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THEORETICAL ANALYSIS OF THE SERIES RESISTANCE OF A SOLAR CELL

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Abstract—An equivalent resistance circuit of a solar cell which takes into account all the sources of linear resistance in a solar cell is developed. Equations which will determine the resistance of the diffused layer of a solar cell are also developed assuming a constant gradient across the diffused layer. The equations for the total series resistance of an *n* dimensional solar cell are evolved where *n* represents the number of grids in the cell. The equations have been utilized in conjunction with experimentally determined values of the component resistances to predict the total series resistance of several cell types. Very good correlation was obtained between the experimentally measured total series resistance and the theoretically predicted total series resistance of these cells.

Résumé—On développe un circuit à résistance équivalente à une cellule solaire qui comprend toutes les sources de résistances linéaires. Des équations qui déterminent la résistance de la couche diffusée d'une cellule solaire sont aussi développées en assumant un gradient constant à travers la couche diffusée. Les équations pour la résistance totale en série d'une cellule solaire à *n* dimensions sont développées (*n* représente le nombre de grilles dans la cellule). Les équations ont été employées avec les valeurs des composantes de résistance déterminées expérimentalement pour prédire la résistance totale en série de plusieurs types de cellules. Une très bonne corrélation a été obtenue entre la résistance totale en série mesurée expérimentalement et la résistance totale en série de ces cellules prédite théoriquement.

Zusammenfassung—Ein Ersatzschaltbild fur den Widerstand einer Solarzelle wird entwickelt, das alle Beitrage zum ohmschen Widerstand berucksichtigt Auch Gleichungen zur Bestimmung des Widerstands der eindiffundierten Schicht in einer Solarzelle werden abgeleitet. Der Ausdruck für den gesamten Widerstand einer '*n*-dimensionalen' Solarzelle wird angegeben, wo *n* die Zahl der Kontaktstreifen zur Stromaufnahme bedeutet Aus den gemessenen Teilwiderstanden wurde der Gesamtwiderstand fur verschiedene Zelltypen berechtnet. Dabei ergab sich gute Übereinstimmung mit Messwerten für den Gesamtwiderstand

INTRODUCTION

SERIES resistance in a solar cell is a parasitic, power-consuming parameter which seriously affects the maximum conversion efficiency of an otherwise good cell. The problem of minimizing cell resistance has taken on somewhat of a different nature with the advent of the extremely shallow diffused cells (junction depths of the order of 0.5 μ presently available). The older deeper-diffused cell resistances were limited mainly by contact resistance at the electrodes. The present-day cells with grid lines, however, are usually limited by the resistance in the diffused sheet due to the very small cross-sectional area which the carriers in this region traverse, while the contact resistance has been made negligible, for the most part, by the technology of the contact fabrication.

The conducting grids on the active surface of the present-day solar cell reduces the average path length of a carrier in the silicon diffused sheet which greatly minimizes the resistance of the diffused sheet. Since, however, the area under the grid itself contributes nothing to current generation due to the fact that all the usable light is absorbed

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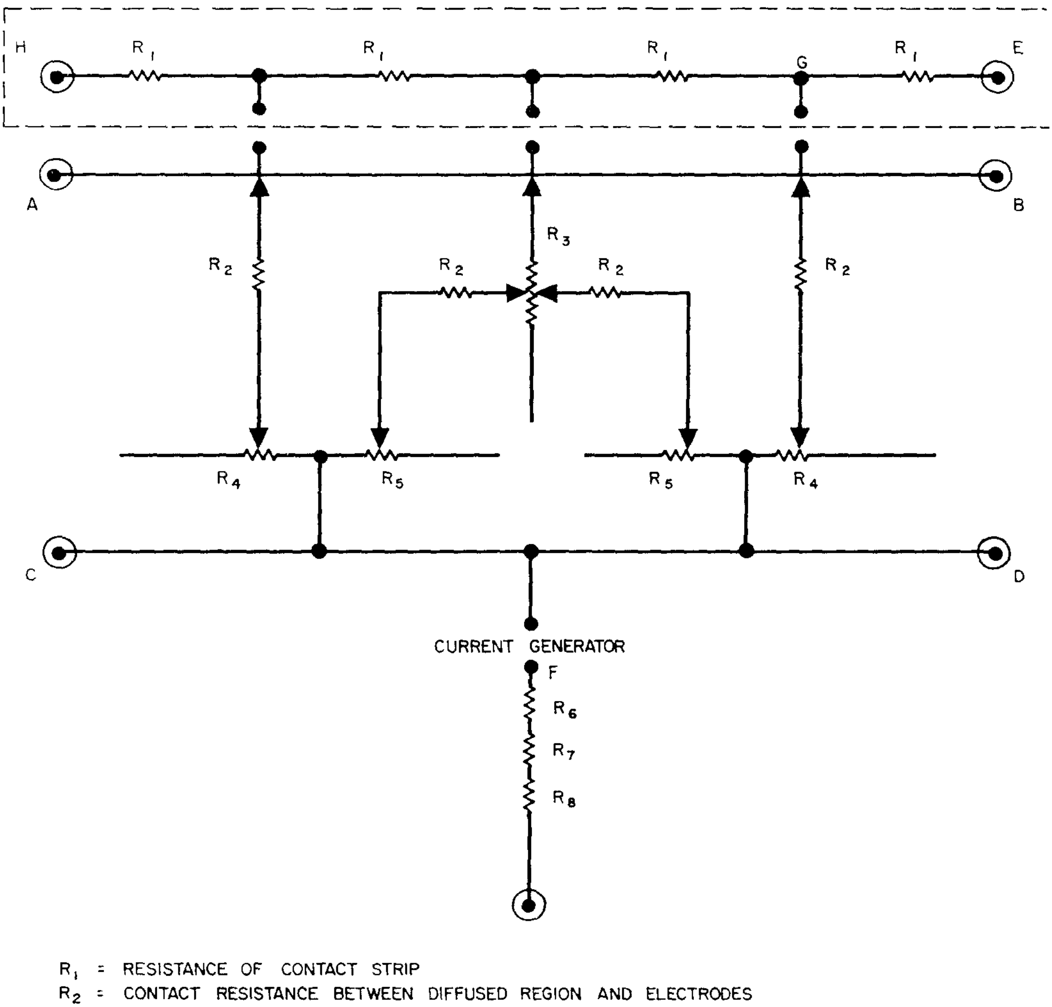
by the metallic grid, there is an upper limit to the number and size of the grids which can be deposited for optimum solar cell performance in any given environment and for given values of the solar cell parameters.

