ONE STEP PROCESS AS A ROUTE FOR EFFECTIVE LIGHT TRAPPING IN THIN FILM SOLAR CELLS

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ABSTRACT: Advanced light trapping in thin film solar cells involves coupling light into guided modes at the front and back interfaces respectively. Accomplishing in an optimal way of these two tasks requires the integrating of properly engineered random or periodic light trapping schemes for both surfaces, which relates to two independent processing steps. Here, we focus on integrating the two-step processes into one-step process by using a nanoscale inverted pyramid structure. We show that the one-step approach can provide excellent broadband light trapping at the front and back surfaces for the solar cells, and a relative gain of 43% for the short circuit current and a gain of 26% for the efficiency have been achieved compared with the results obtained for cells without light trapping structure. The successful use of the one-step process, on the other hand, depends on the geometrical nature of the inverted pyramid, which allows for better conformal sequential deposition. The proposed one-step light trapping approach will simple the process, reduce the tact time and lower the production cost, all of which are believed to be beneficial to the industrial mass production.

Keywords: Light trapping, Thin film solar cell, Nanoscale inverted pyramid, Conformal deposition, One step process

1 INTRODUCTION

To drive the photovoltaics (PV) to the grid parity and compete for the potential energy market, a significant increase in thin film solar cell efficiency and pronounced cost reduction are urgently required. Advanced light trapping scheme will contribute to the both objectives simultaneously, by increasing the light path length in the absorbing layer and reducing the materials usage. In thin film solar cells, light trapping usually involves coupling light into guided modes in the absorber layer at the front and back interfaces, which requires two independent processes to fabricate the engineered light trapping structures at both surfaces respectively. As a result, it is complicated, time consuming and expensive from the point view of the industry. Integrating the two step processes into one step process will definitely simple the fabrication process, reduce the tact time and lower the production cost, all of which are believed to benefit the industrial mass production.

The successful realization of the integrating processing relies on the structure which can not only provide superior light harvesting but also be adapt to the conformal deposition. The common used structures such as the random pyramid, nanowire and nanopillar cannot be used due to the morphologies which lead to pronounced deviations from conformality [1]. On the other hand, the nanoscale inverted pyramid structure, the inclination angle of which is suitable for the conformal growth of the subsequential films, is such a structure that can be used in one step light trapping process to provide excellent light trapping for the solar cells [2, 3].

The goal of this work is to present a one step process as a route for effective light trapping at the front and back interfaces in the thin film solar cell, using the nanoscale inverted pyramid structure. The light trapping properties and the influence of the deviation from the conformal deposition are studied.

2 EXPERIMENTAL

The nanoscale inverted pyramid structure is fabricated on the Si wafer by using a nanoimprinting lithography combined with the anisotropic wet etching process. In brief, on the Si wafer with 100 nm SiO_2, 100 nm PMMA and 100 nm MMS_4 are deposited by the spin coating at 3000 rpm (30 sec) and 4000 rpm (30 sec), respectively. Then a master with array of nanoholes is used to pattern the MMS_4 using the ultraviolet nanoimprint lithography process (UV-NIL). Subsequent the reactive ion etching is used to etch the MMS_4, PMMA and SiO_2, followed by a post-step using Buffered Oxide Etch (BOE) to laterally etch the SiO_2 to control the spacing between adjacent pyramids. After the removal of the MMS_4 and PMMA, the sample is dipped in BOE for 5-10 sec to remove the native oxide. The anisotropic wet etching in an 80 ^oC, 25% aqueous TMAH solution is used to produce the pyramid pattern. Finally, the inverted pyramid structure is formed after the removal of the SiO_2 by BOE.

On the as fabricated nanostructure, the metal back reflector (Al or Al/AZO) and a 300 nm n-i-p a-Si top cell are deposited. The n-i-p a-Si cell has a structure of n-μc-Si (25 nm)/i-a-Si (300 nm)/p-SiO_x (18 nm). The 75 nm ITO is used as the anti-reflective coating layer and front contact. The n-i-p a-Si single junction solar cell is sequentially fabricated in a PECVD with dual frequency power supply (13.56 MHz and 60 MHz). The deposition temperature for all the layers is 200 °C, with power density from 0.015 W/cm^2 to 0.05 W/cm^2. The a-Si layers deposited by the PECVD are produced with a $SiH_4/H_2/PH_3$(10%)/ precursor gas mixture of 50/50/0 for the i-a-Si and 5/500/5 for the n-μc-Si. the p-SiO_x is achieved by adding B_2H_6 and CO_2 in the precursor gases. The solar cell area is $0.1cm^2$ defined by the shadow mask of the ITO layer sputtered.

