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Light management studies by using different surface texturing for thin c-Si solar cells

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Abstract

To realize the high-efficiency solar cell, surface texturing method is one of the well-liked and potential way for the last few decades. Though different research groups have adopted several types of nanostructured anti-reflective geometries for front surface texturing of solar cell but till today which type of dimension will be fruitful to get maximum efficiency of the cell is yet to be exposed. In this work, we are trying to give a comparative study of different types of nanostructure geometries like circle, ellipse, trapezoidal and triangle (or cone) made by same material silicon and try to investigate their potential to give minimum reflectance for better cultivation of electron–hole pair into the junction of the cell. Through this study, it was validated that the triangle or cone structures have the competence to satisfy maximum criteria like low reflectance, Omni-directionality with better harvesting of electron–hole pair into the junction of the solar cell without compromising its material and processing cost. Further these types of structures (cone or triangle) have the potentiality to enhance the efficiency (more than 27% compared to other structures) of solar cell with noticeable increment of short-circuit current of the device. Finally, we fabricated the optimized nanotriangle (or nanocone) geometry through nanosphere lithography technique to realize the structure in real world and found the same optical occurrence which was already explored in our simulation studies.

Keywords Surface texturing · Thin c-Si solar cell · Anti-reflective geometry · Nanocone · Nanotriangle · Nanosphere lithography

1 Introduction

In this present era, majority of the (about 80%) world's energy needs will be fulfilled by fossil fuels to meet the increasing energy demands [1]. As the conventional reserves are very limited in this planet, therefore, overall fossil fuel consumption has been increased approximately 51% from 1995 to 2015 and the usage will increase by about 18% more in 2015–35 [2]. So the continuous usage of fossil fuels will create rigorous environmental problems for our planet in future. To overcome these issues, we have to choose alternative clean energy sources like hydro, solar, wind, biomass, ocean, and geothermal, etc. to protect our enviroment as well as to reduce the dependency on conventional energy [3]. Recently, the diverse groups of researchers are presenting different new and renewable enrgy sources but to mantain the equilibrium between production cost with supply of power is very crucial. In the present age, solar PV technology is the most promising way to meet the current energy demand in a clean and sustainable way.

To improve the efficiency of solar cells, photon harvesting near to the junction is one of the most significant factors. But generally, it will not happen because more than 30–40% of the sunlight will be reflected from the surface and 70–60% absorbed by the solar cell. By reducing reflectance for a wide range of visible spectrum (wavelength of 300–1100 nm), the loss will be reduced by making non-reflective nanostructures on top surface of the solar cell. So, increasing the photon injection into the silicon solar cell without compromising its material and processing cost is the foremost criteria to achieve high-efficiency solar cell. In order to decrease the reflection loss into the solar cell, the most popular method is to

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make some nanostructuring on top of the silicon surface which will offer some multiple bounces of light or embedded some nanoparticles to produce some plasmonics effect which injects maximum photon into the junction. As the different group of researchers did some scattered work by the help of some diverse structures with dissimilar materials had realized some good efficiency of solar cells. But till today the use of only material like silicon whose structure is good yet to be exposed. So, through this work we are trying to give some comparative studies of different silicon nanostructures and analyzing their opto-electrical effects which may be competent to give the pathway to future solar cell developers and researchers [4–11].

Throughout the whole study, we mainly focused on different light trapping silicon 2D nanostructures like circle, ellipse, trapezoid and triangle or cone with aspect ratio ~ 1 on thin silicon (~ 10 μc) substrate and investigate their opto-electrical properties in the course of some simulation studies with the help of Finite Element Method (FEM)-based software. In this work, we primarily give attention on Electric Field and Reflectance profiles offered by different nanostructures. Thereafter, we have inserted these optical responses into electrical simulation model and trying to investigate the ultimate efficiency of solar cell having different types of nanostructure geometry. At last we are trying to fabricate the optimized simulated structure in real world through nanosphere lithography technique.

2 Simulation and optimization

For a normal bare silicon solar cell, the reflectance loss will be more than 30%, and this is a huge photon loss in solar cell efficiency prospective. To get high efficiency from thin c-silicon solar cells, the first and foremost criterion is to collect the maximum number of photons of the solar spectrum for a wide range of wavelengths (300–1100 nm). For that, we need to make an antireflective structure on top of the silicon surface for harvesting maximum photon into silicon. But what type of structure is adequate to satisfy all criteria (like low reflectance, better omni-directionality, lesser material cost etc.) still not exposed much till today. So, through this simulation study we try to establish one structure which will gratify maximum criteria for high-efficiency thin c-Si solar cell without compromising its processing cost and efficiency. Therefore, in this study we are simulating different types of geometries on top of the surface of silicon solar cell and try to investigate their opto-electrical responses.

Simulation has been carried out with the help of 2D simulation model of different nanostructures like circle, ellipse, trapezoid and triangular (or cone) arrangements on top of the thin c-silicon (10 μc) structure. Before initiating the simulation, we must mention the one uniform dimension for all structures to compare the opto-electronics properties of solar cell. So, in this study the dimensions of every structure are 200 or 300 nm (base, height or diameter) and maintaining the aspect ratios (AR) which is very close to 1. The simulations models are shown in Fig. 1.

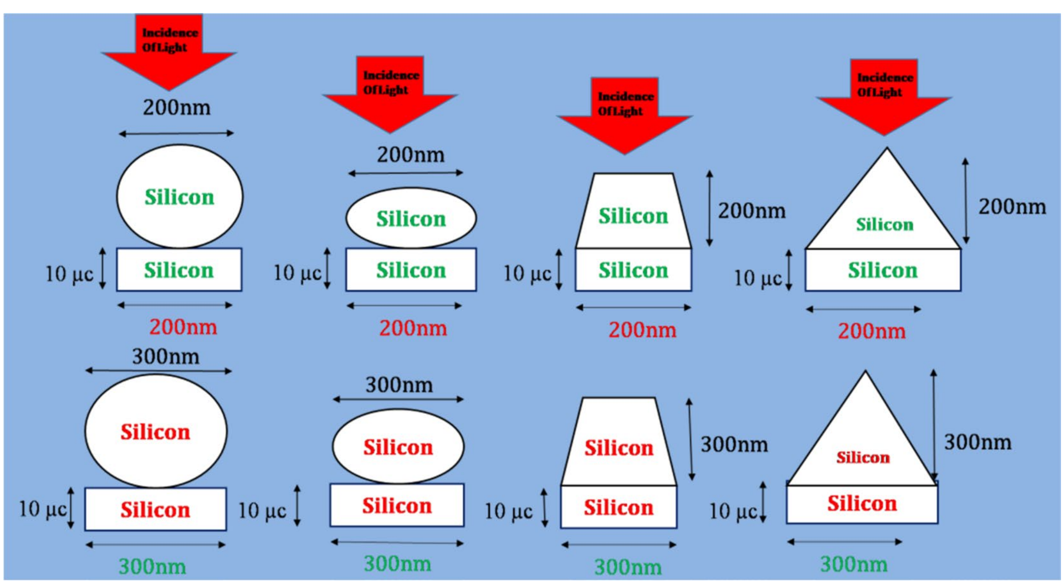


Fig. 1 Model representation of different antireflective nanostructures for thin silicon solar cells

