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Silicon Micro-Nanopillars as Solar Tracker for Thin Crystalline Photovoltaic Application

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Abstract

Silicon micro-nanopillars are fascinating structures which can increase the light trapping phenomenon in solar photovoltaic applications. In this work focus is kept on reducing the reflection for wider ranges of incidence angle. By implementing this wide angle light collection phenomenon the conventional solar tracking system can be replaced which is currently being used to enhance the overall efficiency of the solar photovoltaic system. Further as the solar tracker is having rotating parts it needs regular maintenance which makes them expensive and even prone to hazardous weather conditions. If a similar performance as that of a solar tracker system can be achieved without using conventional mechanical tracking system then cost per watt can be significantly reduced. Here we demonstrate that by using silicon micro-nanopillars we can achieve similar performance reduced reflection at wide variations of incidence angle. Simulations have been carried out to optimize the geometry in COMSOL MULTIPHYSICS, where TE (Transverse Electric) and TM (Transverse Magnetic) polarized light are made incident over the geometry and reflection is observed at different angle of incidence. A simple technique of using silica nanoparticles as the masking layer in the gold assisted chemical etching process has been proposed for fabrication of silicon micro-nanopillars. A reduced reflection of ~5% over a spectral range of 300-1100 nm is obtained by the micro-nanopillars over silicon substrate.
Keywords: Wide angle lightcollection, solar tracking system, Micro Nano pillars.

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1. Introduction

A solar tracker is basically a device on to which solar panels are fitted which tracks the motion of the sun across the sky ensuring that the maximum amount of sunlight strikes the panels throughout the day. It is observed that at 37.6 degrees latitude 32.5% more energy is obtained from the PV panels which tracks the sun. Sun tracking can increase the power output for PV solar power plants by about 25% to 40%, depending on the geographic location. A single axis tracker will increase power output by 26%, while a dual axis tracker increases power by 32% [1]. Single axis trackers follow the sun from east to west, while two axis trackers also track the sun altitude (up/down). Since the sun moves across the sky throughout the day, in order to receive the best angle of exposure to sunlight for collection of energy, a tracking system is often incorporated into the solar arrays to keep the array facing towards the sun. So for this reason solar tracking method is very well established and popular method to increase the power output of PV solar power plants. But it is not so cost effective and also complicated mechanical processes are involved in this method for efficient tracking of the sun. It consists of many rotating parts which need regular maintenance and are even prone to hazardous environments.

It is important to point out here that the primary scaling factor in photovoltaics is the thickness of the absorber layer [2]. As the absorber thickness goes on decreasing so will its light trapping capability. Therefore it is very important to make the physically thin layer optically thick. Tapered Silicon nanostructures [3] have gained significant research attention due to their light trapping ability but we will demonstrate that on properly choosing the dimensions of the nanostructures it is possible to overcome the morning, evening and winter light losses in a solar cell. The reflection characteristics have been studied at various incidence angles and it is observed that the reflection remains low for wide angular variation of incidence angles. The geometry has been fabricated with the help of nanosphere lithography and MacEtch technique.

2. Simulation and Optimization

Simulations have been done on COMSOL Multiphysics to evaluate the Electric fields and Reflection of the geometry [3]. Fig 1 shows the geometry in which a Silicon micro nanopillar has a height ‘h’ and a base of‘d’. The geometry drawn is a unit cell structure and without losing generality the periodic boundary conditions are used which make the geometry continuous in x and y axis.Two ports have been used to obtain the results, one of which is placed at a certain height above the structure and another at the bottom of the geometry. Scattering parameters (S-parameters) in terms of electric field have been defined in the wavelength region of 300-1100nm. Incident light with Transverse Electric (TE) and Transverse Magnetic (TM) polarizations have been considered.

We investigate a tapered nanopillar of different Aspect Ratio (AR) which is the ratio of ‘h’ and‘d’.We take different aspect ratios keeping the width of the base 200 and 800 nm and observe the integrated reflectance response in different angle of incidence of light [Fig2]. It is seen that for very high values of AR the reflectance becomes almost independent of the base width. However, for small values of AR the reflection losses are significantly dependent on the base of the nanopillar and therefore the absolute height. Therefore the actual value of the ‘third dimension’ is very much important for the wide angle light collection. However, it is very important to point out here that structures having a very high value of absolute height will also offer higher surface area to volume ratio and will therefore be detrimental for the performance of the solar cell due to enhanced charged carrier recombination at the surfaces. It is seen that for base widths of ~200nm and AR of 4 a total integrated reflection loss of ~5% is obtained. It is interesting to note the unique dimensions of the device as the base radius is 200nm and the height is 1μm giving them a unique nomenclature of micro-nano structures.

