Temperature Effect on Photovoltaic Parameters For c-Si and a-Si Solar cells

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Abstract:

Although solar cell parameters are generally measured at 20-30 C^o, flat plate modules normally operate at 40-50 C^o under terrestrial conditions and even higher temperatures are used for some concentrator cell applications. Therefore it is interesting to calculate the dependence of cell parameters on temperature. In this paper a simple formulation has been derived for obtaining the temperature dependence of open circuit voltage Voc, short circuit current density Jsc, fill factor FF, and conversation efficiency η, for c-Si and a-Si solar cells.

الخلاصه:

نظرا لاهمية تغير درجات الحراره على أستجابه واداء الخلايا الشمسية عموما, لما لتغّيرها من تأثيرا على متغيرات الخلايا من(voc,Jsc,FF,η) , تم في هذا البحث دراسة وتحليل وملاحظة تأثير تغيّر درجات الحراره على نوعين من الخلايا الشمسية هي الخلايا البلورية والخلايا العشوائية التركيب.
لقد تم في هذا البحث اشتقاق صيغ ومعادلات نظريه لتغير درجات الحراره مع مختلف متغيرات الخلية من (voc,Jsc,FF,η) لنوعين من الخلايا الشمسية, وقد تم ملاحظة أداء وكفاءة الخلية الشمسيه عموما حيث تقل مع ارتفاع درجات الحراره نظرا لنقصان(voc) وزيادة.(Jsc) . كما تم ملاحظة ان زيادة فجوة الحزمة(Eg) يؤدي الى تقليل تأثر تلك الخلية بتغير درجات الحراره ولكن المعامل الحراري للفولتيه والتيار والكفاءة والجوده يزداد وقيمته في الخلايا البلورية اقل من العشوائية.

1. Introduction:

Whether the solar cell is used in space or for power generation on earth, the actual temperature at which cells work does not remain constant. It is therefore, important to understand the behaviors of the cells at different temperature and the influence of changing temperature on cell parameters (efficiency, fill factor, open-circuit voltage, and short-circuit current).

The early studies of temperature effects on the output characteristic of solar cells were made by Walkden [1]. Sinha and Chattopadhyaya [2] calculate the degradation of Voc with temperature by neglected the small increase in Jsc with temperature for AM0 condition (power per unit area per unit wavelength out side the earth's atmosphere with incident power of about 1353W/m^2). Furthermore, Agarwal et.al [3] determine experimentally that the spectral response which represents the number of carriers collected per incident photon at each wavelength of monochromatic light incident on the front surface of solar cell, decreases with increasing of temperature in short wavelength region (0.4-0.8 μm) and increases in longer wavelength region (0.85-1.1μm). Many other researchers [4-7] have reported the influence of temperature on the principle parameters of solar cells, but the results of their investigations are widely different from each other. In this paper, a theoretical formulation is presented for temperature dependence of solar cell parameters for crystalline and amorphous silicon.

Generally there are three basic parameters in the solar cell which is function of temperature: (i) diffusivity, (ii) diffusion length, (iii) intrinsic effective carrier concentration. However, diffusivity and diffusion length are weak functions of temperature compared with intrinsic carrier concentration.

Finally, it is well known that Voc of solar cells decreases rapidly and Jsc increases slowly with increasing temperature [8], and this variation is larger at low and medium level than at high level of illumination [9].

