Front. Optoelectron.
DOI 10.1007/s12200-015-0499-6

RESEARCH ARTICLE

Enhanced absorption of solar cell made of photonic crystal by geometrical design

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Abstract In this paper, via numerical simulation we designed the geometry of solar cell made by one-dimensional (1D) and two-dimensional (2D) photonic crystals with two kinds of materiel (silicon (Si) and hydrogenated amorphous silicon (a-Si:H)) in order to enhance its absorption. The absorption characteristics of light in the solar cell structures are simulated by using finite-difference time-domain (FDTD) method. The calculation results show that the enhancement of absorption in patterned structure is apparent comparing to the unpatterned one, which proves the ability of the structure to produce photonic crystal solar cell. We found solar cell geometries as a 2D photonic crystal enable to increase the absorption between 380 and 750 nm.

Keywords finite-difference time-domain, two-dimensional (2D) photonic crystals, solar cell

1 Introduction

The great challenge of photovoltaics to its widespread application is the reduction of manufacturing cost and improving the efficiency of solar cell. The production of solar cell has still based mainly on crystalline silicon wafer, which hold about 81% of the photovoltaic world market. In particular, silicon has some advantages fully compatible with the well-established microelectronics technology, and one possible application of optimized thin solar cell is the integration in chips where the device thickness is limited. In such devices, the etching procedure needed to realize a photonic pattern is directly comprised in the standard chip processing. In commonly used crystalline silicon solar cells the active layer thickness is a few hundreds of microns [1], and the cost is dominated by silicon processing, this cost can be reduced if the high-quality active layer thickness is reduced to a few hundreds of nanometers.

In recent years, the relative maturity of nanophotonics has enabled the emergence of various new concepts for light management. At the same time, the development of low cost micro- and nanotechnologies compatible with the patterning of wide areas has made the implementation of such nanophotonic structure feasible. The widespread and promising approaches are based on surface plasmons, including ordered top-down metallic grating and bottom-up integrated metallic nanoparticles [2,3]. Other routes make use of non-metallic micro- and nanostructures, these are typically photonic crystal (PhC) structures, sub-wavelength structures (SWS) may be also patterned within the absorbing layer. The PhC structure used to control the absorption in a photovoltaic solar cell was proposed in 2006 [4], where high diffraction orders of a PhC back reflector were used to increase the photon path within the silicon solar cell. In Ref. [5], a PhC patterned thin silicon layer structure was proposed to increase both incident light trapping and photon lifetime in the absorbing layer. The combination of such patterned absorbers with a top anti-reflection (AR) layer and back electrodes was then proposed for one-dimensional (1D) and two-dimensional (2D) PhCs [6–11]. Both reports concluded an expected relative increase of the efficiency up to around 30%, following the integration of a PhC structure within the absorbing layer. As another approach to exploit PhC structures, the integration of conductive inverted opals as the intermediate layer of a tandem cell was proposed and investigated [12].

In this paper, we utilized PhCs to enhance light-trapping in solar cells made by two kinds of materials (silicon (Si) and hydrogenated amorphous silicon (a-Si:H)). We studied

Received December 23, 2014; accepted February 3, 2015

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via numerical simulation the optical properties of both two materials in different kinds of structures (unpatterned layer, 1D PhCs and 2D PhCs), using the finite difference time-domain method (FDTD). The parameters for PhCs were optimized through computer simulations to obtain the maximum absorption and path length enhancement. We investigated the performance of the proposed structure and determined the optimized geometrical parameters, such as period lattice and filling factor (*ff*) that allow better absorption of solar cell. A variety of structure configurations (unpatterned layer, 1D PhCs and 2D PhCs) have been implemented via mode solver program and we proved an enhancement of absorption in PhCs, and this enhancement is more pronounced in 2D PhCs solar cell.

