2-D Photonic Crystal-Based Solar Cell

Mehra Rekha, Mahnot Neha and Maheshwary Shikha

Abstract Light trapping inside a solar cell is a very important parameter needed to be studied at the time of its designing. All conventional silicon solar cells which are currently in use have low light trapping, in turn providing low efficiency. In this paper, null radius defects are introduced in photonic crystals to improve the light trapping capacity of the solar cell. The paper deals with design of photonic crystals with null radius defect and its use in solar cell to increase its efficiency. In this proposed research work, power spectrum of solar cell has been studied and absorptions of photonic crystal-based solar cell and conventional silicon solar cell are compared at different input wavelengths.

Keywords Photonic crystal · Solar cell · Null radius defect · Silicon · Light trapping · Absorption

1 Introduction

Today, there is a need to replace non-renewable sources of energy. Solar energy is a vast source of energy. It, in fact, has the potential to replace conventional source of energy to mankind. The energy delivered by the Sun in 1 h is enough to be used by people in a whole year. Current solar cell systems operate at less than 30 % power conversion efficiency, but the theoretical limit is greater than 86 % [1]. The reason for limited efficiency is the fact that all the photons do not generate electron–hole pair. The first reason behind this is the refractive index contrast of air and solar cell material; some photons are reflected. The second reason is its low absorption

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coefficient, i.e. all the photons do not get absorbed and leave the solar cell system. The third reason is that system itself emits radiation. So it is needed to assure that photons enter the solar cell device or it should prevent photons from leaving. These purposes can be termed as ‘light trapping’. Light trapping in a solar cell allows either to increase its efficiency by enlarging the number of used photons, or it allows decreasing the solar cell’s thickness which is the basic requirement of thin film solar cell.

1-D and 2-D photonic crystals are the centre of attraction for researchers these days. 1-D photonic crystal (i.e. grating) can be used to reduce reflection as anti-reflective coating [2] or can be used as back reflector. 2-D photonic crystal can also be used as back reflector [3]. Double-layer anti-reflective coating is also used to reduce reflection. Materials such as SiO_2, Si_3N_4 and TiO_2 can be used as ARC [4]. Different photonic crystal arrangements can also be used to trap light, i.e. to increase absorption inside the solar cell. To increase the absorption in solar cell further, different defects are being created inside the photonic crystal [5]. Here in this work null radius defects are created to increase absorption in solar cell.

2 Photonic Crystal

Photonic crystals are periodic micro- or nanostructures that affect the motion of photons exactly in the same way as ionic lattice affects the electrons [6]. Photonic crystals are periodic repetition of lower and higher dielectric constants. The phenomenon occurs when the period of photonic crystal (hole radius and a hole to hole spacing) is less than the wavelength of the light. Whether photons propagate through these structures or not depends on their wavelength. The wavelengths which are allowed to travel through these structures are known as modes, and group of modes is called as bands. The bands which are not allowed to propagate through these structures form photonic band gaps. Some photons of wavelength within the band gap are prohibited from propagation in one, or all the direction inside a photonic crystal, providing the possibility to confine and trap the light in a cage. Hence, these photonic crystals can be used in solar cell to trap the photons.

Photonic crystals are classified as 1-D, 2-D and 3-D. They have periodicity, i.e. alternate layers of lower and higher refractive index in one, two and three dimensions, respectively. Bragg grating is the example of one-dimensional photonic crystal; photonic crystal fibre and opal are, respectively, two- and three-dimensional photonic crystals (Fig. 1).

3 Null Radius Defect

First, the defect-free photonic crystal slab is investigated for thin film solar cells with rectangular lattices, and then sub-lattices of defects are introduced to further enhance absorption.

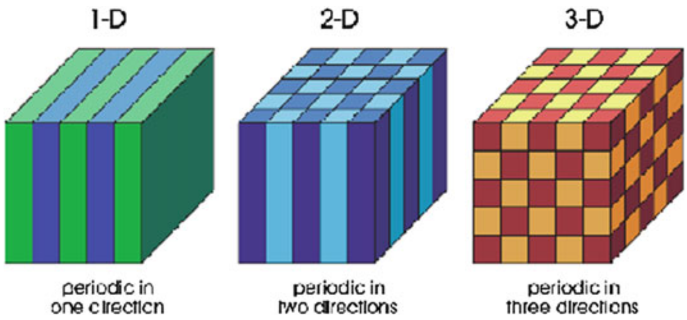

Fig. 1 1-D, 2-D and 3-D photonic crystals are represented, respectively. Different colours in cube denote materials with different refractive indexes [6] (color figure online)

In this design, a 2-D photonic crystal having rectangular lattice is used. Air holes of diameter 350 nm (r = 175 nm) and hole to hole spacing (a) of 500 nm are used. Null radius defect has been created in this photonic crystal to further increase the trapping of photons.