2.1 Simulation setup

The simulations were carried out in finite element method (FEM)-based software to evaluate the electric field and the reflectance responses of the structures. All the simulations accomplished for a single-cell structure with the periodic conditions (Flouquet periodicity), which made the entire geometry continuous in x- and y-axis. In simulation setup, two types of port must be used to obtain the optical results from thin silicon solar cell, where port 1 was used for excited the light and port 2 was treated as PEC/PML (Perfect Electric Conductor/Perfect Matched) layer. The wavelength range lies between 300 and 1100 nm with the 0–10 Degree Angle of Incidence (AOI). The schematic diagram of whole simulation setup has been shown in Fig. 2. The lower position indicates semiconductor material (substrate) silicon and above the silicon layer will be the air region. The models, formulae and further meshing have been developed internally in the software done by it.

The optical simulation investigates the properties like electric field, reflection, absorption and transmission of the particular nanostructure geometry with the help of scattering parameters (s-parameters) provided by the FEM software. The equations which are incorporated into the simulation study are given below.

$$S_{11} = \sqrt{\frac{\text{Power\_Reflecred\_Port1}}{\text{Power\_Incident\_Port1}}}, \tag{1}$$

$$S_{21} = \sqrt{\frac{\text{Power\_Deliverd\_Port2}}{\text{Power\_Incident\_Port1}}}, \tag{2}$$

$$\nabla \times E = 0, \tag{3}$$

where S_{11} and S_{12} are reflectance and absorbance, respectively. E is the electric field.

The port 1 is excited by the sun's light AM 1.5 with wavelength range (300–1100 nm). After passing the air region, the light strike into the substrate material (silicon) and scattered by nanostructured surface. Due to the interaction between two light rays in a particular point inside the material producing mainly hotspots in the electric field profile. These hotspots are the evident of multiple bounces and supper scattering of light inside the material. So, maximum hotspot (mainly red regions) inside the material indicates that the surface of the material offers very low reflection of light. This is the reason behind the high absorption of photon into the material which will increase the short-circuit current of solar cell and further increase the efficiency of the device. So, in our simulation work we also incorporated the reflection responses of different structures and included the integrated reflections in the electrical model to find out the ultimate efficiency of the solar cell. The integrated reflection value (R_{int}) can be expressed as:

$$R_{\text{int}} = \frac{\int_{\lambda=300\text{nm}}^{1100\text{nm}} R(\lambda) N_o(\lambda) d\lambda}{\int_{\lambda=300\text{nm}}^{1100\text{nm}} N_o(\lambda) d\lambda}, \tag{4}$$

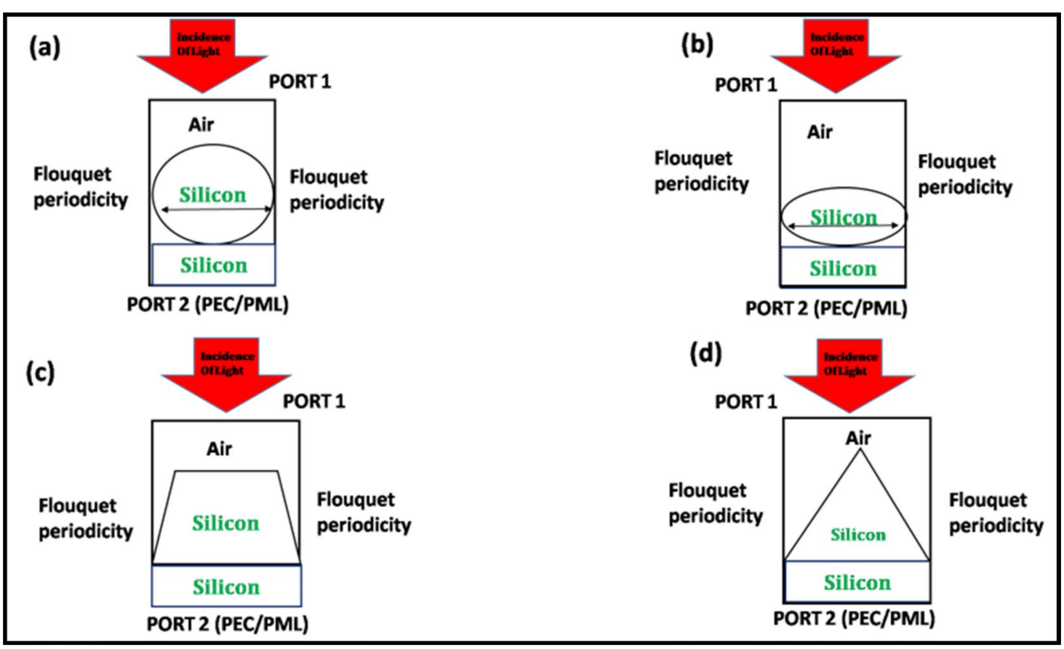


Fig. 2 Simulation setups for different nanostructures **a** circle or sphere, **b** ellipse, **c** trapezoid and **d** triangle or cone

where $R(\lambda)$ is the wavelength-dependent reflectance, $N_0(\lambda)$ is the photon flux corresponding to AM1.5 G solar spectrum.

The refractive index of crystalline silicon has real and negative imaginary part dependent on the wavelength of an incident electromagnetic wave is given as

$$\text{Refractiveindex} = n - j * k, \tag{5}$$

where n and k are real and imaginary part of the refractive index of c-Si. To perform the simulation work, the refractive index of silicon was taken from Palik and Das et al. respectively [4, 10, 12].

2.2 Results and analysis

2.2.1 Electric field profile

Nanostructures on the front surface of the solar cell provides an antireflective effect that improves the absorption over a wide spectral range from ultraviolet to near infrared. The light which is coming from the sun will be directly irradiance on the top of antireflective nanostructures, and the structures absorb the photons that produce an electron–hole pair into the absorber layer of the silicon. If the light-assisted by electric field inside the silicon conductive material, the maximum number of photons injected into the solar cell is considered to be the essential factor for increasing the efficiency of the cell.

To make a comparison between the nanostructures like circle, ellipse, trapezoid and triangle (or cone), the uniform dimensions were considered. For circle, diameter of 200 nm and 300 nm was taken, whereas for ellipse dimensions, a focal point diameter of 200 nm and 300 nm was considered and that for trapezium with aspects of equal parallel sides with base 200 nm and 300 nm was considered. At last triangle with dimensions of 200 nm and 300 nm base has been assumed. The electric field profile of all four structures at zero angle incidence of light for a given wavelength of 500 nm (Figs. 3, 4).

