Experimental Assessment of Temperature Coefficient Theories for Silicon Solar Cells

Olivier Dupré, Rodolphe Vaillon, and Martin A. Green

***Abstract*—This article reports on experimental measurements aimed at assessing general theoretical expressions of temperature coefficients in the case of crystalline silicon solar cells. The relevance of a recently proposed relation between the temperature dependence of the open-circuit voltage and the external radiative efficiency of photovoltaic (PV) devices is demonstrated. It is also shown that the cells made of indirect bandgap semiconductors with insufficient light trapping have unusual temperature sensitivities of short-circuit current and open-circuit voltage. In addition, explanations for the observed discrepancies between the predicted and measured temperature coefficients of fill factors are suggested.**

***Index Terms*—Measurement, photovoltaic (PV) cells, silicon, temperature dependence.**

I. Introduction

It is well known that temperature negatively affects the performances of photovoltaic (PV) devices [1], [2]. This is inconvenient because most of the solar energy that is not converted into electricity turns into heat and causes PV systems to operate at temperatures that can be significantly higher than the ambient. Temperature coefficients (TCs), which quantify temperature sensitivities, are also important parameters for predicting PV energy production.

The temperature dependencies of solar cell parameters have been substantially investigated (e.g., [1]–[8] and references therein). However, because of the use of one or several semi-empirical parameters, some of the conclusions lacked of generality. More recently, Green then Dupré *et al.* investigated theoretically the TCs on the basis of internal device physics [9], [10]. This article reports on experimental measurements that are aimed at assessing the theories described in these previous works in the case of crystalline silicon (c-Si) solar cells.

First, the theoretical formulations of the TCs of the important cell parameters are briefly introduced. Then, the experimental measurements are presented. Finally, an analysis highlights important facts derived from the comparison between theory, measurements, and data from the literature.

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II. Theory

The TC of the maximum output power of a solar cell can be split into three additive components, namely, open-circuit voltage $V_{\rm oc}$, short-circuit current density $J_{\rm sc}$, and fill factor FF TCs. This separation is particularly interesting for understanding the underlying physics because these TCs depend on different loss mechanisms [10]. For example, the variations of series and shunt resistances affect mostly the TC of the FF.

The concept of the external radiative efficiency (ERE) is useful to evaluate how good a PV device is, compared with its performance in the radiative limit. ERE corresponds to the fraction of the total dark current recombination that results in radiative emission from the cell. Using Rau's reciprocity relation between PV quantum efficiency and electroluminescent emission of solar cells, one can write the ERE at open circuit as [11]

$$\mathrm{ERE}_{\rm oc} = \frac{1}{J_{\rm sc}} q \frac{2\pi}{c^2 h^3} \int_0^\infty \frac{\mathrm{EQE}_{\rm norm}\ E^2}{e^{\frac{E - qV_{\rm oc}}{kT_c}} - 1} dE \qquad (1)$$

where q is the electric elementary charge, $\mathrm{EQE}_{\rm norm}$ is the external quantum efficiency at normal incidence, T_c is the cell temperature, c is the speed of light in vacuum, and h and k are the Planck's and Boltzmann's constants, respectively. In the definition of the ERE in [11], the angularly weighted value of the EQE is used, but it is close to the near perpendicular value commonly measured [$\mathrm{EQE}_{\rm norm}$ in (1)] for textured solar cells. Thus, the ERE at open-circuit voltage can be experimentally determined at any given operating temperature T_c from measuring $J_{\rm sc}$, $V_{\rm oc}$, and the EQE at normal incidence (which all depend on temperature).

