# Loughborough University

This item was submitted to Loughborough's Institutional Repository (https://dspace.lboro.ac.uk/) by the author and is made available under the following Creative Commons Licence conditions.

For the full text of this licence, please go to:
http://creativecommons.org/licenses/by-nc-nd/2.5/

# A Modelling Approach for Long-term Degradation of Thin Film Silicon Photovoltaic Modules

J. Zhu*, K. Astawa, T.R. Betts, R. Gottschalg

Centre for Renewable Energy Systems Technology (CREST), Department of Electronic and Electrical Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, United Kingdom
*Corresponding author: Tel.: +44 1509 635313, Fax: +44 1509 635301, Email: J.Zhu@lboro.ac.uk

## Abstract

This paper introduces a new concept of approach for modelling the ageing behaviour of a-Si PV modules with voltage-dependent photocurrent. The basis is the equivalent circuit of a PV module, specifically the modified single diode model. The parameters are extracted from I-V measurements. Ageing is then analysed by relating these to the environmental stresses seen by the devices. This paper focuses on the behaviour the product of carrier mobility and carrier life time ($\mu\tau$), since the $\mu\tau$ has been considered to be an important indicator for module degradation of amorphous silicon thin film devices. A fitting approach for determining $\mu\tau$ is discussed and extended to be applied to the outdoor module IV data. Three a-Si modules of the same type operating under different temperature conditions are analysed to identify changes in the $\mu\tau$.

## 1 Introduction

The performance of PV module in the long-term period or lifetime is important in determining any system's payback time. The module performance degrades over time in a way that is not fully understood yet. Typically, c-Si modules degrade stably with a rate of 0.5-1% per annual, whereas a-Si modules exhibit an initial light-induced degradation at first a few months and experience seasonal variation afterwards. This paper investigates the long-term degradation for a-Si module and presents a modelling approach for it.

Typical modelling methodologies for PV module degradation are based on the analysis of long-term module $P_{MPP}$ behaviour. Based on long-term measurements, one can carry out either linear or non-linear numerical fitting to find the relationship between $P_{MPP}$ and module operation time. An annual degradation rate then can be obtained from the fitting results. Based on the analysis of module annual degradation rate, one can extend the obtained fitting relationship to 10, 20 or 30 years to estimate device long-term performance. More recently, there has been an increasing emphasis on considering the power distribution of a module when analyzing module degradation. The reason is that as module degrades, the output power from the module appears to be more scattering than before. This demonstrates that the deviation of distribution of module output power is increasing over time.

The above described modelling approaches treat PV module pretty much as a black box and consider only module energy/power performance. They do not allow a separation of different degradation mechanisms and are thus only of limited applicability when it comes to comparing observed degradation rates in different climates. The comparison, or even prediction, of device degradation can only be achieved through a comprehensive understanding of the different degradation mechanisms and their driving factors. Amorphous silicon (a-Si) devices are a particularly challenging material because of its relatively large initial light-induced degradation and the following seasonal annealing/degradation pattern. The modelling of seasonal annealing and light induced degradation associated with surrounding environment has not yet been reported in the literatures. The work presented here is a step towards this as well as looking at the long term behaviour of these devices. An analysis of module parameters and their degradation is presented for single-junction a-Si modules deployed outdoors.

## 2 Modelling a-Si Devices

The equivalent circuit for PV modules is shown in Fig 1. The corresponding single diode model for a-Si module can be expressed by the equation below:

$$I(V) = I_{ph}(V) - I_d(V) - I_{sh}(V) \qquad (1)$$

where $I_{ph}(V)$ is the voltage-dependent photocurrent, $I_d(V)$ is the forward bias diode current, and $I_{sh}(V)$ is the current flowing through $R_{sh}$.

The voltage-dependent $I_{ph}(V)$ in a-Si PV modules decreases with increasing bias due to the reduction in the internal electric field. One modified diode model used in [1] expands the Eq (1) as:

$$I = I_{ph0}\left(1 - \frac{di^2}{(\mu\tau)(V_{bi} - V + IR_s)}\right) - I_0\left(\exp\frac{V - IR_s}{AkT/q} - 1\right) - \frac{V - IR_s}{R_{sh}}$$

(2)

where $I_{ph0}$ is optically limited saturated photocurrent at far reverse bias, $R_s$ is series resistance, $R_{sh}$ is shunt resistance, A is diode quality factor, $I_0$ is diode saturation current, $d_i$ is the thickness of i-layer, $V_{bi}$ is the built-in voltage and $\mu\tau$ is the product of carrier lifetime and carrier mobility. While the module degrades, the parameters will change and thus give an indication on the underlying mechanism.

