COMPARISON OF 6 PHOTOVOLTAIC MATERIALS ACROSS 4 ORDERS OF MAGNITUDE OF INTENSITY

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ABSTRACT: A growing number of indoor microelectronic devices with low consumption (average power of mW) require a power source to which Photovoltaic modules can contribute. However, Photovoltaic devices are rated by their power output under Standard Test Conditions (STC), and the 1 sun (AM1.5, 1000W/m^2) intensity used for these tests is several orders of magnitude above what is found indoors. A study was undertaken to establish whether the performance of commercial and laboratory modules and cells were consistent with their STC results for 4 orders of magnitude of intensity below 1 sun. A detailed electrical characterisation was performed and the results presented here show that efficiency curves to have a bimodal pattern. The samples in one mode performed better at low light intensity which maybe due to the uniformly higher R_P (around 10^6-$10^7\Omega$), the poorer mode samples having an R_P around $10^5\Omega$. This suggests that STC are not representative over the range of intensity tested.

Keywords: PV Materials - 1: Solar Cell Efficiencies - 2: Variable Illumination Method - 3

1 INTRODUCTION

The designer of indoor microelectronic systems that seeks a Photovoltaic solution to powering these devices is not well served by existing standardised comparisons. This is the case both between technologies and within a single technology as the Standard Test Conditions (STC) aim to be representative of outdoor conditions. The indoor context is characterised by a less aggressive environment, one of the most significant differences with outdoor conditions being the maximum light intensity encountered that can typically be decades of magnitude below STC intensity. The question therefore arises: can STC 1 sun Photovoltaic (PV) efficiencies (η) be used as a reliable benchmark for comparing competing PV products for use indoors?

This paper contributes to answering that question by making an electrical characterisation of 18 different solar cells representing 6 different PV material technologies. Other factors of importance to low light level applications will be treated in future publications such as the impact of light spectra, angle of light incidence, cell stability, substrate material and cell/module cost.

A number of papers have dealt with similar issues, especially with respect to energy production [1-3]; more articles can be expected, both general [4,5] and technology specific [6]. The novelty of this work lies in the fact that so far no comprehensive electrical comparative study is available other than under Standard Test Conditions with as many technologies as are treated here.

2 EXPERIMENTAL PROCEDURE

STC equipment was used including a Wacom solar simulator connected to a PC running current/voltage (I/V) measurement software. The room temperature was controlled to 22±3°C with air conditioning. The light intensity was controlled with one or more wire mesh filters between the light source and the sample. Each sample was measured with 4 point contacts except for the samples from Edmund Scientific due to lack of space on the sample. Current/voltage (I/V) measurements were made for the following percentages of 1 sun: 100%, 58.2%, 39.7%, 19.1%, 11.0%, 4.1%, 1.1%, 0.439%, 0.211%, 0.08%.

Measuring absolute Photovoltaic cell efficiency is best achieved with the use of a calibrated reference cell made from the material under test [7]. Despite this, a crystalline silicon reference cell was used for all samples tested to ensure comparability between the results. The equipment used did not require recalibration during the duration of the tests. Efficiency values are however relative to the test procedure and are not absolute values.

Samples were selected, based where possible on their applicability to indoor use and across a wide range of possible technologies. At least three samples from each of the following suppliers were tested:

Table I: Technologies and sources of cells tested showing whether the manufacturer was a laboratory or industry, the active area and number of cells of each sample tested [8].