The authors proposed a general relationship between the $\mathrm{ERE}_{\rm oc}$ and the TC of the open-circuit voltage [10] as follows

$$\begin{aligned} V_{\rm oc} &= \frac{kT_c}{q} \ln\left(\frac{X\, J_{\rm sc,1sun}}{(1/\mathrm{ERE}_{\rm oc})\, J_{0,\rm rad}}\right) \\ &= V_{\rm oc,1sun} + \frac{kT_c}{q}\left(\ln(\mathrm{ERE}_{\rm oc}) + \ln(X)\right) \end{aligned} \qquad (2)$$

$$\beta_{V_{\rm oc}} = \frac{1}{V_{\rm oc}} \frac{dV_{\rm oc}}{dT_c} = -\frac{1}{V_{\rm oc}} \frac{\frac{E_{g0}}{q} - V_{\rm oc} + \gamma \frac{kT_c}{q}}{T_c} \qquad (3)$$

$$\gamma = 1 - \frac{d\ln \mathrm{ERE}_{\rm oc}}{d\ln T_c} + \left(2\frac{d\ln E_g}{d\ln T_c} - \frac{d\ln J_{\rm sc}}{d\ln T_c}\right) \qquad (4)$$

where E_{g0} is the semiconductor bandgap linearly extrapolated to 0 K, X is the concentration factor, and $J_{0,\rm rad}$ is the dark current density in the radiative limit. For c-Si, $E_{g0} = 1.206$ eV and $dE_g/dT = -0.273$ meV·K^{-1} in the temperature range of interest [12].

For the TC of the short-circuit current, it can be written as [9]

$$\beta_{J_{\rm sc}} = \frac{1}{J_{\rm sc}}\frac{dJ_{\rm sc}}{dT_c} = \frac{1}{J_{\rm sc,1sun}}\frac{dJ_{\rm sc,1sun}}{dE_g}\frac{dE_g}{dT_c} + \frac{1}{f_c}\frac{df_c}{dT_c} \quad (5)$$

where $J_{\rm sc,1sun}$ is the ideal current and f_c is the collection fraction. The collection fraction is the fraction of potentially useful photons $(E \geq E_g)$ that excites a carrier that gets collected in short circuit. It accounts for optical losses, such as reflection, insufficient or parasitic absorption, as well as electrical losses such as surface recombination. It can be expressed as

$$f_c(T) = \frac{J_{\rm sc}(T)}{J_{\rm sc,1sun}(T)} = \frac{q\int_0^\infty {\rm EQE}(E)\,{\rm PFD}\,(E)\,dE}{q\int_{E_g(T_c)}^\infty {\rm PFD}\,(E)\,dE} \quad (6)$$

where PFD is the incoming photon flux density.

When formulating the FF TC, the transport losses are taken into account through the variations of the series resistance with temperature in the following expression [5]

$$\frac{1}{\rm FF}\frac{d{\rm FF}}{dT_c} = (1 - 1.02\,{\rm FF}_0)\left(\frac{1}{V_{\rm oc}}\frac{dV_{\rm oc}}{dT_c} - \frac{1}{T_c}\right) - \frac{R_s}{V_{\rm oc}/I_{\rm sc} - R_s}\left(\frac{1}{R_s}\frac{dR_s}{dT_c}\right) \quad (7)$$

$${\rm FF}_0 = \frac{v_{\rm oc} - \ln(v_{\rm oc} + 0.72)}{v_{\rm oc} + 1}, \text{ with } v_{\rm oc} = \frac{q}{n\,k\,T_c}V_{\rm oc} \quad (8)$$

where $\rm FF_0$ and *n* are the ideal FF and the ideality factor, respectively.

In the following, these TC formulations are assessed experimentally in the case of c-Si solar cells.

III. Experimental Study

Six 4-cm^2 square cells fabricated from $\langle 1\ 0\ 0 \rangle$ oriented 1-Ω·cm p-type float zone silicon wafers with different thicknesses (200, 380, and 450 μm) were experimentally studied at the Australian Centre for Advanced Photovoltaics. All these cells are textured with inverted pyramids. They are passivated with a thin SiO_2 layer (≈20 nm) and have a double layer antireflection coating (ZnS and MgF_2). The active areas and localized heavy doped areas under the front and rear contacts have sheet resistivities of about 150–200 and about 20 Ω/square, respectively. The heavy Phosphorous diffused area covers about 3% of the active area, and the front contacts are made of stacks of Ti/Pd/Ag. The heavy Boron diffused area covers around 1%–2% of the rear side, and the rear contacts are made of stacks of Al/Ti/Pd/Ag. The cells were sintered at 400 °C for 30 min in forming gas ambient.

