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Performance enhancement of thin film silicon solar cells based on distributed Bragg reflector & diffraction grating

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The influence of various designing parameters were investigated and explored for high performance solar cells. Single layer grating based solar cell of 50 µm thickness gives maximum efficiency up to 24 % whereas same efficiency is achieved with the use of three bilayers grating based solar cell of 30 µm thickness. Remarkably, bilayer grating based solar cell design not only gives broadband absorption but also enhancement in efficiency with reduced cell thickness requirement. This absorption enhancement is attributed to the high reflection and diffraction from DBR and grating respectively. The obtained short-circuit current were 29.6, 32.9, 34.6 and 36.05 mA/cm^2 of 5, 10, 20 and 30 µm cell thicknesses respectively. These presented designing efforts would be helpful to design and realize new generation of solar cells. © *2014 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License.* [http://dx.doi.org/10.1063/1.4904218]

I. INTRODUCTION

Silicon based devices are inexpensive due to compatible existing fabrication technology and availability of silicon in earth crust. Thin film based solar cells have disadvantage of weak absorption of long wavelength spectrum due to indirect band gap of silicon which limits their overall efficiency. Hence, light trapping mechanism is essential for the enhancement of incident light absorption. This requirement can be fulfilled by two mechanisms: one is diffraction or scattering which can change the direction of incident photons so that as much as of photons can propagate at higher angles with prolonged path length within the cell while second is coupling of incident photons provided with the guided mode in the active region of solar cell with a confinement of light. In simple words, once the incident photons entered into the device their mean residing time in active region must be long enough and they are absorbed before escaping the device.

Yablonovitch et al. have first reported on light trapping through analytical solutions for light path enhancement in bulk solar cell with ideal Lambertian light-trapping.[1] Further, M.A. Green has extended the calculations for any degree of absorption in the active material.[2] To have a better performance of solar cell some constraints are to be considered. As direct incident of light on silicon layer yields around 35 % loss of light therefore, the first constraint is an anti-reflection coating (ARC) layer at the top of solar cells with the hope of minimum reflection from the surface. Various design and fabrication concepts of anti-reflection coating layer of different materials such as silicon nitride, indium tin oxide, porous silicon, zinc oxide, silicon oxide, multilayer of silicon nitride, silicon oxide etc. have been reported.[3–10] Second is one-dimensional photonic crystal (1DPC)/distributed Bragg reflector (DBR) used to increase the total internal reflection of light on the backside of solar cell. Various designing concepts have been reported using TiO2/SiO2, a-Si/SiO2, c-Si/SiO2, ITO/a:Si:H, porous silicon layers etc. as bottom layer to assure the absorption of light as once entered into the device.[11–15] Third is diffraction grating used to bend the light at a titled angle and numerous research papers have been reported on the design and fabrication of solar cells for better performance with the combination of anti-reflection coating layer, diffraction grating with one-dimensional photonic crystal.[11–18] L. Zeng et al. have presented an experimental application of a textured photonic crystal as backside reflector in thin film silicon solar cells.[17] Light absorption was strongly enhanced by high reflectivity and large angle diffraction by this mechanism. They have experimentally demonstrated a 5 μm thin film silicon solar cells and found an increment in short circuit current density by 19 % as comparison to a theoretical prediction of 28 %. Xianqin Meng et al. have proposed thin film based solar cell design with combined front and back 1D and 2D diffraction gratings of different periods.[19] The absorption was found to be increased with 750 nm long period back grating and reflection of incident light was observed to be decreased by using 250 nm short period of front grating. The simulated results showed an increment in short circuit current up to 30.3 mA/cm^2 as compared to 18.4 mA/cm^2 of a reference cell. Xing Sheng et al. have explored the mechanism for an efficient light trapping in thin-film silicon solar cell structure by using a distributed Bragg reflector (DBR) and periodic gratings. They have reported that the light can be scattered into the DBR by gratings with an unusual way of light trapping different from metal reflectors and photonic crystals.[12] Alongkarn Chutinan et al. have reported a designing of solar cell with light trapping concept and theoretically demonstrated a significant enhancement in efficiency of thin crystalline silicon solar cells by using photonic crystal as the light absorbing layer.[3] They have observed a relative increase of 11.15% and 3.87 % conversion efficiency for 2 μm and 10 μm thicknesses respectively. L. Zhao et al. have proposed a design of solar cell with an indium tin oxide diffraction grating, an a-Si:H/ITO DBR and an Ag reflector.[14] With the use of metal reflector, they have observed 69 % and 72 % weighted absorptance of solar cell in case 4 and 8 pairs of a-Si:H/ITO DBR respectively. It is claimed that the use of metal reflector is helpful to trap light in a better way with reduced number of DBR pairs and hence makes easy fabrication. Ning Feng et al. have presented a optimization of highly efficient light trapping structure for better efficiency based on crystalline solar cells with the combination of anti-reflection coating layer, grating and DBR.[13] They have observed an improvement in efficiency with optimized parameters and achieved upto 18.88% for 100 μm solar cell. In this work, we have presented a complete design of solar cell based on DBR and grating back reflector. Surprisingly, we have observed enhanced performance with a modified back reflector (bilayer based grating) in the red and infrared part of wavelength of incident solar spectrum.