The electric fields of three different nanostructures like circle or sphere, ellipse, trapezoid and triangle or cone in 500 nm wavelength region have been represented by Fig. 3. The circle and ellipse mainly symbolize for silicon nanoparticles. Though the different literature reviews considered the plasmonic and scattering effects of different nanoparticles but in contrast to other silicon nanostructures (like nanocone, nanopillar etc.), there is still very fewer comparative studies available to establish its light trapping proficiency. In this work, we presented a relative study of silicon nanoparticles with silicon nanocone (or nanotriangle) structures and try to investigate the reality of plasmonic effect provided by silicon nanoparticles to find out whether they are really more dominate over multiple bouncing and super-scattering

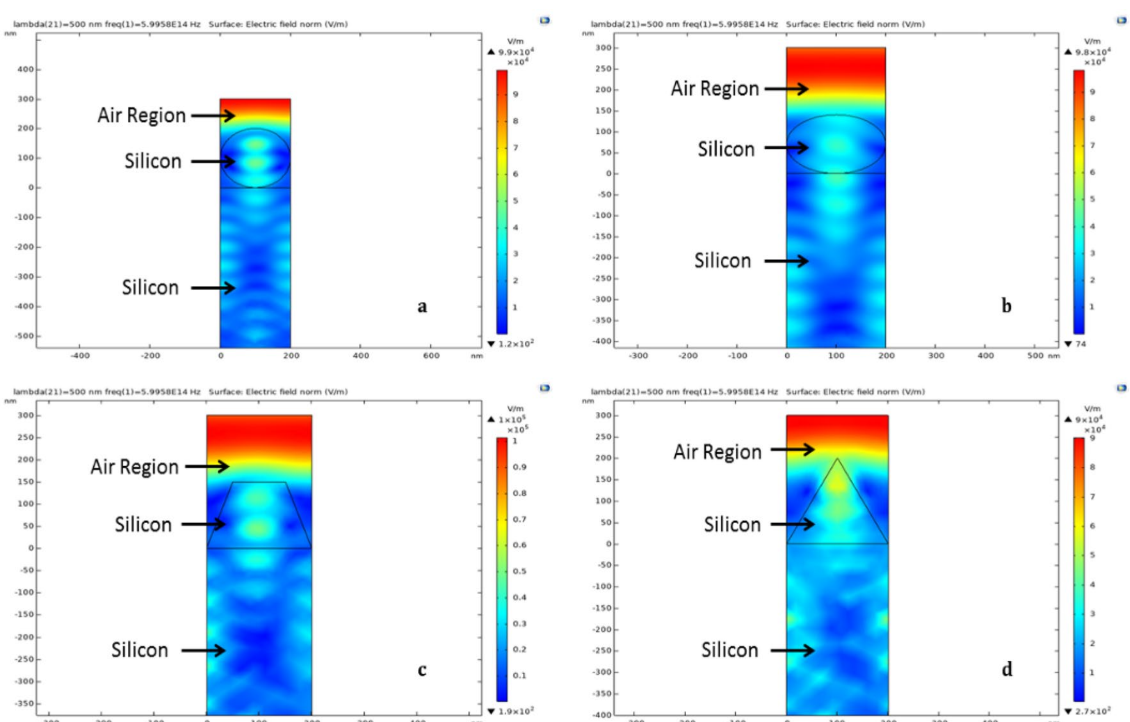


Fig. 3 Electric field profile of nanostructures **a** circle, **b** ellipse, **c** trapezoid, **d** triangle at zero degree angle of incidence for a base of 200 nm for a wavelength of 500 nm

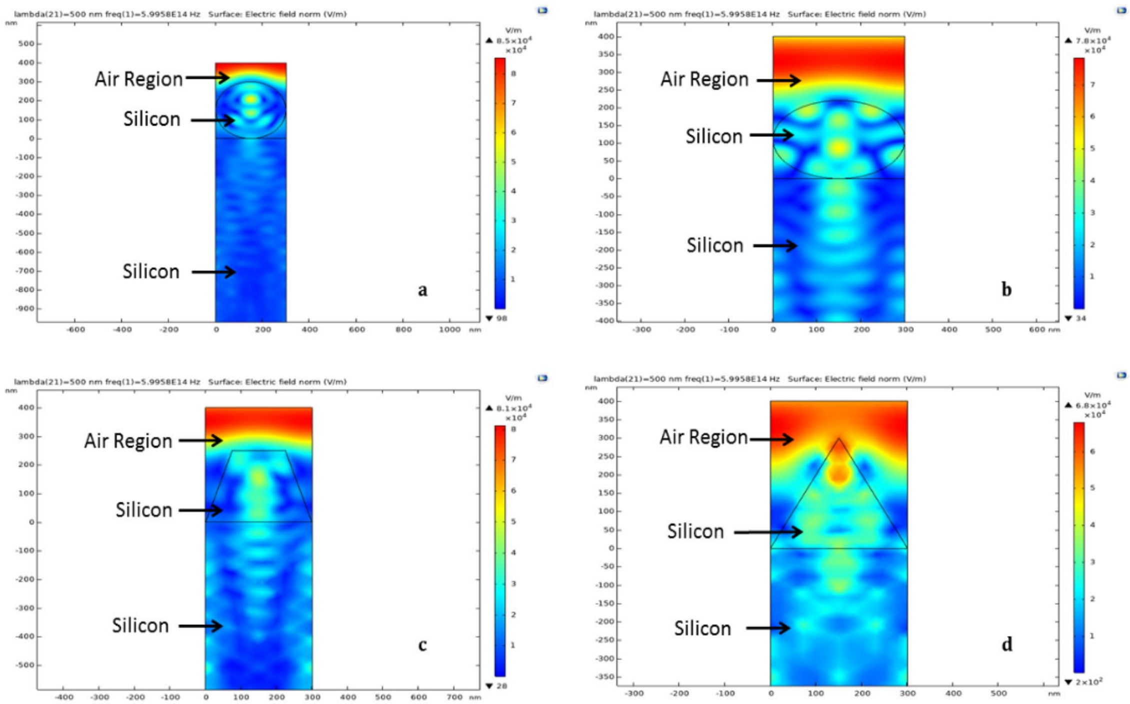


Fig. 4 Electric field profile of nanostructures **a** circle, **b** ellipse, **c** trapezoid, **d** triangle at zero degree angle of incidence for a base of 300 nm for a wavelength of 500 nm

offered by silicon nanotriangle structures or not. If we compare Fig. 3a, b with Fig. 3b, c one fundamental difference was observed that nanoparticles mainly offer funneling of light which will inject through the silicon substrate but nanotriangle structures competent to provide multiple bouncing and super-scattering of light into the surface. But our main motto was not only to investigate the optical phenomenon of light rather to examine the proficiency of each structure on light trapping capability. So, after examining Fig. 3, we established one fact that nanotriangle geometry will be more superior as compared to other geometries (like circle or sphere, ellipse, trapezoid etc.) as per light trapping capability concern (because the maximum yellow region was occurring in nanotriangle structure compared to others). This is the evidence to prove the consequence of nanotriangle geometry over other nanostructures [4, 13, 14].