Technology Classification	Name of Supplier or Laboratory	Indu. = I Labo = L	Active Area (cm^2)	No. of cells in module
Silicon (crystalline)	BP Solar (via IWS)	I	9.36	1
Silicon (crystalline LGBC)	BP Solar	I	0.90	1
Silicon (crystalline)	Spacecells, Edmund Scientifc, US	I	0.38	1
Silicon (crystalline)	Unknown (via Distributor)	I	10.95	1
Silicon (multicrystalline)	MAIN, TESSAG, D	I	12.47	1
Silicon (multicrystalline)	EFG, TESSAG, D	I	10.25	1
Silicon (multicrystalline)	Unknown (via Distributor)	I	2.88	1
Amorphous Silicon	TESSAG, Putzbrunn, D	I	4.95	5
Amorphous Silicon	Sanyo Electric, Hyogo, J	I	3.71	4
Amorphous Silicon	Solems, Paris, F	I	1.76	3
Amorphous Silicon	VHF Technologies, Le Locle, CH	L	3.36	4
Amorphous Silicon	Sinonar Corporation, Taipei, TW	I	1.26	4
Amorphous Silicon	Millenium, BP Solar	I	1.20	1
Polycrystalline thin film (CdTe)	Matsushita / Panasonic, J	I	5.80	5
Polycrystalline thin film (CdTe)	Parma University, I	L	0.79	1
Polycrystalline thin film (CIGS)	ZSW, Stuttgart University, D	L	0.46	1
Photochemical (Nanocrystalline dye)	Greatcell SA, Yverdon, CH	L	1.00	1
Photochemical (Nanocrystalline dye)	EPFL IPC2, Lausanne, CH	L	0.90	1

3 VARIABLE ILLUMINATION METHOD

In order to provide an explanation of sample performance, the I/V curves were analysed with the Variable Illumination Method (VIM). This technique has previously been applied to a single technology at a time, for both amorphous [9-11] or microcrystalline [12] silicon technologies. It requires I/V measurements to be made across a range of light intensities and the recording of open circuit voltage (V_{OC}), short circuit current (I_{SC}), open circuit resistance (R_{OC}), short circuit resistance (R_{SC}), fill factor (FF) and efficiency (η). It assumes an equivalent circuit as follows:

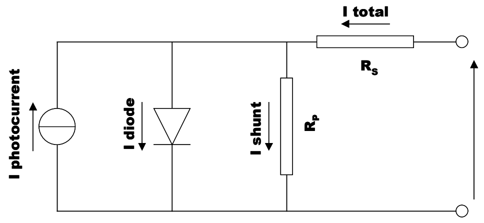

Figure 1: Equivalent circuit of Photovoltaic solar cell or module

Figure 1 [13] does not include a separate recombination effect which has been found better describes amorphous silicon samples [10]. The circuit is applied to explaining efficiency variations. Efficiency can be calculated by:

$$\eta = (I_{SC} \text{ x } V_{OC} \text{ x FF})/\text{Light power} \qquad (1)$$

The usual approach of VIM analysis is to plot graphs of V_{OC}, FF, R_{OC}, R_{SC} and η against I_{SC} (x-axis) where:

$$R_{OC} = \left.\frac{dV}{dI}\right|_{I=0} \qquad (2)$$

$$R_{SC} = \left.\frac{dV}{dI}\right|_{V=0} \qquad (3)$$

For the present study a limited light intensity range was used (always 0.08% – 100% sun) rather than the wider range used in [10] and [11].

A further difference with the VIM as applied to a single technology only was that here I_{SC} was not constant for each intensity level when comparing between technologies and between samples of the same technology. In order to make the graphs clearer, intensity (W/m^2) was therefore used as the x-axis parameter. This did not alter the shape of the graphs, as I_{SC} and light intensity are directly proportional in the whole light range used here.

Graphs were then prepared for all samples tested (a batch of at least 3 from each source) of V_{OC}, FF, R_{OC}, R_{SC} and η against Intensity (W/m^2). The most representative sample of 3 was selected from each batch.

For memory, parallel resistance (R_P) and series resistance (R_S) are values required by the Photovoltaic cell equivalent circuits. They are established at very low and very high illumination respectively. R_P is based on the value to which the R_{SC} tends as illumination is reduced. R_S is based on the value to which R_{OC} tends at highest illumination. An ideal cell therefore has a wide range of light intensity where R_S tends to zero and R_P tends to infinity, both therefore having minimum impact on efficiency.