In this paper, we present a design and optimization of thin film crystalline silicon solar cells based on ARC, diffraction grating and DBR. Various design parameters of ARC, grating and DBR are studied to achieve better performance of solar cells. In section second, theory and design approach of complete solar cell is presented. The simulated results are discussed in section third. Section fourth, concludes the paper.

II. THEORY & DESIGN APPROACH

At first, we have designed a DBR by using plane wave method which is a well known technique used to calculate band structure of photonic crystals. The designed DBR was composed of alternate layers of SiO$_2$/Si with periodicity in x-direction and perfectly matched layers boundary condition was applied to y and z directions. The center wavelength was calculated to be 0.8 μm whereas assumed values of refractive index of SiO$_2$ and c-Si layers were wavelength dependent. Figure 1(a) and 1(c) shows a planar and designed solar device (combination of DBR and grating) of 5 μm cell thickness with their physical location of constituent layers. A planar device comprises of an anti-reflection coating layer of silicon nitride & crystalline silicon layer while designed one is having a distributed Bragg reflector (DBR) and diffraction grating in addition. The DBR works as one-dimensional photonic crystal with center wavelength 0.8 μm and composed of periodic layers of silicon (Si) and silicon dioxide (SiO2) with their refractive index 1.46 and 3.5 and thickness 0.057 μm and 0.138 μm respectively. The grating is made of silicon (SiO$_2$) is embedded into active silicon region in a periodic manner. Figure 1(b) and 1(d) shows electric field profile of a planar and designed devices simulated by using Rsoft (FullWAVE) package. In case of planar solar cell, the incident light is absorbed within the silicon active region and further there is no propagation as can be seen in figure 1(b).

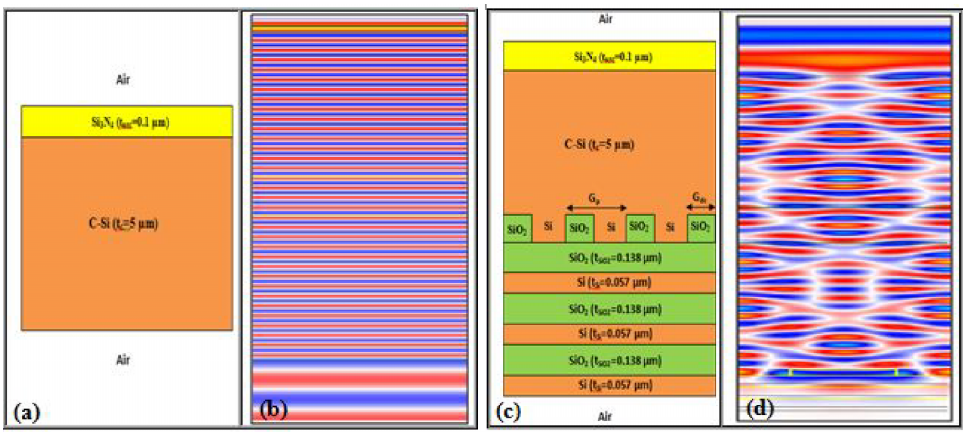

FIG. 1. Schematic of planar Fig. 1(a) and designed Fig. 1(c) solar cells and their electric field profiles Fig. 1(b) and Fig. 1(d) respectively.

While field profile looks different in case of designed structure shown in figure 1(d), as partial incident light is absorbed in active region while partially scattered and diffracted from grating and reflected back from DBR. This whole process provides a mechanism of coupling into guiding modes in the silicon active region as results the trapping of light is sustained. Into the DBR, the electric field is evanescently decayed and reflected back therefore, it doubles light path length. The combination of grating with DBR makes scattering of light and coupling modes with better confinement. In this work, we have considered various parameters of solar cell design and presented the effect of those on the overall cell efficiency.