2 Design

We designed basic structures as shown in Figs. 1(a), 1(b) and 1(c). The first one (Fig. 1(a)) consists of an unpatterned layer on a glass substrate, the second and the third one (Figs. 1(b) and 1(c)) consist of a patterned layer on a glass substrate in 1D and 2D configurations, respectively. Incident light may then be trapped in such resonances at a wavelength related to the parameters of the structure 1D: *ff*: *D*/*L* ratio between the width *D* of the silicon pattern and the lattice parameter *L*. For the purpose of comparison, the structure of solar cell (see Fig. 1(c)) was made by 2D PhC with two configurations of triangular and square array of circular holes. The gap is the same in the two directions of space, allowing an independence of the structure topography over the two planar spatial directions. The main parameters of the PhC are *L* (its lattice constant), and *ff* defined as the ratio of the air holes diameter over the period, *ff* is then given by $(1 - \pi d^2/4L^2)$, *d* is the diameter of the air holes. The thicknesses of all configurations are considered to be the same and equal to 100 nm.

Design and simulation become very important before fabrication. The numerical tools used for our simulations are based on FDTD [13]. It has been used to study the influence of the geometrical parameter of the structure on the absorption in the range of 380–750 nm wavelengths. Using the same method of simulation, we can observe the absorption of the unpatterned layer on glass with the same thickness.

3 Results and discussion

3.1 Unpatterned layer structure made by Si and a-Si:H

Figure 2 shows the absorption spectrum as a function of wavelength on the front surface for unpatterned layer. It is clear that in the unpatterned layer, a-Si:H structure absorbs the incident light better than Si structure. The ratio of enhancement is around 1.2 between 0.375 and 0.425 μm and can reach 10 times for wavelengths range of 0.575–0.650 μm. This is due to the high extinction coefficient of a-Si:H compared with that of Si in this spectral range. Beyond the wavelength of 500 nm, the extinction coefficient of the material is low. Accordingly to the high extinction coefficient of the material, the thickness of several micrometers is necessary to ensure the absorption of the incoming light in one pass within the active layer. But in our case, the thickness of the layer was limited to 100 nm, which can explain the decrease in absorption observed between 500 and 720 nm.

3.2 1D photonic crystal structure

To study the effect of patterning, the integrated absorption of 1D PhC membrane made by a-Si:H, is first optimized by varying simultaneously *L* and *ff* at normal incidence of light and fixed thickness of 100 nm.

Using the FDTD method, we can observe the absorption of a-Si:H 1D PhC on glass with thickness $H = 100$ nm. The corresponding contour mapping of the absorption efficiencies is shown in Fig. 3.

Compared to the sample unpatterned layer of the same thickness a-Si:H that absorbs about 34% of the solar light intensity integrated over the same spectral range, in the 1D PhC, we predicted that the absorption is increased to more than 42% with $L = 300$ nm and $ff = 62\%–75\%$.

Now, we observe the absorption with the 1D PhC

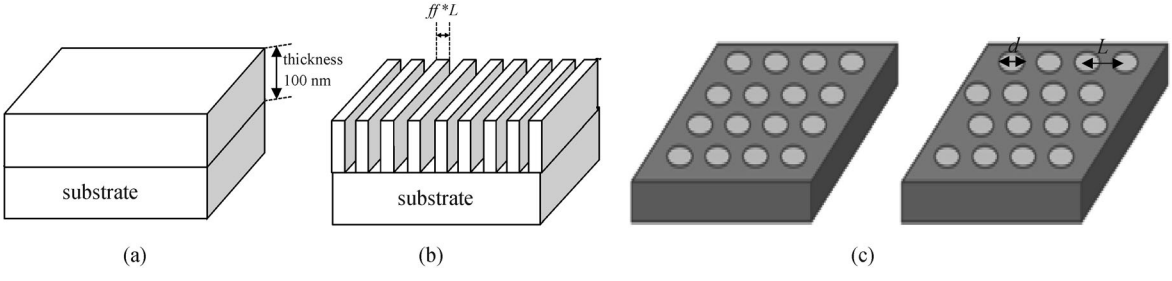

Fig. 1 (a) Structure of solar cell made by unpatterned layer on a glass substrate; (b) one-dimensional photonic crystal (1D PhC); (c) two-dimensional photonic crystal (2D PhC), with a square and triangular array of circular holes

