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The temperature dependence of the spectral and efficiency behavior of Si solar cell under low concentrated solar radiation

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Abstract

Relative spectral response of monocrystalline silicon solar cell is measured at different cell temperatures. At room temperature, the spectral response is found to have its maximum peak in the infrared (IR) range (800–1100 nm). By increasing the cell temperature, modification in the shape of the spectral response is observed and a shift of the peak towards the IR part of the spectrum is found. This behavior is of special importance that the temperature of highly illuminated thin film coated solar cells will be elevated. Other cell parameters as maximum power, fill factor, and cell efficiency are also studied at five illumination levels, viz., 1154, 1329, 1740, 2812, and 4010 W/m^2 and temperature ranging from −3 to 90°C. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction and theory

Photovoltaic cells illuminated with low concentrator systems around 5 suns (about 4000 W/m^2) find increasing interest. This is because of the low cost of static concentrators (parabolic, V-trough, etc.) which do not need any subsystem

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(cooling and tracking subsystems) and thus, they are illuminated with diffuse and direct sun light [1]. They also give the possibility of using the one-sun solar cells. Cell temperatures inside these concentrators are about 20–30°C above ambient temperature, especially in hot desert areas [2,3]. Therefore, spectral and efficiency variation with temperature must be studied well before attempting to use such systems.

Spectral responsivity systems measure how a device responds to selected narrow (spectral) bands of irradiance. Responsivity is reported in terms of quantum efficiency (QE) — a measure of how efficiently a device converts incoming photons to charge carriers in an external circuit.

Measurement of the wavelength dependence of the photocurrent — the spectral response of the solar cell, is a valuable tool for evaluating the material and device characteristic of solar cells [4].

The main reason to measure the spectral response is to use it as a tool to understand the performance of the solar cell. For example, the red response is governed by the minority carrier lifetime in the base or p^--region. The blue response depends on the charge collection from the emitter or n^+-region, which in turn depends upon the surface recombination velocity and junction depth. By appropriate modeling and curve fitting of the spectral response data, values of the various important cell parameters can be evaluated [5]. Previous studies [2] showed that using the polycrystalline type of solar cells in the V-trough concentrator has less current gain in comparison with the amorphous type. This is because of the mismatch between the spectral reflectivity of the commercial mirrors that are coated with aluminum and the spectral response of the polycrystalline solar cell, which is considered another proof of the importance of the solar cell's spectral response analysis.

The efficiency of photovoltaic energy conversion is defined as the ratio of the maximum electrical power output to the incoming radiation. It essentially defines the economy of converter systems.

Maximum electrical power output is achieved under optimum operating conditions as [6]:

$$\mathrm{MPP} = \mathrm{FF} \cdot I_{\mathrm{sc}} \cdot V_{\mathrm{oc}}$$

where FF is the fill factor.

The short circuit current I_{sc} is directly proportional to the effective radiation and can be expressed as:

$$I_{\mathrm{sc}} = q \cdot \int_{v=E_g/h}^{\infty} p_v \cdot Q_v \, \mathrm{d}v$$

where q is the electronic charge, p_v the spectral distribution function of incoming radiation and Q_v the collection efficiency of minority charge carriers.

The open circuit voltage V_{oc} is related to I_{sc} by

$$V_{cc} = \frac{A \cdot k \cdot T}{q} \cdot \ln\left(\frac{I_{sc}}{I_{sp}} + 1\right)$$

The efficiency, therefore, can be expressed by

$$\eta = \frac{FF \cdot V_{\infty} \cdot q \cdot \int_{v=E_g/h}^{\infty} P_v \cdot Q_v \, dv}{\int_{v=0}^{\infty} P_v \, dv}$$

Therefore, the behavior of the spectral response of the cell allows a better modeling and calculation of the cell parameters and efficiency.

In addition, spectral response measurements are equally important in performance measurements and calibration. Spectral response data can be used to directly compute the short circuit current of a solar cell by folding the spectral response with the solar irradiance, according to the preceding equation of I_{sc}.

Also, the temperature is a parameter that has direct influence on the cell performance. Temperature coefficients provide the change (derivative) of different photovoltaic performance parameters with respect to the temperature. The coefficients can be determined for short circuit current (I_{sc}), open circuit voltage (V_{oc}), and maximum power point (I_m, V_m), as well as fill factor (FF) and efficiency (η) [7].

2. Experimental setup and measurements

The experimental setup used, as shown in Fig. 1, consists of:

1. 1000 W_e halogen lamp to produce variable illumination up to about 15 kW/m^2 over the cell under test.
2. Cell temperature-controller with a large serpentine of brass connected to a closed-path water circulator (Polyscience) to control the cell temperature from -20 to 120°C.
3. 32 metallic interference filters (Karl–Zeiss) for spectral response (SR) measurements. These are narrow band filters from 350 to 1100 nm with spacing of 25 nm.
4. Data acquisition system (DAS) with word length 16 bit, connected to a computer for fast *I–V* characteristic curve scan, and determination of cell parameters.

