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2015

Prabhathan, P., & Murukeshan, V. M. (2016). Surface Plasmon Polariton-coupled Waveguide Back Reflector in Thin-film Silicon Solar Cell, *Plasmonics*, 11(1), 253-260.

<https://hdl.handle.net/10356/80301>

<https://doi.org/10.1007/s11468-015-0045-9>

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Surface Plasmon Polariton coupled waveguide back reflector in thin film silicon solar cell

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Abstract. Surface Plasmon Polariton (SPP) waveguide coupled back reflector geometry is proposed for efficient light trapping and broad band absorption enhancement in thin film silicon solar cells. The proposed geometry takes advantage of the localized surface Plasmon (LSP) enhancement, Fabry-Perot (FP) resonance and strong electric field confinement resulting from the SPP interference in a metal waveguide. It is shown that the designed light trapping structures contribute to significant light trapping and enhancement in the red to near infrared part of the solar spectrum. For a thin film silicon solar cell of 220 nm thickness, an absorption enhancement of 153% is obtained when compared to a bare silicon solar cell. In comparison to other SPP excited back reflection geometries such as, nano-gratings and nano-grooves, the proposed configuration shows a higher absorption enhancement factor and uniform field distribution inside the silicon layer. These results are expected to introduce new directions in the design of optimized nanoscale back reflectors in thin film silicon solar cells.

Infex Terms: Photonics, Thin Film, Solar Energy, Surface Plasmons,

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1. Introduction

Light trapping in nanostructured thin film silicon solar cell is a promising way to increase its absorption and conversion efficiency [1-5]. Since the absorption efficiency of silicon (Si) is smaller near its band gap (1.1eV), these light trapping structures should be able to capture and enhance red and near-infrared (0.6 μ m-1.1 μ m) part of the solar spectrum[6,7]. The Plasmonic concept of light trapping is a widely accepted technique for enhanced light localization and, hence, to improve absorption in thin film solar cell [8-11]. Mainly nano- particles or nano-structures are employed as localized surface Plasmon (LSP) excitation elements or Surface Plasmon Polariton (SPP) propagation structures near the active layer of the cell [12-14]. Nano-particles placed on the front surface of a solar cell is found to be very effective for broad band absorption enhancement through enhanced light localization and increased optical path length [15,13]. However, the metal nanostructures on the front surface of a solar cell often leads to destructive Fano-interference for lower wavelength regions of the solar spectrum [16,17]. For a thin film solar cell with a rear surface modified plasmonic structures, the lower part of the solar spectrum is not obstructed and weakly absorbed red to near-infra red part of the spectrum is trapped and enhanced to get an increased optical path length inside the thin film[7]. Apart from being an effective back reflector, the thin metal layer at the rear-side of a thin film solar cell also excites the SPP or LSP modes through nanostructured grooves[14], gratings[10,13,18] or photonic crystals[19]. Light scattering elements in such back reflectors essentially perform two functionalities. It

may excite the surface Plasmon modes for higher field enhancement, at the same time, it may act like a coupling structure of the incident light to enter the waveguide mode of the thin layer[7]. For an LSP excitation structure, the nanostructures should be designed such that, the optical loss inside the structure is smaller and scattering efficiency is maximum[20]. Randomly structured nanostructures have been identified to cause significant optical loss inside the structure[21]. For an SPP excited back reflector, it may excite both the waveguide modes and SPP modes inside the silicon layer. However, for SPP back reflector designs such as nano-gratings and nano-grooves, the plasmon modes are highly lossy and propagates only over a distance of 10-100 μm . They are also tightly confined to the interface, with skin depths on the order of tens of nanometers. The SPP back reflector geometry should be designed in such a way that it is a good light reflector and at the same time an effective light scattering element over a broad band of wavelength with minimum optical loss. In this context, a thin film solar cell plasmonic back reflector geometry is proposed to consider all the aspects of an effective metal back reflector. The SPP waveguide back reflector is designed through the periodic arrangement of thin metal layers to propagate SPP waveguide mode. Since the SPP mode generated in such a configuration is weakly confined inside the thin metal layer, a higher propagation length and minimum optical loss inside the structure is expected. The geometry would also enable LSP excitation and SPP interference to get highly localized and enhanced electric field with higher electric field decay depth in the silicon layer. The proposed configuration is analyzed through full wave electromagnetic simulation in 3-D and the results are compared with those of a bare silicon thin film solar cell and other surface plasmon excited geometries. In the later sections, the parameter optimization of the geometry is presented to show the optimized design and short circuit current density (J_{sc}) is calculated.