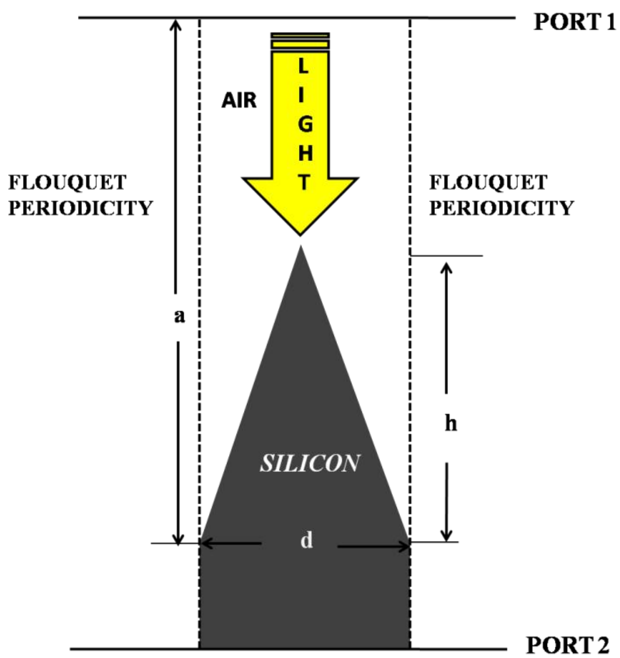

Fig. 1. Schematic diagram of the optimized geometry

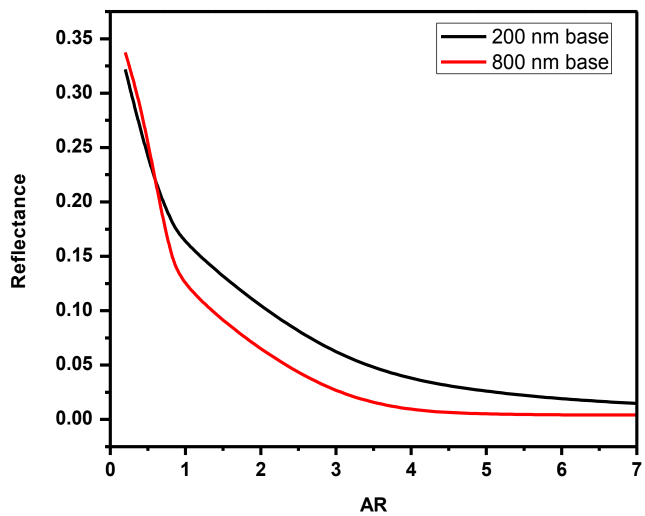

Fig. 2. Reflectance response of 200 nm and 800 nm base silicon nanopillar

Figure 3 shows the reflection characteristics of a 200nm base tapered pillar with an AR of 4. It is seen that the reflection values remain quite low for very high angles of incident light as compared to that of bare silicon [Figure 4].

