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Analytical study of plasmonic effect in ultrathin film silicon solar cells

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In silicon solar cells, the reduced thickness of the absorbing layer has demanded the use of light trapping structure. A light trapping structure felicitates the unabsorbed photons from the absorbing layer and further, folding these back to stimulate the light absorption. Here, we propose a design of 50 nm ultrathin silicon solar cell and investigate the influence of plasmonic effect on its performance. The transverse magnetic field analysis shows the existence of plasmonic effects such as surface plasmon, Fabry-perot mode and surface plasmon polaritons. The obtained cell efficiency for the transverse magnetic mode is twice (~16%) as comparison to transverse electric mode (~8 %). The proposed solar cell design based on dual grating showed optimal performance in a wide wavelength spectrum due to an efficient light trapping mechanism.

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1. Introduction

Solar cell structures are the semiconductor devices in which silicon is the prominent element due to it abundant in nature. There are many avenues to improve optical absorption of silicon based solar cells. Presently, solar cell performance is found to be improved with the use of metal based nanoparticles/thin film attached near to an active region and also various investigations has been reported to enhance cell efficiency with the combination of dielectric as well as metal grating structures. Such approach is proved to be useful to enhance generation of electron-hole pairs with provided efficient light trapping mechanism.

Presently, metal based nanoparticles/thin film incorporated solar cells showed enhanced optical performance due to surface plasmon polaritons (SPP) and localized surface plasmons (LSP) [1]. Battel et al. have studied the optical absorption enhancement of 100 nm thin film silicon based solar cells by using finite-difference time-domain (FDTD) method. This numerical method could yield 21.9 % absorptivity with a single layer of Ag gratings embedded in the absorber region. The absorption was compared for both the polarizations (TE and TM) modes and incident angle. The enhancement in optical absorptivity was attributed to the surface plasmon polaritons, localized surface plasmons, guided waves and Fabry-Perot resonances [2]. Chriki et al. have demonstrated a design of 100 nm ultrathin silicon solar cell integrated with periodic metal and dielectric gratings at the bottom and top respectively. The laterally shifted gratings between two layers showed the coupling of incident light into photonic and plasmonic modes. The single layer of metallic or dielectric grating based solar cell was compared with dual grating cell structure and reported the effect of relative shift of the gratings and enhanced performance of the solar cell was noticed [3]. Sabaelan et al. have presented the influence of three different grating cross sections and their effects on the 50 nm ultrathin silicon solar cells. They have investigated the optical absorption, generation rate and current density in ultrathin solar cells. The plasmonic effect could yield absorption enhancement due to the localization modes. The trapezoid cross-sectional grating structure has proved significant effect in optical and electrical properties as compared to a triangle and rectangle gratings [4]. He et al. have investigated the performance of the plasmonic ultrathin silicon solar cells by using Ag strips on the metal grating structure. The designed solar cell structure was having absorber layer (Si) thickness around 80 nm and showed absorption enhancement up to 170% with respect to reference cell. The plasmonic effects such as localized surface plasmon resonance (LSPR) and surface plasmon polariton (SPP) were observed due to the use of Ag grating at the top and layer bottom of the solar cells. The coupling effect between LSPR and SPP could contribute the remarkable enhancement in the absorption through ultrathin silicon solar cells [5]. Saravanan et al. have proposed enhanced optical absorption in 40nm ultrathin crystalline silicon solar cell structure. This numerical design was integrated with a top dielectric and bottom metal gratings. Due to the optimization of designing parameters the optimal light harvesting was noticed. The obtained cell efficiency was ~25% due to the associated effect of localized surface plasmon (LSP), surface plasmon polariton (SPP) modes and optical resonances [6]. Lal et al. have demonstrated the design and fabrication of an ultrathin amorphous silicon solar cell using finite-difference time-domain (FDTD) method and studied the plasmonic effects. The presented plasmonic solar cell structure was having 50 nm thick active layer. The coupling mechanism between the periodic array of silver nanovoids and randomly textured silver substrate could enhance the performance. By tuning the spacer thickness, 50% enhanced quantum efficiency and current density was noticed as a result of increased optical path length [7]. Saravanan et al. have proposed 40 nm ultrathin crystalline silicon solar cell which showed extraordinary performance due to enhanced light absorption in visible and infrared part of solar spectrum which could yield cell efficiency ~ 15 % and current density ~ 23 mA/cm^2 [8]. Lee et al. have proposed solar cell design architecture to improve the optical performance using ultrathin top metal grating and back reflector embedded in thin amorphous silicon layer. They have observed the strong absorption with a 10 nm top metal layer at incident angle up to 80°. Overall, the optical absorption in thin amorphous silicon layer of 30 nm showed enhanced TM polarization properties up to 25 % as compared to 100 nm thick layer whereas TE polarization result showed 2.5 times improved performance [9]. Wang et al. have reported a design of 100 nm thick amorphous silicon solar cells by using metal grating at the bottom and explored three possible mechanisms to enhance the light absorption. The Fabry-Perot resonance (FP), Plasmonic effect (SPP) and (LSP) and wave guiding modes were found to be responsible for the enhancement of optical absorption. As compared to reference solar cell structure, they have reported about 30 % enhancement in optical absorption [10]. Guo et al. have proposed an ultrathin silicon solar cell design of 200 nm thickness using rigorous coupled-wave analysis (RCWA) and reported enhanced optical absorption due to the adopted light trapping arrangement. With this solar cell design, a metal back reflector and a top dielectric grating were embedded as light trapping structure which showed strong and broad absorption due to associated plasmonic effect [11]. Qin et al. have claimed enhanced optical absorption in near infrared (IR) region through 1000 nm thick silicon solar cell based on bottom silver (Ag) gratings with a reduced cell thickness. However, the anodic aluminum oxide (AAO) material as a back reflector was allowed more than ±10 % tolerance for the period while ±5 % for the thickness [12]. Use of metal nanoparticles in ultrathin film solar cells was reported for the enhancement of optical absorption due to the induced plasmonic effect. Spinelli et al. have presented possible ways of integrating metal nanoparticles in a 200 nm thick solar cell. By employing an in-expensive nano-imprint technique, a design of solar cell was attempted which showed improvement in cell efficiency [13].

