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Solar cells electrical behavior under thermal gradient

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Abstract

This work presents an investigation on the electrical behavior and performances of solar cells under thermal gradient. For constant illumination, the main effect of temperature gradient is the decreasing of the conversion efficiency of solar cells. A slope of 0.063 %/K is observed for the considered silicon solar cell. The obtained results show also that the maximum value of photovoltaic conversion efficiency is below room temperature, a comparative study with other technologies shows that the silicon technology is less recommended in hot environments.

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Keywords: Solar cells; silicon; temperature; conversion efficiency.

1. Introduction

Photovoltaic conversion is an energy application strongly dependent on the temperature because the electric performances of any photovoltaic converter are very sensitive to environmental conditions, especially temperature and illumination. A large number of studies were proposed to investigate the influence of temperature on the behavior of different solar cells technologies performance considering their characteristic parameters. Phillips et al [1] reported an investigation about thermal behavior of CdTe based solar cells, in the same context Kniese et al [2], Singh et al [3] and recently Krustok et al [4] dealt with silicon solar cells technology, $Cu(In,Ga)Se_2$ alloys, $Cu_2ZnSn(Se_xS_{1-x})_4$ mono grain solar cells,

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respectively. The set of the invoked works show a decreasing in solar cells performances with increasing temperature. The main objective of this work is to carry out a comparative study relative to the electrical behavior and performances of different types of solar cells under temperature gradient. Our proper contribution concerns the polycrystalline silicon technology. For a polycrystalline silicon solar cell with (12.5×12.5) cm^2 area, we investigate the thermal effect on its electrical parameters and the evolution of its conversion efficiency in the temperature range (15-50°C) under constant illumination (1kW/m^2).

Nomenclature

E_A	Activation energy of saturation current
G	Irradiance
G_{ref}	Reference irradiance
G_{sh}	Shunt conductance
I	Current
I_{ph}	Photocurrent
I_s	Saturation current
I_{sc}	Short circuit current
k	Constant of Boltzmann
n	Ideality factor
q	Electron charge
R_s	Series resistance
R_{sh}	Shunt resistance
t	Temperature in degrees Celsius
T	Absolute temperature
T_{ref}	Reference temperature
V	Voltage
V_{oc}	Open circuit voltage
μ_{Isc}	Temperature coefficient of the short circuit current
η	Conversion efficiency of the solar cell

2. Theory and analysis

Let us consider the single diode model of the solar cell which is the most popular for solar cells. The current-voltage relation for a solar cell under illumination is given by [5]:

$$I = I_{ph} - I_s\left(e^{\left(\frac{q(V+IR_s)}{nkT}\right)} - 1\right) - G_{sh}(V + IR_s) \quad (1)$$

I_{ph}, I_s, n, R_s, q, k, T and G_{sh} being the photocurrent, the diode saturation current, the diode ideality factor, the series resistance, the electron charge, the constant of Boltzmann, the absolute temperature and the shunt conductance, respectively.

In order to study the electrical behavior of solar cells under temperature gradient, we get hold of the dependence with temperature of the short circuit current I_{sc} and the open circuit voltage V_{oc}. From equation (1) we can find the expression of I_{sc} and V_{oc} after some simplifying assumptions.
For I_{sc}, we take ($V=0$):

$$I_{sc} = \frac{I_{ph} - I_s\left[e^{\left(\frac{qR_sI_{sc}}{nkT}\right)} - 1\right]}{1 + G_{sh}R_s} \tag{2}$$

It is practically difficult to calculate the temperature dependence of I_{sc}, but in many cases we can assume a simple linear dependence [4]. Concerning the shunt resistance, the following approximation is usually true [6]:

$R_{sh} = \frac{1}{G_{sh}} \gg R_s \Rightarrow 1 + G_{sh}R_s \approx 1$. Therefore, the short circuit current of the cell becomes

$$I_{sc} = I_{ph} - I_s\left[e^{\left(\frac{qR_sI_{sc}}{nKT}\right)} - 1\right] \tag{3}$$

