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Temperature dependence of I–V characteristics and performance parameters of silicon solar cell

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ABSTRACT

The temperature dependence of open-circuit voltage (V_{oc}) and curve factor (CF) of a silicon solar cell has been investigated in temperature range 295–320 K. The rate of decrease of V_{oc} with temperature (T) is controlled by the values of the band gap energy (E_g), shunt resistance (R_{sh}) and their rates of change with T. We have found that R_{sh} decreases nearly linearly with T and its affect on dV_{oc}/dT is significant for cells having smaller R_{sh} values. Series resistance also changes nearly linearly with voltage. CF depends not only on the value of R_s and other parameters but also on the rate of change of R_s with voltage. The rate of decrease of R_s with voltage and T are important to estimate the value of CF and its decrease with temperature accurately.

1. Introduction

In terrestrial applications, solar cells are generally exposed to temperatures varying from 10 to 50 °C. The performance of a solar cell is influenced by temperature as its performance parameters, viz. open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), curve factor (CF) and efficiency (η) are temperature dependent. It has been shown earlier [1] that V_{oc} decreases at a rate of ~2.3 mV/K whereas I_{sc} increases slightly with temperature (T). CF also decreases and all these lead to an overall decrease in the cell efficiency [1].

The I–V characteristics of a p–n junction solar cell under steady-state illumination can most simply be described using a single exponential model as

$$I_f = I_{ph} - I_o\left(e^{qV_j/nKT} - 1\right) - V_j/R_{sh} \tag{1}$$

where

$$V_j = V_f + I_f R_s \tag{2}$$

In Eq. (1), I_{ph} represents the photogenerated current, which is nearly equal to I_{sc}, I_o is the reverse saturation current, V_j is the voltage developed or dropped across the junction, n is the ideality factor, k is the Boltzman constant, T is the temperature of the cell and V_f is the terminal voltage, R_s and R_{sh} are series and shunt resistances, respectively.

In many cases the I–V characteristics of cells are better described by a double-exponential model

$$I = I_{ph} - \left[I_{o1}\left(e^{qV_j/n_1KT} - 1\right) + I_{o2}\left(e^{qV_j/n_2KT} - 1\right)\right] - V_j/R_{sh} \tag{3}$$

where I_{o1}, n_1 are the pre exponential constant and ideality factor due to the recombination in quasi-neutral (or bulk) regions and I_{o2}, n_2 are due to the recombination in the space charge (or the depletion) region of the cell.

Essentially, the diode parameters I_o, n of Eq. (1) or I_{o1}, n_1 and I_{o2}, n_2 of Eq. (3) along with R_s and R_{sh} control the effect of temperature on V_{oc}, CF and η of the cell. Surprisingly, however, a very few studies have been reported in literature on the temperature dependence of diode parameters [2–5]. Series resistance is known to affect CF adversely. Arora et al. [2] have observed that R_s decreases more rapidly with T in the low-temperature region (100–250 K) in poly silicon cells as compared to that in single-crystal cells. On the other hand, Ding et al. [3] have found that R_s increases with temperature. Deshmukh and Nagaraju [5] have found that ideality factor n of a solar cell decreases with T. Earlier studies [6,7] have ignored the effect of temperature dependence of R_{sh} on dV_{oc}/dT and that of temperature dependence of R_s on CF and are applicable only for higher efficiency cells which have very low R_s and very large R_{sh} values. In case of cells having screen-printed contacts solar cells R_s may be high and R_{sh} may be low and both may vary with T significantly. Therefore in the present work we have investigated the effect of the change of R_{sh} with temperature on dV_{oc}/dT and the change of R_s with temperature on CF of a silicon solar cell.

