phys. stat. sol. (a) **136**, 261 (1993)

Subject classification: 72.40 and 85

Department of Electronic Science, University of Delhi[1])

General Expression for the Fill Factor of a Real Homojunction Solar Cell Using a Single Exponential Model

By

A. KAPOOR, V. K. SHARMA, and K. N. TRIPATHI

An expression for the fill factor of a real homojunction solar cell having resistive and current leakage losses is derived using Lagrange's undetermined multiplier technique based on a single exponential model. The expression derived is quite general, but not completely analytic and is applicable to various types of solar cells, in particular, polycrystalline solar cells, where series and shunt resistances cannot be excluded. It is observed that for given values of series and/or shunt resistance, the fill factor is determined by reverse saturation current and diode quality factor of the solar cell.

1. Introduction

The fill factor of a solar cell is a measure of the "squareness" of the transtedental current–voltage characteristic curve of the cell and is defined as the ratio of maximum power that can be delivered by a cell to the product of open circuit photo voltage (V_{oc}) and short circuit photo current (I_{sc}). As a solar cell is a non-linear device, the effect of series (R_s) and shunt (R_{sh}) resistances on the power generated from the cell, and hence the fill factor, is not known in explicit manner and this makes the designing of the cell complicated [1 to 7]. It has been observed that series and shunt resistances are parasitic power consuming parameters and their presence affects the illuminated characteristics as well as the dark characteristics of the solar cell, in particular for polycrystalline solar cells (see [2]). The use of lumped circuit models is a convenient and widely used method for simulating solar cell performance [2, 4 6].

In the present paper a general expression for a series and shunt resistance dependent fill factor is derived using Lagrange's undetermined multiplier technique based on a single exponential model as shown in Fig. 1. The expression deduced is quite general in nature, although not completely analytic in nature, is useful for various types of solar cells, in particular, polycrystalline solar cell where R_s and R_{sh} cannot be excluded. The effect of reverse saturation current and diode quality factor on the fill factor of the cell are examined.

2. Theory

A real solar cell $I-V$ characteristic in a single exponential model (Fig. 1) is described by the equation

$$I = I_L - I_0 \left\{ \exp\left(\frac{V + IR_s}{nV_{th}}\right) - 1 \right\} - \frac{V + IR_s}{R_{sh}}, \tag{1}$$

[1]) South Campus, Benito Juarez Road, New Delhi 110021, India.

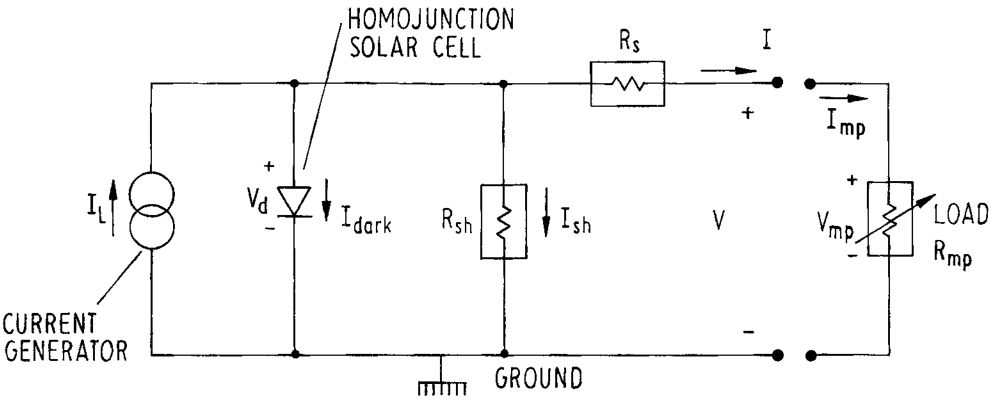

Fig. 1. Single exponential circuit model for an illuminated solar cell

where $V_{th} = kT/q$ is the thermal voltage, I_0 the reverse saturation current of the diode, n the diode quality factor included to model the effects of absorption and recombination of electron–hole pairs in the space charge region of the solar cell, and I_L the light generated current. The output power from a solar cell is given by

$$P = VI. \tag{2}$$

Combining (1) and (2), using Lagrange's method of undetermined multipliers, a new power (P') is defined as

$$P' = VI + \lambda\left[I - I_L + \frac{V + IR_s}{R_{sh}} + I_0\left\{\exp\left(\frac{V + IR_s}{nV_{th}}\right) - 1\right\}\right], \tag{3}$$

where λ is the undetermined multiplier optimising P' with respect to V and I and representing the corresponding value of current and voltage as V_{mp} and I_{mp}, we obtain

$$V_{mp} = -\lambda\left[1 + \frac{R_s}{R_{sh}} + \frac{I_0 R_s}{nV_{th}} \exp\left(\frac{V_{mp} + I_{mp}R_s}{nV_{th}}\right)\right] \tag{4}$$

and

$$I_{mp} = -\lambda\left[\frac{1}{R_{sh}} + \frac{I_0}{nV_{th}} \exp\left(\frac{V_{mp} + I_{mp}R_s}{nV_{th}}\right)\right]. \tag{5}$$

