INFLUENCE OF SPECTRAL EFFECTS ON THE PERFORMANCE OF MULTIJUNCTION AMORPHOUS SILICON CELLS

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ABSTRACT: The average photon energy (APE) is a useful environmental parameter for analysing spectral effects of amorphous silicon cells. Single junction cells have a higher spectral performance as light becomes more blue shifted. Double and triple junction cells have a maximum spectral performance when the absorption profile is matched to the received spectrum. Their performance drops off when the radiation is either red or blue shifted, as the current produced by a multijunction device is limited by the least productive junction. Such mismatch is statistically more likely, and therefore more pronounced, as the number of junctions in a device increases. The majority of energy received at the Loughborough, UK test facility is delivered at redder APEs than for the optimum spectral performance of amorphous silicon cells.
Keywords: a-Si, Spectral Response, Performance

1 INTRODUCTION

It is becoming increasingly apparent that spectral effects have a significant influence on the performance of photovoltaic modules. This is especially true in temperate maritime climates such as the UK, where the spectral quality of the light can vary greatly. The received spectrum is influenced by atmospheric conditions (cloud cover, humidity, pollution *etc.*) and the path-length through the atmosphere. Amorphous silicon and copper indium diselenide have been shown to give greater specific yields than conventional crystalline silicon technologies in northern European climates and this has been attributed partially to a spectral effect.[1,2] These technologies typically show a very high absorption of light below 500 nm. However, the spectral response is only one factor, and a separation from other effects is very much under discussion. Past papers typically underestimate the effect of spectral variations, simply due to the lack of any hard data on variations naturally occurring in the course of a day or year. A clear separation of effects is important to further the understanding of outdoor performance and in the long term improve the device performance.

The response to variations in the spectral irradiance is not straight forward for amorphous silicon (a-Si) devices, as research into degradation has resulted in multi-junctions, thus essentially producing 'third generation' devices. Multi-junction amorphous silicon devices have a particularly complex response to variations in spectral quality. Each junction is tuned to a different region of the solar spectrum to increase the overall efficiency of the device. However, these layers can be treated as if they were separate cells connected in series. By Kirchoff's Law the overall current produced by the device is only equal to the smallest current produced by an individual junction. This means that the least productive layer in a multi-junction device limits the performance of a multijunction cell. The devices are often matched to an idealized spectrum in the laboratory, although some devices are top-cell-limited (*i.e.* the content of blue light determines the overall output). Little consideration is given to variations in the outdoor spectrum. As the incident spectrum varies away from this idealized spectrum, the efficiency of the device will drop. It is statistically more likely that one junction will be limited as the number of junctions in a device increases.

This paper attempts a quantification of spectral effects in the course of a year for different device structures. Initially this requires the definition of a device-independent blueness indicator of the light, which is then used for the modeling of the spectral effects for devices measured in the outdoor test system operated by CREST in Loughborough, UK.

2 MONITORING DETAILS

In order to enable an investigation of spectral effects, a comprehensive measurement system has been set-up at the Centre for Renewable Energy Systems Technology (CREST) in Loughborough. The system combines data from a custom made spectroradiometer, two Kipp&Zonen CM11 pyranometers, and the I-V characteristic and temperature of the measured devices. The I-V characteristic is measured using a switching circuit developed in-house to access the different devices, the actual scanning is performed using a Keithley 2420 source-measure unit (SMU) through a 4 wire connection. Measurements were carried out every 10 minutes, and consist of the incident spectral irradiance in the range from 300 to 1700 nm, the standard environmental data and the device measurements. The environmental data, including spectral information, have been recorded since May 1998. Each device measurement is preceded by a measurement of the global irradiance and the device temperature. The I-V scan of 200 points is then followed by a second measurement of the global irradiance in order to guarantee stability during the measurements.

All measurements were then analysed and stored in a database to simplify analysis. 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.

3 BLUENESS OF LIGHT

It is important to be able to have a simple number indicating the 'blueness' of the light in order to investigate the effect of varying spectra and simulating its impact. Previous papers have analyzed the performance of amorphous silicon cells as a function of the Useful Fraction (UF).[3-6] This parameter is defined as the fraction of the insolation which falls within the spectral absorption window of a given device. This has shown that the fraction of light that can be absorbed by amorphous silicon devices is greater in the summer than the winter, explaining the seasonal performance of these devices to a large extent.[6]

The Useful Fraction has proved to be an extremely useful parameter for demonstrating the influence of spectral effects on the performance of amorphous silicon cells. However, it is not device independent and must be calculated for each different type of cell.

