Postprint: Spectral Characteristics of Broadband Anti-Reflection Surfaces for Solar Cells

Authors: Zhang Yutao, Xuan Yimin

Date: 2017-11-07T00:00:00+00:00

Abstract

This study employs the finite-difference time-domain (FDTD) method to calculate the spectral characteristics of three different gradient-index anti-reflection surfaces for monocrystalline silicon solar cells, and compares the anti-reflection performance of these surfaces. The influence of structural parameters on the anti-reflection characteristics of the structured surfaces is discussed. The research findings demonstrate that monocrystalline silicon solar cells with moth-eye structures exhibit the lowest reflectance across the entire solar radiation spectrum. As the microstructure height increases and the period decreases, the gradient of the effective refractive index becomes more gradual, resulting in more pronounced anti-reflection effects.

Full Text

Spectral Features of Broadband Anti-Reflection Structured Surface for Si Solar Cell

ZHANG Yu-Tao[1], XUAN Yi-Min[1,2] [1] School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing, 210094, China [2] School of Energy and Power, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China

Abstract: This paper calculates the spectral features of three different structured surfaces with graded refractive index for the anti-reflection of Si solar cell with FDTD method. The spectral features of three structured surface are compared. The effects of the structural parameters on the spectral reflection are discussed. It is found that the reflection of moth-eye structured surface is lowest in the full solar spectrum among three structured surfaces. With the increase of height and reduce of period of micro-structure, the gradient of the effective refractive index in z-direction is reduced and the reflection is suppressed more effectively.

Key words: broadband anti-reflection; graded refractive index; solar cell

Funding: Key Project of National Natural Science Foundation of China (No. 51336003), Jiangsu 333 Research Project (No. BRA2011134)

As the global energy crisis intensifies, the development and utilization of new energy sources represent an inevitable trend for humanity to address energy challenges. Solar energy has become one of the primary directions for new energy development due to its inexhaustible and pollution-free nature. Currently, solar energy utilization primarily includes solar cells, thermophotovoltaics, photochemical catalysis, and other energy conversion devices [1-3]. Since the advent of the first silicon solar cell in the 1950s, research and development of solar cells have flourished [4]. In recent years, with extensive attention from researchers, solar cell technology has advanced rapidly. On one hand, the efficiency of silicon cells continues to improve; on the other hand, diverse solar cell types have emerged, with semiconductor materials such as monocrystalline silicon, amorphous silicon, GaAs, CdTe, and InP being applied in solar cell research [4]. At present, the primary challenges affecting solar cell development and application are efficiency and cost. Research on thin-film solar cells plays a crucial role in reducing costs.

Solar radiation reaching the Earth' s surface is concentrated in the 0.3-2.5 m wavelength range. The bandgap of silicon solar cells is 1.12 eV, meaning only solar radiation with wavelengths shorter than 1.1 m can be directly converted into electric current after absorption. Consequently, the working band of silicon solar cells lies in the 0.3-1.1 m range. For a smooth silicon surface, approximately 30% of solar energy is reflected, causing significant energy waste. Therefore, microstructures have been widely applied to silicon solar cells to reduce interface reflection and improve cell efficiency [5-7]. However, most current solar cells only consider utilization of solar energy in the 0.3-1.1 m range, which accounts for approximately 80% of total solar radiation. The remaining 20% of solar radiation in the 1.1-2.5 m band has not been effectively utilized.

Numerous biological structures in nature exhibit excellent optical properties. Research has revealed that moth-eye structures possess graded refractive indices that effectively reduce surface reflection, and they have been applied to solar cell research. Song et al. applied moth-eye structures to GaAs solar cells, achieving significant reduction in reflectivity across the 0.3-2 m range [8]. Therefore, applying such structures to silicon solar cells to achieve anti-reflection in the 0.3-2.5 m range can substantially improve the effective utilization of solar energy.

This paper employs the Finite-Difference Time-Domain (FDTD) method to investigate and compare the spectral characteristics of three graded-refractive-index microstructured surfaces—moth-eye, pyramid, and cone—on silicon solar cells across the 0.3-2.5 m wavelength range. The effects of structural parameters on spectral characteristics are discussed, and the average spectral properties of the three structured surfaces and their variations with structural parameters are compared, providing valuable theoretical guidance for improving solar energy utilization efficiency.

1 Calculation Model

The three types of solar cell surface structures are illustrated in Figure 1 [Figure 1: see original paper]. Moth-eye, pyramid, and cone structures are periodically arranged on the surface of a semiconductor Si film to create graded refractive index profiles. The periods in both x and y directions are Λ. The base diameter of the moth-eye and cone structures equals the period, while the ground side length of the pyramid structure equals the structural period. The heights of the moth-eye, pyramid, and cone structures are all h , the Si film thickness is h , and a SiO film layer is added to the lower surface of the Si film to form a transition layer between the Si film and vacuum, constructing a gradually varying refractive index to reduce reflection. The optical parameters of Si and SiO are taken from the optical handbook [9]. The initial structural parameters are: Λ = 0.3 m, h = 0.6 m, h = 2 m, h = 0.15 m.

Starting from Maxwell' s equations, the spectral characteristics of the three broadband anti-reflection structured surfaces for silicon solar cells are calculated using the FDTD method. According to the Courant stability condition, the time step Δt is taken as 0.009826 fs and the minimum spatial step d as 0.00025 mm to ensure computational convergence and accuracy.

To describe the overall performance of the microstructured surfaces, the average reflectivity and transmissivity within specific wavelength bands are calculated using the following formula:

$$R_{avg} = \frac{\int_{\lambda_1}^{\lambda_2} R(\lambda) \cdot S(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} S(\lambda)\, d\lambda}$$

where $R(\lambda)$ and $T(\lambda)$ represent the spectral reflectivity and absorptivity, respectively, and $S(\lambda)$ is the AM1.5 solar radiation spectrum.