Illuminated *J*–*V* characteristics and EQE were measured at different temperatures between 15 and 70 °C. Fig. 1 shows the *J*–*V* characteristics of these cells at 25 °C. The solar simulator used in this paper consists of a set of tungsten lamps with dichroic rear reflectors (ANSI code: ELH). Its spectral photon flux density is plotted in Fig. 2. Its intensity was set to produce the same $J_{\rm sc}$ for a reference cell as the standard AM1.5 illumination (1000 W m^{-2}). Table I displays the cell thicknesses,

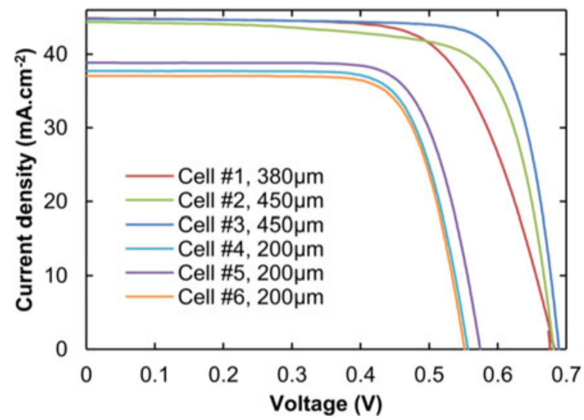

Fig. 1. Illuminated *J*–*V* characteristics at 25 °C of the cells used in this paper.

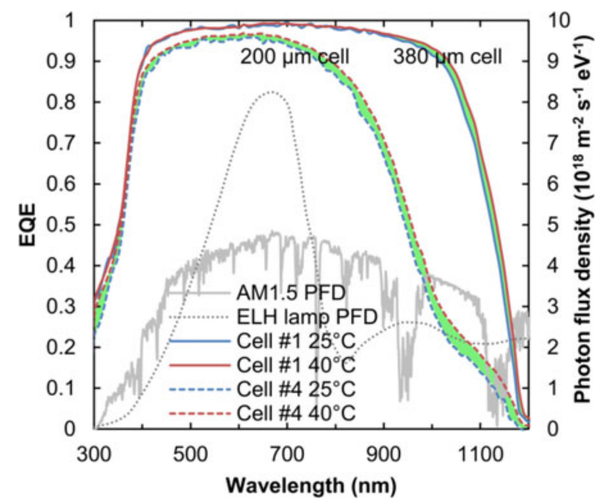

Fig. 2. EQEs at 25 and 40 °C (in blue and red respectively) of a thin cell (#4, dashed lines) and a thicker cell (#1, solid lines). The variations of EQE between 25 and 40 °C are colored green. The AM1.5 (solid line) and the ELH lamp (dotted line) photon flux densities are plotted (in gray).

EREs calculated from EQE, $V_{\rm oc}$ and $J_{\rm sc}$ measurements, γ values calculated from (3) using measured $V_{\rm oc}$ and $\beta_{V{\rm oc}}$, series resistances and their TCs (β_{Rs}), and ideality factors. The EQEs of two cells of different thicknesses (Cell #1 and #4) at 25 and 40 °C are plotted in Fig. 2. A linear regression analysis shows that the cell parameters $J_{\rm sc}$, $V_{\rm oc}$, and FF vary linearly with temperature. TCs (normalized at 25 °C) were extracted and are plotted in Figs. 3–5. Figs. 6 and 7 show the series resistances and the ideality factors, respectively, of the measured cells that were extracted from *J*–*V* curves at different temperatures using the method described in [13] together with the five points analytical method [14] to calculate the initial values of the parameters.

IV. Discussion

Fig. 3 shows experimental TCs of the short-circuit current density as a function of cell thickness, together with the first summand of (5) calculated using the bandgap temperature dependence of c-Si [12] and the spectrum of the lamp used for the measurements. Note that the comparison with the literature

