

Analysis of metal nano-particle embedded silicon nitride thin-films for anti-reflection coating (ARC) in solar cell applications

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Abstract. Anti-reflection coatings (ARC) find viable application in commercial silicon solar cell technology. Most of the solar cell production companies around the world use titanium dioxide, silicon dioxide or silicon nitride thin films as ARC. In this work a study is done to find out the effect of embedded metal nano-particles (NP) in the widely used ARC material (Silicon Nitride) for silicon solar cells. It is shown that the theoretical treatment may be performed for designing such metal nano-particle embedded anti-reflection coatings. A comparative study of silicon nitride ARC without embedded metal nano-particles and silicon nitride ARC with embedded metal nano-particles is made in this article. The chosen values of parameters are well within the technological limits of present time.

Keywords. Antireflection coating, silicon nitride, solar cells, metal nano-particles.

1. Introduction

Anti-reflection coatings (ARC) have been an important area of study to minimize reflection from the front surface of the solar cells. ARCs have been optimized theoretically and experimentally on bare or encapsulated cells. Zhao and Green [1] theoretically optimized a number of different ARCs. Much of work has been reported on dual layer anti-reflection coating, where different type of materials were deposited like $\text{TiO}_2/\text{SiO}_2/\text{SiN}$, by Richards et al. [2], Arturo et al. [3], Bikash et al. [4] etc. The main interest in SiN films is connected with the bulk defect passivation properties of multi-crystalline silicon. It is well-known fact that SiN PECVD films contain hydrogen which can be released during the

thermal treatment passivating the silicon defects. This effect can be enhanced by interaction with Al back contact during a thermal process [5, 6].

In recent years extensive research is reported on surface plasmons, which are collective oscillations of the electrons in conductors, for biologic and luminescence applications [7]. However, there has not been extensive study of surface plasmons for commercial silicon solar photovoltaic applications. Catchpole and Pillai [8, 9] investigated the suitability of localized surface plasmons on silver nanoparticles (NP) for enhancing the absorbance of silicon solar cells in the IR region. They modeled Ag particles as scattering luminescent emitters and made use of the broadened emission peak to facilitate the near band (in IR region) light absorption in a Si thin film. In this paper, we focus on modeling the metal nano-particle embedded silicon nitride ARC for performance enhancement of commercial silicon solar cells. We investigate use of the extinction properties of embedded metal particles in silicon nitride ARC to reduce the reflections. Based on the standard optical theorem and Maxwell-Garnett effective dielectric function theory [10], model of the new ARC system is simulated. The reflection data generated by simulation is used in PC1D photovoltaic simulation software [11] to show the performance improvement of commercial silicon solar cell.

2. Theoretical Background

The bare Si in intimate contact with air reflects about 33% of the incident power over all wavelengths of our interest in which the solar cell works. For air-Si interface this accounts nearly 33% of the reflected power over the whole visible spectrum. The high reflectance of the air-Si interface is clearly unattractive in the development of making highly efficient cells. Commercial single crystalline silicon (c-Si) solar cells employ textured surfaces to curtail the reflection to its minimum. These are produced by etching the Si with alkaline etch that exposes the slowly etched (111) crystallographic planes, which then, intersect to form the randomized up-pyramids on the surface of the wafer. However, controlling the reflectance on multi-crystalline (mc-Si) silicon wafers is not feasible, primarily owing to the different crystallographic orientations that restricts to adequately texturing the mc-Si wafers with the standard alkaline etch solution.

