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Design of Light Trapping Structures for Ultrathin Solar Cells

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Abstract

The conversion efficiency of thin film silicon solar cell is still much below that of wafer silicon solar cell due to low optical absorption. Light trapping techniques can enhance the optical absorption in solar cells. Here, we design light trapping structures of double-side grating for ultrathin silicon solar cells based on a rigorous coupled-wave analysis method. The role of each grating was identified by analyzing the absorption spectra of ultrathin solar cell from 350 nm to 1100 nm wavelength at normal incidence, which shows use of top and bottom light trapping structures can achieve large optical absorption in different wave regimes. Inspired by this observation, the dual dielectric/dielectric and dielectric/ metallic grating structures were proposed and optimized to obtain broadband optical absorption close to the theoretic limit.

Keywords

Thin Film Solar Cell; Light Trapping Structures; Absorption Enhancement

Introduction

This reduction in solar cell thickness has many potential benefits depending on the semiconductor used, including decreased costs from materials availability, increased manufacturing throughput, increased open circuit voltages, improved carrier collection, and improved stability. However, thin layers generally result in poor absorbance due to short optical length. Therefore, the photoelectric conversion efficiency of solar cells based on thin film technology is low. In order to overcome this deficiency, a significant light trapping technique is applied to the development of thin film solar cells with enhanced absorption. The light-trapping concept is presently based on randomly or periodically textured interfaces combined with a back reflector. This component has to provide efficient scattering at large angles of the unabsorbed light and prolong the optical paths back in the thin active layers, thus the absorption can be drastically improved. For example, Youngmin Song et al. fabricated a periodic grating structure on a silicon substrate and such solar cells exhibited a reflectance of less than 10% in 300-1200nm range. Yalin Lu et al. placed a metallic nanograting at the bottom of the active layer and a remarkable 30% broadband absorption improvement was achieved.

In this paper, we aim to design the light trapping structures for ultrathin solar cells. We firstly investigated the absorption spectrum of thin silicon layer with a periodic grating structure above (top grating) or below (bottom grating), respectively. The top dielectric grating enhanced the absorption in blue-green light band, while the bottom grating, no matter dielectric or metallic grating, exhibited better in red to infrared light band. This indicates that combination of top and bottom light trapping structures provides potential to produce broadband light absorption enhancement. Then we proposed and optimized two kinds of double-side grating structures for ultrathin silicon solar cells.

Light Trapping Structures and Simulation Methology

An unpatterned thin film silicon solar cell (Fig. 1 (a)) is considered as a basic reference consisting of 200nm thick silicon layer as the absorbing layer, sandwiched by a 120nm thick layer and a 50nm thick layer of indium-tin-oxide (ITO) on top and bottom of the silicon layer, deposited on a 100nm thick Ag substrate. The back Ag substrate serves as an almost perfect reflector and as a bottom contact, while the front ITO layer plays the role as a top contact. Fig. 1(b) shows a top light trapping structure by only replacing some part of the front ITO layer with a 50nm thick dielectric Si grating. Here, we don’t consider the top metallic light trapping structures as it is confirmed that the dielectric gratings outperform the metallic gratings in optical absorption. Similarly, a bottom grating (Fig. 1(c)) is formed by using a dielectric Si or metallic grating embedded in the back ITO layer. The metallic grating material is chosen to be Ag. The light trapping structure with dual gratings is shown in Fig. 1(d). In real applications, the top and bottom gratings for ultrathin solar cell should be designed with the same geometry because of deposition issues. These cells are illuminated by sunlight at normal incidence over the spectrum of wavelength 350-1100nm.With the aids of the gratings, the Si layer absorbs the incident light as much as possible to produce the photon-generated carriers collected by the ITO layers.