Null radius defect is created in photonic crystal by reducing the radius of some particular air holes to null (no air holes at the particular positions). Here in this design null radius defects are created at all these points: (0,1,1), (0,1,3), (0,1,5), (0,1,7), (0,3,2), (0,3,4), (0,3,6), (0,5,1), (0,5,3), (0,5,5), (0,5,7), (0,7,2), (0,7,4) and (0,7,6). Figure 2 shows the basic view of photonic crystal structure for defect-free photonic crystal and null radius defect in photonic crystal.

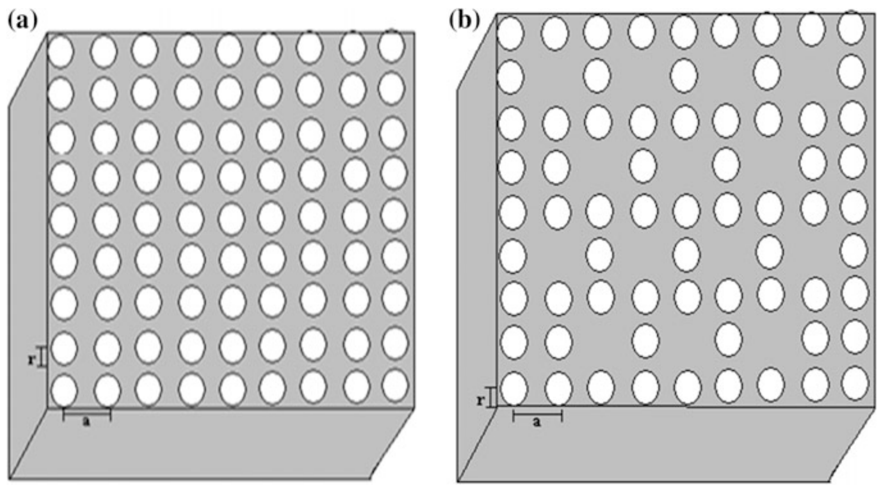

Fig. 2 **a** Defect-free photonic crystal layout **b** null radius defect in photonic crystal layout. Figure shows x–y plane only

4 Design and Simulation

The basic design consists of two layers of anti-reflective coating on photonic crystal and a back reflector. SiO_2 and Si_3N_4 (with refractive index 1.5 and 2.016, respectively) are used as an anti-reflective coating and silver is used as the back reflector. The layer of anti-reflective coating is used to reduce reflection of photons at the surface so that more photons can enter in the solar cell. Back reflector is used to reflect the unused photons back to photonic crystal (Fig. 3).

The layout of the design is drawn on Opti FDTD (Finite Difference Time Domain). To create a defined material profile in FDTD, we just need the refractive index of material. AMPL boundary condition is used with source wavelength in the range of 400–800 nm. This range is chosen so, because AM. 1.5 G spectrum [7] has the maximum solar irradiance in this region.

Figures 4 and 5 show the reflectance and transmittance of photonic crystal with introduced null radius defects. The absorption for the given design can be calculated using the following formula:

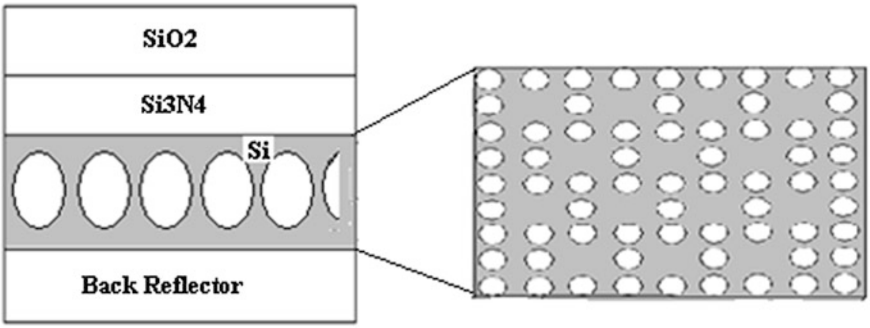

Fig. 3 Basic design of solar cell based on photonic crystal with null radius defect

