Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 92 (2016) 2 – 9

Energy Procedia

6th International Conference on Silicon Photovoltaics, SiliconPV 2016

On the variability of the temperature coefficients of mc-Si solar cells with irradiance

Charly Berthod[a]*, Rune Strandberg[a], Georgi H. Yordanov[a], Hans G. Beyer[a], and Jan O. Odden[b]

[a]*The University of Agder, Jon Lilletunsvei 9, 4879 Grimstad, Norway*
[b]*Elkem Solar AS, P.O. Box 8040 Vaagsbygd, NO-4675 Kristiansand S, Norway*

Abstract

The temperature sensitivity of silicon solar cells is in general assumed to be constant with irradiance in PV forecasting models, although it has been demonstrated experimentally that this is not true. In this study a theoretical model is established that describes the variation of the temperature coefficients of a silicon solar cell as a function of the irradiance. It is shown that the temperature sensitivity of the solar cell efficiency is decreasing with the irradiance and that the main reason for this behavior comes from the increase of the open-circuit voltage with light intensity. Moreover, a dependency of the cell´s ideality factor on the irradiance has to be assumed to receive good modelling results that can be confirmed experimentally.

Peer review by the scientific conference committee of SiliconPV 2016 under responsibility of PSE AG.

Keywords: Temperature coefficients; silicon solar cells; compensated silicon; irradiance; ideality factor.

1. Introduction

Solar cells and PV modules are systematically characterized at standard test conditions (STC) fulfilling the ASTM norms. However, only in rare occasions will the operating conditions correspond to STC. To cope with this fact the parameter "temperature coefficient" has been introduced to describe how the cell and module power output vary with temperature. Knowledge of this temperature coefficient is crucial for the prediction of PV energy production. The operating temperature of a solar panel depends on the environmental conditions (irradiance, ambient temperature, wind speed) and on material properties (absorptance and reflectivity, heat transfer coefficients to air

* Corresponding author. Tel.: +47 908 99 243.
E-mail address: charly.berthod@uia.no

Peer review by the scientific conference committee of SiliconPV 2016 under responsibility of PSE AG.
doi:10.1016/j.egypro.2016.07.002

and support structure, etc.). Various models for forecasting the PV energy production depending on the above mentioned parameters are reviewed in [1].

As given in section 3 below, the temperature coefficient of the efficiency or equivalently of the power output (β_η) can be expressed as the sum of the temperature coefficients of open-circuit voltage (β_{Voc}), short-circuit current (β_{Jsc}) and fill factor (β_{FF}). In a recent paper [2], a theoretical model based on the work of Green [3] and Hirst and Ekins-Daukes [4] establishes the direct link between the temperature dependences and the losses in a solar cell. The temperature coefficient of the open-circuit voltage is strongly related to the open-circuit voltage itself, which is a function of the irradiance. Thus it is pertinent to assume that the temperature sensitivity of a solar cell varies with irradiance as well. This study addresses this question and proposes an expression of the temperature sensitivity of a solar cell as a function of the irradiance. This theoretical model is compared to experimental values for two different feedstocks: compensated silicon solar cells made from ESS® and uncompensated silicon solar cells. The experimental values used in this study as well as the technical procedure to measure them are presented in [5].

The averaged characteristics of the solar cells are summarized in Table 1. Both lifetime and carrier mobilities are generally lower in compensated material [6-11], resulting in a somewhat lower short-circuit current. The open-circuit voltage is slightly higher in this compensated silicon due to a lower ingot resistivity, meaning a higher net doping. This is visible in the series resistance which is lower for compensated silicon.

Table 1. Averaged characteristics of the solar cells

Feedstock	J_{sc} (mA.cm^{-2})	V_{oc} (mV)	*FF* (%)	η (%)	R_s (Ω.cm)
Compensated silicon	34.71	633	77.84	17.10	4.5
Uncompensated silicon	35.17	631	78.43	17.41	5.2

