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NASA TECHNICAL MEMORANDUM

NASA TM X-71486

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DESIGN, FABRICATION AND CHARACTERISTICS OF NEW TYPES OF BACK SURFACE FIELD CELLS

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TECHNICAL PAPER presented at
Tenth Photovoltaic Specialists Conference
sponsored by the Institute of Electrical and
Electronics Engineers
Palo Alto, California, November 13-15, 1973

(NASA-TM-X-71486) DESIGN, FABRICATION AND CHARACTERISTICS OF NEW TYPES OF BACK SURFACE FIELD CELLS (NASA) 8 p HC $3.00 CSCL 10A
N74-10943
Unclas
G3/03 21984

DESIGN, FABRICATION AND CHARACTERISTICS OF NEW TYPES OF BACK SURFACE FIELD CELLS

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E-7814

SUMMARY

Several new types of back surface field (BSF) cells were designed and fabricated. These include boron and phosphorus diffused BSF cells, single crystal epitaxially grown BSF cells and chemically vapor deposited (CVD) polycrystalline BSF cells. Boron diffusion yielded 10 Ω-cm BSF cells with 0.6 volt open-circuit voltages and collection efficiencies equal to those previously reported for aluminum alloying. The epitaxially grown cells also exhibited high open-circuit voltages and collection efficiencies and may be more radiation damage resistant. The polycrystalline cells had very high internal series resistance.

No direct relationship was found to exist between collection efficiency and open-circuit voltage, V_{oc}, in BSF cells. Results indicate that the V_{oc} effect is not caused simply by the mechanism of "blocking" of minority carriers.

INTRODUCTION

A program at the Lewis Research Center involves fabrication of new or improved back surface field, BSF, cells and gaining a better understanding of the BSF mechanism. An important objective is to obtain maximum values of open-circuit voltage, V_{oc}. Several types and structures of solar cells were fabricated and evaluated under the program.

The aluminum-alloyed back surface field (BSF) solar cell has previously been shown to have high open-circuit voltage, high collection efficiency, a desirable temperature behavior, and when thin, improved radiation damage resistance (1). A mechanism was proposed to explain the behavior of the BSF cell (1).

The BSF effect was attained by boron diffusion as well as by aluminum alloying. Boron diffusion has advantages in that boron is more soluble in silicon than aluminum and diffusion yields more uniform junctions than alloying. Boron diffused surfaces are also more suitable for contacting than aluminum alloyed surfaces.

Phosphorus diffusion, using $POCl_3$ vapors, has been developed to a high level at Lewis. It routinely yields high quality very shallow junctions and preserves extremely high bulk minority carrier diffusion lengths. Thus fabrication of cells utilizing n-type silicon and back surface phosphorus diffusions was investigated to obtain BSF cells with good reproducibility.

To improve the radiation damage resistance of cells, a BSF cell fabricated by the deposition of a thin 10 Ω-cm single crystal epitaxial layer on a low resistivity substrate was investigated. Finally, a chemical vapor deposited (CVD), BSF, polycrystalline cell, which represents a unique approach to increasing the current and thereby the efficiency of very thin, low cost, polycrystalline cells, was studied.

PROCEDURE

Cell Design and Fabrication.

The BSF cells under investigation can be broadly divided into two categories based upon the origin of the bulk material of the cell. The first category contains cells made from wafers cut from single crystal silicon ingots. Category 2 cells have bulks formed by deposition of silicon from vapors of silicon compounds upon selected substrates. Within both categories, either n^+-p-p^+ or p^+-n-n^+ cells can be made, but this has been done thus far only for cells in the first category.

Category 1 Cells. The various structures are shown in figure 1. Bulk resistivities of both 1 and 10 Ω-cm were used since these are resistivities common for solar cells. The first BSF cells fabricated at Lewis had aluminum alloyed and diffused back regions made at comparatively low temperatures (~ 800° C) in wafers already containing front junctions (1). The second type had a boron diffused back region. The source of boron was a solution, containing a boron compound, painted on the back surface of wafers. High temperatures (~ 1000° C) were used to achieve estimated junction depths of 0.5-1.0 μ in times of 1 hour or less.