In this paper, we proposed a modeling of ultrathin silicon solar cells to analyze the plasmonic effect and their comparison with a reference solar cell. In section second, theory and designing approach of complete solar cell is presented. In section third, the simulated results are discussed and section fourth concludes the paper.

2. Designing Approach

The design architecture of proposed ultrathin film silicon solar cell is depicted in Fig. 1. A reference solar cell structure composed of 50 nm thick silicon active region, 150 nm thick Aluminum (Al) metal back reflector and 90 nm thick silicon nitride (Si_3N_4) as an anti-reflection layer is shown in Fig. 1(a). Dual grating based solar cell design is depicted in Fig. 1(b) in which top dielectric (Si_3N_4) and bottom metal (Al) gratings are embedded. Here, the purpose of diffraction grating is to assist for multiple bounces of light in the active region. The assumed thicknesses of top (G_t) and bottom grating (G_b) are 50 nm. The shape of the top grating is reported to be promising for the flexible scattering and better field distribution [1].

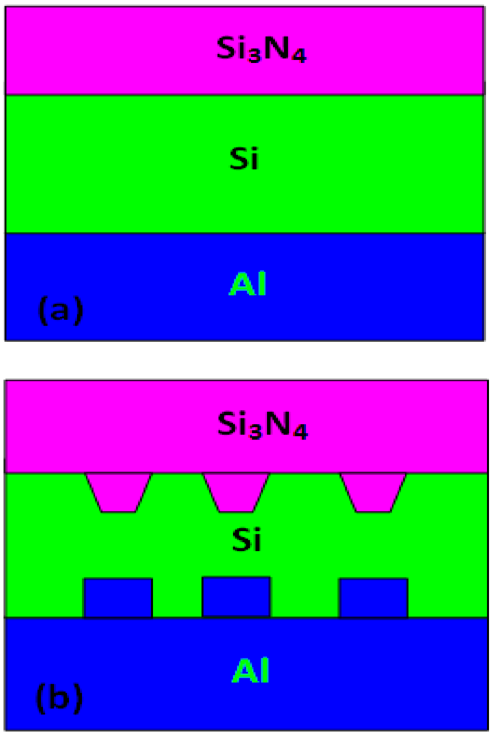

Fig. 1. Schematic diagram of reference (a) and ultrathin dual grating based solar cell (b)

The simulation of proposed design was performed by using RCWA method which is simple and fast. The solar cell was illuminated under normal incidence angle the wavelength range from 300-1200 nm. For simulation, the periodic boundary condition (PBC) was applied in x- and y-directions whereas perfect match layer (PML) condition was performed in z-direction.

3. Results and discussion

The light trapping mechanism in thin silicon solar cell is mainly essential to reuse the longer wavelength photons which are not absorbed by an ultrathin active region, and these can be efficiently folded back towards the active region. Here, we have explored our analysis for both TE and TM polarizations to understand the field behavior in the active region of the solar cell.