2. Design and simulation

Proposed configuration of thin film silicon solar cell with SPP waveguide back reflector geometry is shown in Fig.1.

Fig.1 Schematic diagram of thin film silicon solar cell with the SPP wave guide back reflector at the rear side.

The structure consists of a thin Silicon (Si) layer with Indium Tin Oxide (ITO) layers on top, acting as the top transparent electrode, and SPP waveguide back reflector at the bottom, as the bottom electrode. The SPP waveguide back reflector consists of a thin metal layer of thickness t_1 periodically arranged with a separation of distance W from each other. The thin metal plates are long enough for SPP wave propagation and placed at a separation distance of d from the back metal of thickness t_2 .

The proposed configuration is analyzed through full wave electromagnetic simulation in 3-D using Finite Difference Time Domain (FDTD) method with Lumerical Solutions software. A 3D simulation window with dimensions $X=2.5 \mu\text{m}$, $Y=2.5 \mu\text{m}$ and $Z=1.5 \mu\text{m}$ were considered for the simulation. Periodic boundary conditions are used in the X and Y directions and Perfectly Matched Layer (PML) boundary conditions are used in the Z-direction. The absorption inside the active silicon layer is calculated as follows. Two power monitors are placed inside the silicon layer, in XY-plane, to calculate the absorbed power. One monitor is placed at the top and the other at the bottom of the Si layer. The power monitor estimates the total electric flux passing through the plane. The power at each monitor is normalized with the input source power.

The transmission is given by the formula,

$$T(f) = \frac{\frac{1}{2} \int \text{real}[P(f) \cdot dS]}{\text{source power}} \quad (1)$$

Where, $T(f)$ is the normalized transmission, $P(f)$ is the Poynting vector and dS is the surface normal. The absorbed power is obtained by subtracting the transmitted power through each monitor as given by,

$$P_{abs}(\lambda) = -T(\text{monitor}_{top}) - -(T(\text{monitor}_{bottom})) \quad (2)$$

In order to eliminate the metal absorption from the total power absorbed, the power absorbed by the metal plates is calculated separately and subtracted from the total power. The power absorbed by the metals are calculated through two power monitors placed above and below each metal strips.

3. Results and discussion

To check simulation reliability, initial simulations are performed on a bare silicon solar cell with dimensions and material properties similar to the experimentally reported data in Si thin film solar cell. [22] A good agreement between the simulation and experimental value is observed. For a bare silicon layer of 400 nm thickness, the observed absorption curves are shown in Fig.2. The complex refractive index curve of the silicon (Palik) used in the simulation which is similar to a crystalline Silicon (c-Si) material.[23] The absorption value is observed to be higher in the blue part of the spectrum and gradually decreases at higher wavelengths. For a thin film cell with metal back reflector, the absorption curve shows a series of resonant peaks due to the thin film Fabry-Perot (FP) resonance effect inside the silicon layer.

Fig. 2 Normalized absorption of bare silicon with and without metal back reflector.