It is becoming increasingly important to minimize solar cell series resistance in view of consumer desires to operate cells at higher incoming intensities, either in conjunction with concentrator systems which will allow a given solar array to generate many times the power obtained in present-day unconcentrated configurations, or in conjunction with missions which carry the cells closer to the sun so that significantly more solar energy is



R_1 = RESISTANCE OF CONTACT STRIP
R_2 = CONTACT RESISTANCE BETWEEN DIFFUSED REGION AND ELECTRODES
R_3 = RESISTANCE OF GRID STRIP
R_4 = RESISTANCE OF DIFFUSED REGION FOR CARRIERS FLOWING TO CONTACT STRIP
R_5 = RESISTANCE OF DIFFUSED REGION FOR CARRIERS FLOWING TO GRID STRIP
R_6 = RESISTANCE OF BULK REGION
R_7 = CONTACT RESISTANCE OF BULK REGION TO BOTTOM ELECTRODE
R_8 = RESISTANCE OF BOTTOM ELECTRODE

FIG 1. Equivalent resistance circuit of solar cell available to the system. Under these conditions of increased illumination the solar cell series resistance becomes increasingly detrimental.

In speaking of 'series resistance' one must bear in mind that there are two distinct types of series resistance present in a solar cell, namely a resistance of the diffused sheet, which is a distributed resistance determined by a nonuniform current distribution and other resistance which can be 'lumped' since they are uniformly traversed by the current flowing through the cell. The resistance of the diffused sheet cannot readily be lumped, since the current carriers are injected into this diffused sheet in an essentially uniform distribution with respect to planes parallel to the surface of the cell. Hence the length l, that the carrier traverses through the diffused sheet, in order to reach a highly conducting grid or contact strip, is dependent on the location where the carrier enters the diffused region. From the relationship between resistance and length:

$$R = \rho l/A \tag{1}$$

where ρ is the resistivity of the material and A is the cross-sectional area, it is obvious that no single path length or associated resistance value can be ascribed to all carriers in the diffused sheet, and that when one refers to a particular value of 'resistance' in this region one refers to some sort of average or equivalent resistance, mostly based on the assumption that carriers are generated uniformly in a plane parallel to the junction plane. A detailed equivalent resistance circuit of a solar cell has been developed by the author (see Fig. 1). This configuration takes into account current collection by the contact strip R_1 and the resistance in the base region of the cell R_6, as well as the contact resistances to the grid and contacts R_2, R_7 respectively. The concept of the 'unit field' as defined by WOLF[1] has been adopted here. In utilizing such a model, the cell is broken down into the smallest system which will allow the generation of the entire cell by addition of the appropriate number of such systems. Variable resistance symbols are used in places where the resistance value is likely to be varied due to the geometrical configuration, however, for a given solar cell configuration these resistances have specific values.

Figure 1, exclusive of the portion within the dotted rectangle, depicts the case where the cell is used in a shingle configuration. The line AB represents the contact strip which presents no resistance to the current flow in this configuration. Additional fields are added by connecting the B contact with the A contact of the next field, and the point D of the circuit to the point C of the next field. The resistances in the base are common to all the fields comprising the cell. That is, all the diffused layer fields are connected at F.