Since both the boron and aluminum diffusion processes were undeveloped, it was expected that better and more reproducible BSF cells could be made by diffusing phosphorus into back surfaces of n-type wafers and fabricating p^+-n-n^+ cells.

Also, phosphorus diffusion possesses the advantage that phosphorus atoms fit into the silicon lattice much better than boron atoms and phosphorus has a solid solubility in silicon much higher than that of boron or aluminum (2).

The main fabrication problem of BSF cells stems from the requirement that the back diffused region be of opposite type (p or n) to the front region. Both "p" and "n" type dopant atoms must therefore be diffused at high temperatures into each wafer. Cross doping, intermixing of "p" and "n" type atoms on wafer surfaces, can occur. Erosion of previously diffused regions during second diffusions by gaseous $POCl_3$ can also occur. These undesirable effects were diminished by maintaining a protective oxide layer on the rear diffused region.

Category 2 Cells. These cells were made from Chemical Vapor Deposited, CVD, silicon and correspondingly category 2 cells are called CVD-BSF cells. The various structures are shown in figure 2.

CVD processing was done at Applied Materials Technology Inc. and at Unicorp Inc. The process was carried out using $SiCl_4$ as a source of silicon at a temperature of 1100° C. The entire procedure was a standard one used industrially for epitaxial silicon deposition, and only the resistivity and thickness of the deposited layers was specified by Lewis. Substrates were supplied by Lewis. Quartz was used for polycrystalline cells so as not to contaminate the CVD system.

The 0.5 Ω-cm bulk resistivity of the polycrystalline CVD-BSF cells was selected in an attempt to reduce intergrain resistance, a problem plaguing polycrystalline material. The thickness of the layers was chosen as one grain height.

The top junctions were made at Lewis by the standard $POCl_3$ phosphorus diffusion process.

Contacts. Contacts to BSF cells were made using metal masks and evaporating a thin, 200-500 Å, layer of aluminum followed by evaporation of 3-5 microns of silver onto the wafer surfaces. The contacts were then sintered at 550-650° C. This same silver-aluminum contact is being developed for forming top and bottom contacts to extremely shallow junction BSF cells without the degradation of cell electrical characteristics which occurs for sintered Ag-Ti contacts.

The contacts to the bulk region of the CVD polycrystalline cells were made by etching away the edges of the diffused top junction and plating rhodium to the exposed bulk at the edges.

Cell Evaluation.

Open-Circuit Voltage. The primary criterion that has been applied to BSF cells has been the value of open-circuit voltage, V_{oc}. The conditions for V_{oc} measurement at Lewis were arbitrarily chosen as a cell temperature of 25° C and an illumination level yielding a short-circuit current of 32.5 ma per sq. cm. One objective of V_{oc} measurement was to discover what maximum value of V_{oc} was achievable for BSF cells.

Apparent Diffusion Length. The back field region of BSF cells increases the collection efficiency of thin cells. A proposed mechanism for the collection efficiency effect has been published (3). In this mechanism a diffused back region "blocks" movement of excess minority carriers to the back contact, figure 3. The collection of generated minority carriers at the front junction, I_{sc}, is thereby increased. The overall result is as if the diffusion length were increased. To investigate the relationship, if any, of the "blocking" mechanism to V_{oc}, an evaluation method for measuring the effectiveness of "blocking" was formulated based on diffusion length measurements.

The BSF cells were irradiated with fixed intensity, deeply penetrating, high energy X-rays and the short-circuit current density was measured. The equipment and procedure used was identical to that used to measure minority carrier diffusion length (4). The value of bulk minority carrier diffusion length, L_B, can be related directly to the value of current density and can be read off from a graph if the measured cells are thick (4). For the thin cells, 0.006-0.008 inch, used extensively in this study, the current is dependent upon the cell thickness and the effectiveness of "blocking" as well as upon bulk minority carrier diffusion length. Nonetheless, it is useful to compare thin cells in terms of a diffusion length value taken from the plot of current density vs. diffusion length used for thick cells. Since the value so determined for thin cells does not correspond to the actual bulk minority carrier diffusion length, it is referred to as the "apparent diffusion length", L_A. See figure 4.