If we study Fig. 4, then we can discover that, while increasing the diameter of circle or ellipse then more dipole formation and whispering gallery effect was noticed into structures in 500 nm wavelength regions. But these effects are not so much competent as compared to cone structure in light trapping prospective. Through different literature reviews, it was quite established that more whispering gallery mode will be created in large size particles. But in this work, we considered only two dimensions (200 nm and 300 nm) of nanostructures, so electric field responses of large size of nanoparticles and nanostructures have not been included in this study. Another point we must notice that due to whispering gallery mode some trapped light rays need to leak out through high reflective index material. But in this whole work we took only silicon as material, so probability of escape light from nanoparticles to substrate is very less as well as inefficient. We also considered the electric field responses of nanostructures in higher wavelength region as shown by Figs. 5, 6 and 7 but had found same type of repeated behaviors [11, 15].

Through this simulation study, we observed optical responses of all the four nanostructures from the visible spectrum to the near-infrared region. As per the results (electric field profiles), it is clearly visualized that the triangular (or cone) structure will collect maximum number of photons compared to other three structures. In trapezoid, little flat surface was found on top of the geometry, so some photons will be reflected from the surface. Due to this reason, even if the trapezoids have the capability to perform multiple bounces of light throughout the surface, but it is inefficient to trap same amount of light as compared to cone structure. However, in case of triangle (or cone) structure maximum light will be injected into the substrate throughout the spectrum. The cone structure offers smooth variation of change of refractive indexes from air to silicon substrate (top to bottom) making the entire domain divided into small parts having increasing order refractive indexes. So, it is treated as multilayer ARC (anti-reflection coating) which make sure

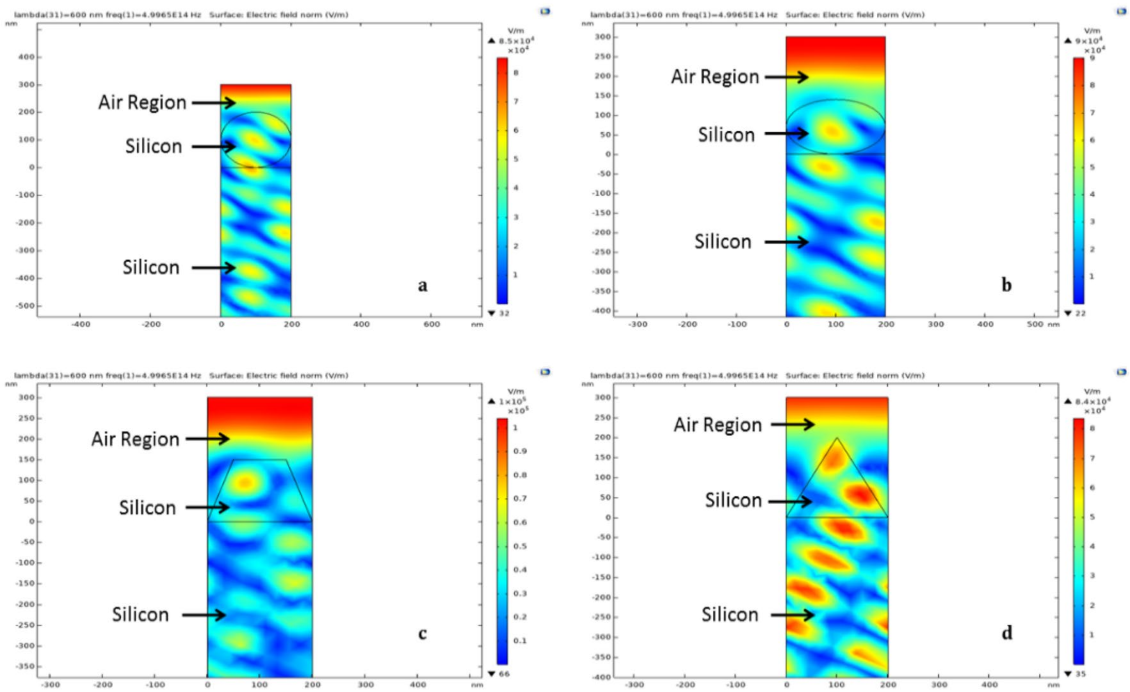


Fig. 5 Electric field profile of nanostructures **a** circle, **b** ellipse, **c** trapezoid, **d** triangle at zero degree angle of incidence for a base of 200 nm for a wavelength of 600 nm

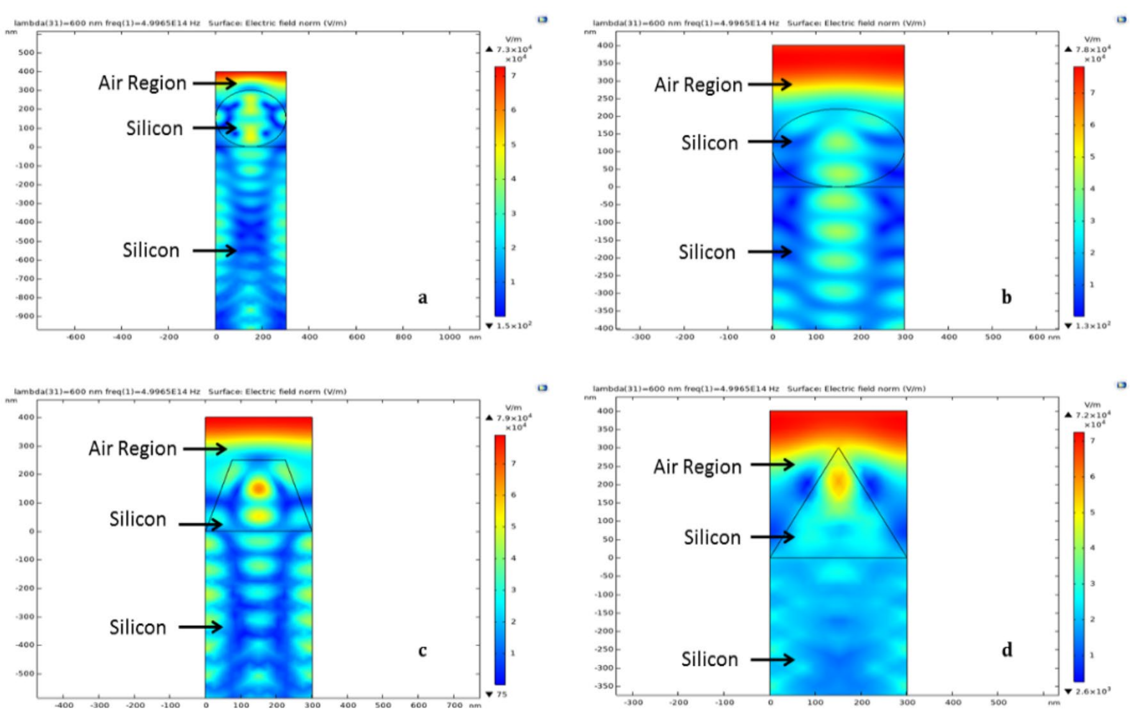


Fig. 6 Electric field profile of nanostructures **a** circle, **b** ellipse, **c** trapezoid, **d** triangle at zero degree angle of incidence for a base of 300 nm for a wavelength of 600 nm

