Impact of spectral effects on the electrical parameters of multijunction amorphous silicon cells

5P-D4-09

IMPACT OF SPECTRAL EFFECTS ON THE ELECTRICAL PARAMETERS OF MULTIJUNCTION AMORPHOUS SILICON CELLS

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ABSTRACT

The influence of spectral variation on the efficiency of single-, double- and triple-junction amorphous silicon cells has been investigated. The average photon energy (APE) proves to be a useful device-independent environmental parameter for quantifying the average hue of incident spectra. Single-junction devices increase in efficiency as light becomes blue shifted, because more of the incident spectrum lies within the absorption window and less in the red/infra-red tail; this is denoted the primary spectral effect. Double- and triple-junction devices also exhibit a secondary spectral effect due to mismatch between the device structure and the incident spectrum. These both reach a maximum efficiency, which drops off as light is red or blue shifted. The effect is more pronounced for triple-junction than double-junction devices, as mismatch between junctions is statistically more likely.

1 INTRODUCTION

The power produced by a photovoltaic cell under real-life outdoor operating conditions is dependent on several key environmental parameters, namely the insolation, the operating temperature and the spectral quality of the light received. It is becoming increasingly apparent that spectral effects have been underestimated in the past, mainly due to a lack of hard spectral data, and their strong correlation with other environmental influences, especially temperature [1-3]. Spectral influences on output are particularly important in temperate maritime climates such as the UK where spectral quality of the light can vary greatly.

Amorphous silicon technologies have been shown to give greater energy yields per kW_p than crystalline silicon technologies and this has been attributed in part to a spectral effect [4]. Amorphous silicon devices typically show a strong absorption of light below 500 nm, and light under overcast conditions is known to be substantially blue shifted. However, quantifying this, and separating the spectral component from other influences is still very much under discussion.

Spectral influences have also been used to explain the seasonal variation in performance of amorphous silicon devices. The Useful Fraction (defined as the proportion of global radiation that falls within the acceptance window of a particular device) shows a seasonal cycle which correlates strongly with the observed seasonal efficiency of amorphous silicon. Light becomes more blue shifted in the summer months due to lower air mass, resulting in a greater proportion of light being absorbed by the a-Si device.

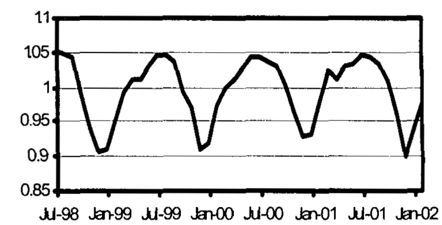

Figure 1: Seasonal variation of the Useful Fraction (relative to the mean).

However, the spectral response of amorphous silicon devices is not straightforward. The drive to reduce degradation and increase efficiency has led to the development of multijunction cells, where each junction is tuned to a different region of the solar spectrum. Electrically these junctions can be considered as separate cells connected in series. However, by Kirchhoff's Law the current flowing through each cell must be equal, limiting the overall current produced by the device to that of the least productive junction. A variation in outdoor spectra that causes a lack of irradiance in a spectral band will therefore limit the performance of the device. A simple statistical model would suggest that as the number of junctions increases, the chance of a given sub-cell limiting performance will increase.

Spectral performance is therefore determined by how the absorption profile of the multijunction device is matched to outdoor spectra. Typically, sub-cell responses are matched to an idealised laboratory spectrum such as AM 1.5, although some devices are top-cell limited, where the content of blue light determines overall output. In this latter case the spectral performance is tuned to take advantage of low air mass high irradiance conditions, although it has the advantage of simultaneously increasing performance under overcast conditions as well.

This paper presents a quantification of spectral effects for single-, double-, and triple-junction amorphous silicon devices. It also employs a novel device independent environmental parameter, the Average Photon Energy (APE), as a measure of the blueness of the available spectrum.

2 AVERAGE PHOTON ENERGY (APE)

Spectral conditions are not trivial to quantify as measured spectra consist of an ensemble of measurements over wavelength. Ideally, these should be distilled down to a single parameter that can then be used in the same manner as irradiance or temperature.

