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Broadband anti-reflection coating using dielectric Si_3N_4 nanostructures. Application to amorphous-Si-H solar cells

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ABSTRACT

Absorption of amorphous-Si hydrogenated (aSi-H) solar cells can be enhanced by using dielectric nanostructures made of Si_3N_4 that work like antireflection coatings. The analysis focus on the short-circuit current delivered by the cell under solar irradiance, and it is made taking into account every layer and structure of an aSi-H cell. A customized design of the antireflection coating in the form of nanostructured dielectric layers, produces a short-circuit current enhancement of 15.2% with respect to the reference flat solar cell, and a lower reflectivity of the cell. Three different geometries of linear nanostructures have been analyzed and compared with quite similar results among them. An improvement in performance has been also obtained for realizable geometrical dimensions that could be fabricated while maintaining electric conductivity of the front contact.

1. Introduction

Solar cell technologies are competing among them to improve energy conversion efficiency at cheaper costs [1]. Multi-junction solar cells are obtaining the best figures adjusting their band absorption to the solar spectrum [2]. When restricting the analysis to silicon (Si) based solar cells, we find three major options: single-crystalline Si, multi-crystalline Si, and amorphous Si hydrogenated (aSi-H). From the efficiency point of view, single-crystalline Si is the best option [1], but at higher price and higher manufacture complexity. The low-cost option is represented by aSi-H solar cells. This material has not an indirect band-gap limiting the absorption as in crystalline silicon, and therefore it absorbs better solar radiation. Therefore, around 1 μm layer of aSi-H is thick enough for this application. Actually, its thickness is limited to about 300 nm by material diffusion length. In this case, light trapping mechanisms are important to improve cell performance [3,4]. There exist a strong activity and interest in improving efficiency and related figures of merit. As a consequence, the increase in the short-circuit current, J_{sc}, delivered by the structure is one of the goals of several recent proposals and ideas. Even moderate improvements of this parameter are of great interest because they may save materials and space in solar power stations relying on this technology. Actually, relative increases in the order of 8–12% have been considered as promising when applied to different types of solar cells incorporating nanostructures and light trapping schemes [5–7]. Large increases in efficiency and J_{sc} are reserved for innovative materials and disruptive technologies.

One of the problems of aSi-H is its structural instability due to the appearance of dangling hydrogen bonds. This mechanism is called Staebler-Wronski Effect (SWE), and it is responsible for up to 20% loss in efficiency because it limits the voltage that could be obtained for aSi-H devices [8]. Fortunately, SWE is reversible with temperature, and defects generated by light irradiation can be mitigated by thermal annealing. This works positively for aSi-H solar cells [8–10]. Then, by using light trapping and confinement strategies, besides improving efficiency, it is possible to increase absorption, generate heat, raise temperature, and partially repair the SWE damage. Several light trapping schemes have been proposed involving plasmonic gratings [11], antireflection coatings [12], photonic crystals [13], waveguides, and dielectric diffractive structures [14]. Guided light increases optical path within the active layer and absorption grows [15]. Si_3N_4 thin film Anti-Reflection Coating (ARC) has been positively proved, with optimum thickness values of 60 nm [16,17]. Dielectric subwavelength nanostructures have also been proposed to enhance efficiency for Si-based solar cells [18–21]. In some cases, the proposed structures have been fabricated and realized in practice. The feasibility of fabrication has been also a main concern when considering different geometries and materials in this contribution, because large improvements in the performance of the cell can be obtained if fabrication constrains are not fully considered [22].

This paper analyzes the design of Si_3N_4 subwavelength nanostructures that work as an ARC, and also traps light towards the aSi-H active

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layer. This study is made using Comsol Multiphysics as a computational electromagnetism package. The results are positively tested and compared with previous experimental works and modeled designs. The proposed design increases the short-circuit current obtained previously and takes into account all the elements in the structure, and some thickness constrains about the front contact deposition. By considering the whole multilayer structure of the cell we improve the reliability of the results with respect to the case of considering only absorption at the active intrinsic aSi-H layer [22]. The capability to analyze absorption at every layer makes it possible to quantify the amount of energy that, although is not converted into electric power, can still be useful to heat the device and help to mitigate the SWE. Besides, we analyze the effect of the thickness of the front contact layer. This is of importance when proposing ultra-thin front-contact ITO (indium tin oxide) layers that could compromise its electric conductivity. Along the paper we have paid special attention to both absorption, caused by trapping at the proposed nanostructured front layer, and reflectance of the whole cell, which has been reduced with respect to previous reported results [23]. Section 2 of this paper evaluates the contributions of the individual layers of aSi-H solar cell, including the analysis of an optimized flat ARC that combines ITO and Si_3N_4. Section 3 presents the main results of the paper when arranging a Si_3N_4 nanostructured ARC layer on top of optimum and realizable ITO layers. The results from the numerical evaluation are compared to the reference solar cell. Finally, Section 4 summarizes the main conclusions of this contribution.