L_A values for thin conventional cells are thickness limited and are equivalent to approximately one half the actual cell thickness when measured by the Lewis X-ray method. L_A values for 0.006-0.008 inch BSF cells have been obtained which are equal to the thickness of the cell. For thicknesses above this range L_A values are always less than cell thickness whereas L_A values for very thin epitaxial BSF cells have exceeded the thickness of the bulk. The only significance attached to L_A values in this study lies in rating BSF cells of equal thickness; a comparatively high L_A value (i.e. where L_A = cell thickness) indicates a high collection efficiency and the existence of a highly effective "blocking" back region. Thus comparison of L_A and V_{oc} for BSF cells of equal thickness will indicate whether the value of V_{oc} depends upon the "blocking" mechanism of such cells.

RESULTS AND DISCUSSION

Aluminum BSF Cells.

The electrical characteristics of aluminum alloyed and diffused BSF cells have been described previously (1). Table I presents data on L_A and corresponding V_{oc} values of such cells. L_A values for cells in the thickness range of 0.006-0.008 inches can equal the thickness of the cell, as shown.

The aluminum BSF cells made at Lewis, had V_{oc} values that ranged from 0.55-0.58 volt. The V_{oc} value, however, appeared sensitive to factors other than just L_A. Although a general trend of high L_A values corresponding to high V_{oc} values may be present, this does not appear to be a necessary condition. For example, in Table I the first four cells all have L_A values equal to the cell thickness and enhanced V_{oc} values. However, cell 355-9 has about the same V_{oc} as cell 334-15. Yet the L_A value of cell 355-9 is less than the cell thickness and in fact is the lowest L_A value in this group of cells. Some commercially made aluminum BSF cells had the highest V_{oc} values measured, 0.59-0.60 V, and the fact that the highest V_{oc} values do not correspond with the highest L_A values is illustrated by cell M-1.

Figure 5 is a plot of L_A vs. V_{oc} for cells of equal thickness. Again, while a general trend is indicated, a high L_A value does not always correspond to a high V_{oc} value.

Boron BSF Cells.

It was necessary to diffuse boron into cell back surfaces at high temperatures (~ 1000° C) in order to achieve high open-circuit voltages. These high temperatures caused indiffusion of any undesirable impurities present on the surface of the silicon with resultant minority carrier lifetime degradation. Considerable variation in diffusion lengths was noted from wafer to wafer in the same diffusion and among groups of wafers diffused in different runs. Very strict cleaning procedures were necessary to keep degradation to a minimum. The Group 1 cells of Table II illustrate the bulk minority carrier lifetime degradation problem of the boron diffusion process. The values of diffusion lengths, L_A, for the thick cells (362-5 and 389-9) whose back regions were removed, are very low. Furthermore, the values of L_A of the thin cells are less than one-half the thickness of the cell indicating degradation of bulk minority carrier diffusion length. However, the V_{oc} values of the thin cells are well above the 0.55 volt maximum of thick non-field 10 Ω-cm cells showing that the back field is functioning. Additional evidence that the back field was effective in these degraded cells was obtained by comparing the characteristics of cell 362-5 before and after removal of the back diffused region. Both V_{oc} and L_A were decreased by removal of the BSF region.

Group 2 cells of Table II have very high L_A values that are equal to the thickness of the cells. The corresponding V_{oc} values of these cells, however, were actually lower than the V_{oc} values of the thin degraded cells of Group 1.

Group 3 cells of Table II had the highest values of V_{oc} thus far obtained for BSF cells, but their values of L_A were significantly lower than their thickness.

Phosphorus BSF Cells.

The back region characteristics of some phosphorus diffused 10 Ω-cm BSF cells are shown in Table III. Uniform characteristics were obtained as expected. The effective "blocking" obtained from the back region is evident from the values of L_A which slightly exceed the thickness of the cells. The corresponding values of V_{oc} are, however, lower than expected in that they are similar to those of the crude aluminum alloyed and diffused cells. Nonetheless, the V_{oc} values show the influence of the back region in varying degrees since they are much higher than the 0.55 volt maximum values of V_{oc} achieved in conventional thick, 10 Ω-cm cells.

