Optical properties of one-dimensional photonic crystal and light absorption enhancement in planar a-Si:H solar cell

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Abstract. The generation of the photovoltaic has intensified over the last decade, moving from the most basic applications based on elementary devices to one of the most important applications of energy. Photonic Crystals (Ph.Cs) are very promising systems for applications in the field of electromagnetic waves and for real achievements in microwaves field. This particular property of the Ph.Cs offers the possibility of the control of light propagation in an increased way, and thus makes possible to consider many applications in nanotechnology and photovoltaic field. The a:Si-H is a very attractive material for simulation and experimental applications, when deposited in thin layers, it has an efficient refractive index. The Plane Wave Expansion (PWE) method was used to assess the band gap of the structure, the Rigorous Coupled-Wave Analysis (RCWA) method integrated in RSoft CAD Software was used to calculate the optical properties, integrates with thin film structure of the solar cell with Ph.Cs. The one-dimensional optical properties of photonic crystal with the absorbent layer of photovoltaic cell on both hydrogenated amorphous silicon (a:Si-H) and silicon (Si) are studied in this paper in order to enhance the yield of the absorption of light on a solar cell with an efficiency geometrical parameters.

1. Introduction

Advanced optical engineering is an important technology in providing new concepts and designs for photovoltaic cells with thin films. Its aim is to reduce the reflection of light at her top surface, as well as to strengthen the photonic path within the absorbed material [1]. This latter, enhances the absorption of photons, and enables the conversion efficiency of photovoltaic cells from photovoltaic engineering. In addition, the use of thin layers reduces the path of photons within the absorbed silicon, which tends to reduce the amount of light absorbed. For example, the use of photovoltaic cells for non-crystalline silicon layer with a total thickness of the absorbed substances is about 100nm [2], even if an anti-reflection coating (ARc) is used. This latter, makes a combination of optoelectronics loses because the conversion efficiency is up to~10% [3]. The optical path-way required to achieve large absorption in long waves exceeds the thickness of the silicon layer. In particular, Bermale P. et al [4] have performed a diffraction grating and reflection on the backside of the silicon solar cells [5], they have realized that it is immature with a thickness of 100 nm.
There is another way to strengthen the light collection and the absorption, this can be done by using a set of golden nano-particles on the front side of a newly introduced silicon in the photovoltaic cell, and this is approved by Matheu P. et al [6]. Before beginning the search, we proposed a planar light surface to collect incident light, and to multiply it with the slow-wave of the guided wave that stands inside the absorbent layer [7]. These echoes have been successfully used to achieve photovoltaic surface devices such as micro-controllers or broadband reflectors. Actually, most economically accessible photovoltaic cells are produced using mono-crystalline or poly-crystalline silicon[8]. These cells can revive photovoltaic yields of around 24.9% with non-concentrated light [9]. Silicon (Si) thin film technology offers many possibilities of production (modules of 1 m² or more). In addition, the moderate temperatures (150-300°C), required for the production of Si thin films induce low power consumption during industrial processes, and offer the possibility of using a wide variety of inexpensive substrates, such as glass, stainless steel or plastics [10].

Our work aims to demonstrate the concept of this interest in the special case of solar cells, based on the a-Si:H and Si layers with a thickness of up to 100 nm. It is not only for economic reasons that the thickness of the absorption thin layer is limited, but also because of the low propagation length of the photovoltaic contained in this material [11]. A One-Dimension Photonic Crystal (1DPh.C), obtained with a full a-Si:H and Si coatings can enhance the optical absorption of this layer [12] and it is therefore expected to enhance the efficiency of photovoltaic cells and increase the yield, provided they are at the lowest cost. Also, such calculations are made for a specific incidence angle and certain absorption, reflection power of a patterned or an un-patterned layers of a-Si:H and Si.

|                          | Si        | a-Si:H   |
|--------------------------|-----------|----------|
| Band gap [eV]            | 1.1       | 1.7-1.8  |
| Photo-conductivity [s/cm]| $10^2-10^4$| $10^4-10^5$ |
| Boiling point [°C]       | 3265      | 2900     |
| Density [g/cm³]          | 2.33      | 2.285    |

We consider the infrastructure as described in figure 1(a) and figure 1(b). The first layer consists of an un-patterned absorbent thin layer on a substrate of glass, while the second absorbent layer consists of a patterned absorbent thin layer on the 1D Ph.C, respectively.