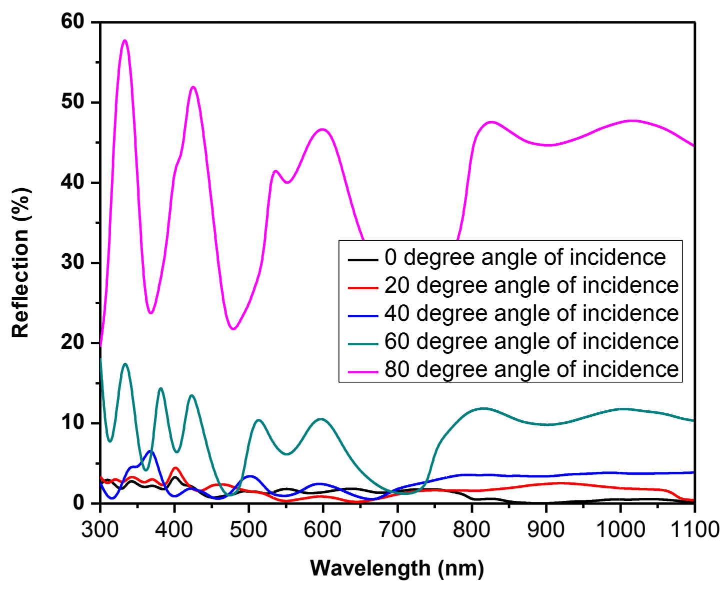

Fig3. Reflection characteristics of a 200nm base tapered pillar with an AR of 4

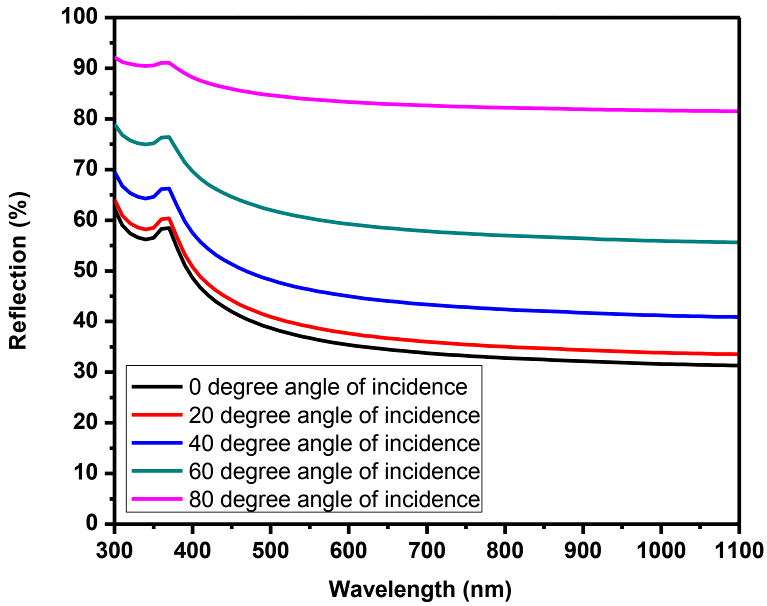

Fig. 4. Reflection characteristics of a bare silicon

3. Fabrication of Optimized Structure

The nanopillars of the optimized geometry are fabricated on thin (~20µm) crystalline silicon wafers obtained by a *patent pending* process. Thereafter the micro-nano pillars are formed by nanosphere lithography and MacEtch technique as described in [3]. Figure 4 shows the FESEM image of the fabricated micro-nanopillar. The base width is approximately 200nm with a height of 1µm. The tapering of the pillar is obtained by carefully controlling the reaction parameters. The slight orthogonal movement of the gold nanoparticles leads to the tapering of the micro-nanopillars. To have an overall idea on the optical behavior of the system in a real solar cell configuration a back reflector is evaporated on the thin crystalline wafers. It is seen that the reflection is in the range of ~5% till 850nm demonstrating not only its immense capability of reducing reflection at wide angles but also suppressing back reflection from the metal interface [Figure 5]. It is mainly due to the combined effect of the scattering within the micro-nanopillar and the substrate housing the same which leads to such advanced light trapping capabilities [3]. The reflection from a bare silicon wafer is also superimposed on the figure.

The authors would like to point out here that the reflection measurements at wide angle of incidence are from a structure having a diffractive/refractive/reflective is immensely difficult. It may be done by the means of a sample being placed inside an integrating sphere and rotating the substrate holder with respect to the incident light. The fabrication of the measurement system is presently being actively pursued by the authors.

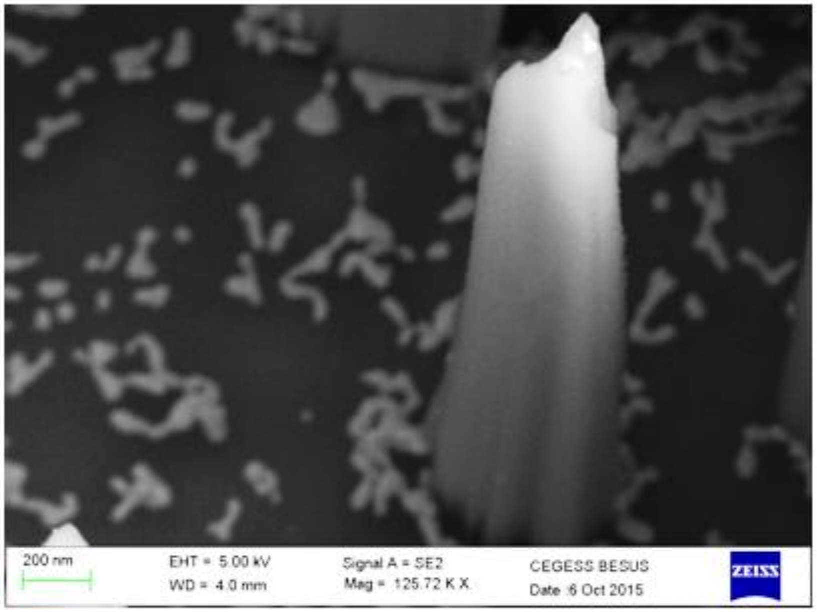

Fig. 5.SEM image of fabricated silicon micro nanopillar

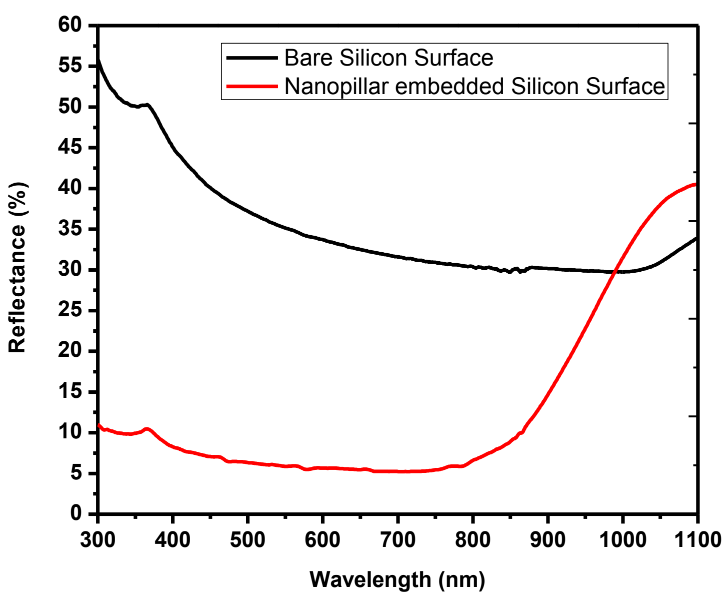

Fig6.Reflectance comparison between Bare and nanopillar embedded silicon surface

4. Conclusion

It is seen that optimally designed micro-nano pillars can not only provide ultra-low reflection but also provide wide angle light collection. Such geometries will therefore enable a thin crystalline solar cell to overcome the morning, evening and winter light losses. The optimized geometry has been fabricated and it is seen that very low values of reflection are obtained even when the 20μm thin silicon wafer is coated with a back reflector. This work demonstrates tremendous potential of micro-nano structures for solar cell applications.

