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ON THE FILL FACTOR OF SOLAR CELLS

D. L. PULFREY
Electrical Engineering Department, University of British Columbia, Vancouver, V6T 1W5, Canada

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Abstract—Calculations are presented which indicate that, for a given series resistance, the fill factor of a solar cell is principally determined by the saturation dark current, rather than the diode factor, as might be inferred from previous analyses.

The fill factor (FF) of a solar cell is a measure of the "sharpness of the knee" in the output current-voltage curve and is defined as the ratio of the maximum power that can be delivered by a cell to the product of its short-circuit photocurrent (I_{sc}) and open-circuit photovoltage (V_{oc}). It is clearly recognised that FF is adversely affected by the presence of series and shunt resistances within the cell[1], but the dependencies of FF on other properties of the cell, namely the saturation dark current (I_0) and the diode factor (γ), have not been so unequivocally identified in previous analyses[2–4]. In the present correspondence the effect of these latter two properties on FF is examined. The model used takes into account the series resistance of the cell, so allowing illustration of the importance of this parameter in cells operating under conditions of sunlight concentration.

If superposition of the dark and light currents of a solar cell is permissible and the dark current can be accounted for by a single exponential relationship then, neglecting shunt resistance effects, it follows that the current-voltage (I–V) relationship of the cell can be expressed as

$$I = I_p - I_0\left[\exp\frac{q}{\gamma kT}(V + IR_s)\right] + I_0 \quad (1)$$

where I_p is the photogenerated current, R_s the series resistance and γ represents the factor which modifies the diode junction voltage to an extent that depends on the particular operative dark current transport mechanism, e.g. $\gamma = 1$ for injection-diffusion currents in $p-n$ junctions and thermionic emission currents in metal-semiconductor junctions[5]; $\gamma \approx 2$ for recombination-generation currents in p–n junctions[5] and minority carrier MIS diodes[6]; $\gamma = 1-3$ for tunnel currents in some MIS[6] and heterojunction diodes[7]. From (1) the maximum output power can be found from which it follows that

$$\mathrm{FF} = \frac{I_m{}^2}{V_{oc}I_{sc}}\left[\frac{\gamma kT/q}{(I_p + I_0 - I_m)} + R_s\right] \quad (2)$$

where I_m is the current at the maximum power point and can be computed from the iterative solution of

$$\frac{\gamma kT}{q}\left[\ln\left(\frac{I_p + I_0 - I_m}{I_m}\right) - \frac{I_m}{I_p + I_0 - I_m}\right] = 2I_mR_s \quad (3)$$

By way of an example, eqn (2) has been used to calculate the dependence of FF on γ and I_0 for the case of a silicon solar cell at 300°K, assuming that the generated (not necessarily the collected) photocurrent density is the maximum possible for $AM1$ sunlight (41.8 mA cm^{-2}[8]). The results are shown in Figs. 1 and 2. From Fig. 1 it can be seen that for a given value of I_0 and for $R_s = 0$, the fill factor does not change with γ. This is because under these conditions the output voltage for a given output current increases monotonically with γ, so V_m (the voltage at the maximum power point) and V_{oc} both change by the factor of γ, and as I_m and I_{sc} are unchanged, the fill factor remains constant. Increasing R_s for a given γ shortens the horizontal segment of the

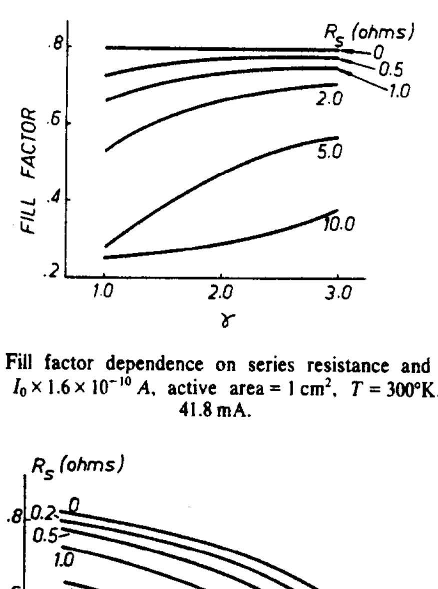

Fig. 1. Fill factor dependence on series resistance and diode factor. $I_0 \times 1.6 \times 10^{-10}\,A$, active area = 1 cm^2, T = 300°K, I_p = 41.8 mA.