The light emitted at this resonance can then be locked at the wavelength associated with the parameters of the two structures [13]. The lattice parameter (Period) is the same in the two directions of space.

![Figure 1](image)
Our study, focused on the use of Si because it is cheaper in the market and most industries are based on it, because of its technological importance in the manufacture of solar chips and photovoltaic production [14], we have also used a:Si-H because it is more sensitive than Si[15], which is a hydrogen atom, it is not present in the chemical bond gave, which make it more sensitive and more reactive to the sunlight compared with Si [16].

Both design and digital simulation are closely related. In our numerical simulations, we used the RCWA Method, which we used to study changes in the shape of the solar cell for its ability to absorb high in the visible field of optical changes [17], ranging from 350nm to 750nm (visible spectrum).

2. Method

The Rigorous Coupled-Wave Analysis Method (RCWA), it is a semi-analytical method used in computational electromagnetic, this method is most often applied to solve the diffusion from periodic dielectric structures [18].It is a Fourier space method in which the devices and the fields are represented by a sum of spatial harmonics [19]. This method allows solving Maxwell’s equations, we start with the calculation of Reflectance (R), the Transmittance (T) and thus the Absorption (A) [11].

\[ A = 1 - R - T \]

The absorbance of a material, denoted by A, is given by [11]:

\[ A = \log_{10} \frac{I_0}{I} = -\log_{10} T \]  

where: \( I_0 \) is the transmitted radiant flux by the material; \( I \) is the received radiant flux by the material; \( T \) is the transmittance of the material.

We calculate the normalized absorption efficiency \( \eta \), defined as follows [20]:

\[ \eta = \frac{\int_{\lambda g}^{\lambda_g} I(\lambda) A(\lambda) d\lambda}{\int_{\lambda g}^{\lambda_g} I(\lambda) \frac{\lambda}{\lambda g} d\lambda} \]  

where: \( \lambda_g \) is the photon wavelength corresponding to the band gap; \( I(\lambda) \) is the solar spectral irradiance.

We chose the spectral range from 350 nm to \( \lambda_g \) in the integration (visible spectrum). In a wave fall incident on a planar structure as well as how to distribute the electromagnetic field in the structure[21], we suggest some of the optical properties contribute to our understanding of how the optical proliferation in the planar structure. Measuring the absorbance throughout [22], the structure means to take into account the reduced area of the active layer due to the patterning of thin layer[23].

3. Results and Discussion

3.1. The absorption with the patterned and the un-patterned thin layers

Spectral properties of a new set of parameters used are shown in figure 2. We use the RSoft simulation software [24], to simulate the two a patterned and an un-patterned thin layer structures. The absorption was monitored as the wavelength varies, we found that the initial values of \( \eta \) are fixed at 60%. All of our studies are in the visible spectrum that’s in between \( (350 \text{nm-750}\text{nm}) \)[25]. With RSoft CAD software, we put the lattice on \( L=500\text{nm} \) for 1D Ph.C to calculate the ideal parameters. The structure of the integrated absorption of 1D Ph.C thin layer is first optimized by varying the \( L \) for the thickness of 100 nm, after that the absorption is compared with the un-patterned thin layer. We noticed that the spectra corresponding to the layer of 1D Ph.C differ from the spectrum of the an un-patterned thin layer.
For the 1D Ph.C layer in a-Si:H, the highest absorption ratio of 62% reaches between \((350 \text{ nm-} 500 \text{ nm})\), and the absorption up to \((500 \text{ nm-} 600 \text{ nm})\) begins to decrease due to the extinction coefficient \((\kappa)[26]\), until the ratio reaches 32% between the ends of the wave of 610 nm and 750 nm. This is for a-Si:H, but for Si, the amount of absorption up to about 52% between the ends of the wave 350 nm and 450 nm, which is less knowledgeable than a-Si:H being more efficient than it. They also start decreasing ranges between \((450 \text{ nm-} 610 \text{ nm})\) until they reach 20% \((610 \text{ nm-} 750 \text{ nm})\).