Another approach to minimize the reflectance is to deposit a suitable anti-reflection layer on the surface of the Si wafer. Hitherto, commercial solar cells have been deposited with single layer TiO_2 . Recently, plasma enhanced chemical vapor deposited (PECVD) silicon nitride ($\text{SiN}_x\text{:H}$) has become popular as an

ARC material because of the additional benefits afforded by the presence of hydrogen in these films. At each wavelength, the reflection coefficient, $R(\lambda)$ is calculated using the Matrix Method. In this method, each layer is represented by a characteristic matrix, M:

$$R(\lambda) = \left| \frac{n_0 B - C}{n_0 B + C} \right|^2 \quad (1)$$

where, n_0 – refractive index of air and B and C are the components of the following matrix, M:

$$\begin{pmatrix} B \\ C \end{pmatrix} = \left\{ \prod_{m=1}^n \begin{pmatrix} A_m & iB_m \\ iC_m & D_m \end{pmatrix} \right\} \begin{pmatrix} 1 \\ n_s \end{pmatrix} \quad (2)$$

where, for $m = 1, 2, \dots, n$,

$A_m = D_m = \cos \delta_m$, $B_m = i \sin \delta_m / \eta_m$, $C_m = i \sin \delta_m \eta_m$ and n_s – refractive index of substrate. The two unknowns in these expressions are defined below:

$$\delta_m \equiv \text{phase difference} = \frac{2\pi \tilde{n}_m d_m \cos \theta_m}{\lambda} \quad (3)$$

$$\eta_m = \tilde{n}_m \cos \theta_m \text{ for s-polarization} \quad (4)$$

$$\eta_m = \tilde{n}_m / \cos \theta_m \text{ for p-polarization} \quad (5)$$

where θ_m is the angle of incidence at layer m and \tilde{n}_m is the complex refractive index of m^{th} layer.

To describe the optical properties of a composite with suspended metal particles, an effective dielectric function theory was proposed by Maxwell-Garnett [10], in which the effective dielectric function of the composite is given by:

$$\tilde{\epsilon} = \tilde{\epsilon}_m \frac{1 + 2f(\tilde{\epsilon}_{sph} - \tilde{\epsilon}_m)/(\tilde{\epsilon}_{sph} + 2\tilde{\epsilon}_m)}{1 - f(\tilde{\epsilon}_{sph} - \tilde{\epsilon}_m)/(\tilde{\epsilon}_{sph} + 2\tilde{\epsilon}_m)} \quad (6)$$

where f is the volume fraction of metal particles in the composite. The complex refractive index \tilde{n} of the composite layer can be extracted from the relation $\tilde{\epsilon} = \tilde{n}^2 = (n + ik)^2$. Thus one can calculate complex refractive index of a composite layer and deduce reflection using equation (1).

3. Modeling Details

An antireflection coating is designed to have embedded metal nano-particles to improve transmission of incident radiation in to the mono/multi-crystalline silicon photovoltaic cell. The schematic diagram of the designed structure is shown in the Figure 1. The aim of this study is to report the effect of embedded metal nano-particle in the performance improvement of solar cell. Here we have presented results for the nano-particles with a diameter of 10 nm scattered within an area of 156.25 cm² (area of commercial 125 mmx125 mm mc-Si wafer based solar cell). The optimization of nano-particle diameter may be taken up in later study.

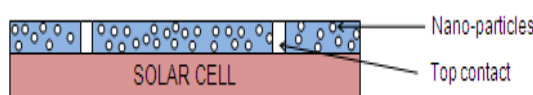


Fig. 1: Schematic diagram of designed anti-reflection coating (top layer) for commercial solar cell.

Based on the theory being outlined in the section 2, composite anti-reflection coating is designed using available optical constant data of silicon nitride [12] and silver [13, 14]. The experimental reflectance data of single layer SiN, with refractive index 1.97 and thickness 81 nm, is extrapolated from B. Kumar et al. [15]. A comparison of the theoretical reflectance for this film, calculated by the outlined theory in section 2, with the extrapolated experimental data for the same thin film is shown in Figure 2.

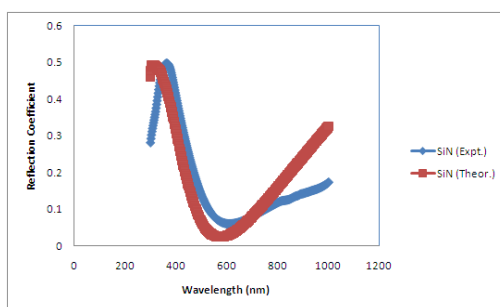


Fig. 2: Comparison of experimental reflection coefficient of SiN with the theoretically calculated reflection coefficient of SiN.

