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Thin-film silicon-based quadruple junction solar cells approaching 20% conversion efficiency

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ABSTRACT

Thin-film silicon-based solar cells are a well-established photovoltaic (PV) technology. The best reported initial and stabilized conversion efficiency is 16.3% and 13.4%, respectively. Thin-film silicon PV technology needs to achieve initial conversion efficiency approaching 20% in order to stay competitive with other PV technologies. The multi-junction approach is regarded as the main strategy for improving cells efficiency. In this contribution, we study thin-film silicon-based solar cells based on a quadruple junction device and discuss their potential for achieving a high efficiency. We carried out optical modelling of this novel device structure using state-of-the-art materials and light management techniques. We demonstrate a quadruple junction cell with simulated photo-generated current density of 8.7 mA/cm^2 in current-matching condition and potential initial conversion efficiency of 19.6%. A significant spectral overlap is observed between the component cells that makes the design of the current-matched device complex. We can control the spectral overlap by employing band-gap engineering of absorber layers and design an improved current-matched quadruple junction solar cell with potential initial conversion efficiency equal to 19.8%.

1. Introduction

Thin-film silicon-based solar cells are a well-established photovoltaic (PV) technology that can especially count on abundant raw material, relatively simple and cost-effective fabrication processes [1], and a lower temperature coefficient with respect to other PV technologies [2,3,4]. As a matured low-cost technology with potential for further cost reduction, thin-film silicon-based solar cells are suitable for very large-scale implementation. According to the most recent confirmed conversion efficiencies, the best R&D (sub-)modules demonstrate up to 12%, while commercial modules achieve 10.5% [5]. The conversion efficiency of small area solar cells (~1 cm^2) is higher with 16.3% and 13.4% record initial and stabilized efficiencies, respectively, achieved with triple-junction configuration [6,7]. To stay competitive with other PV technologies, the efficiency of small area thin-film silicon-based solar cells has to go beyond 20%. In this way the performance gap with other thin-film technologies can be minimized, even when taking into account the light induced degradation (LID) [8–10] and a typical performance decreases from laboratory to mass production [5].

The improvement of conversion efficiency in thin-film silicon-based solar cells is a delicate interplay between three areas: spectral utilization, light management and materials processing. Extending the spectral utilization from single to multi-junction solar cells means to combine materials with different band gaps such as amorphous silicon (a-Si:H), nano-crystalline silicon (nc-Si:H) and their alloys [6,11–13]. On the other hand, it also means applying advanced light management techniques [14] which combine light scattering at textured interfaces [15–19] with internal and rear reflectors [20–28]. Despite the demonstration of highly efficient solar cells based on photonic or plasmonic flattened reflectors [29–32], simpler light scattering approaches more suitable for mass production still rely on textured morphologies that are not optimal for the deposition of high electronic quality materials [15,33,34]. The development and deployment of absorbers and supporting materials which are resilient against defects at both bulk [35,36] and interface levels [22,37] are desirable. However, such materials are obtained by band gap manipulation of a-/nc-Si:H and their alloys that in turn may result in not optimal spectral utilization.

Thin-film silicon-based solar cells can be fabricated in two main configurations, the so-called *superstrate*, using transparent glass as optical window and mechanical support, and *substrate*, using glass or other (flexible) opaque materials only for mechanical support. Considering the best up-to-date single [38,39], double [5,40] and triple [6,31] junction devices, regardless of the fabrication configuration, there is roughly 1% absolute increase in the conversion efficiency when increasing the complexity of the

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device by stacking an additional junction. Therefore, the multi-junction approach has been experimentally proven as the main strategy for improving solar cells efficiency. In this contribution we study for the first time a thin-film silicon-based solar device based on quadruple junction concept. We first discuss its high potential efficiency; afterwards we present our optical modelling which resulted in a very high matched photo-current density (8.7 mA/cm^2), instrumental to obtain initial conversion efficiency approaching 20%. Finally we indicate a strategy for minimizing the issue of spectral overlap between component cells.

2. Assumptions for high potential efficiency

We propose a quadruple junction thin-film silicon-based solar device to achieve 20% conversion efficiency. To discuss the potential of this approach we made four simple assumptions: (i) virtual absorber materials have particular energy band gaps and very sharp absorption edges, (ii) an average external quantum efficiency (EQE) equal to 70%, (iii) a ratio between the open-circuit voltage and the band gap (V_{OC}/E_g) to be 0.56, and (iv) a fill factor (FF) equal to 0.77.

The implied photo-generated current-density ($J_{PH\text{-}70\%}$) of each component cell can be calculated using the first two assumptions. When assuming four absorber materials with band gap energy equal to 1.95 eV, 1.5 eV, 1.12 eV and 0.75 eV, respectively, and the utilization of the solar spectrum in the component cells equals to 70% the $J_{PH\text{-}70\%}$ of the component cells is calculated from the following equation:

$$J_{PH-70\%} = -q\int_{\lambda_1}^{\lambda_2} EQE(\lambda)\cdot\Phi(\lambda)d\lambda = -q\int_{\lambda_1}^{\lambda_2} 0.7\cdot\Phi(\lambda)d\lambda$$

where q is the elementary charge, $\Phi(\lambda)$ is the reference photon flux of Air Mass 1.5 solar spectrum [41] and [λ_1, λ_2] is the wavelength range of interest of each component cell as indicated in Fig. 1.

