

Full length article

Double-sided pyramid texturing design to reduce the light escape of ultrathin crystalline silicon solar cells

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HIGHLIGHTS

- A comparative study on planar, front textured and double-sided textured structures.
- Double-sided textured structure remarkably suppresses light escape.
- Double-sided textured structure improve light absorption in long wavelength range.
- Double-sided textured structure show a small angle dependence.

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ABSTRACT

Reducing the light absorption loss of ultrathin crystalline silicon (c-Si) solar cells is significant to achieve high photocurrent density and photoelectric conversion efficiency. Here, we designed and simulated ultrathin c-Si cells with front pyramids and double-sided pyramids. By adjusting the shape of pyramids, the maximum photocurrent densities reach 36.23 and 37.71 mA/cm² for the cells with front pyramids and double-sided pyramids, respectively. The reflectivity spectrum indicates that the double-sided pyramidal architecture remarkably suppresses light escape and then enhances the light absorption in long wavelength range, which makes the absorption approach the Yablonovitch limit. The calculated conversion efficiencies of planar, front and double-sided textured cells are 16.94%, 19.65% and 20.45% respectively. Additionally, the difference between randomly and periodically textured cells was investigated and the results show that although the randomly front pyramid texture has a better light absorption in the range of 900–1200 nm, the periodically double-sided pyramids texture exhibit almost the same light absorption in the whole range as the random one. Besides, the solar cells with double-sided pyramids show extremely small angular dependence of incident light. Thus, the double-sided light trapping structure designed in the present work provides an alternative pathway to improve the performance of ultrathin c-Si cells.

1. Introduction

Thicker absorption layer materials in traditional c-Si solar cells lead to very high costs. Ultrathin solar cells can effectively reduce costs, but they have poor efficiency due to low light absorption [1–3]. Therefore, it is crucial to improve the optical absorption of ultrathin c-Si cells through optical design. For the sake of this purpose, single-layer anti-reflective coating (ARC) was commonly used to reduce the surface reflectivity of solar cells. Alternatively, surface texture for light trapping such as pyramids [4,5], cones and nanopillar [6] can increase the

optical path length and thereby improve the light absorption. The textured pyramid formation on Si surface through alkaline texturing is a well-known process [7]. Due to the so-called “double bounce effect”, the pyramid surface texture suppresses the front-surface reflectance to improve the light absorption [8,9]. Typically, high-efficiency silicon solar cells consist of a textured front surface and a planar rear surface [10–12]. However, although the ARC films and front-side surface texture can greatly reduce the reflection of incident light, there is still a part of the light escaping from the cell, resulting in a certain amount of optical loss [13,14]. Broadband absorption enhancement in ultrathin c-

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Si cell with double-sided texture has been proved in recent theoretical simulations [15–17]. More recently, some experiments proved that the c-Si solar cells with double-sided pyramids can provide more superior light absorption compare to single front-textured cells [18,19], but they focused on the pyramid texture at a particular angle and size and a further discussion about the rear pyramid texture is still lacking. Moreover, the angle dependence of incident light for the cells with double-sided texture also needs a detailed investigation.

In this paper, we present a double-sided pyramid texture model and study the influence of pyramid size on the optical absorption of ultrathin c-Si cells. The wet-etching preparation of micro-scale pyramidal texture is not only very cheap but also mature for large-scale photovoltaics (PV) industrial application [20]. In the present work, we chose the 20 μm ultrathin c-Si cells to investigate the influence of pyramidal texture. The front surface reflection, the light escaping and the optical absorption in cells with different light trapping structures are simulated. Moreover, the J-V response and the absorption spectra of ultrathin c-Si solar cells with surface texture were calculated.

2. Modelling and simulation methods

Fig. 1 shows the schematic diagram of ultrathin c-Si solar cell models investigated in this work. The Wafer Optics Calculator (WOC) [21] incorporates the effect of the wafer bulk and both of its surfaces, which was used to assess all optical losses and light trapping of a cell. The WOC combines Monte Carlo ray tracing with thin film optics. The optical path length factor adopts “Limit: Green 02”, which is a more realistic limit than an ideal limit of $4n^2$ [22].

$$Z = 4 + \ln[n^2 + (1 - n^2)e^{-4aW}]/aW \quad (1)$$

where a , W , n are the absorption coefficient, thickness and refractive index of c-Si, respectively.

In order to accomplish the present simulation, the refractive indices (n , k) of all materials are required including ARC SiO_2 , Si_3N_4 , Al_2O_3 , SiN_x , c-Si and Ag, which are cited from the experimental data [23–28]. Here, the absorption spectrum $A(\lambda)$ of c-Si can be calculated. It is assumed that all electrons and holes contribute to the generation of photocurrent and therefore the photocurrent density J_{SC} is expressed as [29]:

$$J_{\text{SC}} = e \int \frac{\lambda}{hc} A(\lambda) I_{\text{AM1.5}}(\lambda) d\lambda \quad (2)$$

where e is the amount of electron charge, c is the speed of light in vacuum, h is the Planck constant, λ is the wavelength of incident light, $A(\lambda)$ is the absorption of c-Si at the wavelength λ , and $I_{\text{AM1.5}}(\lambda)$ is the solar irradiance under the global 37° tilt Air Mass 1.5 spectrum [30]. The integration is conducted for c-Si in the wavelength range of 300–1200 nm.

As for single-layer ARC films, the reflectivity has a minimum value when the refractive index of the single-layer material and its thickness satisfies the following equation:

$$\lambda = 4n_1d_1 \quad (3)$$

where n_1 and d_1 are the refractive index and thickness of the single-layer ARC material, respectively.

