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Full Length Research Paper

Reduction of the surface reflectance of an amorphous silicon solar cell by a moth-eye structure

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Abstract:
Hydrogenated amorphous silicon (a-Si:H) is widely used as absorber layer in thin-film silicon solar cells. The performances of a-Si:H solar cells can be enhanced by reducing the surface reflection of the active layer. Here, we propose a moth-eye antireflective structure with conical profile to reduce the surface reflection of a-Si:H. By optimizing the dimensional parameters of the conical nipple arrays, it is found that the average reflectance from the a-Si:H surface can be reduced up to 1.26% under normal incidence in the wavelength range 300-900nm, allowing to expect a relatively high short-circuit current density of 17.123 mA/cm² in the same wavelength range. It is also observed that the reflectance is below 3% for angles of incidence lower than 50° and for two types of light polarisation.
Keyword: amorphous silicon, antireflection, moth-eye, nanocone arrays.

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1. Introduction

Thin-film silicon solar cells are one possible alternative to the relatively high cost bulk crystalline silicon solar cells. As absorber layer in thin-film silicon solar cells, hydrogenated amorphous silicon (a-Si:H), either doped or intrinsic, has been used for decades. However the performance of a-Si:H solar cells is well below fundamental limits. Their short-circuit current density (J_{SC}), and therefore their conversion efficiency, have potential of improvement [1]. Aluminum-doped zinc oxide (ZnO:Al) films have been widely used in a-Si:H thin-film solar cells as front transparent conducting oxide (TCO) due to its excellent optical and electrical properties [2, 3]. For efficient light trapping, the surface of ZnO:Al films are generally textured. Recently, ZnO:Al films with a well faceted hexagonal pyramidal structure have been found to exhibit a high average transmittance of 85.7% at wavelength from 400 to 1100 nm [4]. It has been previously reported that optimized moth eye parabola-shaped nipple arrays allowed for an increase of the short circuit current and conversion efficiency of more than 40% in a-Si:H thin film solar cells [5].

The outer surface of the corneal lenses of moths is covered with a regular array of conical protuberances, termed corneal nipples, typically of sub-300 nm height and spacing. These arrays of subwavelength nipples generate a graded transition of refractive index (GRIN), leading to minimized reflection over a broad range of wavelengths and angles of incidence [6, 7]. The performances of these sub-wavelength structures can be enhanced by optimizing their dimensional parameters for a given shape [8]. Moreover, their performances may depend on the light incident angle [9].

In this work, we propose to reduce the surface reflection of hydrogenated amorphous silicon by optimizing the geometrical parameters of a conical antireflective structure applied on it.

2. Principle and optimization procedure

The AR structure studied in this paper is shown in figure 1. It consists of arrays of periodic ZnO:Al nanocones applied on the amorphous silicon surface. The geometrical parameters to optimize are diameter (or radius), height and pitch of nanocones (or period of the nanostructure).

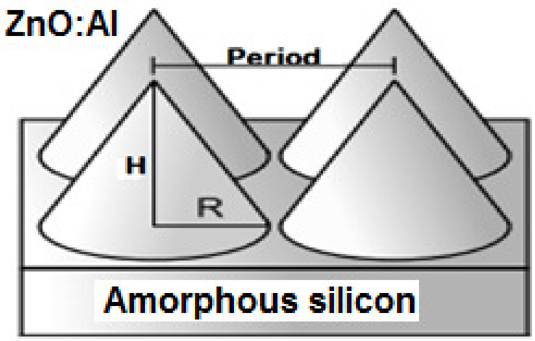

Figure 1: Design of the antireflective structure to optimize in this study

The optical constants needed to calculate the reflectance of this antireflective structure are taken from [10] for the amorphous silicon and from [11] for ZnO:Al. Before calculating this reflectance, we need to evaluate the effective refractive index (n_{eff}) of the composite layer. For this, we can use a coordinate system, Z-axis perpendicular to the AR surface, with z=0 at the base of the nanostructure and z=H at the top were H is the height of the nanocones. The n_{eff} (Eq. 2) depends strongly on the volume fraction (f) of the nanostructure given by:

$$f(z) = \frac{\pi}{3} * \frac{R^2}{P^2}\left[1-\left(\frac{z}{H}\right)^2\right] \qquad \text{[Eq. 1]}$$

$$n_{eff}(z) = \left[f(z) * n_p^q + (1-f(z)) * n_{air}^q\right]^{\frac{1}{q}} \qquad \text{[Eq. 2]}$$

Here, n_p and n_{air} are respectively the refractive index of ZnO:Al nipples and air and q=2/3 [6].

