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Design and optimization of ultrathin crystalline silicon solar cells using an efficient back reflector

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Thin film solar cells are cheaper but having low absorption in longer wavelength and hence, an effective light trapping mechanism is essential. In this work, we proposed an ultrathin crystalline silicon solar cell which showed extraordinary performance due to enhanced light absorption in visible and infrared part of solar spectrum. Various designing parameters such as number of distributed Bragg reflector (DBR) pairs, anti-reflection layer thickness, grating thickness, active layer thickness, grating duty cycle and period were optimized for the optimal performance of solar cell. An ultrathin silicon solar cell with 40 nm active layer could produce an enhancement in cell efficiency ~ 15 % and current density ~ 23 mA/cm^2. This design approach would be useful for the realization of new generation of solar cells with reduced active layer thickness. © *2015 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License.* [http://dx.doi.org/10.1063/1.4921944]

I. INTRODUCTION

Today, the cost reduction of silicon solar cells is a serious issue to scientific community. To address this issue, thin film technology has been employed and demonstrated the low cost silicon solar cells whereas such thin film silicon solar cells are having poor absorption in longer wavelength region due to indirect band gap of silicon material. To overcome this problem several design schemes have been reported in literatures such as textured grating, dielectric grating, metal nanoparticles or nanograting, alternate arrangement of metal/dielectric grating etc.[1–5] These ideas are found to be effective because of scattering the incident light and coupling it into the fundamental material. Recently, application of metal nanostructures such as nanoparticles/nanograting in solar cells have found to be promising for light trapping due to plasmonic surface which yields efficient guiding and manipulation of photons through a mechanism of collective oscillating electrons at the surface of the metal nanostructures. Surface plasmon resonance can be induced between the propagation path of light and metal surface which can ultimately enhance the absorption of light to an optimal level. In simple words, surface plasmon is nothing than gathering of electrons at the surface of metal which makes a path of propagation along it and surface plasmonic energy is concentrated at the tip of metal nanoparticels/nanogratings. Due to this unique nature, surface plasmon resonance have found its application in solar cells which contribute to the enhancement of light absorption if the metal nanostructure is placed adjacent to active region of solar cell.