2. General Formulation:

A study of temperature effect on cell parameters was investged by considering a general structure of n^+-p-n^+ c-Si and n-p-n a-Si:H solar cells where the light impinges on the front layer and reflection in part at the surface of the back electrode. The intrinsic carrier concentration have predominate effect in temperature dependence of solar cell parameters compared with diffusivity and diffusion length. The variation of intrinsic carrier density with temperature can be expressed by the following:
for c-Si [10]

$$n_i(T) = K_o T^{3/2} \exp\left[\frac{-Eg(T)}{2kT}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

and for a-Si by [11]

$$n_i(T) = \sqrt{N_c(T) N_v(T)} \exp\left[\frac{-Eg(T)}{2kT}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

and $N_c(T) = \dfrac{A_{ct} wc}{\dfrac{wc}{kT} - 1}$,

$$N_v(T) = \frac{A_{vt} wv}{\dfrac{wv}{kT} - 1} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

where $\boldsymbol{K}_o$ is an empirical parameter, and equal (3.87×10^{16}) as given by [10], T is the absolute temperature, Eg the energy gap, k is Boltzman's constant, $N_c(T)$, $N_v(T)$ are the effective density of states for conduction and valance band respectively, A_{ct} and A_{vt} are the density of states at the bottom of conduction band and the top of the valence band edges, while w_c, w_v are the characteristic energies of exponentially slop conduction and valence band edges.

Fig.(1) reveals that intrinsic carrier concentration increases with increasing temperature for both c-Si and a-Si materials [12].

Since the band gap Eg also depends on temperature, the variation of band gap for c-Si with temperature can be expressed approximately by [13]

$$Eg(T) = Eg(0) - \frac{\alpha T^2}{(T + \beta)} \quad \ldots\ldots\ldots\ldots\ldots\ldots(4).$$

Where Eg(0)=Eg at T=0 ^{o}k, and α and β are empirical parameters, or it can be expressed as [14]

$$Eg(T) = 1.169\left[\frac{0.1}{\exp\dfrac{350}{T} - 1}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

In a-Si the variation of mobility gap with temperature can be expressed by [13]

$$Eg(T) = Eg(0) - \Delta Eg(T) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where $\Delta Eg(T) = \dfrac{220x10^{-3}}{\exp\left[\dfrac{400}{T} - 1\right]}$ …… ………………………….. (7)

Fig(2) shows the variation of band gap as a function of temperature for c-Si and a-Si.

The temperature dependence of Voc on the other hand is almost completely controlled by the temperature dependence of (Joα ni), where Jo is the dark saturation current density for a solar cell and is given by [15]

$$Jo = k_{\circ} T^{3/n} \exp\left[\frac{-Eg(T)}{mkT}\right] \quad \ldots\ldots\ldots\ldots \quad (8)$$

and Voc is given by

$$Voc = \frac{AkT}{q}\ln\left(\frac{xJsc}{Jo}\right) \quad \ldots\ldots\ldots\ldots \quad (9)$$

Where A is the diode quality factor of p-n junction which has a value between 1(for diffusion current) and 2 (for recombination current) [16], x the concentration ratio and m,n are empirical parameters depending on the quality of cell material and junction. Differentiating equations (8) &(9) with respect to T gives

$$\frac{\partial Jo}{\partial T} = \frac{Jo}{T}\left[\frac{3}{n} - \frac{1}{mkT}\left(T\frac{\partial Eg}{\partial T} - Eg\right)\right] \quad \ldots\ldots\ldots \quad (10)$$

$$\frac{\partial Voc}{\partial T} = \frac{Voc}{T} + \frac{AkT}{qJsc}\frac{\partial Jsc}{\partial T} - \frac{AkT}{qJo}\frac{\partial Jo}{\partial T} \quad \ldots\ldots\ldots \quad (11)$$

By substituting equs.(8) and (10) into equ.(11) we obtain

$$\frac{\partial Voc}{\partial T} = \frac{1}{T}\left[Voc - \frac{AEg}{mq} - \frac{3AkT}{nq}\right] + \ldots \frac{A}{mq}\frac{\partial Eg}{\partial T} + \frac{AkT}{qJsc}\frac{\partial Jsc}{\partial T} \quad \ldots\ldots \quad (12)$$

This equation is a general expression and should be applicable to cells made from crystalline and amorphous materials.