4 RESULTS

Wherever possible, a scientist specialised in each technology was interviewed with regards to the results related to their technology.

The mono-crystalline silicon samples (Figure 2) tested demonstrated greater than 11% efficiencies at 1 sun in 3 out of 4 cases, which all dropped to around 1% at the lowest intensities (i.e. a drop of around 10% efficiency). This is due to drops across the intensity range tested of the V_{OC} (60-70%) and the FF (30-50%).

The R_{SC} and R_{OC} curves seem linear with the logarithm of light intensity and coincide around 0.1% sun indicating that the limit of performance has been reached. The approximate R_P (taken at 0.1% sun) is relatively low (around $10^5\Omega$) compared with most of the other samples tested; this is not ideal for low light efficiency performance as loss of V_{OC} and FF at low light intensities are associated with low R_P.

The distributor-supplied sample appears to have a FF related drop at the highest intensities measured.

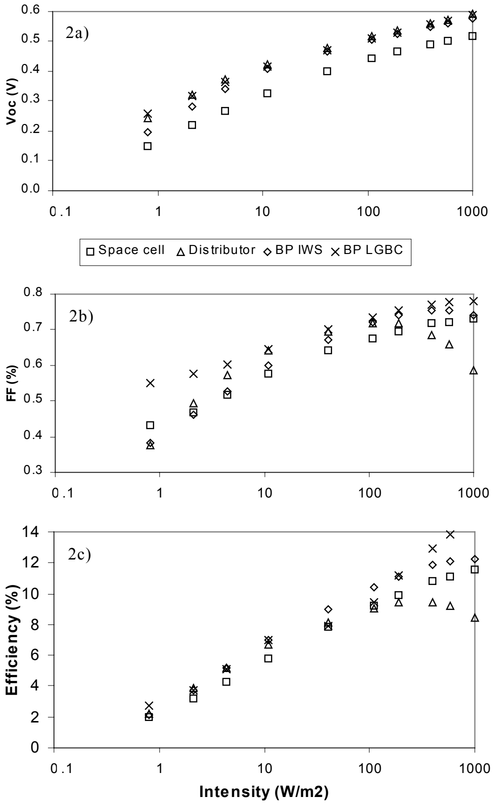

Figure 2 a), b) & c): Comparison of crystalline silicon solar cells over four orders of magnitude of intensity below AM1.5 (1000W/m^2)

The efficiency results for the multi-crystalline silicon cells are relatively similar to the mono-crystalline samples with an 11% efficiency or greater at 1 sun dropping to below 2% at the lowest intensities measured. The V_{OC} and FF curves show more variation between samples and drop further still (around 90% and 60% respectively). The R_{SC} and R_{OC} curves are again linear and coincide around 0.1% sun. The approximate R_P taken at 0.1% sun is lower (around $10^3\Omega$) than the mono-crystalline samples.

Amorphous silicon samples (Figure 3) all exhibited relatively low 1 sun efficiencies (between 2-8%) which were much less variable with intensity, falling in the worst case from 7% to 3.5%, and in one case (Sanyo) slightly increasing with the decrease of light intensity over the range tested. It is of note that all amorphous samples were mini-modules with between 3 and 5 single or stacked (tandem or triple) cells. Therefore, V_{OC} drop should be calculated per cell in series. The average V_{OC} drop for the samples is around 40% that is less than all the crystalline silicon samples. A further favourable aspect for the efficiency is the increasing or at least more constant FF with falling light intensity.

