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A new method to determine the diode ideality factor of real solar cell using Lambert W-function

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Abstract

A new method using Lambert W-function is presented to determine the diode ideality factor of real solar cell.

Keywords: Ideality factor; Lambert W-function; Solar cell

1. Introduction

The diode ideality factor has been introduced for a p–n junction solar cell after consideration of the physical phenomenon that occurs in diode. Several theories have been published to account for the introduction of ideality factor. Sah et al. [1] analyses generation/recombination in space charge layer to predict $n \leqslant 2$. Shockley [2] diffusion theory based on minority carrier diffusion predicted, n should equal to 1. Considering the traps situated in localized region of depletion layer, Faulkner and Buckingham [3] proposed a theory giving values of n between 1 and 2, that was further verified experimentally by Naursabum [4]. As the density of recombination is increased, Ashburn et al. [5] showed an increase of n from 1 to 2. n equal to 2 is

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predicted by Hall [6] at high injection levels whereas it is close to unity at low injection levels and is likely due to recombination. Values of n greater than 2 have been observed owing to various phenomenon including shunt resistance effects [7], or non-uniformities in distribution of recombination centres [8]. Hall [9] also predicted n less than 1 in a junction under high-level injection conditions with saturation current determined by Auger recombination. Nakumara et al. [10] have found that redistribution of heavy metal impurities (gettering) can take place during device processing with strong increases of impurity densities near the surface; this would tend to increase measured recombination currents and measure values of n above values predicted by theory. Sah has postulated that high n values can arise in planar p–n junction devices due to surface channels caused by surface states. In solar cells these channels would live along the device edges and extend into base.

According to Shockley the value $n = 1$ is associated with next to an ideal junction. An increase of n leads to degradation of cell efficiency. Several techniques are available in the literature to determine the value of ideality factor. Some of them include: (a) determination through graphical techniques: a plot of (I_{ph}-I) versus V results in straight line with slope $\varepsilon/\,(nkT)$ that gives value of n. ln I_o is corresponding intercept on current axis. (This method is referred as the direct measurement method, DMM) [11]; (b) determination through the use of numerical analysis (referred to as the normal parameter coordinate method (NPCM) [12–13] and (c) direct method to measure n from illuminated output J–V curve [14].

In this paper a method is described to determine value of ideality factor of solar cell from I–n plot using Lambert W-function. An explicit relation between n and I is determined at $V = V_{oc}$ for plot.

2. Theory

The current–voltage relation for a solar cell modified by the diode ideality factor is given by

$$i = -\frac{V + iR_s}{R_{sh}} - \mathrm{I_o}\left(\mathrm{e}^{\frac{(V+iR_s}{nV_{th}}} - 1\right) + I_{ph}, \tag{1}$$

where n is the diode ideality factor, V_{th} is thermal voltage.

Solution of equation, which is transcendental in nature using Lambert W-function, is as follows [15]:

$$i = -\frac{V}{R_s + R_{sh}} - \frac{\text{Lambert } W\left[\frac{R_s I_o R_{sh} \mathrm{e}^{\left[(R_{sh}(V+R_s+I_o+R_s+I_{ph}\Big/ nV_{th}(R_s+R_{sh})\right]}}{nV_{th}(R_s+R_{sh})}\right] nV_{th}}{R_s} + \frac{R_{sh}(I_o + I_{ph})}{R_s + R_{sh}}. \tag{2}$$

Substituting $V = V_{oc}$ in Eq. (2) we get

$$i = -\frac{V_{oc}}{R_s + R_{sh}} - \frac{\text{Lambert } W\left[\frac{R_s I_o R_{sh} e^{\left[(R_{sh}(V+R_s+I_o+R_s+I_{ph}\big/ nV_{th}(R_s+R_{sh})\right]}}{nV_{th}(R_s+R_{sh})}\right] nV_{th}}{R_s} + \frac{R_{sh}(I_o + I_{ph})}{R_s + R_{sh}}. \tag{3}$$

For a typical cell if values of V_{oc}, R_s, R_{sh}, I_o, I_{ph} and V_{th} are known, an equation containing current and ideality factor can be obtained.

Parameters extracted by Charles et al. For Blue and Grey solar cell:

	Blue solar cell	Grey solar cell
V_{oc} (V)	0.536	0.524
R_s (mΩ)	68.26	77.69
R_{sh} (Ω)	1000.0	25.9
I_0 (μA)	0.1036	5.514
I_{ph} (A)	0.1023	0.5610
V_{th} (V)	0.0258	0.0264

Consider the case of blue solar cell whose parameters are $R_s = 68.26\text{m}\Omega$, $R_{sh} = 1000.0\Omega$, $I_o = 0.1036\mu\text{A}$, $V_{th} = 0.0258$, $V_{oc} = 0.536$ Eq. (3) can be expressed as

$$i = -0.0005359634152 - 0.3779665983 \text{ Lambert} W\left(0.2740795859\ 10^{-6}\frac{e^{(21.044416421/n)}}{n}\right)n + 0.0009999317447\ 1000.0(0.1023001036). \tag{4}$$

Fig. 1 shows the ideality factor–current plot for blue solar cell. The value of ideality factor (n) at which current (i) is zero is 1.5056. This value extracted from the graph is in well accordance with the values calculated using different methods.