Using (4) and (5), an expression for optimum load (R_{mp}) at which maximum power transfer from the solar cell will take place, is obtained as

$$R_{mp} = \frac{V_{mp}}{I_{mp}} = R_s + R_{sh}\left[\frac{I_0 R_{sh}}{nV_{th}} \exp\left(\frac{V_{mp} + I_{mp}R_s}{nV_{th}} + 1\right)\right]^{-1}. \tag{6}$$

The maximum power obtainable from a solar cell is given by

$$P_m = R_{mp} I_{mp}^2 . \tag{7}$$

Using (6) in (7), we obtain

$$P_m = I_{mp}^2 (R_s + R_{sh}/X) , \tag{8}$$

where

$$X = \frac{I_0 R_{sh}}{n V_{th}} \exp\left(\frac{V_{mp} + I_{mp} R_s}{n V_{th}}\right) + 1 . \tag{9}$$

The fill factor of a solar cell is given by

$$FF = (P_m / V_{oc} I_{sc}) = (I_{mp}^2 / V_{oc} I_{sc}) (R_s + R_{sh}/X) . \tag{10}$$

3. Results and Discussion

For an ideal solar cell with no series and shunt resistance ($R_s = 0$, $R_{sh} = \infty$) Fig. 2 shows the dependence of the fill factor on the reverse saturation current (I_0). It is observed that the fill factor is sharply reduced by increasing I_0, which is in confirmity with the observations of Pulfrey [8]. For the case, when R_s is finite and $R_{sh} = \infty$, the fill factor expression reduces to

$$(FF)_{R_s} = \frac{I_{mp}^2}{V_{oc} I_{sc}} \left[\frac{R_s + n V_{th}}{I_L + I_0 - I_{mp}}\right], \tag{11}$$

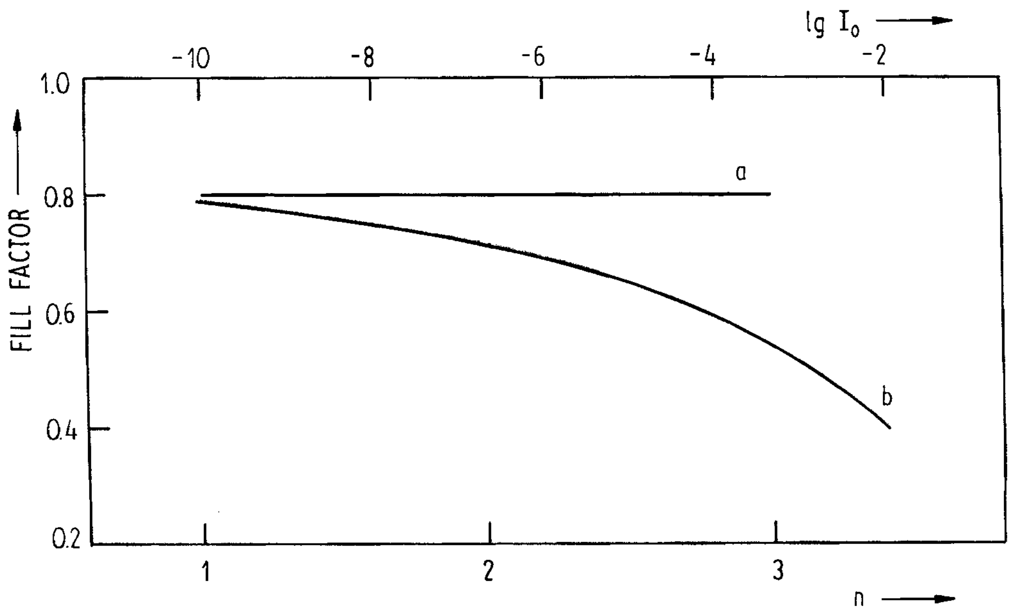

Fig. 2. Fill factor of an ideal solar cell in dependence on diode quality factor (a) and normalised reverse saturation current (b); $T = 300$ K; $R_s = 0$; $R_{sh} = \infty$