Acknowledgements

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References

[1]Tian Pau Chang, Applied Energy. 86 (2009) 2071–2078.
[2]Sonali Das, Avra Kundu, Hiranmay Saha, Swapan K. Datta (2015) Investigating the Potential of Nanoplasmonics for Efficiency Enhancement of Wafer Based Crystalline Silicon Solar Cells, Plasmonics DOI 10.1007/s11468-015-0009-0.
[3]Avra Kundu, Sonali Das , S. M. Hossain , Swapan K. Datta , Hiranmay Saha. (2014), Energy Procedia, 54 (2014) 389 – 399.
[4]Comsol Multiphysics, www.comsol.co.in.

Metamaterial Mirror as Back Reflector for Thin Silicon Solar Cell Application

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Abstract

Metamaterial mirrors as back reflector is an innovative design for light trapping phenomenon in thin silicon solar cells. An optimized design for achieving maximum reflection in such metamaterial mirror is presented in this paper. In conventional metallic mirrors when light is reflected a phase reversal occurs and thus the intensity is reduced at the reflective surface. This effect is highly undesirable in thin solar cell applications where metal is used both as an electrical contact and an optical mirror. A mirror whose reflection phase can be varied from a perfect electric mirror (conventional metallic mirror) to that of a perfect magnetic mirror can be used to overcome this challenge in thin silicon solar cells. In a magnetic mirror no phase reversal of the incident electromagnetic wave occurs resulting in maximum electric field enhancement at the mirror surface. Such magnetic mirrors are classified as metamaterial mirrors. Simulations have been done with ComsolMultiphysics to obtain electric field and reflection for both TE (Transverse Electric) and TM (Transverse Magnetic) polarized light to obtain the optimized geometry. The generation rate and phase conservation has been observed from simulation when magnetic mirror is placed at the back of silicon substrate. The enhancement in the electric field is significantly increased which will lead to an enhanced absorption in the thin solar absorber resulting in high efficiencies.

*Keywords:*Metamaterial mirror, phase reversal, magnetic mirror, electric mirror, solar cell

1. Introduction

In optoelectronic devices, mirrors are essential components which are used as back reflectors in variety of devices. A major drawback of such metallic mirrors is that phase reversal of the incident electromagnetic wave occurs when light is reflected with a standing wave with reduced intensity near the reflective surface. The electric field strength in the region within a quarter wavelength of the metal is significantly lowered [1]. The problem can be overcome by using a different type of mirror which has highest electric field right at its surface by flipping the magnetic field of an incident wave rather than electric field upon reflection. Such type of mirror is called magnetic mirror [2]. To optimize the light matter interaction in a device, spatial distribution of electric field in the active layer is not sufficient and it is required to maximize the overall intensity. Metal films as back reflectors manipulate both field distribution and the optical resonance by controlling the reflection phase of the incident wave. It is important to point out here that the primary scaling factor in photovoltaics is the thickness of the absorber layer [3]. When a conventional metallic mirror is used as a back reflector/ contact, the reduction in thickness of silicon solar cell is limited by the fact that metallic mirror reverses the phase of the incident light and reduces the intensity near the reflecting surface and hence a thicker solar absorber is needed to absorb sufficient light. It has been shown how metamaterial mirrors can be tuned for any desired reflection phase. A thoughtful solution is to therefore to choose the geometry in such way so that maximum field enhancement can be achieved. In this paper investigate the performance of metamaterial mirrors made of different materials and geometry for ultra- thin solar cell applications.

1.1 Structure and Simulation

The geometry of the magnetic mirror as a back reflector for a silicon absorber is shown in figure 1. ‘w’ is width of the unit cell, ‘s’ is the height of the silicon substrate with mirror from horizontal plane, ‘b’ is height of the base metal, ‘a’ is the height of the air above the silicon substrate and ‘g’ is the groove depth in the metal surface. Simulation of the geometry is done with ComsolMultiphysics[4] to optimize the material and groove depth of the metamaterial mirror. Two polarized lights have been made incident on the geometry, one is TE (Transverse Electric) and another is TM (Transverse Magnetic). Two ports have been given, one at the air and another at the bottom of the geometry. For simulations in the solar spectrum it is necessary to define the scattering parameters (S-parameters) in terms of electric field [5].