2. Irradiance dependence of the temperature coefficients

2.1. Temperature coefficient of the short-circuit current

The bandgap of silicon is decreasing with temperature causing the short-circuit current (J_{sc}) to increase. J_{sc} can be written as the product of an ideal current $J_{sc,1sun}$ taken at one sun intensity, a collection fraction f_c and the normalized irradiance *X (in suns)* [3]

$$J_{sc} = J_{sc,1sun} f_c X \quad . \tag{1}$$

The temperature coefficient of J_{sc} can be expressed as:

$$\beta_{J_{sc}} = \frac{1}{J_{sc}} \frac{dJ_{sc}}{dT} = \frac{1}{J_{sc,1sun}} \frac{dJ_{sc,1sun}}{dE_g} \frac{dE_g}{dT} + \frac{1}{f_c} \frac{df_c}{dT} \ , \tag{2}$$

where E_g is the bandgap of the semiconductor. The first right-hand term is fixed for a certain semiconductor; its value is 167 ppm/°C for silicon [3]. The second right-hand term is the temperature sensitivity of the collection fraction, which depends on the design of the solar cell. Assuming that this parameter is independent of the irradiance gives a value for the temperature sensitivity of the short-circuit current which is independent of the irradiance as well.

Up to an irradiance of about 1 sun, the experimental values do not show a dependency on the irradiance, as shown in Fig. 1. For higher irradiances, a slight decrease in the temperature coefficients is observed, indicating that our assumptions give inaccuracies at higher irradiance. The constant temperature coefficients of the short-circuit current for both feedstocks was thus fitted for irradiances below 1 sun.

The benefit of compensated silicon is clear on this temperature coefficient and was already reported [12-14]. This advantage of compensated silicon could come from lifetime improvement in defect areas [10,15], or from the different mobility dependence with temperature [7,9,11,16].

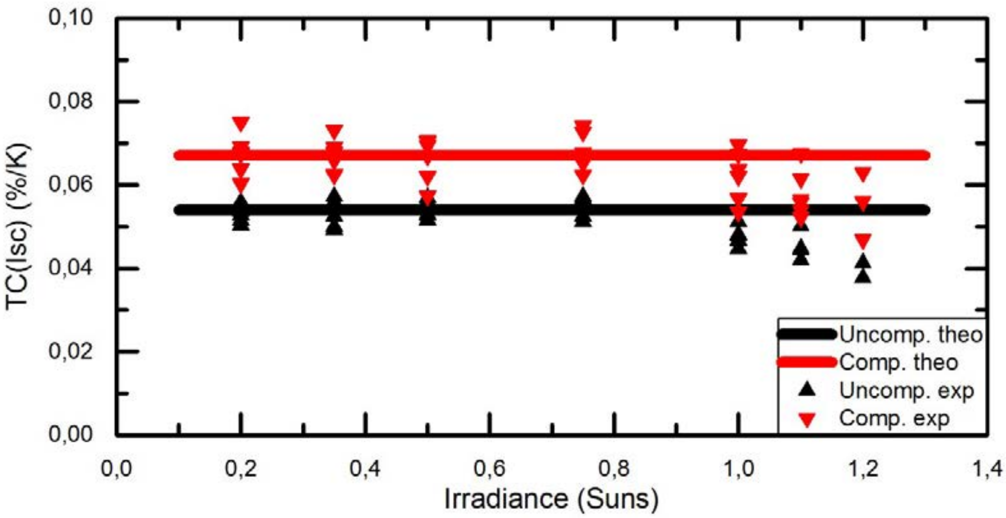

Fig. 1. Temperature sensitivity of the short-circuit current for compensated silicon (black) and uncompensated silicon (red). The triangles represent the experimental values and the lines the theoretical model.

2.2. Temperature coefficient of the open-circuit current

The relative variation of V_{oc} accounts for 80–90% of the overall temperature sensitivity for reasonably good silicon solar cells [2]. The temperature coefficient of the V_{oc} can be expressed as [3]:

$$\beta_{V_{oc}} = \frac{1}{V_{oc}}\frac{dV_{oc}}{dT} = -\frac{1}{V_{oc}T_c}\left[\frac{E_{g0}}{q} - V_{oc} + \gamma\frac{kT_c}{q}\right], \tag{3}$$

where k, q, T_c and E_{g0} are, respectively, the electron charge, Boltzmann's constant, the cell temperature and the linearly extrapolated bandgap of the relevant recombination process at 0 K. γ is a parameter corresponding to the temperature sensitivity of the recombination mechanism determining V_{oc}. An accurate way of calculating this parameter is described in [17]. Justified by the low sensitivity of β_{Voc} to γ (the dominant term on the right hand side of Eq. (3) is E_{g0}/q-V_{oc}), we confined ourselves to the use of an approximate value of $\gamma=3$ here. The only factor with an obvious dependency on the irradiance is V_{oc} itself. This can be described as:

$$V_{oc} = V_{oc,1sun} + \frac{nkT}{q}\ln\left(X\right), \tag{4}$$

where n is the ideality factor, X the irradiance in suns and $V_{oc,1sun}$ the V_{oc} at one sun intensity.