TABLE I
PARAMETERS DERIVED FROM EXPERIMENTS

	Cell #1	Cell #2	Cell #3	Cell #4	Cell #5	Cell #6
Thickness (μm)	380	450	450	200	200	200
ERE at 25 °C	2.5×10^{-3}	2.6×10^{-3}	3.1×10^{-3}	3.0×10^{-6}	7.6×10^{-6}	4.2×10^{-6}
ERE at 40 °C	2.6×10^{-3}	3.0×10^{-3}	3.3×10^{-3}	6.9×10^{-6}	1.1×10^{-5}	8.3×10^{-6}
γ	1.0	0.4	1.7	−1.8	−2.4	−1.6
R_s at 25 °C (Ω)	0.40	0.08	0.09	0.25	0.24	0.23
β_{Rs} (ppm K^{-1})	920	3090	2160	2010	1490	4770
n at 25 °C	1.72	1.49	1.26	1.12	1.21	1.12

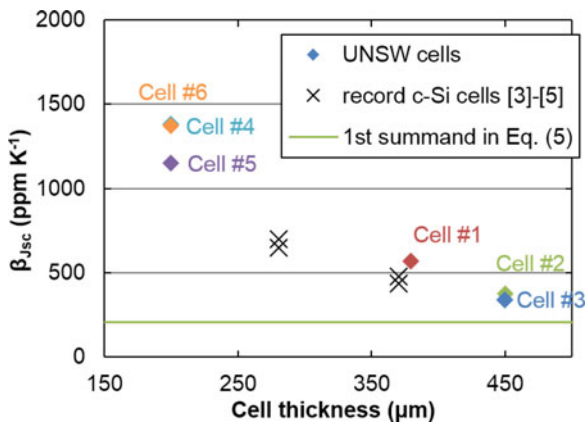

Fig. 3. Experimental TCs of the short-circuit current density (diamonds and x's) and first summand of (5) (green line) plotted as a function of cell thickness.

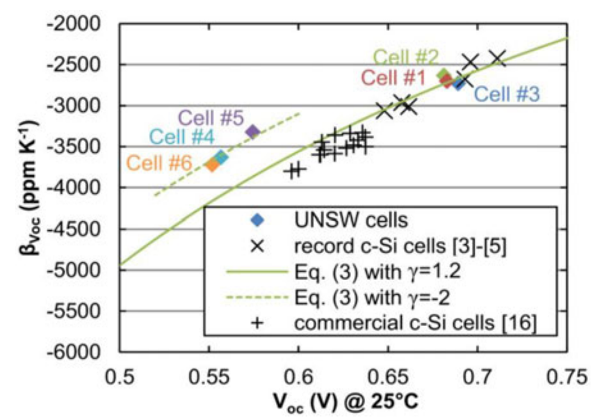

Fig. 4. Experimental TCs of the open-circuit voltage (diamonds, crosses, and x's) and theoretical predictions (green lines) with different values of γ plotted as a function of V_{oc}.

data (x's in Fig. 3) may be biased because of the possible differences in lamp spectra used in different works. Indeed, when the photon flux densities around the bandgap energy are different, the bandgap variations with temperature do not lead to the same changes in short-circuit currents [10]. All the experimental data are significantly larger than the calculated value (green line). This demonstrates that the second summand in (5) is important for these cells. This means that the collection fraction increases with temperature, which is expected since silicon is an indirect bandgap semiconductor, and thus, its interband absorption coefficient increases significantly with temperature. This is confirmed by EQE measurements made at different temperatures (see Fig. 2). More importantly, the difference between measured and calculated values in Fig. 3 increases with decreasing cell thickness. This is because the relative increase with temperature of collection fraction is larger for cells that let a substantial portion of the useful photons escape at room temperature (insufficient light trapping). This is illustrated in Fig. 2 where the increase of EQE between 25 and 40°C is colored in green for a thin (200 μm) and a thicker (380 μm) cell. Cells that do not absorb most of the useful photons at room temperature benefit relatively more from the increased absorption with temperature characteristic of indirect bandgap materials. As shown in Fig. 3, this phenomenon leads to unusually large short-circuit current density TCs for cells #4, #5, and #6, which are only 200 μm thick. It is worth keeping this fact in mind when dealing with thin cells (with insufficient light trapping) made of indirect bandgap semiconductors. More generally, any loss mechanism that decreases with increasing temperature will lead to favorable TCs. For example, it was noticed in [15] that cells containing layers that impede carrier transport more at room temperature than at larger temperatures benefit from advantageous TCs of their FF.