The measurements were carried out on a conventional square shaped Si monocrystalline solar cell of length 1.8 cm.

The incident irradiance measurement on the solar cell in both the spectral response measurements and the I–V measurements is done by a calibrated thermopile type pyrometer (Kipp and Zonen). This is characterized by its nearly constant spectral response (spectral selectivity = ±5% in the range 350–1500 nm), to make it a good and precise tool to measure the irradiance.

The temperature dependence of the relative spectral response of the solar cell is measured by placing it on a temperature-controlled mount, irradiating it uniformly from the monochromatic source, and measuring the short circuit current, the open circuit voltage, and the irradiance at fixed wavelength intervals over the spectral range of interest. The cell temperature was fixed at 5, 23, 45, 66 and 83°C, respectively. The power spectral response (not the maximum power spectral response, as it is experimentally difficult to calculate FF from the I–V curve at certain wavelength) is then calculated by multiplying the spectral responses of short circuit current by the open circuit voltage spectral response.

The I–V curves were recorded for each cell temperature and various values of the illumination level, viz., 1154, 1329, 1740, 2812, and 4020 W/m^2 by converting the current to voltage and simultaneously recording both cell voltage and cell current-converted voltage through two channels in the DAS. The cell temperature was varied from −3 to 90°C.

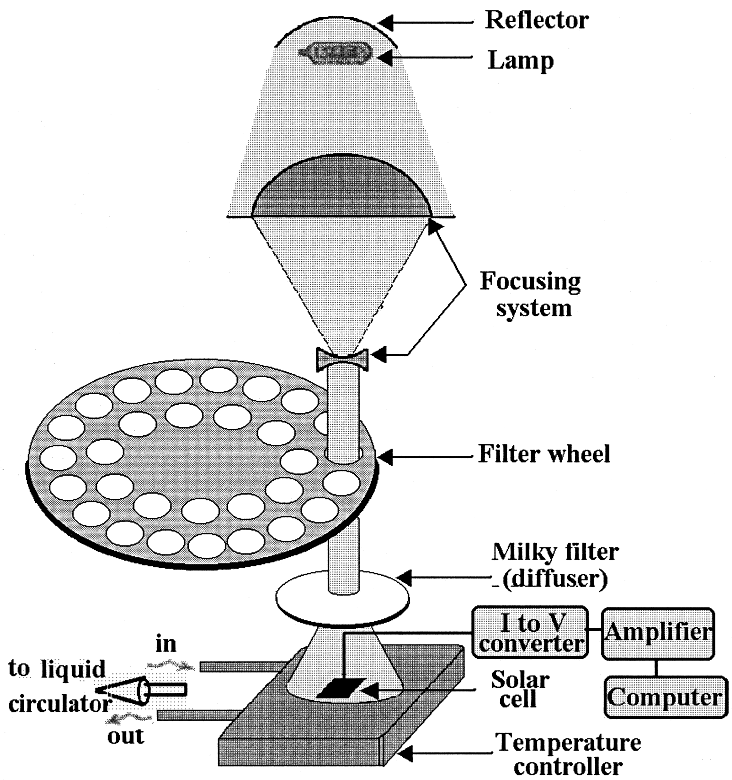

Fig. 1. Experimental setup for SR measurement.