Assuming perfect antireflection and light trapping, the absorption spectrum in a thin film with thickness d_2 and refractive index n_2 is given by the Yablonovitch limit:

$$A_{\text{Yablonovitch}} = 1 - \frac{1}{1 + 4n_2^2\alpha d_2} \quad (4)$$

To find out the optimal planar structure, we firstly studied the effect of the thickness of back Ag electrode on the planar ultrathin c-Si solar cell (shown as Fig. 1(a)). When the thickness of back Ag electrode reaches 100 nm, the transmission no longer decreases any more. The calculated result suggests that the 100 nm Ag film is optimal, which is in agreement with the previous experiments [31]. Hence, the 20 μm c-Si absorber and 100 nm Ag back electrode are selected in the following work.

Besides investigating light trapping of surface texture, the Quokka software (Version: Quokka 2.2.5) [21] is used to simulate the J-V response and calculate the PV parameters of the cells. All input parameters for the present simulation are listed in Table S1 of the supplementary information.

3. Results and discussion

In order to improve the absorption efficiency (the ratio of the light absorbed by the active layer to the total sunlight) in ultrathin c-Si solar cells, it is essential to study the distribution of incident light through the cell. As shown in Fig. 2, 35% of incident light is reflected by the front surface of the cell and 15% escapes from the cell. Simultaneously, the active layer only absorbs 49% of the incident light effectively utilized to excite carriers, and about 1% of incident light is absorbed by the back Ag layer. Therefore, it is very necessary to reduce the reflection of incident light, suppress the light escape and improve the optical absorption of the active layer through structural design and optical management.

Firstly, we added an ARC layer on the front surface to reduce the surface reflectivity of solar cells. Here, some common ARC materials including Si_3N_4 , SiO_2 , Al_2O_3 , SiN_x are compared [32–37]. Among all the calculated ARC materials, Si_3N_4 shows the most superior antireflection and it can effectively reduce the reflection efficiency to below 10% when its thickness reaches 80 nm. Therefore, in the following simulations, we chose the 80 nm Si_3N_4 film as the ARC layer of ultrathin c-Si cells. Based on the above calculations, an optimal planar structure of ultrathin c-Si cell is obtained, which will be used as a reference cell to investigate the optical absorption enhancement of other cells with pyramidal texture.

Based on the planar reference cell, we added pyramid texture to the front surface (shown as Fig. 1(b)) to increase the light path length in the cells. Recent experiments found that compared to the micropyramid texture, the nanopyramid textured wafer has a little higher reflectance

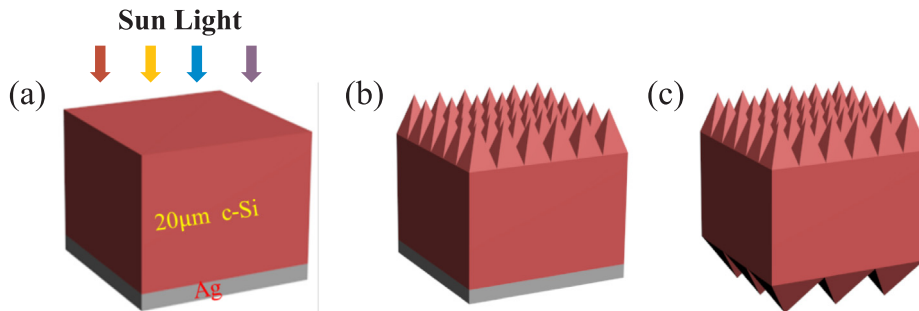


Fig. 1. 3D models of planar ultrathin c-Si solar cell (a), cell with front pyramids texture (b) and cell with double-sided pyramids texture (c).

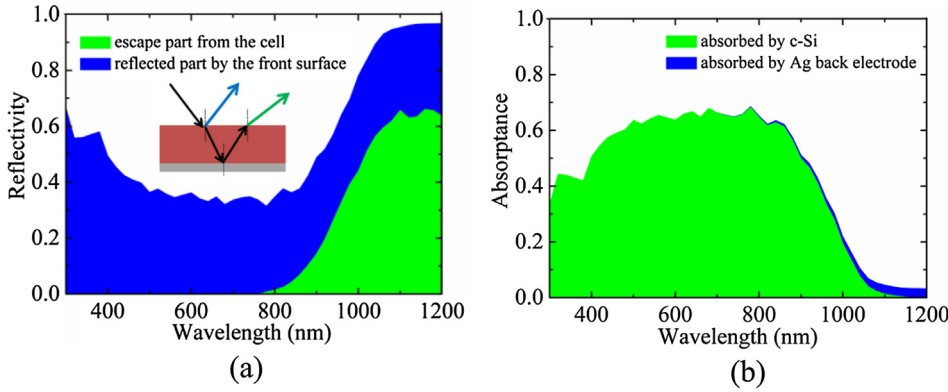


Fig. 2. (a) The reflectivity of planar solar cell; (b) The absorbance of c-Si layer and Ag back electrode of planar solar cell. In (a), the blue area represents the reflected light on the front surface of the cell (just as the blue line of the inset), and the green area represents the escape part of light in the cell (just as the green line of the inset). In (b), the blue and green portions represent the absorbance of light in the Ag back electrode and the planar c-Si layer, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