Previous papers have utilised the Useful Fraction as a measure of the spectrally useful irradiation received by a device[5-7]. It has proved extremely useful, and explains to a large extent the observed seasonal behaviour of amorphous silicon devices (see Figure 1). However, it is device dependent, meaning that the UF has to be recalculated for each different type of cell under study.

We present an alternative parameter for measuring the blueness of light: the average photon energy (APE), which is simply a measure of the average hue of the radiation. It is defined as the irradiance divided by the total photon flux density. It is calculated from the measurements of spectral irradiance by first dividing the power density of each measurement band (width 10nm) by the photon energy corresponding to the wavelength of the centre of the measurement band. By integrating over the spectrum, the total photon flux density is determined. The integrated (broadband) irradiance is divided by the total photon flux density to yield the average photon energy for the spectrum. The APE is a device-independent parameter and can show where mismatch between the device and available spectrum occurs. High values of APE correspond to blue-shifted conditions, whilst low values are red-shifted. For reference, the AM 1.5 spectrum has an APE of 1.6 eV for measurements taken in the 300-1700nm range.

3 EXPERIMENTAL DETAILS

3.1 Outdoor Measurements

Since May 1998, CREST has operated an outdoor measurement system comprising a switched multi channel I-V trace unit and concurrent meteorological data, including spectral irradiance. The I-V measurement unit was upgraded from 20 to 50 channels in October 2002, allowing a much greater number of modules to be tested, and improved data quality. Data presented here are from this improved quality dataset and run from Nov 2002 to April 2003, but are consistent with previously published long-term datasets. The I-V characteristic of each test module is measured in turn through the channel switching by a Keithley 2420 source-measure unit through a 4-wire connection. The same unit measures device back temperature via a bonded PT100 resistor. The spectroradiometer is based on a scanning monochromator, measuring every 10nm from 300 to 1700nm. All of the test modules and the spectroradiometer are fixed at latitude tilt angle (53°). Meteorological instrumentation logs ambient air temperature through a PT100 and irradiance in the horizontal and in the plane of array with Kipp & Zonen CM11 pyranometers. Device data (I-V characteristics and back temperatures) and spectral irradiance are measured every ten minutes during daylight hours. Meteorological data is logged on a ten second basis; with additional in-plane pyranometer measurements to coincide with the beginning and end of each I-V scan to guarantee stability during the measurements. All measurements are stored in a database to simplify analysis.

3.2 Data Handling

Measurements with less than 10 W/m^2 are suppressed, as the spectroradiometer tends to have an unacceptable signal to noise ratio in this region. Also, an attempt is made at filtering out spectral measurements distorted by intensity changes during the acquisition period. This is based on a linear correlation method, firstly comparing measured spectra with their nearest temporal neighbours. Since measurements are made frequently, two neighbouring good-quality measurements should correlate well. Problems are encountered when one measurement is good and one bad (it is unlikely that two bad measurements will correlate, because the regions of the spectra affected are random each time). So a second correlation is performed against a modelled clear-sky spectrum for the time in question, scaled to the measured broadband irradiance. This will not correlate as well, since cloud effects are not included, but setting the tolerances carefully allows undistorted spectra to be passed and interrupted spectra to be rejected in the majority of cases.

4 RESULTS AND DISCUSSION

4.1 Relationship between Average Photon Energy and Useful Fraction

The average photon energy is very strongly correlated with the Useful Fraction (as shown in Figure 2). Amorphous silicon devices do not absorb at wavelengths greater than 780 nm, although a-Si:Ge alloys absorb up to 990 nm. As the spectra become more blue shifted, a greater proportion of incident radiation lies within the absorption window of such devices and less in the red/infra-red tail. This also shows that the two parameters may be used interchangeably depending on whether one wishes to use a device-independent parameter or to obtain more detailed device specific information.

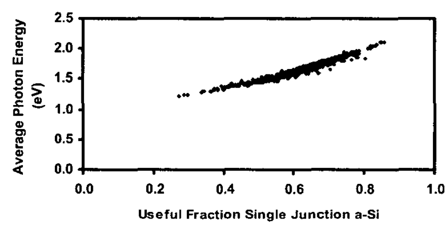

Figure 2: Variation of APE with Useful Fraction.

4.2 Variation of Efficiency with APE

The variation of device efficiency with average photon energy is shown for single-, double-, and triple-junction amorphous silicon devices in Figure 3, below. All graphs are normalised to the mean of the dataset.