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2. Theoretical basis

2.1. Series resistance

For an n^+ p silicon solar cell, it is generally assumed that R_s consists of the resistances of the n^+ front region and the base region and the metal contacts. However, it has been shown by Chakrabarty and Singh [8] that the depletion region also contributes significantly to R_s and this is responsible for the decrease of R_s with V_f. Observation of the decrease of R_s with V_f has been confirmed again recently by Priyanka et al. [9]. Ignoring the contribution of the metal grids and the contact resistance, the total series resistance R_s of the cell can be obtained as

$$R_s = R_b + R_d + R_n \tag{4}$$

where R_b and R_n are the contributions of the p-bulk region and the n^+ front region, respectively, and R_d is the contribution of depletion layer at the p–n junction. We have [8]

$$R_n = (R_{sheet}s^2)/(2A) \tag{5}$$

$$R_b = \rho_b d_p/A \tag{6}$$

It has been shown by Chakrabarty and Singh [8] and Priyanka et al. [9] that R_s decreases linearly with voltage. The voltage dependence of R_s is due to the dependence of R_d on V. From observation of Chakraborty and Singh [8] and Priyanka et al. [9] it can be shown that R_d change with V according to the relation

$$R_d = C - mV \tag{7}$$

In Eqs. (5)–(7) $2s$ is the spacing between two successive grids of the front contact, R_{sheet} is the sheet resistance of the n^+ front region, d_p is the thickness of the quasi-neutral base region, ρ_b is the resistivity of the base region, A is the area of the cell, C and m are constants. We have found during the experiments that for most practical cases of silicon solar cells the values of R_b and R_n can be negligible in comparison with R_d and thus R_s may be largely due to R_d. For such a case R_s will be expected to vary with both V and T.

2.2. Dependence of V_{oc} on T

Some expressions for temperature dependence of V_{oc} are already available in literature [6,7]. However, they had been derived assuming R_{sh} to be infinite. It will be shown a little later that one can consider R_{sh} to vary linearly with T according to the equation

$$R_{sh} = R_{sho} - rT \tag{8}$$

Then from Eqs. (3) and (8) we can obtain a relation for dV_{oc}/dT as

$$\frac{dV_{oc}}{dT} = \frac{-\delta(V_{oc}/R_{sh})r + (V_{oc}/T) - n_1V_{th}(1/I_{o1})(dI_{o1}/dT)}{(1+\delta)} \tag{9}$$

where

$$V_{th} = kT/q, \quad \delta = \left(\frac{n_1V_{th}}{I_{sc}R_{sh} - V_{oc}}\right) \text{ and } \frac{dR_{sh}}{dT} = -r$$

In Eq. (9) the first term in numerator indicates the effect of R_{sh} on dV_{oc}/dT. At any temperature T, $\delta \to 0$ if $R_{sh} \to \infty$. Thus the first term is zero if $R_{sh} \to \infty$ or $r \to 0$. In Eq. (9) I_{o1} and n_1 correspond to bulk recombination and primarily they control the value of V_{oc} of silicon solar cell.

We can describe the temperature dependence of I_{o1} by an equation

$$I_{o1} = A\exp(-qE_A/kT) \tag{10}$$

It is observed that $n_1E_A \approx E_g$, therefore Eq. (10) can be written as

$$I_{o1} = A\exp(-qE_g/n_1kT) \tag{11}$$

Taking natural logarithmic on both sides and, then, differentiating w.r.t. T we have

$$\frac{1}{I_{o1}}\frac{dI_o}{dT} = -\frac{1}{n_1V_{th}}\left(-\frac{E_g}{T} + \frac{dE_g}{dT}\right) \tag{12}$$

where n_1 is assumed to be invariant with T [10].

Following Bludau et al. [11] we can describe the temperature dependence of E_g by an equation

$$E_g(T) = A + BT + CT^2 \tag{13}$$

where $A = 1.1785\,\text{eV}$, $B = -9.025\times10^{-5}\,\text{eV/K}$ and $C = -3.05\times10^{-7}\,\text{eV/K}^2$ for the temperature range $150\,\text{K} \leqslant T \leqslant 300$.

