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Advanced light trapping scheme in decoupled front and rear textured thin-film silicon solar cells

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ABSTRACT

We present the study of an advanced light trapping scheme applied to thin-film silicon-based solar cells, overcoming the broadband Green absorption limit, that is the generalized case of the $4n^2$ classical absorption limit for all wavelengths. This result is achieved by the 3-dimensional optical modelling of a fully functional thin-film hydrogenated nano-crystalline silicon (nc-Si:H) solar cell endowed with decoupled front and back textures. Our results stem from rigorously characterized optical properties of state-of-the-art materials, optimized geometric nano-features on the front and rear surfaces of the solar cell, and thickness optimization of the front transparent oxide. The simulated improvements derive from a gain in light absorption, especially in the near-infrared part of the spectrum close to the band gap of nc-Si:H. In this wavelength region, the material is weakly absorbing, whereas we now find significant absorptance peaks that can only be explained by the concurrent excitation of guided resonances by front and rear textures. This insight indicates the need to modify the temporal coupled-mode theory, which fails to predict the absorption enhancement achieved in this work, extending its validity to the case of decoupled front/back texturing. Our approach results in substantially high photocurrent density (> 36 mA/cm^2), creating a platform suitable for high efficiency single and multi-junction thin-film solar cells based either on typical silicon alloys or on the novel and promising barium (di)silicide ($BaSi_2$) absorber. In the latter case, using the same advanced light trapping employed for nc-Si:H, we demonstrate a very high implied photocurrent density of 41.1 mA/cm^2, for a device endowed with 2-μm thick absorber.

1. Introduction

Solar cells based on silicon as light absorber currently dominate the photovoltaic (PV) market (Fraunhofer ISE, 2017; ITRPV Eighth Edition, 2017). Next to record solar cells fabricated on wafers of crystalline silicon (c-Si) (Battaglia et al., 2016; Glunz et al., 2015; Masuko et al., 2014; Yamamoto, 2015; Yoshikawa et al., 2017; Zhao et al., 1998), thin-film silicon multi-junction solar cells (TFSSC) based on alloys of hydrogenated amorphous silicon (a-Si:H) have been recently reported to have initial conversion efficiencies up to 16.3% (Kim et al., 2013; Liu et al., 2015; Söderström et al., 2012; Yan et al., 2011) and record stabilized conversion efficiency up to 14% (Sai et al., 2016). Even though this PV technology currently realizes lower conversion efficiency than other thin-film technologies, such as CIGS (Solar Frontier, 2015), CdTe (First Solar, 2016), perovskites (Yang et al., 2015), and GaAs (Alta Devices, 2013), it displays the smallest cell-to-module losses (Haug and Ballif, 2015), with demonstrated industrial-scale flexible (Guha and Yang, 2005; Jäger et al., 2013) and rigid modules (Gabriel et al., 2011; TEL SOLAR, 2014; Vetter et al., 2009; Yamamoto et al., 2005) up to 6.5-m^2 wide area. That is, this technology is industrially mature in terms of nanometric-scale thickness uniformity, hundreds of Megawatt-scale throughput, and resilience against moisture (Haug and Ballif, 2015). For these reasons, thin films developed for a-Si:H-based solar cells constitute instrumental building blocks in current record c-Si solar cells (Masuko et al., 2014; Yamamoto, 2015; Yoshikawa et al., 2017) achieved industrially at wafer (i.e. large area) level. In addition, due to the lower absorption coefficient of a-Si:H alloys with respect to other PV absorber materials (Isabella, 2013; Vismara et al., 2016), TFSSC technology is the best platform for testing at both lab- and industrial-scale a variety of photonic approaches aimed to enhance the absorption of light in thin dielectric slabs (random/periodic texturing, dielectric spacers and reflectors, metallic nano-particles, etc.) (Brongersma et al., 2014; Haug and Ballif, 2015; Martins et al., 2012; Pahud et al., 2013; Tan et al., 2012; Zeman et al., 2013).