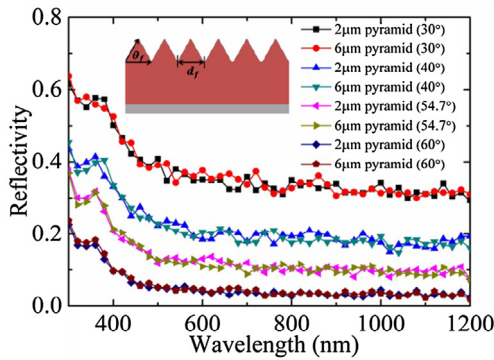


Fig. 3. Reflectivity spectra of ultrathin c-Si cells with different textures. The inset indicates the cross-sectional structure of front-textured ultrathin c-Si solar cell.

due to its much smoother surface [38]. In addition, since the technique to fabricate micropyramid textured surface is more mature in practical applications, the micropyramid texture was employed in the present work. The reflectivity spectrum of front textured c-Si cell was calculated by sweeping characteristic angle θ_f and size d_f of front pyramids. Fig. 3 presents the reflectivity spectra (300–1200 nm) of the cells with various front pyramids textures.

From Fig. 3, it can be seen that at a fixed angle of pyramid, the reflectivity spectra are almost the same for different bottom lengths. The result indicates that the bottom length of pyramid has no remarkable influence on the reflectivity of cells when the characteristic angle of pyramid is fixed, which is consistent with the previous reports [39]. When the length of bottom edge of pyramid is fixed, with the increase of pyramid characteristic angle, the reflectivity decreases obviously in the whole wavelength range of 300–1200 nm. It is concluded that the reflectivity of the front surface of ultrathin c-Si solar cells depends greatly on the pyramid angle rather than the bottom length. Here, we chose the pyramid with characteristic angle 54.7° commonly used in experiments in the following calculations [40,41].

In Fig. 4, one can see that based on the optimized scale of pyramid, the reflectivity of the cells with front texture is reduced to 1% and it almost becomes zero in the wavelength range of 500–800 nm. However, although the remaining 81% is absorbed by the c-Si layer, there is still 14% of the sunlight escaping from the cell. The light trapping in these structures suffers from the first-pass light incident to the rear surface being reflected into the escape cone of a front pyramid and coupled out [42]. Experimentally, in order to further suppress the escape of light, a doubled-sided pyramid texture on the front and rear of ultrathin c-Si solar cells has been attempted in tradition silicon solar cells and it has been observed that the double-sided architecture helps to randomize the direction of light within the cell thereby reducing the chance of escape [43].

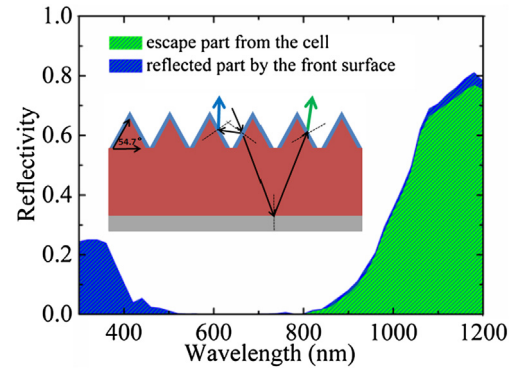


Fig. 4. The reflectivity spectrum of the solar cell in the wavelength range of 300–1200 nm. The blue area represents the reflectivity of light on the front surface, and the green area represents the escape part of light in the cell. The inset is the cross-sectional schematic of front-textured ultrathin c-Si solar cell with Si_3N_4 ARC film. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To give a deeper understanding of double-sided texture of ultrathin c-Si solar cells, we constructed pyramid texture on the back of the cell (shown as Fig. 1(c)). Here, the front optimized pyramid with 2 μm bottom and 54.7° angle was fixed, and the absorption efficiency of ultrathin c-Si solar cell was calculated by sweeping the characteristic angle θ_r (from 25 to 70°) and the size of the bottom length d_r (from 2 to 6 μm) of rear pyramids. Moreover, to make clear the difference of upright and inverted texture, four double-sided texture cells with equivalent Si thickness of 20 μm were investigated. The four cell structures (shown as the insets in Fig. 5) includes: (a) the cell with upright pyramids on front surface and inverted pyramids on the rear surface (cell 1), (b) the cell with inverted pyramids on the front surface and inverted pyramids on the rear surface (cell 2), (c) the cell with upright pyramids on the front surface and upright pyramids on the rear surface (cell 3), (d) the cell with inverted pyramids on the front surface and upright pyramids on the rear surface (cell 4). Fig. 5 shows the calculated mapping of the light absorption efficiency as functions of the characteristic angle and bottom length of the pyramids for the four kinds of cells.

In Fig. 5, it can be seen that the achieved maximum absorption efficiencies are 86.18% (cell 1 with rear pyramid of characteristic angle 35° and bottom length 6 μm), 86.03% (cell 2 with rear pyramid of characteristic angle 35° and bottom length 6 μm), 86.64% (cell 3 with rear pyramid of characteristic angle 35° and bottom length 4 μm) and 86.42% (cell 4 with rear pyramid of characteristic angle 25° and bottom length 4 μm), respectively. Among all the four structures, cell 3 has the maximum absorption efficiency 86.64%, and which is 6% higher than that of the cell with front pyramids, and 17% higher than that of the planar cell. In the four cases, all the cells show a relatively high absorption zone in the characteristic angle range of 25 to 40°. Especially,