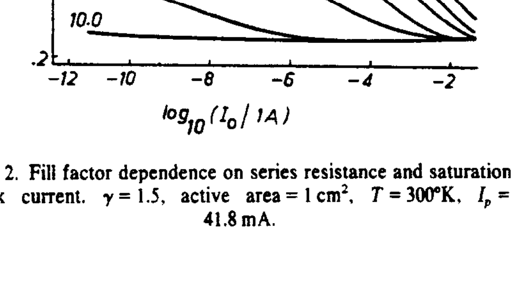

Fig. 2. Fill factor dependence on series resistance and saturation dark current. $\gamma = 1.5$, active area = 1 cm^2, T = 300°K, I_p = 41.8 mA.

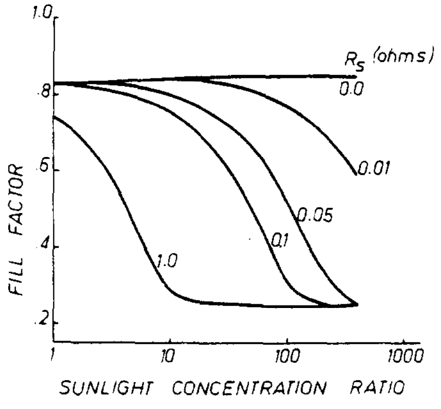

Fig. 3. Fill factor dependence on series resistance and sunlight concentration ratio. $\gamma = 1.5$, $I_0 = 3.3 \times 10^{-12}$ A, active area = 1 cm^2, $T = 300$°K, I_p(mA) = 41.8 × conc. ratio.

output $I-V$ curve yet doesn't affect V_{oc}, therefore FF decreases. But if R_s is kept constant ($\neq 0$) and γ is increased then both the horizontal segment and V_{oc} increase, and thus so does the fill factor. For a constant value of γ and for any value of R_s less than the resistive limit (i.e. that at which the I–V curve is a straight line between I_{sc} and V_{oc}), increasing I_0 decreases both V_{oc} and the horizontal segment of the I–V curve, and so the fill factor decreases rapidly (Fig. 2).

It can be concluded that the fill factor is degraded by the presence of series resistance, can be improved (but not beyond the value for $R_s = 0$) by increasing γ, and is strongly reduced by increasing the saturation dark current. All these effects may not be apparent from earlier discussions of fill factor in which the interplay of γ and V_{oc} has been stressed and from which a reduction of FF with γ might be inferred [2–4]. For a fixed value of V_{oc} at a given I_p, any increase in γ necessitates an increase in I_0 also. It is this latter increase, not that of γ, that reduces the fill factor.

Practically it is doubtful whether complete independence of I_0 and γ can exist and, in general, higher values of I_0 are associated with current transport mechanisms exhibiting increased values of γ [9]. However, as γ has only a slight effect on the fill factor of low resistance solar cells, it is clear that for attainment of high FF values diode structures should be employed which encourage dark current transport mechanisms with low values of I_0.

As solar cells that are utilized in conjunction with sunlight concentrators are not subject to such stringent economic restraints as are cells used in unconcentrated sunlight, a high degree of junction perfection can be sought in the former and low values of I_0 obtained. Under these circumstances R_s becomes the major parameter affecting FF, as can be seen from Fig. 3. For satisfactory operation of silicon solar cells at greater than 100 Suns it appears that R_s values of a few hundredths of an ohm are required.

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