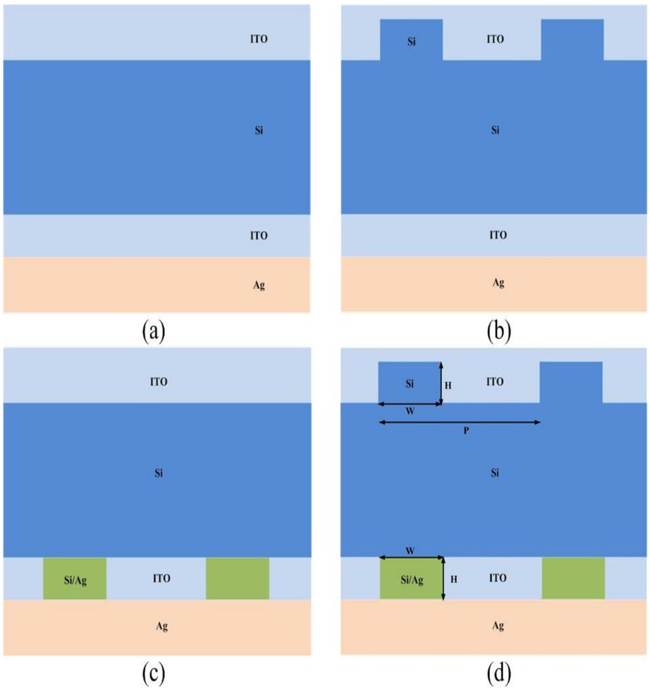

FIG.1 THE SCHEMATICS OF FOUR SIMULATED MODELS: (A) UNPATTERNED STRUCTURE. (B) ONLY-TOP GRATING. (C) ONLY-BOTTOM GRATING. (D) DUAL GRATING.

The absorption enhancement is evaluated for both TE and TM polarizations using Rigorous Coupled Wave Analysis approach. For the specific class of periodic structures composed of layers invariant in the direction normal to the periodicity, the rigorous coupled wave analysis is particularly suitable due to its Fourier basis representation. The total absorption is simply calculated by $A=(A_{TE}+A_{TM})/2$, where $A_{TE/TM}=1-R_{TE/TM}$ and $R_{TE/TM}$ is the reflection for TE or TM polarizations.

The Individual Effect of Top and Bottom Gratings on Optical Absorption

The absorption spectra of the Si layers with top and bottom grating structures are shown in 0. The period P and the line width W are 500nm and 250nm, respectively, and the height H is 50nm. As references, the absorption spectra corresponding to the device (black line) and the theoretic limit (red line) are also given out.

From Fig. 2, it is observed that the unpatterned solar cell exhibits inferior optical absorption as compared to the nanostructured solar cells. With the help of light trapping structures, the nanostructured solar cells achieve large optical absorption. Fig. 2(a) shows the effect of the top grating on optical absorption in the solar cells. The top grating generates substantial absorption enhancement over the entire usable solar spectrum, which confirms that the top grating acts as an efficient anti-reflection structure. But only by a top grating is the solar cell hard to maximize the optical absorption because the absorption is far below the theoretic limit (compare the red and blue lines). In Fig. 2(b), the individual effects of the dielectric and metallic bottom gratings are presented. Similar to the top grating, both bottom gratings lead to an increased broadband absorption almost over the usable solar spectrum except the below 400nm. Moreover, the optical absorptions using the bottom gratings surpass the theoretic limit at the wavelengths over 650nm. There is an interesting phenomenon about use of dielectric and metallic gratings as back scatters.

It can be seen that the two kinds of bottom gratings pose different effects on optical absorption. For dielectric gratings, large absorption enhancement occurs in the wave regime of 500nm-800nm. In the metallic case, large absorption enhancement red-shifts and covers the red and infrared light in the usable solar spectrum. Now let's turn to compare the individual effects for the top and bottom gratings. The top grating is intended to reduce the reflection and thus to trap most of the incident light in the shorter wavelength range into the Si active layer. On the other hand, the bottom grating is intended to diffract back the trapped incident light into the active layer, mainly in the red to near infrared ranges of the spectrum. Thus combining top grating and bottom grating should contribute to a large broadband optical absorption. In next section we presented two light trapping designs for ultrathin solar cells as shown in Fig. 1(d).