Xiao et al. have reported a design of an ultrathin-film silicon solar cell configuration by using one-dimensional plasmonic nanograting onto the bottom of the solar cell.[6] They have observed 90 % enhancement of photocurrent in the considered wavelength range through a 200 nm thickness crystalline silicon solar cell. The analysis of obtained result was suggested for the realization of low cost and high efficiency thin film solar cells. He et al. have proposed a design of an ultrathin silicon solar cell by placing a periodic array of silver strips on a metallic nanograting substrate.[7] The designed structure could give 170 % light absorption enhancement as comparison to the bare silicon thin film. This enhancement has been attributed to the excited multiple resonant and waveguiding modes within the silicon layer, localized surface plasmon resonance and surface plasmon polaritons. Reduced cell thickness is a critical issue in silicon solar cells, when it is less than 2 µm (c-Si) and below 300 nm (a-Si:H). Therefore, ultrathin solar cells light trapping is essential whereas plasmonic solar cells are found to be more promising to overcome this problem. Yan et al. have presented a three modeling methods for a-Si:H solar cells and to observe the light absorption, parabolaconical nanoarrays were introduced into ultrathin a-Si:H solar cells.[8] They observed optimal absorption enhancement (53.9 %) when height/radius ratio was 1 and further, it was increased to 61.9 % for the case when height/radius ratio was 3. This enhancement was due to the graded refractive index of silicon and waveguide mode. Wang et al. have proposed a planar ultrathin absorber concept by exploiting plasmonic resonance absorption enhancement and obtained enhanced absorption about 89.8 % through 5 nm thin film absorber which showed single pass absorption of only 1.7% for the case of TM polarization.[9] The absorption enhancement was broadband and angle-independent. Furthermore, this concept was suggested for 2D periodic grating geometries to achieve a strong angle and polarization independent absorption analysis. Juan et al. have reported a design of solar cell with the influence of relative position of silver metallic nanoparticles which was embedded in a 100 nm anti-reflection coating layer.[10] It was demonstrated that this plasmonic anti-reflection coating layer could achieve lower reflections as comparison to that SiOx anti-reflection coating layer but addition of silver nanoparticles in front surface geometry have generated poor interferences due to which the efficiency of cell was found to be reduced. Sheng et al. have analytically investigated the light trapping mechanism in plasmonic silicon solar cells.[11] This designing was explored by considering absorption enhancement for surface plasmon polaritons (SPPs) at planar silicon-metal interfaces and localized surface plasmon resonances (LSPRs) for metallic spheres in a silicon matrix. They observed that the absorption enhancement factor was not bound to Lambertian limit and localized plasmonic resonances can be used as efficient light trapping schemes for ultrathin silicon solar cells. Chriki et al. have proposed an ultrathin solar cell design by incorporating two periodic layers of metallic and dielectric gratings.[12] Both layers could able to couple the incident light to photonic and plasmonic modes and hence, enhanced absorption of light was achieved. A relative position between the two gratings was analyzed and observed a significant effect. The proposed design was compared with a reference solar cell of a single layer of metallic and dielectric nanostructures respectively and found to be satisfactory in term of high absorption for dual grating design. Plasmonic solar cells are promising to produce high efficiency due to its high carrier collection and less bulk recombination. Spinelli et al. have presented two possible ways of integrating metal nanoparticles in a solar cell: first one is a coating of silver nanoparticles which is acts as antireflective surface and second one is application of regular and random arrays of metal nanostructures which couple light in waveguide modes.[13] By employing a relative inexpensive nano-imprint technique, design of solar cell was attempted which showed an improvement in cell efficiency. In plasmonic solar cells, photons are trapped into localized surface plasmon (LSP) as a result it induces the surface plasmon (SP) which propagates transversely into active layer. Chao et al. have proposed a plasmonic multilayer structure (PMS) for the application in ultrathin solar cell with 30 nm thick amorphous silicon (α-Si) as active layer. With the use of plasmonic multilayer structure, they have observed a large absorbed photon number (~ 28.7 %) as compare to the indium tin oxide (ITO)/α-Si/Ag structure for the normal incident case of transverse magnetic (TM) polarization.[14] Lee et al. have numerically presented the design of amorphous silicon (a-Si) thin film solar cell by employing ultrathin top into a-Si active layer. They have observed enhanced absorption with a wide range of incident angle for TM polarization through the solar cell with 30 nm thickness. The overall absorption for TM polarization was improved about 25 % as comparison to a solar cell with thicker metal grating however, for TE polarization 2.5 times improvement was observed.[15]

In this work, we propose a novel design of ultrathin silicon solar cells with an efficient light trapping structure comprising of top anti-reflection coating (ARC) of silicon nitride and bottom reflector composed of aluminum (Al) grating and a distributed Bragg reflector (DBR) made of