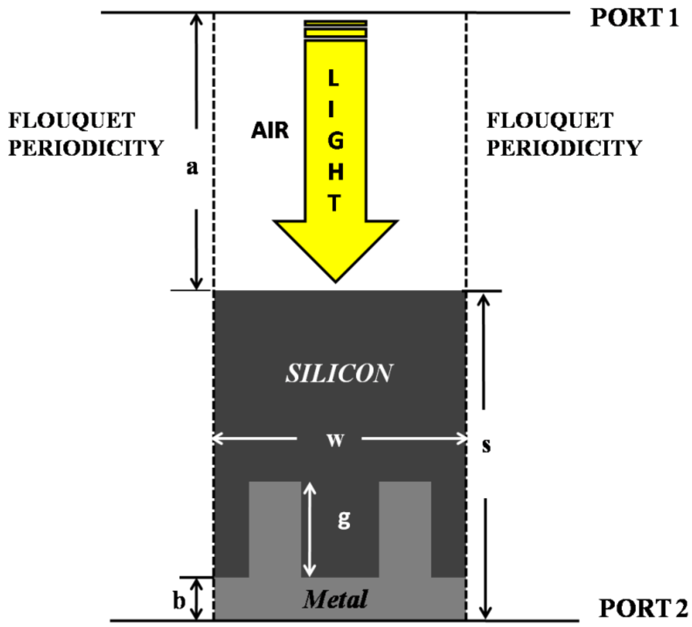


Fig1. Geometry of the proposed structure

1.2 Optimization of reflector material

The choice of the rear reflector metal is very critical to achieve the best reflection characteristics from the mirror surface for solar cell applications. Mirrors are inherently lossy in the solar spectrum region of 300-1100nm due to the imaginary portion of the refractive index of the metal. Here we compare the reflection characteristics of three (3) different materials viz. gold, silver and aluminium which are commonly used as contacts for solar cell applications. To start with, the simulations have been done neglecting the silicon absorber to better understand the performance of the mirror. The simulations have been carried out at a wavelength of 550nm where the photon flux of the solar spectrum is the highest. The groove depth is being varied from 10nm to 190nm and illuminated with both Transverse Electric (TE) andTransverse Magnetic (TM). Figure 2 shows the total reflection characteristics from the mirror surface as a function of the groove depth in the metal surface. One may note here that for small heights of the groove the metal surface will resemble that of a conventional electric mirror. It is seen that the gold surface has the minimum reflection (maximum losses) and the silver surface has the maximum reflection (minimum losses). More importantly it is seen that the reflection characteristics can be varied as a function of the groove height to either have a perfect reflector (for solar applications) or a lossy reflector (for sensing applications).Further, the grooves will also lead to efficient coupling of the incident planewave to the gap surface plasmonpolariton (SPP) modes supported by the grooves and funnelling of light into the grooves.As our paper will focus on the use of the metal as back reflector in solar cells, parasitic losses would be detrimental for the solar cell performance and hence we have focussed our subsequent studies using silver as the metal material.

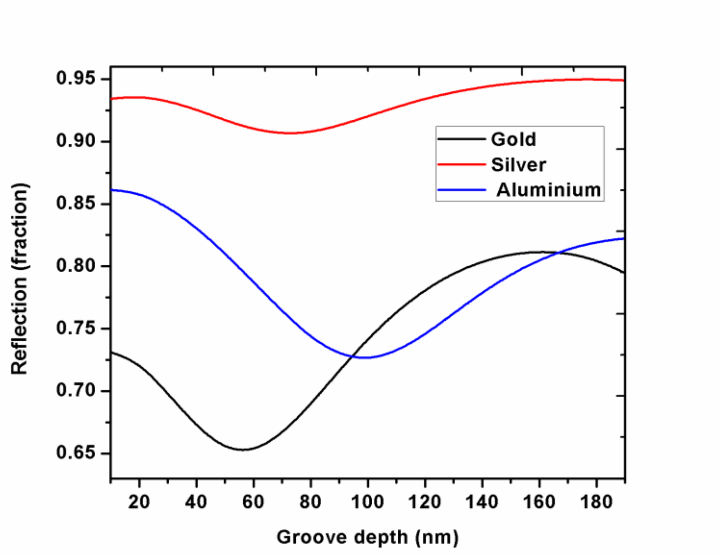


Fig2. Reflection characteristics vs. grove depth for different metals at a wavelength of 550nm

2. Results

The reflection profile of silver magnetic mirror is observed in detail for both TE and TM polarization along with the total reflection in figure 3. For a groove depth of 70nm the parasitic losses in the metal is seen to be highest (lowest) while for larger and smaller groove depths the parasitic losses are lower (higher values of reflection). Highest losses in the metal arise due to the electromagnetic field enhancement in the metal. Thus if we place an active absorber close to such a grooved mirror the electromagnetic field enhancement would lead to increased absorption in the absorber thickness (silicon in our case). But, it is very important to note that the absorption in the ultra-thin absorbing layer should be more than that obtained with a conventional mirror and the parasitic loses in the metal should not dominate over the increased absorption due to field enhancement.

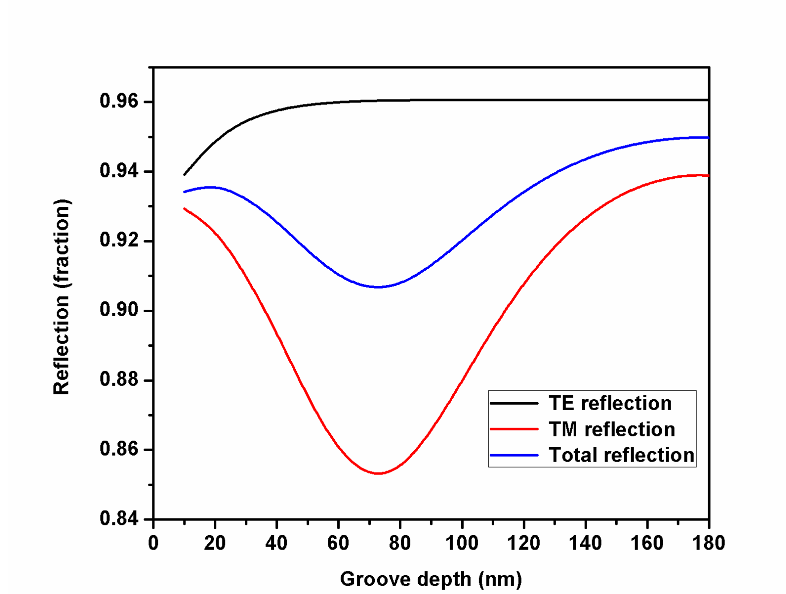


Fig3. Reflection profile of magnetic mirror with TE incident wave at various groove depth