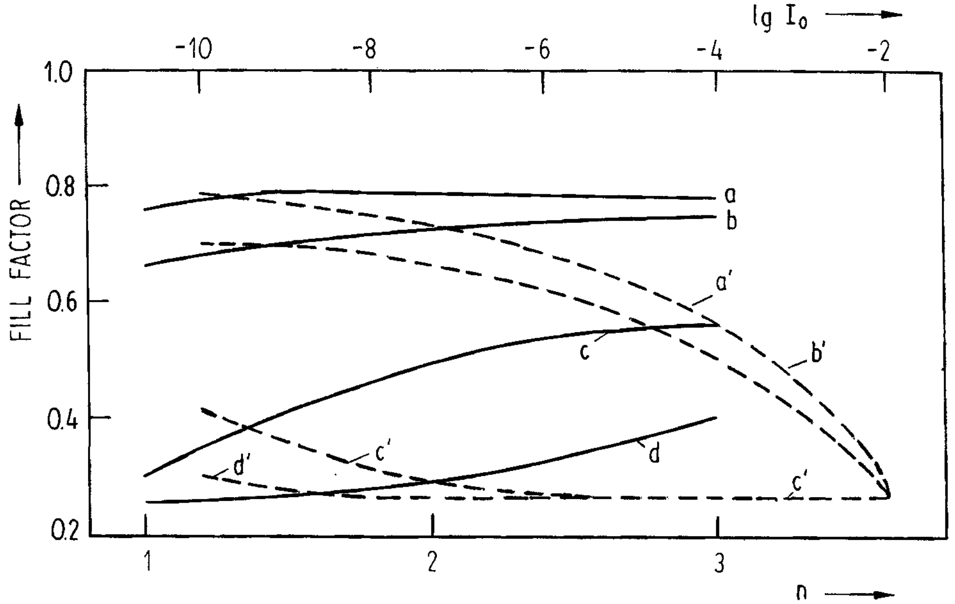

Fig. 3. Solid lines show the variation of the fill factor with series resistance and diode quality factor for a given reverse saturation dark current and dashed curves represent the variation of FF with series resistance and normalised reverse saturation dark current. $T = 300$ K, $R_{sh} \to \infty$. (a), (a') $R_s = 0.1$, (b), (b') 1, (c), (c') 5, (d), (d') 10 Ω

where I_{mp} is the current at the maximum power point and can be computed from the iterative solution of

$$nV_{th}\left[\ln\left(\frac{I_L + I_0 - I_{mp}}{I_0}\right) - \frac{I_{mp}}{I_L + I_0 - I_{mp}}\right] = 2I_{mp}R_s. \tag{12}$$

Fig. 3 shows the variation of the fill factor for different values of series resistance. Curves a to d of Fig. 3 represent the dependence of the fill factor on diode quality factor for a given I_0 and $R_s = 0.1$, 1, 1.5, and 10 Ω. Curves a' to d' of Fig. 3 represent the dependence of the fill factor on normalised reverse saturation current for a given diode quality factor ($n = 1.5$). By increasing the value of series resistance, for given n, the horizontal segment of the output characteristic gets shortened without affecting the open circuit voltage (see Phang et al. [4]), therefore, the fill factor decreases by increasing R_s as shown in curves a to d of Fig. 3. But if R_s is kept constant and n is increased, both the horizontal segment and V_{oc} increase, thereby increasing the fill factor. Curves a' to d' indicate that for given values of n and R_s, by increasing the normalised reverse saturation current, which in turn decreases both V_{oc} and the horizontal segment of the I–V curve, the fill factor decreases very sharply. To study the effect of shunt resistance, we consider a situation where $R_s = 0$ and R_{sh} is finite. In this case the fill factor expression becomes

$$(\mathrm{FF})_{R_{sh}} = \frac{I_{mp}^2}{V_{oc}I_{sc}}\left[\frac{nV_{th}}{I_L + I_0 - I_{mp}} + \frac{nV_{th} - V_{mp}}{R_{sh}}\right], \tag{13}$$

