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Response to simulated typical daily outdoor irradiation conditions of thin-film silicon-based triple-band-gap, triple-junction solar cells

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ABSTRACT

We studied the response to various realistic outdoor conditions of thin-film silicon-based triple-band-gap, triple-junction cells that were made in house. The triple-junction cells consist of a stack of proto-Si:H/proto-SiGe:H/nanocrystalline (nc)-Si:H cells in an n–i–p configuration, fabricated using hot-wire chemical vapour deposition (CVD). Current matching was determined for modeled spectra of four different days of the year that are typical for the northwestern European climate. Spectral modeling was based on measured irradiation data. The results showed that on a clear day in June, when the actual spectrum was closest to the reference AM1.5 spectrum, the matching was ideal. As the spectral shape varied during the course of the day with respect to the AM1.5 reference the matching became progressively worse. We found that the top cell (1.8 eV) and bottom cell (1.1 eV) are most sensitive to spectral changes, whereas the middle cell (1.5 eV) is less sensitive. Overall, it was evident that either cloudiness or seasonal variations led to an increase in current mismatch between the cells. If the sub-cells are closely matched, it may even occur that a cell designed to be current limiting no longer fulfills that role.

1. Introduction

Solar cell performance is affected by irradiation intensity, cell temperature, and solar spectral distribution, in order of decreasing importance. In performance models usually a spectral mismatch factor is included, which represents an aggregated annual energy loss of several percent. This is in contrast to variations in spectral distributions due to varying meteorological conditions, besides variations induced by location, time, and season, see e.g., Ref. [1]. The magnitude of solar spectral effects on different photovoltaic (PV) technologies depends on the band gap of the cells, i.e., solar cells made from materials with a larger band gap lead to a larger spectral effect [2]. Therefore, a PV device with a narrow spectral response such as amorphous silicon (a-Si) is more sensitive to changes in the spectral composition of irradiation, compared to a wider spectral response device such as crystalline silicon (c-Si).

Multi-junction solar cells are optimized using the standard Air Mass 1.5 (AM1.5) spectrum, as its use is prescribed in the present measurement standard test conditions (STC). Current matching is essential in these devices, and spectral response optimization of each cell in the device is performed on the basis of this standard spectrum. As the spectral distribution varies from the standard, the currents in the various cells in the device vary as well, leading to increased spectral and current mismatch and concomitant loss of power. Hirata and Tani [3] and Hirata et al. [4] reported varying performance of an a-Si tandem module by direct measurement of the module performance; a difference of −6% to +14% in output of the module was found with respect to calculated performance using the standard AM1.5 spectrum, depending on different seasons. Minemoto et al. [5] showed that a-Si:H/μc-Si:H ‘micromorph’ modules are spectrally more sensitive than c-Si modules. Detailed results on the spectral variation in the Israeli desert and its effect on the outdoor performance of PV modules have been published by Berman et al. [6]. Gottschalg et al. [7] have shown that the useful fraction (UF), defined as the ratio of observed radiation in the useful spectral range for the PV device studied to the global radiation, for different thin-film devices, varies considerably. Clearly the higher the UF, the more energy will be produced, and UF is always lower than 1. The UF of CIGS cells varied between +1.5% and −1.5% compared to the annual average, while the UF of CdTe cells varied between +4% and −6%. For a-Si:H, the most strongly affected device, the variation is between +6% and −9% [7]. The geography of the testing is a significant variable. A similar study in Japan showed a variation up to 14% for a-Si:H cells and 5% for polycrystalline-Si (poly-Si) cells [3,4].

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The present paper aims to assess the effect of spectral variation on silicon thin-film triple proto-Si:H/proto-SiGe:H/nanocrystalline (nc)-Si:H cells in an n–i–p configuration, fabricated using in-house hot-wire chemical vapour deposition (HWCVD) equipment. The effect is studied quantitatively by looking at the current matching of the triple cell as the daily spectrum changes. To this end, spectra are modeled based on measured irradiation data using the spectrum simulation model SEDES2 [8]. The band gap of the three layers is about 1.8, 1.5, and 1.1, from top to bottom. High-energy light of short wavelengths in the ultraviolet and blue regime (about 350–450 nm) is absorbed in the top cell of the triple structure. Green light at wavelengths of 500–600 nm is absorbed in the middle cell. Lower-energy light of longer wavelengths in the red and infrared regime (800–1000 nm) is absorbed in the bottom cell. The cell output currents are matched, and the cell with the lowest current is the *current-limiting* cell. Changes in the incident spectrum can alter the output of each sub-cell. For example, a higher intensity in the blue wavelength regime causes the top cell to have a higher output than the other cells. This is the challenge that is posed by spectral variation—how to design cells such that they provide optimum matching under a wide range of conditions?