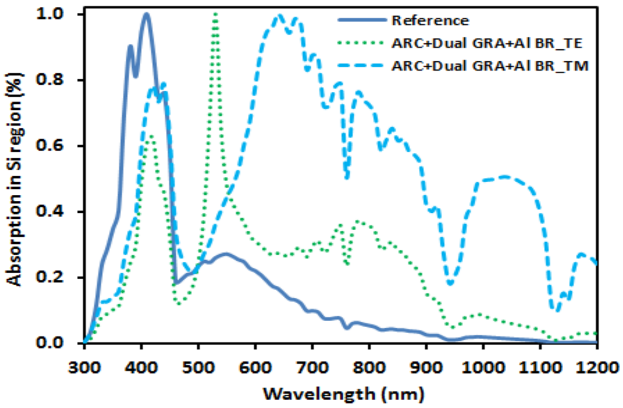

Fig. 2. Absorption spectra of reference cell (solid line) and proposed dual grating based cell for TE(dotted line) and TM (dashed line) polarization modes

Fig. 2 shows absorption spectra of reference and dual grating based solar cells. An enhancement in light absorption can be observed for dual grating based solar cell as comparison to reference cell. However, remarkable enhancement in absorption can be noticed for TM case, particularly in longer wavelength region. This extraordinary performance has been attributed to the plasmonic effect.

Further, we have explored our analysis to electric and magnetic transverse modes which are shown in Fig. 3 and 4. The electric field profile shown in figure 3 reveals strong absorption at shorter wavelength 419 nm, 619 nm and longer wavelength 919 nm, 1170 nm. As a consequence, strong electric field distribution can be observed in the active layer as shown in figure 3(a) and 3(b). The reflections supported by the back reflector is responsible for the absorption enhancement in the active region which produces super-position of the photons. However, strong scattering of light can also be observed between the top gratings. It seems that transmitted light from anti-reflection coating layer is scattering towards the active layer due to which residual photon life time increases and stimulates more electron-hole pair generation.

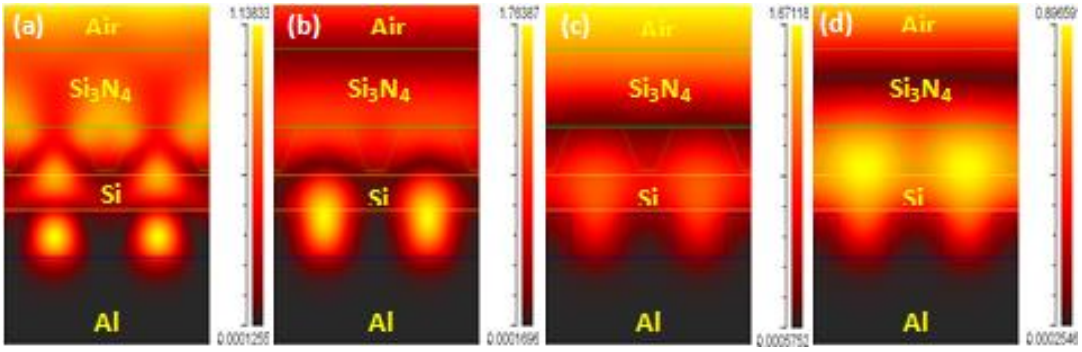

Fig. 3. Electric field profile in solar cell at wavelengths 419, 619, 919 and 1170 nm, respectively

Fig. 3(c) shows symmetrical wave phenomenon between gratings (metal and dielectric) like Fabry-perot resonance mode at wavelength 919 nm which, indicates coupling of light [8]. In Fig. 3(d), the guiding mode resonance (bright light) can be clearly seen at near IR wavelength 1170 nm of the solar spectrum. By this way, the collection of photon can be enhanced through guiding mode resonance (GMR). It is known that guiding mode resonance is one of the essential parameter among others such as plasmonic effect and Fabry-Perot resonances which contribute to the enhancement of optical absorption [7].