To evaluate the performance of the proposed AR structure, we have determined the weighted reflectance of the solar radiation (R_w) and the short-circuit current density (J_{sc}) that can be expected. They are defined respectively by the following equations 3 and 4[13]:

$$R_W = \frac{\int_{\lambda_{min}}^{\lambda_{max}} F(\lambda).IQE(\lambda).R(\lambda).d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} F(\lambda).IQE(\lambda).d\lambda} \qquad \text{[Eq.3]}$$

$$J_{SC} = q\int_{\lambda_{min}}^{\lambda_{max}} F(\lambda).IQE(\lambda).A(\lambda).d\lambda \qquad \text{[Eq. 4]}$$

In these equations $F(\lambda) = \frac{I(\lambda).\lambda}{h.c}$ is the incident photon flux where $I(\lambda)$ represents the solar radiation; $IQE(\lambda)$ is the internal quantum efficiency of the solar cells, $R(\lambda)$ refers to the reflectance given by the AR structure, $A(\lambda)$ is the absorption factor of the active layer, q and λ are respectively the elementary charge and the incident wavelength . The main objective of the optimization is to reduce the weighted reflectance (R_w) and to maximize the short circuit current density over the widest range of wavelengths, incident angles and the polarization types of the light.

3. Results and discussions

The main advantage of using moth-eye structure instead of a thin-film antireflective layer is that any gradual effective refractive index profile can be created between the refractive index values of the two media by careful choice of the nipple feature shape. If the nipples are tapered, like nanocones, the fraction of material varies from zero at the tips of the nipples to one at their base, resulting in a gradual change of refractive index across the interface. This effectively smoothes the transition across the interface between two media and therefore ensures that incident light does not encounter a sudden change in refractive index which would cause a large proportion to be reflected. This fraction of materials depends greatly to the geometrical parameters such as base radius (R), period (P) and height (H) of nanocones. Therefore, it is essential to optimize them for reducing the reflection losses and increasing the performances of solar cells.

In the first time, we search the optimal diameter of nanocones. For that, we have varied the diameter of the nanocones from 40 to 100 nm and the results are shown in figure 2 below. This figure shows that the nanocones having a diameter around 60 nm are more efficient in reducing the reflection. With this diameter, the structure of the nanocones gives an average reflection below 5% over the range 300 - 900 nm of the wavelengths. Indeed, very small and very large cones respectively give an airy and dense structure. Thus, short and long wavelengths will not be well trapped.

After founding an optimal diameter, we have studied the effect of the period of the nanostructure on the antireflective performance. The period was varied from 400 to 1000 nm and the results obtained are shown in figure 3 below. Then, the structure with a period around 700 nm gives a better antireflective performance according to the curve of figure 3. With this period, the structure acts as an effective medium for the longer wavelengths (>700 nm), as a photonic crystal for the wavelengths comparable to the period and as a grating diffraction for the smallest wavelengths (<700 nm). That is why this period is more effective in the reduction of reflection on the wavelength range. On the other hand, a periodic structure makes it possible to trap better the incident light.

The last parameter to optimize is the height of nanocones. By appointing the optimal diameter and period of nanocones, the height was chosen in the range of 500-1000 nm. By increasing the height of the nanostructures, the reflectance decreases effectively (figure 4). In fact, the long nipples make it possible to obtain multiple rebounds of the light inside the antireflective structure. These multiple rebounds increase the probability of incident light transmission. However, there is a trade-off between the performance of very long nanostructures and their production cost. Because the height of nanostructures depends on the etching time and long nanostructures lead to a high production cost. The table 1 summarizes the optimal parameters and the corresponding performances.