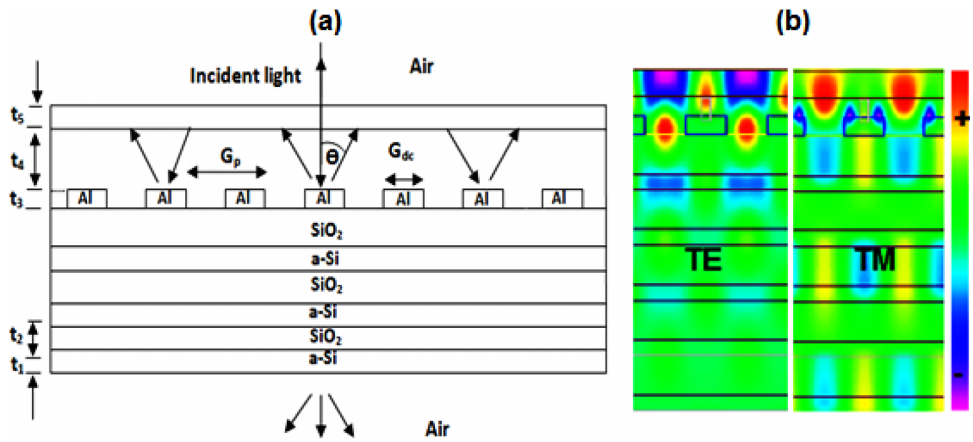

FIG. 1. **Schematic diagram of ultrathin silicon solar cell (fig.a) and field distribution in the device for TE and TM polarizations (fig.b)**.

a-Si/SiO_2 materials. The optimized solar cell design could produce enhanced cell efficiency due to broad band absorption in visible and infrared part of solar spectrum. In section second, design approach is presented and simulated results are discussed in section third. Finally, section fourth concludes the paper.

II. DESIGN & SIMULATION APPROACH

A schematic design of crystalline silicon (c-Si) thin film solar cell with an ultrathin active layer (50 nm) is shown in **figure** 1. It is comprised of an ARC layer (Si_3N_4), a DBR structure (a-Si/SiO_2) and metal grating structure (Al). The DBR pairs was composed of alternate layers of a-Si and SiO_2 with their refractive index 3.6 and 1.45 and thicknesses 41(t_1) and 103 nm (t_2) respectively whereas center wavelength of DBR was 600 nm. The assumed thicknesses of ARC layer (t_5) and Al grating (t_3) were 70 and 50 nm respectively. In this simulation, the refractive index of the active region 'n_c=3.5' and its thickness 't_4=50 nm' were used.

The aluminum (Al) gratings help to diffract the incident light at oblique angles whereas distributed Bragg reflector (DBR) resists the metal diffusion and sustain the mechanism of light trapping. The back reflector with the combination of DBR and metal grating is supposed to be an efficient light trapping structure which utilizes the longer wavelength light by enforcing those in active region of solar cell. Table I displays the initial parametrical values considered for the design of ultrathin solar cell.

TABLE I. Design parameters of ultrathin silicon solar cell.

Parameters	Values
grating period (G_p)	600 nm
grating duty cycle (G_{dc})	0.5
grating thickness (t_3)	50 nm
grating tooth width (G_w)	300 nm
no. of DBR pairs	5
anti-reflection coating thickness (t_5)	70 nm
DBR center wavelength (λ_c)	600 nm
active layer thickness (t_4)	50 nm
DBR first layer a-Si thickness (t_1)	41 nm
DBR second layer SiO_2 thickness(t_2)	103 nm

For simulation, commercial available finite difference time domain method (FDTD) tool supplied by Rsoft Design Group was used. The periodic boundary conditions were applied in x and y-directions whereas in z-direction, perfectly matched layer boundary condition was performed. The solar cell was illuminated by plane wave under normal incidence from wavelength 400-1200 nm. Figure 1(b) depicts electric field profile of designed solar cell for TE (at 741 nm) and TM (at 839 nm) polarizations with defined parameters in table I. For the case of TE polarization, electric field is visible near the gratings however, localized field at the tip of metal gratings is visible for the case of TM polarization. This cell could give cell efficiency 10.5 % with the use of five pairs of DBR for s-polarization case. The optimization of solar cell design by considering ARC thickness, grating thickness, active layer thickness, duty cycle and grating period is presented in next section. As solar radiation is having both transverse electric (TE) and transverse magnetic (TM) waves therefore, we have extended our study for both polarizations.