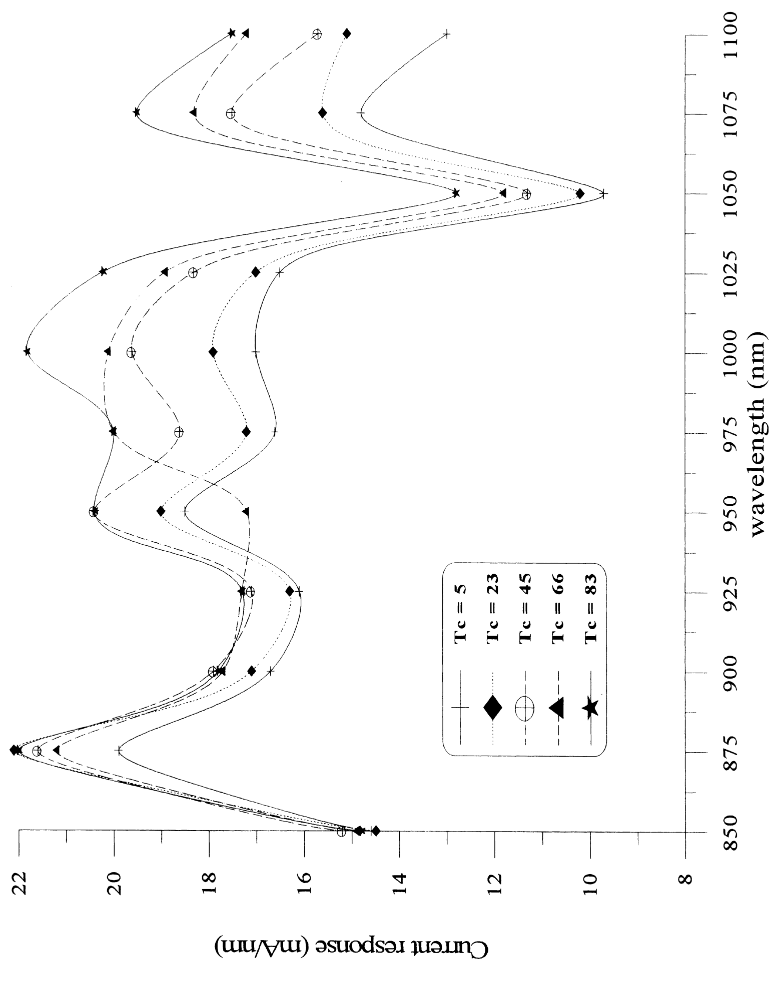

Fig. 2. Spectral response of the solar cell short-circuit current at five cell temperatures 5, 23, 45, 66, and 83°C.

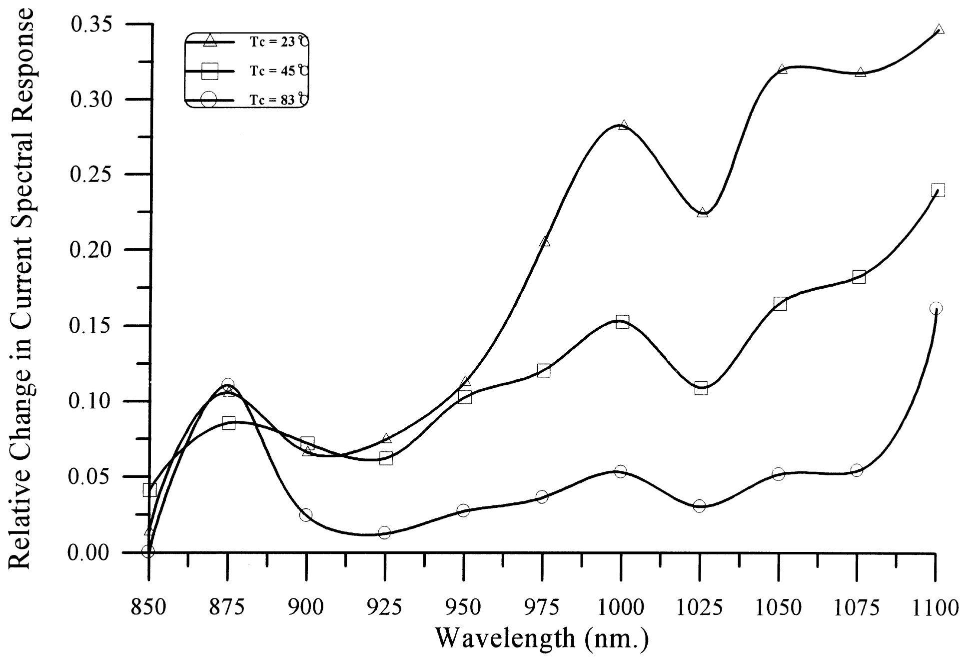

Fig. 3. Percent of change of current spectral response.

3. Results and discussion

3.1. Spectral response measurements

Increasing the temperature of the cell modulates the spectral response of the solar cell. This resembles the current response represented in Fig. 2; only the region of interest of the spectrum is shown. A shift of the peak in the infrared (IR) range from $\lambda = 950$ nm at temperature $T_c = 5°C$ to $\lambda = 1000$ nm at $T_c = 83°C$ is observed. This is because the elevation of the cell temperature makes the electrons require less photon energy, causing a shift in the spectral response towards the longer wavelengths.

This shift is of considerable importance especially in case of optical coating of the cell surface, provided that the operating temperature of the uncoated cell is known. Iterative procedures could be done in order to optimize the cell temperature with the actual transmitted spectrum.

The percentage of change of the current (or power) spectral response with temperature relative to the spectral response at $T_c = 5°C$ is calculated by subtracting the current (or power) spectral response at $T_c = 5°C$ from the current (or power) spectral response at this temperature, and then dividing the obtained result by the current (or power) spectral response at $T_c = 5°C$.