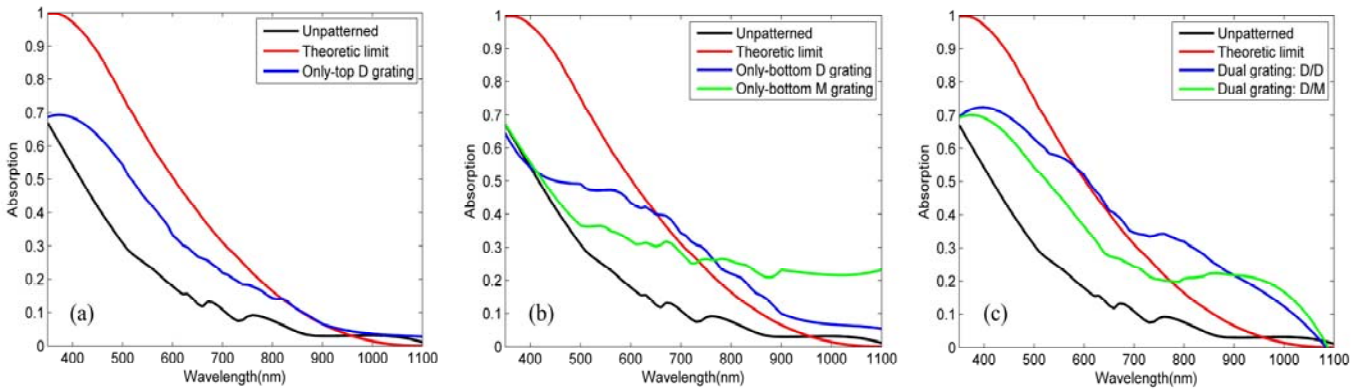

FIG.2 THE ABSORPTION SPECTRA FOR (A) ONLY-TOP GRATING, (B) ONLY-BOTTOM DIELECTRIC (D) OR METAL (M) GRATING, (C) DUAL GRATING OF TOP DIELECTRIC GRATING AND BOTTOM DIELECTRIC GRATING (D/D), AND OF TOP DIELECTRIC GRATING AND BOTTOM METALLIC GRATING (D/M). THE BLACK LINE IS THE ABSORPTION SPECTRUM OF UNPATTERNED SOLAR CELL. THE RED LINE IS THE THEORETIC LIMIT.