III. RESULTS & DISCUSSION

Initially, we have optimized the number of DBR pairs required for optimal performance of proposed solar cell and found that three DBR pairs were satisfactory. Anti-reflection coating (ARC) layer plays a significant role to trap and pass light into the photovoltaic devices. Among other ARC materials, single layer of Si_3N_4 have been preferred for effective reduction of surface reflections of incident light. A solar cell with the parameters discussed in previous section was simulated for the analysis of effect of ARC layer thickness. Figure 2 depicts the cell efficiency (solid line) in accordance to ARC thickness. Reasonably, an enhancement in cell efficiency from 10.5 % to 11.6 % is observed at ARC layer thickness (t_5) of 65 nm instead of 70 nm used previously. This result is a supplementary evidence of importance of ARC layer in term of its thickness which can be tuned to have optimal transmission of solar light into silicon active region.

The diffraction grating as a part of the back reflector plays vital role in light trapping of longer wavelength light. By replacing the optimized value of ARC layer thickness further, we have

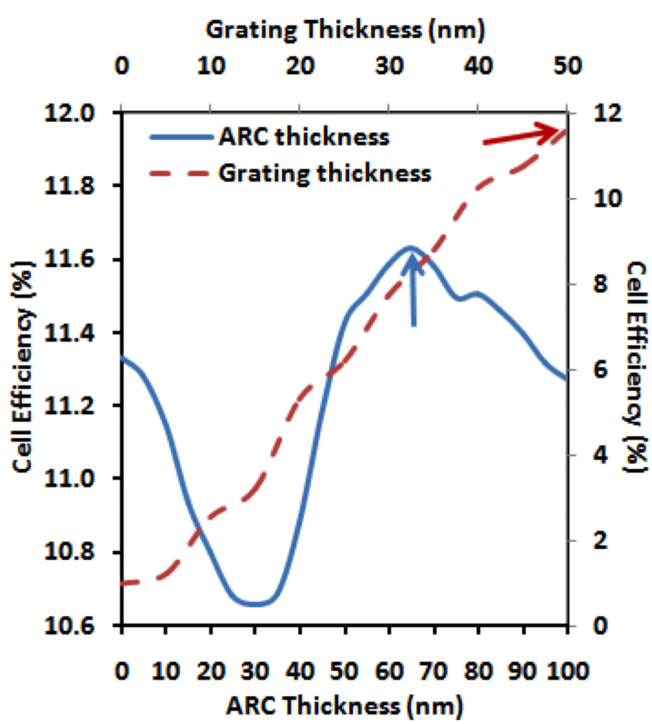

FIG. 2. **Solar cell efficiency as a function of ARC thickness (solid line) and grating thickness (dashed line).**

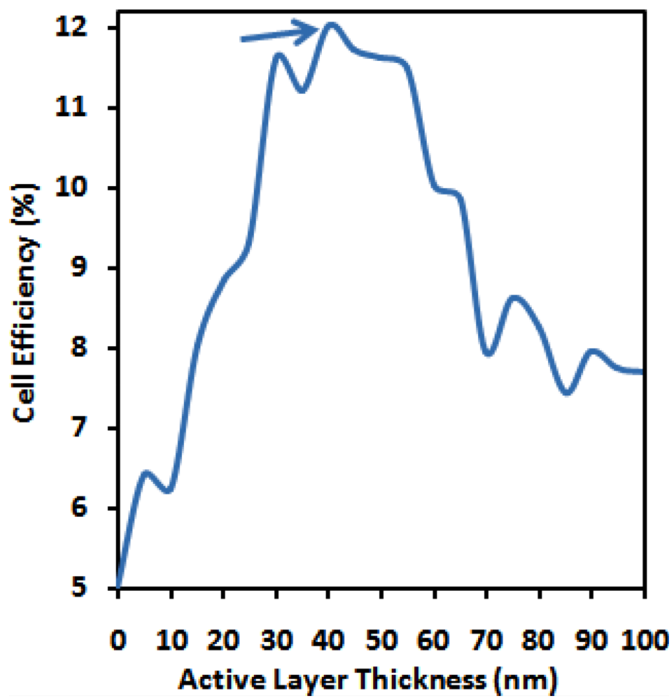

FIG. 3. **Solar cell efficiency in accordance with active layer thickness**.

optimized the thickness of aluminum grating. Figure 2 depicts the cell efficiency (dashed line) as a function of grating thickness. As the grating thickness increased the conversion efficiency was also found to be increased, gradually. The usual behavior of grating thickness can be observed whereas maximum efficiency 11.6 % (same as previous) was obtained at 50 nm. Our result shows that initial considered value of grating thickness was correct one. The obtained short-circuit current density was 17.67 mA/cm^2.

