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Spectral matching and outdoor solar to electrical conversion efficiency in thin-film silicon multi-junction solar cells

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Abstract. Semi-empirical computer modelling is used to investigate spectral matching in tandem and triple-junction thin film silicon solar cells. In amorphous/microcrystalline silicon (a-Si:H/μc-Si:H) tandem cells, current mismatch is offset by an increase in fill-factor, resulting in a broad peak in efficiency versus average photon energy. For a-Si:H/a-Si:H tandem cells, photo-generated currents in both sub-cells increase with increasing average photon energy, and efficiency is predicted to increase monotonically over a wide spectral range. a-Si:H/a-Si:H/μc-Si:H triple cells exhibit spectral behaviour similar to a-Si:H/μc-Si:H tandem cells, but with a smaller fill-factor dependence. Variations in spectral quality are predicted to account for only a small reduction in annual electrical energy yield, of some 2 to 4%.

1. Introduction
Stacked multi-junction solar cells enable thermalisation and transmission losses to be reduced over the constituent single-junction cells, leading to an overall increase in photovoltaic conversion efficiency. This has been utilised in the development of multi-cell combinations of thin-film (amorphous and microcrystalline) silicon, yielding laboratory efficiencies of over 14% [1-4]. Further, increased terminal voltages (> 1.5 volts) are sufficient to drive photochemical water-splitting reactions directly, an application that has attracted considerable recent interest [5-7].

Careful matching of photogenerated currents is needed to optimise efficiency for a given spectrum [1,2], which in the laboratory is normally AM1.5G. However substantial variations in the solar spectrum occur naturally; multi-junction cells seldom operate outdoors in a current-matched condition, impacting on annual energy return. We present a model [8,9] that enables these effects to be evaluated. Realistic outdoor spectra are generated using a linear weighting function, and characterised in terms of average photon energy (APE) [10,11]. The short-circuit currents generated by sub-cells as a function of APE are calculated by numerical integration, and used to scale the J-V characteristics of reference single cells from which the overall J-V characteristic is obtained. Statistical distributions of spectral irradiance vs. APE are used to estimate long-term outdoor performance at a given location.

2. Experimental
2.1. Solar cell deposition
All cells were deposited in p-i-n superstrate configuration by plasma-enhanced chemical vapour deposition onto TCO coated glass. The top cell absorber layer of the a-Si:H/μc-Si:H tandem cell was
deposited at 180 °C with a silane concentration (SC) of 10%. For the a-Si:H/a-Si:H tandem cell and the a-Si:H/a-Si:H/µc-Si:H triple cell, the top a-Si:H absorber layer was deposited at 130°C with a SC of 4%, and the following a-Si:H layer at 180°C with a SC of 10%. Representative measured solar cell parameters are provided in table 1. Additional details are given elsewhere [2, 7].

Single junction ‘reference’ solar cells corresponding to top, middle and bottom were deposited under the same conditions. Layers representing the top, and (top + middle) sub-cells, used to filter the solar spectrum when measuring \( J-V \) characteristics of single cells representing the middle and bottom sub-cells, were deposited on glass slides and placed in the optical path.

Table 1. Representative measured cell parameters. \( V_{oc} \) is open-circuit voltage, \( J_{sc} \) short-circuit current, \( FF \) fill-factor and \( \eta \) conversion efficiency.

| Cell configuration | a-Si/µc-Si | a-Si/a-Si | a-Si/a-Si/µc-Si |
|--------------------|-----------|-----------|-----------------|
| \( V_{oc} \) (V)   | 1.40      | 1.87      | 2.28            |
| \( J_{sc} \) (mA/cm\(^2\)) | 11.8      | 6.96      | 8.44            |
| \( FF \) (%)       | 67.4      | 76.3      | 68.0            |
| \( \eta \) (%)     | 11.1      | 9.9       | 13.1            |

2.2. Solar cell characterisation

Current–voltage (\( J-V \)) measurements under standard test conditions (100 mW/cm\(^2\), 25°C) were made using a double source (Class A) AM1.5 sun simulator. External quantum efficiency (EQE) measurements were conducted over the wavelength range 300 nm to 1100 nm using chopped light from a monochromator. Individual sub-cell EQEs of tandem and triple cells were determined separately, by using bias light sources to saturate those sub-cells not under measurement.

2.3 Modelling procedure

The modelling procedure has been described in detail elsewhere [8,9]. It consists of three main steps: (i) Solar spectra with \( APEs \) between 1.75 and 2.05 eV are generated by applying a linear spectral weighting function pivoted at 630 nm to the AM1.5 spectrum. The resulting spectra are similar in shape to those corresponding to a given \( APE \) [12,13]. (ii) The \( J_{qe} \) values for each sub-cell are calculated by numerical integration of the product of the EQE and a given spectrum, between 350 and 1050 nm. (iii) The relevant \( J_{qe} \) values are then used to shift each \( J-V \) curve along the current axis such that \( J_{sc} = J_{qe} \). It is then straightforward to calculate points on the multi-junction \( J-V \) curve by adding the voltages for each sub-cell at the same current value.

