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The temperature functional dependence of VOC for a solar cell in relation to its efficiency new approach

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Abstract

The temperature functional dependence of the solar cell efficiency is studied without neglecting (dI_{sc}/dT). The temperature dependent parameters that determine the value of the short circuit current I_{sc} are considered I_{sc} is also given as a function of the incident solar irradiance. The variation of the efficiency with temperature along the local day time is also evaluated. The conditions governing the sign of (dV_{oc}/dT) are indicated an illustrative example for a silicon cell is given.

Keywords: Temperature functional dependence; Solar cell efficiency

1. Introduction

The efficiency of the solar cell and the methods to increase it, have aroused the interest of many investigators [1–16]. The efficiency is a measure of the cell performance. The operating cell temperature affects its efficiency through the functional dependence of the different psychical quantities limiting its value.

Three main parameters are usually used to characterize the solar cell outputs [17], these are

– I_{sc}, the short-circuit current. Ideally, this is equal to the light-generated current.
– The open-circuit voltage V_{oc} which in principal depends on I_o, the diode saturation current.
– The fill factor FF, which in turn is a function of V_{oc}.

The above mentioned parameters dependent on the cell temperature, nevertheless, different authors assume in evaluating the efficiency and its rate of variation, that the increase of I_{sc} with temperature is negligible and accept its temperature rate of variation to be zero [17].

The aim of the present work is to clarify to what extent this assumption is valid, and to

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study the efficiency behavior with temperature not neglecting the dependence of I_{sc} on the cell temperature.

2. Derivation of the basic equations

Let us define the efficiency η as [17]

$$\eta = \frac{V_{oc}\, I_{sc}\, FF}{P_{in}} \tag{1}$$

where, P_{in} is the total power is the light received by the cell.

For an ideal p–n junction cell, where [17]

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{I_{sc}}{I_0}+1\right) \tag{2}$$

where, q is the charge of the electron = 1.6×10^{-19}. The saturation current density as a function of the band gab and temperature can be written in the form:

$$I_0 = AT^{\gamma}\mathrm{e}^{-\frac{E_{g0}}{kT}} \tag{3}$$

The value of $\gamma = 3$ is accepted in the present work, also the value of the non-ideality factor A is taken as unity. The relation between short-circuit current and open-circuit voltage is:

$$I_{sc} = I_0\left(\mathrm{e}^{\,qV_{oc}/kT} - 1\right) \tag{4}$$

$$I_{sc} \approx I_0\mathrm{e}^{qV_{oc}/kT} \tag{5}$$

In Eq. (3), the factor A is independent of temperature, and γ includes the temperature dependencies of the remaining parameters determining I_0, its value generally lies in the range 1–4.

E_{go} is the linearly extrapolated zero temperature band gap of the semiconductor making up the cell.

Let us find from Eq. (2) the rate of temperature variation of V_{oc}, this is obtained in the form:

$$\frac{\mathrm{d}V_{oc}}{\mathrm{d}T} = \frac{V_{oc}}{T} + \frac{AkT}{q}\frac{1}{\left(I_{sc}+I_o\right)}\left[\frac{\mathrm{d}I_{sc}}{\mathrm{d}T} - \frac{I_{sc}}{I_o}\left(\frac{\mathrm{d}I_o}{\mathrm{d}T}\right)\right] \tag{6}$$

Experimentally, it is shown, that V_{oc} decreases with temperature the condition for that is given from eq. (6) as

$$\frac{AkT}{q}\frac{I_{sc}}{I_o}\frac{1}{\left(I_{sc}+I_o\right)}\frac{\mathrm{d}I_o}{\mathrm{d}T} > \frac{V_{oc}}{T} + \frac{AkT}{q}\frac{1}{\left(I_{sc}+I_o\right)}\frac{\mathrm{d}I_{sc}}{\mathrm{d}T} \tag{7}$$

If both sides of Eq. (7) are equal, then V_{oc} will be no longer dependent on the temperature T.