The back region characteristics of phosphorus diffused 1 Ω-cm BSF cells are presented in Table IV. Enhancement of collection is evident from the values of L_A which far exceed the one-half-the-cell-thickness limit of L_A of conventional thin cells. However, values of V_{oc} do not exceed the 0.60 volt maximum V_{oc} value of conventional, thick, 1 Ω-cm cells (5,6).

V_{oc} Effect Mechanism.

For each type of BSF cell (aluminum, boron, or phosphorus diffused), several 0.006-0.008 inch thick cells made had very high L_A values which equaled the cell thickness. All such cells had values of V_{oc} considerably lower than the highest V_{oc} values obtainable, namely 0.6 volts. This result leads to the conclusion that very high collection efficiency (i.e., high L_A or effective "blocking") is not directly related to the value of V_{oc} or at least is not sufficient to yield high V_{oc}. Important corroboration of this conclusion is available from data showing that V_{oc} values of 0.575 volts were readily obtained for 10 Ω-cm BSF cells 0.029 inches (725 μm) thick (5). Measured bulk minority carrier diffusion lengths, L_B, of very thick cells have ranged from 150-250 μ. The conventional equations relating V_{oc}, L_B, and cell thickness, W, given in reference 7, indicate that a back region located three times the bulk minority carrier diffusion length from the front contact, i.e. $W/L_B \geqq 3$, cannot affect the value of V_{oc}. Thus the 0.575 value of V_{oc} of the 725 μ thick 10 Ω-cm cells cannot be attributed to minority carrier "blocking" at the back contact. A similar case can be made for the degraded bulk minority carrier diffusion length, thin, BSF cells in Table II. Their high values of V_{oc} also cannot be attributed to the "blocking" mechanism since their $W/L_B \geqq 3$.

Epitaxial BSF Cells.

The characteristics of epitaxial cells with two extremes in bulk thickness, 10 μ and 75 μ, are shown in Table V. The structures are shown in figure 2. During the deposition step boron within the substrate diffused into the deposited silicon creating a BSF. Values of V_{oc} were uniform in value and as high as those achieved for the better Category 1 BSF cells. L_A values exceeded the thickness of the bulk. This is not surprising since generation of minority carriers must take place within the very thick p^+ region and collection of some of these generated charges should occur. The value of I_{sc} of the 75 μm thick cells are only 5% below those of thick conventional cells whereas the I_{sc} values of the 10 μm thick cells are 25% below those of thick conventional cells.

The results are encouraging in terms of being able to obtain high efficiencies from very thin BSF silicon cells.

Polycrystalline BSF Cells.

The chief criticism of thin film polycrystalline silicon cells is that the available current would be low because of limited photon absorption in thin layers of silicon. A back field could possibly double the available current of very thin cells.

It was impossible to make valid measurements on the completed cells because of their extremely high series resistance. The resistance was attributed to inter-grain effects. These effects also include non-ohmic behavior which would affect V_{oc} values. Also, contact to the p region was made on the front of the cell, as shown in figure 2. Direct contacting of the cell back surface would diminish the inter-grain effects considerably. Maximum values of V_{oc} of 200 mv were measured for some of the cells.

CONCLUDING REMARKS

The highest value of V_{oc} obtained in BSF cells at present is 0.6 volt, and is attainable in either boron diffused or aluminum alloyed and diffused cells having phosphorus diffused front junctions. Boron diffusion is considered to have the greatest potential for making improved BSF cells because of known advantages of boron diffusion as compared to aluminum alloying and diffusion.

A study of the collection efficiency and values of V_{oc} of BSF cells did not show a direct relationship existed between these characteristics. This result suggests that the V_{oc} effect is not caused simply by the mechanism of "blocking" of minority carriers by the back region of BSF cells.

Epitaxial BSF cells have been made with high V_{oc} (0.59 volt) and high collection efficiency. These results are encouraging and more experimentation is warranted.

The polycrystalline CVD-BSF cells made were very poor; the major problem being very high internal series resistance. V_{oc} values up to 0.2 volt were measured for some of the cells.