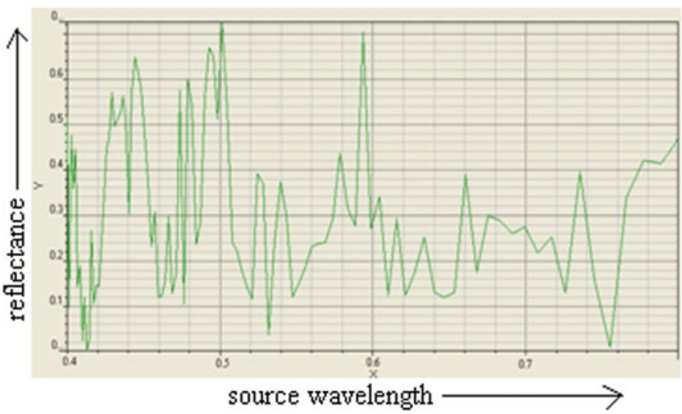

Fig. 4 Reflectance at different input wavelengths at $a = 500$ nm and $r = 175$ nm

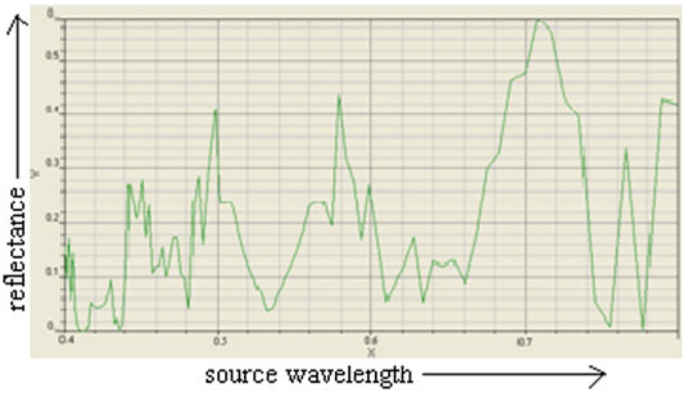

Fig. 5 Transmittance at different input wavelengths at a = 500 nm and r = 175 nm

Table 1 Comparison of absorption of null radius defect in photonic crystal solar cell and conventional silicon solar cell

Source wavelength	Absorption of photonic crystal with null radius defects solar cell	Absorption of silicon-based semiconductor solar cell
400	0.35	0.07
500	0.05	0.02
600	0.5	0.12
700	0.22	0.08
800	0.12	0.09

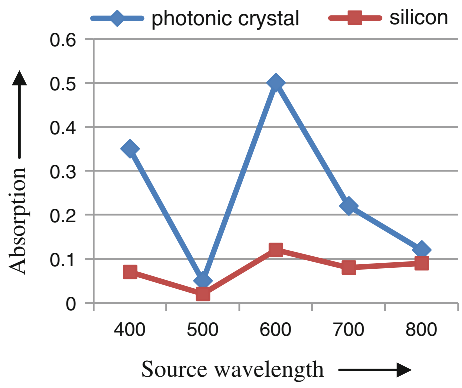

Fig. 6 Absorption at different input wavelengths at a = 500 nm and r = 175 nm

$$A = 1 - R - T. \quad (1)$$

In this work, the absorption of photonic crystal solar cell with null radius defect and the semiconductor solar cell has been compared. The power spectrum of photonic crystal solar cell with null radius is found to be far better than that of conventional solar cell. The graph has been plotted for the input range of 400–800 nm in Fig. 6 (Table 1).

5 Conclusion

We have presented periodically textured Si to increase light trapping inside a solar cell. We have designed null radius defects in 2-D photonic crystal formed by etching holes in silicon wafer. We have compared the normalized absorbed power of photonic crystal solar cell having null radius defect to that of conventional silicon solar cell, whereas in [5] current densities at different defect diameters are presented.

In this paper, absorption is taken as key parameter because absorption can be easily linked to the reflectance and transmittance in solar cell. Light trapping can be further enhanced by either reducing reflectance at front end or by increasing reflectance at rare end. This can be done using anti-reflective coating [5] or by using texturing at front surface. It can also be linked to the techniques like use of Bragg grating [8] or diffraction grating [9] to direct photons back into solar cell. So the use of absorption in the analysis of 2-D photonic crystal is an effective approach as compared to that of current density [5] for light trapping in a solar cell as predicted.

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