3. Results and discussion

3.1. Sub-cell currents

The EQE data, from which \( J_{qe} \) values are computed for given model spectra, are presented in figure 1. The wavelength regimes over which each sub-cell generates photocurrent can be clearly identified. Figure 2 shows sub-cell currents vs. \( APE \) obtained when the solar spectrum is modelled for the three configurations studied here. The performance of multi-junction cells under given spectral conditions is constrained by the smallest of the currents generated by the component sub-cells. The a-Si:H/µc-Si:H tandem cell (figure 2(a)) is top-cell limited below \( APE = 1.90 \) eV, and bottom-cell limited above this. A peak in short-circuit current, of approximately 11.3 mA/cm\(^2\) is predicted at around 1.90 eV. The a-Si:H/a-Si:H tandem cell (figure 2(b)) exhibits rather different behaviour. While the sub-cell currents are equal (around 7 mA/cm\(^2\)) at \( APE = 1.82 \) eV, the short-circuit current is predicted to increase monotonically with increasing \( APE \) over the range investigated. This is a consequence of differing...
band-gaps of the bottom cells in these two cases, with the former requiring a thicker top-cell to generate sufficient current to achieve optimal matching.

In the a-Si:H/µc-Si:H tandem cell, lower-energy photons generate a substantial fraction of the µc-Si:H bottom-cell current, as the higher-energy photons are absorbed by the thick (300 nm) top cell. This ‘shadowing’ causes the bottom-cell current to fall with increasing APE. In the a-Si:H/a-Si:H tandem cell however, the top cell is thinner (90 nm) and sufficient higher-energy photons are transmitted to the bottom-cell to increase the photogenerated current with increasing APE. As can be seen from figure 1(b), the a-Si:H bottom cell does not absorb significantly at wavelengths above 750 nm, so lower-energy photons have little bearing on performance of the a-Si:H/a-Si:H tandem. As APE increases beyond the range normally encountered outdoors, the a-Si:H bottom-cell current would ultimately begin to fall as the top-cell absorbs an increasing proportion of the total photon flux.

It can be seen from figure 2(c) that the a-Si:H/a-Si:H/µc-Si:H triple cell passes from top-cell limited to middle-cell limited (but still increasing short-circuit current) to bottom-cell limited (decreasing short-circuit current) as the APE is gradually increased. The triple-cell thus shares some of the properties of both tandem cells, but detailed behaviour will depend on layer thicknesses.

### 3.2 Fill-factor and efficiency

The variations in short-circuit current described in section 3.1 give a good indication of how the PV conversion efficiency of the tandem and triple cells will vary as a function of APE. However, while the open-circuit voltage does not vary greatly with APE [14], fill-factor may be quite strongly affected. Figure 3(a) reveals that FF increases significantly when the tandem cell becomes mismatched, particularly when bottom-cell limited, in agreement with [15]. This moderates the down-turn in efficiency when the short-circuit current decreases either side of the matching point. It should also be noted that the current-matched condition does not correspond exactly to the maximum-power
condition. We have previously shown [9] that maximum power is predicted to occur when the tandem cell is mis-matched by 0.8 mA/cm$^2$, in favour of the top-cell. The a-Si:H/a-Si:H tandem cell (figure 3(b)) shows an increased FF when bottom-cell limited but a slight decrease when top-cell limited. Overall, efficiency increases quite strongly with increasing $APE$. The a-Si:H/a-Si:H/µc-Si:H triple-cell (figure 3(c)) simulation curves are similar to the a-Si:H/µc-Si:H tandem-cell, but FF variations are comparatively minor, leading to a narrower peak in efficiency. Figures 3(a) and 3(c) indicate that the power-matching for these cells occur at a bluer $APE$ (1.93 eV) than the AM1.5G spectrum (1.88 eV).

3.3 Annual-average conversion efficiency

Figure 4 presents the PV conversion efficiencies of the three multi-junction cells as a function of $APE$. In order to determine whether these variations affect longer-term energy yield, a comparison between the efficiency curves and the annual-average spectral irradiance distribution must be made. This reveals variations in the position of the peak of the distribution depending on geographical location. A generic curve based on literature data has been added to figure 4 for comparison. For optimum annual energy yield, the peak in spectral irradiance distribution should be aligned with the peak in conversion efficiency. Figure 4 indicates that for the a-Si:H/µc-Si:H and a-Si:H/a-Si:H/µc-Si:H cells, the majority of the annual spectral irradiance is converted to electricity at a normalised efficiency of $>$98% of the peak value. More detailed calculations suggest that a 2-4% loss in annual energy due to spectral mismatch is a realistic estimate [9]. For the a-Si:H/a-Si:H cell there is no peak in efficiency, and provided the efficiency increases roughly linearly the gain at higher $APE$ will tend to cancel the loss at lower $APE$. Thus spectral mis-match is predicted to have smaller impact in this case.