Since the outlined theory is in good agreement with experiment in this case so this theory could be used to study the effect of embedded metal nano-particles. Theoretical calculations for the reflection coefficient of the composite layers are done as shown in Figure 3.

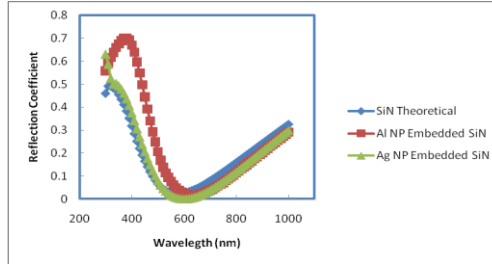


Fig. 3: Reflectance from the modeled metal nano-particle embedded SiN anti-reflection coating.

The reflection data generated using the theoretical treatment is used in the PC1D simulation software to calculate the enhancement in maximum power from the solar cell. The modeling parameters for PC1D simulation are listed in Table 1.

Table 1. Parameters of the baseline model

Solar Cell Parameters	Values
Area	156.25 cm ²
Thickness	200 μm
Emitter contact resistance	4.5 x 10 ⁻⁵ Ω
Base contact resistance	7.2 x 10 ⁻⁵ Ω
Emitter doping, N-type	3.81 x 10 ²⁰ cm ⁻³
Base doping, P-type	1.5 x 10 ¹⁶ cm ⁻³
Rear doping, P-type	1 x 10 ¹⁸ cm ⁻³
Bulk recombination lifetime	25 μs
Surface recombination velocity	S _n = 4.5 x 10 ⁵ cm/s S _p = 1000 cm/s
Primary light source	0.1 W/cm ² AM 1.5
<ul style="list-style-type: none"> • Intensity • Spectrum 	

4. Results and Discussion

All the results discussed in this section are based on the theoretical treatment and the model outlined in previous sections. Effect of Al and Ag nano-particles embedded in SiN is studied. It is observed that the nano-particles may have adverse effect also. That means it may decrease the efficiency of the solar cell due to enhanced reflection. It needs careful design of ARC, proper selection of

metal and optimization of size of nano-particles to have enhanced light trapping and therefore enhanced efficiency of the solar cell. A comparison of I-V curves for three cases is shown in Figure 4. This could be found that Al nano-particles of same size as of Ag nano-particles have adverse effect on the performance of silicon solar cells. The performance improvement is observed with Ag nano-particle embedded ARC. The net efficiency increment is calculated as 0.35% due to Ag nanoparticle embedded ARC.

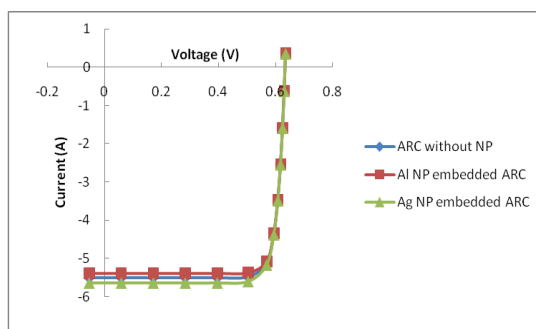


Fig. 4: I-V curves for comparison of performance of solar cell with ARC without NP, Al NP embedded ARC and Ag NP embedded ARC.

5. Conclusion

A theoretical model is used for designing the metal nano-particle embedded silicon nitride anti-reflection coatings. The study is done for single layer anti-reflection coating with embedded Al and Ag nanoparticles. Performance improvement is observed for Ag NP embedded ARC. Adverse effect is seen for Al NP embedded ARC. The net efficiency increment is calculated as 0.35% due to Ag NP embedded ARC. So it could be concluded that the Ag nano-particles embedded silicon nitride ARC helps in performance improvement of commercial silicon solar cells.

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