In many cases it is possible to apply the following approximation [6]:

$$I_{ph} \gg I_s \Leftrightarrow I_{sc} \approx I_{ph} \tag{4}$$

According to [7] I_{ph} is observed to depend on the absorbed solar irradiance (G), temperature (T) and the short circuit current temperature coefficient (μ_{Isc}). The photocurrent I_{ph} for any operating condition is assumed to be related to the irradiation and the current at reference conditions by:

$$I_{ph}(T) = \frac{G}{G_{ref}}\left[I_{ph,ref} + \mu_{I_{sc}}\left(T - T_{ref}\right)\right] \tag{5}$$

μ_{Isc}: is the temperature coefficient of the short circuit current (A/K).
G and T: are operating conditions (irradiance and temperature respectively).
G_{ref} and T_{ref}: are reference conditions of irradiance and temperature respectively. They are numerically $G_{ref} = 1kW/m^2$ and $T_{ref} = 298.15\ K$ [8].
In our case: $G = G_{ref}$. We get a simple linear dependence relationship

$$I_{sc}(T) \approx I_{ph}(T) = I_{ph,ref} + \mu_{I_{sc}}\left(T - T_{ref}\right) \tag{6}$$

For V_{oc}, we take ($I=0$):

$$V_{oc} = \frac{nKT}{q}\ln\left(1 + \frac{I_{ph}}{I_s} - \frac{G_{sh}V_{oc}}{I_s}\right) \tag{7}$$

The order of magnitude of the photocurrent is of 5A, the magnitude of ($G_{sh}V_{oc}$) is of 10^{-3}A and of I_s is of 1µm then ($I_{ph} >> G_{sh}V_{oc}$) and ($I_{ph} >> I_s$), V_{oc} becomes [4]:

$$V_{oc} = \frac{nKT}{q}\ln\left(\frac{I_{ph}}{I_s}\right) \tag{8}$$

I_s is a function of the material properties and it is also sensitive to temperature [9]

$$I_s(T) = I_{s0}e^{\left(-\frac{E_A}{nKT}\right)} \tag{9}$$

Where I_{s0} is a constant, E_A is the activation energy of saturation current, n is the ideality factor and kT is the thermal energy. The combination between (8) and (9) give a linear dependence of V_{oc} on temperature:

$$V_{oc}(T) = \frac{E_A}{q} - \frac{nKT}{q}\ln\left(\frac{I_{s0}}{I_{ph}}\right) \tag{10}$$

3. Results and discussion

In Table 1, experimental values of short circuit current, open circuit voltage and efficiency conversion of polycrystalline silicon solar cell at different temperatures under constant illumination (1kW/m^2) are presented. From this measured data, we can see that increasing temperature leads to an increase of I_{sc} and a decrease of V_{oc} in the same time.

Table1: Experimental values of I_{sc}, V_{oc} and η for the Polycrystalline silicon solar cell under (1kW/m^2) of irradiance.

t (°C)	I_{sc} (A)	V_{oc} (V)	η (%)
15	5.1261	0.6380	16.25
20	5.1367	0.6277	15.95
25	5.1470	0.6172	15.65
30	5.1582	0.6065	15.32
35	5.1685	0.5964	15.03
40	5.1791	0.5857	14.69
45	5.1899	0.5751	14.36
50	5.1997	0.5645	14.04

The temperature dependence of I_{sc} ($I_{sc} \approx I_{ph}$) is shown in Fig. 1. We observe a linear increase of I_{sc} with temperature in the range 288–323 K. For 1 kW/m^2 we found $dI_{sc}/dT=2.1$ *mA/K*. We indicate that this calculated temperature coefficient of the short circuit current ($\mu_{Isc}=2.1mA/K$) is in good agreement with the value obtained by De Soto et al [8] (*2.38 mA/K*) for the same technology under the same conditions.