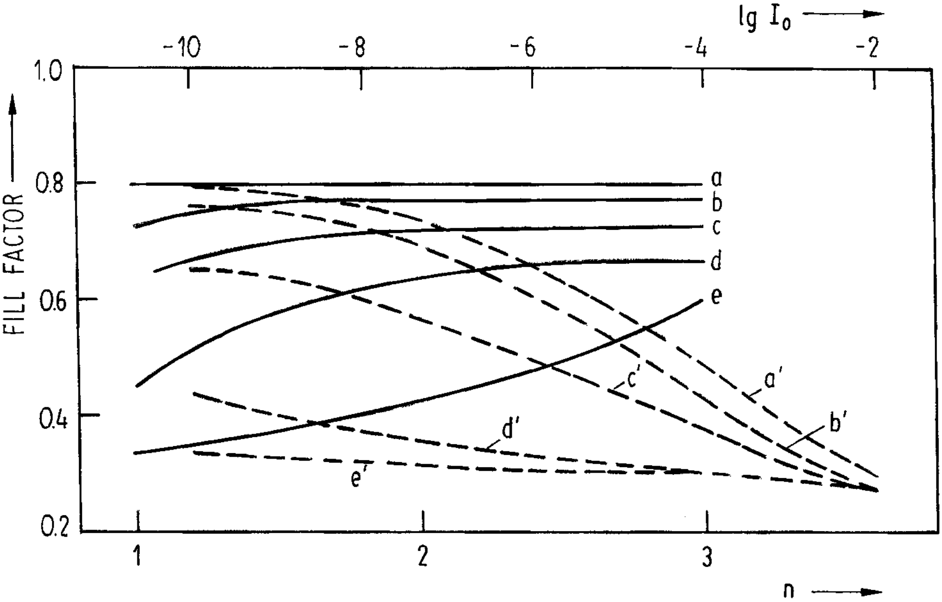

Fig. 4. Solid lines show the dependence of the fill factor on shunt resistance and diode quality factor for a given reverse saturation dark current and dashed curves show the dependence of FF on shunt resistance and normalised reverse saturation current for a given diode qualitiy factor ($R_s = 0$). (a), (a′) $R_{sh} = \infty$, (b), (b′) 500, (c), (c′) 100, (d), (d′) 20, and (e), (e′) 10 Ω

where V_{mp} and I_{mp} can be computed from the iterative solution of the following equation:

$$I_L + I_0 - I_0 \exp\left(\frac{V_{mp}}{nV_{th}}\right)\left\{1 + \frac{V_{mp}}{nV_{th}}\right\} = 2\,\frac{V_{mp}}{R_{sh}} \tag{14}$$

and

$$I_L + I_0 - I_0 \exp\left(\frac{V_{mp}}{nV_{th}}\right) - \frac{V_{mp}}{R_s} = I_{mp}\,. \tag{15}$$

Curves a to d of Fig. 4 respresent the dependence of the fill factor on n for a given value of I_0 and $R_{sh} = \infty$, 500, 100, 20, and 10 Ω. Curves a′ to d′ of Fig. 4 represent the dependence on normalised I_0 for given n. By decreasing R_{sh} for a given value of n, the vertical segment of the $I-V$ curve gets shortened without affecting V_{oc}, therefore the fill factor decreases by decreasing the value of R_{sh}. When R_{sh} is fixed and n is increased, the horizontal segment of the $I-V$ curve increases, thereby increasing the fill factor. For a solar cell with finite R_s and R_{sh}, which is the most practical case, the fill factor is computed from (10). The numerical solution can be performed efficiently and accurately using various single exponential model parameters. For a blue cell, $V_{oc} = 0.536$ V, $I_{sc} = 0.1023$ A, $R_{sh} = 1003.1\ \Omega$, $I_0 = 1.032 \times 10^{-7}$ A, and $I_L = 0.1023$ A, the value of the fill factor of the solar cell is determined to be 0.6587. Using Pulfrey's expression which does not take into account the shunt resistance, the fill factor comes to be 0.6322.

References

[1] H. J. HOVEL, Semiconductors and Semimetals, Vol. II, Chap. 3, Academic Press, New York 1975.
[2] K. W. BÖER, Survey of Semiconductor Physics. Vol. II, Van Nostrand/Reinhold, New York 1990 (pp. 493, 783, 815, 825, and 832).
[3] R. KISHORE, Solid State Electronics **32**, 493 (1989).
[4] J. C. H. PHANG, D. S. H. CHAN, and J. R. PHILLIPS, Electronics Letters **20**, 406 (1984).
[5] C. M. SINGAL, Solar Cells **3**, 163 (1981).
[6] J. P. CHARLES, I. MEKHASOUI-ALAOUI, G. BOREDURE, and P. MIALHE, Solid State Electronics **28**, 807 (1985).
[7] D. S. H. CHAN, J. R. PHILLIPS, and J. C. H. PHANG, Solid State Electronics **29**, 329 (1986).
[8] D. L. PULFREY, Solid State Electronics **21**, 519 (1978).

(Received February 19, 1992; in revised form October 29, 1992)