3. Temperature dependence in c-Si:

For crystalline silicon n,m is equal to (2) and A equal to (1) as in [15], and equ.(10) becomes

$$\frac{\partial Jo}{\partial T} = \frac{Jo}{T}\left[\frac{3}{2} - \frac{1}{2kT}\left(T\frac{\partial Eg}{\partial T} - Eg\right)\right] \quad \ldots\ldots\ldots \quad (13)$$

and

$$\frac{\partial Voc}{\partial T} = \frac{1}{T}\left[Voc - \frac{Eg}{2q} - \frac{3kT}{2q}\right] + \ldots \frac{1}{2q}\frac{\partial Eg}{\partial T} + \frac{kT}{qJsc}\frac{\partial Jsc}{\partial T} \quad \ldots\ldots \quad (14)$$

Substituting equ.(4) in to equ.(14) gives

$$\frac{\partial Voc}{\partial T} = \frac{1}{T}\left[Voc - \frac{Eg}{2q} - \frac{3kT}{2q}\right] + \ldots \frac{\alpha T}{2q}\frac{(T+2\beta)}{(T+\beta)^2} + \frac{kT}{qJsc}\frac{\partial Jsc}{\partial T} \quad \ldots\ldots \quad (15)$$

No analytical expression is available for $\frac{\partial Jsc}{\partial T}$. To evaluate this differential at temperature T_o, Jsc values were calculated for T_o, T_{o+2}, and T_{o-2}, using the formulation presented in [15]. In calculating each Jsc values, the AM1 solar spectrum (which represents the sun light at the earth's surface when the sun is at zenith; with incident power of about 925 W/m^2) was integrated to the value of Eg given by equ.(4) for appropriate temperature. The values of Jsc were then used to evaluate

$$\left(\frac{\partial Jsc}{\partial T}\right)_{To} = \frac{\left(\frac{\partial Jsc}{\partial T}\right)_{To+1} + \left(\frac{\partial Jsc}{\partial T}\right)_{To-1}}{2} \quad \ldots$$
…………………… (16)

$$\left(\frac{\partial Jsc}{\partial T}\right)_{To+1} = \frac{(Jsc)_{To+2} - (Jsc)_{To}}{2} \quad \ldots$$
……………………… (17)

$$\left(\frac{\partial Jsc}{\partial T}\right)_{To-1} = \frac{(Jsc)_{To} - (Jsc)_{To-2}}{2}$$
………………………….. (18)

This procedure was used to obtain $\left(\frac{\partial Jsc}{\partial T}\right)$ for c-Si and a-Si at various values of To.

4. Temperature dependence in a-Si:

For a-Si the dark saturation current Jo1 is given by [17]

$$Jo1 = \sqrt{Nc(T)Nv(T)}\exp\left[\frac{-Eg(T)}{2kT}\right]$$
………………………… (19)

Differentiating above equation with respect to T gives

$$\frac{\partial Jo1}{\partial T} = \sqrt{Nc(T)Nv(T)}$$

$$\exp\left[\frac{-Eg}{2kT}\right]\frac{1}{2k}\left[\frac{Eg - T\frac{\partial Eg}{\partial T}}{T^2}\right] + e$$

$$xp\left[\frac{-Eg}{2kT}\right]\frac{1}{2\sqrt{Nc(T)Nv(T)}}$$

$$\left[Nc(T)\frac{kwv}{(wv-kT)^2} + Nv(T)\frac{kwc}{(wc-kT)^2}\right] \ldots$$
………. ………. ………. ……(20)

Simplifying equ.(20) gives

$$\frac{\partial Jo1}{\partial T} = \frac{Jo1}{T}\left[\begin{array}{l}\frac{1}{2kT}\left(Eg - \frac{T\partial Eg}{\partial T}\right) + \\ \frac{1}{2}\left[\frac{wv}{(wv-kT)} + \frac{wc}{(wc-kT)}\right]\end{array}\right]$$
………
……. (21)