The FP resonance in thin film contributes to the enhanced absorption in the cell as shown in Fig.2. The metal back reflector in a bare silicon solar cell is modified to incorporate the proposed SPP waveguide structure and the absorption curve obtained is shown in Fig.3. In the simulation, Aluminum (Al) is taken as the metal with the thin metal layers having a thickness of 20 nm and length 1.5 μm , periodically arranged with a spacing $W=100\text{nm}$ and placed at a separation distance $d=30\text{ nm}$ from the back metal. Along with absorption curve, the absorption of a bare silicon (with metal back reflector) and Yablonovitch limit is also shown for comparison. For a perfect light trapping thin film solar cell the Yablonovitch limit is calculated from the following formula [24,25]

$$A_{\text{Yablonovitch}} = 1 - \frac{1}{1 + 4n^2\alpha t} \quad (3)$$

Where, n is the real part of refractive index of silicon, α is the absorption coefficient and t is the thickness of silicon layer. Transverse Magnetic (TM) polarized light source with a spectral range 400nm to 1100nm is used in the simulation to study the plasmonic effect of the back reflector. It is observed that there is a considerable absorption enhancement in the proposed SPP waveguide back reflector when compared to the bare silicon solar cell. It is also observed that, the enhancement is more prominent in the red and near infrared part of the solar spectrum. The average absorption is calculated in two different regions of the solar spectrum, viz., Blue-green region (400nm-600nm) and red- near-infrared (600nm-1100nm). For the bare silicon solar cell the average absorption is obtained as, 42.79% and 12.33 %, in the blue-green and red-near-infrared regions, respectively. Whereas, for the SPP waveguide coupled configuration the absorptions are, 47.37% and 38.77 % in the blue-green region and red-near-infrared regions, respectively. This shows an absorption enhancement of 4.58% in the blue-green part and 26.44 % in the red-near-infrared part of the solar spectrum, validating the near band gap light enhancement in the thin film solar cell with the proposed back reflector geometry.

Fig. 3 Absorption enhancement in SPP waveguide coupled thin film silicon solar cell in comparison to bare silicon and Yablonovitch limit.

In comparison to other metal back reflector geometries, such as nano-grating and nano-grooves, the proposed configuration shows a higher enhancement factor and uniform field distribution inside silicon layer. Figure 4 shows a comparison in electric field intensity distribution for these back reflector geometries. Since surface plasmon effect is more visible in the Z-component (E_z) of electric field, E_z field distribution is shown for comparison. In the simulations, the grating dimensions are taken as 300nm in pitch with a duty cycle of 33.3% and 50 nm grating depth[13,26]. For the nano-grooved back reflector, grooves are of 100 nm width and 50 nm in depth [14]. The higher field enhancement in SPP waveguide geometry is attributed to the LSP excitation in the structure and SPP waveguide mode interference.

It is observed that the dielectric space between the thin metal and the back metal is occupied by a series of high intensity fringes arising from SPP mode interference. Since the SPP modes in such a configuration are weakly confined in thin metal, the electric field components will have higher penetration depth into the active Si layer as observed in Fig.4 (b). For the nano-gratings and nano-grooved reflector, the electric field enhancement is observed to be less and is localized at the sharp edges of the structure as shown in Fig.4 (d) and Fig.4 (f). For the grooved reflector the SPP wave gets excited at the sharp edges and then quickly decays due to energy loss inside the metal. Figure.5 shows, the absorption curves of these back reflector geometries in comparison to the proposed SPP waveguide configuration. For a nano-grating back reflector the enhancement is limited to a narrow bandwidth and it is grating pitch dependent[26]. A 300 nm pitch gratings shows enhancement located near 600 nm wavelength. For the nano-grooved back reflector the field enhancement is in the red part of the spectrum and it is much lower when compared to the SPP waveguide configuration. The SPP waveguide back reflector is characterized by strong LSP enhancement, FP resonance enhancement and SPP waveguide mode interference enhancement, which results into a broadband absorption enhancement over the whole solar spectrum, prominently in the red to near-infrared part. The average absorption is observed to be always less than Yablonovitch limit. However, It is to be noted that the absorption peak is overbeating Yablonovitch limit near the band gap region in SPP waveguide configuration, which

might be due to the strong light enhancement. It has been reported that the effective absorption in a thin film solar cell can exceed the conventional limits with an efficient light trapping and enhancement structures [27,28]

Fig. 4 Structure design and Ez electric field intensity distribution (X-Z plane) in various thin film silicon solar cell with different back reflector geometry (a), (b) SPP waveguide (c), (d) Nano-grooved and (e), (f) nano-gratings.