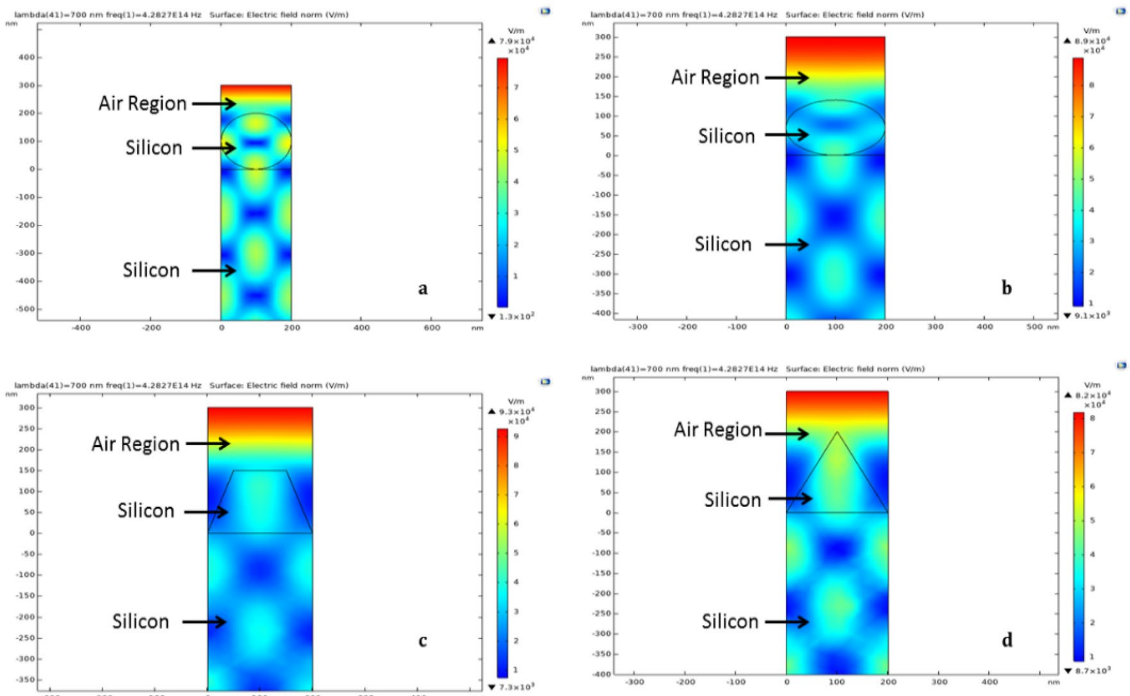


Fig. 7 Electric field profile of nanostructures **a** circle, **b** ellipse, **c** trapezoid, **d** triangle (or cone) at zero degree angle of incidence for a base of 200 nm for a wavelength of 700 nm

to provide maximum injection of photon into the silicon surface through smooth bending of incident rays. Additionally, the triangular (or cone) structures offer multiple bounces of light rays into the silicon surface, that's why the path length of the light injected into the silicon surface will increase and further generate the electron–hole pairs which may convert into the short-circuit current of the solar cell. Throughout the analysis, we can easily recognize that among all the structures, triangular structures will give good electric filed profile and capable to harvest more electron–hole pairs into the substrate material compared to trapezoid, circle and ellipse (Fig. 8) [11, 15].

2.2.2 Reflectance profile

For increasing the total absorption of light into the silicon substrate with reducing internal reflection, the most effective procedure we must follow is to form an anti-reflective structure on the top of the solar cell. For that purpose, we make the top surface of the solar cell rough which will scatter light into many angles. In this section, we are going to analyze the reflectance property of different anti-reflective structures like circle, ellipse, trapezoid and cone (or triangle) embedded on top of the silicon substrate. In the simulation, we are setting an angle of incidence at 0^0 (zero degree) for 200 nm and 300 nm size for all the arrangements.

For circle, the wavelength from 300 to 500 nm the reflectance is more than 40%. Later in 500–1100 nm region, the reflectance is less than 30%. Due to the dipole formation with some plasmonic effect, this type of phenomenon may be observed. In case of ellipse, the reflectance is greater than 40% for the wavelength that ranges from 300 to 500 nm, thereafter in 500–1100 nm wavelength region this reflectance is decreased, i.e., less than 40%. Though we noticed some whispering gallery effect in ellipse structure but due to the usage of the same material as substrate (silicon), the trapped light rays into the structure are incapable to go inside the substrate. This is the reason for not recognizing good light trapping quality demonstrated by ellipse structure. For the trapezoid, the wavelength ranges from 300 to 500 nm the reflectance is greater than 40% followed by 500–1100 nm region the reflectance is less than 30%. As we know that due to some flat surface on top of the trapezoid structure some high reflectance may be observed. But this type of structure also offering some multiple bounces of light and for this reason some reduction in reflectance may occur during 500–700 nm wavelength region. For the triangle or cone-like structure, the reflectance responses from the silicon substrate were decreased in whole visible spectrum. It was observed that during 300–500 nm region the reflectance of the surface is less than 30% and between 500 and 1100 nm wavelength region it was reduced by 25% which is validated by Fig. 9.