A combination of Eqs. (9)–(13) gives

$$\frac{dV_{oc}}{dT} = \frac{-\delta(V_{oc}/R_{sh})r + (V_{oc}/T) - (A/T - CT)}{(1+\delta)} \tag{14}$$

2.3. Curve factor

An expression for CF can easily be derived using single exponential model given by Eq. (1). For the maximum power point (V_m, I_m) the required condition is

$$\frac{d}{dV}(IV) = 0 \tag{15}$$

Linear dependence of R_s on V can be expressed as

$$R_s = R_{so} - mV \tag{16}$$

where R_{so} and m are constants.

Combination of Eqs. (1), (15) and (16) yields an expression for CF as

$$CF = \frac{(V_m/V_{oc})}{\{1 + (nV_{th}/V_m) + R_s(I_{sc} - I_m)/V_m + m(I_{sc} - I_m - V_m/R_{sh}) + (1/R_{sh})(V_m/I_m - R_s)\}} \tag{17}$$

where V_m and I_m are the values of V and I at the maximum power point and R_s stands for R_s^{CF}.

3. Experimental

Solar cells used in this study were based on n^+–p structure and were fabricated from $\langle 100\rangle$ oriented, $1\,\Omega\,\text{cm}$ resistivity, p-type, Cz silicon wafers ($5\times5\,\text{cm}^2$ pseudo square, $350\,\mu\text{m}$ thick). Phosphorous was used to create an n^+–p junction on the front side. The wafers were textured in a hot NaOH solution prior to junction fabrication. The contacts were made by screen printing of Ag paste on the front and Ag/Al paste on the back sides of the cells followed by sintering at $\sim700\,^\circ\text{C}$ in dry air. Subsequently, an antireflection coating of PECVD silicon nitride was applied on the front side. Illuminated I–V characteristics of a few silicon solar cells were measured in 3rd and 4th quadrants at temperature varying from 295 to 320 K at an interval of 5 K to determine R_s and R_{sh} using the method given by Priyanka et al. [9]. The temperature of the tested solar cell was held uniform to within $\pm0.5\,^\circ\text{C}$. For all measurements reported in this work the illumination consisted of a simulated AM1.5 spectrum of $100\,\text{mW/cm}^2$ intensity. The intensity was varied only for measurement of V_{oc}–I_{sc} characteristics to determine the values of I_o and n at different temperatures [10]. I–V measurements are performed using a Keithley model 2400 Sourcemeter, having 0.012% basic accuracy with 5–1/2-digit resolution.

In the following we shall present the results of our measurement for two single crystalline silicon solar cells, viz. cell#1 and cell #2.

3.1. Measurement of series and shunt resistances

A number of methods are available in literature for measurement of series resistance of a silicon solar cell [12–15]. They assume R_s to be invariant with V_j and have a limitation in that they determine R_s using a certain small region of the I–V characteristics. In the present study we have used the method given by Priyanka et al. [9] as it enables determining R_s corresponding to different values of V_f and is applicable to whole region of I–V characteristics except a small portion near the open-circuit point. With this method [9] the values of R_s corresponding to maximum power point for cells #1 and #2 were obtained from the I–V characteristics of the cells in 3rd and 4th quadrant at different temperatures using the relation [9]

$$R_s = \frac{1}{I_f}\left(\left(\frac{nkT}{q}\right)\ln\left(\frac{I_r P - (V_r + V_f + I_f P)}{I_o(P - R_s)}\right) - V_f\right) \tag{18}$$

where $P = R_s + R_{sh}$.

In Eq. (18) V_f, I_f represent voltage and current in the 4th quadrant and V_r, I_r represent voltage and current in the 3rd quadrant of I–V characteristics of the cell plotted in the I–V graph. The value of I_o, n or I_{o1}, n_1 and I_{o2}, n_2 were obtained independently using I_{sc}–V_{oc} characteristics of the cell as described in detail elsewhere [9,10]. Henceforth we shall drop the suffix f and denote V_f by V.