For the case where the cell is to be used in a shingle configuration, the entire contact strip is soldered to the base electrode of the preceding cell to provide a series connection, the equivalent resistance of one solar cell unit field is given by:

$$R_{T_s} = \frac{R_2+R_4}{2+\dfrac{R_2+R_4}{R_3+1/2(R_2+R_5)}}+R_6+R_7+R_8. \tag{2}$$

If the cell is not operated in a shingle array, however, and a lead is attached at point A, the proper representation of the conduction strip is given by the line HE as shown in the dotted rectangle. This would replace the contact line AB of the shingled-cell model. This says that carriers which have been collected by the grid, and consequently have passed through a resistance R_3, must pass through an additional resistance $2R_1$. Carriers created in the sheet to the left of the grid strip which are collected by the contact strip will see an average resistance of approximately R_1. It is assumed here that the contact strip is almost an equipotential and that the current distribution is fairly uniform along its length. Similarly, carriers collected by the contact strip to the right of the grid strip see a resistance of $3R_1$ in the contact. The equivalent resistance of one field when the lead connection is made at point H (and assuming area contact made to base) is given by.

$$R_{T_s} = R_1 + \frac{1+\dfrac{R_1}{R_3+1/2(R_2+R_5)}+\dfrac{R_1}{R_1+R_2+R_4}(R_2+R_4)}{2+\dfrac{R_1+R_2+R_4}{R_3+1/2(R_2+R_5)}} + R_6+R_7+R_8. \tag{3}$$

The R_1 between points E and G enters into the picture only when another field is connected to the right (i.e. to points E and H). In this case, current would also flow through this R_1 which is then in series between the two parallel connected diffused layer fields.

RESISTANCE OF THE DIFFUSED LAYER

Determination of the actual values of the diffused layer resistance R_4 and R_5, of Fig. 1 presents somewhat of a different problem than the other resistances in the equivalent circuit, since these

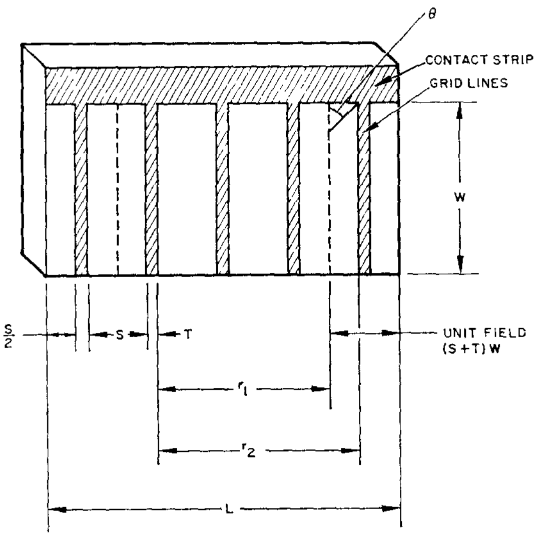


FIG. 2 Solar cell representation.

resistances are not physically separable for individual measurement. Also, one must take into consideration the fact that current density in this region is not uniform since current generation occurs over the entire surface, with a subsequent flow to the collecting contacts. The only easily measurable property of this region is the sheet resistance or sheet resistivity.[2] It is therefore necessary to develop an expression which accurately describes the resistance of this layer in terms of these measurable quantities (i e. sheet resistivity and dimensions of the cell unit field).

Referring to Figs. 2 and 3, it will be seen that the diffused layer can be broken up into identical parts which correspond to a unit field. Within this unit field there are two areas which are symmetrical about the grid line and have dimensions $\frac{1}{2}S \times W$. These regions are the basic areas which are repeated throughout the cell and are electrically connected in parallel. If one considers the probability of the generated current paths, the collection of the generated current from areas

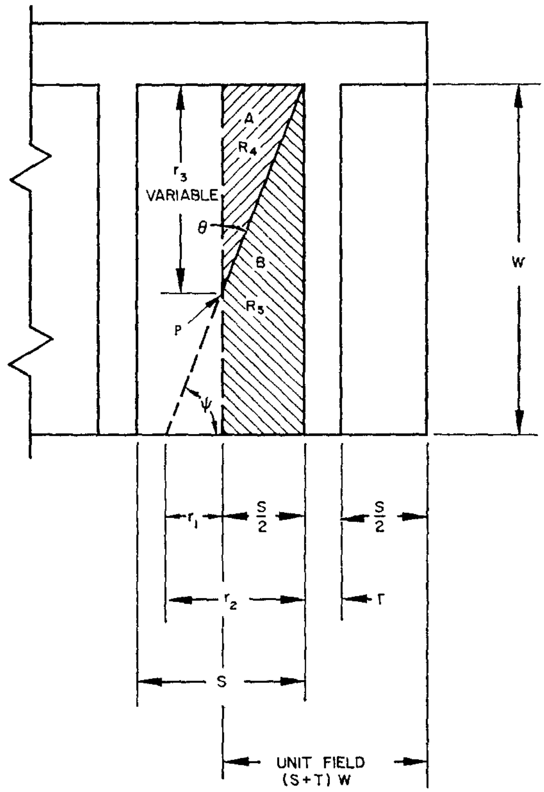


FIG. 3 Expanded view of unit field

A and B will be made at the main contact strip and the grid lines respectively. There will be an artificial boundary line formed at an angle θ which separates these areas. The two regions A and B are assumed to be a triangle and trapezoid respectively. The first step in determining the resistance of these areas is to find the electric field developed in the layer due to the current flow.