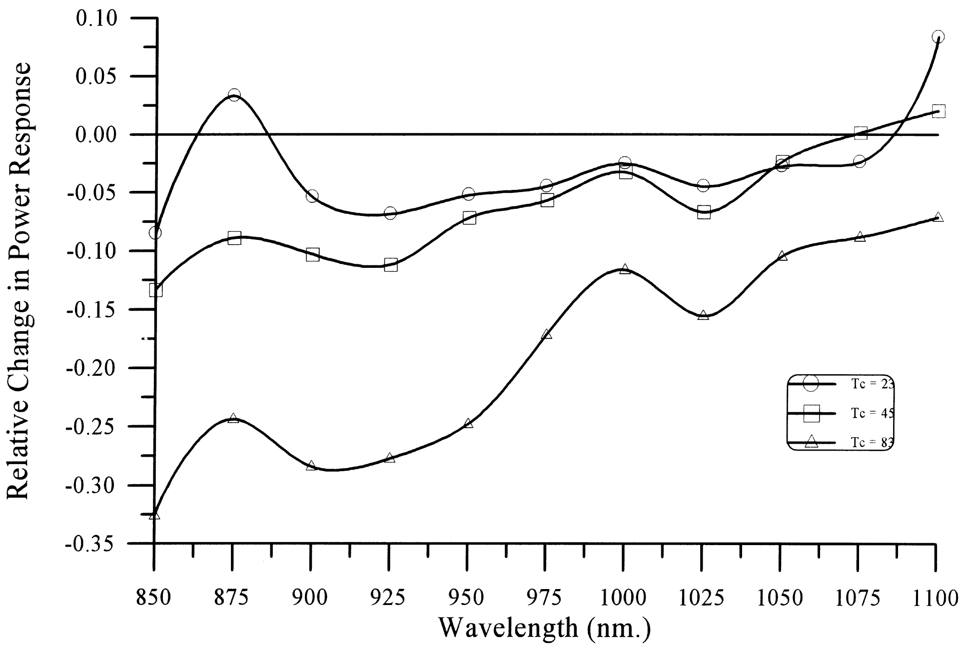

Fig. 4. Percent of change of power spectral response.

Fig. 3 shows the percentage of change of the current response. At $\lambda = 875$ nm, the percentage of change is nearly equal for the three curves corresponding to the three temperatures. Changes in relative spectral response increase towards the IR part of the spectrum; it is about 17% at $T_c = 23°C$, whereas it is about 35% at $T_c = 83°C$.

Fig. 4 shows the percentage of change of the power spectral response, which is the result of multiplying the short circuit current and the open circuit voltage spectral responses at the measuring temperature, and then dividing by the power spectral response of the cell at $T_c = 5°C$. The figure shows an increase of the percentage of change of the power spectral response with decreasing the temperature.

All the three curves represented in this figure have negative values, except the

Table 1
Change of the short circuit current and the maximum power with the temperature at different illumination levels

	1154 W/m^2	1329 W/m^2	1740 W/m^2	2812 W/m^2	4010 W/m^2
dI_{sc}/dT_c	0.063	0.055	0.194	−0.54	−1.8
d(m.p.)/dT_c	−0.11	−0.16	−0.43	−0.53	−1.01

curve for $T_c = 23°C$ at wavelength 875 nm, and also at the IR edge. This indicates that operating at cell temperature $T_c = 23°C$ for the wavelength 875 nm is optimum since its variation with the temperature is positive, a result that agrees with [8].

3.2. Short circuit current and open circuit voltage

The experimental results show, as seen in Fig. 5, that the short circuit current increases slightly for low illumination levels as the back cell temperature increases. For high illumination levels, the short circuit current shows a drastic decrease with increase in the temperature. This behavior is due to high temperature to a short circuit current less dependent on the illumination level. This behavior is seen for low illumination levels due to the increase in generation of electronhole pairs by thermal energy. In higher illumination levels like 2812 and 4010 W/m^2, the illustrated behavior is due to the increase in the series resistance of the cell and cables. Table 1 shows the change of the short circuit current with the temperature (dI_{sc}/dT_c) at different illumination levels. The obtained results are positive for the first three illumination levels and negative for the higher illumination levels.

Fig. 6 shows the variation of I_{sc} by increasing the illumination levels with the back cell temperature as a parameter. It shows that at $T_c = 0°C$, the increase is