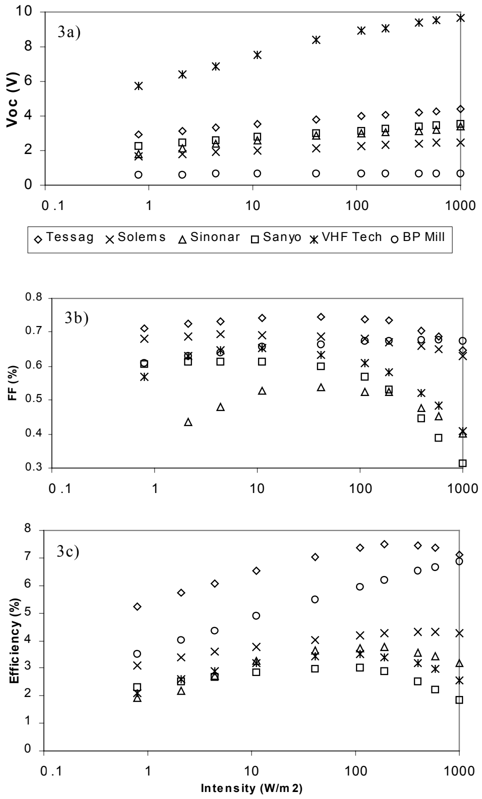

Figure 3 a), b) & c): Comparison of amorphous silicon solar cells over four orders of magnitude of intensity below AM1.5 ($1000W/m^2$)

The values to which R_{SC} and R_{OC} tend (R_P and R_S respectively) are significantly higher than for crystalline silicon samples. The value for R_P is in the range 10^6 up to $4.1 \cdot 10^6 \Omega$ (VHF Technologies) and this contributes to maintaining V_{OC} and FF at low light levels.

The results for the polycrystalline CdTe and CIGS thin film cells are reminiscent of the difference between the amorphous silicon and crystalline silicon results. Like amorphous silicon, the CdTe samples have lower starting efficiency which remains more constant with decreasing intensity, whilst the CIGS like the crystalline silicon have greater than 10% starting efficiency which drops tenfold over the four orders of magnitude of intensity. The lines traced by the points are similar in each respective case as are the explanations for each mode. Equally the resistances graph have similar patterns between amorphous silicon and CdTe on the one hand and crystalline silicon & CIGS on the other.

The photochemical samples exhibit some of the lowest 1 sun efficiencies of all samples tested due to R_s saturation at these high values, the points making an asymmetric parabola with maxima at $100W/m^2$ (10% sun). Reducing the intensity further, the efficiency then returns to approximately the 1 sun value at 0.1% sun. From 10% sun up to 100% sun efficiency decreases by around 2%; this decrease is reflected more in the FF than the V_{OC}. In the 2 decades of intensity below 10% sun, the efficiency also drops 2%. In this case it is the V_{OC} value that has the principal impact falling by 30%. The negligible variation of the FF contributes little to this drop in efficiency.

5 DISCUSSION

Whilst the efficiency results are not absolute, one may note that the line traced by each sample in any given technology were similar and that the efficiency graphs across all technologies fell into two typical signatures: on a logarithmic scale, either a straight line drop with intensity such as crystalline silicon, multi-crystalline silicon and CIGS or a parabolic shaped curve with a maximum between 0.1 to 0.3 suns for amorphous silicon, CdTe and photochemical cells. For the samples tested it can be concluded that for light powers of 1/1000th sun ($1W/m^2$), those with the latter parabolic efficiency curve perform better. One of the reasons for this may be the uniformly higher R_P that is in the range 10^6-$10^7\Omega$ for these samples, whilst those samples having a linear efficiency curve on a logarithmic scale have an R_P around $10^5\Omega$. As can be seen in Figure 4, R_P appears to have a logarithmic relationship with the band gap for the solid-state samples. However, other than the semiconductor material used, Rp may be related to other issues such as macroscopic defects caused by cutting a cell.