The temperature coefficient of V_{oc} is negative and can be increased by raising V_{oc}, which will decrease the temperature sensitivity of the solar cell. This means that decreasing the recombination currents in the bulk and on the surfaces of the cell greatly improves β_{Voc}. As a result, the solar cells with the highest V_{oc} will show good β_η [18].

The irradiance dependence of the β_{Voc} which is made by inserting Eq. (4) in (3) will now be compared to the experimental results from [5].

V_{oc} is increasing with irradiance and as a consequence the temperature sensitivity of V_{oc} is reduced. This can be seen in Fig. 2 where experimental values for β_{Voc} of both compensated and uncompensated silicon solar cells are plotted together with results from modelling. The green dashed and dotted lines show the temperature coefficient modelled with fixed values for the ideality factor (used here $n=1$ and $n=1.25$). It is clear that when assuming a constant ideality factor, the model captures the general trend, but fails to match the experimental results across the entire range of irradiances. Therefore, an ideality factor varying linearly with the irradiance was introduced to the modelling. The relevance of assuming an ideality factor that depends linearly on the irradiance is discussed in subsection 2.4. Using a linear ideality factor for curve fitting improved the results to nicely fit the experimental values on the complete range of irradiances.

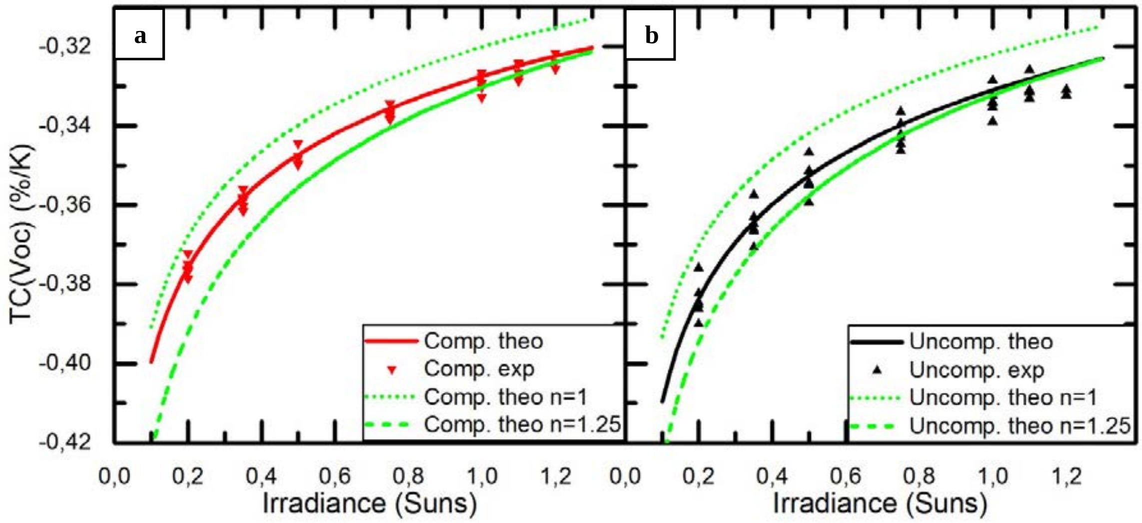

Fig. 2. Temperature sensitivity of the open-circuit voltage for a) compensated silicon and b) uncompensated silicon. The green dashed lines and dots represent the temperature sensitivity with a fixed ideality factor while the red and black lines show a linear-fitted ideality factor. Triangles are experimental values.

The temperature coefficient of compensated silicon is slightly better, which is mainly due to a smaller ideality factor compared to uncompensated silicon. The compensated silicon solar cells have a V_{oc} a few mV higher (2mV in average for these cells) than the uncompensated cells due to an increased doping level. This is explained by the use of lower resistivity ingots for compensated silicon. However this effect is rather small compared to the influence of the lower ideality factor.