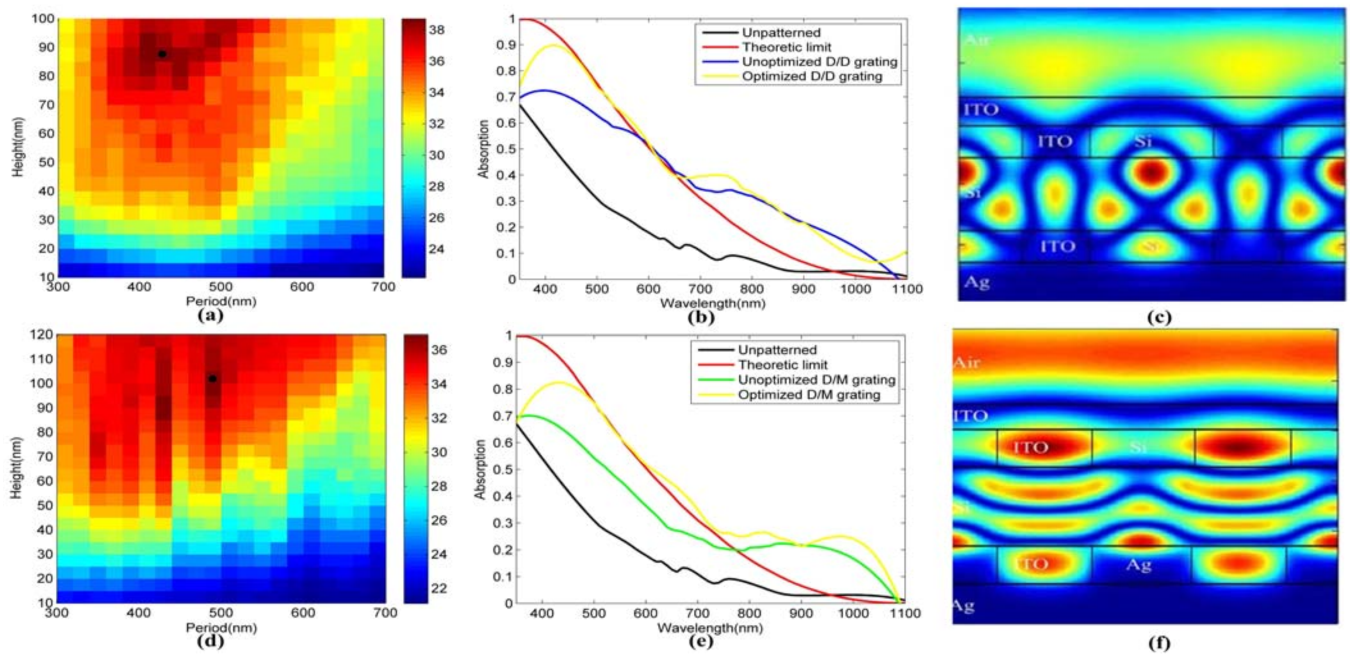

FIG.3 OPTIMIZATION OF THE PERIOD AND HEIGHT OF THE DUAL GRATING: (A) AND (D) ARE OPTIMIZATIONS OF A DUAL D/D GRATING AND A DUAL D/M GRATING RESPECTIVELY. THE BLACK DOTS INDICATE THE POSITION OF THE MAXIMUM SHORT CIRCUIT CURRENT DENSITY. (B) ABSORPTION SPECTRA FOR THE OPTIMIZED D/D GRATING STRUCTURE: PERIOD P= 420NM, HEIGHT H= 85NM. (E) ABSORPTION SPECTRA FOR THE OPTIMIZED D/M GRATING STRUCTURE: PERIOD P= 480NM, HEIGHT H= 100NM. (C) AND (F) PLOTTED THE ELECTRIC FIELD DISTRIBUTIONS IN TWO OPTIMIZED CASES.

Design and Optimization of Dual-Grating Light Trapping Structures

Through the analysis described above, dual gratings, dielectric/dielectric (D/D) and dielectric/metallic (D/M) are proposed as high efficiency light trapping structures. We plotted the absorption curves for the solar cell with dual gratings shown in Fig. 2(c). The dual grating parameters are same as the top or bottom gratings'. It can be seen that the combined light trapping structures make full use of individual grating's advantages. The interaction between the top and the bottom grating plays a significant role in broadband absorption enhancement from 350nm to 1100nm. To make the optical absorption of new designs approach the theoretic limit, we optimized the height and period of the dual gratings, which is described in Fig. 3(a) and (d) corresponding to the D/D and D/M cases. The line widths were set to a constant value of 250nm. The optimization effects were evaluated by maximizing short circuit current density. The short circuit current density was calculated by integrating the wavelength-dependant absorption between 350 and 1100nm, weighted by the AM1.5G solar spectrum function, and by summing the contributions from both TE and TM polarization accounting for the randomly polarized light emanating from the sun. The optimized dual D/D grating structure was attained at P=420nm and H= 85nm corresponding to a short circuit current density of 38.71 mA/cm^2 while the optimized dual D/M grating structure at P=480nm and H=100nm corresponding to a short circuit current density of 36.89mA/cm^2(see the black dots in Fig. 3(a) and (d)). Using the optimized grating parameters, we illustrated the optical absorption curves shown in Fig. 3(b) and (e). The optimized optical absorption is much better than the un-optimized especially in short wave regime, almost approaching the theoretic limit. Fig. 3(c) and (f) plotted the electric field distributions in two optimized cases. The field simulations have been done by MIT MEEP, an open-code FDTD software. It can be seen that most of the light energy is located in the Si absorbing layers, which confirms our designs are correct.

Conclusion

Two light trapping structures of D/D dual gratings and D/M dual gratings were proposed based on the analysis of the optical absorption of individual gratings. It was demonstrated that use of the dual gratings in ultrathin solar cell is clearly superior to use of an only-top or an only-bottom grating. The dual gratings provide potential to produce larger optical absorption over entire usable solar spectrum. After optimization of the dual grating geometry, the optical absorption in ultrathin solar cell approaches to the theoretic limit and even surpasses it in the regime of red to infrared. Our designs provide an effective way to enhance the conversion efficiency of thin film solar cell.

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