Assuming a one-dimensional linear, homogeneous flow, we have that

$$E_r = J_r \rho \tag{4}$$

where E_r, J_r and ρ are the electric field, current

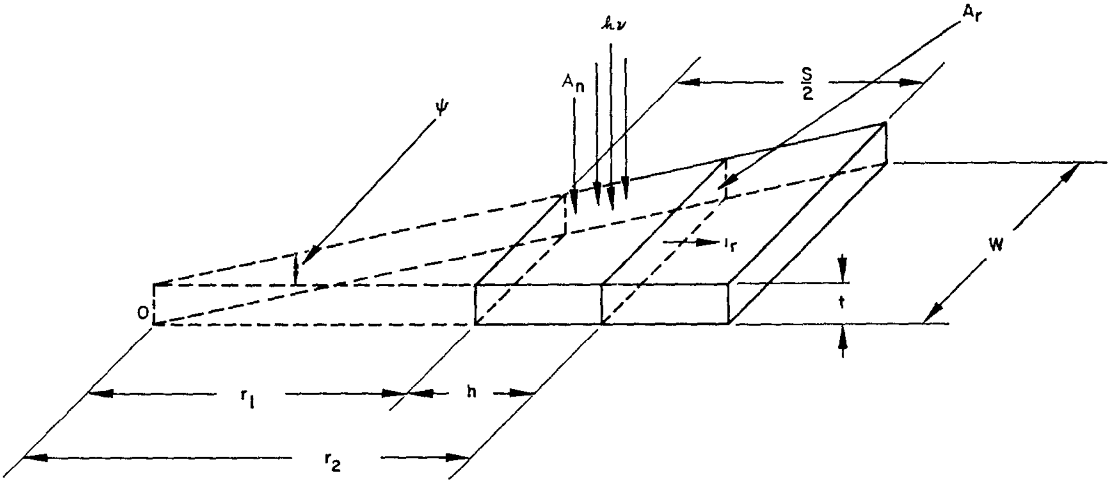


FIG. 4. Trapezoid region representing resistance, R_5.

density and the resistivity of the media respectively.

The total current i_r flowing in the direction of the electric field can be represented by the product of the current density J_r in the direction of the current flow and the area A_r perpendicular to this flow giving

$$i_r = (J_r)(r_2 \tan\psi)(t) \tag{5}$$

where t = thickness of media and $r_2 \tan\psi$ is the length of the rectangular area A_r, r_2 distance from 0 (the apex). Figure 4 is a representation of this model and can be used for analyzing both the triangle and the trapezoid regions, the triangle being a special case of the trapezoid.

The amount of current i_r flowing in the lateral direction is a function of the light intensity incident on the surface of the solar cell, and from the continuity equation we have

$$i_n = i_r \tag{6}$$

where i_n = current produced by photon absorption at steady state conditions in the normal direction to the surface of the cell. Since, in general, the total current i is equal to the product of the current density J times the normal area A through which the current is flowing, equation (6) can be put in the form

$$J_n A_n = (J_r)(r_2 \tan\psi)(t) \tag{7}$$

where J_n is the generated current density in the normal direction and A_n is the area normal to this current density. A_n is always taken to be that area which lies to the left of the area A_r (see Fig. 4). From Fig. 4 we have

$$A_n = \tfrac{1}{2}h(r_1+r_2)\tan\psi \tag{8}$$

and since $h = r_2 - r_1$, we have

$$J_r = \frac{J_n(r_2^2 - r_1^2)}{2r_2 t} \tag{9}$$

from the substitution of A_n from equation (8) into (7). This equation represents the current

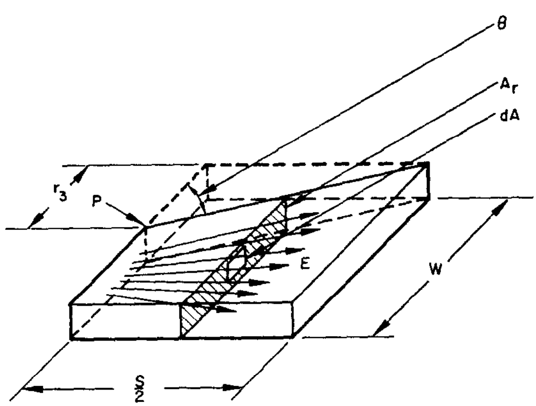


FIG. 5. Expanded view of resistance R_4 and R_5

density flowing in the radial direction as a function of current density generated in the normal direction. The substitution of equation (9) into (5) gives

$$i_r = \tfrac{1}{2}[J_n(r_2^2 - r_1^2)\tan\psi] \tag{10}$$

which represents the current flowing in the radial direction as a function of the light generated current density J_n. The substitution of equation (9) into (4) gives

$$E_r = \frac{J_n(r_2^2 - r_1^2)\rho}{2r_2 t}. \tag{11}$$

This gives the value of the electric field E_r as a function of r_2, r_1 and J_n. The potential that is produced by an electric field may be calculated from

$$\phi = \int_{\text{path}} \boldsymbol{E}\cdot \mathrm{d}\boldsymbol{r} \tag{12}$$

where $\mathrm{d}\boldsymbol{r}$ represents the path over which the field exists. By substitution of equation (11) into (12) we can calculate the potential that will exist in the media due to the field produced by the light generated charges. The potential ϕ is given by

$$\phi = \frac{\rho(J_n)}{2t}\left\{\int_{r_1}^{r_2} r_2\,\mathrm{d}r_2 - \int_{r_1}^{r_2} \frac{r_1^2\,\mathrm{d}r_2}{r_2}\right\}. \tag{13}$$