III. RESULTS & DISCUSSION

This designed structure is simulated using FDTD method and solar cell efficiency was observed to be 16.95 % as comparison to 14 % of planar/reference solar cell. Afterwards, optimization of solar cells was done by using various parameters which are discussed as below. Figure 2(a) is plotted for cell efficiency (η) as a function of refractive index of anti-reflection coating (n_{arc}). As depicted in figure, the cell efficiency is observed to be 17.18 % at $n_{arc} = 1.8$ however, our earlier considered value of n_{arc} was 2. As per anti-reflection coating theory, ARC layer has zero reflection with refractive index $n_{arc} = \sqrt{n_c}$ and thickness $t_{arc} = \lambda_c/4n_{arc}$ where n_c and λ_c are refractive index of active crystalline silicon region and center wavelength respectively. The simulated result shows the cell efficiency dependency on refractive index of ARC coating and maximum efficiency is observed to be at $n_{arc} = 1.8$. Analytically, refractive index can be calculated as $n_{arc} = \sqrt{n_c}$ and our simulated result is closer to it.

To observe the effect of ARC layer thickness, we have plotted figure 2(b) by keeping $t_{arc} = 0.1\ \mu m$ and $n_{arc} = 1.8$ instead of 2. Here, we have observed that the cell efficiency is decreased as the ARC layer thickness is increased and upto a maximum 17.18 % is obtained for 5 μm cell thickness. As per ray theory, ARC layer thickness should be $t_{arc} = \lambda_c/4_{narc} = 0.1\ \mu m$ and once again our simulated result is same as the analytical value which shows validation. For next level of optimization, we kept $n_{arc} = 1.8$ & $t_{arc} = 0.1\ \mu m$ while keeping other parameters constant. Figure 2(c) depicts the variation in cell efficiency in accordance with grating width 'G_w'. There is an increase in efficiency (17.52 %) is observed at $G_w = 0.3\ \mu m$ rather than 17.18 % at $G_w = 0.4\ \mu m$ (assumed one). For next level of simulation, we have fixed $G_w = 0.3\ \mu m$ while keeping other parameters constant. One-dimensional photonic crystal also known as distributed Bragg reflector (DBR) is used in solar cells as a back reflector part and helpful to redirect the light transmitted through diffraction grating due to non-bending towards active crystalline silicon region. To possess the required property of DBR i.e. high reflectivity, quarter wavelength thickness of constituent layers