2. Experimental method

2.1. Solar cells

At Utrecht University (UU), several proto-Si:H/proto-SiGe:H/nc-Si:H triple cells were fabricated. The a-Si:H and nc-Si:H layers were made using HWCVD and the a-SiGe:H and doped layers were made using plasma-enhanced CVD. All cells have a transparent conductive oxide (TCO) made out of indium tin oxide (ITO); 80 nm thickness was determined with quarter wavelength interference theory to provide the maximum performance in the range of 550–600 nm, which is the region of the standard spectrum with the highest intensity. Gold contacts were deposited on top of the ITO in 'V' and 'Christmas tree' shapes. Fig. 1 shows a triple-cell sample. Each square is a $4 \times 4\,mm^2$ solar cell with a gold contact. The cells have a transparent back reflector (TBR) made out of Ag/ZnO with a thickness of 100 nm to optimally reflect light in the range of 700–1000 nm [9]. Details of each sub-cell are provided in Table 1.

Two triple cells were used: a well-matched and a poorly matched cell. The current matching was determined under AM1.5 conditions. The normalized current densities of the cells are shown in Table 2. The lowest current was set to 1. These results were obtained through spectral response measurements. It can be seen that in the well-matched cell, the maximum variation of current between the cells is about 11%. By contrast, the current varies by as much as 45% in the poorly matched cell.

One of the drawbacks of the UF method is that it is complicated to study multi-junction devices. Each sub-cell has a different spectral response, which overlaps with that of its neighbours. So it is difficult to define boundaries of spectral range for each sub-cell. Therefore, the UF method was not employed. Instead, the average photon energy (APE) was used. APE is defined as the ratio of total irradiance in the spectrum to total photon flux density in a particular spectral range [5,10]. It provides information about the energy content of the spectrum at each wavelength.

2.2. Spectral data simulation

Solar spectral data are not available in most countries. Therefore we modelled the spectra by employing the SEDES2 spectral model [8]. This model is an extension of SPCTRAL2 [11], which is able to model clear-sky spectra. SEDES2 includes modelling of spectra for cloudy skies, and was updated recently [12]. Required model inputs are total, diffuse and direct irradiance, ambient temperature, pressure, and relative humidity, on any time base. The spectra are calculated in the wavelength range of 300–1400 nm with a step size of 10 nm.

Since March 2005, the Royal Netherlands Meteorological Institute (KNMI) has established its own irradiance measurement station, which continuously records the total, diffuse, and direct irradiance every minute at geographical location of 51.971°N, 4.927°E in Cabauw, a village close to the city of Utrecht. It is part of the Baseline Surface Radiation Network (BSRN) [13]. The data are used in order to derive minutely simulated solar spectrum for a 1-year period from March 1st, 2005 to February 28th, 2006, constituting a full year. Ambient temperature, relative humidity, and pressure were measured on a site near (<100 m) the irradiance measurement set-up. Spectra are calculated by SEDES2 for a 37°-tilted surface directed towards the south. Irradiances less than $10\,W/m^2$ were ignored. We can thus compare the spectra with the ASTM AM1.5G standard [14]. More details are given in Refs. [15,16], in which the spectral effects on amorphous and c-Si solar cells are also discussed as measured on a site near the irradiance measurement set-up.

In the present study, the global intensity for wavelengths between 350 and 1050 nm was used for four typical days to reflect summer and winter days: one clear and one cloudy day in June 2005, and one clear and one cloudy day in December 2005. The data was averaged for each illuminated hour of the day and reported at half-past each hour. In the winter, there were five such data columns for the hours between 0900 and 1500 h. In the summer, there were 12 data columns for the hours between 0600

Table 1
Composition and thickness of each layer of the triple cell's sub-cells

Layer	Top cell	Middle cell	Bottom cell
n	a-Si:H, 5 nm+μc-Si:H, 27 nm	μc-Si:H, 30 nm	μc-Si:H, 30 nm
i	a-Si:H, 180 nm	a-SiGe:H, 250 nm	μc-Si:H, 1700 nm
p	a-Si:H, 23 nm	a-Si:H, 23 nm	a-Si:H, 23 nm

Table 2
Normalized initial sub-cell current densities of the triple-junction cells, and absolute total-cell current

Cell	Top	Middle	Bottom	J_{sc} (mA/cm^2)
Well-matched cell	1.11	1.00	1.04	8.0
Poorly matched cell	1.45	1.00	1.29	8.4

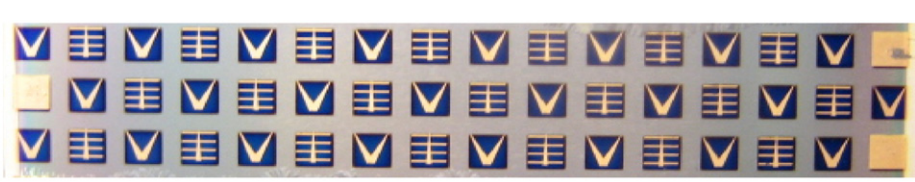

Fig. 1. Triple-cell image showing $4 \times 4\,mm^2$ cells with gold contacts in both V and 'Christmas tree' shapes.