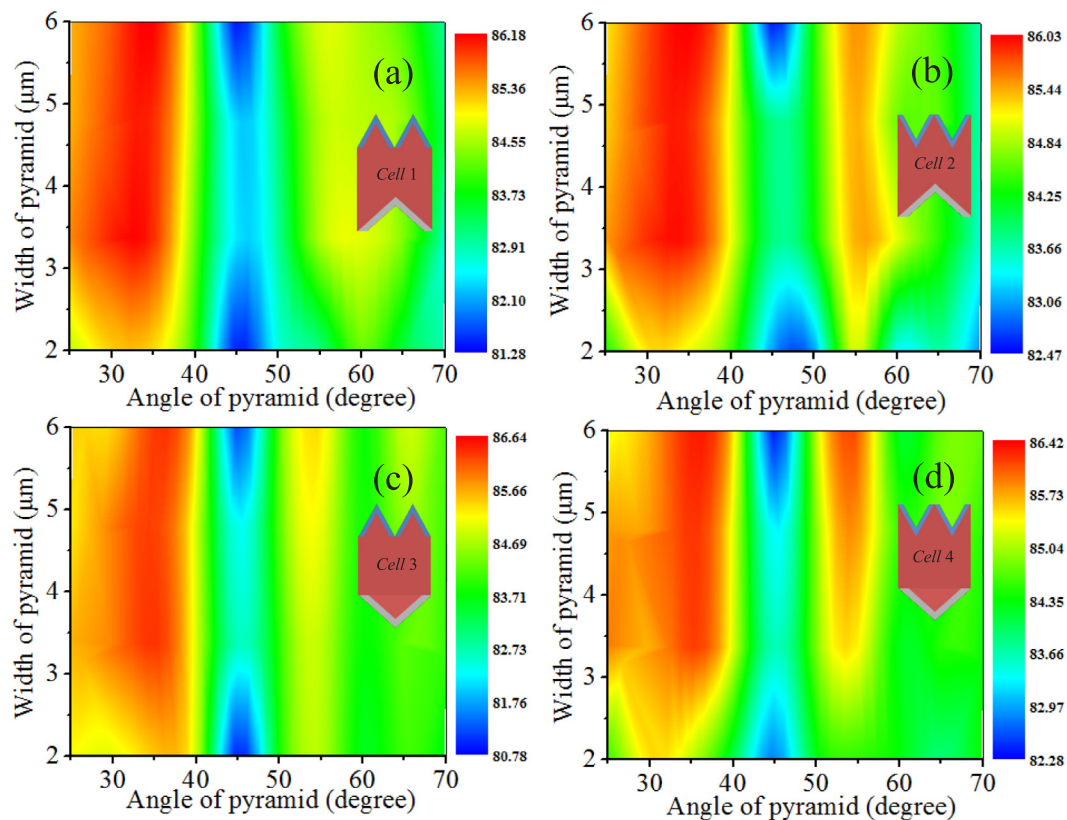


Fig. 5. The plotted mapping of the absorption efficiency as functions of the characteristic angle and the length of the bottom side of pyramid. The insets are the cross-sectional schematic of ultrathin c-Si solar cells with double-sided pyramids texture.

it was also found that a lower absorption area appears at the characteristic angle at $45^\circ \pm 2.5^\circ$. The possible reason is the total internal reflection occurring at this angle on the back Ag layer, which suggests that 45° rear pyramids hardly has a significant impact on the light escape. Thus, the rear pyramids of angle 45° should be avoided in the fabrication of c-Si solar cells.

According to the optimal light trapping structure, the electrical performance of cells also was investigated by Quokka software. In Fig. 6(a), one can see that compared with the reference planar cell, the cell with front pyramids significantly increase the light absorption, but it has not reached the Yablonovitch limit yet. Experimentally, it is a common issue that c-Si cells have a weaker light absorption in the longer wavelength range. Compared with only front texture, the double-sided light trapping structure designed in this work substantially enhances the light absorption in the range of 850–1200 nm,

which closes to the Yablonovitch limit [16–18]. By analyzing the reflectivity spectra of cells, it was found that the absorption enhancement mainly originates from the rear pyramid texture suppressing light escaping from cells. However, it also should be recognized that the cell with double-sided texture shows a lower light absorption in short wavelength range (300–500 nm) than the Yablonovitch limit, which should be associated with the designed double-sided pyramids structure with relatively low aspect ratio. However, much larger surface area, more defects were introduced. Thus, with the increase of pyramid characteristic angle, significantly higher surface recombination results in poor performance of solar cells, so we chose the characteristic angle 54.7° and 35° with lower surface recombination [44]. In fact, the light trapping structure with low aspect ratio involving surface recombination and degradation of electronic properties should be less severe than those of other high aspect ratio structures [16]. That is to say, the

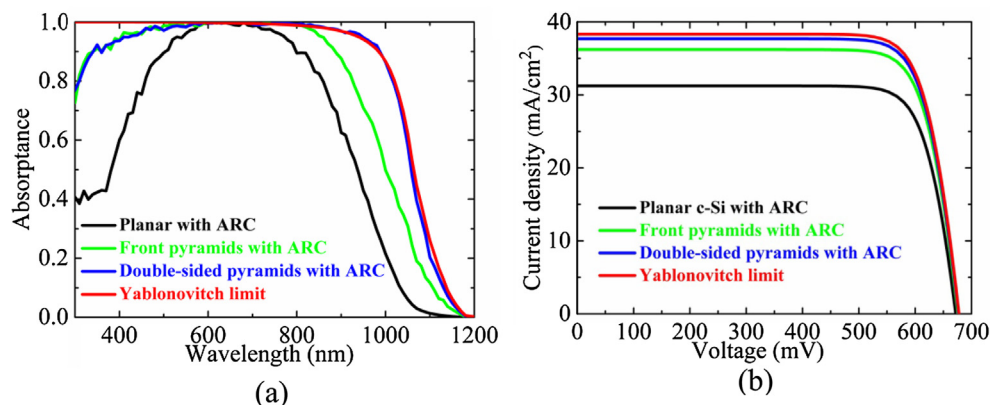


Fig. 6. Comparison of the absorption spectra (a) and J-V responses (b) for three cells.