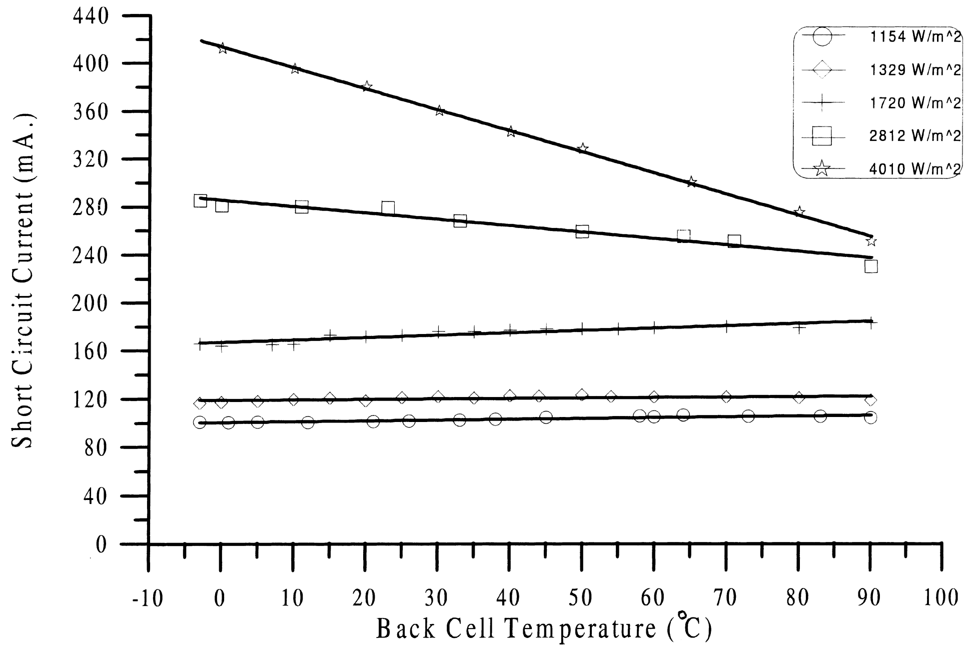

Fig. 5. Variation of short-circuit current as a function of back cell temperature at different illuminations.

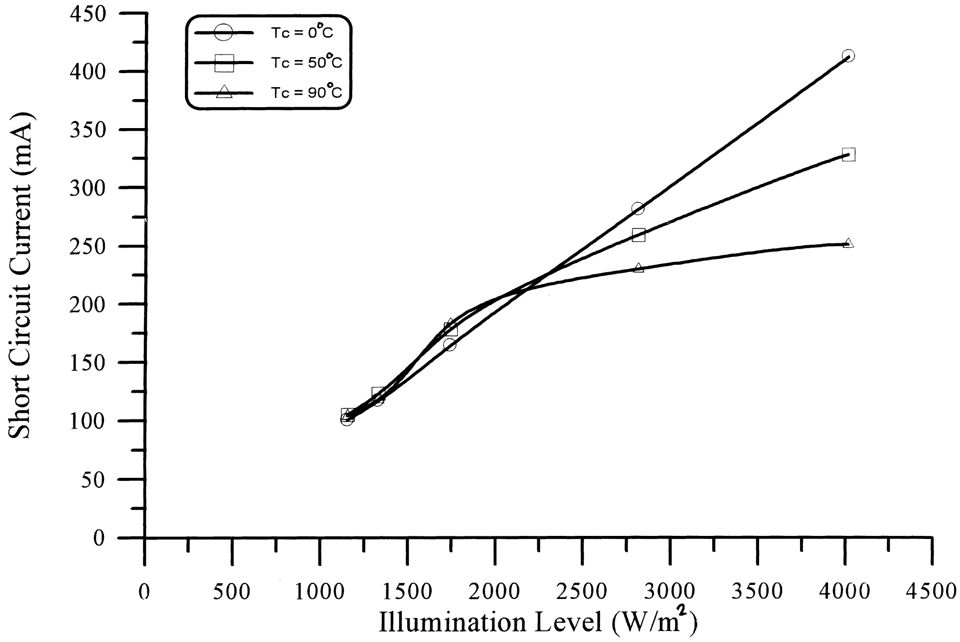

Fig. 6. Variation of short-circuit current with increasing illumination at different cell temperatures.

linear, whereas at T_c = 90°C, saturation is seen due to the increase of the series resistance of the cell.

Fig. 7 shows the decrease of the open circuit voltage V_{oc} for different illumination levels with increasing the back cell temperature.

3.3. Maximum power (m.p.) and efficiency

Fig. 8 show that the m.p. generally decreases linearly with the temperature of the cell at constant illumination. The change of the m.p. with respect to cell temperature is high for higher illumination levels.

From the figure, it can be seen that by using illumination of 4010 W/m^2 at 90°C temperature, electric gain will be about 8% relative to the illumination of 2812 W/m^2 at the same temperature. This indicates that there is no need for high illumination levels when working in very hot climates.

Table 1 shows the change of m.p. with the temperature (d(m.p.)/dT_c) at different illumination levels.