Current–voltage characteristics are measured under the simulated AM1.5G sunlight at 100 mW/cm^2 irradiance, generated by a light source of a 450-W xenon lamp (Oriel, Sol2A). The light intensity was calibrated using an NREL calibrated Si reference cell. Scanning electron microscopy images are obtained using an analytical field emission SEM (JSM-7100F). AFM images are performed using Digital Instruments Dimension 5000 Scanning Probe Microscope (SPM) in "tapping" mode.

3 RESULTS AND DISCUSSION

3.1 The conformal deposition

The nanostructure morphology is crucial to the conformal subsequential deposition using one step process to achieve the light trapping at the front and back sides of the thin film solar cells. A vertical morphology was believed to lead to pronounced deviation from conformality of the silicon layers [1]. Figure 1(a) shows the top view SEM image of the nanoscale inverted pyramid structure fabricated on the Si wafer substrate, the inclination angle of which is demonstrated by the AFM heigh profile in Figure 1(b) and is determined by the anisotropic wet etching properties of the silicon, namely, 54.7°. The spacing between adjacents pyramids could be controlled by the BOE etching time. A 0-200 nm spacing can be obtained in our case. The perodic of the pyramid structure is 1000 nm.

When the a-Si cell is depositited on the nanostructured substrate, as can be see from the cross section of the SEM images in Figure 1(c, d), it is possible to realize the conformal growth of the subsequential films, resulting in a “nanopyramid-like” top surface of the a-Si cell after the ITO deposition. We ascribe the conformal deposition of the a-Si on the strucure to the relatively small inclination angle of the pyramid geometry and the large feature size of 1000 nm. The conformal structure of the a-Si cell on the nanoscale inverted pyramid structure indicates that the back and front sides light trapping unit can be integrated by one step process. Doule-sided light trapping is therefore achieved within the one step pattening by using the nanopyramid structure.

The deposition process of the subsequantial film also has impact on the resulting morphology, shown in Figure 1(c) and (d). The deposition of the Al by thermal evoporation will not change the morphology and nanoscale morphology could be better inheritted by the a-Si cell; while the deposition of the ZnO:Al (AZO) film by the sputtering will cause a deviation of final strucutre of the a-Si cell, since the valley of the pyramid is filled with more AZO materials. Deviation from the conformal deposition will lead to the low light trapping properties and thus has large impact on the solar cell efficiency, which will be discussed later.

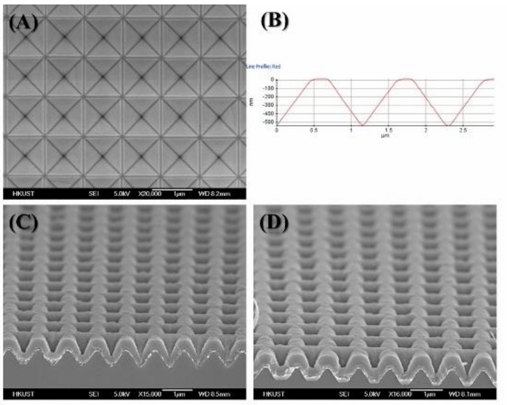

Figure 1 (a) the top view SEM image of the fabricated nanoscale inverted pyramid structure on the silicon wafer substrate; (b) the AFM height profile of the nanoscale inverted pyramid structure; (c) the cross section SEM image of the a-Si cell with Al back reflector; (d) the cross section SEM image of the a-Si cell with Al/AZO back reflector.

3.2 The light absorption

In order to get direct insights into the light trapping properties of the one step processed light trapping structure, numerical simulation using the finite-difference time-domain (FDTD) method is performed to find out the spatial distribution of the carrier generation rate for the device.