4. Results and discussion

The plots of n, n_1 and n_2 with T are shown in Fig. 1. It can be noted that the rate of decrease of n_1 with T is very small compared with those of n and n_2 in the 295–320 K range. Similar dependence of n, n_1 and n_2 has been reported by earlier researchers also [5,10]. The values of R_{sh}, I_o, n, I_{o1}, n_1 and R_s^{CF} (corresponding to the maximum power point) obtained for cell #1 and #2 for the temperature range 295–320 K are given in Tables 1 and 2, respectively.

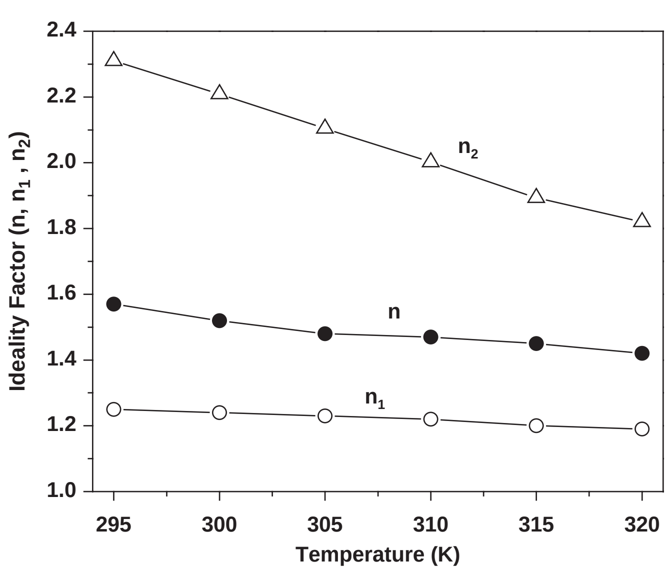

Fig. 1. Variation of ideality factors n, n_1, n_2 for cell #1 with temperature in the range 295–320 K.

Table 1
Experimental values of performance and diode parameters of cell #1 in the temperature range 295–320 K

T (K)	V_{oc} (V)	I_{sc} (A)	R_{sh} (Ω)	Single-exponential model			Double-exponential model	
				I_o (A) ($\times 10^{-7}$)	n	R_s^{CF} (Ω)	I_{o1} (A) ($\times 10^{-8}$)	n_1
295	0.593	0.555	425	1.80	1.57	0.063	3.69	1.25
300	0.582	0.557	407	2.02	1.52	0.059	5.76	1.24
305	0.571	0.558	393	2.74	1.48	0.055	8.09	1.23
310	0.561	0.560	378	3.92	1.47	0.052	11.8	1.21
315	0.549	0.562	364	5.93	1.45	0.047	19.9	1.20
320	0.538	0.563	350	7.62	1.42	0.043	30.4	1.19

Table 2
The values of performance and diode parameters of a silicon solar cell (cell #2) determined in 295–320 K temperature range

T (K)	V_{oc} (V)	I_{sc} (A)	R_{sh} (Ω)	Single-exponential model			Double-exponential model	
				I_o (A) ($\times 10^{-6}$)	n	R_s^{CF} (Ω)	I_{o1} (A) ($\times 10^{-7}$)	n_1
295	0.567	0.494	110	4.48	1.67	0.091	1.10	1.41
300	0.552	0.496	104	5.63	1.62	0.086	1.48	1.39
305	0.541	0.498	90	7.06	1.59	0.083	2.01	1.38
310	0.528	0.501	75	8.85	1.56	0.075	2.98	1.36
315	0.517	0.502	61	1.11	1.53	0.071	4.27	1.35
320	0.508	0.504	49	1.39	1.50	0.069	5.97	1.31