All devices show a general increase in efficiency as the APE increases. This is termed a first-order spectral effect; the increased blueness of the spectrum causes a greater proportion of the incident radiation to lie within the acceptance window of the device. The response of the single junction device is virtually linear with APE, but double and triple-junction devices exhibit a different behaviour. Here the primary spectral effect is still dominant, but a secondary spectral effect is also observable. The efficiency peaks at a maximum of 1.9 eV for the double-junction cell and 1.75 eV for the triple junction cell. Mismatch between junctions when the received spectrum is either red or blue shifted results in a marked drop in efficiency.

As expected from a purely statistical model, this effect is more pronounced for triple than double junction devices, because mismatch between the device structure and the received spectrum is more likely. The efficiency of triple junction devices peaks at an APE of 1.75 eV. It is clear that increasing the number of junctions in a device

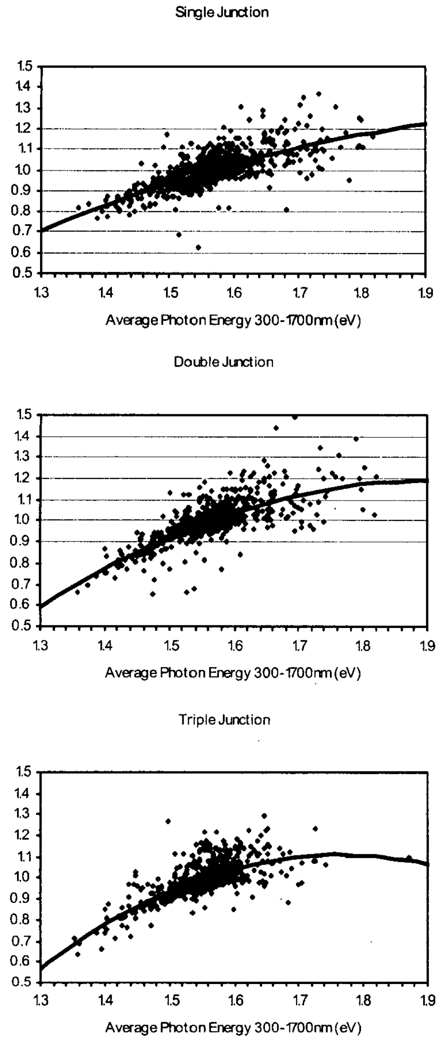

Figure 3: Normalised cell efficiency as a function of Average Photon Energy for single junction, double junction and triple junction amorphous silicon cells.

will result in an increase in efficiency (and may also increase the stability of the device), but that this will be counteracted by a decrease in spectral performance and lowering of specific yields produced under outdoor conditions.

4.3 Influence of Temperature

In order to separate spectral effects from temperature effects, the data was grouped into bins of APE and the temperature coefficient for the efficiency extracted from a plot of efficiency versus temperature for each bin. Figure 4 shows the influence of temperature for single-, double- and triple-junction amorphous silicon devices.

All devices show a decrease in temperature coefficient with increasing APE. It is expected that the temperature effect will have some connection with the incident spectrum, since temperature reduces the band gap. This alters the spectral response, and hence photocurrent, of the cell. Under red-shifted spectra, the temperature coefficient becomes positive as an increased proportion of the available irradiance is accessible, boosting the photocurrent. Under blue-shifted spectra the temperature coefficient is negative, as the energy loss from higher energy photons dominates.

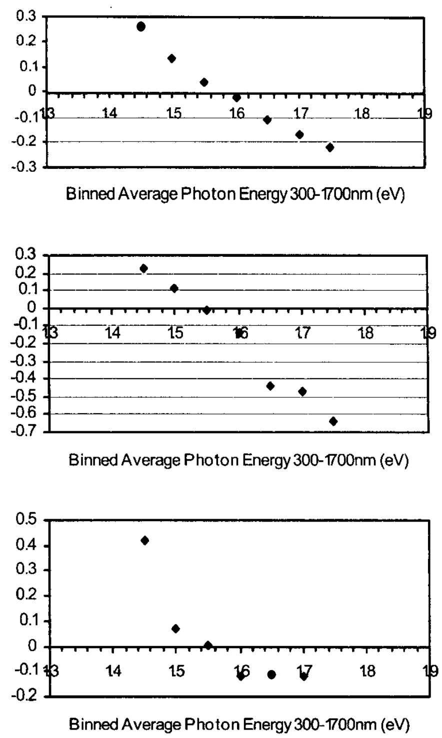

Figure 4: Temperature Coefficient of Efficiency (% deviation relative to STC value) as a function of Spectrum for single- (top), double- (middle) and triple-junction (bottom) amorphous silicon devices