In the second curve, an un-patterned thin film solar cell (without 1D Ph.C), we can observe; as for a-Si:H, the absorption ratio reaches 54% \((350 \text{ nm-} 520 \text{ nm})\) and is also declining due to the effect of extinction coefficient and the efficiency of the solar cell until it reaches 20% \((620 \text{ nm-} 750 \text{ nm})\). As for the Si, up to about 41% \((350 \text{ nm-} 520 \text{ nm})\) and then to decrease to reach the ratio of 15% \((630 \text{ nm-} 750 \text{ nm})\). As a primary result, the absorption in the solar cells and increase the yield ratio is better by using photonic crystals that have the ability to do so [27], and the quantity of the Si absorption is little compared with a-Si:H.

3.2. The lattices parameters variation

The dimension was chosen in order to maintain as much of the optical band gap as possible [28]. The simulation of certain values of parameter \(L\) (lattice parameter) was repeated. Thus, for the used process, we determine the absorption of different values for the lattice parameter \(L=400 \text{ nm}, L=500 \text{ nm}\) and \(L= 600 \text{ nm}\) respectively. In addition, we calculate the absorption in the two structures with the same thickness \(= 100 \text{ nm}\).

The two curves cross the 1D Ph.C patterned layer for the purpose of studying the role change in two different a-Si:H and Si in the absorbent layer of the solar cell. In the a-Si:H patterned layer 1D Ph.C, the absorption ratio up to about 70% at \(L=600 \text{ nm}\), and reaches the lowest drop between 580 nm and 750 nm. With the lattices varying, in \(L=400 \text{ nm}\), we notice that the absorption ratio reached about 55%, which is lower compared to \(L=600 \text{ nm}\). On the other hand, with the Si absorbent layer 1DPh.C, we can observe that the absorption rate in thin layer solar cell, reached 52% at \(L=500 \text{ nm}\) and \(L=600 \text{ nm}\), but starting from 400 nm, increases the ratio of \(L=600 \text{ nm}\) to 55% to start decreasing \((550 \text{ nm-} 750 \text{ nm})\). As for \(L=400 \text{ nm}\), it is less than 48% until it reaches 32% between 600nm and 750nm.

When we conducted a study of the variation of lattice parameter constant \((L)\), we found that the better one is \(L= 600 \text{ nm}\) in both curves. Which can be deduced here, is that the \((L)\) is larger, the absorption rate increased especially between 350nm and 500nm. That is, the \((L)\) is a powerful factor for increasing yield in thin-film solar cells and in nanotechnology for nanoparticle and patterning [29].
In fact, the absorption is usually higher regardless of the wavelength used. For example, the absorption between 350 nm and 500 nm for the a-Si:H patterned thin layer (Figure (3.a)), approximately two times greater than the Si patterned thin layer (Figure (3.b)).

(a)  
(b)

Figure 3. Variation of lattice parameter (L = 400 nm, L = 500 nm and L = 600 nm) on the absorption power of a:Si-H (a) and Si (b) with a thickness of layer 100 nm.

The absorption can be improved globally by a combination of the effect of slow lighting patterns and the thorough regression of reflection [30], probably because of the high average index in the case of 1D Ph.C. The absorption of the patterned structure becomes two times greater in the wavelength range between 350 nm and 500 nm in the a-Si:H patterned thin layer.

3.3. The incidence angle

Figure 4 shows the adoption of the absorption spectra angle in many solar cell structures. The patterned thin film photovoltaic cell is characterized by the diffraction of the conversion efficiency on the angle of the incident light occurrence [31].