Research has been carried out for investigation the long-term behaviour of thin film PV modules based on diode parameters [2]. The $R_s$ and A tends to be increasing, whereas $R_{sh}$ is decreasing over time. In this paper, the study is focused on the product of carrier lifetime and carrier mobility ($\mu\tau$), as it is considered to be a direct indicator for module degradation.
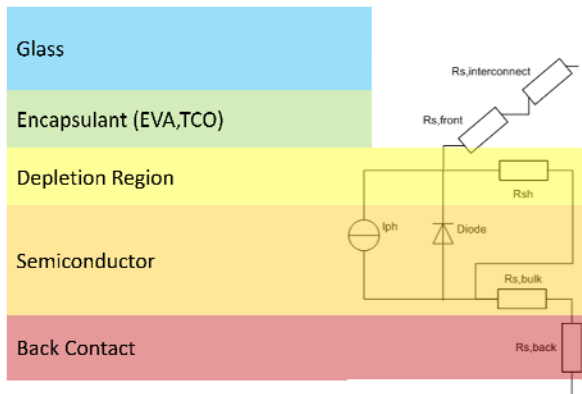


Fig 1: PV module equivalent circuit

## 3 Modelling Environmental Stresses Seen by Devices

Outdoor module exhibits different degradation mechanism, which is significantly affected by the environmental conditions where module installed. It is wise to investigate the mechanism separately. Thus, various indoor accelerated tests are introduced, e.g. damp-heat test, light-soaking test etc., to study the effect of different factors on degradation [3-4]. Among these factors, three environmental stresses, i.e. light, temperature and humidity, are considered to be the fundamental driven factors, which are studied in this work. Generally, the stresses of light, temperature and humidity cause different mechanism to degrade a part of module, and the temperature can accelerate certain processes. A superposition of Arrhenius treatments may be appropriate for these.

The modelling approach for degradation is required to relate the change in different module parameters ($\Delta p/\Delta t$) to the environmental stresses (A, B and C) in terms of the following Arrhenius formula:

$$\Delta p/\Delta t = A+B+C$$

$$A = a*G(t)*e^{-Ea/[R*T(t)]}$$
$$B = b*e^{-Ea/[R*T(t)]}$$
$$C = c*RH(t)*e^{-Ea/[R*T(t)]}$$

(3)

The factors A, B, and C represent the effects of light, temperature and humidity on modules. The changes occurred in physical properties are considered as a result from the combined effect of the three environmental factors. The analysis of environmental effects of irradiance, thermal and humidity are based on the Arrhenius equation. The $E_a$ represents the activation energy for different reactions and thus it is different in the term A, B and C. Each environmental stress has the influence on a number of device properties. This can explain some of the physical changes observed in modules, such as the light-induced degradation and thermal annealing effects on a-Si modules.

## 4 Experimental Setup

The IV data used for this work are from three single junction a-Si modules deployed outdoors at CREST, Loughborough, UK, for over one year. The module IV curves are recorded at the frequency of ten minutes while module is operating. 100 points are measured for each IV curve under the condition of forward bias. Unlike the indoor testing, outdoor are affected by scattered measurements. This is apparent, especially at low light levels. This results in errors in measured IV curves during dark, which cannot be used as estimation for the diode current $I_d$. Three different thermal operating conditions are created by mounting these modules either on an open racked, insulated on the back or insulated and heated. Thus the modules experience the same irradiance conditions but different temperature conditions. Thus, the averaged daily irradiation seen by the module surface and the irradiance-weighted module temperature is plotted in Fig 2 for three different modules in each month. Loughborough is with a maritime climate at relative high latitude. Its irradiance is lower compared to continental climate, especially during winter time. With different mounting conditions, the measured module temperatures of heated module are always five to ten degrees higher than that of open racked module because of the heating from the back. The insulated module temperatures are five to ten degrees higher than normal mounting during daytime when irradiance is high and at the same level

during night. This means the heated module experiences the largest thermal effect all the time and the insulated module experiences the largest temperature difference between daytime and night as well as between winter and summer. These may affect the modules annealing behaviours.
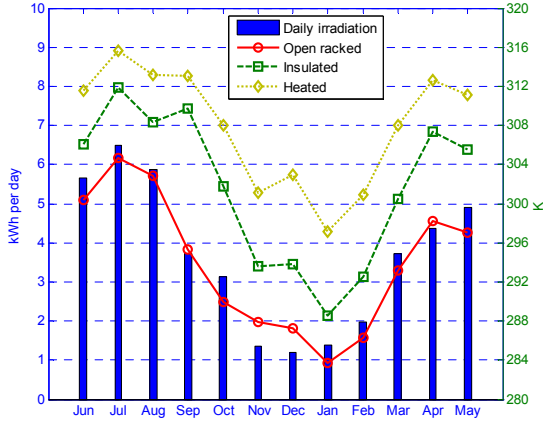


Fig 2: Average daily irradiation (bar plot and left Y-axis) and irradiance-weighted module temperature for three different modules (curves and right Y-axis)

## 5 Determination of µτ

The µτ can be derived from voltage or current decay measurements of solar cells [5-6]. Special experiments are needed for this purpose. In this work, the µτ is numerically extracted from measured outdoor I-V curves. Thus, certain assumptions are necessarily required.