By substituting equs.(19) and (21) in to (11) we obtain

$$\frac{\partial Voc}{\partial T} = \frac{1}{T}\left[Voc - \frac{A}{2q}Eg\right] + \frac{A}{2q}\frac{\partial Eg}{\partial T} +$$

$$\frac{Ak}{2q}\left[\frac{wv}{wv-kT} + \frac{wc}{wc-kT}\right] + \frac{AkT}{qJsc}\frac{\partial Jsc}{\partial T}$$
…. (22)

For high quality a-Si cell, the parameter A is close to unity, and equ.(22) becomes:

$$\frac{\partial Voc}{\partial T} = \frac{1}{T}\left[Voc - \frac{1}{2q}Eg\right] + \frac{1}{2q}\frac{\partial Eg}{\partial T} +$$

$$\frac{k}{2q}\left[\frac{wv}{wv-kT} + \frac{wc}{wc-kT}\right] + \frac{kT}{qJsc}\frac{\partial Jsc}{\partial T}$$
… (23)

Substituting equ.(7) in to equ.(23) we get

$$\frac{\partial Voc}{\partial T} = \frac{1}{T}\left[Voc - \frac{1}{2q}Eg\right] + \frac{1}{2q}\frac{220*10^{-3}}{\exp\left[\frac{400}{T} - 1\right]} +$$

$$\frac{k}{2q}\left[\frac{wv}{wv-kT} + \frac{wc}{wc-kT}\right] + \frac{kT}{qJsc}\frac{\partial Jsc}{\partial T}$$

…(24)

The values of fill factor FF can be calculate for different temperature by using the equ.(9) :

$$FF = \frac{Vm}{Voc}\left[1 - \frac{\exp\left(\frac{qVm}{kT}\right) - 1}{\exp\left(\frac{qVoc}{kT}\right) - 1}\right] \quad \ldots\ldots\ldots$$
………………………….. (25)

where Vm is given by the relationship

$$\exp\left(\frac{qVm}{kT}\right)\left(1 + \frac{qVm}{kT}\right) = \frac{xJsc}{Jo} + 1 \quad \ldots\ldots$$
…………………………… (26)

Solar cell conversion efficiency η is given by

$$\eta = \frac{(Voc)(Jsc)(FF)}{Pin} \quad \ldots\ldots\ldots\ldots$$
………………………………. (27)

The temperature dependence of η is generally expressed as a relative variation

$$\frac{1}{\eta}\left(\frac{\partial \eta}{\partial T}\right)=\frac{1}{Voc}\frac{\partial Voc}{\partial T}+\frac{1}{Jsc}\frac{\partial Jsc}{\partial T}+\ldots \frac{1}{FF}\frac{\partial FF}{\partial T} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (28)$$

5. Results and Discussion:

We studied the influence of temperature variation on the principle parameters of c-Si and a-Si:H will thermally excited intrinsic charge carriers along with the narrowing of the band gap for both c-Si and a-Si:H solar cells, resulting in a red shift in optical absorption with a small difference in intrinsic charge carriers between each types because a-Si:H begins to recrystallized as revealed in Fig.(1) and Fig.(2). Fig.(3) shows that open-circuit voltage decreases linearly as a function of increasing temperature on both c-Si and a-Si:H layers, but this dependence is lower for good c-Si than for a-Si:H. Generally, the variation of Voc with temperature can be explained by the strong increases in dark saturation current Jo with temperature, this explanation seem compatible with study proposed by Liang, et al.[18]. Fig.(4) shows that the short circuit current increases with increasing temperature, this is partly caused by the increase in diffusion length and partly by shift in the absorption edge to lower energies. But the short circuit current shows much larger variation with temperature in a-Si:H than in c-Si, this because in a-Si:H the dominated effect of Jsc will be due to mobility variation [19]. Fig.(5) illustrate the decreasing of fill factor with increasing temperature for both c-Si and a-Si:H with rapidly decreases of a-Si:H than in c-Si cell, while Fig.(6) shows the decreasing of efficiency with increasing temperature in c-Si and a-Si:H. Note that table (1) indicates the rate of change of solar cell parameters with temperature for c-Si and a-Si:H cells. We can see that the solar cells had a negative temperature coefficient, meaning that as temperature increased series resistance decreased resulting in a reducing of output power.