Today's and next-generation high efficiency TFSSCs are and will be entirely dependent on two factors. The first is the fabrication of a-Si:H

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alloys with band gap between 0.75 eV and 2 eV, to ensure high open-circuit voltage as well as wide utilization of the solar spectrum in multi-junction architectures (Isabella et al., 2014b). The second is the enforcement of an efficient *light trapping* scheme to maximize light absorption and thus to generate substantial short-circuit current density. The expression *light trapping* means the concurrent application of several light management techniques for (i) broadband light in-coupling at the front side of the (multi-junction) solar cell, (ii) light scattering inside the absorber layer(s) and (iii) high internal rear reflectance (Holman et al., 2013; Ingenito et al., 2014). Next to the optical properties of silicon-based absorbers and their bandgap, also their material properties needs to be considered. For amorphous absorbers with bandgap higher than 1.2–1.4 eV, the property to enhance is the resilience against light induced degradation (Kakinuma et al., 1983; Matsui et al., 2013; Staebler and Wronski, 1980), using triode-based plasma-enhanced chemical vapour deposition (Matsui et al., 2015) and/or varying deposition temperature and plasma compositions (Melskens et al., 2014; Stuckelberger et al., 2013). For nano-crystalline absorbers with bandgap lower than 1.2 eV (e.g. hydrogenated nano-crystalline silicon, nc-Si:H), properly designed light management is instead helpful for ensuring high photocurrent density while keeping the thickness in the range of 2–3 μm. This is to cope with the reduced electrical performance of the material with respect to higher quality c-Si when textured substrates are deployed (Sai et al., 2013b).

The maximization of the photocurrent density delivered by a fully functional single junction nc-Si:H solar cell is the primary aim of this study. The perspective is that a solar cell based on a low band gap nano-crystalline absorber material endowed with a light trapping scheme delivers a certain photocurrent density. This value can be interpreted as the sum of the photocurrent densities of a monolithically integrated multi-junction device. In this respect, the cell based on the nano-crystalline material is the bottom cell and the thicknesses of the (amorphous) top cells need only to be tuned to meet the current-matching condition (Isabella et al., 2014a). It follows that the maximization of light absorption in the bottom cell *alone* results in the maximized total photocurrent density available for a multi-junction device in which such bottom cell is deployed.

For enhancing the absorption of light, a commonly applied light management technique is the texturing of (internal) surfaces of the device to scatter incident light away from the specular direction. Random surface textures are customarily used in solar cells for this purpose (Berginski et al., 2008; Boccard et al., 2012; Hongsingthong et al., 2010; Isabella et al., 2011; Kambe et al., 2008; Sato et al., 1992; Tan et al., 2015; Tan et al., 2013). Periodic surface gratings are newer, but proven textures used in single and multi-junction devices and in both *superstrate* and *substrate* configurations(Biswas and Xu, 2011; Ferry et al., 2009; Isabella et al., 2008; Isabella et al., 2010; Paetzold et al., 2011; Sai et al., 2016; Sai et al., 2013b; Söderström et al., 2009; van Erven et al., 2010). Depending on the geometry of the grating and involved materials, such textures diffract light into discrete angles and can couple light into guided modes in the active layer (Söderström et al., 2010). Combined with a thin absorber and an efficient back reflector, periodic textures constitute an advanced light trapping scheme that can potentially induce an absorption enhancement beyond the classical *Tiedje-Yablonovitch* (TY) absorption enhancement limit (Tiedje et al., 1984) (see Section 3.4) by exciting absorption resonances (Yu et al., 2010a, b). In fact, recent findings on the limit of light absorption in the diffraction regime have shown that periodic surface textures are not only very useful from theoretical standpoint (Naqavi et al., 2013), but also enable the determination of design rules for the optimization of light in-coupling (Battaglia et al., 2012).