The transverse magnetic field profile is depicted in Fig. 4. Guiding mode resonance can be observed at wavelength 419 nm as shown in Fig. 4(a). However, localized surface plasmon is visible at wavelength 619 nm at the tip of Al grating as reveals in Fig. 4(b). The transverse magnetic (TM) analysis showed optimal performance of the solar cell with respect to the different physical parameters such as shape, size or thickness and surface density [14]. The transverse magnetic field deals with the plasmonic effect in different optical wavelength region in which the conduction electrons (in metal) and light particles (from sunlight) plays important role. Fig. 4(a) & 4(b) shows the guiding mode resonance (GMR) and the surface excitation obtained strongly between the metal and dielectric interface which can be observed in the figure. With semiconductor, the metal part is the best candidate to enhance the optical performance via coupling mechanism due to the scattering of the light. Tan et al. have reported the plasmonic effect from amorphous silicon solar cell and observed enhanced current density increased upto 2mA/cm^2 as compared to reference cell [15]. Similar plasmonic effect has been reported in the literatures [2-13].

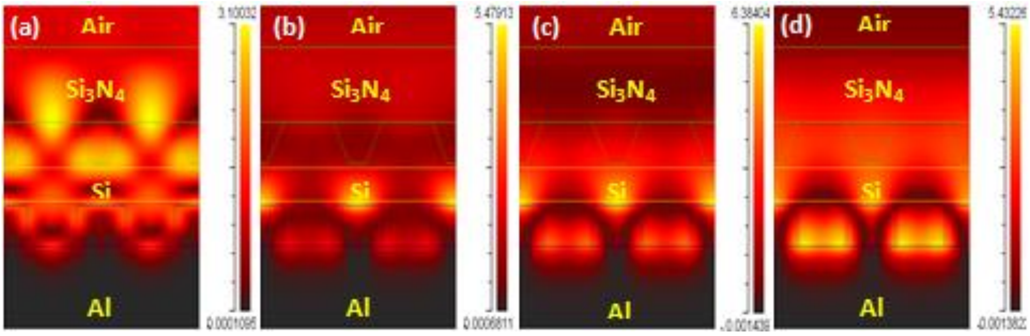

Fig. 4. Magnetic field profile in solar cell at wavelengths 419, 619, 1030 and 1170 nm, respectively

Similarly, Fig. 4(c) shows the localized surface plasmon excited at infrared wavelength 1030 nm with strong light scattering in silicon active region. Fig. 4(d) depicts the surface plasmon polariton (SPP) between the metal and semiconductor interface at wavelength 1170 nm. Mainly, plasmonic effect is dominant in TM polarization which shows improved absorption two times greater than TE polarization and these LSP, SPP and guiding modes are responsible for the performance of the solar cells.

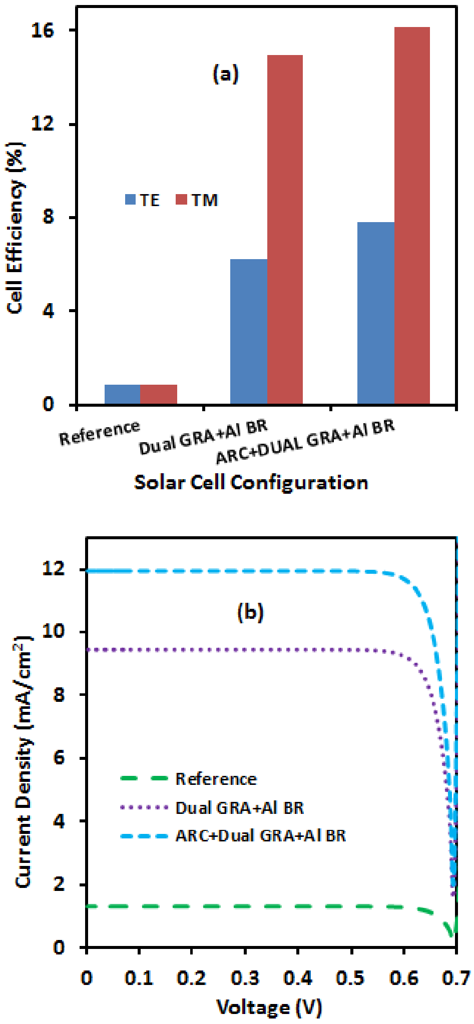

Fig. 5. Solar cell efficiency versus various solar cell structures for both TE and TM polarizations (a) and short-circuit current density for TE polarization (b)

Fig. 5(a) depicts the cell efficiency of various configured solar cell structures for TE and TM polarization modes. The collection of photons is enhanced over the entire spectral region with cell efficiency 7.85% (TE) 16.16% (TM) for the case of ARC+Dual GRA+Al BR solar cell. In another case, Dual GRA+Al BR solar cell structure shows good performance due to plasmonic effect but it is limited because of no anti-reflection coating which results high reflection of incident light. In case of ARC+Al BR, the optical absorption is low, as a result weak performance and the lowest efficiency are observed from reference solar cell. The enhancement of light absorption particularly in shorter wavelength and longer wavelength can be observed in figure 2. In similar way, the effect of grating (top and bottom) is illustrated in the Fig. 3 plotted for the analysis of the electric field profile in the solar cell structure.