A methodology for determining the µτ is used elsewhere [7] with the assumptions that the forward bias diode current $I_d(V)$ is independent of irradiances and the $I_{sh}(V)$ is too small to be considered. This approach is extended in this paper that taking the $I_{sh}(V)$ into account as the outdoor modules investigated are extremely shunting. The IV data are selected and filtered near two different intensities, i.e. 1 and 0.6 suns, using the self-reference effective irradiance and outliers identification criterion [8] to minimise the spectral effect as well as random errors. All the IV data then are corrected to the module temperature of 35°C for analysis. Fig 3 plots the IV curves of the heated module selected for Jun 2008 and Jun 2009.

Applying the Eq (1) to the data measured at two different intensities and taking the difference of the $I_1(V)$ at 1 sun and $I_2(V)$ at 0.6 suns gives:

$I_1(V)-I_2(V) = [I_{ph1}(V)-I_{d1}(V)- I_{sh1}(V)]-[I_{ph2}(V)-I_{d2}(V)-I_{sh2}(V)]$
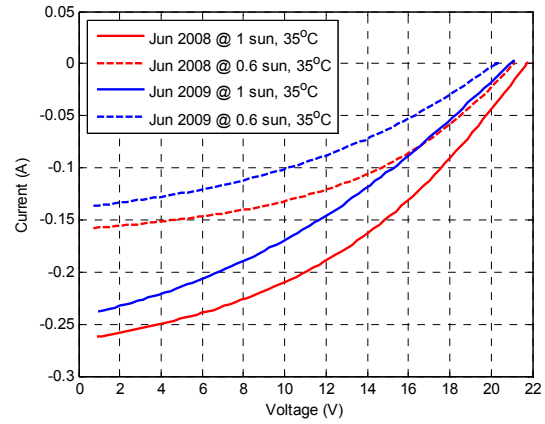
(4)



Fig 3: IV curves of the heated module at conditions of 1 and 0.6 suns, 35°C selected from Jun 2008 and Jun 2009

The $I_d(V)$ is assumed to be identical at different intensities. Therefore, applying Eq (2) to Eq (4) gives:

$$\Delta I = I_{ph1}\left[1 - \frac{di^2}{(\mu\tau)(V_{bi} - V_1 + I_1R_s)}\right] - \frac{V_1 - I_1R_s}{R_{sh}} - \left\{I_{ph2}\left[1 - \frac{di^2}{(\mu\tau)(V_{bi} - V_2 + I_2R_s)}\right] - \frac{V_2 - I_2R_s}{R_{sh}}\right\}$$

(5)

Thus, applying the measured outdoor IV data to Eq (5) with pre-determined $d_i$ and $V_{bi}$, the value of µτ can be fitted according to the least mean square criterion. This approach can be applied to any type of modules either measured indoors or outdoors. It achieves high stability as all the fitted parameters are linear parameters.

## 6 Results and Discussions

Applying the fitting approach described in the last section, the fitted results of $\mu\tau/d_i^2$, $R_{sh}$ and $R_s$ for heated, insulated and open racked modules are summarized in Fig 4 and Fig 5. The $\mu\tau/d_i^2$ decreases from 1.57 $V^{-1}$ in June 2008 to 0.52$V^{-1}$ in June 2009 for the open racked case, which is the largest degradation compared with other two cases. The insulated module shows a degradation of $\mu\tau/d_i^2$ from 0.95$V^{-1}$ to 0.72$V^{-1}$, whereas heated module degraded from 1.11$V^{-1}$ to 0.62$V^{-1}$. The changes in $R_{sh}$ and $R_s$ are quite different for the three modules. Both $R_{sh}$ and $R_s$ for the open racked module increase from June 2008 to June 2009. The insulated module has an increase in $R_{sh}$ and a decrease in $R_s$, while the heated one shows a decreased $R_{sh}$ and an increased $R_s$.
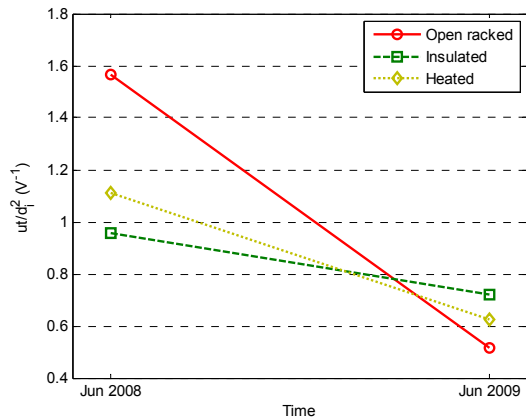
Fig 4: Fitted $\mu\tau/d_i^2$ for modules of different mounting conditions in Jun 2008 and Jun 2009
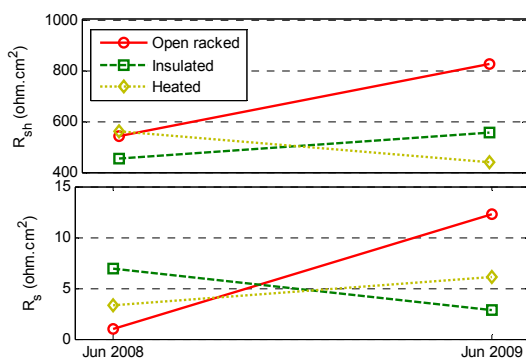