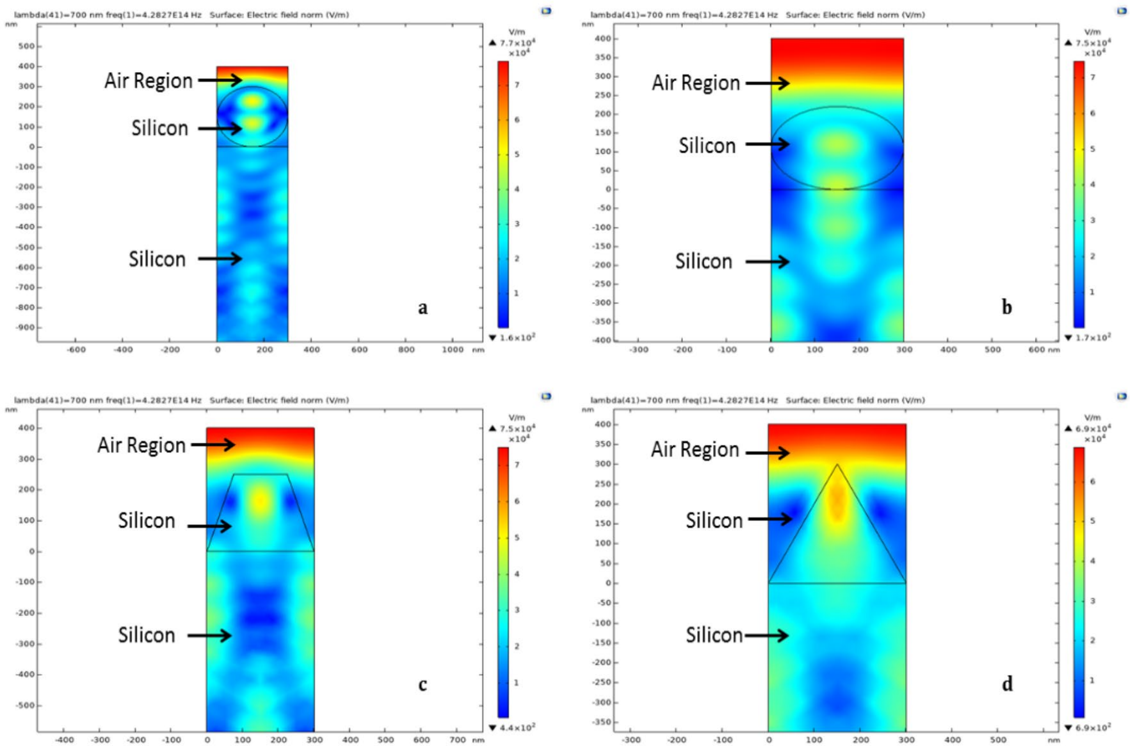


Fig. 8 Electric field profile of nanostructures **a** circle, **b** ellipse, **c** trapezoid, **d** triangle (cone) at zero degree angle of incidence for a base of 300 nm for a wavelength of 700 nm

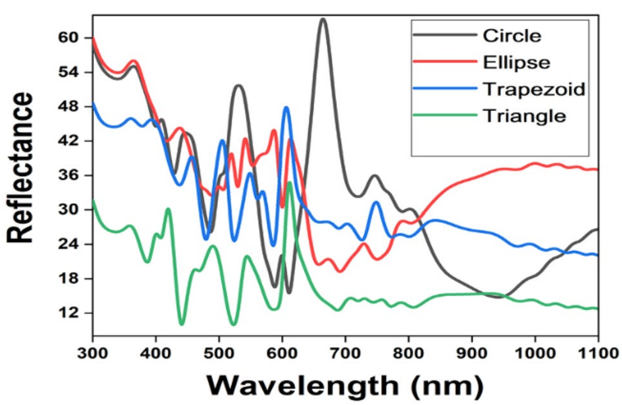


Fig. 9 Reflectance profile of ARC-type nanostructures **a** circle, **b** ellipse, **c** trapezoid, **d** triangle at zero degree angle of incidence for a base of 200 nm for a wavelength of 300–1100 nm

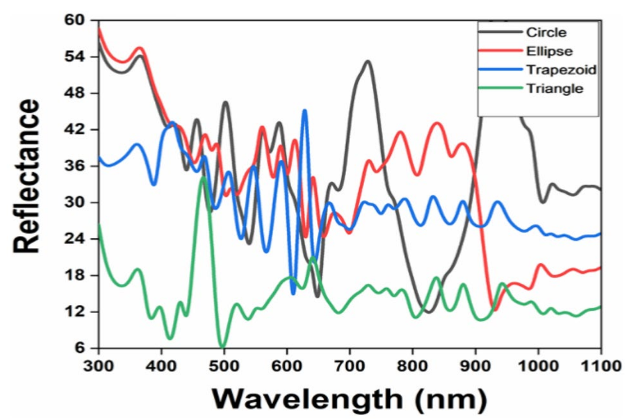


Fig. 10 Reflectance profile of ARC-type nanostructures **a** circle, **b** ellipse, **c** trapezoid, **d** triangle at zero degree angle of incidence for a base of 300 nm for a wavelength of 300–1100 nm

The same type of behavior was also noticed in 300 nm base structures, i.e., for circle, the reflectance is (> 30%) and that for ellipse as well as trapezoid (< 35%), whereas for the triangle it was reduced to (< 20%) during the 300–1100 nm wavelength region. The reflectance profile of the 300 nm structure (base or diameter) is presented in Fig. 10.

As we know that reflectance is one of the significant characteristics of solar cell which indicates its potential to absorb photon and converted it toward the electron–hole pair for producing electrical energy. But in solar cell point of view, the reflectance value of just one degree of light is not sufficient. One efficient solar cell must have the potential to supply maximum output power throughout the day. For this reason, we must consider the reflectance profile of different nanostructures in the higher angle of incidence of light as well [16]. So the integrated values of reflectance in different angle of incidence (AOI) were calculated for all

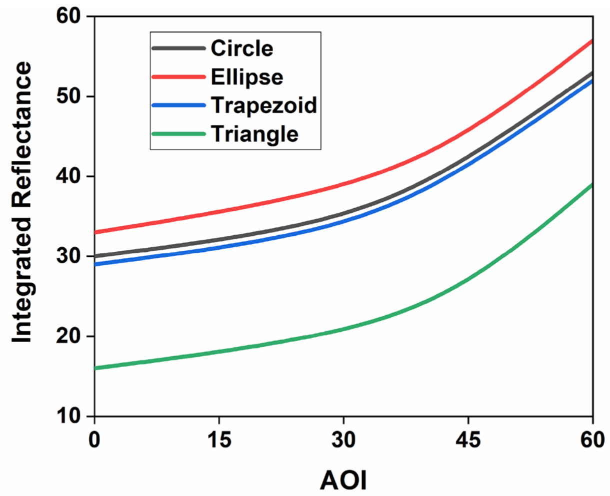


Fig. 11 Integrated reflectance profile of ARC-type nanostructures (circle, ellipse, trapezoid and triangle) in different angle of incidences (AOI) for 200 nm structures (base or diameter)

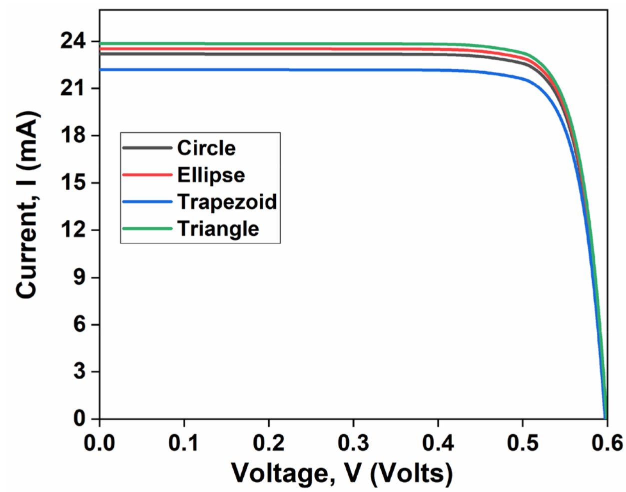


Fig. 13 Current–voltage characteristics of the thin solar cell with different nanostructures (200 nm size)

