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A Front Surface Optimization Study for Photovoltaic Application

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Abstract
In this paper, we presented a possible front surface optical enhancement of Si solar cell by optimizing the Antireflection (AR) and light trapping (LT) schemes. Conventional plasma enhanced chemical vapor deposition (PECVD) and in house hot wire chemical vapor deposition (HWCVD) tool was used to deposit Silicon Nitride (SiNX) layer and optimized at 668nm wavelength. This was followed by surface texturing of random pyramids to further enhance the broadband reflectance of the front surface. Broadband reflectance measurement using integrating sphere method showed achieved weighted average reflectance (WAR) value of as low as 1.8% and 1.5%, when 85nm SiNX was deposited on top of random pyramids structure using HWCVD and PECVD methods, respectively.

Keywords*: antireflective layer, pyramids, black silicon, silicon solar cell*

1. Introduction

Renewable energy especially solar cell becomes widely important caused by its non-pollutant behaviour [1],[2] and reducing the optical losses in photovoltaic (PV) devices has become one of the most important aspect in the quest of increasing the power conversion efficiency of PV devices. Light reflections from the front surface of any photovoltaic device is undesirable, because higher reflection will lead to lower number of electron-hole pairs that can be created, lowering the power conversion efficiency. To minimise incident light reflection, two common approaches are popular amongst PV manufacturers, (1) deposit antireflective (AR) layer, and (2) introducing surface texturing onto the front surface of solar cell.

The first approach deals with finding materials with appropriate optical properties and thicknesses, which lead to destructive interference between the light reflected from the interfaces in the film structure. For an Air-Si interface, the optimum refractive index for Single Layer AR (SLAR) is about 1.95. Therefore, the material with refractive index value close to this value is usually selected. SLAR coating such as PECVD SiN_X, stoichiometric silicon nitride (Si_3N_4), grown by LPCVD [3], titanium dioxide (TiO_2) [4], and Silicon dioxide (SiO_2) [5] are among the widely used material. To further reduce the reflectance over a broad range of wavelength, Double layer ARC (DLAR) can also be used. Minghua et al. reported the use of SiO_2/SiN_X stack fabricated by electron beam evaporation, as an antireflection layer for their black silicon solar cell [6]. Zhao et al. showed that 24% efficiency can be achieved for their PERL design by using stack of MgF_2/Zns DLAR coating [7].

On the other hand, for the second approach, the front surface texturing reduces the front surface reflectance through the so-called ‘multiple bounce’ effect, whereby the reflected light from one inclined facet of the texture is incident on another adjacent facet (providing them with two chances to be coupled into the cell [8],[9]). In addition to antireflection, texturing can also increase the optical path length of light passing through a cell, by changing the propagation angle through scattering or refraction, leading to increased absorption within the cell. Haynos and colleague were the first to report the use of anisotropic etching for texturing solar cells on their Comsat cell [10]. Whilst micron-scale texturing is already an industrial standard, new nano-texturing approaches have emerged to improve optical absorption, such as biomimetic

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'moth-eye' structures [11], Mie resonator arrays [12], nanoparticles [13] and silicon nanowires [14].

In this work, a comparison study of AR schemes was conducted by means of simulation on silicon surface using materials deposited from two different approach, (1) conventional PECVD deposited nitride, and (2) nitride deposited in house commercial hot wire chemical vapour deposition (HWCVD) system build by Echerkon Technologies Ltd. The reflectance value of each materials as SLAR coating was assessed using transfer matrix method. Random pyramid structures was realized using KOH etching technique, and combined with previous AR coating. Finally, the reflectance spectra was obtained from two of the samples using the integrating sphere technique [15].

2. Research Method

2.1. Silicon Nitride (SiN_X) deposition and reflectance measurement

The single antireflection coating (SLAR) of silicon nitride (SiN_X) thin film was deposited using standard recipe available on our HWCVD and PECVD system. $SiH_4/NH_3/N_2$ gaseous was used with the ratio of 12.5/20/500 sccm flow rate to deposit 100nm silicon nitride thin film using PECVD, at 300^{O}C. On the other hand, SiH_4/NH_3 was used in the ratio of 30/450 sccm to deposit the same thickness of silicon nitride using HWCVD system at the same temperature. Both thickness was measured using variable angle spectroscopic ellipsometer (VASE) from J.A Wollam and verified. The optical properties of the deposited thin film was obtained using the same ellipsometer. Resulting n and k value for both nitride deposited by standard recipe used for HWCVD and PECVD is shown in Figure 1. This value was then inserted into simulation and the resulting reflectance value is shown in Figure 2.