If the R.H.S of Eq. (7) is greater than its L.H.S, then the behaviour of V_{oc} with temperature will be reversed, and the rate $(\mathrm{d}V_{oc}/\mathrm{d}T)$ will be positive.

From Eq. (3) it can be proved that:

$$\frac{1}{I_o}\frac{\mathrm{d}I_o}{\mathrm{d}T} = \left\{\frac{\gamma}{T} + \frac{E_{go}}{kT^2}\right\} \tag{8}$$

Substituting Eq. (8) into Eq. (6) one gets

$$\frac{\mathrm{d}V_{oc}}{\mathrm{d}T} = \frac{V_{oc}}{T} + \frac{AkT}{q}\frac{1}{\left(I_{sc}+I_o\right)}\left[\frac{\mathrm{d}I_{sc}}{\mathrm{d}T} - I_{sc}\left\{\frac{\gamma}{T} + \frac{E_{go}}{kT^2}\right\}\right] \tag{9}$$

Neglecting I_o with respect to I_{sc}, and neglecting $(\mathrm{d}I_{sc}/\mathrm{d}T)$ in comparison with more significant terms in Eq. (9), results in the expression:

$$\frac{\mathrm{d}V_{oc}}{\mathrm{d}T} = \frac{V_{oc}}{T} - \frac{AkT}{q}\left\{\frac{\gamma}{T} + \frac{E_{go}}{kT^2}\right\} \tag{10}$$

Since $E_{go} = V_{go}\, q$, Eq. (10) for $A = 1$, gives

$$\frac{\mathrm{d}V_{oc}}{\mathrm{d}T} = -\frac{\left(V_{go} - V_{oc} + \gamma\left(kT/q\right)\right)}{T} \tag{11}$$

Eq. (11) is the expression given in [17] for $(\mathrm{d}V_{oc}/\mathrm{d}T)$.

Evaluating the rate $(\mathrm{d}I_{sc}/\mathrm{d}T)$ from Eq. (5) and substituting into Eq. (9), one obtains:

$$\frac{\mathrm{d}V_{oc}}{\mathrm{d}T}=\frac{V_{oc}}{T}+\frac{AkT}{q}\left(\frac{I_o}{I_{sc}+I_o}\right)\left[\mathrm{e}^{qV_{oc}/kT}\left\{\frac{\gamma}{T}+\frac{E_{go}}{kT^2}-\frac{qV_{oc}}{kT^2}\right\}\right]-\frac{AkT}{q}\left(\frac{I_{sc}}{I_{sc}+I_o}\right)\left(\frac{\gamma}{T}+\frac{E_{go}}{kT^2}\right)\tag{12}$$

Eq. (12) does not reveal explicitly the functional depends of $(\mathrm{d}V_{oc}/\mathrm{d}T)$ on the solar source function or the geometrical and optical properties of the solar cell material.

Let us now consider, the following expression for I_{sc} [1]:

$$I_{sc}=\beta\left(A_0+A_1T(o,t)\right)\left(1-\mathrm{e}^{-\alpha t}\right)q\cdot n_{ph}\left(E_g\right)\tag{13}$$

Eq. (13) relates I_{sc} to the input radiation, where n_{ph} (E_g) is the number of photons with energy greater than the band gab E_g, $A=(A_0+A_1\,T(o,t))$, is the optical absorption coefficient of the front face of the solar convertor, A_0 is constant, A_1 (K^{-1}) reflects the dependence of A on the temperature of the absorbing surface itself.

α (m^{-1}) represents the absorption coefficient in the semi conductor, ℓ (m), the thickness of absorbing semiconductor bulk.

β-collection efficiency of p–n junction.

n_{ph} (E_g) number of photons with energy greater than the band gap E_g.

For simplicity the value $n_{ph}=(q(t)/E_g)$ is accepted where, $q(t)$ is the solar irradiance at the considered time.