2. Amorphous-Si-H solar cells

A full characterization of a solar cell begins with the description of the material and geometric arrangement of its structure (see Fig. 1a). Our starting point is the flat configuration aSi-H thin film solar cell ([24]) with the following layer structure (bottom-to-top): Ag (200 nm)/AZO (100 nm)/n-aSi-H (22.4 nm)/i-aSi-H (350.5 nm)/p-aSi-H (17.5 nm)/ITO (70 nm). n-aSi-H and p-aSi-H are buffer layers that adjust electric field for photo-generated charge carrier separation. The active layer is the i-aSi-H layer, and AZO means ZnO:Al. The refractive index for the i-aSi-H and ITO are obtained from SOPRA material database [25], the refractive index for Ag and Si_3N_4 are obtained from [26], and the refractive index for n, p aSi-H and AZO are obtained from [27,28]. Instead of focusing only on the intrinsic active i-aSi-H layer [22], in this paper we have always considered every layer in the solar cell structure. Actually, the thickness of the i-aSi-H active layer is relevant in the overall performance of the cell [29–31]. Larger thickness means larger absorption within the band gap of the material, specially at longer wavelengths. However, this increase reaches an asymptotic value, meaning that a thicker active layer does not produce a significant larger absorption. Table 1 shows the total absorbed power irradiance as a function of thickness of the i-aSi-H active layer. At the same time, the role of the other auxiliary layers should be considered when evaluating the performance of the whole cell and the absorption at the active layer.

Table 1
Total absorbed power irradiance in i-aSi-H layer for different thicknesses.

Thickness [nm]	100	200	300	500	1000
Absorbed irradiance [W m^2]	183	225	243	251	266

Absorption rate is defined as the ratio of absorbed power to incident power, and can be used to calculate the absorptance in each individual layer of the cell by integrating over the volume of each layer. The spectral absorption rate can be calculated as:

$$A(\omega) = \frac{1}{2}\,\omega\varepsilon''|E(\omega)|^2, \tag{1}$$

where ω is the angular frequency of the incoming radiation, ε'' is the imaginary part of the dielectric permittivity of the material, and $E(\omega)$ is the electric field. As far as we are interested in optical losses in the i-aSi-H layer for an incoming broad-band radiation, we evaluate the absorbed power as:

$$P_{abs}^{i} = \int A(\omega)\Phi_{\mathrm{AM1.5}}(\omega)d\omega, \tag{2}$$

where $\Phi_{\mathrm{AM1.5}}(\omega)$ is the solar spectral irradiance as a function of frequency [32]. Although Eqs. (1) and (2) are given in terms of the angular frequency, our results will be expressed using wavelength, λ. In a solar cell we are primarily interested in knowing the short-circuit current, J_{sc}, circulating through the structure for a given solar irradiance. This parameter is the one that we need to optimize in a solar cell structure. Assuming that each absorbed photon will create an electron-hole pair contributing to the short-circuit current, J_{sc} can be given in terms of the wavelength as:

$$J_{sc} = \int \frac{q}{hc} A(\lambda)\lambda\Phi_{AM1.5}(\lambda)d\lambda, \tag{3}$$

where q is the electron charge, c is the speed of light in vacuum, and h is the Plancks constant.

To better understand the role of each layer, we have evaluated the individual spectral absorption of them for the reference solar cell structure of Fig. 1a. The results are given in Fig. 1b. We may see that, as

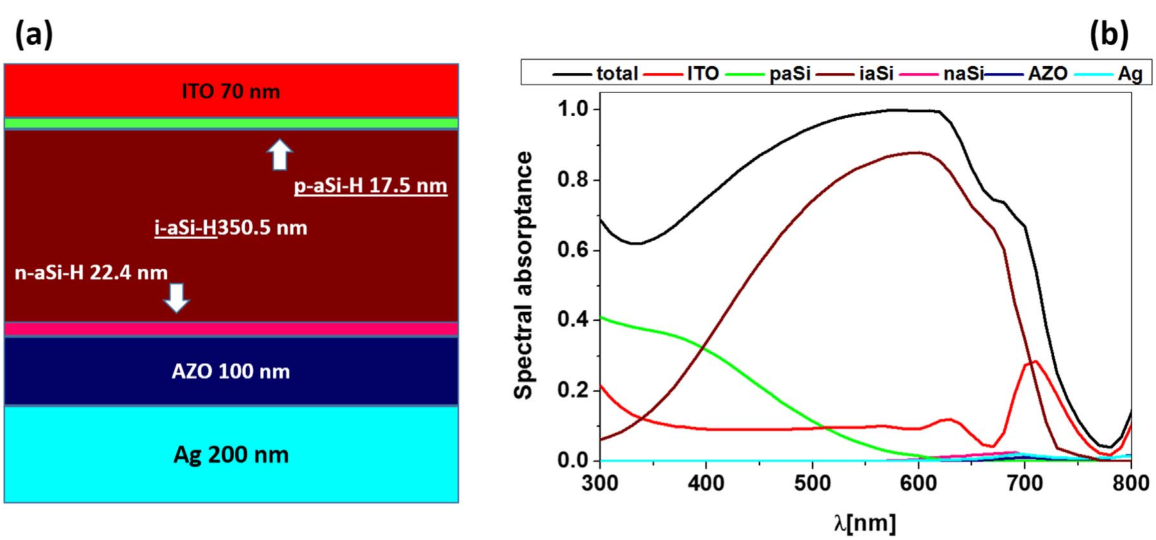

Fig. 1. (a) Geometrical arrangement of the layers of a reference solar cell. (b) Spectral absorptance of each layer for the reference cell described in (a).