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

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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>
<thead>
<tr>
<th>Cell configuration</th>
<th>a-Si/μc-Si</th>
<th>a-Si/a-Si</th>
<th>a-Si/a-Si/μc-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{OC}$ (V)</td>
<td>1.40</td>
<td>1.87</td>
<td>2.28</td>
</tr>
<tr>
<td>$J_{SC}$ (mA/cm²)</td>
<td>11.8</td>
<td>6.96</td>
<td>8.44</td>
</tr>
<tr>
<td>$FF$ (%)</td>
<td>67.4</td>
<td>76.3</td>
<td>68.0</td>
</tr>
<tr>
<td>$\eta$ (%)</td>
<td>11.1</td>
<td>9.9</td>
<td>13.1</td>
</tr>
</tbody>
</table>

2.2. Solar cell characterisation

Current–voltage ($J-V$) measurements under standard test conditions (100 mW/cm², 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 $APE$s 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/cm² 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/cm²) 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
EQE measurements on: (a) a-Si:H/µc-Si:H tandem cell; (b) a-Si:H/a-Si:H tandem cell; (c) a-Si:H/a-Si:H/µc-Si:H triple cell.

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

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Figure 1. EQE measurements on: (a) a-Si:H/µc-Si:H tandem cell; (b) a-Si:H/a-Si:H tandem cell; (c) a-Si:H/a-Si:H/µc-Si:H triple cell.

Figure 2. Modelled sub-cell currents for multi-junction cells: (a) a-Si:H/µc-Si:H; (b) a-Si:H/a-Si:H; (c) a-Si:H/a-Si:H/µc-Si:H.
condition. We have previously shown [9] that maximum power is predicted to occur when the tandem cell is mis-matched by 0.8 mA/cm², 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 mis-match 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]
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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References