The dependence of the band gap on temperature is expressed as [18]:

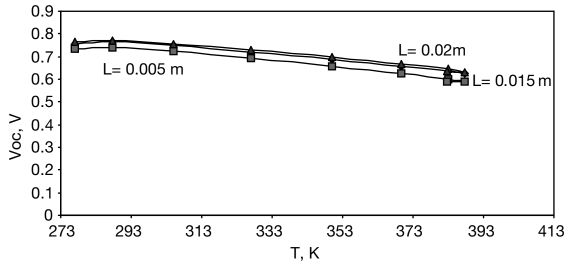

Fig. 1.

$$E_g\left(T\right)=E_g\left(o\right)-\frac{\alpha' T^2}{T+b}\tag{14}$$

for silicon: $E_g(0)=1.16\,\mathrm{eV}$, $\alpha'=7\times10^{-4}\,\mathrm{eVK}^{-1}$, $b=1100\,\mathrm{K}$.

For silicon from 300 K up to 1682 K the following information are available [19],

$$\alpha=a\exp\left(\frac{T}{T_1}\right),\quad T_1=346\mathrm{K},$$

$$a=3.17\,\mathrm{m}^{-1},\quad A=0.678,\quad A_1=3.12\times10^{-5},$$

The value $(\mathrm{d}I_{sc}/\mathrm{d}T)$ is obtained from Eq. (13) in the form

$$\frac{\mathrm{d}I_{sc}}{\mathrm{d}T}=\beta q n_{ph}\left[A_1\left(1-\mathrm{e}^{-\alpha\ell}\right)+\left(A_o+A_1\,T\left(o,t\right)\right)\frac{\ell a}{T_1}\exp\left(\frac{T}{T_1}\right)\exp\left(-\alpha\ell\right)\right]\tag{15}$$

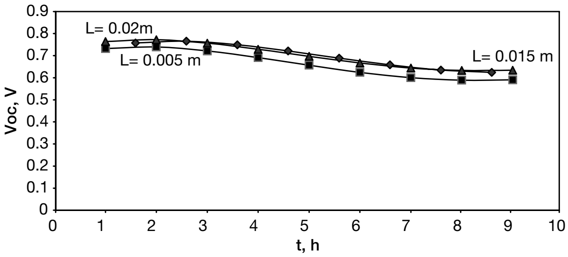

Fig. 2.

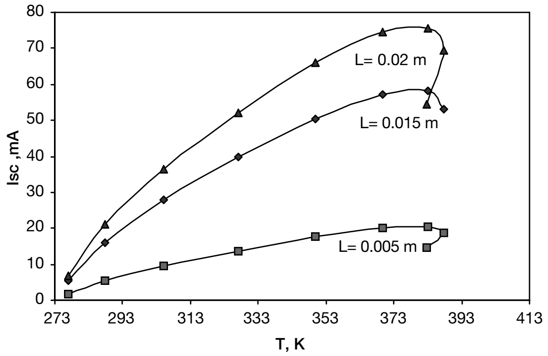

Fig. 3.

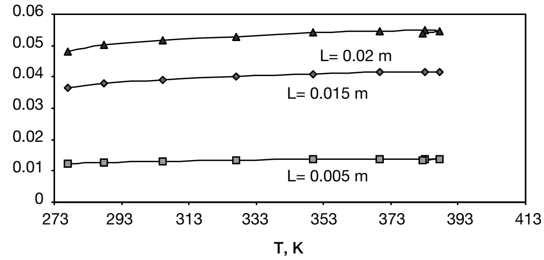

Fig. 5.

$$\frac{\mathrm{d}\eta}{\mathrm{d}T}=\frac{\mathrm{FF}}{P_{\mathrm{in}}}\left\{I_{\mathrm{sc}}\frac{\mathrm{d}V_{\mathrm{oc}}}{\mathrm{d}T}+V_{\mathrm{oc}}\frac{\mathrm{d}I_{\mathrm{sc}}}{\mathrm{d}T}\right\} \tag{17}$$