2.3. Temperature coefficient of the fill factor

The fill factor is a parameter describing how much power you can extract from a cell given its J_{sc} and V_{oc}. It depends mainly on the V_{oc} and on the ideality factor which are related to the recombination mechanisms. On the other hand, parasitic series and shunt resistances decrease the fill factor and lower the maximum power that can be extracted from a device. For cells with a large shunt resistance, the temperature coefficient of the fill factor can be expressed as [3]:

$$\beta_{FF} = \frac{1}{FF}\frac{dFF}{dT} = \left(1 - 1.02 FF_0\right)\left(\frac{1}{V_{oc}}\frac{dV_{oc}}{dT} - \frac{1}{T}\right) - \frac{R_s}{\left(V_{oc}/J_{sc} - R_s\right)}\left(\frac{1}{R_s}\frac{dR_s}{dT}\right), \tag{5}$$

where R_s is the series resistance, FF_0 the ideal fill factor (free of series and shunt resistances effects), and v_{oc} is the normalized V_{oc}. The latter two parameters can be expressed as

$$FF_0 = \frac{v_{oc} - \ln\left(v_{oc} + 0.72\right)}{v_{oc} - 1} \tag{6}$$

and

$$v_{oc} = \frac{q}{nkT} V_{oc} \ . \tag{7}$$

For good crystalline solar cells Eq. (5) can be simplified with $R_s=0$. Nevertheless, this assumption can be erroneous for solar cells with complex passivating layers where β_{FF} can be found positive for such device [19]. The charge transfer mechanisms (thermionic emission or tunneling) strongly depend on temperature affecting the series resistance, thus leading to potential improvement of the *FF* at higher temperature.

When inserting the irradiance dependency of V_{oc} from Eq. (4) into (7) and then into (5), and fitting the temperature coefficient of the series resistance we obtain the results in Fig. 3. This gives $\beta_{Rs}=0.15$ *%/K* for compensated silicon and *0.3 %/K* for uncompensated silicon which are typical values for multicrystalline silicon solar cells [20].

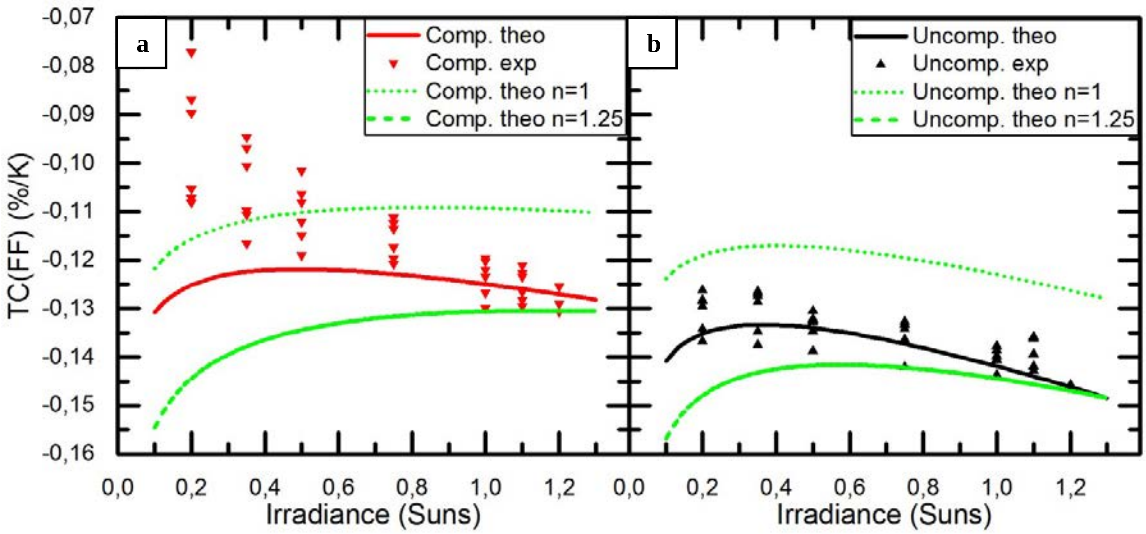

Fig. 3. Temperature sensitivity of the fill factor for a) compensated silicon and b) uncompensated silicon. The green dashed lines and dots represent the temperature sensitivity with a fixed ideality factor while the red and black lines show a linear-fitted ideality factor from Fig. 2. Triangles are experimental values.