(a)  
(b)

Figure 4. The variation of the absorption of: (a) a-Si:H patterned and un-patterned thin layers, (b) Si patterned and un-patterned thin layers, in terms of the incidence angle (°).

In the two curves, the red line represents the absorbance process during the polarization state in the patterned thin layer, while the blue corresponds to the absorption in the un-patterned thin layer. The patterned thin layer is more sensitive to the incidence angle [32].
In the a-Si:H thin layer, the absorption process starts increasing ranges between (49%-67%) for the patterned structure (with 1D Ph.C), beginning from the vertical position of the angle to reach 50°, which in turn recorded the largest absorption rate at this angle, which reaches ~70%, which is very high in terms of studying the impact of incidence angles. Then, they begin to gradually decrease to the absence at a 90°. As for the un-patterned thin layer, they begin to increase gradually between 0° and 50° until they reach ~58% at 60°, which in turn records the largest absorption rate in the layer is not engraved with a-Si:H, then gradually decrease until it reaches the 90°. Therefore, their variability with respect to the incidence angle is considered, which may account for the high global absorption decline in the case of 1D Ph.C.

As for the incidence angle using Si, it is the lowest percentage of a-Si:H, which is an active and most sensitive material in photovoltaic. Between 0° and 50°, we notice an increase in the absorption ratio, to reach ~58.5% of the patterned thin layer and ~50% for the un-patterned thin layer at 60°. And then, the gradual extinction, as well as with the effect of the coefficient (k), Begin to gradually decrease until the angle 90°. Furthermore, such as mentioned above, the slow light pattern is affected by a relatively low refractive index, therefore the spatial spacing between places of diffusion of light is limited [33], and the incidence angle is increasing.

The manufacture of these solar photovoltaic cells requires the need to verify the uniformity of absorption with respect to the change of topographic parameters [34]. After that, we need to know the processing techniques that are usually used, to develop new patterns of Sub-Wavelength (SbW) on a planar surface[35]. After the comparative study of solar cells influencing the optical properties, we found that the improvement in light absorption was between ~ (350 nm-580 nm), which means an increase in yield. That is to say, that there is a qualitative improvement through the choice of material quality is a:Si-H compared with Si[36]. We explain chemically that the loss of hydrogen in a:Si-H compared with Si, has caused a high agitation and a high sensitivity to this substance, which in turn causes more agitation of the sun to the lattice parameter in the absorbent layer of the solar cell [37], which in turn contributes to a high yield. Furthermore, Ouanoughi A. et al [38] have done the study of improving the absorption of light in the solar cell, In our work we tried to develop the idea by studying the vertical position of the incidence angle in the solar cell, which in turn contributed to the enhancement of the absorption of light in the solar cell using photonic crystals.

We conclude the difference between silicon (Si) and Hydrogenated amorphous silicon (a-Si:H) in terms of cost and ease of fabrication is probably, that the Si was condition to rapidly cooled in a vacuum environment [39], and the a-Si:H was rapidly cooled in an aerated (in the present of H2) environment[40]. In addition, the Si would cost more to fabricate in a comparison to the a-Si:H[41].

4. Conclusion

In this work, we have shown some properties related to both the absorption of photons lifetime in photo-voltaic cells using one-dimensional photonic crystal and the absorption of light in the hard cells to enhance the performance of the yield. The coupling of emitted light greatly increases the absorption of the a-Si:H layer, using a simple one-dimensional photonic crystal layer, which makes it possible to find out how to enhance the absorption of light in absorbent thin layer of the solar cell. In addition, the absorption offers good stability for the incident angle. The proposed design is completed tolerant in terms of malfunctions during the manufacturing process, which make it possible to fabricate with low cost for nanotechnology such as the three-dimensional lithography or a nanoparticle. The cost of this additional technological step should be overcome by the advantages of using a higher absorbent layer in the solar cell, with optimal absorption of sunlight.

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