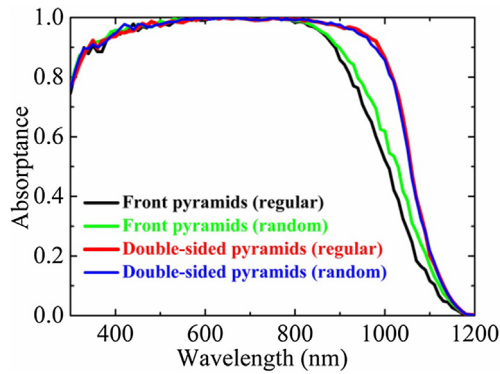


Fig. 7. Absorption spectra generated by structures as a function of wavelength.

present light trapping structure with low aspect ratio is more practical for c-Si solar cells.

In Fig. 6(b), the achieved maximum short circuit current densities are 36.23 mA/cm^2 and 37.71 mA/cm^2 for the cell with front pyramid texture and double-sided pyramid texture, which are 15.97% and 20.71% higher than that of the planar reference cell, respectively. Correspondingly, the conversion efficiencies of the planar reference cell, the cell with front pyramids and the cell with double-sided pyramids are 16.94%, 19.65% and 20.45%, respectively. It is concluded that double-sided surface texture is an optimal strategy to enhance short circuit current densities and conversion efficiency.

In practical applications, common industrial alkaline etching method easily produce fully randomized surface texture, while most of designed light trapping structures are in periodic mode [15–17]. To explore the difference between random and periodic mode, we calculated the light absorption spectra of both surface texture modes. As can be seen from the Fig. 7, for the front pyramid structure, the random mode exhibits a better light absorption in long wavelength range (900–1100 nm) compared with the periodic mode. However, the absorption of periodic double-sided texture is almost the same as that of random texture. The results indicate that the double-sided pyramid texture not only improves the optical absorption of long wavelength range, but also overcomes the influence of randomness on the structure absorption.

Fig. 8(a) shows that the relation between the photocurrent density of cells and the size of the bottom of the front and rear pyramids. Here, the pyramid characteristic angle in the double-sided textured structure is fixed. It can be seen that as the size of the bottom length of the pyramid changes from micron to nanometer, the photocurrent density of the cell increases up to the maximum value and then decreases. When the bottom length of the pyramid is $1 \mu\text{m}$, the height of the front

pyramid is 700 nm and the height of the rear pyramid is 350 nm, and the photocurrent density of the cell reaches an optimal value of 41.5 mA/cm^2 . Fig. 8 (b) shows the absorption spectra of the double-sided pyramidal cell when the bottom lengths of pyramid are $0.5 \mu\text{m}$, $1 \mu\text{m}$ and $1.5 \mu\text{m}$, respectively. From Fig. 8 (b), we can see that with the reduction of pyramid size, the absorption efficiency in short wavelength range gradually increases. The cell with the bottom length $1 \mu\text{m}$ of the pyramid shows better absorbance in the longer wavelength range than other two cases.

The angle dependence of the incident light is another important issue in the practical applications of solar cells, and installing sun-tracking component is a common way to produce maximum daily power throughput. Therefore, the angle-dependent absorption, reflection and escape efficiency of the three kinds of cells are compared in Fig. 9. It can be seen that the absorption efficiency of ultrathin c-Si cells with front pyramids and double-sided pyramids show a lower dependence on the incident angle relative to the planar reference cell, and the double-sided architecture has more excellent performance in the absorption of solar light. The cells with front and double-sided pyramids show weakly angle-dependent reflection efficiency than the planar cell does. Also, it is interesting that a weakly angle-dependent escape efficiency of the cell with double-sided texture can be observed in Fig. 9(c). The results show that the double-sided pyramidal structure provides a more effective method to reduce the escape efficiency and then improve the angle dependence for ultrathin c-Si cells.

As can be seen from Fig. 10, when the angle of incident light changes from 0° to 80° , the absorbance of planar structure cell decreases significantly at 400–1100 nm, which fully shows that the planar structure is highly angle-dependent. For the front-pyramidal cell, the angle dependence of the absorption spectra is remarkable in the wavelength range of 300–950 nm. However, when the wavelength is longer than 950 nm, the light absorption at the incident angle 80° is superior to that at zero incident angle. For the double-sided pyramidal cell, it has obvious advantages over the front-pyramidal cell in the long wavelength range. When the incident light angle is 80° , the absorbance of the double-sided pyramidal cell at 950–1200 nm is higher than that of the front-pyramidal cell. However, only from the perspective of angle dependence, the light absorption of double-sided cell at incident angle 0° in the range of 300–1200 nm is always superior to that at 80° , which suggests that the double-sided pyramidal cell exhibit the larger angular loss in long wavelength range than the front-pyramidal cell. The result is accordance with the difference on absorption efficiency at larger incident angles between front-pyramidal and double-sided pyramidal cell (shown as Fig. 9(a)).