A different approach would be to calculate a colour temperature of the incident spectrum, as done in the lighting industry. This will, however, be very difficult as molecular absorption in the atmosphere affects different wavelengths at the same time, perturbing the spectrum further away from the ideal black body shape used for colour temperatures. Furthermore, this approach would invariably involve some estimation as it involves a comparison of a black body spectrum with a degenerated spectrum.

An alternative parameter for the characterization of the incident spectrum is suggested here; the average photon energy (APE). This is a measure of the average hue of the incident radiation. It is device independent, and can show where mismatch between device and the incident spectrum occurs.

The average photon energy 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.

High values of average photon energy correspond to a blue shifted spectrum, whilst low values indicate a red-shifted spectrum. For reference, an AM 1.5 spectrum has an APE of 1.597 eV. The disadvantage of the APE is that it does not allow a direct feedback to the available useful irradiance as the UF does. However, the UF is not appropriate for the comparison of the effects on different devices, as it includes device specific information. The APE is a device independent, environmental parameter.

There is a very strong correlation between the average photon energy and the useful fraction for single, double and triple junction amorphous silicon devices, as exemplified by a single junction device in Figure 1.

All technologies show an increase in the useful fraction as the spectrum becomes energy richer or more blue-shifted. Amorphous silicon devices do not utilize radiation at wavelengths greater than 800 nm, although

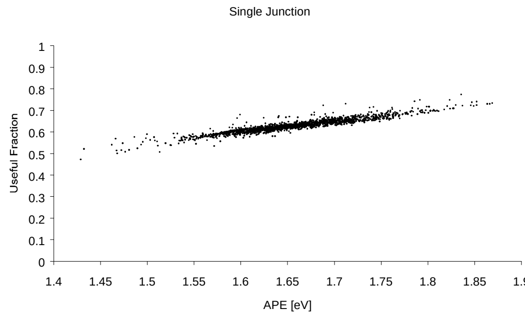

Figure 1. Relationship between average photon energy and useful fraction for a single junction a-Si device.

some amorphous silicon-germanium alloys absorb up to 1000 nm. As light becomes increasingly blue shifted, a greater proportion of received radiation lies within the absorption profile of the device, and less in the ‘infra-red tail’

3 RESULTS AND DISCUSSION

3.1 Seasonal variation of the average photon energy

The average daily and monthly variations in average photon energy are presented in Figure 2, below.

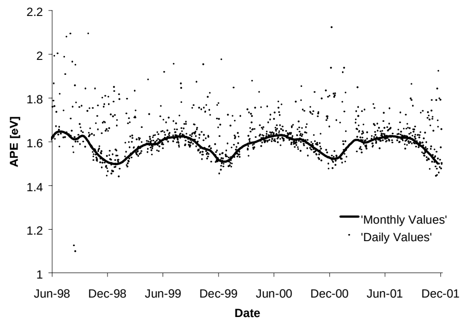

Figure 2. Seasonal Variation of the average photon energy.

The APE varies seasonally, as could be expected from the known variation of UF.[3] It reaches a maximum in the summer months, the exact position of which is dependent on the year-specific weather conditions. The light is more blue shifted in the summer due to the higher elevation of the sun and subsequent lower air mass. This plot is very similar to the seasonal variation in the useful fraction, which to a large extent explains the observed increase in efficiency of single junction a-Si devices in the summer months.

3.2 Influence of APE on devices.

The performance of the different devices is analysed by examining the I_{SC} over G ratio versus the average photon energy, as it has been shown in the past that the main influence of varying blueness is on the current.[3] The I_{SC} over G ratio is essentially a measure of the efficiency of the device. Results presented in Figure 3 have been normalized by the average I_{SC}/G for each device to allow different device structures to be compared.