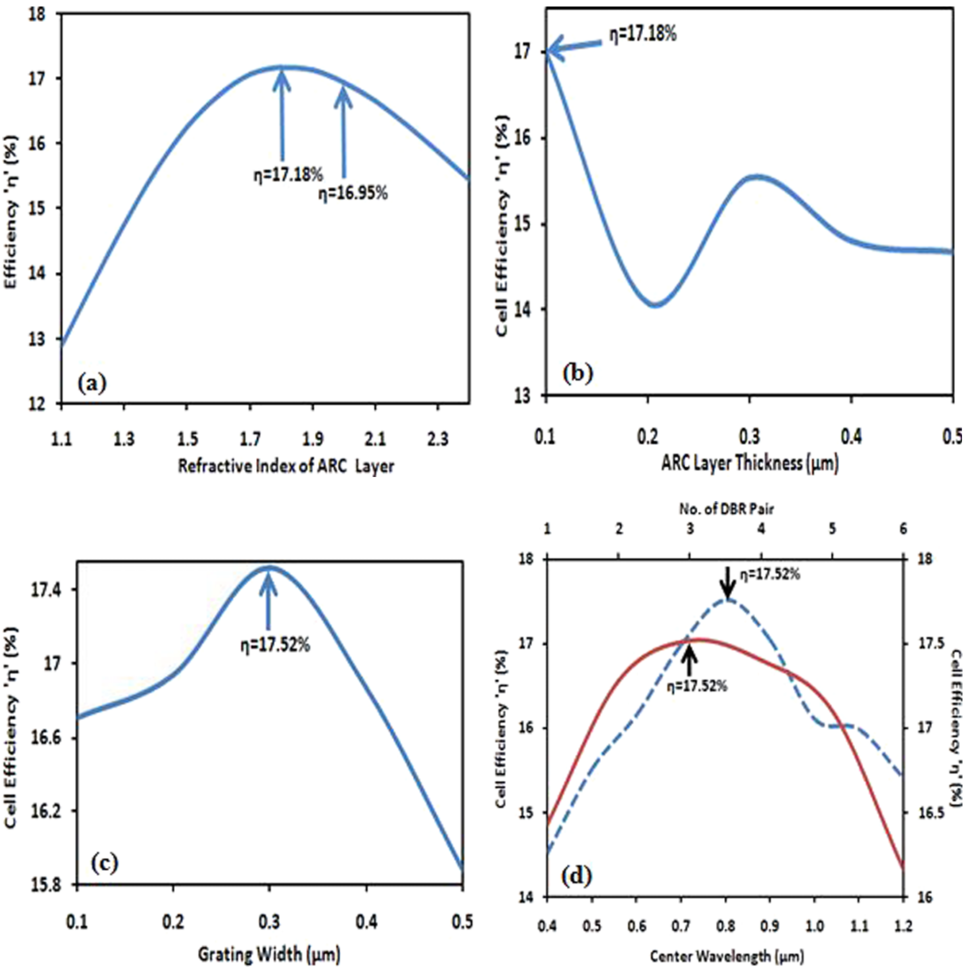

FIG. 2. Solar cell efficiency as a function of refractive index fig(.a), anti-reflection layer thickness fig.(b), grating width fig.(c) and centre wavelength & no. of DBR fig.(d).

(t_{Si} = 0.057 μm & t_{SiO_2} = 0.138 μm) were considered. If DBR is properly designed then twice optical path length can be assured according to ray theory. In this context, center wavelength is a significant parameter which corresponds to maximum (100%) reflection of incident light with a sufficient number of DBR pairs. We have plotted figure 2(d) to observe the effect of center wavelength and number of DBR pairs on overall efficiency of solar cell. The designed device shows maximum efficiency at center wavelength λc = 0.8 μm (dotted line). Till now in our designing, λ_c was the same value which shows validation of simulated result. The selection of center wavelength is mainly important for thin solar cells, however for thicker cells the maximum photons are absorbed in a single path of light and trapping of light needed only for the wavelength near to band gap. Solid curve shows solar cell efficiency as a function of number of DBR and can be observed that the maximum efficiency is obtained with the use of three DBR pairs only. The performance of DBR is saturated and decayed after three DBR pairs which would be attributed to the evanescent wave decay into the DBR structure.

Diffraction grating is a important component in solar cells in addition to the DBR as a part of back reflector and depending upon its design diffracts the light at various angles. The design of diffraction grating has mainly three considerations such as grating period (G_p), grating thickness (G_t) and grating duty cycle (G_{dc}). Figure 3(a) shows effect of grating period on cell efficiency for various cell thicknesses. As can be seen in the figure there are two maxima points which are attributed to the first and second order diffractions of the grating. An improvement in cell efficiency

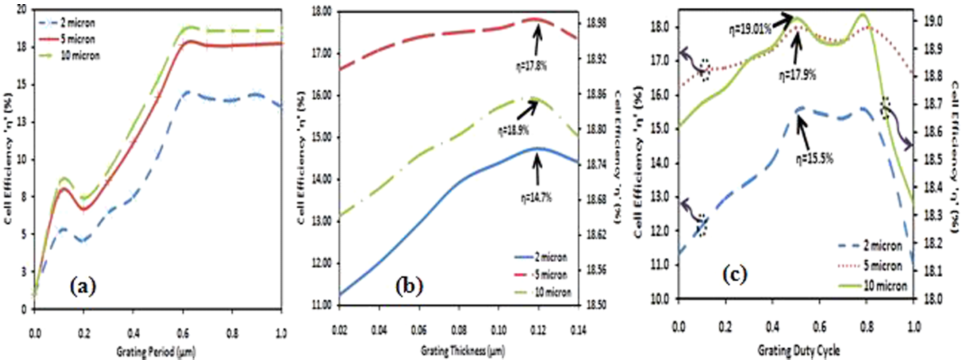

FIG. 3. Solar cell efficiency variation in accordance to grating period fig.(a), thickness fig.(b) and duty cycle fig.(c) for 2, 5 & 10 μm cell thicknesses.

is observed for all the thickness of cells at grating period $G_p = 0.6\,\mu$m with maximum efficiency $\eta = 18.8\,\%$ for 10 μm solar device. Figure 3(b) shows a variation of grating thickness (G_t) for different thicknesses of solar cells. The grating thickness 0.1 μm was fixed and simulated from 0.02 – 0.14 μm. At $G_t = 0.12\,\mu$m, maximum cell efficiency was observed i.e. 14.7%, 17.8% and 18.9% corresponding to the cell thicknesses 2, 5 and 10 μm respectively. A significant variation in cell efficiency is observed due to change in grating thickness in case of thinner cells. Further, $G_t = 0.12\,\mu$m was fixed and simulated for analysis of effect of duty cycle on the device performance. The effect of grating duty cycle (G_{dc}) on solar cell efficiency is plotted in figure 3(c) for various thicknesses of solar cells. The maximum efficiency has been observed at $G_{dc} = 0.5$ for all cell thicknesses and further it is observed to be reduced after 0.9 duty cycle which indicates a significant role of grating duty cycle in solar cells.

