Simulation of multi-layer antireflection film for crystalline silicon solar cell

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Abstract. Based on the design theory of single-layer, double-layer and multi-layer antireflection films, the thickness and refractive index of each layer of three-layer antireflection films are designed and calculated. The theoretical results of double-layer and three-layer antireflection films was simulated by PC1D, and reflectance, internal and external quantum efficiency and device characteristics of solar cells with double-layer and three-layer antireflection coatings were comparative studied. The results show that the three-layer antireflection film has a wider wavelength response range and higher external quantum efficiency, and the conversion efficiency of the three-layer antireflection film Crystalline silicon solar cells is improved by 0.2% compared with the double-layer antireflection film Crystalline silicon solar cells.

1. Introduction
Solar energy has the characteristics of clean, pollution-free and inexhaustible. At present, the use of non-renewable energy is limited. Therefore, the effective use of solar energy in this century and for a long time will be a subject worthy for further study.

The matching of thickness and refractive index of antireflection film has a great influence for the surface antireflection of solar cell. Although a lot of theoretical and experimental studies on single-layer, double-layer and multi-layer antireflection films of different materials have been reported at home and abroad [1-5], the research on three-layer and more antireflection films mainly focuses on simulation optimization, and the detailed theoretical calculation and analysis of the system are less. In this paper, based on the theoretical research of single-layer and double-layer antireflection films, the theoretical design and calculation of three-layer antireflection films are carried out. PC1D software is used to simulate and analyze the influence of the thickness and refractive index of the double-layer and three-layer antireflection films on the performance of crystalline silicon solar cells.
2. Theoretical analysis of antireflection film

2.1. Theoretical analysis of double-layer antireflection film.

Figure 1. Double-layer antireflection films model

Figure 1 shows the double-layer antireflection films models. On the basis of the previous research on antireflection film, the reflectivity $R_1$ and $R_2$ of the double-layer antireflection film 1 and film 2 can be obtained respectively.

\[
R_1 = \left( \frac{n_0 n_2 - n_1^2}{n_0 n_2 + n_1^2} \right)^2, \quad R_2 = \left( \frac{n_1 n_3 - n_2^2}{n_1 n_3 + n_2^2} \right)^2
\]  

(1)

Where, $R_1$ and $R_2$ are the reflectance of the top layer (film 1) and the bottom layer (film 2) respectively. $n_0$ is the reflective index of air, $n_3$ is the reflective index of crystalline silicon, $n_1$ and $n_2$ are the reflective indices of the top and bottom layer respectively.

In order to minimize reflectivity, $R_1$ and $R_2$ in formula (1) can be equal to zero, the reflectivity formula can be reduced to

\[
n_1^2 = n_0 n_2, \quad n_2^2 = n_1 n_3
\]  

(2)

The optimum film thickness $d_1$ and $d_2$ of each layer can be calculated by formula (3).

\[
d_1 = \frac{\lambda}{4n_1}, \quad d_2 = \frac{\lambda}{4n_2}
\]  

(3)

d_1 and $d_2$ are the optimum film thickness of the top and bottom layer respectively.

For the air / film 1 / film 2 / silicon structure double-layer antireflection film crystalline silicon solar cell, the film parameters of the double-layer antireflection film can be calculated by formula (2) and (3). When $n_1 = 1.57$ and $n_2 = 2.46$, the corresponding film thickness $d_1 = 100$nm and $d_2 = 64$nm [2].
2.2. Theoretical analysis of three-layer antireflection film.