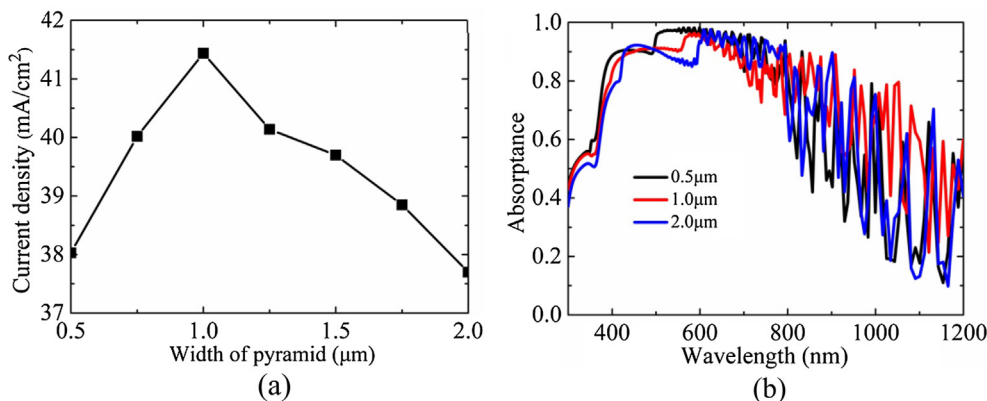


Fig. 8. (a) The photocurrent density as a function of the bottom length of pyramid; (b) The absorption spectra of the double-sided pyramidal cell when the bottom length of pyramid is $0.5 \mu\text{m}$, $1 \mu\text{m}$ and $1.5 \mu\text{m}$, respectively.

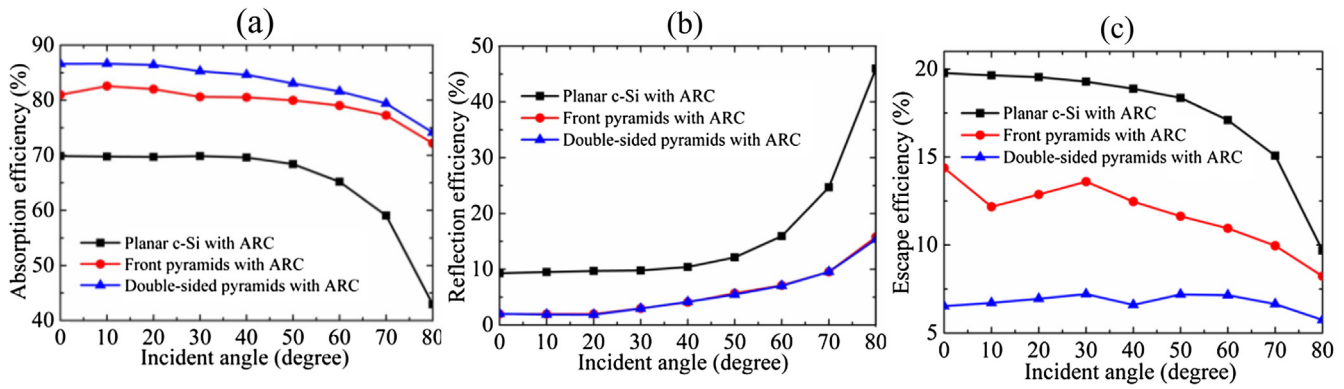


Fig. 9. The absorption efficiency (a), reflection efficiency (b) and escape efficiency (c) of the three kinds of solar cells as a function of the angle of incidence in the range of 0–80°.

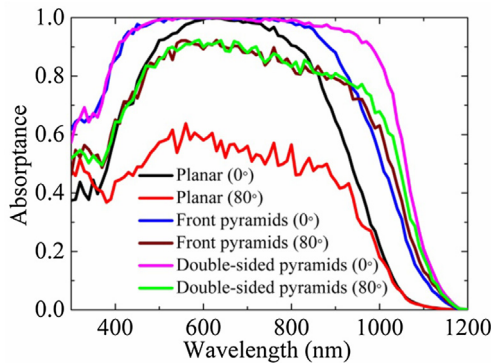


Fig. 10. Absorption spectra of planar, front-pyramidal and double-sided pyramidal cell with incident light angles of 0° and 80°.

4. Conclusions

In summary, in order to achieve enhanced photocurrent density and conversion efficiency of ultrathin c-Si solar cells, we designed the double-sided pyramids texture for ultrathin c-Si cells. Through the simulations and optimizations, it is found that the maximum photocurrent densities 37.71 mA/cm² and conversion efficiency 20.45% are achieved for the cell with the upright pyramids (characteristic angle 54.7° and bottom length 2 μm) on the front surface and upright pyramids (characteristic angle 35° and bottom length 4 μm) on the rear surface. The double-sided pyramids texture exhibits better light absorption comparable to the fully-randomized pyramids texture. Moreover, the absorption and reflection efficiency of ultrathin c-Si cells with double-sided pyramids show a less dependence on the incident angle of light. The cell with the bottom length of the pyramid 1 μm shows better light absorbance. This architecture has more excellent performance in reducing the light escape in longer wavelength range, leading to its light absorption approaching the Yablonovitch limit.

The designed double-sided pyramid texture in this work provides a realistic strategy in conversion efficiency improvement and cost reduction for ultrathin c-Si solar cells.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.optlastec.2019.105700>.

