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SUMMARY

The characteristics and behavior of p^+, p solar cells were investigated. The p^+, p cells were made by removal of the n^+ surface layer from n^+, p, p^+, BSF cells followed by application of a suitable contact to the resultant p^+, p structures. The open-circuit voltage, V_{oc}, of p^+, p cells was found to increase with increasing "p" bulk resistivity. The measured V_{oc}-temperature-coefficients were positive and increased with increasing resistivity. This behavior is exactly the opposite of that observed for conventional cells, n^+, p or p^+, n structures. Furthermore, it was found that the V_{oc} value of a p^+, p cell correlated directly with the V_{oc} value of the n^+, p, p^+ BSF cell from which the p^+, p cell was made; that is, the higher the V_{oc} of an n^+, p, p^+ cell, the higher was the V_{oc} of the p^+, p cell made from it. The results indicate that the value of V_{oc} and the unique behavior of V_{oc} of n^+, p, p^+ cells result from the V_{oc} at the front, n^+, p, junction being influenced by a photovoltage generated at the back, p^+, p, junction. The concept of majority carrier collection is proposed as a possible mechanism for generation of the photovoltage at the back p^+, p junction.

An outline of prior limitations in solar cell design is presented, and the removal of these limitations through use of BSF effects is pointed out.

The study of BSF effects has made feasible production of very thin high efficiency silicon cells as well as high resistivity-high efficiency cells, two desirable types of silicon cells which were previously impossible to make.

INTRODUCTION

Methods for fabricating high resistivity thin silicon solar cells so that they have hitherto unattainable high open-circuit voltage, V_{oc}, and high short-circuit current, I_{sc}, were developed and disclosed (1). One of these methods has been adapted to production of thin, high efficiency cells (2). Theories have been advanced to explain the high I_{sc} (3) and the high V_{oc} (4) of the new type of cell, designated a Back Surface Field, BSF, cell.

The study reported herein is part of a continuing effort to determine the behavior of BSF cells and the influence of fabrication processes and bulk material properties on such behavior. This effort has two objectives: (a) the utilization of BSF effects to create improved solar cells; (b) aiding the formulation of a comprehensive theory for such effects.

The high value of I_{sc} of thin BSF cells has been theoretically based upon the back surface field acting as an effective barrier to flow of minority carriers from the bulk to the back contact (3). The minority carrier barrier effect has also been used to explain the high V_{oc} values of cells, assuming very long minority carrier lifetimes exist in the cell bulk (4). However, a prior study (5) showed no correlation existed between the blocking effectiveness of the back barrier and the value of V_{oc} of cells; several 10 Ω-cm BSF cells with highly effective barriers and good junctions had the same value of V_{oc} as conventional 10 Ω-cm cells. The study of the photovoltaic properties of the p^+, p, back junction of BSF cells was undertaken to help resolve the factors giving rise to the V_{oc} characteristics of BSF cells.

Procedure

The p^+, p cells studied were fabricated from "parent" n^+, p, p^+, BSF cells as shown in Fig. 1. The back surfaces of the BSF cells were protected by apiezon and the top n^+ surface etched off. Following this, the metal contact to the back p^+ surface was removed with hydrochloric acid, leaving a contactless p^+, p structure. A silver-aluminum contact (6) was then applied over the entire "p" surface. The silver-aluminum makes a low resistance ohmic contact to very high resistivity "p" type silicon, an important consideration in the study of high resistivity p^+, p cells.

Evaluation consisted basically of measuring and comparing the photovoltages of various cells. The cells were held by vacuum suction, "p" side down, on the surface of a thick brass block. Water, kept at a constant temperature, was rapidly circulated through the block so that the block temperature always equalled the water temperature. A probe contact was made to the top, p^+, surface of the cells. A fabricated contact to this surface is not necessary for photovoltage measurement because it is so heavily doped. Photovoltages were measured upon illuminating the p^+ surface of the cells with tungsten light, the intensity of which was maintained constant at a level normally used for measuring the performance of conventional cells. Measurements were made at 25° C. V_{oc} versus temperature measurements were made by varying the circulating water temperature.