In a previous contribution (Wang et al., 2012), decoupled front and rear surface textures were considered to structure an ultra-thin c-Si absorber. Using the Rigorous Coupled Wave Analysis, the front and back surfaces were separately optimized for light trapping and anti-reflection, respectively, leading to broadband light absorption close to the classical TY absorption limit. In this study, starting from the concept of decoupled texturing, we shift the focus from structured and uncoated ultra-thin c-Si absorber slabs to fully functional thin-film solar cells based on structured nc-Si:H (see Fig. 1), appropriate as bottom cell in thin-film multi-junction devices (Zeman et al., 2013). The resulting performance is compared to the broadband *Green* absorption limit (Green, 2002) (see Section 3.4), which is the general case of the classical TY absorption enhancement limit.

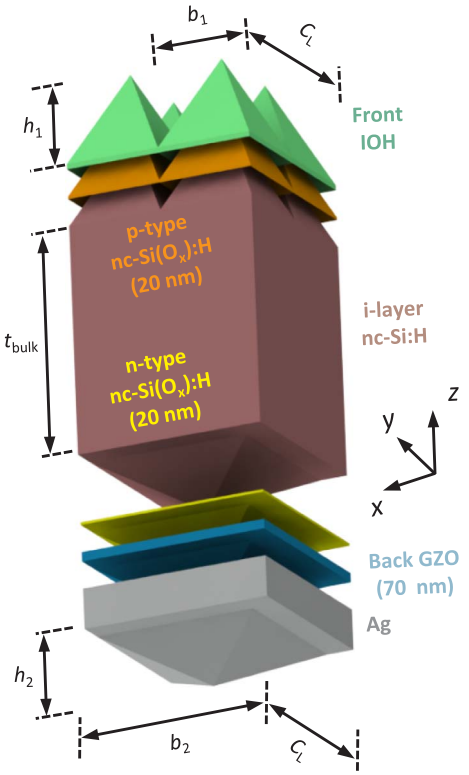

Fig. 1. 3-D view of a typical simulated unit cell with parameters defining the geometry of the front and the rear nano-pyramidal surface textures: front period (b_1) and height (h_1), rear period (b_2) and height (h_2), and common lattice (C_L) (see Section 3.2). Deployed layers in the solar cells are (from top to bottom): hydrogen-doped tin-oxide (IOH) as front TCO, p-type nc-Si(O_x):H, i-layer nc-Si:H, n-type nc-Si(O_x):H, gallium-doped zinc-oxide (GZO) as back TCO and silver. The shown unit cell is asymmetric with respect to its centre, due to non-commensurate front and rear nano-pyramids (see Section 2.1).

At the front side of the device, high aspect ratio nano-pyramids arranged in a two-dimensional (2-D) rectangular lattice were used. This front texture of nano-pyramids enables efficient light in-coupling, as the spatially averaged effective refractive index nearly adiabatically varies from that of air to that of the silicon absorber (Ingenito et al., 2015; Isabella et al., 2016). At the rear side, nano-pyramids, also arranged in a 2-D rectangular lattice, were deployed, but this time with a lower aspect ratio (Zeman et al., 2013). Using this sort of structure, long wavelength photons close to the nc-Si:H bandgap can be efficiently scattered in several discrete directions. At the same time, the smaller height reduces scattering of light into the metallic back reflector, which would lead to plasmonic losses in the metal. To model the structure of the complete solar cell, parasitic optical losses in the layers surrounding the absorber were considered using rigorously characterized optical properties of state-of-the-art materials. Deploying an optical modelling software based on three-dimensional (3-D) Finite Element Method (FEM) (ANSYS), we could accurately simulate absorptance and reflectance spectra (Isabella et al., 2013) as well as calculate the implied photocurrent density related to each layer of the device. Furthermore, the spectral position of peaks in the absorptance curve of the absorber layer was explained by means of waveguide mode theory.

The optimization of both front and rear textures consisted of four