To understand the electromagnetic field distribution at the mirror surface it is important to understand the behaviour of the reflected wave. The complex reflection coefficient for a light reflected from a surface is given by:

$$r = r_0 e^{i\phi} = \frac{Z_s - \eta_m}{Z_s + \eta_m} \ldots.(1)$$

Where r_0 and φ are the reflection amplitude and phase, η_m is the characteristic impedance of the incident medium, and Z_S is the surface impedance of the reflector surface. As we can see from the equation lower value of Z_S will lead to complete phase reversal i.e. $\varphi=\pi$. But by judicious patterning the surface impedance and the reflection phase from the metal surface can be tailored. Due to groove array structure current has to follow convoluted path, thus the surface impedance can be increased. The impedance $Z_S$can be accurately controlled by varying groove dimension resulting negligible phase reversal [1]. To study the effect of grove depth on the performance of the silver mirror the simulations are again performed without the active silicon absorber.

From fig 4 it can be seen that when light (Transverse Electric /Transverse Magnetic) is incident on a planar silver mirror, it results in suppressed electric field. A similar field is observed in fig 4(b) with periodic groove array (depth=80nm) when TE polarized light is incident over the geometry. But result dramatically changes when the grooved mirror is illuminated with TM polarized light shown in fig 4(c). A maximum field enhancement can be observed around the surface of the grooves.

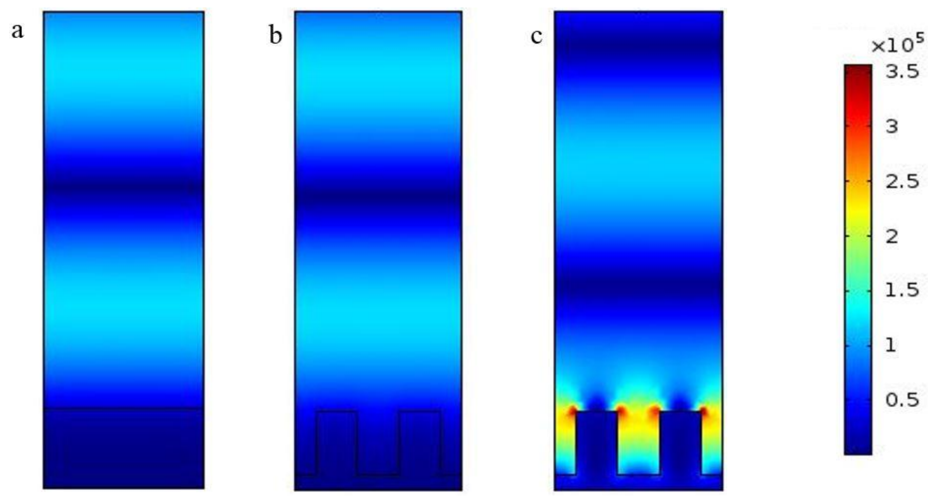


Fig4.Normal Electric Field (V/m) at wavelength 550nm for (a) Planar metallic (Silver) mirror illuminated by TE and TM polarized light (TE and TM response for planar surface is same) (b) Grooved mirror illuminated by a TE polarized light (c) Grooved mirror illuminated by a TM polarized light

Further, it can be clearly seen from fig 5 that the normal electric field at 80nm groove depth is highest as compared to shallower groove depth (40nm) and deeper groove depth (120nm). This also collaborates with the reduction in reflection due to increased absorption in the metal itself. Thus one can easily tune the properties of magnetic/metamaterial mirror by varying the groove depth from a perfect electric mirror to a perfect magnetic mirror.

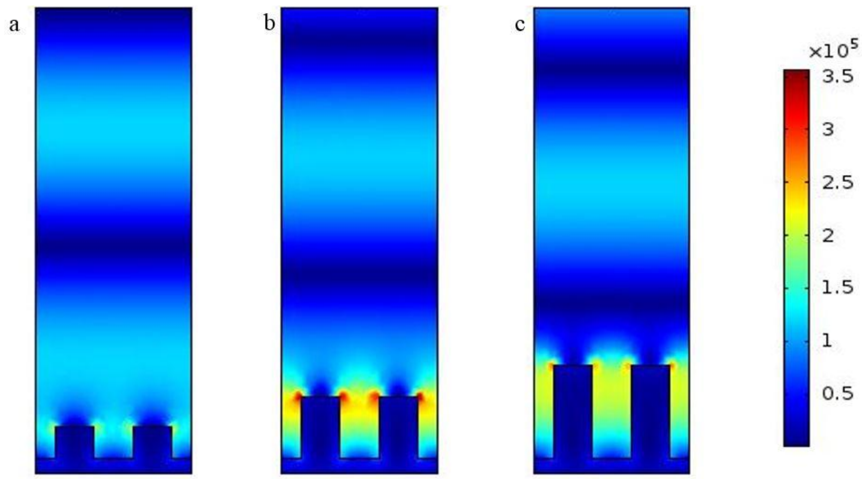


Fig5. Normal electric field (V/m) for magnetic mirror at (a) 40nm groove depth (b) 80nm groove depth (c) 120nm groove depth when illuminated with TM polarized light

Simulations are now being performed using silicon substrate (200nm thin)having both plane metallic mirror and magnetic mirroras the rear reflector with both TE and TM polarized light. Simulation results are shown for higher wavelength regions as for an ultra-thin absorber it is essential to make it optically thick for larger wavelengths. Fig6 and Fig7 shows the normal electric field of both metallic and magnetic mirror at wavelength of 700nm and 900nm where magnetic mirror enhances the electric field value to a noticeable extent for both the wavelength.