The implied photo-generated current-densities generated in the individual component cells with the above selected absorber materials are also reported in Fig. 1. A current-matched quadruple-junction device should deliver an implied photo-generated current-density of 9.40 mA/cm^2. In order to evaluate a potential V_{OC} of

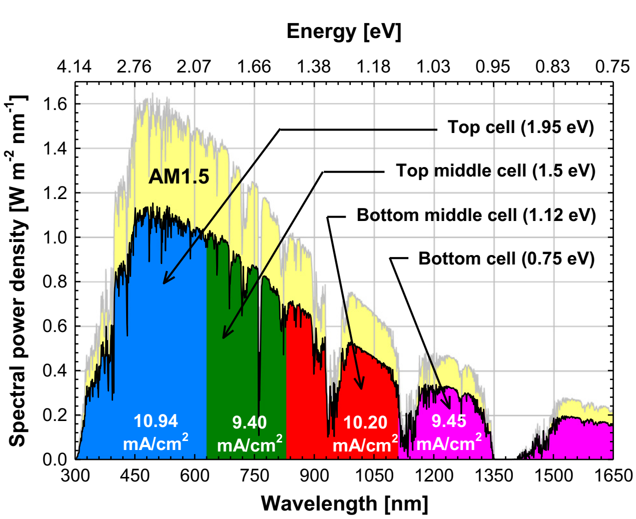

Fig. 1. Spectral power density AM1.5 [41] and its 70% utilization split in four wavelength ranges: 300 nm to 637 nm (blue area), 638 nm to 828 nm (green area), 829 nm to 1108 nm (red area) and 1109 nm to 1650 nm (pink area). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

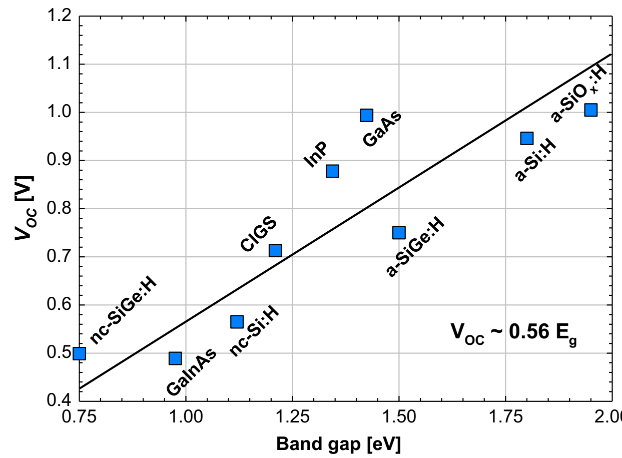

Fig. 2. Open-circuit voltage of different solar cells as function of the band gap of their absorber materials (nc-SiGe:H [42], GaInAs [44], nc-Si:H [34], CIGS [45], InP [5], GaAs [5], a-SiGe:H [6], a-Si:H [30], a-SiO$_x$:H [46]).

the component cells we evaluated V_{OC} of several single junction solar cells based on different absorber materials. It can be observed in Fig. 2 that the V_{OC} is on average 56% of the E_g of the absorber material, which justifies our third assumption. Applying this assumption to our quadruple junction device with the above mentioned four absorber materials, the predicted V_{OC} of the device can reach 2.98 V. The FF of highly efficient triple junction thin-film silicon-based solar cells with nc-Si:H bottom sub-cell exhibits at least 0.77 [6,31]. We assume that adding another junction with an absorber material with (likely) nano-crystalline structure having a lower band gap than nc-Si:H will not decrease further the FF. From these assumptions, it is straightforward to calculate a potential initial conversion efficiency of our quadruple-junction device to be almost 22%. In the next sections we analyze whether a quadruple-junction thin-film silicon-based solar cell can be realized with conversion efficiency approaching 20% using not virtual realistic materials. Of the four aforementioned assumptions, only the one on FF will be used.

3. Optical model: materials, layers thickness and structures

The simulations were carried out using an optical model *GenPro4* that is implemented in the in-house developed opto-electrical device simulator Advanced Semiconductor Analysis (ASA) [30,47]. The *GenPro4* model is capable to handle simultaneously ray tracing, incoherent/coherent propagation of light and application of the scalar scattering theory, which describes scattered light at rough interfaces [48].

The considered quadruple-junction solar cell structure is sketched in Fig. 3(a). We chose the *superstrate* configuration, because the supporting glass carrier offers an anti-reflective effect in terms of refractive index matching between the air and the front transparent conductive oxide (TCO) without the need of an additional material. For our study, the glass was optically treated as an incoherent layer and air was considered as the incident medium. To further decrease the reflectance at air/device interface we added an MgF_2 layer on the front side of the glass. The MgF_2 layer acts as an anti-reflecting coating (ARC) designed for maximal performance at 550 nm in order to increase the absorptance of both top and top–middle sub-cells.

The four component cells rest on etched glass coated with randomly-textured front TCO forming an ideal modulated surface-textured (MST) substrate [16]. This type of advanced texture is deployed for randomizing incident light inside the device and thus