This represents the general equation for the potential. In the determination of the resistance R_5, $\boldsymbol{r}_1$ will be equal to a constant and $\boldsymbol{r}_2$ the variable of integration. The potential equation takes the form

$$\phi_{R_5} = \frac{J_n}{2t}\left\{\int_{r_1}^{r_2} r\,\mathrm{d}r - r_1^2\int_{r_1}^{r_2} \frac{\mathrm{d}r}{r}\right\}. \tag{14}$$

In the determination of the resistance R_4, $\boldsymbol{r}_1$ will be equal to zero, and the variable of integration will be $\boldsymbol{r}_3$ (see Fig. 3). This is done so that one will be reminded that the limits of integration are different in the determination of R_4 and R_5 This gives us the potential equation for R_4

$$\phi_{R_4} = \frac{\rho J_n}{2t}\int_0^{r_3} r\,\mathrm{d}r. \tag{15}$$

In determining the limits for equation (14) and (15) one can assume that R_4 is a right 45° triangle, but this would be a false assumption since there is no guarantee that current flow is not taking place between R_4 and R_5. It would be more appropriate to let the potential ϕ_{R_4} and ϕ_{R_5} be equal at the point P (see Fig. 3) and solve for the limits of integration, by solving these equations in terms of one variable, such as r_3. That is, find r_1 and r_2 in terms of r_3 and solve for the r_3 which makes the potential ϕ_{R_4} and ϕ_{R_5} equal at the point P, thus guaranteeing no current flow between R_4 and R_5. From Fig. 3, we get the following relationships.

$$r_1 = \frac{S(W-r_3)}{2r_3}$$

and

$$r_2 = \frac{SW}{2r_3}$$

and upon the substitution of these limits into equations (14) and (15), we get the following potential equation in terms of one variable $\boldsymbol{r}_3$.

$$\phi_{R_5} = \frac{\rho J_n}{2t} \times \left\{\int_{S(W-r_3)/2r_3}^{SW/2r_3} r\,\mathrm{d}r - \frac{S^2(W-r_3)^2}{4r_3^2}\int_{S(W-r_3)/2r_3}^{SW/2r_3} \frac{\mathrm{d}r}{r}\right\} \tag{16}$$

$$\phi_{R_4} = \frac{\rho J_n}{2t}\int_0^{r_3} r\,\mathrm{d}r. \tag{17}$$

Upon integrating equations (16) and (17) and letting $\phi_{R_4} = \phi_{R_5}$ one gets

$$\left(\frac{2r_3}{S}\right)^2 = \frac{2W}{r_3} - 1 - 2\left(\frac{W}{r_3} - 1\right)^2 \times \log\left(\frac{W}{W-r_3}\right). \tag{18}$$

The graphical method was used in the determination of numerical values for r_3 from this transcendental equation (18). The values of $\boldsymbol{r}_3$ for constant

W and for different values of S (grid stripes) are given in Table 1. Also given are the values of the angle θ (see Fig. 3) determined by the computed r_3 values.

From Table 1 we observe that as the spacing between the grids decreases, the angle θ also decreases so that the area of the trapezoid which represents R_5 actually increases. This indicates that the grid stripe carrier collection increases as the distance between the grid stripes decreases.

Table 1

Case	r_3, cm	S, cm	W, cm	θ
1	0 5	$\frac{2}{3}$	0.9	33°41′
2	0 37	$\frac{2}{5}$	0.9	28°24′
3	0 286	$\frac{2}{7}$	0.9	26°34′
4	0.24	$\frac{2}{9}$	0.9	24°51′

That is, the ratio of the number of generated carriers collected by the grid stripe to the number collected by the contact strip increases with a decreasing inter-grid spacing.

The value of resistance of any configuration, by Ohm's law, is equal to the total potential existing across the configuration divided by the total current flowing through it.

The total current flowing through the section represented by the resistance R_5 in terms of r_3 is

$$i_r = J_n \tfrac{1}{4} S(2W - r_3). \tag{19}$$

Thus the value of R_5 from equations (16) and (19) is from the above definition

$$R_5 = \frac{2\rho}{St(2W-r_3)} \times \left\{ \int\limits_{S(W-r_3)/2r_3}^{SW/2r_3} r\,\mathrm{d}r - \frac{S^2(W-r_3)^2}{4r_3^2} \int\limits_{S(W-r_3)/2r_3}^{SW/2r_3} \frac{\mathrm{d}r}{r} \right\} \tag{20}$$