4.4 Influence of Fill Factor

The variation of FF for a representative single junction device is shown in Figure 5.

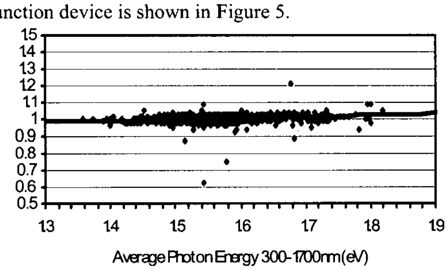

Figure 5: Normalised Fill Factor with Spectrum for a Single Junction Device

It can be seen that there is only a small variation in FF with changing APE. A similarly weak trend was observed for V_{OC}. This reinforces earlier research that spectral effects on efficiency are primarily due to changes in I_{SC} as expected from changes in the useful fraction[5].

4.5 Regional Variation of Spectral Conditions

The importance of spectral effects at a given location can be determined by examining the spectral conditions at that site. Figure 6 shows the annual energy delivered and the number of hours spent under different APEs, for two locations, Loughborough, UK and Golden, Colorado, USA. The average photon energy was separated into 0.01 eV bins. The amount of time spent in each bin at each site was summed, and the total radiation received was also calculated. The Golden, Colorado site measures spectral data between 300 and 1100 nm, so the Loughborough data has been recalculated in these terms. In this spectral range, an AM 1.5 spectrum has an APE of 1.85 eV.

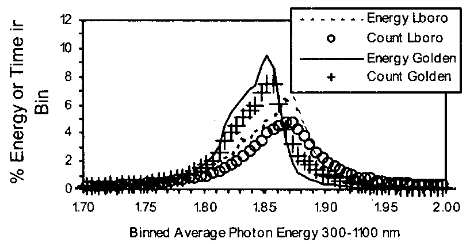

Figure 6: Comparison of Spectral Conditions at Loughborough, UK and Golden, CO, USA[1]

For both sites, red shifted values correspond to low elevation clear sky conditions, and reach a peak corresponding to high insolation, high elevation conditions. Higher APEs correspond to blue shifted overcast skies, and it is no surprise that the UK site has more energy delivered at high APEs. Interestingly, the Colorado energy peaks at an APE of 1.85 eV, whereas the UK energy peaks at an APE of 1.87 eV, despite being further south and receiving lower air mass radiation. This is due to the extreme prevalence of clear sky conditions in Colorado, as well as the higher pitch of the spectroradiometer, which results in a high direct component. Direct radiation is naturally richer in red wavelengths than diffuse radiation.

5 CONCLUSIONS

The average photon energy is a useful parameter for characterising irradiance spectra and examining spectral effects on the performance of amorphous silicon cells. It is strongly correlated with the useful fraction for single junction devices, but has the advantage of being device independent and does not require knowledge of the absorption profile of a given device. As a result, it can be used with multijunction devices and makes it possible to examine the spectral performance of a-Si. Single junction devices show a linear increase in efficiency as the received radiation becomes more blue-shifted, since a greater proportion of the irradiance lies within its absorption window. As the received spectrum becomes either red- or blue-shifted from the device design spectrum, performance drops off due to mismatch between the absorption profile and the received spectrum. The output of multijunction devices is affected to a greater extent since it is essentially limited by the junction generating the least current. It has proved possible to separate effects of temperature and changes in V_{OC} and FF to show that the spectral effects are indeed dominated by changes in the photocurrent.

ACKNOWLEDGEMENTS

The authors would like to thank J.A. del Cueto of the National Renewable Energy Laboratory (NREL) for supplying data for the spectral environment comparison. Tom Betts is funded through the UK EPSRC grant number GR/N35694.

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