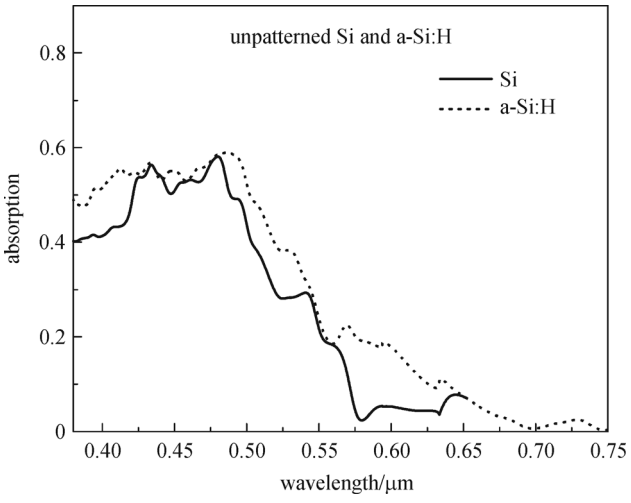

Fig. 2 Absorption spectra of the unpatterned layer of Si and a-Si:H with thickness $H = 100$ nm

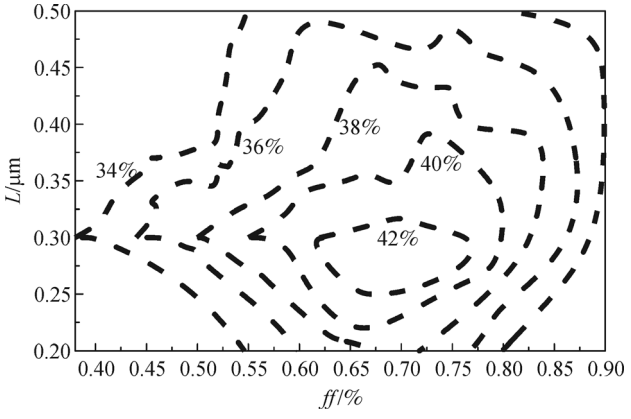

Fig. 3 Integrated absorption efficiency of a 100 nm thick a-Si:H layer in glass, as a function of the 1D PhC parameters L (in μm) and ff (in %)

membrane made by Si with the same thickness. The optimum parameters are $L = 310$ nm and $ff = 65\%$ for the 1D configuration. The resulting integrated absorptions for two kinds of material are depicted in Fig. 4.

It was observed that the spectra of the 1D PhC membrane made by Si differ from that of the 1D PhC membrane made by a-Si:H. In fact, the absorption in the a-Si:H structure was higher than that in the Si structure for all wavelengths. We observed also that absorption between 380 and 500 nm was around 60% for the two structures. In this spectral range, the extinction coefficient of the two kinds of material is so large that the optical absorption path length is lower than the layer thickness. Above the wavelength of 500 nm, the absolute values of the absorption are reduced, due to the lower absorption coefficient of the material.

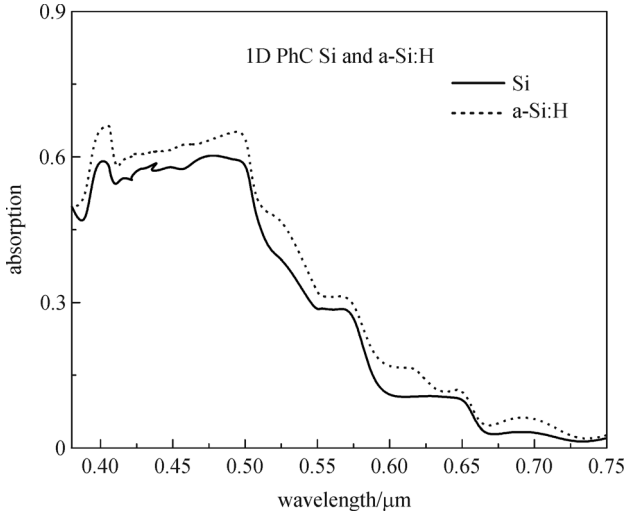

Fig. 4 Absorption spectra of 1D PhCs made of Si and a-Si:H with the same thickness $H = 100$ nm