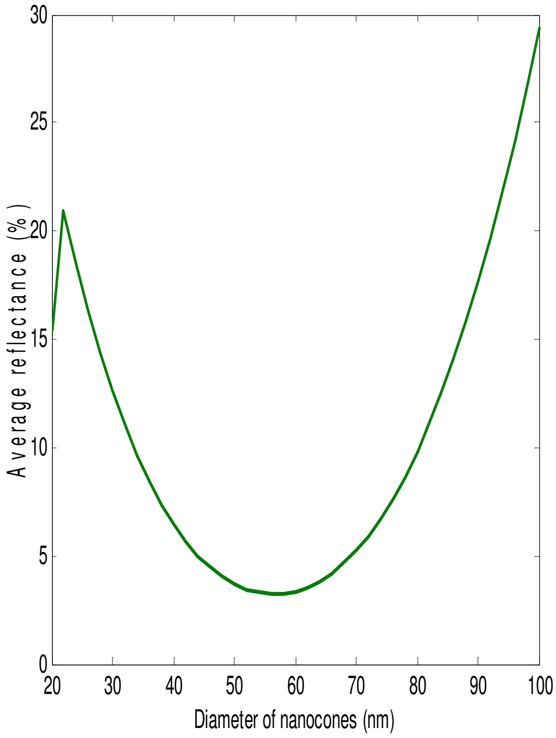

Figure 2: Variation of the average reflection as function of the diameter of cones

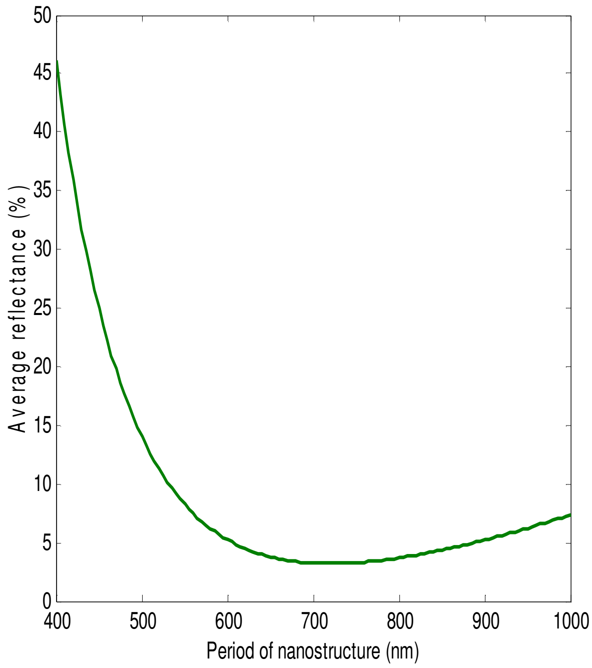

Figure 3: Variation of the average reflection as function of the period of nanostructure.

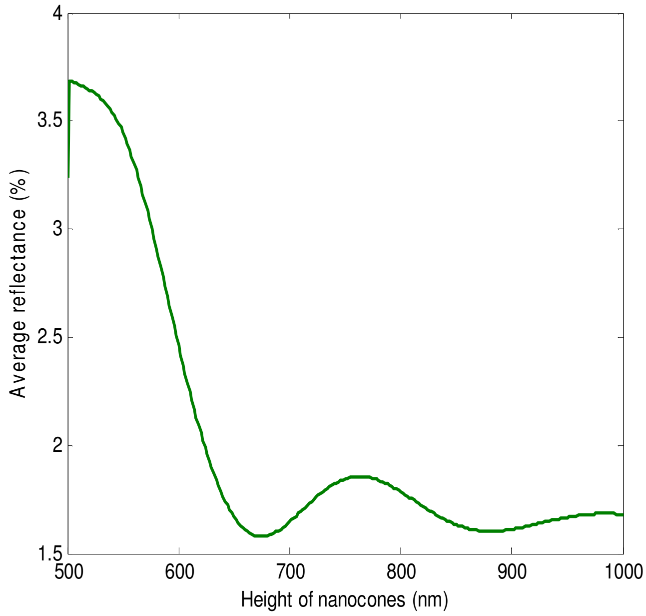

Figure 4: Variation of the average reflection as function of the height of nanocones.