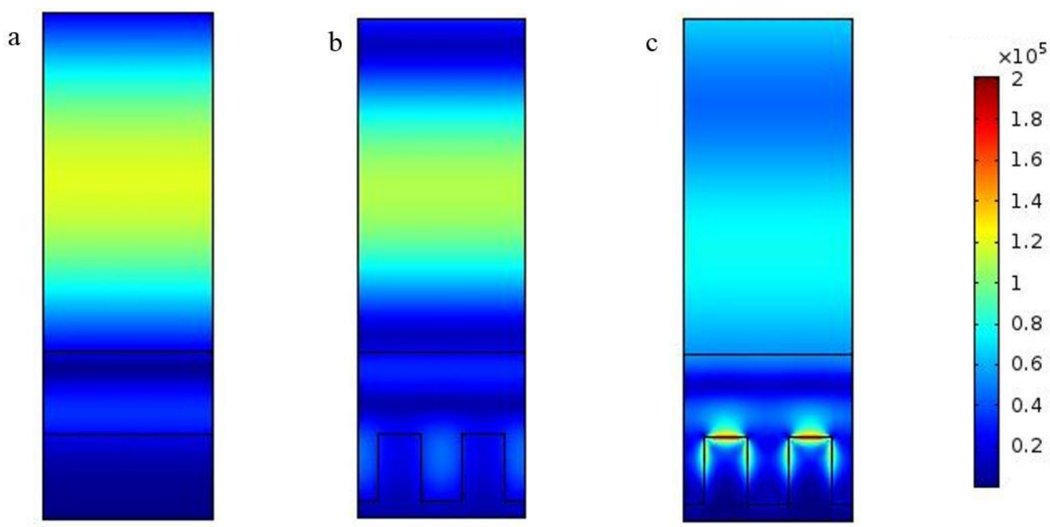


Fig6.Normal Electric field profile (V/m) at 700nm wavelength for(a) Plane metallic mirror (b) Magnetic mirror with TE polarized light (c) Magnetic mirror with TM polarised light.

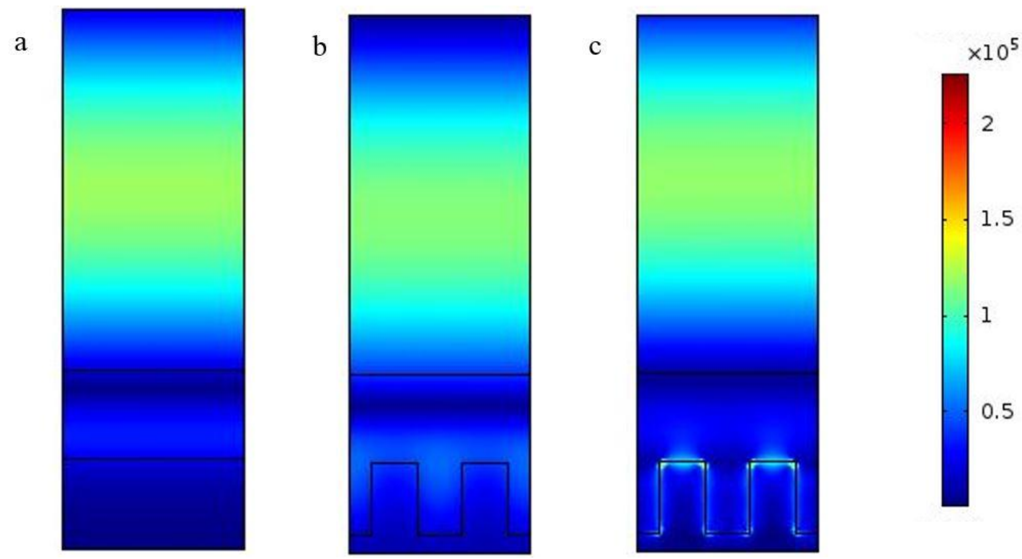
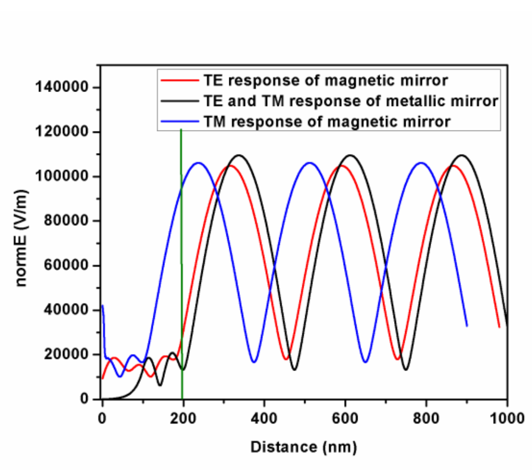
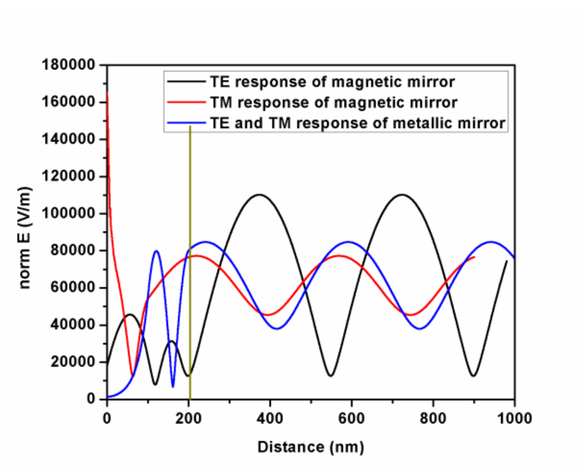