The total current flowing through the section represented by resistance R_4 is

$$i_n = J_n \tfrac{1}{4} S r_3. \tag{21}$$

The value of R_4 can be obtained from equations (17) and (21) and is

$$R_4 = \frac{2\rho}{Str_3} \int\limits_0^{r_3} r\,\mathrm{d}r. \tag{22}$$

The above expressions for R_5 and R_4, equations (20) and (22) are the desired expressions which describe the resistance as a function of the configuration only. In the above analysis it should be remembered that it was assumed that the electric field E_r was in the same direction as the path dr. This implies that the expression for the potential

$$\phi = \int\limits_{\text{path}} \mathbf{E} \cdot \mathrm{d}\mathbf{r} \tag{23}$$

can be represented by:

$$\phi = \int\limits_{\text{path}} E\,\mathrm{d}r. \tag{24}$$

Since the field E_r is not in the direction of the path then the potential should be expressed as:

$$\phi = \int\limits_{\text{path}} E \cos\alpha\,\mathrm{d}r \tag{25}$$

for R_4 and

$$\phi = \int\limits_{\text{path}} E \cos\beta\,\mathrm{d}r \tag{26}$$

for R_5 where α and β are the angles between the normal to the surface and the field leaving the surface.

If one were to express equations (25) and (26) as a function of only one variable, the function of integration would become too complex due to the geometry of the configuration. In this analysis, it is assumed that

$$\int\limits_{\text{path}} E \cos\alpha\,\mathrm{d}r$$

and

$$\int\limits_{\text{path}} E \cos\beta\,\mathrm{d}r$$

can be, due to the model used, represented by the expression

$$\cos\theta \int_{\text{path}} E\,\mathrm{d}r$$

and

$$\sin\theta \int_{\text{path}} E\,\mathrm{d}r$$

respectively. The expression for R_4 and R_5 [equations (22) and (20)] now may be written as

$$R_4 = \frac{2\rho}{Str_3}\cos\theta_i \int_0^{r_3} r\,\mathrm{d}r \tag{27}$$

and

$$R_5 = \frac{2\rho}{St(2W-r_3)}\sin\theta_i \times \left\{ \int_{S(W-r_3)/2r_3}^{SW/2r_3} r\,\mathrm{d}r - \frac{S^2(W-r_3)^2}{4r_3^{\,2}} \int_{S(W-r_3)/2r_3}^{SW/2r_3} \frac{\mathrm{d}r}{r} \right\}. \tag{28}$$

The values of θ_i, where $i = 1, 2, 3, 4$ represent the different θ values in Table 1, for each case (i.e. $\theta_1 = \theta$ value for case 1, which is equal to 33° 41′ from Table 1 and so forth for each case). When the appropriate values of r_3, S, θ_1 and W from Table 1 are substituted into equations (27) and (28), and given the sheet resistance (ρ/t) for an n^+/p cell as 40 Ω while that of a p^+/n cell is 24 Ω, the values of R_4 and R_5 can be calculated and are shown in Table 2 for each case used in Table 1.

The values of R_4 and R_5 for case 2 (5-line

Table 2

Case	n^+/p		p^+/n	
	R_5, Ω	R_4, Ω	R_5, Ω	R_4, Ω
1	6.36	24.9	3.82	15.0
2	3 78	27 0	2.28	16.2
3	3 36	35 8	2 02	21 4
4	2 88	39.1	1.67	23.4