Maximum power variation with illumination levels at three temperature values 0, 50, and 90°C is shown in Fig. 9. The solar cell delivers about 150 mW at T_c = 0°C, about 95 mW at T_c = 50°C, and about 55 mW at T_c = 90°C. At 0°C, the maximum power is increasing linearly with illumination; while at very high

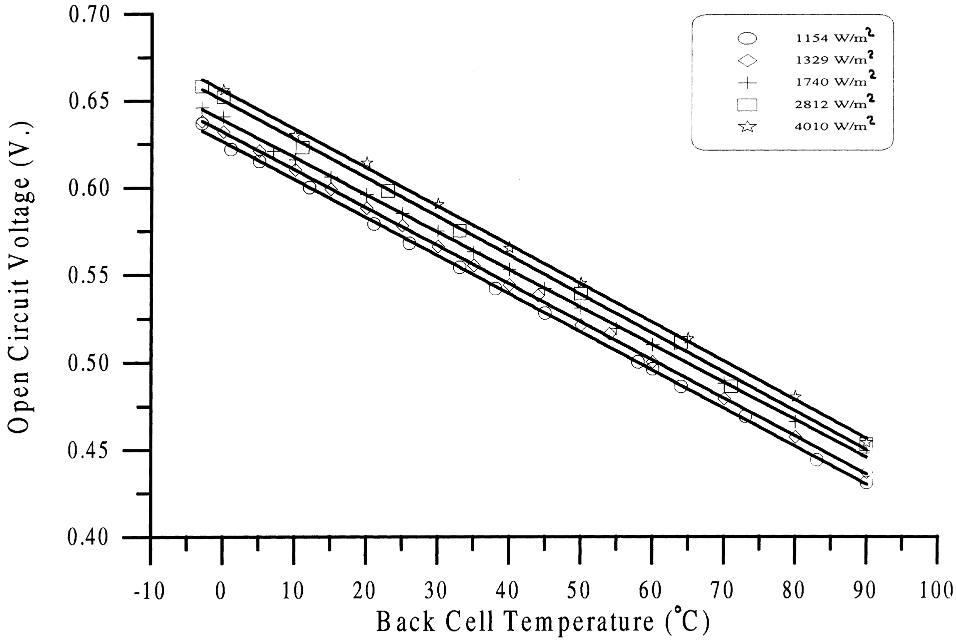

Fig. 7. Variation of open circuit voltage with increasing illumination at different cell temperatures.

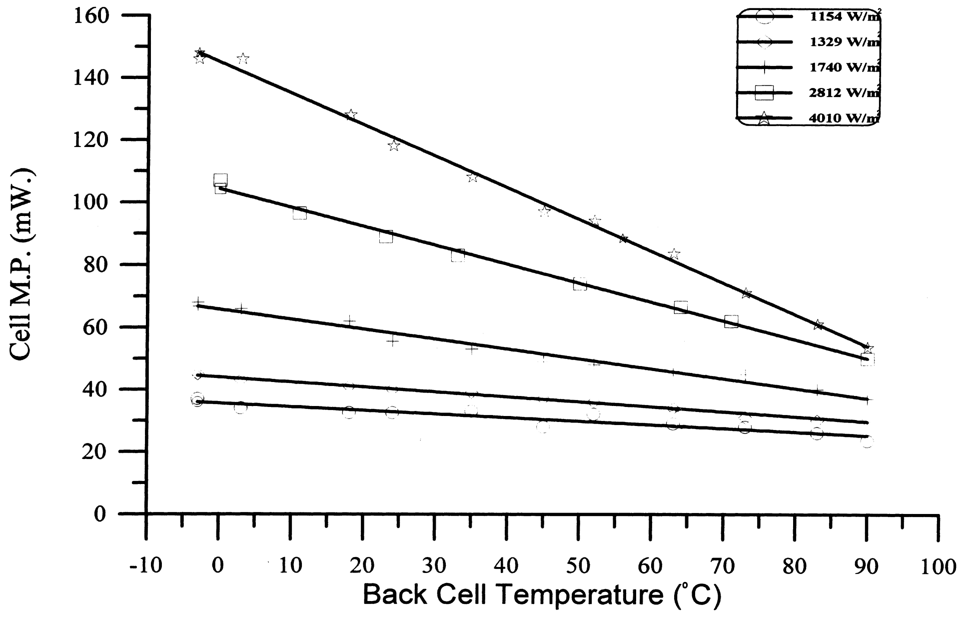

Fig. 8. Cell's m.p. decrease with temperature at different illumination levels.