A good fit is obtained for uncompensated silicon (Fig. 3b) whereas for compensated silicon (Fig. 3a) the theoretical curve matches experimental data for high irradiance (above 1 sun), while at low irradiance, the actual temperature sensitivity of the fill factor is higher than expected from the model. The ideality factor used to calculate this coefficient is the one fitted to the β_{Voc} of Fig.2. Small variations of the ideality factor (as shown by the green dashed lines and dots in Fig. 3) result in large variations of the temperature coefficient of the fill factor. However, the good agreement of the theoretical model with the measured β_{FF} for uncompensated silicon validates our method of fitting the ideality factor. The temperature coefficient of the *FF* is very sensitive to the ideality factor variations but less to the variations of the series resistance or to its temperature coefficient. The cause is the presence of the ideality factor in the dependence of V_{oc} on the irradiance, and in the definition of the normalized V_{oc}. The rise of β_{FF} at low irradiance for the compensated material could be due to shunt resistance effects that were not considered in Eq. (5).

2.4. Ideality factor varying with irradiance

The ideality factor used to achieve the values in Fig. 2 was modelled with a linear dependency on the irradiance. To verify this assumption we compared our fitted function with experimental data of the ideality factor in Fig. 4.

The local ideality factor along the *I-V* curve of two generic mc-Si PV modules is evaluated by the R_S-corrected *n-I* plot method [21]. First, the series resistance is estimated from classic *n-I* plot. The estimates are then fitted versus the equivalent cell temperature (ECT) determined from the open-circuit voltage. Then the R_s-corrected *n-I* plot is made which is supposed to be flat between open-circuit and the maximum power point. Finally, the module's local ideality factor at open-circuit for multiple *I-V* curves recorded outdoors at different illumination levels is plotted over irradiance. The results for the two multicrystalline modules called Multi1 and Multi2 are given in Fig. 4.

The two panels show a linear trend from 0.2 suns to 1.1 suns, however the slope is weaker compared to the ideality factors used in the fitting. And at low irradiance, below 0.2 suns, the experimental ideality factors increase rapidly. This behaviour is not taken into account in the model for the temperature coefficients. The linear model used in the fitting has, however, a trend and a magnitude comparable to that found experimentally for most of the relevant irradiance interval. Further experiments are needed to confirm if compensated silicon solar cells in general have a lower ideality factor than uncompensated silicon solar cells.

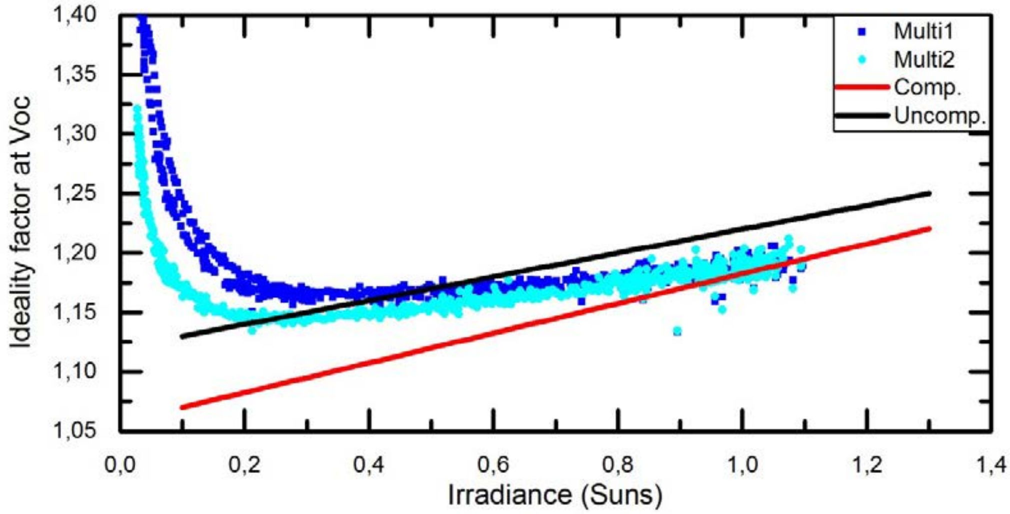

Fig. 4. The ideality factor as a function of irradiance. The red line is the fitted function described in section 2.2 for compensated silicon and the black line is the one for uncompensated silicon. The square blue and round cyan dots represent the ideality factor at V_{oc} of two multicrystalline silicon modules measured during one day.