References

- [1] W. Zhu, F. Xiao, I.D. Rukhlenko, J. Geng, X. Liang, M. Premaratne, R. Jin, Wideband visible-light absorption in an ultrathin silicon nanostructure, *Opt. Express*. 25 (5) (2017) 5781–5786.
- [2] L. Wang, A. Lochtefeld, J. Han, A.P. Gerger, M. Carroll, J. Ji, A. Lennon, H. Li, R. Opila, A. Barnett, Development of a 16.8% efficient 18-μm silicon solar cell on steel, *IEEE J. Photovoltaics* 4 (2014) 1397–1404.
- [3] I. Kim, D.S. Jeong, W.S. Lee, W.M. Kim, T.S. Lee, D.K. Lee, J.H. Song, J.K. Kim, K.S. Lee, Silicon nanodisk array design for effective light trapping in ultrathin c-Si, *Opt. Exp.* 22 (S6 Suppl 6) (2014) A1431–A1439.
- [4] M. Lee, J. Ahn, T.H. Yim, Effects of electroformed Fe-Ni substrate textures on light-trapping in thin film solar cells, *Int. J. Electrochem. Sci.* 13 (2018) 5612.
- [5] G. Hashmi, A.R. Akand, M. Hoq, H. Rahman, Study of the enhancement of the efficiency of the monocrystalline silicon solar cell by optimizing effective parameters using PC1D simulation, *Silicon* 10 (2018) 1653.
- [6] T. Xu, Z. Tian, O.I. Elmi, C. Krzeminski, O. Robbe, Y. Lambert, D. Yakeda, E. Okada, B. Wei, D. Stievenard, Optical and electrical properties of nanostructured implanted silicon n + -p junction passivated by atomic layer deposited Al₂O₃, *Phys. E* 93 (2017) 190–195.
- [7] A. Khanna, P.K. Basu, A. Filipovic, V. Shanmugam, C. Schmiga, A.G. Aberle, T. Mueller, Influence of random pyramid surface texture on silver screen-printed contact formation for monocrystalline silicon wafer solar cells, *Sol. Energy Mater. Sol. Cells*. 132 (2015) 589–596.
- [8] P.K. Basu, A. Khanna, Z. Hameiri, The effect of front pyramid heights on the efficiency of homogeneously textured inline-diffused screen-printed monocrystalline silicon wafer solar cells, *Renew. Energy*. 78 (2015) 590–598.
- [9] O. Höhn, N. Tucher, B. Bläsi, Theoretical study of pyramid sizes and scattering effects in silicon photovoltaic module stacks, *Opt. Express*. 26 (2018) A320–A330.
- [10] J. Zhao, A. Wang, P. Campbell, M.A. Green, A 19.8% efficient honeycomb multi-crystalline silicon solar cell with improved light trapping, *Electron Devices* 46 (10) (1999) 1978–1983.
- [11] J. Zhao, Passivated emitter rear locally diffused solar cells, *Bull. Adv. Technol. Res.* 41–43 (2011).
- [12] E. Franklin, K. Fong, K. McIntosh, A. Fell, A. Blakers, T. Kho, D. Walter, D. Wang, N. Zin, M. Stocks, E.C. Wang, N. Grant, Y. Wan, Y. Yang, X. Zhang, Z. Feng, P.J. Verlinden, Design, fabrication and characterisation of a 24.4% efficient interdigitated back contact solar cell, *Prog. Photovolt. Res. Appl.* 24 (2014) 411.
- [13] B. Dou, R. Jia, Y. Sun, H. Li, C. Chen, Z. Jin, X. Liu, Surface passivation of nano-textured silicon solar cells by atomic layer deposited Al₂O₃ films, *J. Appl. Phys.* 114 (2013) 174301.
- [14] D. Wang, H. Cui, G. Hou, Z. Zhu, Q. Yan, G. Su, Highly efficient light management for perovskite solar cells, *Sci. Rep.* 6 (2016) 18922–18932.
- [15] M.A. Alshal, N.K. Allam, Broadband absorption enhancement in thin film solar cells using asymmetric double-sided pyramid gratings, *J. Electron. Mater.* 45 (2016) 5685.
- [16] K.X. Wang, Z. Yu, V. Liu, Y. Cui, S. Fan, Absorption enhancement in ultrathin crystalline silicon solar cells with antireflection and light-trapping nanocone gratings, *Nano Lett.* 12 (2012) 1616.
- [17] H. Ma, B. Wu, J. Zhou, H. Huang, X. Xu, C. Wang, Efficiency enhancement in ultrathin crystalline silicon solar cells with composite surface gratings, *Opt. Commun.* 393 (2017) 207–212.
- [18] N. Zin, K. McIntosh, S. Bakhshi, A. Vázquez-Guardado, T. Kho, K. Fong, M. Stocks, E. Franklin, A. Blakers, Polyimide for silicon solar cells with double-sided textured pyramids, *Sol. Energy Mater. Sol. Cells*. 183 (2018) 200–204.
- [19] W.C. Hsu, J.K. Tong, M.S. Branham, Y. Huang, S. Yerci, S.V. Boriskina, G. Chen,