Figure 4 may be used to estimate the consequences of deploying cells or modules optimised for use at a specific value of $APE$, at a location where the most probable $APE$ is not aligned with module peak efficiency. When the different spectral bandwidths are taken into account, distributions measured at a range of sites, including NREL (Colorado USA) [11,12], Ispra (Italy) [12], Loughborough (UK) [11],

![Figure 3](image1.png)

**Figure 3.** Modelled short-circuit current, fill-factor and efficiency for tandem and triple cells. All scales are normalised to 1.0 at the current-matched point.

![Figure 4](image2.png)

**Figure 4.** Modelled efficiencies for tandem and triple cells, normalised to overlap low-energy section of curves. Annual average irradiance distribution enables comparison.
and Kusatsu (Japan) [16] span a peak APE range of some 0.05 eV, similar to the widths of the distributions. For a tandem or triple cell matched for maximum efficiency under AM1.5G spectrum, the resulting variation in annual electrical energy production across these sites is of a similar magnitude to that due to the widths of the distributions.

Gottschalg et al [17] have differentiated band-gap effects and current mis-match effects for single and multiple cells, as ‘primary’ and ‘secondary’, respectively. Our model results indicate that the influence of these factors on long-term outdoor electrical output from multi-junction cells is complex. Spectral effects in multi-junction cells are generally minor compared with other site-related effects, such as temperature variations and degradation/annealing cycles [18], though some studies [19] suggest a greater significance.

3.4 Comparison of model predictions with laboratory and outdoor data
A number of the predictions made here, relating to variation of fill factor and the distinction between current-matching and power-matching, have been demonstrated in the lab for the case of a-Si:H/µc-Si:H tandem cells [14, 15, 20]. This supports the view that the approximations inherent in our model are not an over-simplification. Outdoor data are inherently quite noisy due to limitations in controlling or cancelling the influence of variables other than the set being studied, plus the non-unique nature of APE as a measure of spectral quality, which can make it challenging to identify trends. However, a peak in efficiency vs. APE, of a similar magnitude and profile to that predicted by our model, has been identified in outdoor test data from a-Si:H/µc-Si:H modules [16]. The tandem and triple-junction ‘amorphous silicon’ modules studied by Jardine et al [10] and Betts et al [11] behave quite similarly to our a-Si:H/µc-Si:H and a-Si:H/a-Si:H/µc-Si:H cells. Both show a peak in normalised current vs. APE, with that of the triple cell being more distinct, when compared with an amorphous silicon single junction. Krishnan et al [21] have performed modelling using actual spectra recorded in the Netherlands, for a-Si:H/a-SiGe:H/µc-Si:H triple cells. They have examined two cells, one well-matched to AM1.5G, and one poorly-matched. For the well-matched cell, the photogenerated current data agree quite well with our figure 3(c), although there are differences in detail, particularly regarding middle-cell current. This can be anticipated since the bandgap is smaller for the a-SiGe:H alloy than for our a-Si:H layer. Overall, results in the literature are in keeping with model predictions.

4. Conclusions
A semi-empirical model has been used to study the influence of solar spectral variations on current-matching in tandem and triple-junction thin film silicon solar cells, in terms of average photon energy. In a-Si:H/µc-Si:H tandem cells, current mis-match reduces photovoltaic conversion efficiency due to top-cell limitation at low APE and bottom-cell limitation at high APE. This is mitigated by an increase in fill-factor either side of the current-matched condition, resulting in a broad peak in efficiency vs. APE whose maximum occurs under slightly bottom-cell limited operation. As the majority of solar terrestrial spectral irradiance falls within a comparatively narrow APE range, within ±0.04 eV of the peak cell response, spectral variation is predicted to be a minor concern, accounting for a reduction in annual electrical energy yield of some 2 to 4%.

For a-Si:H/a-Si:H tandem cells, photo-generated currents in both sub-cells increase with increasing APE over the range of interest. The short-circuit current thus increases monotonically, with a reduction in gradient rather than a peak being observed at the current-matched point. FF is not strongly influenced, with a slight increase occurring under bottom-cell limitation. A peak in efficiency with APE is thus not anticipated for this combination. The model predicts that a-Si:H/a-Si:H/µc-Si:H triple cells will exhibit spectral behaviour similar to a-Si:H/µc-Si:H tandem cells, but with smaller variations in fill-factor. The modelled efficiency vs. APE peak is slightly narrower, leading to a greater (but still small) reduction in annual electrical energy yield than for the tandem cell.
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