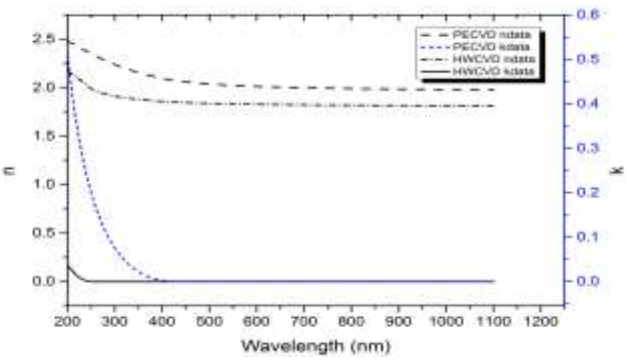

Figure 1. Experimental setup for Si nanowire etching

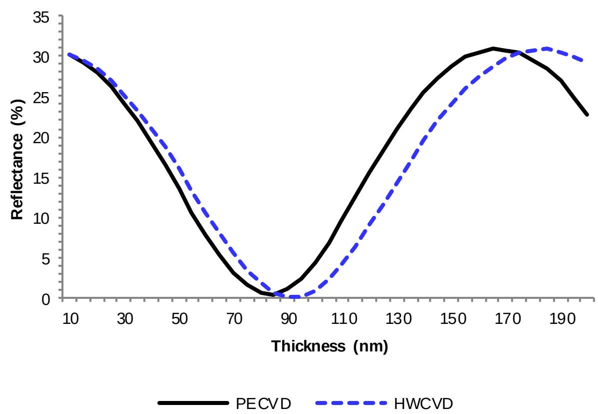

Figure 2. Simulated reflectance value

From Figure 2, the lowest reflectance was obtained from HWCVD method (0.1%) at 90nm thickness. The optimum thickness for PECVD method is 85nm with reflectance value as low as 0.5%. The Silicon Nitride with optimized thickness was then deposited on the silicon and the reflectance was measured in the wavelength range of 400nm to 1000nm, as shown in Figure 3. As expected, the reflectance value near to simulated value was achieved. The bare silicon reflectance was also included in Figure 3 as a reference.

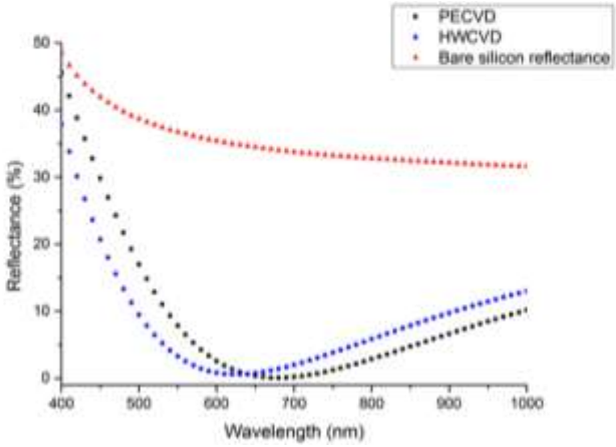

Figure 3. Reflectance spectra of 85nm of SiN_X deposited using HWCVD and PECVD

2.2. Texturing process development

The recipe for surface texturing was based on optimized parameters from King *et al*.[16]. The etching time was varied from 5 min to 60 minutes in the 1.5% KOH+ 3.8% IPA etching solution at $70^{O}C$ to obtain the surface texturing with minimum reflectance. Figure 4 shows the reflectance measurement for these random pyramid, and 30 minutes of etching time resulted in the lowest resultant reflectance spectra. The formed pyramids is shown in Figure 5.

