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Pseudo-disordered structures for light trapping improvement in mono-crystalline Si thin-films

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ABSTRACT

Thin film solar cells may exhibit high conversion efficiencies provided their active material exhibits a high quality, like in the case of crystalline silicon, and if incident light coupling and absorption are appropriately controlled. We propose to integrate an advanced light trapping process relying on photonic crystals including a controlled pseudo-disorder. Thanks to Rigorous Coupled Wave Analysis, we determine the optimized nanophotonic structures that should be appropriately introduced in 1 μm thick crystalline silicon layers standing on a metal layer like aluminum. Thanks to a carefully controlled pseudo-disorder perturbation, absorption in these designed nanopatterns overcome that predicted in the case of fully optimized square lattice photonic crystals. Fabricated structures are analyzed in light of this numerical investigation to evidence the impact of such controlled perturbations, but also the influence of the measurement method and the technological imperfections. Thanks to the optimized perturbated photonic crystals, the integrated absorption in 1 μm thick crystalline Silicon layer increases from 37.7%, in the case of the unpatterned stack, to 70.7%. The sole effect of pseudo-disorder on the fully optimized simply periodic photonic crystals leads to an absolute increase of the integrated absorption up to 2%, as predicted by simulations, while both structures are fabricated using exactly the same process flow.

1. Introduction

Thin film solar cells using deposited material like hydrogenated amorphous silicon (a-Si:H) as an active material offer an alternative to photovoltaic (PV) devices made of bulk crystalline silicon (c-Si); they allow for cost reduction and specific characteristics like the integration on flexible modules, but generally at the expense of the conversion efficiency. Another approach consists in using a c-Si layer with a thickness in the 1–10 μm range. This is expected to lead to cost effective photovoltaic devices based on a high quality material, with reduced carrier bulk recombination. In order to achieve high conversion efficiency with such thin film c-Si solar cells, it is essential to optimize the incident light in-coupling and trapping in an otherwise relatively inefficient absorber, especially for long wavelength photons. Light trapping for photovoltaics has been a topic of strong interest in the past years, with the use of diffraction gratings [1], surface plasmons [2,3] or photonic crystals (PC) [4] in layers with thicknesses around 100 nm. Among all these possibilities, photonic crystal structure is a promising route. Indeed, adding a periodic pattern in a thin film enables the conversion of out-of-plane wave-vectors into in-plane-wave-vectors results in an increase of the "effective" absorbing material thickness. Moreover, thanks to the periodicity of the photonic crystal, the dispersion law can be controlled to create slow Bloch modes guided into the thin film. Moving to higher quality materials, the theoretical absorption for a thin c-Si film over a broad wavelength range can be increased up to 50% when compared to the unpatterned case [5]. A few research groups recently demonstrated the operation of real solar cell devices, including such periodic nanophotonic structures within a solar cell based on c-Si layers. Among all the advances reported in this area, Chen et al. at MIT achieved a 15.7% efficiency with a 10 μm thick c-Si solar cell including periodic inverted pyramids [6]. Jeong at Stanford integrated nanocones structures on top of a 10 μm thick c-Si solar cells, leading to 13.7% efficiency [7], and PC patterning of a 1 μm thick c-Si layer on an aluminum back mirror leading to a J_{sc} of 15.4 mA/cm^2, which corresponds to an increase of 20% compared to the unpatterned reference case [8]. Recently more complex structures that combine a front and a back photonic crystal structure [9–11] have been proposed to overcome this value by adding new optical modes

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and/or tailoring the reflection at the bottom interface of the solar cell. Still, this approach is technologically quite complex, and the integration of an optimized and technologically feasible and cost effective light trapping strategy on a realistic solar cell stack has been barely addressed, in particular in the case of thin c-Si layers.

Due to the periodicity of the photonic crystal this approach is highly efficient only for specific wavelengths and angles as traduced by the high quality factor peaks obtained on a typical absorption spectrum. An alternative approach to this strictly periodic structuration that could decrease the coherence of the absorption processes is to use random structuration [12–14]. Such structures exhibit then rich Fourier spectra like the well-known quasi-crystal [15,16] that can also increase the absorption in a thin-film thanks to guided modes introduced by a rotational order that leads to an equivalent increase of 9% compared to a square lattice of holes for a 0.3 μm thick c-Si layer. As such structures are not deterministic, one may prefer to introduce a certain degree of disorder in the periodic pattern [17–20], to combine random fluctuations with a periodic pattern [21] or to use a binary grating approach [22]. In our approach, a supercell is made of randomly located holes periodically repeated in a square lattice in order to define a pseudo-disordered photonic crystal. Such an approach allows to quantify the magnitude of disorder introduced in an optimized nanopattern and to "engineer" the optical resonances related to the periodic pattern. Our approach was conducted on a technologically realistic thin photovoltaic stack. The thickness of the absorbing layer is chosen in order to eventually achieve a high absorption; of course, the absorption increase related to the photonic structure is then reduced compared to the case of an ultra-thin (< 500 nm) absorbing layer [16]. Lastly, our method relies on carefully positioned holes, in a way that can be achieved with a conventional lithography technique with a reduced effort compared to complex and very small patterns that have been proposed elsewhere [22]. Finally, to avoid additional surface passivation issues in the future development, keeping a lattice of cylindrical holes prevents any extra sidewall or nanopatterned shape differences, and enables to use the same conformal depositions conditions for the subsequent passivation of the nanopattern.