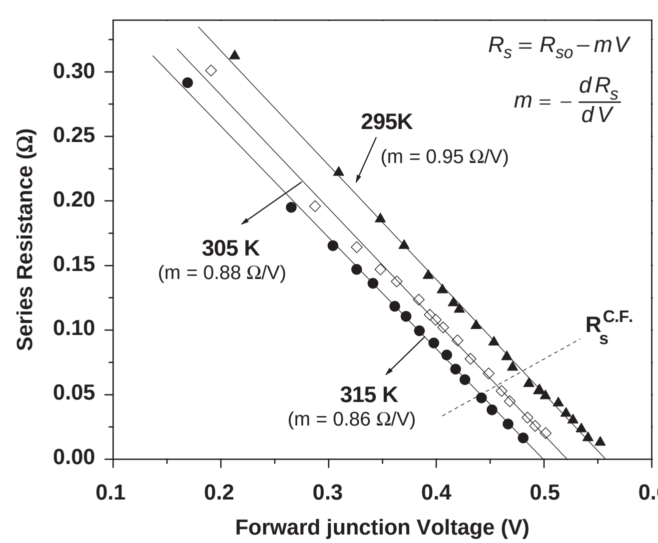

Fig. 2. Variation of R_s with forward junction voltage for the temperatures 295, 305 and 315 K for cell #1.

The values of I_o and n of Table 1 were used in Eq. (18) to determine the values of R_s for cell #1 at different V values for temperatures 295, 305 and 315 K. The dependence of R_s on V for cell #1 is shown in Fig. 2. It is clear from Fig. 2 that R_s decreases linearly with V and the rate of change of R_s with V (i.e. m) is less at a higher temperature. The dotted line delineates the values of R_s corresponding to maximum power point, i.e. V_m values, at different temperatures. The values of R_s corresponding to V_m are denoted as R_s^{CF} and have been listed in Table 1 along with R_s^{CF} for other temperatures in 295 K < T < 320 K range.

For cell #1 the plot of R_s^{CF} and R_{sh} with T normalized with respect to their values at 295 K are shown in Fig. 3. It can be noted that both R_s^{CF} and R_{sh} decrease with T nearly linearly. The rate of decrease of R_s with T is $\approx 0.78\,\mathrm{m\Omega/K}$. The rate of decrease of R_{sh} is $2.96\,\Omega/\mathrm{K}$ and is much larger in magnitude than decrease of R_s with T. The values of dR_s^{CF}/dT are governed by the decrease of both m and V_m with T.

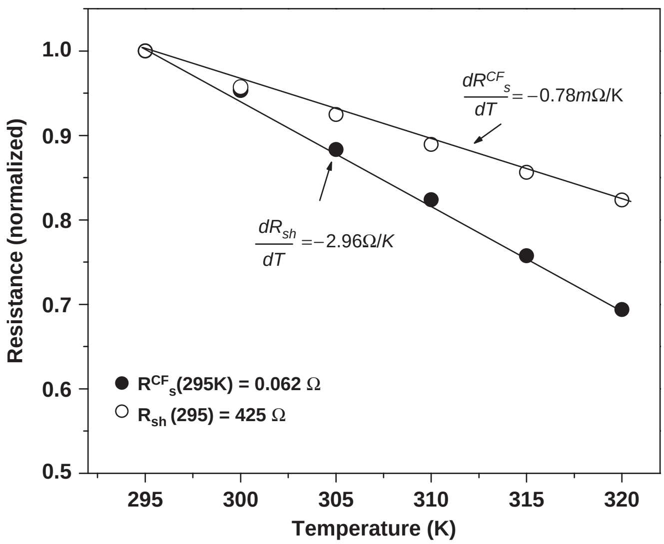

Fig. 3. Normalized plots of series (R_s) and shunt (R_{sh}) resistances for cell #1 with temperature in the range 295–320 K.

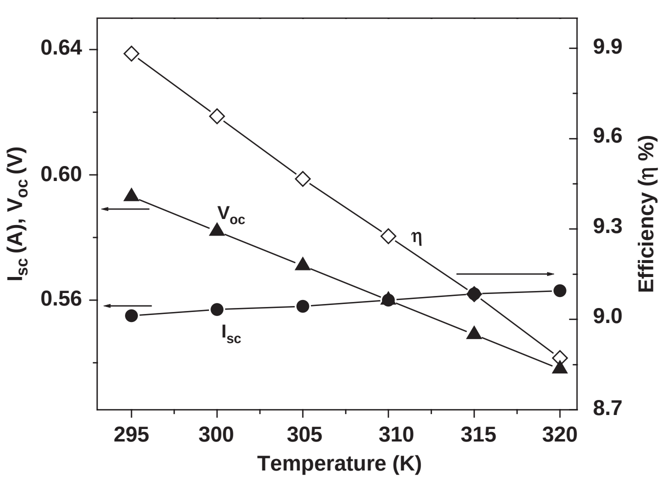

Fig. 4. Variation of V_{oc}, I_{sc} and efficiency (η) with temperature in the range 295–320 K .