Fig. 5 Absorption variation in thin film silicon solar cell for different nanostructured back reflector geometries.

Since the proposed structure is periodic in X- direction and infinitely long in the Y-direction, plasmonic modes are not excited by a Transverse Electric (TE) polarized illumination. However, the back reflector can excite the waveguide mode and contribute to the absorption enhancement. Fig.6 (a) shows the absorption curve comparison of different thin film silicon solar cell under TE wave incidence. A maximum enhancement occurs when the single mode guidance occurs in the active layer. Here, the silicon layer thickness is taken as 220 nm to obtain a maximum absorption enhancement. F-P resonance in the structure is another factor which determines the absorption enhancement. It is observed that for nano-grooved and SPP waveguide structures, the FP resonance inside the

structure is undisturbed, in comparison to the grating back reflector. In the case of nano-gratings, the absorption enhancement is highly gratings dimension dependent. TE mode absorption is dominant for lower pitch dimensions (e.g. $\Lambda=300\text{nm}$). The peak observed at the higher wavelength region ($\sim 950\text{nm}$) in Fig.6 (a) is the grating contribution for a TE wave incidence. It is observed that for higher grating pitch dimensions TE mode contribution reduces and TM mode contribution increases in small amount. The calculated spectral averaged absorption for these structures are, 22.14%(Bare metal back), 24.68%(nano-grooved), 23.55%(SPP waveguide), 23.92%(gratings $\Lambda=300\text{nm}$) and 23.51%*(gratings $\Lambda=400\text{nm}$). This shows that all the nanostructured back reflectors have higher absorption in comparison to the plane metal back reflector under a TE wave illumination and the absorptions are approximately similar, depending on whether the features helps the incoming wave for a waveguide mode coupling or F-P resonance.

Fig.6. (a) Absorption curve for thin film silicon (220nm) solar cell for different back reflector geometries under TE wave illumination.(b) Electric field(E_y) distribution (X-Z plane) in the active layer for different configuration

Even though the proposed concept is demonstrated in c-Si thin film cell, it is also extendable to other solar cell with different active materials. In order to evaluate the effect of SPP waveguide back reflector geometry on the solar cell performance, it is assumed that the enhanced electric field amplitude gives rise to an increased electric field intensity, which in turn increases the electron-hole pair generation in the solar cell[29]. For this, the spectral variation of absorption enhancement $g(\lambda)$ and spectral integrated enhancement factor (G) are evaluated and analyzed. The enhancement factor $g(\lambda)$ can be calculated from the Quantum Efficiency (QE) of the solar cell as follows[30],

$$QE(\lambda) = \frac{P_{abs}(\lambda)}{P_{in}(\lambda)} \quad (4)$$

Where, $P_{abs}(\lambda)$ and $P_{in}(\lambda)$ are the absorbed power and incident power per unit volume inside the solar cell at wavelength λ . The spectral Integrated Quantum Efficiency (IQE) is given by,

$$IQE = \frac{\int \frac{\lambda}{hc} QE(\lambda) I_{AM1.5}(\lambda) d\lambda}{\int \frac{\lambda}{hc} I_{AM1.5}(\lambda) d\lambda} \quad (5)$$

Where, h is the Plank's constant, c is the speed of light in free space and $I_{AM\ 1.5}$ is AM 1.5 solar spectrum. Using the Eqn.4 and Eqn.5, $g(\lambda)$ and G is defined as follows

$$g(\lambda) = \frac{QE_{SPP}(\lambda)}{QE_{bare}(\lambda)} = \frac{P_{SPP}(\lambda)}{P_{bare}(\lambda)} \quad (6)$$