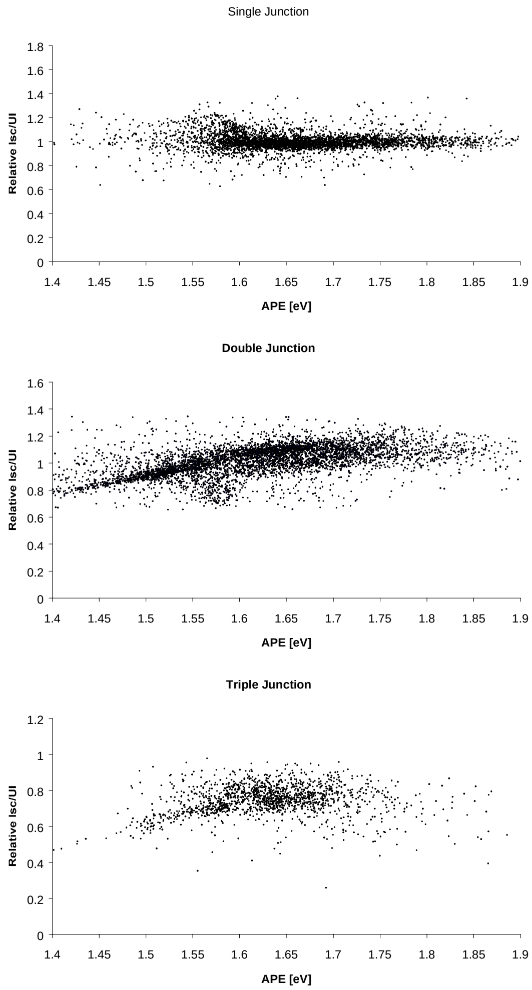

Figure 3. Empirical influence of APE on spectral I_{SC}.

There is a marked difference in behavior between the different amorphous silicon devices. However, these data also include temperature influences on the output of the devices, as well as effects due to the varying magnitude of incident irradiance. It is useful to separate temperature and spectral components, in order to examine the true magnitude and form of the spectral effect. Spectral and temperature effects can be of similar magnitudes for amorphous silicon, because temperature coefficients for this material are small.[3] If of opposite influence, the effects of temperature and spectrum may not be readily apparent.

3.3 Including spectral influences.

The short circuit current is typically modeled using an equation of the form of:

$$I_{SC} = (C_0 + C_1 T_{device})G$$

where C_0 and C_1 are empirically determined coefficients, and T_{device} is the temperature of the module. This does not allow for any spectral variations. This can be overcome by fitting the data to an equation of the form:

$$I_{SC} / G_{total} = (C_0 + C_1 T_{device}) \times f(APE)$$

where f(APE) indicates a structure dependent function in dependence of APE.

This allows the fit to be performed in two simple stages. First, a 'spectral version' was created by plotting I_{sc}/Useful Irradiance *versus* the device temperature from which the coefficients C_0 and C_1 were determined. Second, plots of I_{sc}/Gtotal(C0+C1*Tdev) *versus* APE enable the spectral correction function of APE to be determined, as shown in Figure 4

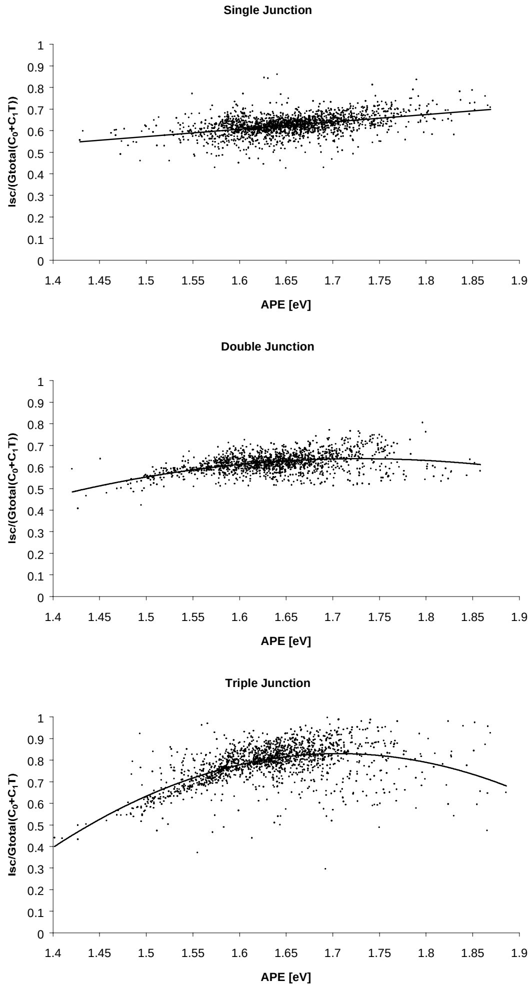

Figure 4. The purely spectral influence of APE on device efficiency.

The spectral effect for the single junction device is linear with varying APE as expected.[7] As the light is more blue shifted, the useful fraction of incident radiation increases and the current generated per global radiation increases, when corrected for temperature effects. This depends on the spectral behavior of the device under investigation. Some single junctions with a particularly small blue response will actually show a small reduction in the produced short circuit current.