3. Irradiance dependence of the temperature sensitivity of a solar cell

The temperature sensitivity of the power extracted from a solar cell at the maximum power point can be written as the sum of the temperature coefficients of the V_{oc}, J_{os}, and *FF* as follows:

$$\eta(T) = V_{oc}(T) \times J_{sc}(T) \times FF(T)\,, \tag{8}$$

which, after differentiation gives:

$$\beta_\eta = \beta_{Voc} + \beta_{Jsc} + \beta_{FF} \tag{9}$$

When summing up the three theoretical models described by Eq. (2), (3) and (5), Fig. 5 is obtained. We can observe that the theoretical model in general overestimate the temperature sensitivity, although the model gives good predictions for cells made from uncompensated silicon. This overvaluation of the magnitude of β_η is also observed when the three experimental temperature coefficients (β_{Voc}, β_{Jsc}, and β_{FF}) from [5] are summed up. Therefore the model presented in this study gives good values for the three temperature coefficients of a solar cell, but when summed up it tends to overestimate the temperature sensitivity of the efficiency.

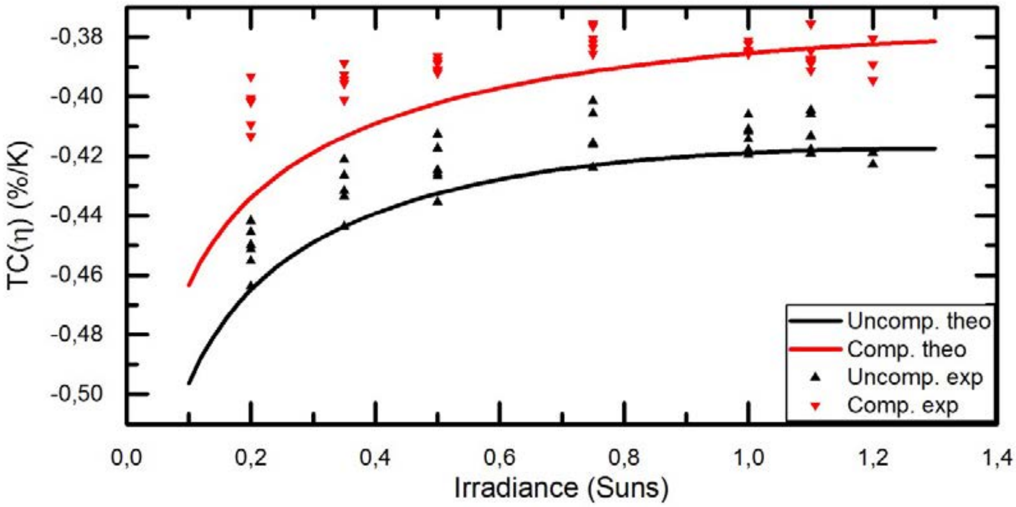

Fig. 5. Temperature sensitivity of the efficiency (or power output) for compensated silicon (black) and uncompensated silicon (red). The triangles represent the experimental values and the lines the theoretical model.

4. Conclusion

In this study, a theoretical model was developed that explains the increase of the temperature sensitivity of solar cells at low irradiance. This is shown to come mainly from a decrease of the open-circuit voltage and thus of its temperature coefficient. The model does not account for the decrease of the temperature coefficient of the short-circuit current at high irradiance, neither does it take into consideration the shunt resistances in the temperature coefficient of the fill factor which could explain the trend at low irradiance of compensated silicon. Finally, taking into account the irradiance dependency of the ideality factor is required to have a good fitting of the temperature coefficient of the open-circuit voltage, and this trend was subsequently confirmed on the module level.

Acknowledgements

The authors would like to thank Dr. Muhammad Tayyib for graciously providing his experimental data.