Fig 5: Fitted $R_{sh}$ and $R_s$ for modules of different mounting conditions in Jun 2008 and Jun 2009

The $\mu\tau/d_i^2$ of the insulated and heated modules is relatively lower than that of open racked module in June 2008, one month after the modules started operation. The modules then experienced the initial light-induced degradation. At this stage, the effect of light $A=a*G(t)*e^{-Ea/[R*T(t)]}$ defined in Eq (3) tents to be the dominant factor on module degradation behaviour. Thus, for the same G(t) seen by these modules, the higher temperature for insulated and heated module results in larger degradation and lower $\mu\tau/d_i^2$. In June 2009, the modules had already been stabilised and started annealing. The annealing effect is modelled by the factor of $B=b*e^{-Ea/[R*T(t)]}$ defined in Eq (3). At this stage, the environmental effect on modules consists of 1) degradation by light effect, 2) annealing by thermal effect, and 3) degradation by humidity effect. For the analysis of $\mu\tau/d_i^2$, the third effect of humidity can be ignored for the time being, as the humidity tends to degrade the electrical circuitry rather than the structure of semiconductor material. Thus, for the heated and insulated modules, as the temperatures are higher, the annealing effect on these two is greater than that on the open racked module,

which counteracts the degradation effect from light.

## 7 Conclusions

A modelling approach for degradation of a-Si thin film PV modules with voltage-dependent photocurrent is introduced in this paper. It focuses on the analysis of $\mu\tau$, which can be fitted by outdoor module IV curves. The analysis of the change in $\mu\tau$ relating to the environmental stresses is carried out. But long-term behaviour is not determined yet. Future work of indoor testing is planned to investigate the $\mu\tau$ behaviours under different light conditions.

## References

[1] J. Merten, J. M. Asensi, C. Voz, A. V. Shah, R. Platz, and J. Andreu, Improved Equivalent Circuit and Analytical Model for Amorphous Silicon Solar Cells and Modules, *IEEE Transactions on Electron Devices*, Vol 45, No 2, pp 423-429, 1998.
[2] J.A. del Cueto, S. Rummel, B. Kroposki, A. Anderberg, Long-term Performance Data and Analysis of CIS/CIGS Modules Deployed Outdoors, *SPIE Optics and Photonics Conference*, San Diego, California, USA, 2008.
[3] C.R. Osterwald, T.J. McMahon, History of Accelerated and Qualification Testing of Terrestrail Photovoltaic Modules: A Literature Review, *Progress in Photovoltaics: Research and Applications*, Vol 17, pp 11-33, 2009.
[4] T.J. McMahon, Accelerated Testing and Failure of Thin-film PV Modules, *Progress in Photovoltaics: Research and Applications*, Vol 12, pp 235-248, 2004.
[5] M.A. Green, Solar cell minority carrier lifetime using open-circuit voltage decay, *Solar Cells*, Vol 11, pp 147-161, 1984.
[6] K. Burgard, W. Schmidt, W. Warta, Applicability of electrical short circuit current decay for solar cell characterization: limits and comparison to other methods, *Solar Energy Materials and Solar Cells*, Vol 36, pp 241-259, 1995.
[7] S.S. Hegedus, Current-voltage analysis of a-Si and a-SiGe solar cells including voltage-dependent photocurrent collection, *Progress in Photovoltaics: Research and Applications*, Vol 5, pp 151-168, 1997.
[8] J. Zhu, Y. Qiu, T.R. Betts, R. Gottschalg, Outlier Identification in Outdoor Measurement Data – Effects of Defferent Strategies on the Performance Descriptors of Photovoltaic Modules, *34th IEEE Photovoltaic Specialists Conference*, Philadelphia, USA, 2009.