Fig. 4 shows experimental measurements together with theoretical predictions of the open-circuit voltage TCs (green lines). The experimental data include the cells measured in this study, reported values for record silicon solar cells (between 1980 and 1994 [3]–[5]), and reported values for commercial silicon cells fabricated with different processes and from different wafer types [16]. The theoretical value of $\gamma = 1.2$ (used to plot the solid green line) is calculated from (4) with the bandgap temperature dependence of c-Si [12], the spectrum of the lamp used for the measurements (a similar value of γ is found with the AM1.5 spectrum) and assuming that $\mathrm{ERE}_{\mathrm{oc}}$ does not vary with temperature (i.e., neglecting the second summand in (4)). We observe in Fig. 4 that the measured $\beta_{V\mathrm{oc}}$ are in quite good agreement with the theory and especially for the cells with large V_{oc} (or, equivalently, large $\mathrm{ERE}_{\mathrm{oc}}$). However, there is a noticeable difference between the measured values for cells #4, #5, and #6 and the theoretical line. This is mostly due to a substantial increase of $\mathrm{ERE}_{\mathrm{oc}}$ of these cells with temperature, and thus, nonnegligible values of $d\ln \mathrm{ERE}_{\mathrm{oc}}/d\ln T_c$ leading to negative values of γ significantly far from the theoretical value of 1.2 (see Table I). These temperature dependences of $\mathrm{ERE}_{\mathrm{oc}}$ are attributed to the unusually large increases with temperature of

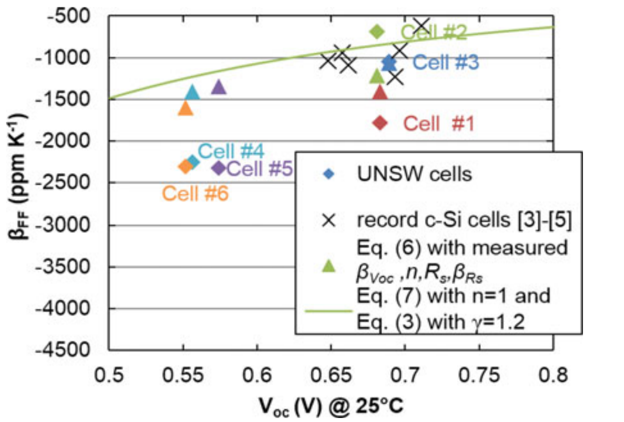

Fig. 5. Experimental TCs of the FF (diamonds and x's), generic theoretical calculation (green line), and specific theoretical predictions (triangles) plotted as a function of V_{oc}.

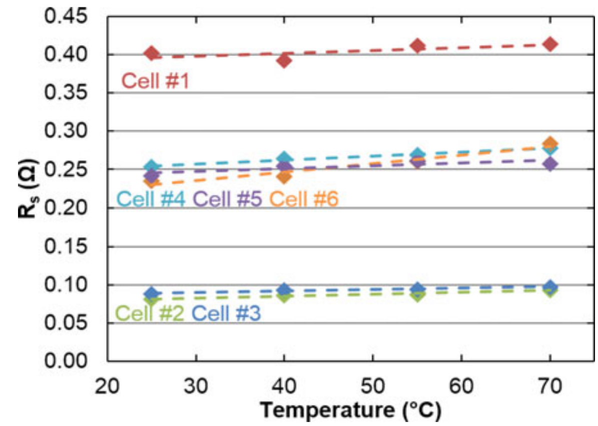

Fig. 6. Series resistances of the measured UNSW cells at different temperatures (diamonds). The dashed lines are linear regressions used to calculate β_{Rs} in Table I.

the collection fractions of these cells (notice the EQE term in (1)). The term $d\ln J_{\mathrm{sc}}/d\ln T_c$ in (4) is also larger for these cells but accounts for a change in γ of only 0.25 on average. It is worth noticing that the deviation between the experimental results and the theoretical line in Fig. 4 is always proportional to the difference between γ and its reference value (1.2) divided by V_{oc}. The dotted green line in Fig. 4 shows that the TC of the open-circuit voltage of the cells #4, #5, and #6 can be modeled with a different value of γ (-2). As demonstrated in [10] using the work of Siefer and Bett [17], the value of γ is an indicator of the internal device physics and can be used to identify the mechanisms that limit the device performances.