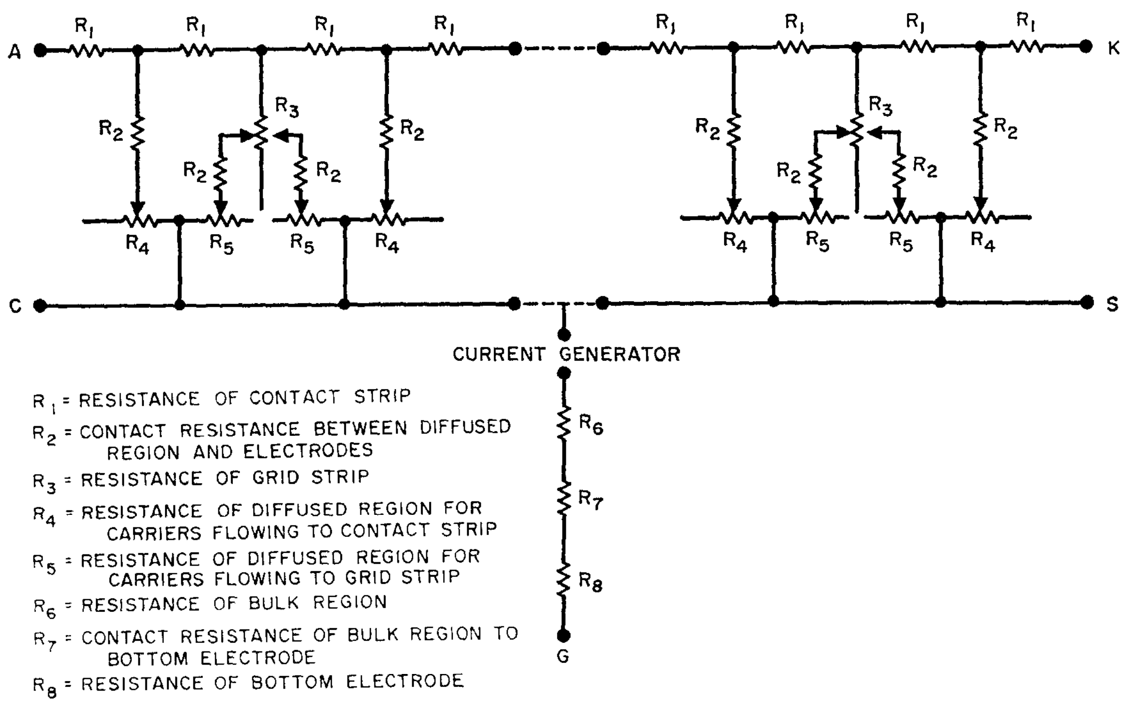


FIG 6. Representation of a n-unit field solar cell

gridded 1×2 cm^2 cell), thus obtained were then used to predict the total solar cell series resistance.

In determining the total series resistance of a solar cell, one must remember that equation (3) represents the resistance of a unit cell only, and Fig. 1 is representative of the unit cell. Actually we have, for a 5-grid cell, 5 unit cells in parallel with each other and these 5 all in series with resistances R_6 and R_7 and R_8 (see Fig. 6).

The total series resistance R_T between points K and G, can be represented by the following equations

$$R_T = \frac{R_c}{1+(R_c/R_p)} + R_1 + R_6 + R_7 + R_8 \quad (29)$$

where

$$R_c = \frac{\left\{1+\dfrac{R_1}{R_3+1/2(R_2+R_5)}+\dfrac{R_1}{R_1+R_2+R_4}\right\}(R_2+R_4)}{2+\dfrac{R_1+R_2+R_4}{R_3+1/2(R_2+R_5)}} \quad (30)$$

and

$$R_p = \frac{2R_c(R_c+R_1)}{(n-1)(2R_c+R_1)} \quad (31)$$

where n is the number of grid lines on cell.

As indicated in Table 2, R_4 for an n^+/p was determined theoretically to have a value of 27, while that of R_5 was 3.78 Ω. Values of R_1, R_2, R_3, R_6, R_7 and R_8 were determined experimentally and were found to have the following values: 0.002, 0, 0.4, 0.25, 0.08 and 0 Ω, respectively. When these values are substituted into equations (29) to (31) for the n^+/p cell indicated above, the total theoretical series resistance was calculated and found to have a value of 0.73 Ω. A similar calculation was done for a 5 grid line p^+/n production type solar cell where R_1, R_2, R_3, R_4, R_5, R_6, R_7 and R_8 had the following values: 0.002, 0, 0.4, 16.2, 2.3, 0.02, 0.08 and 0 Ω, respectively giving a total theoretical series resistance of 0.38 Ω.

It should be realized that the value of R_1 is not a constant value but is a function of its position in the n-dimensional solar cell. This variation exists due to the current generation and accumulation along the cell. Since the value of R_1 is so small, to assume that it has a constant value for the cell introduced very little error in the total series resistance. A value of $R_1 = 0.002$ to $0.01\ \Omega$ was assumed to determine its effect on the total series resistance. This variation in R_1 introduced a 0.1 percent error in the total series resistance value.

EXPERIMENTAL DETERMINATION OF SERIES RESISTANCE

The following method was used to experimentally determine the approximate series resistance encountered. The I–V curves of the cells to be measured are obtained under several different light intensities. A point is marked on each curve a fixed Δi from the short circuit of that curve. (In this case, $\Delta i = 10$ mA was used.) It is then possible to connect the marked points of all curves with a straight line. If there were no series resistance present, the line would be parallel to the current axis. If the line is not parallel to the current axis a change in voltage has occurred which is proportional to the iR drop caused by the series resistance in the cell itself and/or in the external circuitry up to the point where the voltmeter is connected to the current carrying portion of the circuit. An example of the application of this method is shown in Fig. 7. The results of the experimental measurements are in excellent agreement with the predicted theoretical value of 0.73 Ω, since this is well within the spread of series resistance values for the 13 percent cells and, in fact, extremely close to the average value experimentally determined. Larger values of series resistance (and lower efficiency cells) result from processing difficulties and could be predicted theoretically by substituting the higher value of the component resistance or resistances involved. For example, if a problem in contact deposition occurred, giving rise to a higher contact resistance, this new value would be utilized in the theoretical calculation in place of the value of 0.08 Ω which was used in the previous calculations.

For p^+/n cells having efficiencies of 13 and 14 percent under 2800°K tungsten light, the series resistance was experimentally found to be 0.43 and 0.42 Ω, respectively. This compares quite well with the theoretically predicted value of 0.38 Ω.