By solving the Maxwell’s equations, the distribution of the electric and magnetic field intensity could be obtained. With the imaginary part of the permittivity of the materials, it is possible to calculate the absorption directly from the below formula [4]:

$$P_{abs} = -0.5\omega |E|^2 imag(\varepsilon) \quad \ldots (1)$$

The number of absorbed photons per unit volume can then be calculated by dividing this value by the energy per photon:

$$G = \frac{P_{abs}}{\hbar\omega} = \frac{-0.5\omega |E|^2 imag(\varepsilon)}{\hbar} \quad \ldots (2)$$

The generation rate is the integration of G over the simulation spectrum.

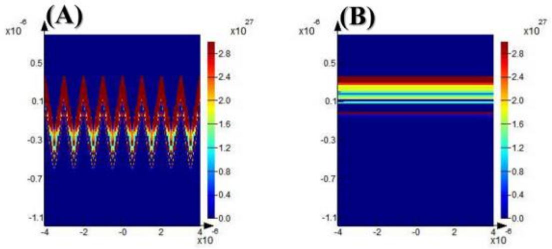

Figure 2 spatial distribution of the generation rate of the a-Si cells with (a) one step processed nanopyramid structure; (b) planar structure. Al/AZO are used as the back reflector in the simulation.

As can been seen from Figure 2, the cell with the one step processed light trapping nanopyramid structure shows pronounced light absorption throughout the absorber layer, while in the planar cell, the enhanced region is limited to the top surface.

3.3 Solar cell performance

The quantum efficiency in Figure 3(a) shows the pronounced broadband light trapping properties of the one step fabricated light trapping stucture. At the short wavelength, the enhancement mainly comes from the front surface texturing, where a nanopyramid-like surface provides a gradual change of refractive index from the air to the a-Si at the top surface, which can be seen by the incoming light as an effective averaged index. The light absorption result is consist with the observed morphology from the SEM images. Furthermore, the reduction of the reflection is especially remarkable at the short wavelength because the absorption depth is limited to tens of nanometers as a result of the high absorption coefficient at the short wavelength. At the long wavelength, the enhancement results from the back surface reflection.

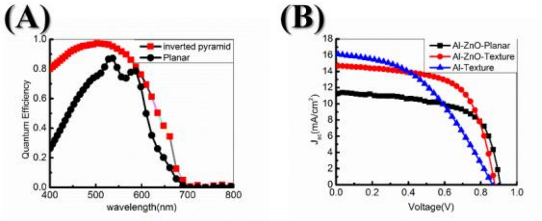

Figure 3 (a) the quantuam efficiency of the a-Si cells with one step light trapping stucture and planar structure; (b) the I-V curves of the a-Si cells with different back reflectors and light trapping schemes.

The I-V curves of the a-Si solar cells with nanoscle inverted pyramid structure and without light trapping scheme are shown in Figure 3(b). the largest enhancement of the J_{sc} is the cell with 100 nm Al back relfector, due to the better confomal growth of the a-Si cell, a relatively gain of 43% is obtained. while the cell with Al/AZO back reflector suffers from loss of the J_{sc} because of the deviation from the conformal deposition. However, a gain of 26% for the efficiency is also achieved with respect to the planar cell. The low fill factor of the nanopyramid cell with Al back reflector mainly arises from the poor contact between the Al and the n-μc-Si, as well as the porous and crack formed in the a-Si materials, as demostrated in Figure 1(c). Further improvement of the Al/Si interface and removal of the porous and crack regions could boost the cell efficiency, which is beyond the present work. The cell performance is summaried in Table I

Table I: The performance of the solar cells with different back reflectors and structures

Cell structure	V_{oc}[mV]	FF[%]	J_{sc}[mAcm^{-2}]
Al/AZO, planar	910	64	11.2
Al/AZO, nanopyramid	880	64	14.6
Al, nanopyramid	865	44	16.1

4 CONCLUSION

In summary, we have demonstrated that the one step process can be used to fabricate the front and back sides light trapping structures in a-Si thin films solar cells, by using the nanoscale inverted pyramid, which allows for not only the conformal deposition but also excellent light trapping properties. We show the light absorption enhancement arises from the front surface anti-reflection effect and the back surface reflection. The deviation from the conformal deposition will lead to poor light trapping properties and thus solar cell efficiency.

5 REFERENCES

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