We have explored our analysis for the effect of active layer thickness by keeping all parameters constant except active layer thickness (t_4). Figure 3 shows the variation of active layer thickness against cell efficiency. An exponential enhancement in cell efficiency is observed and further than 40 nm a decrease in cell efficiency is observed.

This reduction of cell efficiency indicates no longer use of back reflector due to increased cell thickness. This result is validated with reported work in which effective role of back reflector was found below 10 μm cell thickness and beyond it, the contribution of back reflector was rapidly decreased.[16] An enhancement in cell efficiency (12 %) is observed with cell thickness 40 nm while short-circuit current density was 18.28 mA/cm^2. For further simulation, 50 nm cell thickness was replaced with an optimized one i.e. 40 nm.

The grating duty cycle and period are the important parameters for the diffraction of light in term of diffraction angle for example; a larger diffraction angle represents the long optical path length of photons. Figure 4 shows the effect of grating duty cycle and period. As the duty cycle (solid line) is increased the cell efficiency is found to be increased exponentially and it is maximum at 0.8. Further, the cell efficiency goes down beyond 0.8 which shows the importance of duty cycle as a sensitive parameter for the best performance of solar cell. The obtained optimal cell efficiency is 14.55% with current density 22.13 mA/cm^2 at 0.8 duty cycle.

For next level of simulation, all parameters were kept constant while duty cycle value was replaced with its optimal one. Dashed line in figure 4 depicts a variation in cell efficiency as a function of grating period. It shows optimal cell efficiency (14.9 %) at 500 nm period which would be attributed to the high order diffraction angle. Our previous value of grating period was 600 nm which is now optimized to 500 nm.

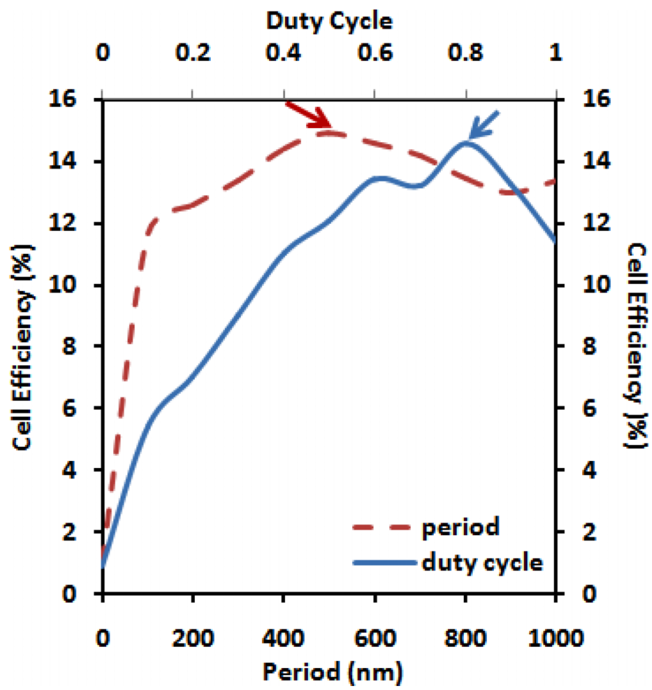

FIG. 4. **Solar cell efficiency in accordance with grating duty cycle (solid line) and grating period (dashed line).**

Finally, with all optimized parameters we could able to obtain ~15 % cell efficiency with 40 nm cell thickness. To conclude the simulation results after above discussed optimization, we have plotted the absorption curves in figure 5.