Table 1. Summary table of the optimal parameters of the antireflective structures with the performances obtained

Antireflective structure	Optimal geometric parameters	Estimated performances
Quarter wavelength thick layer	Thickness = 80 nm	Rw = 12.84% Jsc = 12mA/cm²
Periodic nanocone arrays	Diameter = 60nm Period = 700 nm Height = 675 nm	Rw = 1.26% Jsc = 17.12mA/cm²

We also considered the effect of incident angle on the antireflective performances given by the conical shape. The results are shown in the figure 5. This curve shows that the reflection is only sensitive for angles greater than 50° and remains below 3% for angles lower than 50°.

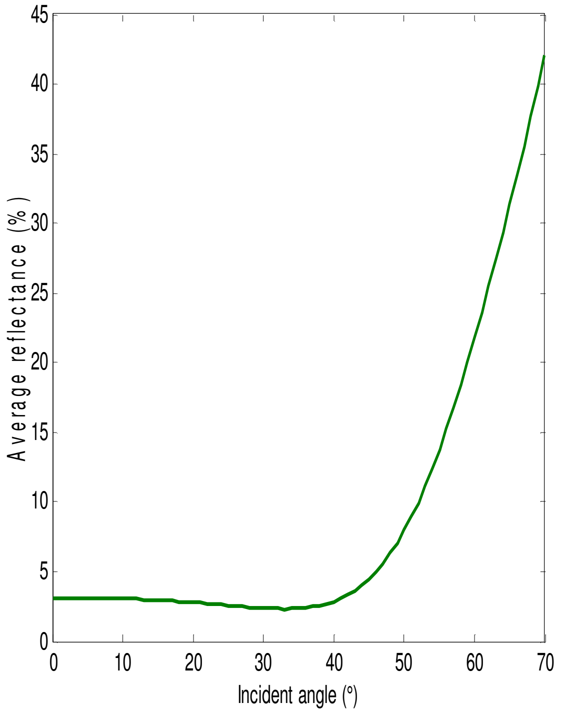

Figure 5: Dependence of the reflection on the incident angles.

We have also compared the reflectance reduced by planar layer and conical structure of ZnO:Al applied on amorphous silicon solar cells. Analysis of these results (see figure 6) shows that a moth-eye structure performs better in reducing reflection in the range of wavelengths.

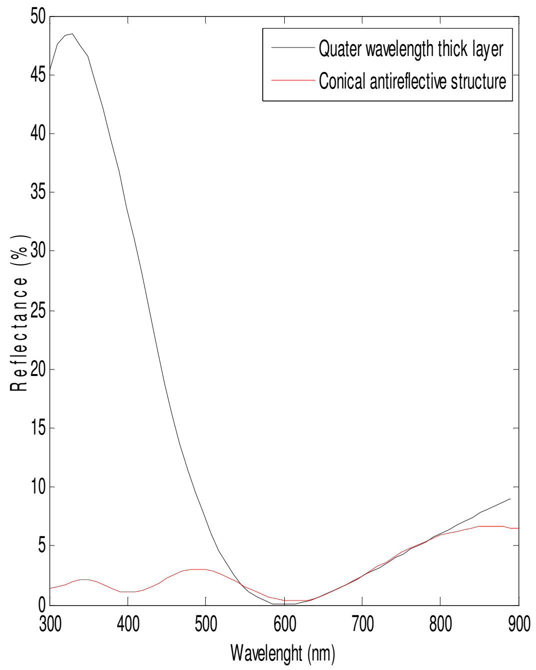

Figure 6: Reflectance as function of wavelength reduced by optimized planar layer and conical AR structure of ZnO:Al.

4. Conclusion

The conversion efficiency of amorphous silicon solar cells can be improved by reducing losses such as surface reflection and recombination. The biomimetic antireflective structure optimized in this work give best performances in the reduction of these reflection losses when we compare to a planar layer. This conical antireflective structure has permited to reduce the reflectance of amorphous silicon substrate below 1 % in the wavelength range of 300-900nm. This reduction has allowed to obtain a short-circuit current density of 17.12 mA/cm².

These results do not take into account the other optical losses such as the shading effect caused by the front contacts and the non-absorption of the long wavelengths due to the reduced thickness of the active layer. The antireflective structures optimized in this study are under experimentation in order to valid the theoretical results.

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