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TABLE I

ALUMINUM ALLOYED AND DIFFUSED BSF CELLS

10 Ω-cm, n^+-p-p^+

CELL	V_{OC} [1]	CELL THICKNESS	APPARENT DIFFUSION LENGTH (L_A)		GROUP
NUMBER	VOLT	MILS	MILS	MICRONS	
334-8	0.582	8.4	8.4	210	L_A = CELL THICKNESS
334-14	0.581	8.0	8.4	200	
334-C	0.583	7.8	7.6	190	
334-15	0.577	7.6	7.6	190	
335-1	0.568	7.0	5.8	145	L_A < CELL THICKNESS
355-5	0.564	7.0	6.2	155	
355-9	0.571	7.0	5.1	128	
353-1	0.553	7.0	5.3	132	
M-1[2]	0.598	6.3	5.4	135	

[1] V_{OC} MEASURED AT 25° C FOR I_{SC} = 65 ma

[2] COMMERCIAL CELL (HIGHEST V_{OC}), Al ALLOYED DIFFUSED

TABLE II

BORON DIFFUSED BSF CELLS

10 Ω-cm, n^+-p-p^+, 1 x 2 cm

CELL	V_{OC} [1]	THICKNESS	APPARENT DIFFUSION LENGTH (L_A)		AFTER FIELD REMOVED L_B	V_{OC} [1]	GROUP
NUMBER	VOLT	MILS	MILS	MICRONS	MICRONS	VOLT	
389-1	0.586	7.2	3.5	87	47	.517	1 DEGRADED
389-4	0.581	7.4	3.0	75	59	.517	
389-9	0.515	14.4	2.1	52	52	.512	
362-5	0.551	12.3	3.1	78	60	.525	
360-22	0.571	7.3	7.3	183	--	--	2 HIGHEST L_A
360-23	0.571	7.1	7.1	178	--	--	
360-24	0.572	7.1	7.2	180	--	--	
382-1	0.599	5.8	5.1	128	--	--	3 HIGHEST V_{OC}
382-3	0.599	6.1	5.0	126	--	--	
382-4	0.598	5.8	5.1	128	--	--	

[1] V_{OC} MEASURED AT 25° C, I_{SC} = 65 ma

TABLE III

PHOSPHORUS DIFFUSED BSF CELLS

10 Ω-cm, p^+-n-n^+, 1 x 2 cm

CELL	V_{OC} [1]	CELL THICKNESS	APPARENT DIFFUSION LENGTH, L_A		BULK DIFFUSION LENGTH, L_B
NUMBER	VOLT	MILS	MILS	MICRONS	MICRONS
401-1	0.581	6.6	6.8	170	--
401-2	0.567	6.5	6.7	167	--
401-4	0.581	6.5	6.8	170	--
401-5	0.574	6.3	6.4	161	--
401-6	0.582	6.5	6.8	170	--
401-7	0.587	6.5	6.8	171	--
[2]	0.525	6.0	3.0	75	--
[2]	0.555	20.0	--	--	200

[1] V_{OC} MEASURED AT 25° C FOR I_{SC} = 65 ma

[2] CONVENTIONAL p^+-n CELLS

TABLE IV

PHOSPHORUS DIFFUSED BSF CELLS

1 Ω-cm, p^+-n-n^+

CELL	V_{OC} [1]	CELL THICKNESS	APPARENT DIFFUSION LENGTH (L_A)		BULK DIFFUSION LENGTH (L_B)
NUMBER	VOLT	MILS	MILS	MICRONS	MICRONS
401-9	0.579	7.5	5.8	146	--
401-10	0.568	8.0	5.2	132	--
401-11	0.583	6.2	5.3	132	--
401-13	0.576	7.0	5.5	139	--
401-14	0.575	6.5	4.8	123	--
401-15	0.590	6.8	6.1	153	--
401-16	0.588	6.3	5.7	142	--
[2]	0.6 MAX	15.0			180

1 V_{OC} MEASURED AT 25° C for I_{SC} = 65 ma

2 CONVENTIONAL p^+-n 1 Ω-cm CELL

TABLE V

CHARACTERISTICS OF EPITAXIAL BSF CELLS

n^+-p-p^+, 1.7 cm^2 ACTIVE AREA, BARE

QUANTITY OF CELLS	V_{OC} [1] VOLT	EPITAXIAL BULK THICKNESS MICRONS	APPARENT DIFFUSION LENGTH (L_A) MICRONS	I_{SC} [2] ma
4	.591-.593	10	24	40-41
4	.592-.593	75	90	50-51
[3]	0.55	300	150	53 MAX