RESULTS AND DISCUSSION

Much higher photovoltages were obtained from 100 Ω-cm bulk p^+, p cells than from 10 Ω-cm p^+, p cells, as shown in Table I. The data indicate that the V_{oc} of p^+, p cells increases with increasing "p" bulk thickness and resistivity. For valid comparisons, it is therefore necessary to make measurements on equally thick cells.

Table II shows that for equally thick 100 Ω-cm p^+, p cells, the value of V_{oc} of a p^+, p cell correlates directly with the value of V_{oc} of its "parent" BSF cell; the higher the V_{oc} of a BSF cell, the higher is the V_{oc} of the p^+, p cell made from it. This suggests that the increased V_{oc} of BSF cells is directly related to a photovoltage generated at their p^+, p back surface junctions. It should be noted that BSF cells have higher values of V_{oc} than conventional cells of equal resistivity even at very low illumination levels and, correspondingly, very low injection levels. The higher V_{oc} cannot, therefore, be an effect dependent upon high level injection.

As shown in Table II, V_{oc} values of 0.6 volt were obtained in 100 Ω-cm BSF cells equal to the maximum values obtained in 10 Ω-cm BSF cells. Thus, a mechanism exists which makes the V_{oc} of the BSF cell independent of bulk resistivity.

Solid state voltage generators have characteristic V_{oc}-temperature-coefficients. As shown in Table III, the V_{oc} temperature coefficient of n^+, p cells is negative, that is, V_{oc} decreases as temperature increases, whereas that of p^+, p cells is positive. The temperature coefficients of both types of cell increase with increasing resistivity. The data indicate that for the BSF, n^+, p, p^+, cell, the coefficient of the back p^+, p junction adds to the coefficient of the front n^+, p junction to give high resistivity BSF cells an advantageous, unusually low V_{oc} temperature coefficient. These results further substantiate the concept that the p^+, p junction functions as a voltage generator within the BSF cell.

In 1953, Brattain published a theory for p^+, p and n^+, n junction photovoltages (6). Basically, a photovoltage is possible because of the difference in Fermi level between the p^+, and p regions. In conformance with this concept, it has been observed, in production (2), that the maximum V_{oc} values of BSF cells made with boron diffused p^+ regions are approximately 10 mV higher than those of BSF cells made with aluminum diffused p^+ regions. This observation was originally made by the authors on small numbers of laboratory made cells. It is presumed that the higher solubility of boron in silicon as compared to aluminum yields a greater Fermi level difference for boron diffused cells.

The effects of changes in the Fermi level difference across the p^+, p junction can be used to explain the unique V_{oc} characteristic of BSF cells. Table IV points out the changes in Fermi-level-difference, ΔF, which theoretically occur as the "p" bulk resistivity of cells is increased. A decrease in ΔF theoretically should result in a decrease of V_{oc} for any junction. Considering the n^+, p cell, as "p" bulk resistivity is increased, ΔF is decreased, and, correspondingly, V_{oc} will decrease. As illustrated, the 100Ω-cm n^+p cell has a lower V_{oc}, 0.48 volt, than the 0.55 volt V_{oc} of the 10 Ω-cm n^+, p cell. However, for p^+, p cells, the increase in "p" bulk resistivity produces an increase in ΔF and an increase in V_{oc}. Table IV illustrates hypothetically that, by addition of V_{oc} values at the back, p^+, p, junction and the front, n^+, p, junction, we can account for the V_{oc} values of BSF cells being independent of resistivity. In an analogous manner, the independence of V_{oc}-temperature-coefficient and bulk resistivity of BSF cells can be accounted for.