3.3 2D photonic solar cells

3.3.1 2D photonic square lattice made by Si

The absorption spectra of 2D PhC square array of circular holes with different lattice constants (L) for thickness $H = 100$ nm is depicted in Fig. 5. Comparing the results of 300, 380 and 400 nm periods, the period is the same in the two directions of space, allowing an independence of the structure topography over the two planar spatial directions. For relatively small lattice constant ($L = 300$ nm), the ultimate efficiency first increases due to an increase in the field concentration. When the lattice constant is large enough ($L = 380$ nm), the excitation of guided resonance modes will further improve the absorption. However, when the lattice constant is too large ($L = 400$ nm), the absorption in the medium and high frequency range decreases, hence the ultimate efficiency compromises. We can also observe that at short wavelengths, the 2D PhC square array of circular holes has an antireflection coating effect, but for long wavelengths, the absorption spectra decreases versus the extinction coefficient k (k decrease rapidly). Furthermore, from Fig. 5, a significant improvement in absorption is clear, especially in the wavelengths range of 500 – 700 nm. At short wavelengths, where the material is already highly absorbing, the patterning has an antireflection coating effect. At long wavelengths, where the material's extinction coefficient k decreases extremely rapidly, the absorption is affected. Light is coupled in a PhC Bloch mode and therefore photon lifetime in the structure is increased, resulting in subsequently increasing of absorption. For 1D PhC absorption spectra, the effect of polarization is clearly observable, this is due to the coupling of the incident light in the vertical direction into Bloch modes of the PhC [14].

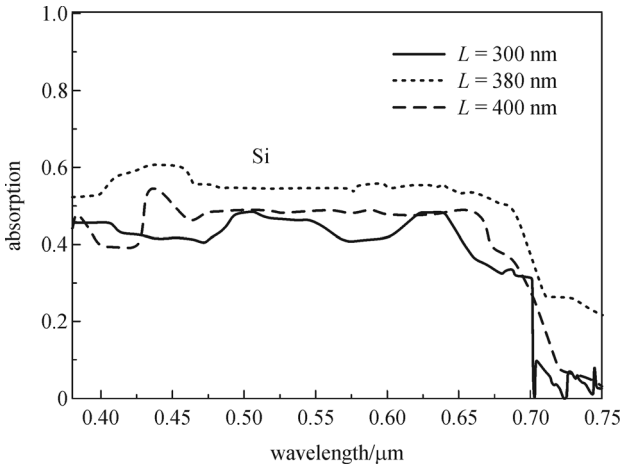

Fig. 5 Absorption spectra of 2D PhC Si square array of circular holes with different lattice constants (L) for thickness H = 100 nm (Optical simulation performed under normal incidence)

3.3.2 2D photonic triangular lattice made by Si

Figure 6 shows the absorption spectra of 100 nm thick triangular lattice Si arrays with a fixed filling ratio of around 62% and varying lattice constants. From the figure, we can observe that the absorption for Si arrays is shifted toward higher wavelengths for the three values of L, until wavelength of 650 nm. This is due to the localization of the photonic band gap in this range of frequency. Beyond this value, the absorption decreases rapidly because the extinction coefficient vanishes in this range of spectra.

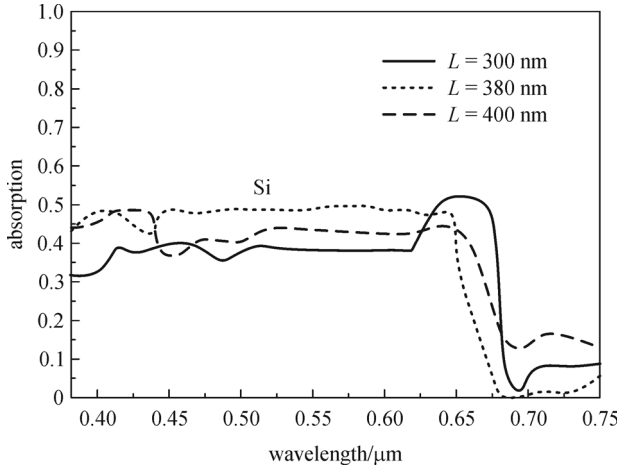

Fig. 6 Absorption spectra of 2D PhC Si triangular array of circular holes with different lattice constants (L) for thickness H = 100 nm (Optical simulation performed under normal incidence)

3.3.3 2D photonic square lattice made by a-Si:H

To study the effect of the lattice constant L on the absorption, the *ff* was fixed at 62% and we were varying L from L = 300 nm to L = 400 nm in a-Si:H.