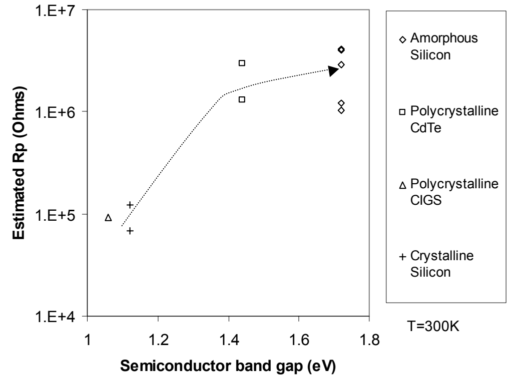

Figure 4: Comparison of estimated parallel resistance R_P against solid-state sample semiconductor band gap

One limitation of the experimental equipment in reproducing real use conditions was with regards to the proportion of diffuse light. The solar simulator is designed to provide a solar spectrum with a direct parallel beam. Indirect light is neither expected nor typically measured. Given that wire-mesh filters further channelled this relatively direct light, it is suggested that less indirect light will have reached the samples than would have been the case had they been tested outside using the clouds to filter the sun. This therefore favoured those technologies that perform better under direct light. It has been suggested [14] that this distinction can make over 12% difference in annual kWh/kWp yield outdoors.

Further issues with recreating real-use light conditions regard the spectrum. Firstly, the spectrum of light changes with light intensity due to irregular filtering by the atmosphere, especially clouds. This was not accounted for in the procedure used as the WACOM solar simulator produces an approximately AM1.5 spectrum and the light intensity was lowered by the wire-mesh filters which can be assumed to reduce the light evenly across the spectral range. The actual light spectrum encountered indoors is further complicated both by additional light filtering (by the window for example), reflection from non-perfectly reflecting surfaces and addition of light sources other than the sun that possess different spectra (e.g. fluorescent and incandescent light).

Apart from the experimental procedure, four issues related to the variety of samples can be noted. Firstly, **dimensional variation**, the impact of which was minimised by testing no samples with side dimensions greater than 5cm.

Secondly **cell construction** that ideally for comparing materials would be produced to be as similar as possible regardless of source. Practically in this case not only the materials but also the constructions (e.g. glass super- or substrate, metal substrate and wafers) were under test; the number of cells ranged from 1 to 12. Those with no series connections were therefore favoured in terms of series resistance and efficiency.

Thirdly the number of sources of samples meant some **variation in the contacts** taken on the samples; this has been found to impact the parallel resistance [11].

Lastly with regards to the samples, some technologies such as amorphous silicon and photochemical are more prone to **instability** such as light induced degradation (e.g. Staebler Wronski effect for amorphous silicon) than other technologies e.g. CdTe, CIGS and crystalline silicon. None of the samples were subjected to defined light soaking or other stability tests before measurement, favouring the results of the former technologies. This may be more of an issue for outdoor applications than for indoor applications as degradation is often proportional to intensity.

As mentioned in the introduction, for indoor applications some issues are less significant (warming of the solar cells by sun radiation, damage or hindrance of the cells by the weather) or are circumvented (voltage transformation may not be required) when compared with outdoor applications.

6 CONCLUSIONS

The relationship between efficiency and light power appears to show a bi-modal pattern (either linear with the logarithm of light intensity or parabolic). A single signature appears to be related to each technology. It is therefore concluded that STC alone are not a reliable guide to performance over the light intensity range from AM1.5 (1 sun) down to 0.1% sun.

The samples that performed best at 0.1% sun, which is typical of the light power encountered indoors, had a relatively flat efficiency curve signature. It can therefore be concluded that the samples whose technologies had this pattern (amorphous silicon, CdTe and photochemical) are likely to be better suited for indoor use than those possessing a linear drop of efficiency with the logarithm of light intensity such as crystalline silicon, multi-crystalline silicon and CIGS.

The Physical significance of R_P is not clear for all the technologies evaluated.

7 FURTHER WORK

ECN's paper [14] has suggested importance of diffuse light. A future Photovoltaic cell testing standard would therefore be more representative of real conditions if it included known levels of diffuse light.

Indoor applications are different from outdoor applications at a number of levels. This paper has only considered one significant factor (the daylight power) which leaves a number of others to be investigated such as the additional light spectra (fluorescent and incandescent), importance of indirect light, light stability, light incidence angle, substrate material and the costs.

In order to better understand the physical reasons for the results, further models and equivalent circuits are required.

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