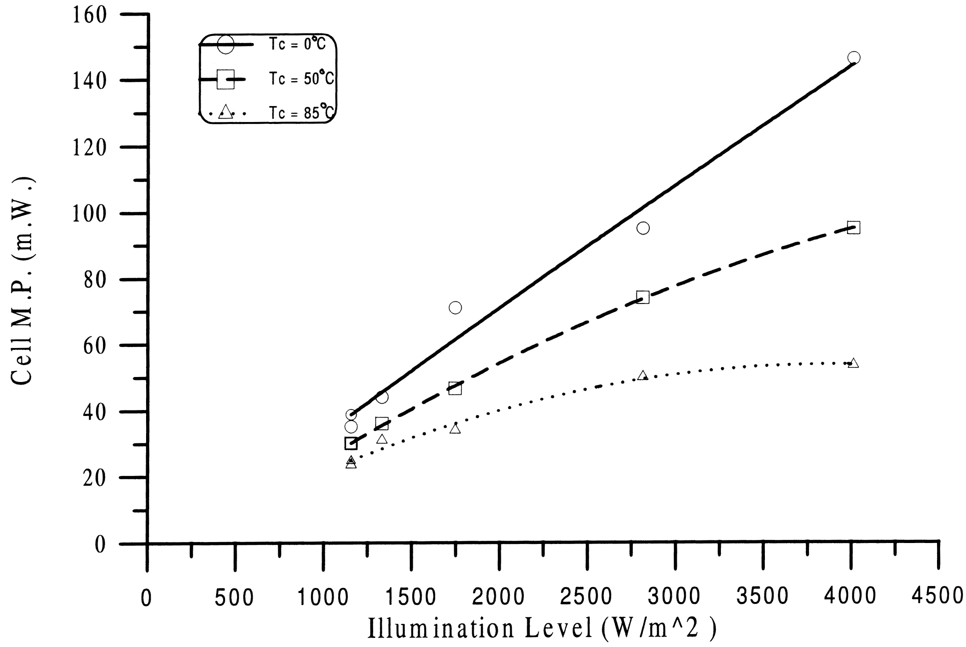

Fig. 9. Maximum power variation of the cell with illumination levels at three cell temperatures.

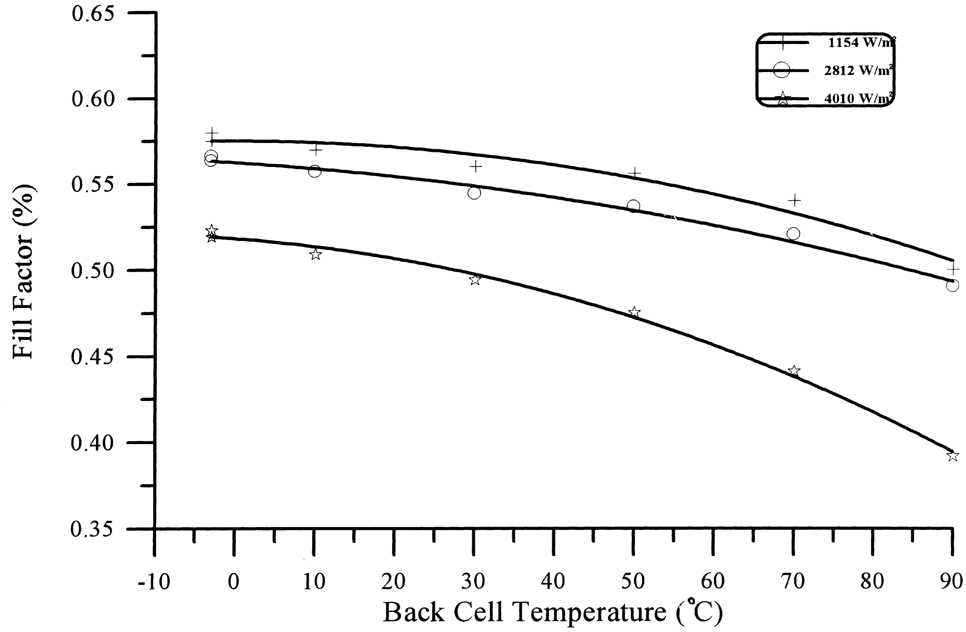

Fig. 10. Variation of fill factor with cell temperature at different illuminations.

