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APPLICABILITY OF EQUIVALENT DIODE MODELS TO MODELING VARIOUS THIN-FILM PHOTOVOLTAIC (PV) MODULES IN A WIDE RANGE OF TEMPERATURE AND IRRADIANCE CONDITIONS

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ABSTRACT

In the paper results of fitting of current-voltage (*I-V*) curves acquired in a wide range of irradiances and temperatures with use of equivalent either single (SEM) or double (DEM) diode model as applied to several commercial thin-film photovoltaic (PV) modules are presented. It is shown that like in case of crystalline silicon PV modules also for CIGS ($CuInGaSe_2$) as well as CdTe thin-film modules both models may be reliably applied whereas in case a-Si (amorphous silicon), whether it is single or multi-junction structure, obtained results can not be accepted as being credible.

1. Introduction

Equivalent electrical models, either single or double diode, of photovoltaic (PV) cells and modules can be very useful tools when predicting performance of PV generator to be operated in natural, changeable conditions. On the other hand, such models may be also very helpful even when analyzing basic physical processes occurring in the devices, including recombination/diffusion processes. Applicability of both models has been commonly accepted when applied to crystalline silicon PV cells and modules yet there is a very little work analyzing usefulness of these models for thin-film PV devices existing on the market. Here we would like to present a unique approach of applying both models to various commercial thinfilm PV modules, like CIGS, CdTe or even amorphous Si, using large number of *I-V* curves acquired in natural outdoor conditions during long term monitoring [1]. For that purpose special software allowing numerical fit of measured *I-V* curves to either of the two models was developed [2]. It automatically imports *I-V* data stored in SolarLab's database enabling fitting of thousands curves within reasonably short time. After completing each fitting process, which typically takes few seconds only, obtained results are immediately processed showing on the screen dependences of such parameters as components of the dark saturation currents as well as series and parallel parasitic resistances on module temperature and irradiance.

To perform experiments data collected for four commercial modules were analysed. These were $Cu(GaIn)Se_2$ (CIGS) thin-film module ST40 from Shell Solar, CdTe FS50D from First Solar, single junction amorphous silicon (a-Si) A13P-1X from Free Energy Europe and finally triple junction a-Si from Unisolar. As for *I-V* curves of the last of listed modules practically no satisfactory fitting with neither of the models was obtained hence no data for this module will be presented in further parts of this work.

2. Diode models

The current-voltage (*I-V*) characteristics of the solar cells and/or PV modules under light conditions can be described by either of two general equations, i.e. using Single Diode (SEM):

$$I = -I_{PH} + I_S \exp\left[\frac{qV_D}{AkT} - 1\right] + \frac{V_D}{R_{SH}} \qquad (1)$$

or Double Diode equivalent Model (DEM), respectively [3]:

$$I = -I_{PH} + I_{S1} \exp\left[\frac{qV_D}{kT} - 1\right] + I_{S2} \exp\left[\frac{qV_D}{2kT} - 1\right] + \frac{V_D}{R_{SH}} \qquad (2)$$

where $V_D = V - IR$ and diode dark saturation current I_S is given as:

$$I_S = I_0 \exp\left(\frac{-E_A}{AkT}\right). \qquad (3)$$

Here, I_{PH} and T are module's photocurrent and temperature, respectively, k is Boltzmann constant and q elementary charge. R_S and R_{SH} denote module's series and shunt parasitic resistances, respectively. The diode ideality factor A and prefactor I_0 are constants dependent on the energy band gap E_A and recombination mechanisms specific for a semi-conductor material and structure of solar cells used for PV module manufacturing. In case of DEM model value of A in (3) takes value equal to one for diffusion related component I_{S1} and is equal two for I_{S2} which is recombination component of the dark saturation current, respectively. Basically, diode ideality factor A in (1) should vary between 1 and 2. General expressions for A, E_A, and I_0 in the case of different recombination mechanisms can be found in [3], [4].

3. Results and discussion

Fitting *I-V* data acquired during outdoor monitoring to either of two diode models has been done with help of specially developed PC program. Arrhenius plots calculated for CIGS and CdTe modules at the whole available irradiance range, as shown in Fig. 1, suggest suitability of both equivalent diode models for this type of PV devices. As may be concluded from (3) the product of diode ideality factor A and E_A (Eq. 3) corresponds to the band gap energy E_g which means that Arrhenius plots may be directly used to determine E_g.