[1] V_{OC} MEASURED AT 25° C FOR I_{SC} = 65 ma

[2] I_{SC} MEASURED WITH FILTER WHEEL SOLAR SIMULATOR AND X-25L SPECTROSUN SIMULATOR

[3] CONVENTIONAL 10 Ω-cm CELL

CATEGORY 1 BSF SOLAR CELLS
BULK: SINGLE CRYSTALLINE SILICON

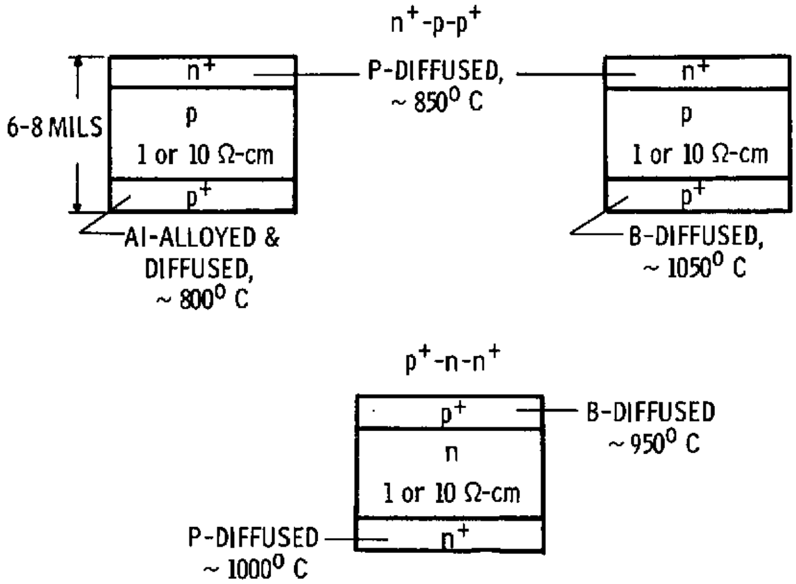

Fig. 1

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CATEGORY 2 BSF SOLAR CELLS
BULK: CHEMICAL VAPOR DEPOSITED SILICON