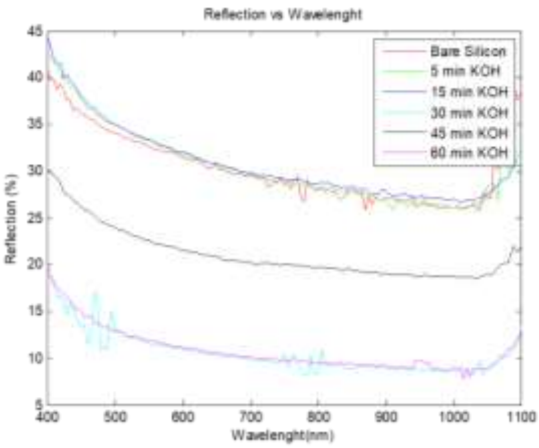

Figure 4. Reflectance spectra of random pyramids etched for different time

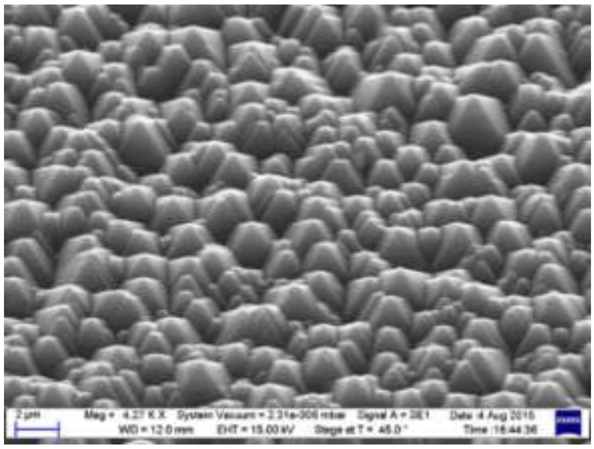

Figure 5. SEM image of pyramid structure with lowest reflectance (30 minutes etching)

2.3. Combination of surface texturing and antireflection

After the individual optimization process of SLAR and surface texturing, 85 nm of HWCVD SiN_X of PECVD SiN_X was deposited using the same recipe as mentioned above on top of the random pyramids. The reflectance was then measured and shown in Figure 6.

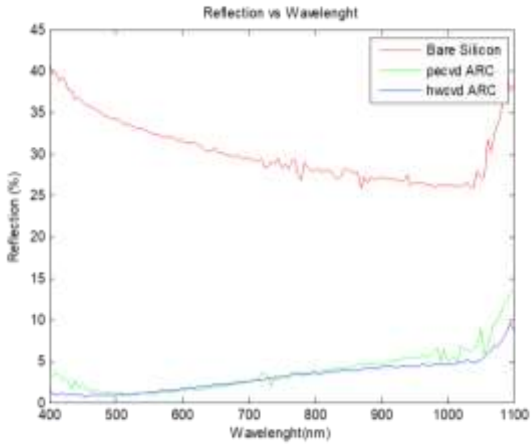

Figure 6. Reflectance spectra of 85nm SiN_X deposited using HWCVD and PECVD on top of random pyramid, bare silicon included as comparison

In photovoltaic applications, AR coating should be optimized to minimize reflection over a broad spectral range. Hence, weighted average reflectance (WAR) offers a better quantitative comparison for each type of AR scheme used for this work. Each measured or calculated reflectance spectrum is weighted to the AM1.5 solar spectrum (ASTM173G, global tilt) expressed as a photon flux density (*PFD*, equation 1), and averaged to give a single figure-of-merit called the weighted average reflectance (R_W, equation 2).

$$PFD = \frac{I(\lambda,\theta)\lambda}{hc} \tag{1}$$

$$Rw = \frac{\int_{\lambda \min}^{\lambda \max} R(\lambda) PFD(\lambda) d\lambda}{\int_{\lambda \min}^{\lambda \max} PFD(\lambda) d\lambda} \tag{2}$$

Here, *I* is the incident solar spectrum in ($W/m^2/\mu m$), λ is the wavelength, *h* is the plank constant, *c* is the speed of light, *R*(λ) is the reflectance of the material, and *PFD* ($photons/m^2/s$) is the incident photon flux density. The HWCVD method results in WAR of 1.8%, slightly higher than PECVD method, which gave WAR value of 1.5%.

3. Conclusion

In summary, we have developed and optimized the traditional Silicon nitride antireflection layer that is widely used in solar cell research using the standard recipe available in our PECVD and HWCVD system. Furthermore, we have also developed and evaluated the best recipe for obtaining reasonable reflection measurement for random pyramid structure to be a comparison to our novel light trapping and antireflection technique, which is the second part of the paper. WAR value of as low as 1.5% and 1.8% was achieved for the SiNx deposited on the random pyramid structure using PECVD and HWCVD, respectively. More emerging structures such as hybrid nanowires on top of random pyramids will be investigated in the future and incorporated with device simulation.

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