The dependence of performance parameters, viz. I_{sc}, V_{oc} and η of cell #1 with temperature is shown in Fig. 4. The parameters V_{oc} and η decrease linearly with T. There is a small increase in I_{sc} with temperature, which can be attributed to the increased light absorption due to a decrease in the bandgap of silicon [7]. The decrease in η with temperature is mainly controlled by the decrease of V_{oc} and CF with T.

Theoretical values of dV_{oc}/dT were obtained in the temperature range 295–320 K cell #1 and #2 using Eq. (14) and the measured parameters V_{oc}, I_{sc}, R_{sh}, n_1 and I_{o1} for the two cases considering (i) R_{sh} to be finite and varying with T (i.e. the values of δ and r being finite), (ii) R_{sh} to be infinitely large and constant with T (i.e. $\delta = 0$, $r = 0$). The calculated values of dV_{oc}/dT for the two cases are listed in Table 3 for both the cells along with the experimental values. It can be noted from Table 3, that for cell #1, the theoretical values of dV_{oc}/dT are nearly equal for cases (i) and (ii) and vary from -2.07 to -2.10 mV/K with change in temperature from 295 to 320 K. For case (i) δ varies in the range $1.72\times10^{-4} < \delta < 2.06\times10^{-4}$ and $r = 2.96\,\Omega/\mathrm{K}$. The experimental value of dV_{oc}/dT is -2.2 mV/K. The difference in experimental and theoretical value of dV_{oc}/dT is highest ~(6)% at 295 K and is lowest ~(4.5)% at 320 K. Theoretical values indicate that in the case of cell #1 the effect of R_{sh} and its variation with T has no significant effect on dV_{oc}/dT. This is because the values of R_{sh} were large and r was small. The error in the measurement of V_{oc} and T are ~0.017% and ~1.3%, respectively, and this leads to an error of ~0.1% at 295 K and ~0.45% at 320 K in the measurement of dV_{oc}/dT.

Table 3 shows that for cell #2 the experimental value of dV_{oc}/dT is 2.3 mV/K and the calculated values of dV_{oc}/dT are not equal for cases (i) and (ii). For case (i) dV_{oc}/dT decreases from -2.17 to -2.26 mV/K and for case (ii) from -2.16 to -2.19 mV/K as temperature increases. Theoretical values of dV_{oc}/dT are close to the experimental value for case (i). The difference in experimental and theoretical value of dV_{oc}/dT for cell #2 for case (i) is highest (~6%) at 295 K and is lowest (~1.7%) at 320 K. This shows that it is important to consider the effects of R_{sh} (through δ) and temperature dependence of R_{sh} (through r) for a cell having low R_{sh} value and Eq. (14) can be utilized to get a reasonably accurate estimate of dV_{oc}/dT value.

The values of CF for cell #1 were calculated using Eq. (17) for R_{sh} values as given in Table 1 at different temperatures assuming R_s to vary with V linearly ($m>0$) and R_s to be constant with V ($m=0$) and plotted in Fig. 5. Curve CF_1 has been obtained for $R_s = R_s^{CF}$ with finite values of m, which were found to lie in $0.94 < m < 0.86\,\Omega/\mathrm{V}$ range, whereas curves CF_2 and CF_3 correspond to $m = 0$ for two fixed values of R_s. Curves CF_2 and CF_3 are for $R_s < R_s^{CF}$ and $R_s > R_s^{CF}$, respectively, in the temperature range