Figure 2 shows the three-layer antireflection films model. According to the theoretical analysis results of the double-layer antireflection film, each layer of the three-layer antireflection film can be regarded as an independent layer, then the reflectivity of each layer can be given by formula (4).

\[
R_1 = \left( \frac{n_0 n_2 - n_1^2}{n_0 n_2 + n_1^2} \right)^2, \quad R_2 = \left( \frac{n_1 n_3 - n_2^2}{n_1 n_3 + n_2^2} \right)^2, \quad R_3 = \left( \frac{n_2 n_4 - n_3^2}{n_2 n_4 + n_3^2} \right)^2
\]

(4)

Where, \( R_1 \), \( R_2 \) and \( R_3 \) are the reflectance of the top layer (film 1), the middle layer (film 2) and the bottom layer (film 3) respectively. \( n_0 \) is the reflective index of air, \( n_4 \) is the reflective index of crystalline silicon, \( n_1 \), \( n_2 \) and \( n_3 \) are the reflective indices of the top, the middle layer and the bottom layer respectively.

In order to minimize reflectivity, \( R_1 \), \( R_2 \) and \( R_3 \) in formula (4) can be equal to zero, the reflectivity formula can be reduced to

\[
\frac{1}{n_1^2} = \frac{1}{n_0 n_2}, \quad \frac{1}{n_2^2} = \frac{1}{n_1 n_3}, \quad \frac{1}{n_3^2} = \frac{1}{n_2 n_4}
\]

(5)

The optimum film thickness \( d_1 \), \( d_2 \) and \( d_3 \) of each layer can be calculated by formula (6).

\[
d_1 = \frac{\lambda}{4n_1}, \quad d_2 = \frac{\lambda}{4n_2}, \quad d_3 = \frac{\lambda}{4n_3}
\]

(6)

\( d_1 \), \( d_2 \) and \( d_3 \) are the optimum film thickness of the top, the middle layer and the bottom layer respectively.

For the air / film 1 / film 2 / film 3 / silicon structure three-layer antireflection film crystalline silicon solar cell, the film parameters of the three-layer antireflection film can be calculated by formula (5) and (6). When \( n_1 = 1.4 \), \( n_2 = 1.97 \) and \( n_3 = 2.76 \), the corresponding film thickness \( d_1 = 113\text{nm} \), \( d_2 = 80\text{nm} \) and \( d_3 = 57\text{nm} \).

3. PC1D simulation and analysis of crystalline silicon solar cells

The theoretical calculation results of refractive index and thickness of double-layer and three-layer antireflection films are substituted into PC1D for simulation and analysis. Table 1 shows the simulation parameters of PC1D.
Table 1. Simulation parameters of PC1D.

| Device parameter                  | Size             |
|-----------------------------------|------------------|
| Device area                       | 244.33cm$^2$    |
| Surface texture depth             | 4μm              |
| Thickness                         | 180μm            |
| Base contact                      | 1.6×10$^3$cm$^3$|
| Emitter contact                   | 1.6×10$^3$cm$^3$|
| Internal conductor                | 0.033S           |
| P-type background doping          | 1.513×10$^{16}$cm$^3$ |
| Front diffusion                   | 1.734×10$^{20}$cm$^3$ |
| Sheet resistance                  | 86Ω/□            |
| Rear diffusion                    | 5.561×10$^{18}$cm$^3$ |
| Bulk recombination                | 21μs             |
| Front-surface recombination       | $S_n=S_p=20000$cm/s |
| Rear-surface recombination        | $S_n=S_p=20000$cm/s |

3.1. Reflectivity simulation and discussion

Figure 3 shows the reflectance simulation curves of double-layer and three-layer antireflection films. The simulation results show that the reflectivity curve of the double-layer antireflection film is W-shaped, and the minimum reflectivity parameters of the model is located at 470 nm (reflectivity is 1.48%) and 910 nm (reflectivity is 1.08%) respectively. The reflectivity of the three-layer antireflection film is W-W superposition type, and the minimum reflectivity parameters of the model is located at 420 nm (reflectivity is 2.48%), 630 nm (reflectivity is 1.0016%) and 980 nm (reflectivity is 2.35%). The weighted average reflectivity values of the double-layer and three-layer antireflection films in 300 nm to 1200 nm range are 11.546% and 9.837%, respectively. From the above analysis, it can be seen that the three-layer antireflection film has a wider antireflection band and a lower weighted average reflectivity values than the simulation results of the double-layer antireflection film. On the one hand, it may be because the refractive index of the top layer of the three-layer antireflection film is lower than that of the top layer of the double-layer antireflection film, resulting in better antireflection effect; on the other hand, it can be calculated by formula (7)\[6\], the equivalent refractive index of the two-layer and three-layer antireflection film is about 1.92 and 1.89 respectively, which may be another reason that the weighted average reflectivity values of the three-layer antireflection film to be lower than that of the double-layer antireflection film.
3.2. Internal quantum efficiency simulation and discussion