The absorption spectrum of 100 nm-thick square lattice a-Si:H is shown in Fig. 7. Compared to the structure with Si, it is clear that the absorption is increased for all wavelengths under consideration and for the three values of period. And it can be found that comparing with square lattice of Si, the a-Si:H has better absorption efficiency for all the wavelengths range.

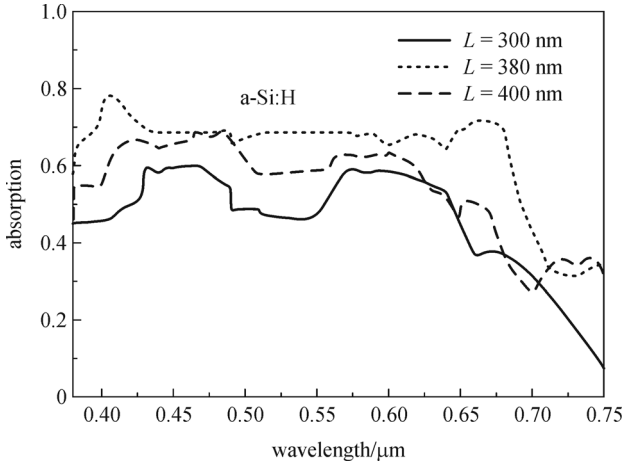

Fig. 7 Effect of 2D PhC square array of circular holes in TE mode, with a fixed filling factor and varying lattice constants (L) on the absorption spectra of a-Si:H layer

3.3.4 2D photonic triangular lattice made by a-Si:H

To understand the trend of the absorption as a function of the wavelength for several different lattice constants, we plot in Fig. 8 the absorption spectra of 100 nm-thick triangular lattice a-Si:H arrays, the same behavior of absorption in the square lattice a-Si:H is observed here for the triangular lattice, but the absorption spectrum is slightly higher than the triangular one. As a result of this study, we can conclude that optical absorption in both a-Si:H nanohole arrays (square and triangular) is better than that of silicon nanohole between 380 and 750 nm.

4 Conclusions

To summarize, we used FDTD to study the optical properties of unpatterned, 1D PhC and 2D PhC triangular and square arrays of Si and a-Si:H. Results showed that significant optical absorption enhancement occurs for both

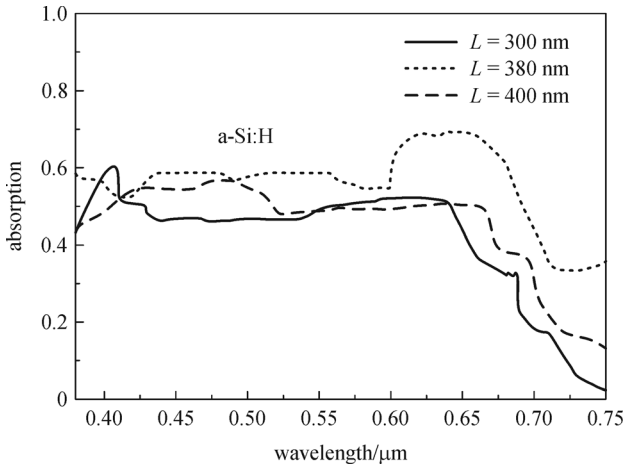

Fig. 8 Effect of 2D PhC triangular array of circular holes, with a fixed filling factor and varying lattice constants (*L*) on the absorption spectra of a- Si:H layer

triangular and square arrays comparing with the unpatterned and 1D PhC layer. Using mode solver program, an optimization study was conducted to determine the best geometrical parameters for better absorption and thus more efficient solar cell. It was found that for the optimized *ff* and period lattice values the optical absorption in both a-Si: H nanohole arrays was better than that of Si nanohole. We also found that the absorption for the square lattice configuration was slightly higher than that for the triangular lattice one.

Acknowledgements This work was supported by Ministère de l'Enseignement Supérieur et de la Recherche Scientifique via funding through the CNEPRU National program (No. J0205620130046).

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