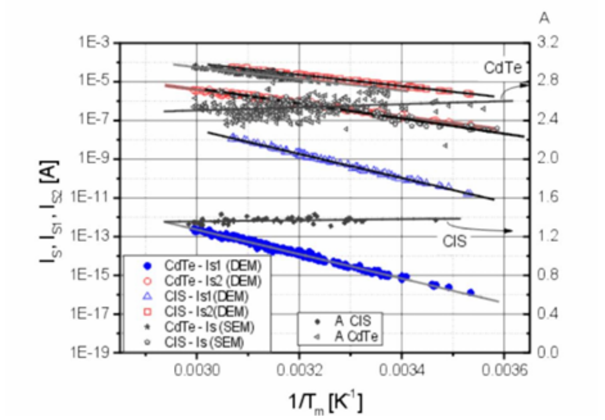

Fig. 1. Arrhenius plots of the dark current components and diode ideality factor A calculated for CIS and CdTe thin-film modules using either of two equivalent diode models; *I-V* curves used for fitting were taken for full range of available irradiance values.

Energy band gap E_g value calculated for CIGS module and plotted as a function of irradiance level has been shown in Fig. 2. Characteristic features, observed also for other CIS modules tested in SolarLab's DAS, are lower values of E_g obtained when using SEM model and lower value of E_g calculated from Arrhenius plot of I_{S2} (recombination component of dark current) as compared to value obtained from I_{S1} (diffusion component) plot when using DEM model. In the latter case steady increase of calculated E_g value with irradiance level could be additionally noticed.

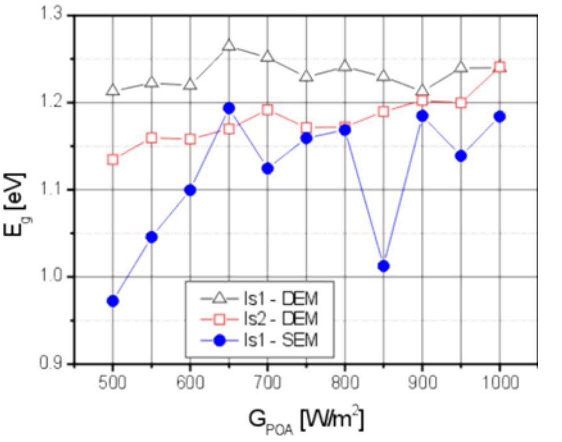

Fig. 2. Comparison of the band gap energy E_g determined for CIGS thin-film module using Arrhenius for both equivalent diode models.

A possible explanation for such a behavior may be evolving saturation of the traps present in the band gap of CIGS material with increase of absorbed photon flux. Nevertheless, it should be stressed here that though obtained values of E_g depended on the applied diode model still they all remain quite common for CIGS material used for solar cell manufacturing (typical values of E_g in $Cu(In,Ga)Se_2$ may vary between ~1.06 and ~1.4 eV depending on Ga contents). Applicability of either of diode models for CIGS module suggested already earlier in [5] confirm additionally Figs. 3 and 4 where calculated values of module shunt (R_{SH}) and series (R_S) parasitic resistances were plotted as function of temperature.

Figure 4 shows effect of temperature on series and shunt resistance of the CIGS module determined using only two diode model. Since quite similar results have been obtained with use of one diode model so it means that neither R_S nor R_{SH} should be taken as a criterion for applicability of a chosen model. Effect of irradiance level on values of both resistance well visible in Fig. 4 should be noted.

However, in case of CdTe module both value of diode ideality factor A for SEM model being much higher than 2 (~2.6 !, see Fig. 1) as well as obtained values of E_g – being 0.99 eV, 1.09 eV and 1.08 eV as calculated using Arrhenius plots for I_{S1}, I_{S2} (DEM), I_S and A (SEM), respectively – were far from realistic values commonly claimed for CdTe ($E_g \approx 1.5$ eV).

This suggests that, in spite of good numerical fitting process, diode model should be very carefully applied for this type of solar cell structures. A possible explanation for the behavior of both parts of the dark current may be saturation of the traps in defect band present in the band structure of CIGS [6] and CdTe materials occurring with increase of absorbed photon flux.