If we observe the absorption curve of grating thickness (t3), an enhanced absorption can be observed in infrared wavelength region with a peak centered at 680 nm. The curves of grating thickness (t_3) and ARC layer thickness (t_5) are superimposed as the assumption of grating thickness value

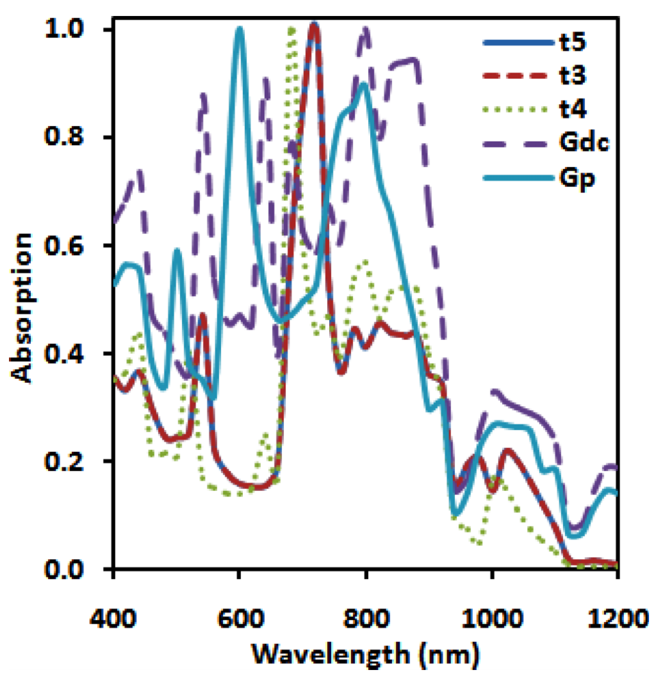

FIG. 5. **Light absorption behavior in silicon active layer of each optimization.**

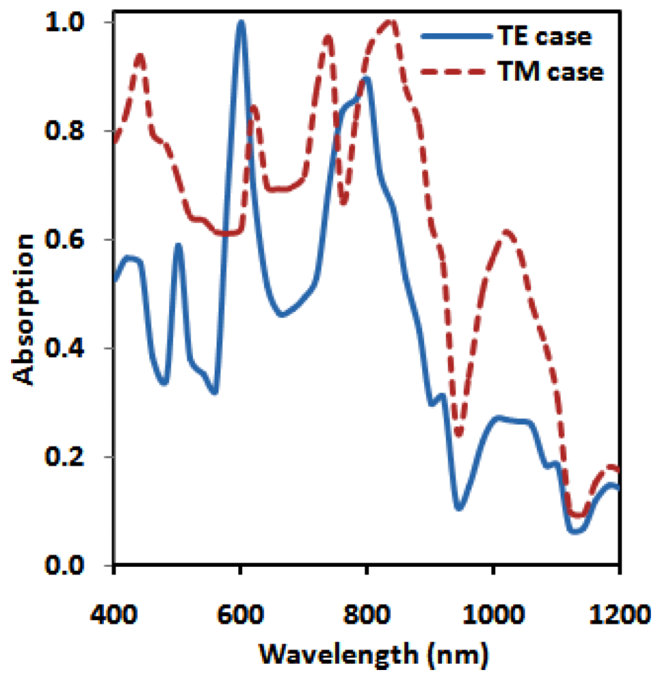

FIG. 6. **Light absorption behavior in silicon active layer for TE and TM cases**.

was coincided with optimized one. The curve of duty cycle (G_{dc}) shows high absorption in visible range with intense absorption peaks centered at wavelength 540, 640 and 680 nm. However, the absorption curve of (G_p) reveals extraordinary wider absorption peaks in visible and infrared region centered at 500, 600 and 800 nm. In case of t_3, t_4 and t_5, various absorption peaks are observed from 400 to 1020 nm. However, for the case of G_{dc} and G_p, absorption is observed to be enhanced in far infrared region too. It indicates enhanced light absorption not only in visible but also infrared part of solar spectrum. Due to this, our designed solar cell shows amazing enhancement in cell efficiency with an ultrathin active layer thickness '40 nm' which has not been reported earlier.