Table 3
Comparison of experimental values of dV_{oc}/dT of cells #1 and #2 for 295–320 K temperature range with the theoretical values determined using Eq. (15) for case (i) considering $\delta>0$, $\beta>0$ and case (ii) $\delta=0$, $\beta=0$

T (K)	Cell #1				Cell #2			
	$\delta\times10^{-4}$	dV_{oc}/dT (mV/K)			$\delta\times10^{-3}$	dV_{oc}/dT (mV/K)		
		Case (i) ($\delta>0$ and $r=2.96\,\Omega$/K)	Case (ii) ($\delta=0$ and $r=0$)	Expt.		Case (i) ($\delta>0$ and $r=2.65\,\Omega$/K)	Case (ii) ($\delta=0$ and $r=0$)	Expt.
295	1.72	−2.07	−2.08		0.95	−2.17	−2.16	
300	1.79	−2.08	−2.08		0.96	−2.19	−2.18	
305	1.85	−2.08	−2.09	−2.2	1.07	−2.20	−2.18	−2.3
310	1.92	−2.09	−2.09		1.25	−2.22	−2.19	
315	1.99	−2.09	−2.09		1.51	−2.23	−2.19	
320	2.06	−2.10	−2.10		1.89	−2.26	−2.19	

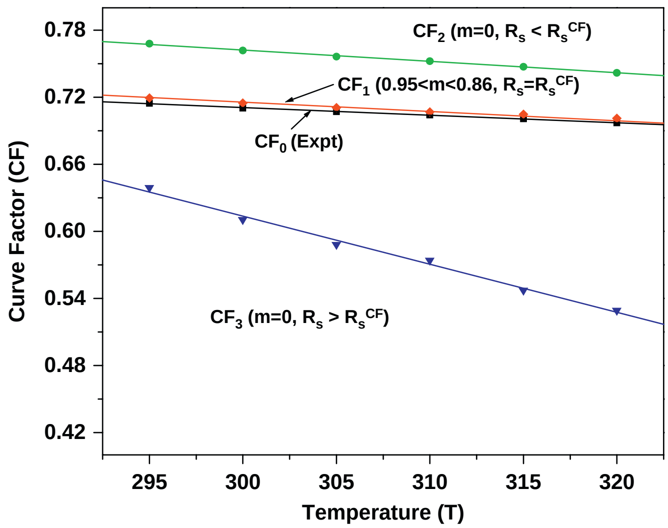

Fig. 5. Variation of CF with temperature in the range 295–320 K. CF_0 is the experimental curve factor and CF_1, CF_2, CF_3 are theoretical curves. Curve CF_1 is for $0.94<m<0.86\,\Omega/\mathrm{K}$ and $R_s = R_s^{CF}$. Curves CF_2 and CF_3 are for $R_s<R_s^{CF}$ and $R_s>R_s^{CF}$, respectively, in the temperature range 295–320 K.

295–320 K. It is noted that curve CF_1 is closest to the experimental curve (CF_0) and matches well in the entire temperature range. The curve CF_2 lies above the CF_0 because $R_s<R_s^{CF}$ and CF_3 curves lie below the CF_0 curve as $R_s>R_s^{CF}$. This behavior can be understood well with the help of Fig. 6 that shows three theoretical I–V curves #1–3 and the experimental curve (Expt.) for $T = 295$ K. Curve #1 has been generated for variation of R_s with V such that $m = 0.95$ whereas curves #2 and 3 are for $m = 0$, $R_s = 0.038\,\Omega$ and $m = 0$, $R_s = 0.201\,\Omega$, respectively. Curve #2 shows better I–V characteristics than the experimental curve (Expt.) whereas CF_3 shows inferior I–V characteristics than the experimental curve. On the other hand curve#1 matches fairly well with the experimental curve at all points except in a small region near the maximum power point. The deviation in the CF_1 and CF_0 curves of Fig. 5 is attributed to this small deviation between the curve#1 and the experimental curve of Fig. 6. From Table 4 it is clear that the magnitude of the deviation between CF_1 and CF_0 is $<0.7\%$ whereas between CF_2 and CF_0 is $>7\%$ and between CF_3 and CF_0 is $>23\%$. It is also noted that the rate of decrease of CF with T for curves CF_2 and CF_3 which ignore the dependence of R_s on V is higher than observed experimentally. This shows that it is very important to take the dependence of R_s on voltage into account to determine CF accurately.