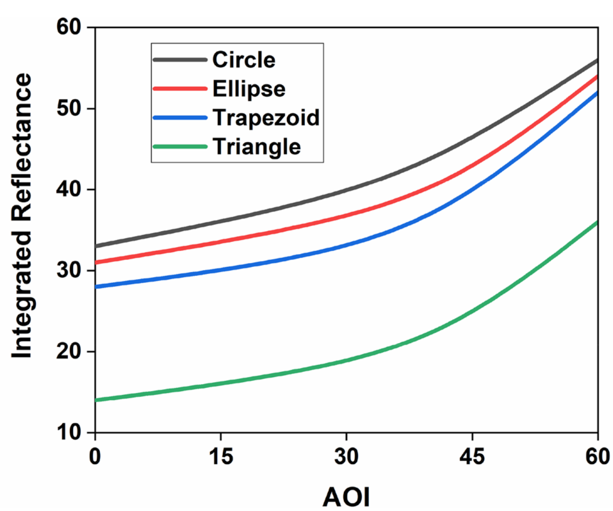


Fig. 12 Integrated reflectance profile of ARC-type nanostructures (circle, ellipse, trapezoid and triangle) in different angle of incidences (AOI) for 300 nm structures (base or diameter)

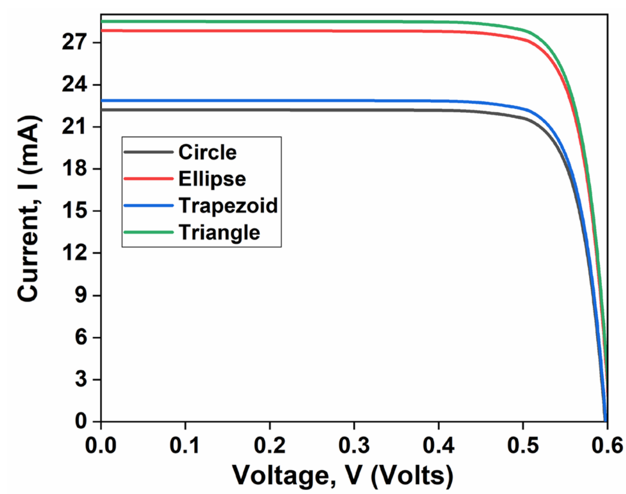


Fig. 14 Current–voltage characteristics of the thin solar cell with different nanostructures (300 nm size)

nanostructured geometries as shown in Figs. 11 and 12. In this study, the triangle or cone-type geometries also prove their competence and confirmed the minimum reflectance in higher angle of degree of incidences also.

2.2.3 Current–voltage (I–V) characteristics

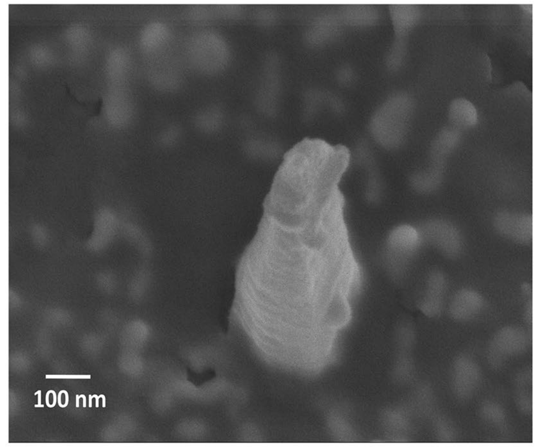
To determine the efficiency of solar cell, the standard solar cell simulation model was considered [10]. The optical responses (like reflectance, transmittance etc.) of different nanostructures is included into this model, and we tried to investigate the output efficiencies of the solar cells embedded with different nanostructures. In this method, the standard parameters of the solar cell were taken as an input for the simulation. And we also considered all the solar cells with different geometries encompassed with good passivation layer. That's why the nanostructure geometries on top of the solar cells were not going to affect the minority carrier's lifetime of the device. In this study, we only considered the optical behavior offered by nanostructure geometries embedded on top of the cell. Figures 13 and 14 show the current–voltage (I–V) characteristics of different nanostructured solar cell under AM 1.5G illumination with 1cm^2 active area. The highest conversion efficiency (13.07%) was achieved by the nanocone (or triangle)-embedded solar cell with $V_{oc} = 600$ mV, $I_{sc} = 14.19$ mA and fill factor (FF) = 82% as shown in Table 1. Further this efficiency will be enhanced up to 14% for 300 nm base structure.

3 Fabrication process

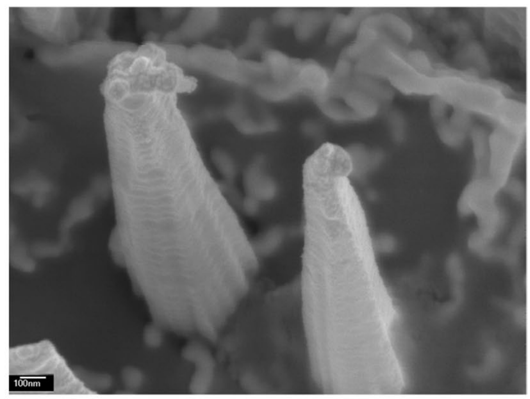
To realize optimized cone-like nanostructures, metal-assisted chemical etching (MacEtch) with nanosphere lithography was chosen as the fabrication process. The whole fabrication process was carried out with p-type flexible mono-crystalline < 100 > silicon wafer of ~ 10 µm thickness scaled down from 180 µm wafer using chemical etching technique [10, 11]. Due to need of thorough comparative study in practical prospective, we have fabricated trapezoid-type nanostructured geometry on top of the thin silicon substrate. The same metal-assisted chemical etching technique (MacEtch) with almost same conditions was adopted to fabricate trapezoidal-type nanostructured geometry without introducing nanosphere lithography step. The FESEM image of nanotriangle and nanotrapezoidal structures on top of the thin silicon surface is shown in Figs. 15, 16 and 17.

Reflectance measurements of fabricated nanostructured embedded thin silicon wafers were done by Bentham PVE300 spectrometer with integrated sphere and the characteristics are presented in Fig. 16. It was quite evident from the reflectance data that the synthesized silicon nanotriangle structures can successfully offer low reflectance and can inject maximum photon into the solar cell very efficiently in comparison with the other samples prepared in this study.