This enhancement in absorption was due to use of aluminum grating and ultrathin absorbing layer. An ultrathin active layer can make pass of generated electrons and holes towards electrodes with less recombination chance whereas localized surface plasmon excited by aluminum grating can generate surface plasmon.

To observe the effect of metal grating and comparison of TE and TM polarization cases, figure 6 is plotted. The absorption in active silicon region is considerably enhanced for the case of TM as comparison to TE polarization. For TE case, strong absorption peaks are centered at 600 and 800 nm whereas for TM case it is at 741 and 841 nm. Remarkably, the absorption peaks are found to be shifted to infrared part and became wider for magnetic transverse case.

For validation of plasmonic effect, electric and magnetic field profile of optimized solar cell is plotted in figure 7.

Two high absorption peaks 600 and 800 nm corresponding to electric field and 741 and 841 nm corresponding to magnetic field were selected for the analysis. For transverse electric case, at wavelength 600 nm (fig.a) we can observe strong electric field within the grating and waveguiding mode in silicon region however, at wavelength 800 nm DBR is supporting light reflection back to active region which would be a cause of getting wider absorption peak and hence strong field in active region. For transverse magnetic case, localized plasmon is visible at the top of aluminum gratings which could give enhanced absorption in active region (fig.c) at wavelength 741 and for wavelength 841 nm, surface plasmon is clearly visible (fig.d) due to which enhanced absorption can be seen in figure 6 (dashed line). With this analysis, the enhanced efficiency of designed solar cell is attributed to the plasmonic effect. We have compared the performance of different solar cell structures for TE and TM polarization modes which is shown in table II.

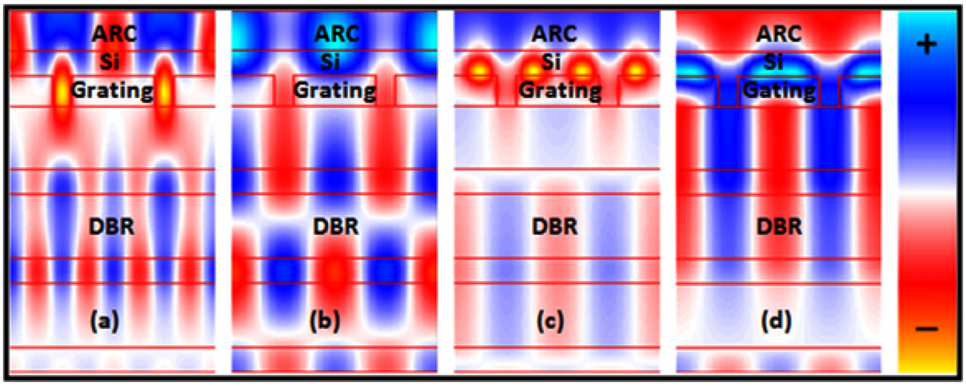

FIG. 7. **Electric field profile at 600 & 800 nm (fig.a-b) and magnetic field profile at 741 & 841 nm (fig.c-d)**.

TABLE II. Performance comparison of various designed silicon solar cells.

	TE		TM	
Structure	**C. E (%)**	**J_{SC} (mA/cm^2)**	**C. E (%)**	**J_{SC} (mA/cm^2)**
Reference (Only ARC)	0.71	1.09	0.72	1.1
C1 (3DBR+ARC)	0.89	1.35	0.92	1.4
C2 (GRA+ARC)	9.79	14.89	10.92	11.16
C3 (3DBR+GRA+ARC)	14.90	22.66	14.93	22.71

An extraordinary enhancement in performance can be observed from solar cells C2 and C3 which is due to the use of back reflector of metal grating (GRA) and DBR. Compare to all solar cells, cell C3 is found to be best performed with cell efficiency ~15 % however, for TM case a small increment in cell efficiency is observed.

