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2014- LIGHT TRAPPING IN HOLES OR PYRAMID  
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## LIGHT TRAPPING IN HOLES OR PYRAMID PATTERNS FOR THIN FILM SOLAR CELLS

H.Ding<sup>1,2</sup>, J. Liu<sup>1,3</sup>, L. Lalouat<sup>1,2</sup>, R. Orobtcchouk<sup>1,3</sup>, C. Seassal<sup>1,2</sup> and E. Drouard<sup>1,2</sup><sup>1</sup>Université Lyon, Institut des Nanotechnologies de Lyon (INL) UMR 5270 CNRS-INSAS-ECL-UCBL, France<sup>2</sup>Ecole Centrale de Lyon, 36 avenue Guy de Collongue, 69134, Ecully Cedex, France<sup>3</sup>INSA de Lyon, Bat. Blaise Pascal, 7 avenue Jean Capelle, 69621, Villeurbanne, France**1) Context**

Light trapping is expected to enable the generation of promising thin film photovoltaic solar cells based on crystalline silicon (c-Si) [1]. In particular, photonic crystal (PhC) structures have a great potential to improve the thin-film solar cell absorption thanks to their slow Bloch modes [2].

In this work, we investigate numerically the influence of different kinds of PhC patterns in thin c-Si layers (less than 2  $\mu\text{m}$  thick). We focus on arrays of cylindrical holes and inverted pyramids structure, as depicted in Fig. 1. The numerical results are then supported by experimental realizations of nano-patterns.

**2) Description of approach and techniques**

Using finite difference time domain (FDTD) optical simulations [3], we calculate the absorption of the thin film silicon solar cell with 2D photonic crystal structures, as well as the maximum achievable short-circuit current density ( $J_{sc}$ ), assuming the internal quantum efficiency equals unity. Standard AM1.5G spectrum is used and optical indices are experimental data.

The considered cells typically consist of an ITO front electrode, an amorphous hydrogenated silicon (a-Si:H) layer, then a lowly doped c-Si layer acting as the main active region, lying on a highly doped c-Si acting as a BSF layer.

In a preliminary step, we investigate numerically the influence of the patterns only acting as front anti-reflection coating, i.e. in structure having a thick BSF layer as presented in Fig. 1. The thickness of the active region is 1.535  $\mu\text{m}$ . The parameters are the period, the air filling fraction (ff) of the pattern (for both patterns) and the etching depth (only in the case of cylindrical hole structure, since for the pyramid structure this parameter is set by the angle of wet etching of the c-Si).

Then the BSF thickness is reduced and lies on an optical spacer on a back metallic contact, in order to obtain a complete thin film solar cell structure as depicted in Fig. 2a. In this case, the thickness of the optical spacer (110nm) has been adjusted in the numerical simulation. It can be noted that the thickness of the lowly doped c-Si layer changes from 1.535  $\mu\text{m}$  to 1.1  $\mu\text{m}$  due to fabrication aspect.

Finally, we present the fabrication of the designed structures. In order to pattern such stacks, we develop a high throughput process based on laser interference lithography (LIL), reactive ion etching (RIE), possibly combined to wet c-Si etching. The LIL is employed to form the initial mask by double exposing an ultrathin, high resolution photoresist [4]. This pattern is then transferred to a  $\text{SiO}_2$  hard mask by using RIE process with  $\text{CHF}_3$ . Subsequently, the inverted

pyramids are obtained by wet-chemical etching in a KOH solution, whereas the cylinders are formed by another RIE etching with a mixture of gases ( $\text{SF}_6$  and Ar) into the silicon side.

**3) Results / Conclusions / Perspectives**

Both photonic crystal structures (inverted pyramid and cylindrical hole) enhance the absorption compared to the unpatterned reference. This enhancement can be mainly associated to a decrease of the sunlight reflected by the patterns structure as it can be seen in Fig. 3.

Fig. 4 summarizes the maximal achievable short-circuit current that can be obtained from three different periods (300, 450 and 600nm) for both the pyramidal and cylindrical patterns. It shows that an increase of the period induces the increase of the pattern size to obtain a good anti-reflection coating. In addition, the inverted pyramid structure enables to achieve higher short-circuit current than cylindrical hole structure for each simulated period.

Experimental structures are realized in a c-Si substrate by the technique described previously. The SEM images in Fig. 5a and Fig. 5b illustrate respectively the top view of inverted pyramid structure with a 300 nm period and cylindrical hole structure with a 450 nm period. The lower part of each image (see Fig. 5c and Fig. 5d) is the corresponding cross-sectional image, which clearly demonstrates the shape of each photonic structure.

In the case of the complete solar cell (see Fig. 2a), the behavior of the absorption spectra changes. Slow Bloch mode appears in the red part of the solar spectrum as it can be shown in the dash region in Fig. 2b. As in the previous case, the inverted pyramid structure ( $J_{sc}=23.59 \text{ mA/cm}^2$ ) enables to achieve higher short-circuit current density than the cylindrical hole structure ( $J_{sc}=17.65 \text{ mA/cm}^2$ ).

To summarize, we clearly evidence that with the targeted solar cell architecture, a smooth pattern enables to achieve a higher short-circuit current density than a sharp pattern (from an optical point of view). To go further, electrical aspect will be taken into account and other kinds of smooth pattern samples are under realization.