Where, P_{SPP} and P_{bare} are the power absorbed per unit volume in proposed SPP waveguide configuration and bare silicon configurations, respectively, at wavelength λ . And,

$$G = \frac{IQE_{SPP}(\lambda)}{IQE_{bare}(\lambda)} = \frac{\int \lambda P_{SPP}(\lambda) I_{AM1.5}(\lambda) d\lambda}{\int \lambda P_{bare}(\lambda) I_{AM1.5}(\lambda) d\lambda} \quad (7)$$

The spectral variation of $g(\lambda)$ for the proposed SPP waveguide coupled thin film silicon solar cell is shown in Fig.7 (a). It is observed that the enhancement factor is nearly unity until 600 nm and then increases to higher values in the red and infra-red part of the spectrum. This shows that the surface Plasmon coupling to the waveguide geometry happens at these wavelengths. The curve has resonance dips corresponding to the surface Plasmon resonance modes in the geometry. It has been reported that, the enhancement factor gets increased or suppressed, respectively, above and below, at each resonant wavelength[29]. The spectral integrated enhancement factor (G) is calculated for different parameter variation in the geometry. It is observed that the thickness of the Si layer (t), the thickness of the thin metal (t_l) and the separation distance between the metal plates (d) plays an important role in the G factor variation. The results are shown in Fig.7 (b), Fig.7 (c) and Fig. 7(d).

The silicon layer thickness at which maximum enhancement occurs is observed to be 220 nm as shown in Fig.7 (b). This is due to the single mode waveguide guidance of the silicon layer at this thickness. The SPP waveguide geometry helps to couple the incoming light to enter the single mode guidance of the silicon, which leads to better field enhancement in the layer. When the separation distance d reduces, the enhancement factor increases due to the strong coupling between metal plates. An optimal distance of 30 nm is observed for maximum enhancement as shown in Fig.7(c). Another important factor which affects the enhancement factor is the thin metal layer thickness (t_l). As the thickness goes down the electric field is less confined inside the metal layer and higher absorption enhancement is observed. However, depending on the momentum matching condition and the effective index of 220 nm thick silicon layer, the optimum metal thickness is observed to be 20 nm for maximum enhancement as shown in Fig.7 (d).

Fig.7 (a) Enhancement factor variation of the SPP waveguide back reflector thin film silicon solar cell Spectral integrated enhancement factor(G) variation with respect to (b) thickness of the Si (c) separation distance between metal plates (d) thickness of the thin metal plates.

While considering the variation in the metal layer spacing from each other W , the absorption is observed to be nearly constant in the dimension range from 100 nm to $\sim 1\mu\text{m}$. This gives lots of fabrication tolerance to the proposed design, when compared to other nano-structured metal back reflector. The structure is also easy to fabricate through simple metal deposition and lift-off process. The G is also calculated for other two SPP excited geometries such as, nano-gratings and nano-grooves, and is shown in Table 1.

Table 1. Spectral averaged enhancement factor (G) for different SPP excited metal back reflector geometry in thin film silicon solar cell.

Back reflector geometry	G
SPP Waveguide	1.53
Nano-gratings	1.15
Nano-grooved	1.10

Among the three SPP excited geometries, higher enhancement factor is observed for the proposed SPP waveguide geometry. The enhancement factor $g(\lambda) > 1$ signifies a higher number of photons inside the solar cell. As each photon is expected to generate an electron-hole pair in an ideal situation, increased photon concentration inside the cell would increase the photo current considerably. Assuming that all the photons absorbed generate electron-hole pairs, the photo-generation current (J_{SC}) is calculated using the following equation.

$$J_{SC} = e \int \frac{\lambda}{hc} \frac{P_{abs}(\lambda)}{P_{in}(\lambda)} I_{AM1.5}(\lambda) d\lambda \quad (4)$$