- Mismatched front and back gratings for optimum light trapping in ultra-thin crystalline silicon solar cells, *Opt. Commun.* 377 (2016) 52–58.
- [20] X. Tan, W. Yan, Y. Tu, C. Deng, Small pyramidal textured ultrathin crystalline silicon solar cells with double-layer passivation, *Opt. Express* 25 (2017) 13.
- [21] Free access of the software at < <https://www2.pvlighthouse.com.au/resources/quokka2/quokka%202.aspx> > .
- [22] M.A. Green, Lambertian light trapping in textured solar cells and light-emitting diodes: analytical solutions, *Prog. Photovolt: Res. Appl.* 10 (2002) 235–241.
- [23] E. Palik, *Handbook of Optical Constants of Solids* vol. I, (1985) 759.
- [24] K.R. McIntosh, T.C. Kho, K. Fong, S. Baker-Finch, Y. Wan, S. Zin, E.T. Franklin, D. Wang, M.D. Abbott, N.E. Grant, Quantifying the optical losses in back-contact solar cells, 40th IEEE Photovoltaic Specialists Conference, Denver, 2014, pp. 115–123.
- [25] P. Kumar, M. Wiedmann, C. Winter, I. Avrutsky, Optical properties of Al₂O₃ thin films grown by atomic layer deposition, *Appl. Opt.* 48 (28) (2009) 5407–5412.
- [26] S. Baker-Finch, K.R. McIntosh, Reflection of normally incident light from silicon solar cells with pyramidal texture, *Prog. Photovoltaics Res. Appl.* 19 (4) (2011) 406–416.
- [27] M. Green, Self-consistent optical parameters of intrinsic silicon at 300K including temperature coefficients, *Sol. Energy Mater. Sol. Cells* 92 (2008) 1305–1310.
- [28] Y. Jiang, S. Pillai, M. Green, Realistic silver optical constants for plasmonics, *Sci. Rep.* 6 (2016) 30605.
- [29] T. Tiedje, E. Yablonovitch, G.D. Cody, B.G. Brooks, Limiting efficiency of silicon solar cells, *IEEE Trans. Electron Devices* 31 (1984) 711–716.
- [30] ASTM < <http://rredc.nrel.gov/solar/spectra/am1.5/> > .
- [31] N. Song, U. Römer, A. Gentle, S. Lim, Z. Li, P.C. Hsiao, B. Gong, X. Zhang, P. Verlinden, A. Lennon, Metallization method for interdigitated back-contact silicon solar cells employing an insulating resin layer and a Ti/Ag/Cu metal stack, *IEEE J. Photovoltaics* 2156 (2018).
- [32] G.K. Chang, Antireflection layer coatings on the Si solar cell using SiO₂ and Si₃N₄, materials science forum, *Mater. Sci. Forum* 449 (2004) 1013–1016.
- [33] K. Islam, A. Alnuaimi, H. Ally, A. Nayfeh, ITO, Si₃N₄ and ZnO: Al – simulation of different anti-reflection coatings (ARC) for thin film a-Si: H solar cells, modelling symposium, *Model. Sympos.* 673–676 (2014).
- [34] M.M. Tavakoli, K.H. Tsui, Q. Zhang, J. He, Y. Yao, D. Li, Z. Fan, Highly efficient flexible perovskite solar cell with anti-reflection and self-cleaning nanostructures, *ACS Nano* 9 (2015) 10287–10295.
- [35] E.C. Cho, J. Xia, A.G. Aberle, M.A. Green, Antireflection and surface passivation behaviour of SiO₂ quantum wells on silicon, *Sol. Energy Mater. Sol. Cells* 74 (1) (2002) 147–154.
- [36] C. Xue, Y. Gu, M. Deng, Investigation on antireflection coatings for silicon solar cells, *Appl. Mech. Mater.* 521 (2014) 33–36.
- [37] S. Chhajed, M.F. Schubert, J.K. Kim, E.F. Schubert, Nanostructured multilayer graded-index antireflection coating for Si solar cells with broadband and omnidirectional characteristics, *Appl. Phys. Lett.* 93 (2008) 251108.
- [38] M. Ju, K. Mallem, S. Dutta, N. Balaji, D. Oh, E.C. Cho, Y.H. Cho, Y. Kim, J. Yi, Influence of small size pyramid texturing on contact shading loss and performance analysis of Ag-screen printed mono crystalline silicon solar cells, *Mater. Sci. Semicond. Process.* 85 (2018) 68–75.
- [39] S. Zhong, W. Wang, Y. Zhuang, Z. Huang, W. Shen, All-solution-processed random Si nanopillars for excellent light trapping in ultrathin solar cells, *Adv. Funct. Mater.* 26 (2016) 4768.
- [40] Q. Tang, H. Shen, H. Yao, K. Gao, Y. Jiang, C. Zheng, W. Yang, Y. Li, Y. Liu, L. Zhang, Potential of quasi-inverted pyramid with both efficient light trapping and sufficient wettability for ultrathin c-Si/PEDOT:PSS hybrid solar cells, *Sol. Energy Mater. Sol. Cells* 169 (2017) 226–235.
- [41] Y. Jiang, H. Shen, T. Pu, C. Zheng, Q. Tang, K. Gao, J. Wu, C. Rui, Y. Li, Y. Liu, High efficiency multi-crystalline silicon solar cell with inverted pyramid nanostructure, *Sol. Energy* 142 (2017) 91–96.
- [42] P. Campbell, M. Green, Light trapping properties of pyramidally textured surfaces, *J. Appl. Phys.* 62 (1987) 243.
- [43] K.R. McIntosh, N. Zin, H.T. Nguyen, M. Stocks, E. Franklin, K.C. Fong, T.C. Kho, T.K. Chong, E.C. Wang, T. Ratcliff, D. Macdonald, A.W. Blakers, Optical evaluation of silicon wafers with rounded rear pyramids, *IEEE J. Photovolt.* 7 (6) (2017) 1596–1602.
- [44] Keith R. McIntosh, Luke P. Johnson, Recombination at textured silicon surfaces passivated with silicon dioxide, *J. Appl. Phys.* 105 (2009) 124520.