A comprehensive theory for BSF cells must account for the additional unique V_{oc} characteristic of such cells illustrated in Table V. BSF cells were made from wafers taken from the same region of an ingot using a selected aluminum p^+ process to yield maximum V_{oc} values. Equal, high V_{oc} values were obtained for all the cells made irrespective of cell thickness, in the thickness range investigated of 0.010 to 0.033 inch. Similarly, high V_{oc} values were obtained in 10 μm thick cells (5). This complete independency of V_{oc} and cell thickness over such a large thickness range does not appear consistent with any mechanism involving movement of generated minority carriers to create a back junction photovoltage. It is therefore proposed that the p^+, p junction photovoltage is generated by majority carrier collection, as depicted in Fig. 2. The difference in hole concentration between the p^+ and p regions of the BSF cell results in diffusion of holes from the p^+ region into the "p" region. A depletion region and associated equilibrium hole density are established. Under illumination, electron-hole pairs are generated, primarily at the front of the bulk. Most of the generated excess electrons leave the bulk by being collected at the n^+p junction. Excess holes cannot cross the n^+p junction because the n^+ region constitutes a hole barrier. The presence of the unbalanced excess holes in the bulk disturbs the equilibrium at the p^+p junction and a balancing flow of holes into the p^+ region (hole collection) takes place. Figure 2 depicts the photovoltage mechanism in its simplest form. It is recognized that the bulk constitutes a feedback element between the front and rear junctions, therefore the voltage and currents at both junctions must be inter-related (7) The voltages and currents are also dependent upon the properties of each element of the cell in accordance with semiconductor theory.

Although a comprehensive theory has, as yet, not been formulated, sufficient information has been gathered to apply BSF effects effectively. The advantages of using high resistivity silicon for cells are improved, stable characteristics for very shallow junctions and increased radiation damage resistance, as reported many years ago (8). However, the then known penalties preventing the use of high resistivity silicon were low V_{oc}, high bulk series resistance, and high V_{oc}-temperature-coefficient (8). This is pointed out in Table VI. Since the V_{oc} and V_{oc}-temperature-coefficient of BSF cells are improved and independent of resistivity and thickness, it is now possible to make very high resistivity thin cells having high quality extremely shallow junctions and high initial efficiency. Furthermore, such cells can have improved high temperature performance and radiation damage resistance. The achievement of V_{oc} values of approximately 0.6 volt and high values of I_{sc} for 10 μm thick cells (5) opens up new horizons for attaining high efficiency, extremely thin, low cost chemical vapor deposited, CVD, cells.

Thus, BSF effects permit a new latitude in solar cell design.

CONCLUSION

The empirical study of BSF cell fabrication and characteristics has revealed several unique properties of such cells as well as the fabrication controls necessary to optimize cell performance. Possible mechanisms for BSF cell behavior have been considered in the light of observations made, and it is concluded that a photovoltage is generated at the p^+, p back junction of the cell. Several limitations in solar cell design have been removed by the advent of the BSF cell. Removal of these limitations has made it possible to fabricate high efficiency thin cells from high resistivity silicon. The advantage of this for space application lies in improvement of radiation damage resistance and reduction in weight, whereas, for terrestrial applications, low cost-high efficiency cells are achievable. It is also possible that development and control of BSF processing may result in the highest efficiencies being obtained from high resistivity BSF cells.

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TABLE I. - V_{oc} OF p^+, p CELLS

Bulk resistivity, Ω-cm	Thickness, mils	V_{oc}, mV
10	[illegible]	5 - 10
100	13	64
	25	74
	30	91

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TABLE II. - V_{oc} CORRELATION

$n^+, p, p^+ \rightarrow p^+, p$

[100 Ω-cm, 10-mil thick.]

Cell	V_{oc}, V	
100 Ω-cm	n^+, p, p^+	p^+, p
443-3	0.526	0.038
443-2	.540	.038
441-2	.587	.049
457-2	.602	.063
457-3	.605	.064
10 Ω-cm	0.6 Max.	