IV. CONCLUSION

A novel ultrathin silicon solar cell have been proposed and demonstrated for its optimal performance. The designing parameters such as anti-reflection coating thickness, grating thickness, active layer thickness, grating period and duty cycle were optimized to design a solar cell structure with improved light absorption. Strong absorption peaks centered at 600 and 800 nm (TE case) whereas 741 and 841 nm (TM case) were observed. Remarkably, the absorption peaks were found to be shifted to infrared part and became wider for magnetic transverse case. The optimized solar cell of 40 nm active region could produce best performance with extraordinary enhancement in cell efficiency (~15 %) and current density (~23 mA/cm^2). The proposed design efforts would be helpful to realize plasmonic solar cell structures and fabrication implementation by employing advanced technology tools.

ACKNOWLEDGMENTS

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[1] Darin Madzharov, Rahul Dewan, and Dietmar Knipp, **19** (S2), A95-A107 (2011).
[2] R. S. Dubey, S. Saravanan, and S. Kalainathan, AIP Advances **4**, 127121-1-6 (2014).
[3] Y. Premkumar singh, Anil Kumar, Amit Jain, and A. Kapoor, The open renewable energy Journal **6**, 1-6 (2013).
[4] Benjamin Curtin, Rana Biswas, and Vikram Dalal, Applied Physics Letters **95**, 231102-3 (2009).
[5] Xiaowei Guo, Jia Liu, and Shouqiang Zhang, Photonics and opto-electronics **3**, 66-69 (2014).
[6] Sanshui Xiao, Erik Stassen, and N. Asger Mortensen, Journal of Nanophotonics **6**, 061503-1-061503-7 (2012).

[7] Jinna He, Chunzhen Fan, Junqiao Wang, Yongguang Cheng, Pei Ding, and Erjun Liang1, Advances in OptoElectronics, Article ID 592754, doi:10.1155/2012/592754, 8 pages (2012).
[8] Wensheng Yan and Min Gu, J. Opt. **16**, 045003-6 (2014).
[9] Zhu Wang, Thomas P. White, and Kylie R. Catchpole, IEEE Photonics Journal **5**(5), 8400608-8 (2013).
[10] F. Cortes-Juan, C. Chaverri Ramos, J. P. Connolly, C. David, F. J. Garcıa de Abajo, J. Hurtado, V. D. Mihailetchi, S. Ponce-Alcantara, and Guillermo Sanchez, J. Renewable Sustainable Energy **5**, 033116-12 (2013).
[11] Xing Sheng, Juejun Hu, Jurgen Michel, and Lionel C. Kimerling, Optics Express **20**(S4), A496-501 (2012).
[12] Ronen Chriki, Avner Yanai, Joseph Shappir, and Uriel Levy, Optics Express **21**((S)3), A382-A391 (2013).
[13] P Spinelli, V E Ferry, J van de Groep, M van Lare, M A Verschuuren, R E I Schropp, H A Atwater, and A Polman, J. Opt. **14**, 024002-11 (2012).
[14] Chien-Chang Chao, Chih-Ming Wang, Yia-Chung Chang, and Jenq-Yang Chang, Optical Review **16**(3), 343-346 (2009).
[15] Sangjun Lee and Sangin Kim, IEEE Photonics Journal **5**(5), 4800610-11 (2013).
[16] Ning-Ning Feng, J. Michel, Lirong Zeng, Jifeng Liu, Ching-Yin Hong, L. C. Kimerling, Duan, and Xiaoman, IEEE Transactions on Electron Devices **54**(8), 1926-1933 (2007).