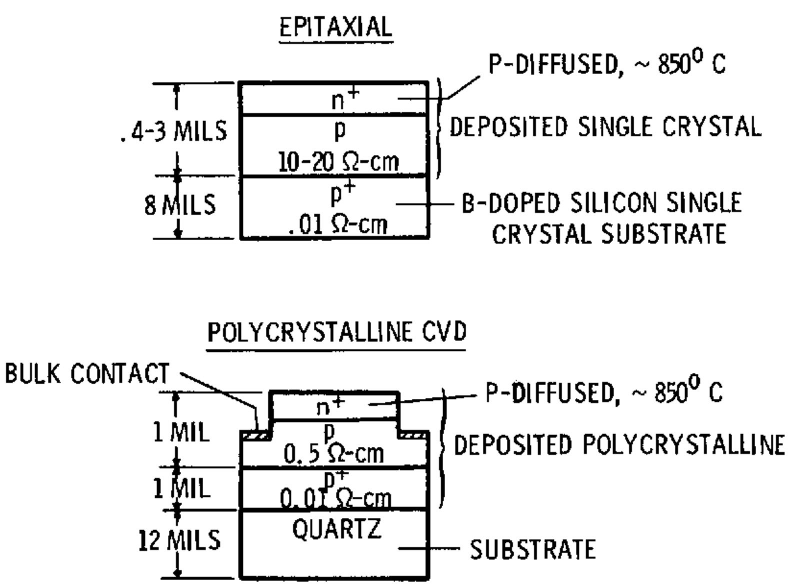

Fig. 2

BLOCKING MECHANISM OF BSF SOLAR CELL

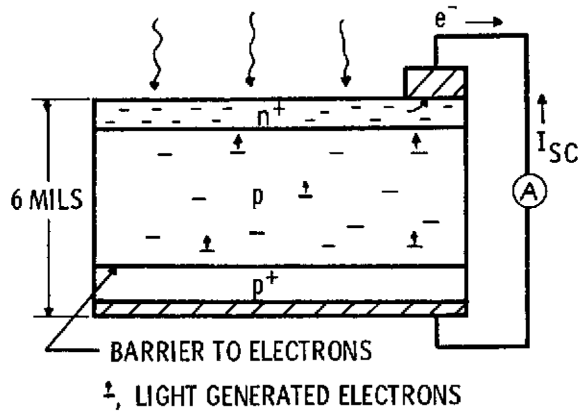

Fig. 3

APPARENT DIFFUSION LENGTH, L_A, OF THIN SOLAR CELLS

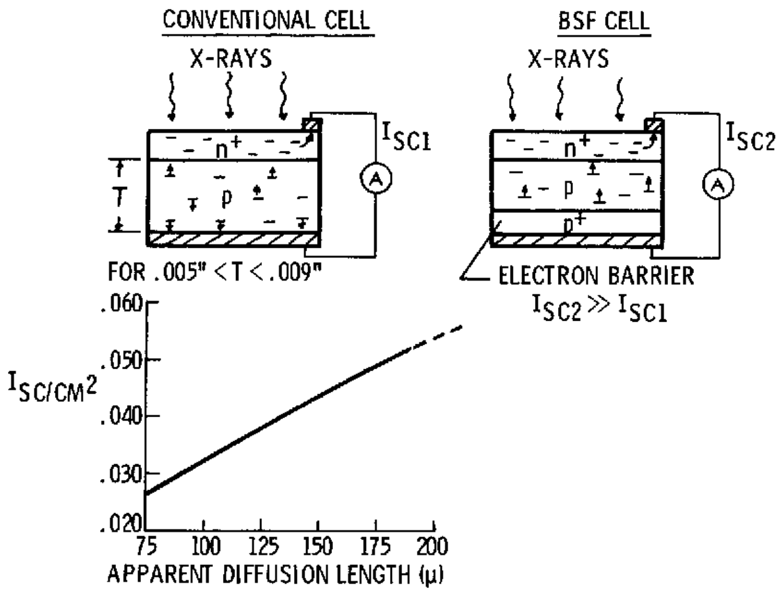

Fig. 4

OPEN CIRCUIT VOLTAGE VS APPARENT DIFFUSION LENGTH

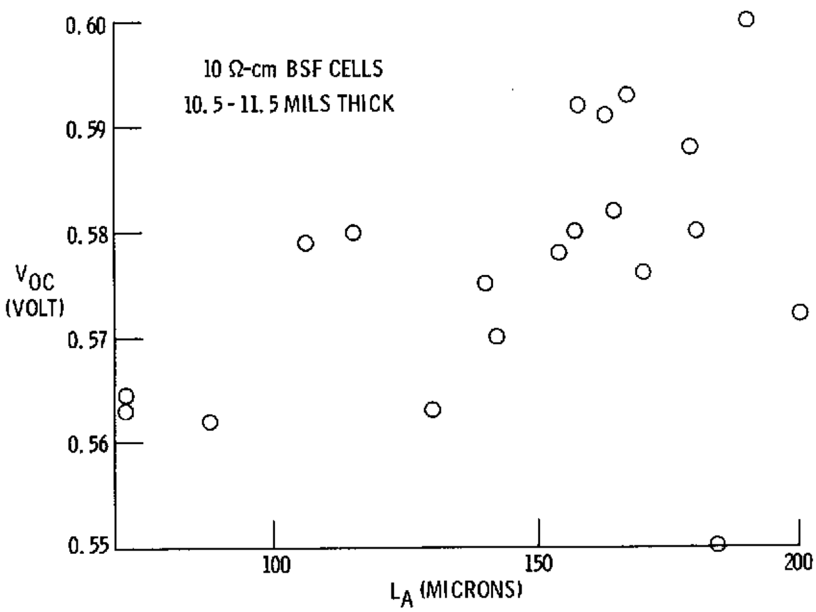

Fig. 5

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