Fig. 5 displays the measured TCs of the FF of the studied cells and that of record silicon cells together with a generic theoretical calculation (green line) and specific theoretical predictions based on experimental values for each cell (triangles). The first theoretical calculation, in order to be generic, uses a single value of the ideality factor, i.e., 1, assumes a single value of γ, i.e., 1.2, to calculate $\beta_{V\mathrm{oc}}$ and neglects the second summand in (7), which considers the effect of series resistances. As expected, the measured values of β_{FF} of cells with relatively large series resistances (cells #1, #4, #5, and #6; see Table I) differ appreciably from the green line. The impact of the series resistance and its temperature dependence on β_{FF} was introduced in [5] with the addition of the second summand in (7). In [5], a TC of R_s of 6450 ppm·K^{-1}, which is that of 0.5 Ω·cm silicon, was used. In this study, the TCs of the series resistances β_{Rs} calculated from linear regression of the calculated R_s (see Fig. 6) vary from 920 to 4770 ppm·K^{-1} (see Table I). The triangles in Fig. 5 represent results from the theoretical expressions (7) and (8) with the experimental values of $\beta_{V\mathrm{oc}}$, R_s, β_{Rs}, and n of the cells studied in this paper. While these specific theoretical predictions are somewhat closer to the measured values of β_{FF}, there are still some large discrepancies between theory and measurements. These discrepancies may be due to the fact that the semiempirical expressions (7) and (8) were derived for high quality cells. This could explain why they fail to be accurate for cells suffering from more loss mechanisms. When the shunt resistance is particularly small, R_{sh} and $\beta_{R\mathrm{sh}}$ may have a significant impact on β_{FF}. This could explain why cell #2, which has a really small shunt resistance (≈ 70 Ω), as can be seen in Fig. 1, has the only measured β_{FF} that is above the theoretical prediction. In addition, variations of the ideality factor with temperature (illustrated in Fig. 7) are not taken into account in the theoretical expression discussed here. These effects of R_{sh}, $\beta_{R\mathrm{sh}}$, and β_n on β_{FF} demand additional investigations.

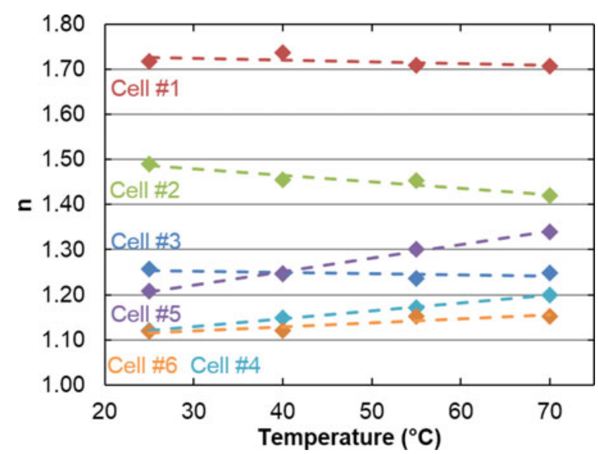

Fig. 7. Ideality factors of the measured UNSW cells at different temperatures (diamonds). The dashed lines are linear regressions.

V. Conclusion

Experimental measurements of temperature coefficients of c-Si solar cells have been presented and discussed. It has been shown that the external radiative efficiency of PV cells plays a significant role in the temperature dependence of open-circuit voltage; cells with insufficient light trapping made of indirect bandgap semiconductors exhibit unusual temperature sensitivities of short-circuit current and open-circuit voltage; and additional investigations are necessary to completely assess the existing theoretical formulation of the temperature coefficient of the fill factor.

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Prof. Green's work has been recognized with major international awards, including the 2002 Right Livelihood Award, also known as the Alternative Nobel Prize, the 2007 SolarWorld Einstein Award, and the 2010 Eureka Prize for Leadership. In 2012, he was appointed as a Member of the Order of Australia in recognition of his contributions to photovoltaics and photovoltaics education. He has been elected to Fellowship of both the Australian Academy of Science and the Royal Society of London.