Double junction devices show a different behavior. The relative I_{SC} of this particular same band gap device reaches a maximum at an average photon energy of approximately 1.72 eV. The relative I_{SC} drops off significantly at red shifted, low average photon energy values, and decreases less markedly at high average photon energies. There is therefore a mismatch between the spectral response of the double junction devices and the available spectrum under red-shifted light, but less so under blue shifted light.

The spectral performance of the investigated triple junction device peaks at an APE of 1.7 eV and shows a more pronounced mismatch than the double junction device, as expected from a purely statistical model. As the number of junctions increases, the extent of spectral mismatch increases under non-ideal conditions. Therefore, the increase in efficiency of introducing extra junctions into a multijunction device is offset by a loss in annual energy yields due to increased mismatch between the absorption profile of the device and the available spectra. In the case of a-Si this might not be as important as for other devices, as the spectral loss due to an increased number of junctions will to some extent be offset by a reduction in the device degradation. This highlights the importance of a separation of effects. It will, however, be important when considering multijunction devices that are not prone to degradation.

3.4 Spectral conditions in the UK.

The importance of the spectral performance at a given location can be determined by examining the spectral conditions specific to that site. This is illustrated for the example of Loughborough in Figure 5. The average photon energy for the year 2000 was separated into 0.01 eV bins. The amount of time spent in each bin was summed. Similarly, the annual global radiation received in each of these APE bins was also determined. In both cases datapoints where the G_{total} was less than 10 Wm^{-2} were excluded.

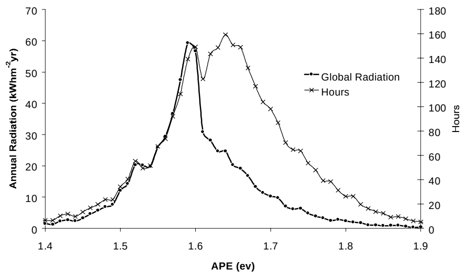

Figure 5. Spectral conditions at Loughborough, UK.

An interesting difference is seen when comparing the time spent in a given bin with the energy delivered in this given bin. The majority of time is spent under spectral conditions with an APE of 1.65 eV. However, the amount of energy received under such conditions is significantly lower, as blue shifted light is found primarily under overcast, diffuse lighting conditions. The majority of annual energy is received at APEs between 1.55 and 1.65 eV, which is similar to the APE of AM 1.5 radiation. In sunnier climates than the UK, there is likely to be less energy received at high APEs, although higher elevation of the sun at more southerly latitude will result in a blue shift of the direct component of the insolation.

This shows a slight mismatch between the received spectra and the actual spectral performance of the multijunction cell, that was shown in Figure 4 to have a maximum performance with APEs in the range of 1.7 eV. The spectral performance of multijunction cells in the UK could therefore be improved by designing cells where the maximum spectral performance occurs at lower APEs of *ca.* 1.58 eV. This would ensure maximum cell efficiency at the APE where the majority of the energy is delivered.

4 CONCLUSIONS

The average photon energy is a useful parameter for examining spectral effects on the performance of amorphous silicon cells. It is strongly correlated with the useful fraction, but is a device independent parameter that does not require knowledge of the absorption profile of a given device.

It is possible to examine the purely spectral performance of amorphous silicon devices after removing temperature effects from the data. Single junction devices show a linear increase in corrected I_{SC}/G_{total} as the received radiation becomes more blue shifted, as a greater proportion of the insolation lies within its absorption window.

Double and triple junction devices do not vary linearly. The devices investigated here reach maxima at 1.72 and 1.7 eV, respectively. As the received spectrum becomes either red or blue shifted from this ideal, performance drops off due to mismatch between the absorption profile and the received spectrum. The output of multijunction devices is essentially limited by the layer generating the least current. The performance of triple junction cells is more susceptible to changes in the incident spectrum than double junction cells, although this will be countermanded with lower degradation in the case of a-Si devices.

The maximum spectral performance of multijunction devices occurs at APEs higher than the APE where most energy is received. There is an opportunity to improve the spectral performance of multijunction devices such that they are most efficient at APEs where the majority of the energy is delivered.

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Acknowledgements
The authors would like to thank the BOC Foundation and Solar Century for their financial support of the work carried out at Oxford University. Tom Betts would like to acknowledge the support of EPSRC under contract no. GR/N35694. Ralph Gottschalg is funded through EPSRC contract no. GR/N04232.