLOYED Al
N+ FRAME
BACK SURFACE COMPLETED CELL
N+
P
N+
P+
CROSS-SECTION COMPLETED CELL
TYPE 2, ENTIRE BACK CONTACTED
HIGH V_{OC}
P
N+ DIFFUSED
EVAPORATED Al
CROSS SECTION PRIOR TO HEATING
N+
P
P+
CROSS-SECTION COMPLETED CELL

Fig. 2.

MODEL FOR EFFECT OF P^+ REGION ON OPEN-CIRCUIT VOLTAGE



V_{oc} IS FUNCTION OF HOLE CONCENTRATION NEAR N^+ REGION, FOR INCREASED HOLE CONCENTRATION V_{oc} IS INCREASED

Fig. 3.

MINORITY CARRIER DIFFUSION LENGTHS

PRESERVED IN BOMBARDED 10 OHM-CM CELLS

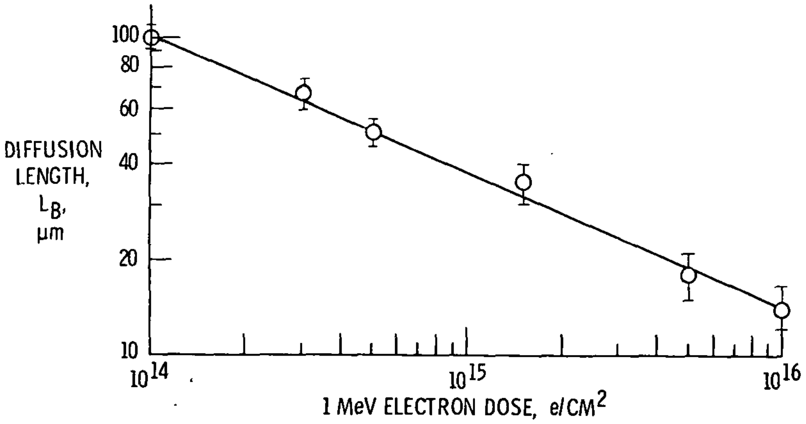
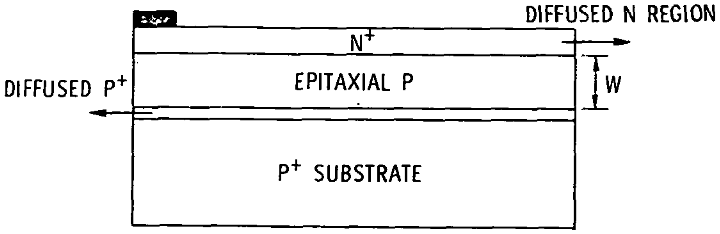


Fig. 4.

RADIATION DAMAGE RESISTANT BACK SURFACE FIELD CELL



CRITERIA: $W < 1.5\ L_B$

L_B, DIFFUSION LENGTH OF P BULK AFTER A SPECIFIED IRRADIATION

RESISTIVITY OF P BULK - 10-20 OHM-CM

Fig. 5.