References

[1] Skoplaki E, Palyvos JA. On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. Solar Energy. 2009;83(5):614-24.
[2] Dupré O, Vaillon R, Green MA. Physics of the temperature coefficients of solar cells. Solar Energy Materials and Solar Cells. 2015;140:92-100.
[3] Green MA. General temperature dependence of solar cell performance and implications for device modelling. Progress in Photovoltaics: Research and Applications. 2003;11(5):333-40.
[4] Hirst LC, Ekins-Daukes NJ. Fundamental losses in solar cells. Progress in Photovoltaics: Research and Applications. 2011;19(3):286-93.
[5] Tayyib M, Odden JO, Saetre TO. Irradiance Dependent Temperature Coefficients for MC Solar Cells from Elkem Solar Grade Silicon in Comparison with Reference Polysilicon. Energy Procedia. 2014;55:602-7.
[6] Forster M, Cuevas A, Fourmond E, Rougieux FE, Lemiti M. Impact of incomplete ionization of dopants on the electrical properties of compensated p-type silicon. Journal of Applied Physics. 2012;111(4):043701.
[7] Rougieux FE, Macdonald D, Cuevas A, Ruffell S, Schmidt J, Lim B, et al. Electron and hole mobility reduction and Hall factor in phosphorus-compensated p-type silicon. Journal of Applied Physics. 2010;108(1):013706.
[8] Rougieux F, Samundsett C, Fong KC, Fell A, Zheng P, Macdonald D, et al. High efficiency UMG silicon solar cells: impact of compensation on cell parameters. Progress in Photovoltaics: Research and Applications. 2016;24(5):725-34.
[9] Schindler F, Forster M, Broisch J, Schön J, Giesecke J, Rein S, et al. Towards a unified low-field model for carrier mobilities in crystalline silicon. Solar Energy Materials and Solar Cells. 2014;131:92-9.
[10] Dubois S, Enjalbert N, Garandet JP. Effects of the compensation level on the carrier lifetime of crystalline silicon. Applied Physics Letters. 2008;93(3):032114.

[11] Veirman J, Dubois S, Enjalbert N, Garandet JP, Lemiti M. Electronic properties of highly-doped and compensated solar-grade silicon wafers and solar cells. Journal of Applied Physics. 2011;109(10):103711.
[12] Ponce-Alcántara S, Connolly JP, Sánchez G, Míguez JM, Hoffmann V, Ordás R. A Statistical Analysis of the Temperature Coefficients of Industrial Silicon Solar Cells. Energy Procedia. 2014;55:578-88.
[13] Tanay F, Dubois S, Enjalbert N, Veirman J. Low temperature-coefficient for solar cells processed from solar-grade silicon purified by metallurgical route. Progress in Photovoltaics: Research and Applications. 2011;19(8):966-72.
[14] Tayyib M, Odden JO, Saetre TO, editors. Effect of temperature and sun intensity on multicrystalline silicon solar cells. European Photovoltaic Energy Solar Conference (EU PVSEC); 2013.
[15] Macdonald D, Cuevas A. Recombination in compensated crystalline silicon for solar cells. Journal of Applied Physics. 2011;109(4):043704--8.
[16] Modanese C, Acciarri M, Binetti S, Søiland A-K, Di Sabatino M, Arnberg L. Temperature-dependent Hall-effect measurements of p-type multicrystalline compensated solar grade silicon. Progress in Photovoltaics: Research and Applications. 2013;21(7):1469-77.
[17] Dupre O, Vaillon R, Green MA. Experimental assessment of temperature coefficient theories for silicon solar cells. Photovoltaics, IEEE Journal of. 2016;6(1):56-60.
[18] Lee Y, Park C, Balaji N, Lee YJ, Dao VA. High-efficiency Silicon Solar Cells: A Review. Israel Journal of Chemistry. 2015;55(10):1050-63.
[19] Seif JP, Descoeudres A, Filipič M, Smole F, Topič M, Holman ZC, et al. Amorphous silicon oxide window layers for high-efficiency silicon heterojunction solar cells. Journal of Applied Physics. 2014;115(2):024502.
[20] Yordanov GH. The PVGIS relative efficiency model: equations for k1 through k6. Proc. 29th EU PVSEC, Amsterdam, the Netherlands, 2014, pp. 3297-3301.
[21] Yordanov GH, Saetre TO, Midtgård O-M. Differential analysis of PV module I-V curves. Proc. 28th EU PVSEC, Paris, France, 2013, pp. 3207-3211.