In this paper, we investigate numerically and experimentally the absorption in a thin c-Si structure patterned with a pseudo-disordered photonic crystal. More precisely, the stack under consideration is a 1 μm thick c-Si film bonded onto a 1 μm thick Al layer on a glass substrate as depicted in Fig. 1a. The Al layer acts as a back mirror, especially at the wavelengths above 0.5 μm where the single pass absorption in c-Si is low. It also acts as a back contact in a solar cell. A PC structure is then partially etched in the c-Si film, with a depth in the 100–200 nm range; it was shown elsewhere that such a design enables efficient in-coupling of the incident light into the pseudo-guided Bloch modes of the structure [5], leading to an efficient light trapping.

To establish a fair comparison, the integrated absorption of the sun light in the pseudo-disordered patterns is compared to the one of the perfect-square lattice of holes that maximizes the absorption in the same stack. It will be shown that the use of an optimized PC structure in front of our stack almost doubles the integrated absorption compared to the flat reference (a relative increase of 87.8% is obtained). Then, a pseudo-disordered PC, that can be realized in the same way as the optimized PC, can exhibit experimentally as well as theoretically a larger integrated absorption as the case of a square lattice of holes, at almost no extra technological cost.

Section 2 is dedicated to a numerical investigation on the effect of a controlled pseudo-disorder introduced in a periodic photonic crystal structure. The total absorption of the thin c-Si films on metal is numerically optimized using the Rigorous Coupled Wave Analysis (RCWA) method [23]. Let us underline that this

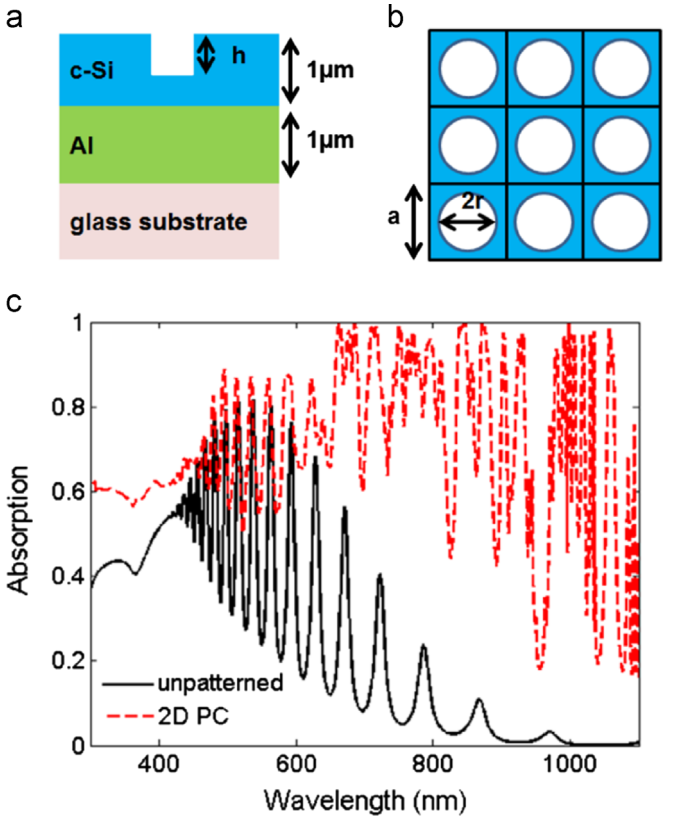

Fig. 1. (a) A patterned thin (c-Si) film lies on a metallic layer bonded on a glass substrate. (b) A square lattice (period a) of partially etched (etching depth h) hole (radius r) is used to increase the absorption of the stack. (c) Comparison between the absorption of the unpatterned thin film (black curve) and the absorption of the optimized photonic crystal structure (red dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

enhancement of the total absorption is chosen such as to be compared to the experimental values of the reflectance. Section 3 presents the experimental methods. The structures are realized thanks to Electron-Beam Lithography (EBL) and then optically characterized. Then in order to remove the influence of the back mirror, a preliminary experimental validation of our approach is obtained using a thin Silicon-On-Insulator (SOI) structure, this is discussed in Section 4. In addition even if not realistic at a larger scale, this stack exhibits an almost perfect flatness that can partly prevent from experimental deviations of the geometry. In Section 5, pseudo-disordered structures are realized in a thin c-Si film [24] and bonded on metal. The optical measurements performed on these structures are then analyzed in light of the numerical simulations.

2. Design and simulation results

Let us first consider a two-dimensional (2D) lattice of holes partially etched in a c-Si layer bonded on Aluminum on glass, as depicted in Fig. 1a. Thanks to an in-house developed analytical Rigorous Coupled Wave Analysis (RCWA) code, we compute the absorption in the whole stack. The number of orders used in the simulation and the wavelength step are chosen in order to achieve accurate numerical results. The incident light is an unpolarized plane wave at normal incidence. The figure-of-merit consists of the integrated absorption of the whole stack from 300 to 1100 nm (which corresponds to the relevant range of interest for c-Si solar cells), taking into account the solar spectrum [25].

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