The use of plasmonic (metal) structure is a significant way to enhance light absorption within the absorber layer of the thin film solar cell. Single layer rectangular metal nanograting buried into the absorber layer have shown the improved performance of the ultrathin film solar cells. It is observable that the use of dual gratings (dielectric/metal) based solar cell yields the large optical absorption over the considered spectral region.

Generally, light intensity of the solar cell is called the number of sun which has standard illumination i.e. AM1.5. The optical wavelength or light intensity irradiating perpendicular onto the solar cell and solar cell parameters such as current density, fill factor, open-circuit voltage, quantum efficiency and cell efficiency varies. The necessity of grating structure is originated due to the weak absorption of sunlight coming to the active region of the solar cell. In our proposed design, the dielectric grating provides the scattering and waveguiding of the shorter wavelength light at the same time bottom metal grating generates the plasmonic mode particularly in longer wavelength light of solar radiation. Therefore, the combination of plasmonic and photonic modes are significant in order to enhance the light absorption within the thin active region through scattering, wave guiding, surface plasmon polaritons and localized surface plasmon effects.

Fig. 5(b) shows the current density (TE case) of different structures of silicon solar cells. The reference structure depicts least current further, dual grating based solar cell without anti-reflection coating layer shows enhanced performance which is again defeated by adding an anti-reflection coating layer (ARC) with dual grating based structure. The above analysis indicates the importance of anti-reflection coating layer and grating to achieve the high performance of the solar cell.

4. Conclusions

A complete design and analysis of ultrathin film silicon solar cell is discussed. The performance of 50 nm solar cell showed the influence of anti-reflection coating and dual grating. The top and bottom gratings were supported to light guiding and plasmonic effects respectively. Field profile analysis of solar cell has confirmed the various associated modes of surface plasmon, Fabry-Perot and surface plasmon polariton. The maximum solar cell efficiency ~16 and 8 % is obtained for transverse magnetic and transverse electric wave modes respectively. The proposed ultrathin film solar cell design is not only enhanced performance in shorter wavelength but also in longer wavelength which has been attributed to the efficient light trapping mechanism.

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References

[1] A. Abass, Q. Le Khai A. Alu, M. Burgelman, B. Maes, Phys. Rev. B. **85**, 115449 (2012).
[2] E. Battel, T. Alper Yogurt, L. Erdal, K. Okyay Ali, Opt. Express. **20**(8), 9458 (2012).
[3] R. Chriki, A. Yanai, J. Shappir, U. Levy, Opt. Express **21**(S3), A382 (2013).
[4] M. Sabaeian, M. Heydari, N. Ajamgard, AIP Advances **5**, 087126-1-12 (2015).
[5] J. He, C. Fan, J. Wang, Y. Cheng, P. Ding, E. Liang, Adv. Optoelectron. **1155**, 1 (2012).
[6] S. Saravanan, R. S. Dubey, Opt. Commun. **377**, 65 (2016).
[7] N. N. Lal, H. Zhou, M. Hawkeye, J. K. Sinha, Philip N. Bartlett, Gehan A. J. Amaratunga, Jeremy J. Baumberg, Phys. Rev. B. **85**, 245318 (2012).
[8] S. Saravanan, R. S. Dubey, S. Kalainathan, D. K. Gautam, M. A. More, AIP Advances **5**, 057160-1-9 (2015).
[9] S. Lee, S. Kim, IEEE Photon. J. **5**, 1 (2013).
[10] W. Wang, S. Wu, K. Reinhardt, Y. Lu, S. Chen, Nano Lett. **10**(6), 2012 (2010).
[11] X. Guo, J. Liu, S. Zhang, Design Photonics and Optoelectronics (P&O) **3**, 66 (2014).
[12] F. Qin, H. Zhang, C. Wang, J. Zhang, C. Guo, Opt. Commun. **331**, 325 (2014).
[13] P. Spinelli, V. E. Ferry, J. Van De Groep, M. Van Lare, M. A. Verschuuren, R. E. I. Schropp, H. A. Atwater, A. Polman, J. Opt. **14**, 024002-1-11 (2012).
[14] A. A. Yu, W. S. Koh, Nanotechnology **21**, 235201-1-6 (2010).
[15] H. Tan, R. Santbergen, A. H. M. Smets, M. Zeman, Nano Lett. **12**, 4070 (2012).

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