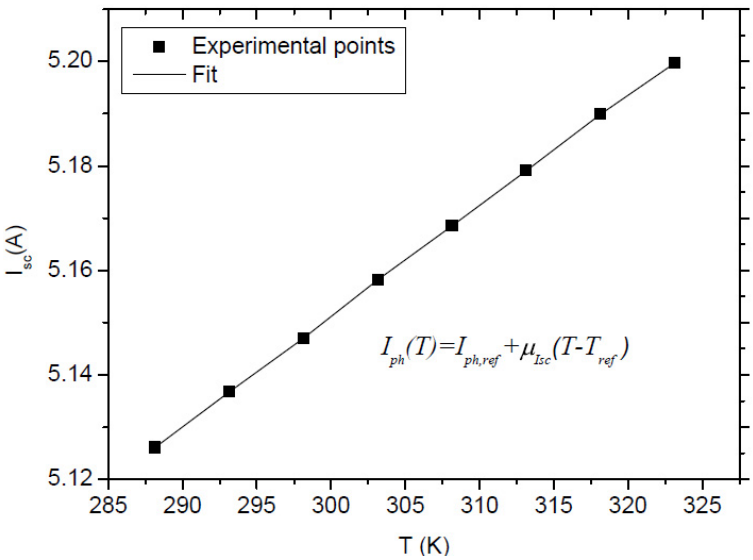

Fig. 1: Temperature dependence of the short circuit current ($I_{sc} \approx I_{ph}$) of a polycrystalline silicon solar cell.

The thermal behavior of the V_{oc} is shown in Fig. 2. Under an illumination of (1kW/m^2) the open circuit voltage decreases with increasing temperature by (*2.1mV/K*). This is in good agreement with the assessment of Singh et al [3] for silicon solar cells $dV_{oc}/dT = -2.2$ *mV/K*.

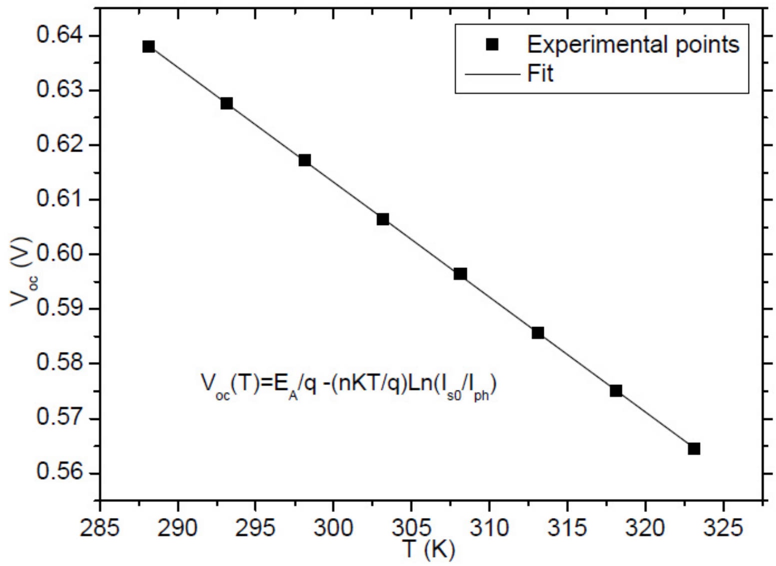

Fig. 2: Thermal dependence of V_{oc} of a polycrystalline silicon solar cell.

Fig. 3 illustrates the shape of the photovoltaic conversion efficiency η as a function of temperature. We find that the maximum value of η is less than that obtained at room temperature. In the considered temperature range *i.e.* 288-323 K, the decrease in photovoltaic conversion efficiency with temperature is linear and the corresponding slope is estimated by $\frac{d\eta}{dT} = -0.0063\ \%/K$ which agrees with the assessment of Singh et al [3] for silicon solar cells; $\frac{d\eta}{dT} = -0.0042\ \%/K$.