Theoretically this can be proved by substituting values of series and shunt resistances, V_{th}, I_{ph}, I_o, $i = 0$ and $V = V_{oc}$ (open-circuit voltage) in Eq. (1). After substitution, we get the equation in n as

$$0. = 0.1017641036 - 0.1036000000\ 10^{-6} e^{(20.77519380/n)}.$$

Solving it value of n is found as $n = 1.5057$.

The same method is applied to grey cell ($I_{ph} = 0.5610\,\text{A}$, $I_o = 5.514\,\mu\text{A}$, $R_s = 77.69\,\text{m}\Omega$, $R_{sh} = 25.9\,\Omega$, $V_{oc} = 0.524\,\text{V}$, $V_{th} = 0.0264\,\text{V}$). Combined plot for grey and blue solar cell is plotted (Fig. 2).

Ideality factors obtained from W-function method is compared with iterative method [16] and analytical method by Phang et al. [17]. Results obtained are shown in Table 1.

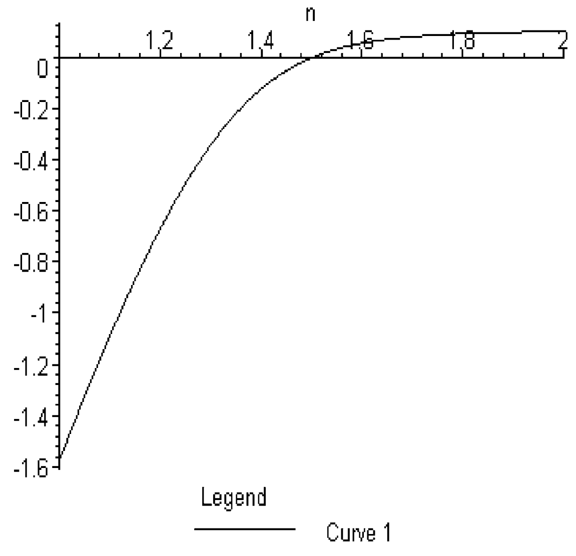

Fig. 1. Curve between current and ideality factor.

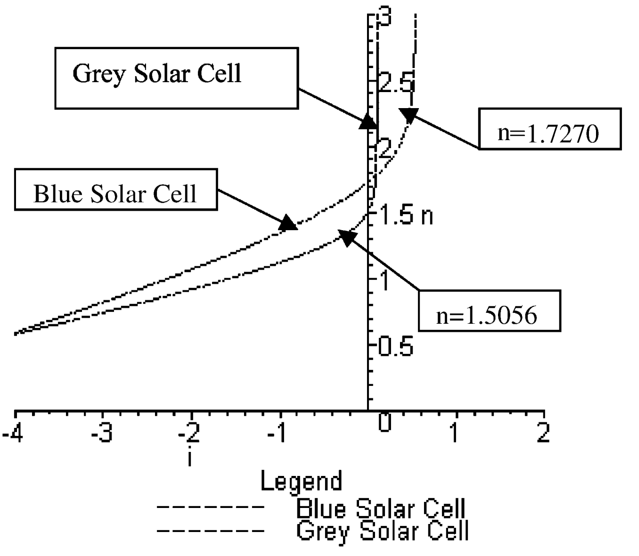

Fig. 2. I versus n for blue and grey solar cell.

Above table suggests that values of ideality factors obtained are in good approximation with previous methods. Although other methods are based on some approximations, W-function method does not have any approximation.

A comparative study of current–voltage characteristics of a solar cell with small changes in ideality factor is made.

Table 1
Ideality factors obtained by different methods

Cell type	Iterative solution	Analytical solution (Phang et al.)	*W*-function solution	% Accuracy
Blue solar cell	1.5017	1.5019	1.5056	0.246
Grey solar cell	1.7168	1.7225	1.7270	0.261

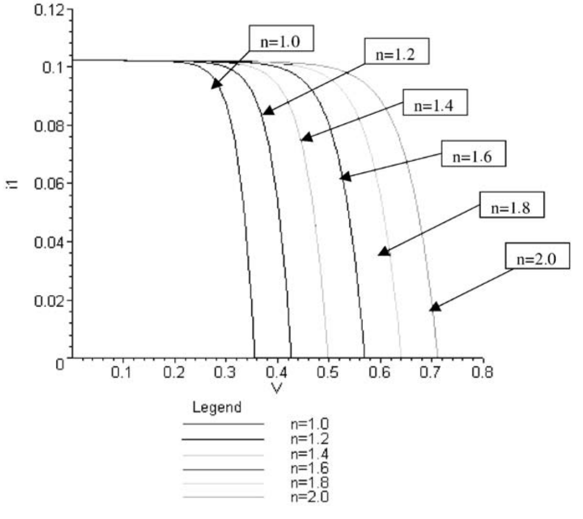

Fig. 3. Current–Voltage curves of a solar cell for different values of ideality factors.

From the Fig. 3 it is evident that as value of ideality factor increases beyond the value1.0 the squareness of the current–voltage curve of solar cell decreases.

3. Conclusion

A simple and accurate (without approximations) method using Lambert *W*-function has been described which could be used to measure the junction ideality factor *n* directly from current–ideality factor curve for a solar cell. Relative accuracy with a well-established analytical method by Phang et al. [17] is also obtained to verify the method.

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