6. Conclusion:

The effect of temperature variation on cell parameters for two types of material has been investigated. Theoretical formulation of temperature dependence for solar cell parameter has been derived for crystalline and amorphous silicon. Generally open circuit voltage decrease and short circuit current increases by increasing temperature for c-Si and a-Si:H materials, but Jsc increase more rapidly in a-Si:H than c-Si . Fill factor and efficiency will decrease by increasing temperature and the absolute temperature coefficient of $\frac{\partial voc}{\partial T}$, $\frac{\partial Jsc}{\partial T}$, $\frac{\partial FF}{\partial T}$,and $\frac{\partial \eta}{\partial T}$ in c-Si will be less than a-Si:H.

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Table (1)

T °K	c-Si				a-Si:H			
	$\frac{1}{voc}\frac{\partial voc}{\partial T}$ %deg^{-1}	$\frac{1}{Jsc}\frac{\partial Jsc}{\partial T}$ %deg^{-1}	$\frac{1}{FF}\frac{\partial FF}{\partial T}$ %deg^{-1}	$\frac{1}{\eta}\frac{\partial \eta}{\partial T}$ %deg^{-1}	$\frac{1}{voc}\frac{\partial voc}{\partial T}$ %deg^{-1}	$\frac{1}{Jsc}\frac{\partial Jsc}{\partial T}$ %deg^{-1}	$\frac{1}{FF}\frac{\partial FF}{\partial T}$ %deg^{-1}	$\frac{1}{\eta}\frac{\partial \eta}{\partial T}$ %deg^{-1}
273	-0.235	0.0293	-0.077	-0.298	-0.234	0.130	-0.128	-0.636
300	-0.275	0.0312	-0.082	-0.329	-0.357	0.094	-0.142	-0.678
323	-0.296	0.0320	-0.096	-0.361	-0.340	0.087	-0.112	-0.877
353	-0.337	0.0331	-0.111	-0.408	-0.682	0.067	-0.244	-1.393
373	-0.364	0.0329	-0.114	-0.444	-0.781	0.066	-0.257	-1.710