Figures 5 and 6 show results of calculations performed for single junction a-Si module. In this case fitting process was not so satisfactory as was in the case of CIGS structures causing high spread in values of the obtained results. This is particularly true in case of modeling with use of SEM model.

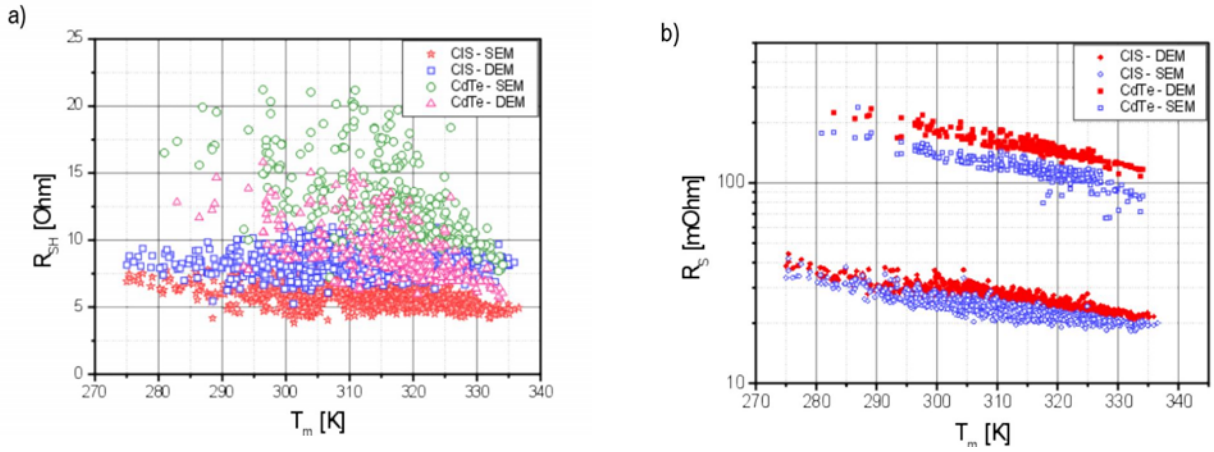

Fig. 3. Dependence of module shunt R_{SH} (a) and series R_S (b) resistances on module temperature T_m determined for CIS and CdTe thin-film modules using *I-V* curve fitting to either of two equivalent diode models; *I-V* curves used for fitting were taken for whole range of available irradiance values.

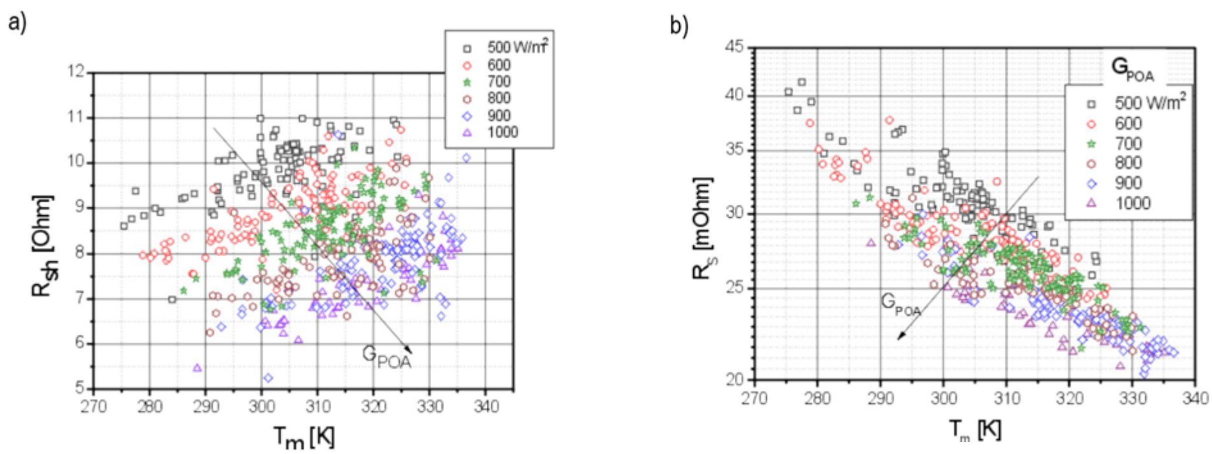

Fig. 4. Dependence of module shunt R_{SH} (a) and series R_S (b) resistances on module temperature T_m determined for CIGS thin--film module using *I-V* curve fitting to DEM model showing regular dependence of both parameters on irradiance level.