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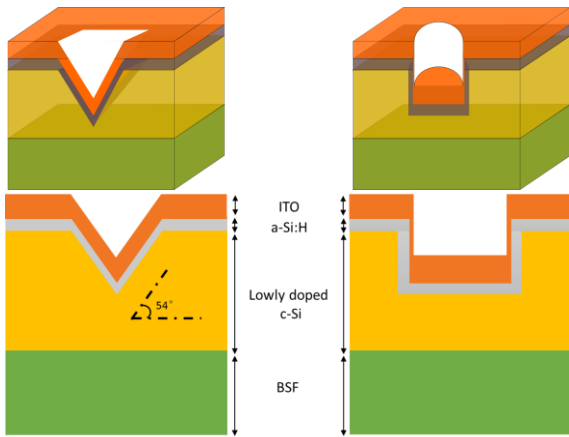


Figure 1. Schematic 3D and side-view of the inverted pyramid structure and the cylindrical hole structure simulated thanks to 3D FDTD Lumerical software.

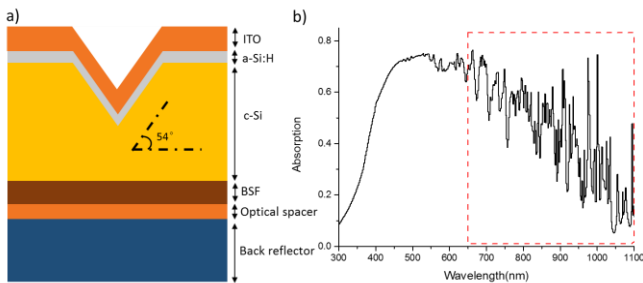


Figure 2. a) Schematic side-view of full solar cell with inverted pyramid structure. b) The absorption spectra of the local layer (c-Si) in the inverted pyramid structure for the optimal parameters (period: 800nm, ff: 0.85,  $J_{sc}=23.59$  mA/cm<sup>2</sup>).

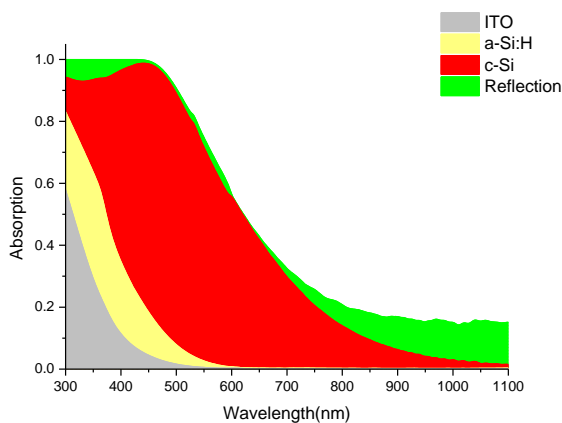


Figure 3. Absorption spectra of the each layer (ITO, a-Si:H, lowly doped c-Si) for a PhC structure of inverted pyramid (period:600nm, ff:0.7) and spectrum of the reflected sunlight.

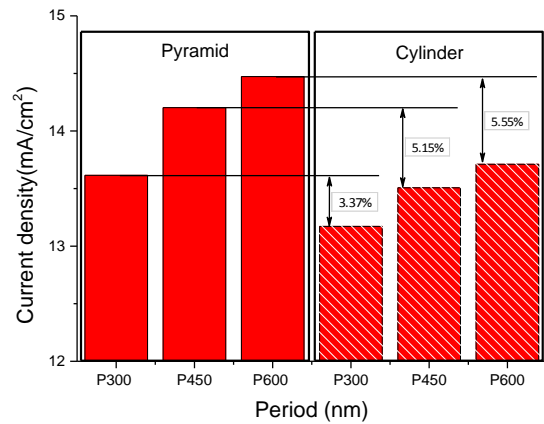


Figure 4. Highest achievable short-circuit current density for both pattern kinds for 3 different periods with 1.535  $\mu\text{m}$  thick c-Si. In the case of the inverted pyramid structure, filling fraction (ff) varies from 0.1 to 0.8 (optimal ff is 0.7 for all these three periods). In the case of the cylindrical hole structure filling fraction varies from 0.1 to 0.5 and etching depth varies from 50 nm to 250 nm (optimal ff : 0.3; optimal etching depths: 100 nm for the 300 nm period, 150 nm for the 450 nm period and 200 nm for the 500 nm period).

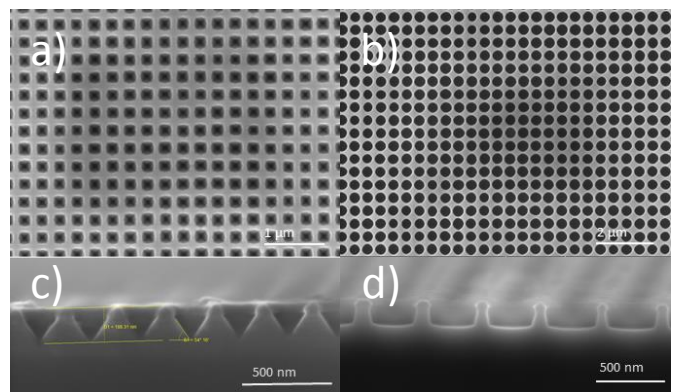


Figure 5. SEM images of (a c) the inverted pyramids structure (period: 300 nm) and (b d) the cylindrical holes structure (period: 450 nm) fabricated by laser interference lithography technique.

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