In the solar cell fabrication process p-type < 100 > , 20 µc thin c-Si substrate realized by chemical etching process was mainly used as substrate material. All the wafers were cleaned by 10% HCl solution for 2–3 h in 80 °C and then dipped in 10% HF solution for 5 min. Then all samples were entered in a capacitively coupled PECVD system (RF



(a)



(b)

Fig. 15 FESEM image **a** top side and **b** 15° tilled angle view of fabricated silicon nanocone (triangle) structure on top of the thin silicon substrate

Table 1 Comparison of electrical parameters of different nanostructure embedded thin c-Si solar cells

S. no	Angle of incidence of light (AOI)	0 Degree				
	Types of nanostructure	Open-circuit voltage V_{oc} (V)	Short-circuit current I_{sc} (mA)	Maximum power P_m (mW)	Fill factor FF	Efficiency η (%)
1	Circle_200_nm	0.59	23.21	11.45	0.83	11.36
2	Circle_300_nm	0.59	22.21	10.94	0.83	10.87
3	Ellipse_200_nm	0.59	22.21	10.94	0.83	10.87
4	Ellipse_300_nm	0.59	22.87	11.28	0.83	11.19
5	Trapezoid_200_nm	0.59	23.54	11.62	0.83	11.52
6	Trapezoid_300_nm	0.59	23.87	11.79	0.83	11.68
7	Triangle or Cone_200_nm	0.6	27.85	13.85	0.82	13.07
8	Triangle or Cone_300_nm	0.6	28.51	14.19	0.82	14.02

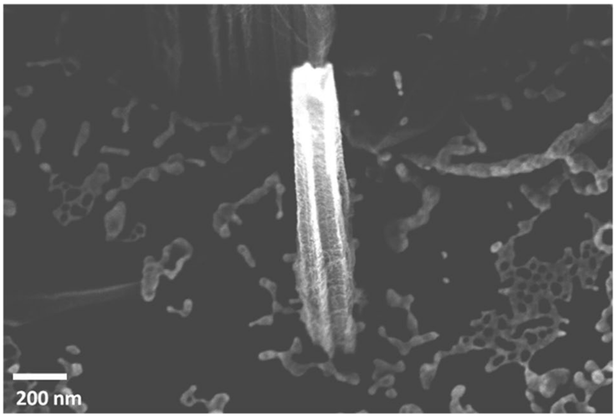


Fig. 16 FESEM image of fabricated silicon nanotrapezoid structure on top of the thin silicon substrate

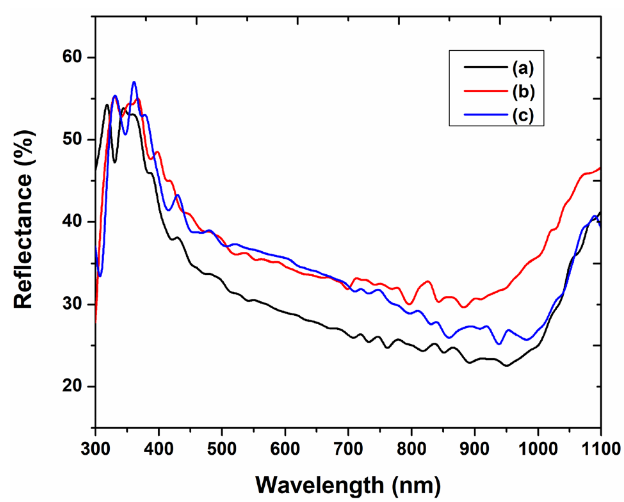


Fig. 17 Reflectance curves for optimized **a** nanotriangle, **b** nanotrapezoid structures with (**c**) bare ultrathin wafers prepared in this study

excitation frequency of 13.56 MHz) to deposit the n-type a-Si layer (1% PH_3 in SiH_4 and H_2 in ratio of 1:5).

To measure the efficiency of such sample-fabricated devices with different nanostructured geometries, 5 sets of current–voltage (I–V) characteristics for each type of cell were tested under AM 1.5 G illumination (using a Cell Tester CT-50AAA from PET, California, USA, active cell area was ~ 1 cm^2), and the finest results are presented in Fig. 16. A conversion efficiency of 6.53% was observed for the solar cell with nanotrapezoid structure with V_{oc} = 413 mV, I_{sc} = 0.025 A and fill factor (FF) = 63.24%. For the thin silicon solar cells with nanotriangle like structures, the conversion efficiency was found to be 7.37% with V_{oc} = 427 mV, I_{sc} = 0.03 A and fill factor (FF) = 57.53%. This indicates about 20% enhancement in I_{sc} and 12.86% improvement in conversion efficiency, which were achieved by deploying the nanotriangle photon trappers on top of the device. This further signifies that the c-Si with nanotriangle geometries were capable of trapping and pushing more photons into the cell that results in more carrier generation and better Isc value than that of other nanostructures (Fig. 18).

4 Conclusion

At the end of the study, we proposed a triangle (or cone)-type ARC nanostructure geometry which will give better efficiency of solar cell by offering less reflection loss while compared to the other structures. Further this type of geometry can be competent to give better omni-directional photon capture capability throughout the day compared to other geometries. In fact, through this study we tried to establish the proper geometry for front surface texturization of solar cell using same material so variation in dimension of nanostructures was not considered in this study. Further, a simple fabrication method was adopted in this work which will minimize the market price of the solar cell very effectively. In future, through proper optimization the aspect ratio of the nanotriangle geometry will be accomplished to get maximum efficiency of solar cell as well. The authors believe that, this study will give the right pathway to future researchers and developers for designing and developing proper antireflective surfaces for solar cells that establish the PV technology as a prime power source in generation sectors.

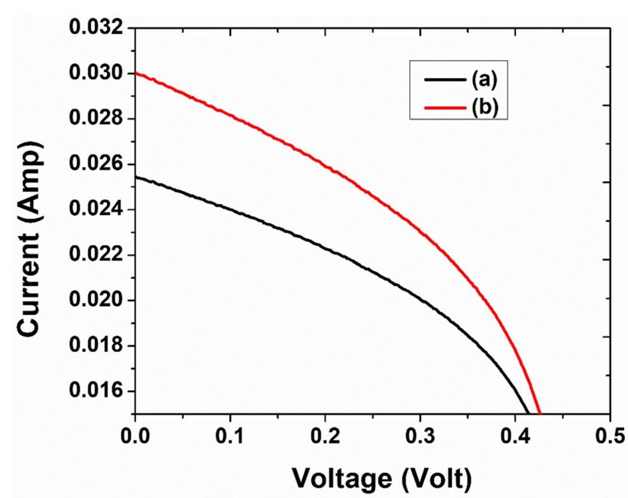


Fig. 18 I–V characteristics of solar cells embedded with **a** nanotrapezoid and **b** nanotriangle structures

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