For the current density calculation, total power absorbed $P_{abs}(\lambda)$ is obtained considering the TE polarization of the spectrum also, through the relationship $P_{abs}(\lambda) = [P_{abs}(\lambda)_{TM} + P_{abs}(\lambda)_{TE}]/2$. Short circuit current (J_{SC}) for the

proposed SPP waveguide back reflector configuration is calculated as 25.6 mA/cm². The J_{SC} for bare thin film silicon solar cell with plane metal back reflector is observed to be 17.2 mA/cm². Current densities for other SPP excited back reflector geometries such as, nano-gratings and nano-grooved for thin film silicon solar cell is also calculated and is obtained as, 19.7mA/cm² and 18.9 mA/cm², respectively.

4. Summary and conclusions

In Summary, a Surface Plasmon Polariton (SPP) coupled back scattering geometry is proposed for thin film silicon solar cell for efficient light trapping and broad band absorption enhancement. The proposed geometry takes advantage of the LSP enhancement, F-P resonance and strong light confinement resulting from the SPP interference in a thin metal waveguide. As a back side modified geometry, significant light trapping and enhancement is observed in the red and near infrared part of the solar spectrum. Absorption enhancement of 153% is observed for an ultra-thin silicon solar cell of 220 nm thickness in the solar spectral range 400nm to 1100nm. In comparison to other back reflector geometries such as, nano-gratings and nano-grooves, the proposed configuration shows a higher field enhancement and uniform field distribution inside the active silicon layer. The configuration is easy to fabricate and will provide large fabrication tolerance, giving a new direction to the design of optimized nanoscale back reflectors in thin film solar cells.

Acknowledgments

The authors acknowledge the financial support received through MOE- RG 98/14 and MOE RG 34/10.

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We would like to thank the reviewer for his valuable suggestions and feedbacks that helped to improve the manuscript. Based on the comments, following modifications are done in the manuscript to explain the points.

Comment1: The manuscript (ID: PLAS-D-15-00191) by P. Prabhathan and V. M. Murukeshan explores a new silicon solar cell configuration based on surface plasmon polariton waveguide back reflector. They show calculation on different systems to discuss about the efficiency of their original configuration. They propose to use a thin metal waveguide to take advantage about the strong light confinement resulting from the surface plasmon polariton interferences. They calculate and compare the absorption enhancement between their configuration and more conventional ones like bare silicon with metal back reflector or efficient ones like nanogrooved back metal reflector. They clearly show an increase of the absorption efficiency in the red and near infra-red wavelength whatever the other configuration they compared. Finally they calculated the enhancement factor by changing different parameters that can allow to define optimal ones in order to maximize the spectral averaged enhancement factor.

My only remark is about the different polarization modes, TE and TM. The authors mentioned it at the end of the manuscript but didn't discuss so much about the absorption comparison (Fig. 5b) between these two modes which show drastic different behaviours. I expect to have a little more explanation about this result in the manuscript.

The results are good but this point must be discussed before acceptance of the manuscript.

Reply: Following paragraph is added in the manuscript to explain the response of the solar cell under a TE wave incidence.

Since the proposed structure is periodic in X- direction and infinitely long in the Y-direction, plasmonic modes are not excited by a Transverse Electric (TE) polarized illumination. However, the back reflector can excite the waveguide mode and contribute to the absorption enhancement. Fig.6 (a) shows the absorption curve comparison of different thin film silicon solar cell under TE wave incidence. A maximum enhancement occurs when the single mode guidance occurs in the active layer. Here, the silicon layer thickness is taken as 220 nm to obtain a maximum absorption enhancement. F-P resonance in the structure is another factor which determines the absorption enhancement. It is observed that for nano-grooved and SPP waveguide structures, the FP resonance inside the structure is undisturbed, in comparison to the grating back reflector. In the case of nano-gratings, the absorption enhancement is highly gratings dimension dependent. TE mode absorption is dominant for lower pitch dimensions (e.g. $\Lambda=300\text{nm}$). The peak observed at the higher wavelength region ($\sim 950\text{nm}$) in Fig.6 (a) is the grating contribution for a TE wave incidence. It is observed that for higher grating pitch dimensions TE mode contribution reduces and TM mode contribution increases in small amount. The calculated spectral averaged absorption for these structures are, 22.14%(Bare metal back), 24.68%(nano-grooved), 23.55%(SPP waveguide), 23.92%(gratings $\Lambda=300\text{nm}$)