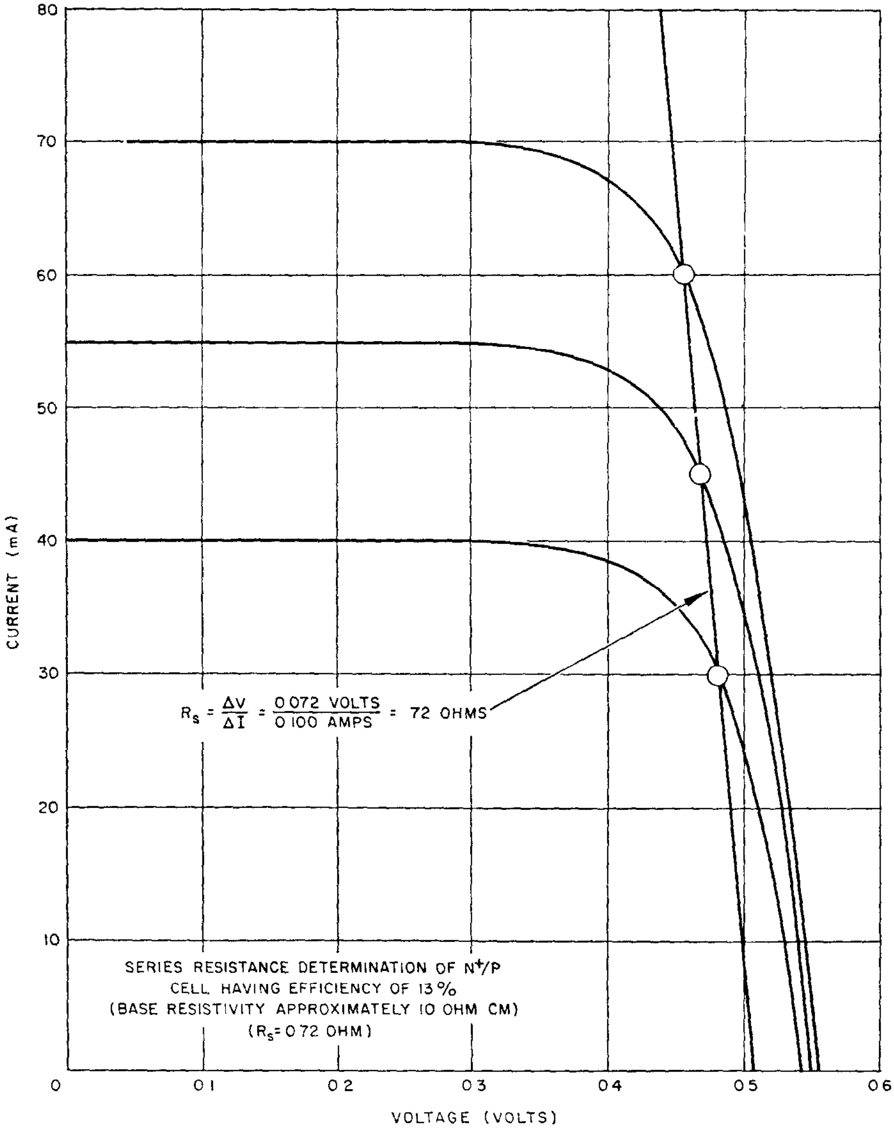


FIG 7. Series resistance determination of n^+/p cell

OPTIMIZING GRID SPACING

In considering the behavior of a solar cell, a number of simplifying assumptions can be used over certain limits. For low levels of about 30 mW/cm^2 the representative I–V relationship can be expressed as

$$I = I_0[\exp(BV)-1]-I_L. \tag{32}$$

For higher light levels, between about 50 to 400 mW/cm^2 the effects of series resistance must be considered and the following equation is applicable

$$I = I_0\{\exp[B(V-IR_s)]-1\}-I_L \tag{33}$$

where

R_s = lumped series resistance approximation of the internal resistance of the cell

$B = q/AKT'$
A = 'a factor' which represents departure from ideal diode curves
K = Boltzmann's constant
q = electronic charge
T' = temperature, °K
I = terminal current without series resistance
V = terminal voltage
I_L = total light generated current
I_0 = total saturation current.

For still higher light levels, probably above 400 mW/cm^2, the distributed nature of the sheet resistance must be taken into account.

It should be strongly emphasized that the approximate limits over which these equations are valid are dependent upon the value of the iR_s products. As either the value of the series resistance or of load current i increases, more complicated equations must be used. This can occur even at the somewhat lower light levels, if the values of series resistance are large.

By utilizing equation (29) it should be possible to optimize the grid spacing to obtain the most advantageous configuration. Unfortunately, it will not be enough to simply minimize R_T as this would undoubtedly result in a cell which had 100 percent of its surface covered with contacts. An optimum trade-off between minimum resistance and maximum current generation must be calculated. This can be done by obtaining the resistance R_T as a function of the spacing, S, between the grids and substituting this into the following equation

$$I = I_0\{\exp[B(V-IR_T)]-1\}-I_L. \quad (34)$$

CONCLUSION

The circuit which represents the total series resistance of a solar cell and the theoretical equations which are developed in this paper seem to be representative of the solar cell in determining its total resistance. The agreement between the theoretical and experimental values for the cell series resistance for both p^+/n and n^+/p cells were quite good. The theoretical prediction for the series resistance of n^+/p cells was 0.73 Ω, while the experimentally measured value for high efficiency n^+/p cells was 0.72 Ω, the equation also predicted a total series resistance of 0.38 Ω, for p^+/n cells while experimentally measured value for high efficiency cells of this type was 0.42 Ω.

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