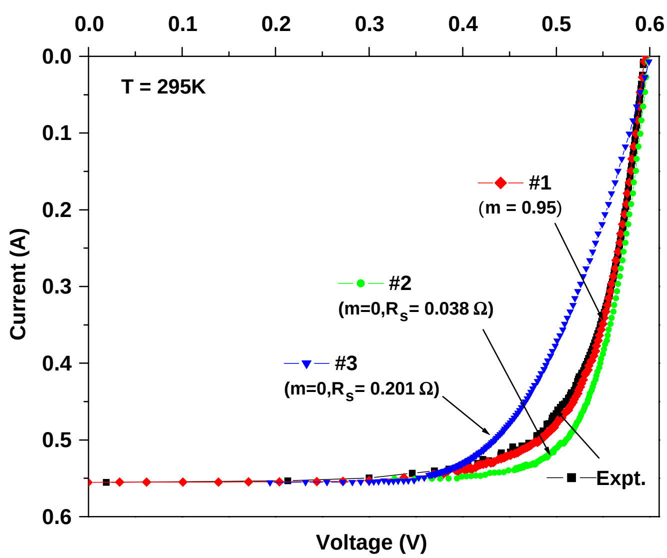

Fig. 6. Experimental and theoretical I–V curves at $T = 295$ K. Theoretical curves are marked as #1–3. Curve #1 is for variation of R_s with V such that $m = 0.95$ whereas curves #2 and 3 are for $m = 0$, $R_s = 0.038\,\Omega$ and $m = 0$, $R_s = 0.201\,\Omega$, respectively.

5. Conclusion

The temperature dependence of V_{oc} and CF of a silicon solar cell has been investigated in temperature range 295–320 K. Rate of decrease of dV_{oc}/dT is controlled not only by the value of E_g and its decrease with T but also by the value of R_{sh} and its temperature dependence. R_{sh} has been found to decrease with T nearly linearly. The rate of decrease of V_{oc} with T can be determined using Eq. (14). The value of series resistance of cell R_s depends on V and changes with V linearly. The values of R_s obtained corresponding to maximum power point also decreases linearly with temperature. Besides R_s and the other parameters, the dependence of R_s on voltage also has a significant effect on CF.

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Table 4
Comparison of values of curve factor CF_1, CF_2 and CF_3 of Fig. 4 which were obtained in the temperature range $295<T<320$ K using Eq. (17)

T (K)	CF_0 (Expt.)	m	CF_1		CF_2		CF_3	
			(a) (when $m\neq 0$)	Er_1 (%)	(when $m = 0$, $R_s<R_s^{CF}$)	Er_2 (%)	(when $m = 0$ $R_s>R_s^{CF}$)	Er_3 (%)
295	0.714	0.95	0.719	+0.67	0.768	+7.4	0.639	−10.5
300	0.710	0.94	0.715	+0.64	0.762	+7.25	0.610	−14.0
305	0.707	0.88	0.711	+0.51	0.756	+6.9	0.588	−16.8
310	0.704	0.87	0.707	+0.39	0.752	+6.8	0.574	−18.4
315	0.701	0.86	0.705	+0.57	0.747	+6.6	0.547	−21.9
320	0.697	0.90	0.701	+0.59	0.742	+6.4	0.529	−24.0

CF_1 is for $0.94<m<0.86\,\Omega/\mathrm{K}$ and $R_s = R_s^{CF}$, CF_2 and CF_3 are for $R_s<R_s^{CF}$ and $R_s>R_s^{CF}$, respectively, in the temperature range 295–320 K. CF_0 is the experimental curve.

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