2 Results and Discussion

The spectral characteristics of the three different broadband anti-reflection structured surfaces for silicon solar cells are shown in Figure 2 [Figure 2: see original paper]. Due to the formation of graded refractive indices, reflectivity is significantly reduced, particularly in the visible light band where Si has a relatively large extinction coefficient and pronounced absorption. After being captured by the surface structure, energy is effectively absorbed by Si. For silicon cells with a bandgap of 1.12 eV, photons in the 0.3-1.1 m range can be effectively converted into photocurrent output after absorption; therefore, higher absorptivity in this band is desirable. Conversely, photons in the 1.1-2.5 m range cannot be directly converted into photocurrent and instead generate heat, causing cell temperature to rise and reducing photoelectric conversion efficiency. Therefore, to achieve full-spectrum solar energy utilization, photons in the 1.1-2.5 m band should ideally transmit through the solar cell to be absorbed and utilized by a thermal module, thereby improving overall solar energy utilization efficiency.

Comparing the spectral characteristics of the three structures reveals that the moth-eye structure exhibits a broader low-reflection band and better absorption in the 0.3-1.1 m range, while demonstrating the lowest reflectivity and best transmission in the 1.1-2.5 m range. To better compare their anti-reflection performance, the reflectivity and transmissivity of the three structures in the 0.3-1.1 m and 1.1-2.5 m ranges are calculated using Equation (1) and presented in Table 1 . Although the differences in average reflectivity and transmissivity are small, they clearly indicate that the moth-eye structure achieves the highest absorptivity in the 0.3-1.1 m range and the lowest reflectivity/highest transmissivity in the 1.1-2.5 m range. Overall, the moth-eye structure is most suitable for broadband anti-reflection surfaces in silicon solar cells.

Figure 3 [Figure 3: see original paper] illustrates the variation of spectral characteristics with microstructure height h for the three broadband anti-reflection structured surfaces. As h increases, the reflectivity of all three structures decreases significantly, with particularly noticeable anti-reflection effects in the visible band. In the infrared band, larger h makes the microstructure effect more prominent and the thin-film characteristics weaker, resulting in smaller reflectivity oscillations. When h = 0.3 m, the microstructured surface exhibits the largest oscillations in the 1.1-2.5 m range. With increasing h , the absorption of all three microstructured surfaces in the 0.3-1.1 m range shows an increasing trend.

Table 2 lists the average spectral characteristics of the three different broadband anti-reflection structured surfaces under various microstructure heights h . As h increases, the gradient of the effective refractive index in the z-direction gradually decreases, effectively reducing reflectivity. Additionally, the moth-eye structure maintains the lowest average reflectivity across the 0.3-2.5 m range, minimizing reflective energy loss. However, as microstructure thickness increases, transmissivity in the 0.3-1.1 m range increases significantly while absorption decreases, affecting the photoelectric efficiency of Si cells. Therefore, the microstructure thickness should not be excessively large and requires comprehensive optimization.

Figure 4 [Figure 4: see original paper] shows the effect of structural period on the spectral characteristics of the three broadband anti-reflection structured surfaces. When the period increases from 0.1 m to 0.3 m, the reflectivity and transmissivity of all three structures decrease slightly, but the change is minimal. When the period further increases from 0.3 m to 0.5 m, reflectivity increases significantly, primarily because the larger period increases the effective refractive index gradient, leading to enhanced reflection. However, when the period is smaller, transmissivity in the 0.3-1.1 m range is relatively large, resulting in lower absorption and reduced cell efficiency.

3 Conclusion

This study investigated the spectral characteristics of three different monocrystalline silicon solar cell surface structures in the 0.3–1.1 m and 1.1–2.5 m ranges. The findings demonstrate that due to their graded refractive index characteristics, all three structures effectively suppress reflectivity. The moth-eye structured silicon solar cell achieves the lowest reflectivity across the entire solar radiation spectrum because of its relatively gradual effective refractive index variation. As microstructure height increases and period decreases, the gradient of the effective refractive index decreases, resulting in more pronounced anti-reflection effects and enhanced transmissivity in the 1.1–2.5 m band.

References

[1] Bermel P, Luo C, Zeng L, et al. Improving thin-film crystalline silicon solar cell efficiencies with photonic crystals [J]. Optics Express, 2007, 15(25): 16986-17000.
[2] Mauk M G, Andreev V M. GaSb-related materials for TPV cells [J]. Semiconductor Science and Technology, 2003, 18(5): S191.
[3] Duan H L, Xuan Y M. Enhanced optical absorption of the plasmonic nanoshell suspension based on the solar photocatalytic hydrogen production system [J]. Applied Energy, 2014, 114: 101-093105.
[4] YANG Deren. Solar cell materials [M]. Beijing: Chemical Industry Press, 2007.
[5] Pillai S, Catchpole K R, Trupke T, et al. Surface plasmon enhanced silicon solar cells [J]. Journal of Applied Physics, 2007, 101: 093105.
[6] Tsakalakos L, Balch J, Fronheiser J, et al. Silicon nanowire solar cells [J]. Applied Physics Letters, 2007, 91: 233117.
[7] Jang S J, Song Y M, Park C I, et al. Antireflective property of thin a-Si solar cell structures with graded refractive index structure [J]. Optics Express, 2011, 19(S2): A108-A117.
[8] Song Y M, Jang S J, Yu J S, et al. Bioinspired parabola subwavelength structures for improved broadband antireflection [J]. Small, 2010, 6(9): 984-987.
[9] Palik E D. Handbook of optical constants of solids [M]. New York: Academic Press Inc, 1985, 350-357.