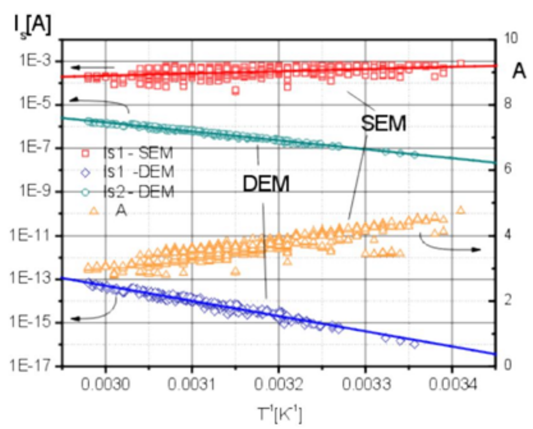

Fig. 5. Results of fitting of *I-V* curves for thin-film a-Si (1J) using both equivalent diode models; wide spread in obtained values for saturation current I_S and diode ideality factor A with the latter parameter exceeding 2 and increasing with emperature value of I_S in a whole module temperature range clearly indicates inappropriateness of the applied SEM; in case of using DEM model spread of resulting I_{S1} and I_{S2} values is much lower though reaching ten orders of magnitude difference between both components of saturation currents suggests that current in these type of structures is dominated by recombination processes and simple two diode model can not be used here.

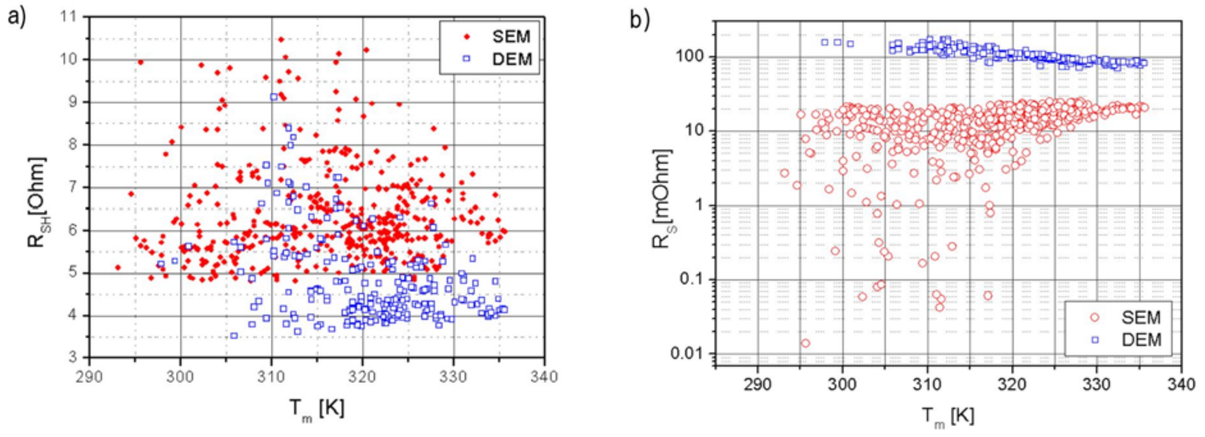

Fig. 6. Dependence of a-Si thin-film module shunt R_{SH} (a) and series R_S (b) resistances on module temperature T_m determined using fitting *I-V* curves to either of two equivalent diode models; huge spread of obtained data suggests that none of the applied models can not be used for proper modeling these type device.

4. Conclusions

Applicability of the diode equivalent models for several different type of thin-film PV modules was analyzed. Obtained results show that for a wide range of irradiance and module temperature values two basic equivalent diode models may be used for modeling CIGS and CdTe PV devices though in the latter case obtained values of E_g are much lower than common value of CdTe band gap. In case of CIGS structures two diode model seems to give even more reliable results than most commonly used SEM.

In spite of fitting process for individual *I-V* curves module usually seemed to look quite well yet huge spread in calculated values of cell's internal parameters clearly shows that neither of simple equivalent diode models may not be considered as reliable for single junction a-Si module whereas for triple junction a-Si module even fitting process failed for vast majority of *I-V* curves selected for calculations.

Acknowledgements

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