Enhanced Light Absorptions of Pyramid Square Grating Structure for Crystalline Silicon Solar Cells

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Abstract: A special structure of pyramid square grating (PSG) is designed to reduce the light reflection of crystalline silicon solar cells. Reflectance and optical absorptions which are calculated by Finite Difference Time Domain (FDTD) methods suggested that the PSG structures had highly efficient anti-reflection effects from 300 to 400 nm. Moreover, the photocurrent density of PSG calculated in the wavelength range of 300-1000 nm has been improved by 45.09 % compared to that of planar structure, under the air mass 1.5 (AM1.5) solar illuminations.

1. Introduction
The crystalline silicon solar cells are still predominant in the commercial solar cells although many other cells including organic solar cells [1–3], thin film solar cells [4] and nanowire-based cells[5] have been developed. But the high cost of crystalline silicon solar cells is the main barrier for the further development. In order to cut the cost, numerous works have been done to improve the performance of silicon-based solar cells. Various technologies have been developed to improve the performance of solar cells [6,7]. Significantly enhancing the optical absorption is an effective approach of cutting the cost of single crystalline solar cells. The methods of improving optical absorption generally include light trapping and anti-reflection effects. Anti-reflection effects can be achieved by textured surface [8] and hybrid nanostructure [9].New methods for light trapping in solar cells are to use the metallic nanoparticles to enhance the absorption of the cells due to the coupling of surface plasmon and the light [10]. Moreover, Bragg mirrors of porous silicon were used as the back reflector for light trapping [11]. However, these methods of improving the absorption are not only expensive but also complex for mass production except for texturing the surface of cells. Moreover, improving the absorption of solar cells in broader wavelength range is important for the enhancement their performance.

In this present work, a novel structure of pyramid square grating (PSG) was proposed. The optical properties of PSG structures were calculated by Finite Difference Time Domain (FDTD) methods. The PSG structures have a low reflectance and strong absorptions in the wavelength range of 300 to 1000 nm.

2. Calculation Modes
Figure. 1 shows the simulated PSG structure model where \( \Lambda \) and \( d \) are the period and the width of silicon pillars, respectively. The period \( \Lambda \) varies from 1.0 \( \mu \text{m} \) to 2.0 \( \mu \text{m} \). The silicon pillar width \( d \) varies from 0.5 to 1 \( \mu \text{m} \). In order to obtain the enhanced anti-reflection effects of PSG, we calculated the optical properties of PSG structures with different periods by the finite difference on time domain (FDTD) methods, using a freely available software package [12].The calculated PSG structure is schematically shown in fig. 1. Both the silicon thickness and the depth of grating are 10 \( \mu \text{m} \).
Figure 1. Schematic diagram of PSG structure (a), top-view SEM image of the pyramid groove array (b), top-view (c) and side-view (d) SEM images of a pyramid groove.

3. Results and Analyses

Figure 2 (a) shows the reflectance of the PSG structure as a function of wavelength when \( \Lambda = 1000 \) nm and \( d = 500 \) nm (solid line). For the square grating, the reflectance is larger than 40% in the wavelength range of 300 to 600 nm, but decreases sharply from 600 to 1000 nm. The low reflectance in the wavelength range of 600 to 1000 nm is due to the fact that the silicon pillars with the width of 500 nm act as the effective scattering centers coupling with the light [13]. Compared to the reflectance of square grating, the reflectance of the PSG is lower than that of square grating structures in the wavelength range of 300 to 1000 nm. Especially, in the wavelength range of 600 to 1000 nm, the reflectance of the PSG is smaller than 0.05. Furthermore, compared to the reflectance of commercial solar cells, as shown in fig. 2 (a), it is interesting to note that the PSG structures have a lower reflectance in the wavelength range of 300 to 400 nm, clearly suggesting the PSG has enhanced anti-reflection effects. The reasons for the low reflectance of PSGs can be clearly illustrated further by the electric field intensity. As shown in fig. 2 (b), the electric field intensity distributions in the PSG and square grating at the wavelength of 903 nm and 420 nm. From fig. 2 (b), it is also observed that the light is significantly focused and intensely scattered by PSG structures, which ultimately leads to the enhancement of absorptions.

Figure 2. (a) the reflectance of PSG (red solid line) and square grating (blue dot-dash line) from 300 nm to 1000 nm and a traditional crystalline silicon solar cell with SiNx ARC [15] (black dash line) and (b) Calculated electric field intensity distributions at 903 nm and 420 nm for PSG and square grating.
Figure 3. (a) and (b) show the absorptance of PSG structures with different period and silicon pillar width, respectively. The absorptance in the wavelength range of 300 to 1000 nm is enhanced slightly by increasing the period of PSG. Because the increase of the PSG period results in the higher-order diffraction modes which is obtained by the following grating diffraction equation

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 = \frac{m \lambda}{a} \]  

where \( n_1 \) and \( n_2 \) are the refractive index of air and silicon, respectively, \( m \) is the diffracted order, \( \theta_1 \) and \( \theta_2 \) are the angles of propagation in air and silicon, \( \lambda \) is the wavelength and \( a \) is the grating period. The light, hence, couples to the diffraction orders propagating outside the escape cone of Si [19], which results in the strong light absorption. In addition, decreasing the width of silicon pillars enhances the absorption of PSG, as shown in fig. 5 (b). The absorptance of PSG with the silicon pillar width of 500 nm is higher than that of square grating with the silicon pillar width of 1000 nm. Since the light strongly interact with the silicon pillars in the subwavelength scale.

Figure 4. the absorptance of PSG structures with different period \( \Lambda \) (a) and different silicon pillar width \( d \) (b)

To gain insight into the effects of the enhanced anti-reflection effects and light trapping on the performance of solar cells based on the PSG, the photocurrent density in this structure has been calculated. Assuming that all the photo-generated electron-hole pair contributes to the photocurrent. So, the photocurrent density \( J_{ph} \) can be given by

\[ J_{ph} = e \int A(\lambda)AM1.5(\lambda)d\lambda \]  

Where \( e \) is the charge on an electron, \( A(\lambda) \) is the absorption spectrum obtained by FDTD simulation and the AM1.5 (\( \lambda \)) is the standard AM1.5G spectrum. Table I lists the photocurrent density of different
light-trapping structure. By fabricating square grating, the photocurrent density is raised by 4.21 mA/cm². As expected, the photocurrent density of the PSG increases as the period increases from 1000 to 2000 nm. The photocurrent density (34.46 mA/cm²) of the PSG with the period of 2000 nm increases by 45.09 % and by 23.24% compared to the planar structure and the square grating structure, respectively.

Table I. the short circuit current density Jph generated by different structures

| Light trapping structure | Parameters | Jph (mA cm⁻²) |
|-------------------------|------------|--------------|
|                         | a (nm)     | b (nm)       |
| Planar                  | N.A        | N.A          | 23.75        |
| Square grating          | 1000       | 500          | 27.96        |
| PSG                     | 1000       | 500          | 33.86        |
|                         | 2000       | 500          | 34.46        |

4. Conclusion
In summary, the PSG structures have significantly enhanced anti-reflection effects in the wavelength range of 300 to 400 nm. FDTD calculation results indicate that photocurrent density generated in the PSG solar cells is as high as 34.46 mA/cm² which is 90% of the ideal photocurrent density generated by AM1.5 solar illumination in the wavelength range of 300 to 1000 nm.

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6. References
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