Figure 4 shows the simulation curves of the internal quantum efficiency in double-layer and three-layer antireflection film crystalline silicon solar cells. As a whole, the internal quantum efficiency of double-layer and three-layer antireflection film crystalline silicon solar cells did not change obviously in 300 nm to 1200 nm range. It is shown that the internal quantum efficiency of crystalline silicon solar cells is almost unaffected by adding a layer antireflection film on the double-layer antireflection film.

$$n = \frac{n_1d_1 + n_2d_2}{d_1 + d_2}$$ (7)

![Internal quantum efficiency simulation curves of double-layer and three-layer antireflection film solar cells](image1)

**Figure 4.** Internal quantum efficiency simulation curves of double-layer and three-layer antireflection film solar cells

3.3. External quantum efficiency simulation and discussion

Figure 5 shows the simulation curves of the external quantum efficiency in double-layer and three-layer antireflection film crystalline silicon solar cells. Compared with the reflectivity curves, when the wavelength is in the range of 300nm-1000nm, the reflectivity curves of double-layer and three-layer antireflection film are basically in agreement with the simulation results.

![External quantum efficiency simulation curves of double-layer and three-layer antireflection film solar cells](image2)

**Figure 5.** External quantum efficiency simulation curves of double-layer and three-layer antireflection film solar cells

The external quantum efficiency is defined as the probability that the incident photon corresponding to each wavelength provides an electron to the external circuit in the whole range of the incident solar spectrum [7].
of the external quantum efficiency of double-layer and three-layer antireflection film crystalline silicon solar cells. The three-layer antireflection film can indeed make the incident photons generate more electron-hole pairs in the crystalline silicon; However, in the wavelength range of 1000nm-1200nm, the change of external quantum efficiency is different from the reflectivity simulation results, which is caused by the high absorption of high refractive index materials.

3.4. Electrical characteristics analysis and discussion

|                              | $I_{sc}$/A | $V_{oc}$/V | $\eta$/% |
|------------------------------|-----------|-----------|-----------|
| Double-layer                 | 9.531     | 0.6326    | 19.43     |
| Three-layer                  | 9.634     | 0.6328    | 19.61     |

Table 2 shows the electrical characteristics simulation results of the double-layer and three-layer antireflection film crystalline silicon solar cells. Compared with the double-layer antireflection film crystalline silicon solar cells, the short-circuit current, open circuit voltage and conversion efficiency of the three-layer antireflection film crystalline silicon solar cells increased by 0.103A, 0.2mV and 0.18%, respectively. Based on the above analysis, it can be seen that the lower reflectivity and higher external quantum efficiency of the three-layer antireflection film and its crystalline silicon solar cell are the main reasons for its better electrical output characteristics. Better antireflection and efficient generation of electron-hole pairs are beneficial to the improvement of short circuit current and open circuit voltage. Thus, the photoelectric conversion efficiency of solar cells can be improved.

4. Conclusion

Based on the design theory of single-layer, double-layer and multi-layer antireflection films, the thickness and refractive index of each layer of the three-layer antireflection films are designed and calculated. The theoretical calculation results of the double-layer and three-layer antireflection films are brought into PC1D software for simulation. The reflectivity, the internal and external quantum efficiency and conversion efficiency of the double-layer and three-layer antireflection films and its crystalline silicon solar cells are analyzed. The results show that the three-layer antireflection film crystalline silicon solar cells have lower reflectivity, higher external quantum efficiency and better electrical output characteristics than the double-layer antireflection film crystalline silicon solar cells.

Acknowledgments

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