and 23.51%*(gratings $\Lambda=400\text{nm}$). This shows that all the nanostructured back reflectors have higher absorption in comparison to the plane metal back reflector under a TE wave illumination and the absorptions are approximately similar, depending on whether the features help the incoming wave for a waveguide mode coupling or F-P resonance.

Fig.6. (a) Absorption curve for thin film silicon (220nm) solar cell for different back reflector geometries under TE wave illumination.(b) Electric field(E_y) distribution (X-Z plane) in the active layer for different configuration

List of major changes made in the revised manuscript based on the reviewer's comments

S/N	Section	List of Amendments	Page
1	3	<p>Fig.4 is replaced with high resolution images.</p> <p>Few sentences are modified or added in the explanation section as below</p> <p>“Since the SPP modes in such a configuration are weakly confined in thin metal, the electric field components will have higher penetration depth into the active Si layer as seen in Fig.4 (b). For the nano-gratings and nano-grooved reflector, the electric field enhancement is observed to be less and is localized at the sharp edges of the structure as seen in Fig.4 (d) and Fig.4 (f). For the grooved reflector the SPP wave gets excited at the sharp edges and then quickly decays due to energy loss inside the metal.”</p>	5
2	3	<p>Fig.4 caption is changed to indicate which electric field component is shown in the picture.</p>	6
3	3	<p>Following sentences are added in the revised manuscript, explaining the TE wave illumination response.</p> <p>“Since the proposed structure is periodic in X- direction and infinitely long in the Y-direction, plasmonic modes are not excited by a Transverse Electric (TE) polarized illumination. However, the back reflector can excite the waveguide mode and contribute to the absorption enhancement. Fig.6 (a) shows the absorption curve comparison of different thin film silicon solar cell under TE wave incidence. A maximum enhancement occurs when the single mode guidance occurs in the active layer. Here, the silicon layer thickness is taken as 220 nm to obtain a maximum absorption enhancement. F-P resonance in the structure is another factor which determines the absorption enhancement. It is observed that for nano-grooved and SPP waveguide structures, the FP resonance inside the structure is undisturbed, in comparison to the grating back reflector. In the case of nano-gratings, the absorption enhancement is highly gratings dimension dependent. TE mode absorption is dominant for lower pitch dimensions (e.g. $\Lambda=300\text{nm}$). The peak observed at the higher wavelength region ($\sim 950\text{nm}$) in Fig.6 (a) is the grating contribution for a TE wave incidence. It is observed that for higher grating pitch dimensions TE mode contribution reduces and TM mode contribution increases in small amount. The calculated spectral averaged absorption for these structures are, 22.14%(Bare metal back), 24.68%(nano-grooved), 23.55%(SPP waveguide), 23.92%(gratings $\Lambda=300\text{nm}$) and 23.51%*(gratings $\Lambda=400\text{nm}$). This shows that all the nanostructured back reflectors have higher absorption in comparison</p>	6-7

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Fig.6. (a) Absorption curve for thin film silicon (220nm) solar cell for different back reflector geometries under TE wave illumination.(b) Electric field(E_y) distribution (X-Z plane) in the active layer for different configuration

Figure1

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Figure7

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Table 1. Spectral averaged enhancement factor(G) for different SPP excited metal back reflector geometry in thin film silicon solar cell.

Back reflector geometry	G
SPP Waveguide	1.53
Nano-gratings	1.15
Nano-grooved	1.10