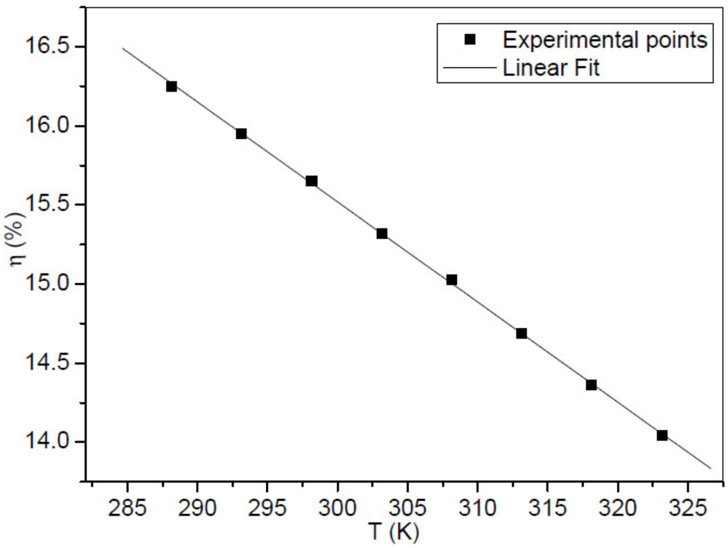

Fig. 3: Temperature dependence of the conversion efficiency η of a polycrystalline silicon solar cell.

Table 2 shows the values of dI_{sc}/dT, dV_{oc}/dT and $d\eta/dT$ of single crystalline, polycrystalline silicon and thin film solar cells. In this section we are typically interested in the photovoltaic conversion efficiency η because it is the most important factor for describing the performances of any photovoltaic device. The analysis of temperature effect on the conversion efficiency shows that silicon technology has larger temperature coefficient, this leads to a problem in exploitation of silicon based solar cells in hot regions where solar irradiation is important, *i.e.* high temperatures, for photovoltaic applications. So, it is recommended to adopt other technologies for hot environment. Both technologies, CdTe and Cu(In,Ga)Se cannot be good alternatives for silicon technology, in particular in terrestrial applications; the first contains a toxic element (cadmium), the second contains expensive rare metals (indium and gallium). However, the quaternary semiconductor CZTSSe contains abundant, cheaper and nontoxic elements. In addition, it has a low temperature coefficient. Thus, CZTSSe solar cells show a great potential in photovoltaic applications in hot environment.

Table2: Temperature coefficients of I_{sc}, V_{oc} and η.

Technology	Silicon			Other compounds		
	Polycrystalline		Single crystalline	$Cu(In,Ga)Se_2$ [2]	CZTSSe [4]	CdTe [1]
Temperature coefficients	This work	Literature				
dI_{sc}/dT (*mA/K*)	2.1	2.38[a]	1.75[a]	-	-	-
dV_{oc}/dT (*mV/K*)	-2.1	[-2.3, -2.2][b]		[-3.3, -2.01]	-1.91	[-2.2, -2.1]
$d\eta/dT$ (*%/K*)	-0.063	-0.042[b]		[-0.064, -0.017]	-0.013	-

a: Reference [8], b: Reference [3].

4. Conclusion

We have investigated the electrical behavior of different solar cells under thermal gradient. For an illumination of ($1kW/m^2$), the polycrystalline silicon technology has temperature coefficients of $dI_{sc}/dT=2.1\ mA/K$, $dV_{oc}/dT=-2.1\ mV/K$ and $d\eta/dT=-0.063\ \%/K$. The maximum value of photovoltaic conversion efficiency η is below room temperature. A comparison between different technologies; CdTe, CuIGaSe, CZTSSe and silicon, has been made. CdTe contains a toxic element which is cadmium. CIGS thin film based solar cells contain expensive rare metals as indium and gallium. Crystalline silicon based technology has a relative high temperature coefficient, and then it is not very recommended for hot environment compared to CZTSSe.

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