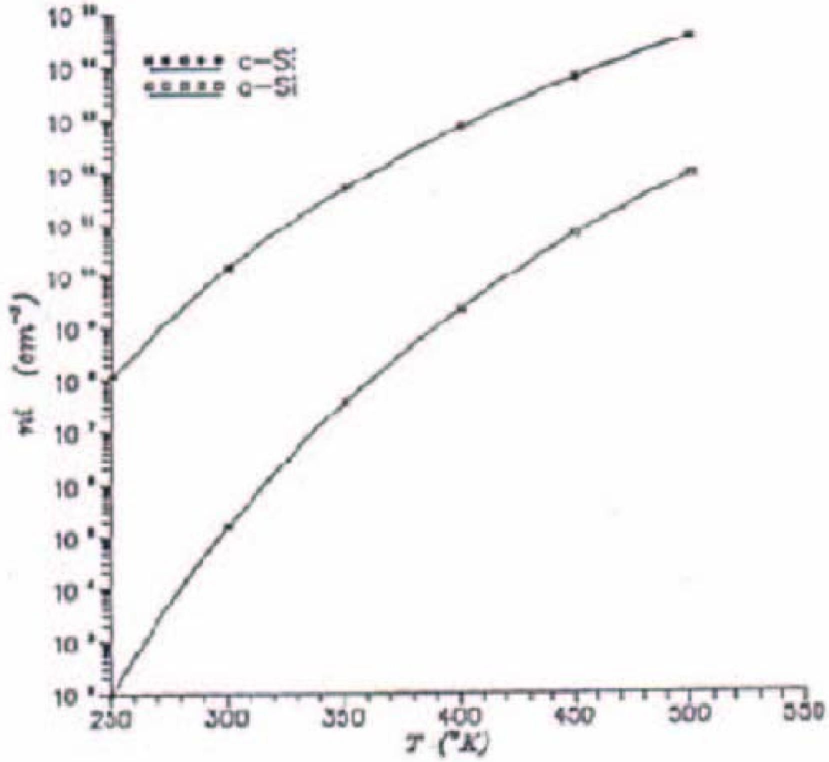

Fig.(1): The variation of intrinsic carrier density with tempera
for undoped c-Si & a-Si [11]

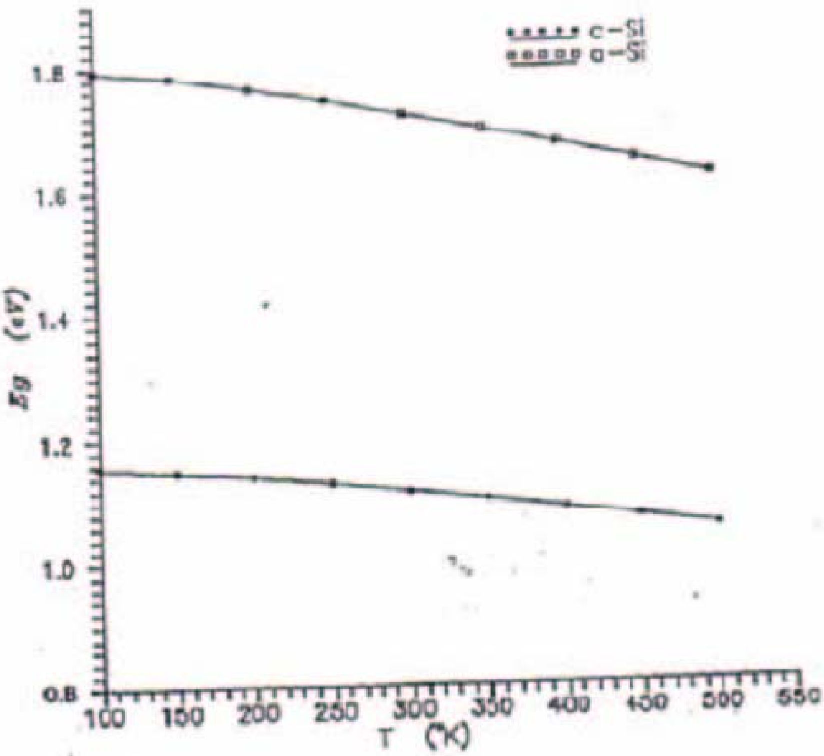

Fig.(2): Energy gap variation with temperature
for undoped c-Si & a-Si [11]

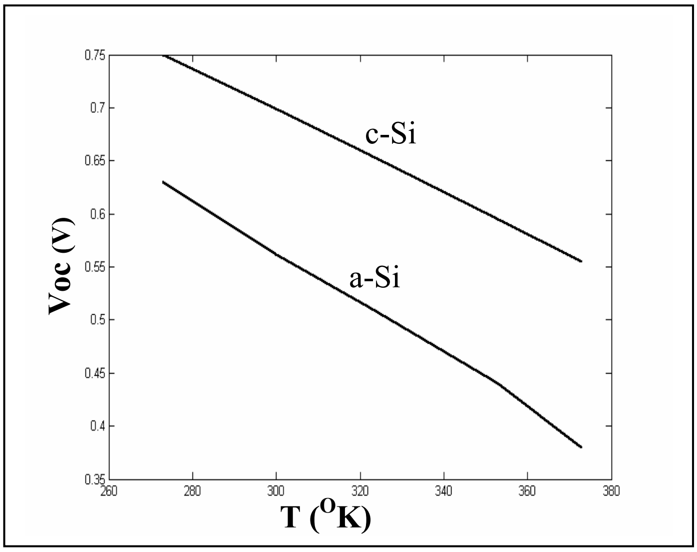

Fig. (3):The Variation of Voc with Temperature in c-Si and a-Si .