Fig7. Normal Electric field profile (V/m) at 900nm wavelength for (a) Plane metallic mirror (b) Magnetic mirror with TE polarized light (c) Magnetic mirror with TM polarised light.

From Fig 8, it can be observed clearly that the electric field near the surface of the mirror in case of magnetic mirror is considerably high as compared to that of a plane metallic mirror at both the wavelengths of 700nm and 900nm. Moreover the phase change phenomenon in case of plane metallic mirror can be seen by the nature of the normal electric field plot which is comparable to sine function whereas magnetic mirror plot is comparable with cosine function. The enhancement in the electric field is due to the addition of electric field occurring in magnetic mirror as it reflects the electric field in same phase while flipping the magnetic field.



(a)



(b)

Fig8.Electric field profile of a plane metallic mirror and a magnetic mirror placed at the back of silicon substrate at wavelengths of (a) 700nm (b) 900nm.

Further, with the use of magnetic mirror generation rate is seen also seen to enhance proportionally which will finally result in an increased efficiency of thin silicon solar cells. Generation rate is a function of wavelength and power flow within the geometry. Figure 9 shows the generation within the silicon substrate having a thickness of 200nm for a wavelength of 550nm. It is seen that the parasitic losses in the metal are indeed negated by the increased absorption by the silicon layer due to the confinement of the electromagnetic filed in the vicinity of the reflecting surface.

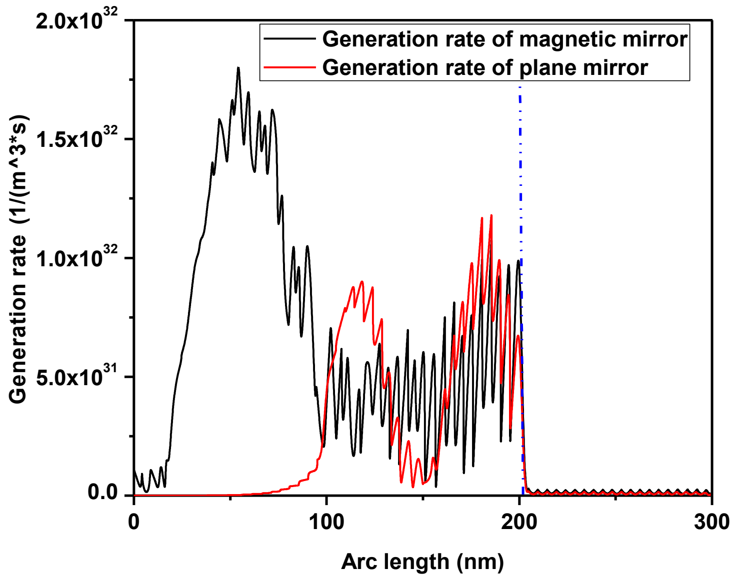


Fig9. Generation rate of plane metallic mirror and magnetic mirror placed at the back of silicon substrate.

3. Conclusion

In this workthe potential of magnetic mirrors for ultra-thin silicon solar cell (200nm and lower) has been shown by simulation. The key geometric metrics like the groove depth and period are taken up from parametric optimization. From the paper it can be concluded that magnetic mirror preserves the electric field and thus enhancement can be seen at the surface of the mirror. It is been shown on how absorption within an ultra-thin silicon layer can be increased with the help of such mirrors.

4. Acknowledgement

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5. References

[1] MajidEsfandyarpour,ErikC.Garnett,YiCui,MichaelD.McGehee, Mark L.Brongersma (2014)Metamaterial mirrors for optoelectronic devices*Nature Nanotechnology*, DOI:10.1038/NNANO.2014.117.
[2] Schwanecke, A. S. et al. (2007) Optical magnetic mirrors, *J. Opt. A Pure Appl*, Opt.9, L1–L2 (2007).
[3] Sonali Das, Avra Kundu, Hiranmay Saha, Swapan K. Datta (2015)Investigating the Potential of Nanoplasmonics for Efficiency Enhancement of Wafer Based Crystalline Silicon Solar Cells, Plasmonics DOI 10.1007/s11468-015-0009-0.
[4] www.comsol.co.in
[5] Yang Liu , Yitung Chen , Jichun Li , Tzu-chen Hung , Jianping Li. (2012) Study of energy absorption on solar cell using metamaterials, *Solar Energy*, 86 (2012) 1586–1599.