Further, we have extended the designing of 5 μm cell thickness device by embedding three bilayers of grating (Si/SiO_2) within silicon active region while keeping same parametrical values of grating thickness, duty cycle and period (see inset of figure 4). As it was expected, we have got better performance of this device as comparison to earlier design with single layer grating. Similar design of solar device has been reported where they had used three layers based antireflection coating.[20] Figure 4(a) shows absorption and quantum efficiency of bilayer grating based solar cell. An enhancement in absorption can be clearly seen in the wavelength range of 450-1100 nm. In addition, an overlapping of absorption curve with incident solar spectrum is noticed in a short wavelength

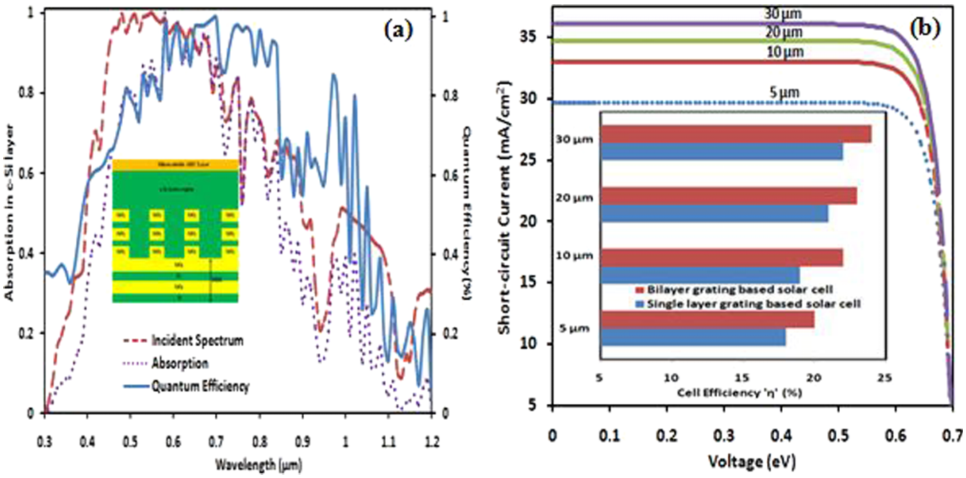

FIG. 4. Absorption & Quantum efficiency of three bilayer grating based solar cell (a) and Short-circuit current (b) with cell efficiency chart (inset figure).

range 650-780 nm. Quantum efficiency curve (solid line) reveals better performance of the device and observed maximum in the wavelength range 580-850 nm. Figure 4(b) shows J-V characteristics of single layer and bilayer grating based solar cells of 5, 10, 20 and 30 μm thicknesses. J-V curves demonstrate an improvement in short-circuit current with the use of three bilayer grating based devices. The maximum obtained short-circuit current are 29.6, 32.9, 34.6 and 36.05 mA/cm^2 of 5, 10, 20 and 30 μm cell thicknesses respectively. An inset figure shows a comparison of bilayer and single layer grating based solar cells of 5, 10, 20 and 30 μm thicknesses. In comparison to reference solar cell with 14 % efficiency, we have achieved 42.8 % relative enhanced efficiency for three bilayer grating while it was 28.5 % for single layer grating based solar cell of 5 μm cell thickness.

IV. CONCLUSION

A complete design and optimization of thin film silicon solar cells have been presented by using FDTD method. Our designing showed good performance of device with the use of three pair of DBR, 0.8 μm center wavelength and 0.3 μm grating width. By optimizing grating period, we have observed two maxima points which are attributed to the first and second order diffractions of the grating. Improved solar cell efficiency was observed for 5, 10, and 20 μm cell thicknesses at grating period 0.6 μm. Grating thickness analysis showed a significant variation in cell efficiency in thinner cells whereas 0.5 duty cycle was optimal value. With optimized parameters, a significant enhancement in absorption and quantum efficiency was noticed with maximum cell efficiency upto 24 % from 50 μm cell thickness. A relative enhancement in efficiency of 42.8 % was observed for 5μm cell thickness as comparison to reference cell. Remarkably, modified designing of bilayer grating embedded in active silicon region is competed our previous design by giving 24 % cell efficiency for 30 μm cell thickness. Finally, efficient light trapping structures with three bilayer grating was designed and achieved enhanced performance as comparison to single layer grating based solar cells.

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