Substituting ($\mathrm{d}I_{sc}/\mathrm{d}T$) (14) into (10) one gets

$$\begin{aligned}\frac{\mathrm{d}V_{\mathrm{oc}}}{\mathrm{d}T}=&\frac{V_{\mathrm{oc}}}{T}+\frac{AkT}{q}\frac{\beta q n_{\mathrm{ph}}}{I_{\mathrm{sc}}+I_{\mathrm{o}}}\\&\left[A_1\left(1-\mathrm{e}^{-\alpha\ell}\right)+\left(A_{\mathrm{o}}+A_1T\left(o,t\right)\right)\right.\\&\left.\frac{\ell a}{T_1}\exp\left(\frac{T}{T_1}\right)\exp\left(-\alpha\ell\right)\right]\\&-\frac{AkT}{q}\frac{I_{\mathrm{sc}}}{\left(I_{\mathrm{sc}}+I_{\mathrm{o}}\right)}\left\{\frac{\gamma}{T}+\frac{E_{\mathrm{go}}}{kT^2}\right\}\end{aligned} \tag{16}$$

On the other hand, accepting the definition for the efficiency η given by Eq. (1), one can derive the following expression for the rate of temperature variation of the efficiency as

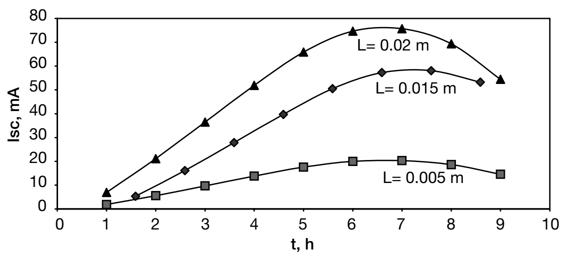

Fig. 4.

3. Computations

A silicon cell is considered different thicknesses 0.005, 0.015, 0.02 m are indicated. The authors of the present work [20] obtained an expression to predict the diurnal global solar irradiance $q(t)$ on a horizontal surface. Heating problem of a solar cell subjected to incident solar radiation is considered [21]. The integral transformer method is applied to get the solution.

This makes it possible to determine theoretically the diurnal temperature variation of the cell temperature. The experimental data of $q(t)$ measured in Jeddah, Saudi Arabia, April 1983 [22] are used in the computations [21].

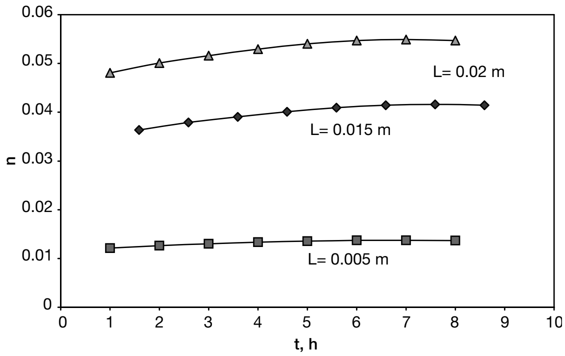

Fig. 6.

This makes it possible to determine, the temperature T of the considered silicon solar cell at different local time in hours from sunrise up to sunset.

For each temperature T [20] all the following physical quantities are computed, namely:

$$E_g n_{ph}\left(E_g\right), I_o, I_{sc} V_{oc}, \frac{dI_{sc}}{dT}$$
$$\frac{dV_{oc}}{dT}, \quad \eta \quad \text{and} \quad \frac{d\eta}{dT} \tag{18}$$

The obtained values corresponding to different local day time for the solar cell thickness, 0.005, 0.0150, and 0.020 m, respectively.

4. Conclusions

The obtained results reveal that

1) Though the value of (dI_{sc}/dT) is in general negligible, but it varies in a wide range along the whole daytime, thus it must not be neglected in evaluating the efficiency of the solar cell.
2) The efficiency behaves as a slowly varying function with temperature along the local daytime.
3) Neglecting (dI_{sc}/dT) gives overestimated negative values of (dV_{oc}/dT)
4) The functional dependence of I_{sc} on the incident solar irradiance makes it possible to increase the efficiency using a more concentrated beam of high intensity thus suitable laser beams will be benefit.

The thickness within the considered values is not effective in changing the efficiency.

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