TABLE III. - V_{oc} TEMPERATURE COEFFICIENTS

Resistivity, Ω-cm	10	100
Cell type	Temperature coefficient, mV/°C	
n^+, p	-2.3	-2.6
p^+, p	+0.14±0.002	+0.05±0.05
n^+, p, p^+	-2.15±0.02	-1.9±0.01

TABLE IV. - FERMI LEVEL DIFFERENCE, ΔF, AND V_{oc}

$\Delta F \downarrow \rightarrow V_{oc} \downarrow$

	n^+, p	p^+, p	n^+, p, p^+
As "p" resistivity ↑, ΔF	↓	↑	
V_{oc}	↓	↑	No change

↑, Increases, ↓ Decreases

	n^+p	p^+, p	n^+, p, p^+
V_{oc} 10 Ω-cm	0.55	0.050	0.6
V_{oc} 100 Ω-cm	.48	.120	.6

TABLE V. - MAXIMUM V_{oc} VERSUS THICKNESS OF BSF CELLS

Thickness, mils	V_{oc}, V
[a]0.4	0.594
10.5	.601
16.5	.603
24.0	.603
33.0	.595

[a]Epitaxial cell (5).

TABLE VI. - THE SIGNIFICANCE OF BSF EFFECTS

Cell characteristic	"p" Bulk requirement	Conventional cell penalty
Lightweight	Thin	Low efficiency
Low cost	Extremely thin	Very low efficiency
Increased radiation resistance	High resistivity	Low efficiency High temperature coefficient
Best junction "A" value	High resistivity	Low efficiency High temperature coefficient
Stable junction "A" value	High resistivity	Low efficiency High temperature coefficient
Low temperature coefficient	Low resistivity	Poor junctions High radiation damage Low I_{sc}
Low series resistance	Low resistivity	Poor junctions High radiation damage Low I_{sc}

BSF effects → thin-high resistivity cells; high efficiency, low temperature coefficient, high radiation resistance, stable junction, best junction "A" value, super blue response.

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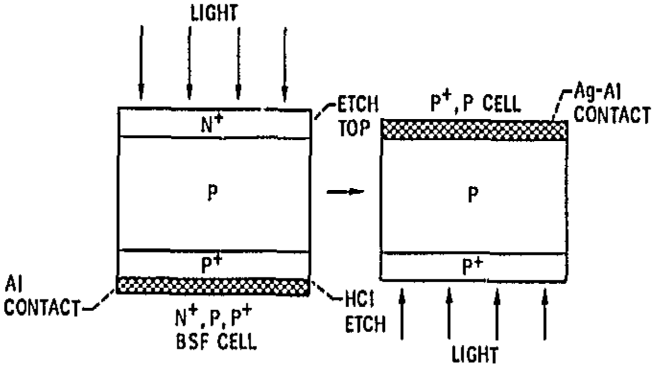

Figure 1. - Fabrication of p^+, p cells.

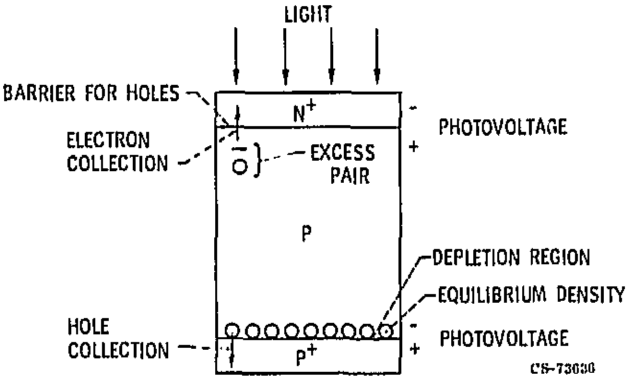

Figure 2. - Mechanism for generation of voltages in n^+, p, p^+ cells.

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