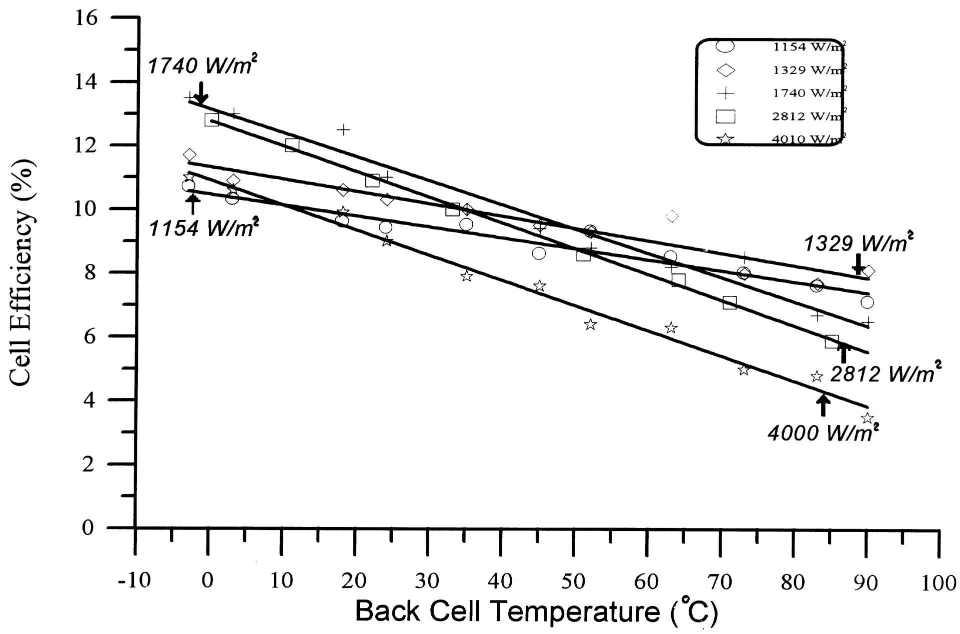

Fig. 11. Efficiency behavior of the cell with its temperature at five illumunations.

temperature (90°C), saturation is shown with nearly no power gain after 4000 W/m^2.

Fig. 10 shows the fill factor as a function of the back cell temperature at different illumination levels. It is high at low illumination level and back cell temperature and decreases by increasing both illumination and cell temperature. This can be attributed to the effect of the increase of the series resistance of the cell as the temperature and/or illumination increases.

Fig. 11 gives the variation of the cell efficiency as a function of the back cell temperature. From the figure, it is evident that while its value decreases with increasing the cell temperature, its slope increases with increasing the illumination levels leading to the crossing in the curves with low illumination levels. The variation of the cell efficiency with increasing illumination levels for different cell temperatures is shown in Fig. 12. At low cell temperatures such as $T_c = 3$°C, maximum efficiency lies around 1700 W/m^2; whereas it lies around 1300 W/m^2 for higher cell temperatures.

4. Conclusion

Solar cell's spectral response is found to be temperature dependent. Changes of the relative spectral response are found in the IR part of the spectrum. It could be

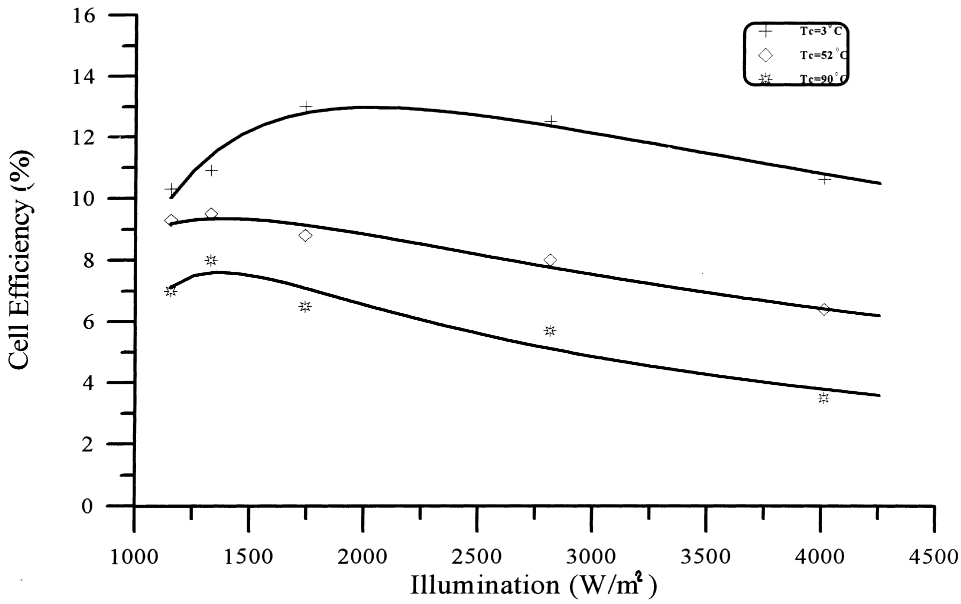

Fig. 12. Cell efficiency variation with increasing illumination at three temperatures.

of special importance for thin film coating researches, especially the response at wavelength 875 nm and cell temperature $T_c = 23°C$ at which the percentage of change of power spectral response is positive.

Also high illumination is applied on a one-sun Si solar cell, and its behavior is tested. One-sun solar cells can be used in soft concentrators depending on the cell's temperature. At high temperatures, high illumination is of no use in the cell unless some type of cooling is used. At high temperature and illumination value, the cell has its lowest value of efficiency. Therefore, the likely optimum concentration ratio is around 4 × or about 3000 W/m^2.

Therefore, local modeling and test of each field should be done in order to determine the most appropriate illumination level and its accompanied cell temperature.

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