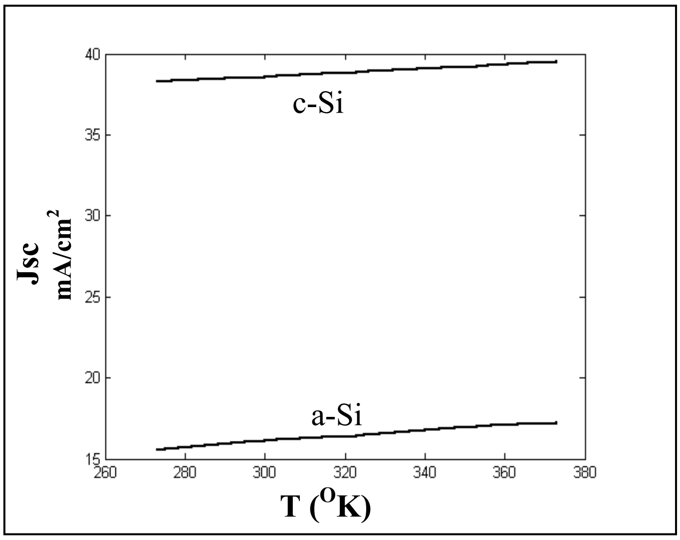

Fig.(4): The short-circuit current variation with temperature in c-Si and a-Si

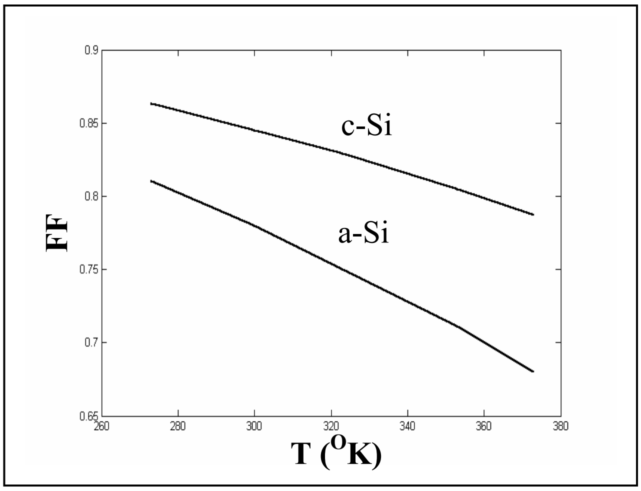

Fig.(5): The variation of fill factor with temperature in c-Si and a-Si

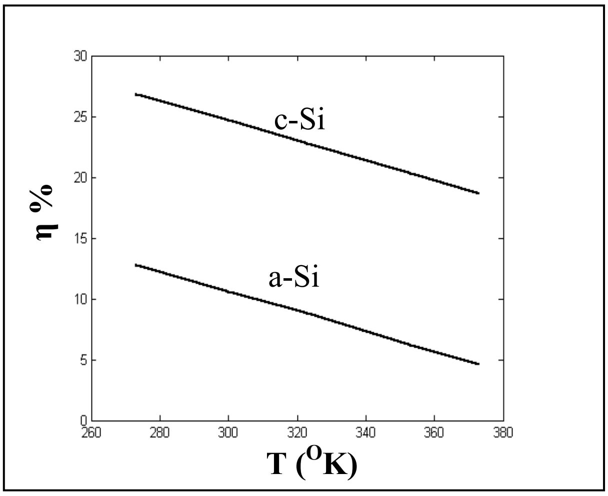

Fig.(6): The variation of efficiency with temperature in c-Si and a-Si